DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR SUSTAINABLE AND RESILIENCE EVALUATION OF URBAN UNDERGROUND SPACE PHYSICAL INFRASTRUCTURE

By

Lewis O. Makana (MEng)

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School of Civil Engineering
University of Birmingham
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ABSTRACT

Urban underground space is a complex socio-ecological system, housing several integrated sub-systems, of which utility infrastructure systems account for the bulk share in urban centres. Each of these individual geo-structures housed in underground space retains unique characteristics that facilitate the retention of functional performance. It often is the case that sustainability evaluation of underground space use is complex, owing to the interdisciplinary nature of the integrated systems. To appraise the sustainability or otherwise of such systems, geotechnical engineers employ the use of sustainability evaluation tools. The large proportion of these evaluation tools for the geo-professional focus on environmental and/or economic sustainability, at the expense of social sustainability, and hardly ever consider the continued functional performance (resilience) of a geo-structure during sustainability assessment(s). Furthermore, the proclivity towards adoption of a forecasting (trend analysis) approach to planning, remains the current modus operandi for the geo-professional.

The research described in this thesis proposes a new, novel evaluation 'framework' and accompanying operational 'model', the 'SUURE' (Sustainable Underground Use Resilience Evaluation) 'framework', which adopts a socio-ecological systems (SES) approach to evaluation, combining sustainability science and resilience theory, at the same time incorporating a range of interdisciplinary tools and methods to achieve this. It purposes at its core to aid in sustainability evaluation of urban underground space, by evaluating the process to the outcome of sustainable solutions i.e. the capacity to adapt to change in different steady states. In consequence, a fundamentally different approach to planning that utilises future socio-ecological scenarios (NSP, PR, MF and FW) is incorporated in the 'framework' as a means of evaluating through its operational 'model', the sensitivity of investment decisions made today in the name of sustainability i.e. will the proposed engineering sustainability solution continue to deliver its intended function into the future, whatever that may be.

The SUURE operational 'model' was employed as a proof of concept to the case study area of Birmingham Eastside, evaluating the potential use of multi-utility tunnels (MUT) in Eastside as a means of engendering sustainable and resilient use of urban underground space, through sustainable utility placement, both now and into the future. The flush-fitting MUT was found to be having the highest overall baseline (present-day) performance resilience index ratio at mean of 0.739, the shallow MUT second at 0.656, and the deep MUT last at 0.212. With regard to the evaluation of continued MUT functional performance into the future (whatever that may be), all three MUT options, if implemented today in the name of sustainability, would continue to deliver and retain their core functional performance, the deep MUT showing the most significant increase across all evaluation clusters (social, economic, physical, bio-physical and location aspects).

The SUURE operational 'model' evaluation on the case study area of Birmingham Eastside demonstrates that it is a suitable tool to provide better decision-making for the geo-professional, urban planner and policy-maker, aimed at advancement of resilient and sustainable engineering solutions. It markedly improves the defensible formulation of evidenced-based administrative polices, that work towards incorporating an effective measure of resilience, for both the built environment and urban underground infrastructure, for adaption and mitigation, in light of future change.

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"*Every youth should be taught the necessity and the power of application. Upon this, far more than upon genius or talent, does success depend. Without application the most brilliant talents avail little, while with rightly directed effort persons of very ordinary natural abilities have accomplished wonders. And genius, at whose achievements we marvel, is almost invariably united with untiring, concentrated effort*."

[Ellen G. White, Education - 232.3]

USED ACRONYMS

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
BCC	Birmingham City Council
BE^2ST in-Highways	Building Environmentally and Economically Infrastructure Highways
BREEAM	Building Research Establishment Environmental Assessment Methodology
CBA	Cost Benefit Analysis
CEEQUAL	Civil Engineering Environmental Quality Assessment & Award Scheme
CHP	Combined Heat and Power
DDBMS	Decision Database Management System
DGMS	Dialog Generation and Management System
DSS	Decision Support System
DSSs	Decision Support Systems
EGI	Environmental Geotechnics Indicators
EIA	Environmental Impact Assessment
E&R	Excavation and Reinstatement
FW	Fortress World
GAPI	Green Airport Pavement Index
GeoSPeAR	Geotechnical Sustainable Project Appraisal Routine
GIS	Geographical Information Systems
GLEG	Legend File
GSI3D	Geographical Survey and Investigations in Three Dimensions
GSHP	Ground Source Heat Pump
GVS	Generalised Vertical Sequence
ISA	Environmental Sustainability Index
ISI	Sustainability Index
ITA	International Tunnelling Association
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MC-SDSS	Multi-Criteria Spatial Decision Support System
MF	Market Forces
MBMS	Model-Base Management System
MUT	Multi-Utility Tunnel
NJUG	National Joint Utilities Group
NSP	New Sustainability Paradigm
PR	Policy Reform
SEGM	Sustainable Geotechnical Evaluation Model
SES	Socio-Ecological System
SESs	Socio-Ecological Systems
SESEF	Socio-Ecological System Evaluation Framework
SESEFs	Socio-Ecological System Evaluation Frameworks
SI	Sustainability Index
SMCDA	Spatial Multi-criteria Decision Analysis
SPeAR	Sustainable Project Appraisal Routine
SUURE	Sustainable Underground Use Resilience Evaluation
UF	Urban Futures
UUI	Urban Underground Infrastructure
UUS	Urban Underground Space

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The United-Nations (2010) forecasts that the UK urban population (present-day ~84% as a percentage of total population) is only set to increase to ~90% by 2050. This world-wide phenomenon is a trend that will continue into the future, with an anticipated 70% being urbanised by 2050 (Hall & Pfeiffer, 2013). This is in stands in stark contrast to the rural agricultural communities of yesteryear (see Figure 2-1). Current trends in urban land use put a large focus on expansion above ground, and in many urban centres, the underground space is currently underutilised (Sterling et al., 2012). The underground comprises a "*space*", able to house activities which are problematic, impossible or objectionable to locate on the surface (Godard, 2004). This trend cannot however continue in perpetuity, and Bergman (1986), drew attention to the limits that exist for urban centres with respect to the scale of their growth both vertically or horizontally at the surface, emphasising the need for exploitation of the third dimension, namely 'urban underground space'. This significant projected population growth in urban centres, will no doubt lead to greater densities, and resultant stresses within urban areas (Rönkä et al., 1998; Bobylev, 2009a), thus highlighting the key role that urban underground space has to solving mankind's future urban space challenges and delivery of urban underground physical infrastructure. Additionally, this phenomenon has a direct correlation to several wide-ranging contemporary research agendas, e.g. climate change (Bobylev, 2009b), socio-ecological scenario planning (Hunt et al., 2011), law (Matsumoto, 2005), architecture (Duffaut & Labbé, 2008), sustainability (Sterling et al., 2012), and resilience (Sterling et al., 2012; Sterling & Nelson, 2013).

This recognition of the need to utilise the underground space, especially in urban environments, brought about by increased land pressures on the surface as a means of enabling sustainable development (*meeting present and future needs in an equitable manner* – see Brundtland (1987)), is now widely accepted (de Mulder et al., 2007; Parriaux et al., 2007; Bobylev, 2009a; Rogers, 2009; Sterling et al., 2012). The lateral expansion of cities and enlargement in inhabitants that have embodied urban expansion thus far, and development patterns of the last few decades, have shaped metropolises that are time and again contradictory with the principles of sustainable development (Parriaux et al., 2006). For example, more compact cities are looked upon as a conceivable channel on the road to sustainability (Besner, 2002), and cities that optimise the utilisation of the sub-surface are therefore looked upon as a potential route to a more sustainable urban form (Rogers, 2009). A well-functioning urban environment with well-balanced social cohesiveness relies squarely upon use of underground space, to be precise, urban underground infrastructure and its continued delivery i.e. its capacity to adapt to SES change. The provision of utility infrastructure often forms the first stage of any regeneration project, and is by far the most extensive present-day functional use of urban underground space (Carmody & Sterling, 1993; Cano-Hurtado & Canto-Perello, 1999; Rogers & Hunt, 2006; Bobylev, 2009b; Canto-Perello & Curiel-Esparza, 2013; Hunt et al., 2014). Underground space has in times past and presently offered the provision of being utilised for mining (e.g. coal), energy supply (e.g. AC electricity networks and hydroelectric facilities), water supply and removal (e.g. waste water and storm water), transportation (e.g. road and rail), and a whole range other uses including car parks, basements and communication networks (de Mulder et al., 2007). Currently the demand for sub-surface facilities/ infrastructure is increasing, whereas the ability to host them has even now been exceeded in some cities at an advanced stage of development (Evans et al., 2009). However, urban underground space is not a limitless resource, and so if past mistakes of unsustainable development (above ground) are to be prevented, a clear planning and evaluation strategy for the effective use for both short and long term is essential. It is this key driver that set the stage for the work presented in this thesis.

1.2 AIMS AND OBJECTIVES

The overarching aim of this project is to realise through a Socio-Ecological System (SES) evaluation framework (SESEF), grounded in a resilience approach, the quantification of the spatial and temporal impacts of today's urban underground utility physical infrastructure development and regeneration solutions (MUTs) on their sub-surface environments, in light of future change, whilst measuring their long term sustainability. In order to realise this aim, the following objectives were identified:

1. To investigate the current knowledge of resilience through the prism of sustainable development and the existing methodologies and frameworks used to evaluate them in the context of urban underground space use, through a comprehensive literature review.
2. To evaluate as part of the critical literature review, sustainable means of utility service provision and justify the need for improvement against the current practice of open-cut trenching.
3. To develop a sustainability evaluation decision support system that is driven by a resilience approach, to enable a SES evaluation of urban underground space physical infrastructure.
4. To identify a case study area where underground utility service physical infrastructure could be installed using MUTs as an alternative to the current practice of open-cut trenching.
5. To develop a computational model of the complex geology of the case study area in question that can be used as part of an SES evaluation.
6. To carry out a SES evaluation of MUTs (urban underground physical infrastructure – flush-fitting, shallow and deep) as proof of concept on the case study area in question (Birmingham Eastside), in addition to incorporating as part of the SES evaluation, the complex geology of the case study area under evaluation.
7. To establish the impact of different socio-ecological future scenarios on the SES under evaluation i.e. its capacity to adapt to change, specific to utility service provision through MUTs (flush-fitting, shallow and deep) in the case study area under examination as a by-product of the novel SESEF developed.

1.3 SCOPE AND STRUCTURE OF THE THESIS

The outline of the thesis is shown in Figure 1-1. Chapter 1 presents the background to the research areas relevant to the thesis, aims and objectives. In Chapter 2 presents an overview of the urban underground space, touching on the key aspects of resilience and sustainability, including but not limited to cases of sustainability related issues and implementation of sustainable underground space utilities infrastructure use. Chapter 2 also presents the state-of-the-art review with respect to current methods of evaluation of underground projects, both in terms of sustainability and resilience. Chapter 3 introduces a new sustainability evaluation decision support system, the 'Sustainable Underground Use Resilience Evaluation' (SUURE) Framework and accompanying Operational Model, which merges sustainability science and resilience theory (Socio-Ecological System - SES) as a means of bridging the gap identified in the published literature. Chapter 4 presents the case study area of Birmingham Eastside and its developmental history relevant to urban underground space infrastructure use. The chapter continues on to outline the development of a 3D sub-surface geological model of Birmingham Eastside, thus permitting for complex geology to be accounted as stipulated by the SUURE evaluation Operational Model. Chapter 5 presents the application of the developed SUURE Operational Model on the case study area of Birmingham Eastside, with regard to urban underground utilities infrastructure (MUTs) as a proof of concept. Chapter 6 presents the conclusions and summary of the thesis, in addition to recommendations for future work.

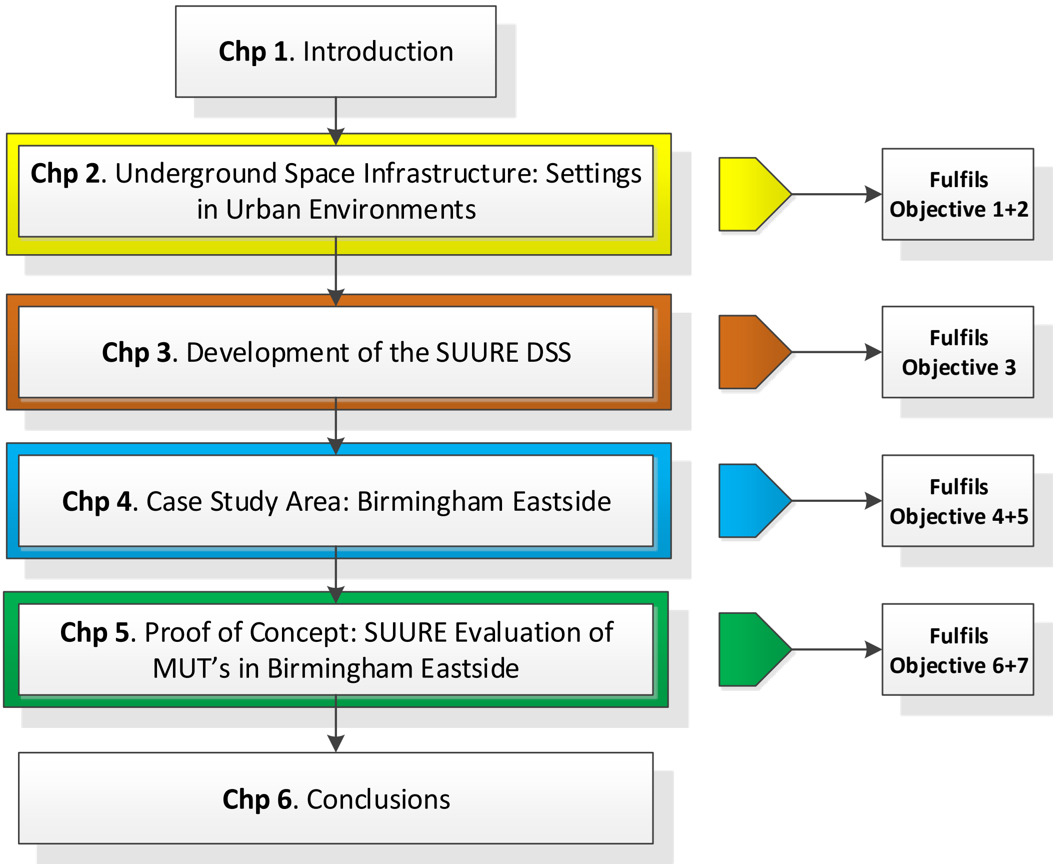


Figure 1-1: Thesis Outline

CHAPTER 2: UNDERGROUND SPACE: SETTINGS IN URBAN ENVIRONMENTS

2.1 INTRODUCTION

The subsurface (underground) environment functions in the role of a dynamic terminal through which anthropological systems and the ecosystem interact and impact each other. The recognition of this interdependence is vital to understanding sustainability as it pertains to civil engineering. The burgeoning consensus points to the fact that realising a sustainable built environment begins through integrating considerations of sustainability at the planning and design stages of an infrastructure construction project (Braithwaite, 2007; Wallbaum et al., 2010; Rogers et al., 2012). The need to account for resilience as a defining agenda in this on-going debate has increased exponentially in recent times (Boin & McConnell, 2007; Hodson & Marvin, 2009). It is this interaction and interface between the realms of sustainability and resilience that will be the work of years to come and forms the underlying focus of this thesis; in the context of the present work, a different way of understanding urban underground space (Sterling & Nelson, 2013). Urban underground space (UUS) has been used for many centuries; nonetheless acceptance that it is an irreplaceable, valuable, and in-demand resource has only materialised recently (Parriaux et al., 2007; Bobylev, 2009a; Sterling et al., 2012). UUS can be defined as a space beneath urban areas that provide direct services to a city (e.g. groundwater supply or geothermal energy). UUS encompass geologically formed rocks and soils, and artificial structures, as well as caverns of various origins. Parriaux et al. (2007) have identified four basic UUS resources: space, materials, water, and energy. These resources have different degree of renewability, depending on their use and/or rate of extraction (Sterling et al., 2012). The underground space embodies a significant means for future solutions in the progress and development of living conditions for mankind and these have to carefully considered (Godard, 2004; Jefferson et al., 2006; Simpson & Tatsuoka, 2008; Rogers, 2009; Hunt et al., 2011). This chapter surveys the sustained development in the usage of UUS underneath urban environments, in addition to the prevalent absence of important and wide-ranging planning efforts for its use. It seeks to draw upon the fundamental question of what reasons qualify a more demanding and better designed utilisation of this space, examining the role that both resilience and sustainability have to play in this process, in addition to reviewing present-day evaluation frameworks (in terms of resilience and sustainability) designed for underground space.

2.2 UNDERGROUND SPACE IN AN URBAN ENVIRONMENT

The pursuit for additional space in large urban areas is a global phenomenon. By 2009, in excess of half of the world-wide inhabitants were living in urban centres, and this is only set to increase (Besner, 2002; Parker, 2004). Angel et al. (2005) projected growth in urban centres in developed nations from 300 000 km^2 in the year 2000, to 700 000 km^2 by 2030 as well as in emerging nations, from 250 000 km^2 in 2000, to 820 000 km^2 by 2030. According to Godard (2004), the manifestation of this movement is a continuous growth and increasing density in our towns and cities, as the preferred space for the development of humanity. Examination of Figure 2-1 suggests that urbanisation in reference to global physical city area expansion (276% by year 2030) will take place much more speedily as opposed to the global population growth in cities (66% by 2030) (Grimm et al., 2008). Logically, this drift raises a certain number of challenges in regard to urban underground infrastructure provision and development which grow proportionately with the size of the city (Hunt & Rogers, 2005; Rogers & Hunt, 2006; Hunt et al., 2009; Admiraal, 2010).

Thoughts regarding the importance of UUS to address urban development were raised approximately a century ago by Hénard (1903). These assertions regarding the importance UUS have been re-examined intermittently since that time by a range of authors and institutes comprising (Utudjian, 1952; Utudjian & Bernet, 1966), Fairhurst (1976), Duffaut (1977), Parker and Daly (1981), Carmody and Sterling (1993) and Godard and Sterling (1995). The most recent discussions include Hunt and Rogers (2005); Jefferson et al. (2006); Parriaux et al. (2006); Rogers and Hunt (2006); Simpson and Tatsuoka (2008); Bobylev (2009a); Sterling et al. (2012) and the collective works by the International Tunnelling Association (ITA) (1970-2014).

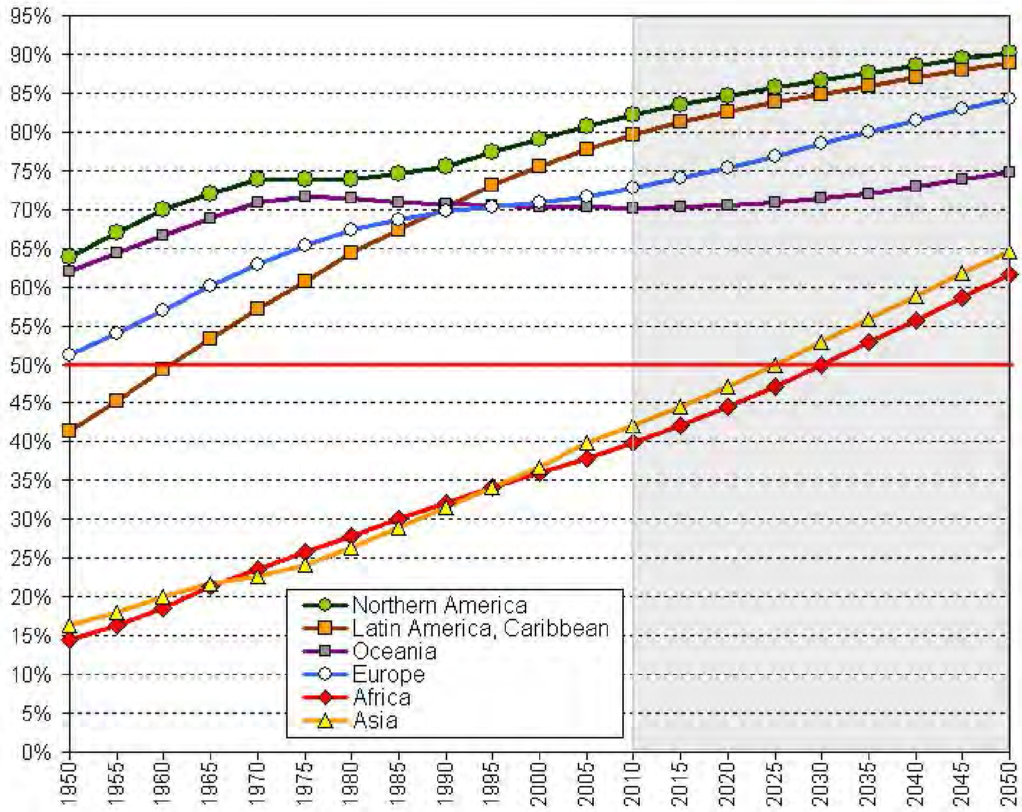


Figure 2-1: Urban population by major geographical area (in % of total population), United-Nations (2010)

Existing urban areas usually produce the greatest challenges for underground construction for the reason that land is scarce for new facilities, vast population densities subsist, and the pre-existence of heritage and cultural resources. Contrary to this scenario in present urban environments, the imminent development of 'up-and-coming' cities (see Figure 2-1), mainly in regions undertaking underground construction projects for the first time on land lacking other valuable structures, offers an exceptional opportunity for prudent planning and evaluation of underground infrastructure development policies as well as the prevention of miscalculations made by many older cities (Bobylev, 2009a).

Figure 2-2 below advocates that high population densities, and perhaps, building stock densities are driving forces for the development of the UUS; this indicates that cities with high population densities cannot avoid development of their UUS, and according to several authors this is a reasonable assumption (Horvat et al., 1998; Monnikhof et al., 1998; Chow et al., 2002; Evans et al., 2009). The fundamental difficulty in realising appropriate planning and development of UUS appears to lie in the slow but sure increase of UUS usages and their invisibility to planners and policy makers and the public under ordinary circumstances.

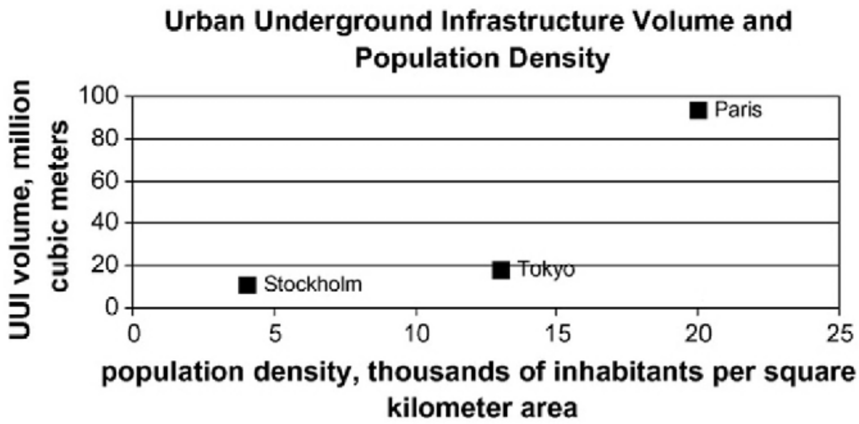


Figure 2-2: Relationship between population densities in urban areas and volumes of urban underground infrastructure (Bobylev, 2009a)

Uses of UUS propagate in importance when basic needs in major cities have to be met. For example, Hanamura (1998) asserts that it is fundamentally inconceivable for a modern city to exist or be sustainable devoid of UUS water diffusion and sewerage conduits. Then again, adequate utilisation of UUS time and again is considerably hindered by the first-come, first-served tendency of pre-existing usage/ underground structures (Jefferson et al., 2006; Sterling, 2007; Rogers, 2009). The main point for 'up-and-coming' cities is for all planners and policy makers to be aware of the opportunities and threats with reference to use of UUS and to put in place well-thought-out systems of underground planning that will provide the platform for UUS use if required (e.g. evident population density growth). This proactive approach to planning is essential to avoid the conflicts that arise (environment vs. infrastructure) due to increased dense urban development, and subsequently land use. The supreme opportunities for significant restructuring of cities by means of underground development transpire in dense developments where land availability for redevelopment is scarce and surface land prices high (see Figure 2-2). Nonetheless as a consequence of the high initial cost and long-lasting modification of the underground environment, underground construction lays a special emphasis on long-term planning (Abreu et al., 2008; Hunt et al., 2011), which accounts for life-cycle cost-benefits as well as the selection of projects that comprise the maximum input to urban sustainability as opposed to a short-range solution leaning towards a singular need; thus ensuring that the sum of the whole is greater than the individual parts.

Consideration of UUS as a policy issue is consistently brought about by increasing land use pressures or development opportunities as evidenced in countries such as China, Finland, Sweden, Norway, Netherlands and Japan. Cutting-edge tunnelling machinery in Japan for instance, has paved the way to the widespread usage of underground space in soft ground conditions (for example the soft estuary soils below the metropolises of Osaka and Tokyo) to ensure provision of urban infrastructure requirements (Hanamura, 2002). To enable corresponding underground developments comparable to those in Tokyo and Osaka, Japan has enforced through legislation the usage of deep underground space (see Figure 2-3) intended for municipal infrastructure even underneath private lands (Matsumoto, 2005). By the same token, the administrative strategy document 'Management regulation of the development and utilization of urban underground space of China', published in October 1997, affords legislative grounds intended for the development of UUS in China (Li et al., 2009). Similarly, the National Planning Agency of the Netherlands in 2000, dedicated its yearly publication to the theme 'Good use of the underground', making it the first official recognition at policy level aimed squarely at the need to organise the utilisation of UUS (Admiraal, 2006).

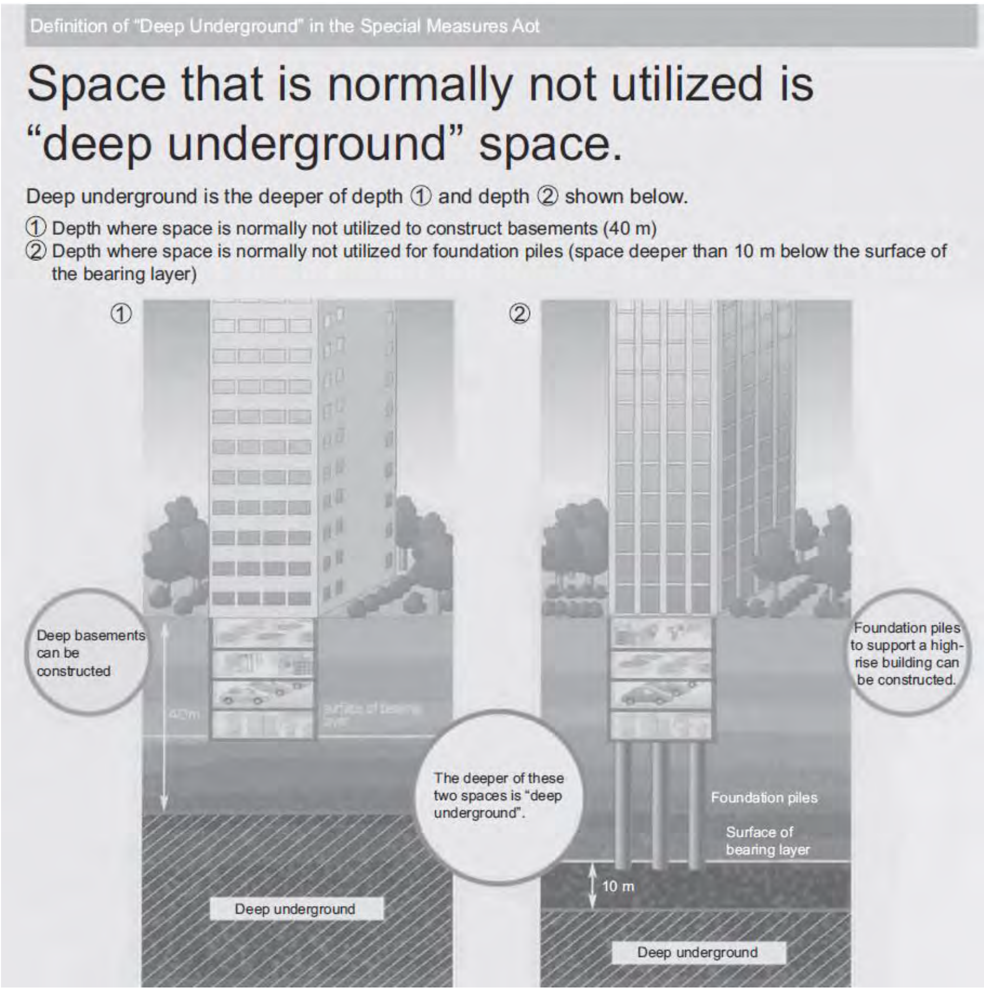


Figure 2-3: Illustration of 'deep' underground space in the Underground Special Measures Act in Japan (Sterling et al., 2012)

These policy models in relation to UUS are good examples of the kind of approach needed to engender resilient and sustainable use of UUS. Nevertheless, they stand in contrast to various countries for instance the UK and France where utilisation of UUS is widespread, wide ranging debates on UUS issues abound, yet few efforts exist to institute UUS master planning initiatives. Instances of systematic management of UUS in the USA exist but they are dotted about (e.g. Vitt and Kjelshus (1980); Subspace (1990)) with inadequate consideration from the civil planning community (Sterling et al., 1983). Singapore stands as case-and-point of a country that is presently establishing a path toward future sustained use of underground space as a result of severe land pressures and sought after economic growth, causing it to commence a broad master planning exercise for UUS in addition to underground space in less developed (rural) regions (Singapore-Government, 2010).

The significance of resiliency and sustainability has grown to be more evident in the past twenty five to forty years – owing to various familiar and every now and then contentious events and issues. Sterling and Nelson (2013) highlight some of the key concerns which comprise but are not limited to: (i) Future accessibility and supply of adequate food and clean water; (ii) Limits to the availability of fossil energy and mineral resources; (iii) The possible effects of climate change/global warming; (iv) The tangible and/or perceived rise in catastrophic natural events; (v) The growing impact of such events on infrastructure and the built environment, and (vi) The growing risk of terrorist attacks on critical public systems. When considered independently or simultaneously, the terms resilience and sustainability are beneficial for the reason that they make available readily logical and suitable attributes for the public, an infrastructure system, an urban centre or country. They offer the provision to take account of long-term future concerns within present-day public discourse; urban planning and facility design choices all the more so when direct benefit-cost analysis is not accessible. The definitions of resilience and sustainability are not in all cases explicit. The scope of issues considered is broad and resilience and sustainability have several different possible explanations in relation to distinctive research clusters, and in divergent settings. The following section introduces the concept of sustainability in both form and function, and Section 2.5 in relation to resilience and sets the theoretical basis upon which a socio-ecological systems evaluation framework (SESEF) can be formulated (see Chapter 3).

2.3 SUSTAINABLE DEVELOPMENT: A COMPREHENSIVE AGENDA

Sustainability is a comprehensive agenda and in most cases a challenging, open and contested concept (Lele, 1991; Gladwin et al., 1995; Mebratu, 1998; Giddings et al., 2002; Banerjee, 2003; Neumayer, 2003; Parris & Kates, 2003; Robinson, 2004; Redclift, 2005; Bagheri & Hjorth, 2007; Connelly, 2007; Milne et al., 2009; Martínez-Alier et al., 2010; Dempsey et al., 2011; Lombardi, Porter, et al., 2011; Dryzek, 2012; Elliott, 2012). Though represented as a contemporary theory, it is, in reality, entrenched in what we determine to do and constantly has been. On the other hand, the significance in reinforcing 'sustainability' as a subject matter that needs close attention is that it demands being clear-cut and precise in the policymaking process, besides being implied (see Figure 2-4). The classical conventional three-pillar model of sustainability, comprising economy, society and the environment as coined by Brundtland, is frequently cited as the core of sustainability rational and time, cost and quality (triple bottom-line model), has been popularised when bearing in mind sustainability performance in project costing (Rogers, 2009). The classical three-pillar model has provided a platform that has raised the concerns of sustainability to the foreground of present-day rational, and has been applied in specifying and evaluating, by use of 15 headline indicators (DEFRA, 2003), sustainable development inside the UK at a national level; the condition for 'economic growth' has since been revised to 'economic stability and competitiveness' (DEFRA, 2004), thus demonstrating the universal boundaries that economic progress indicates within UK sustainable development.

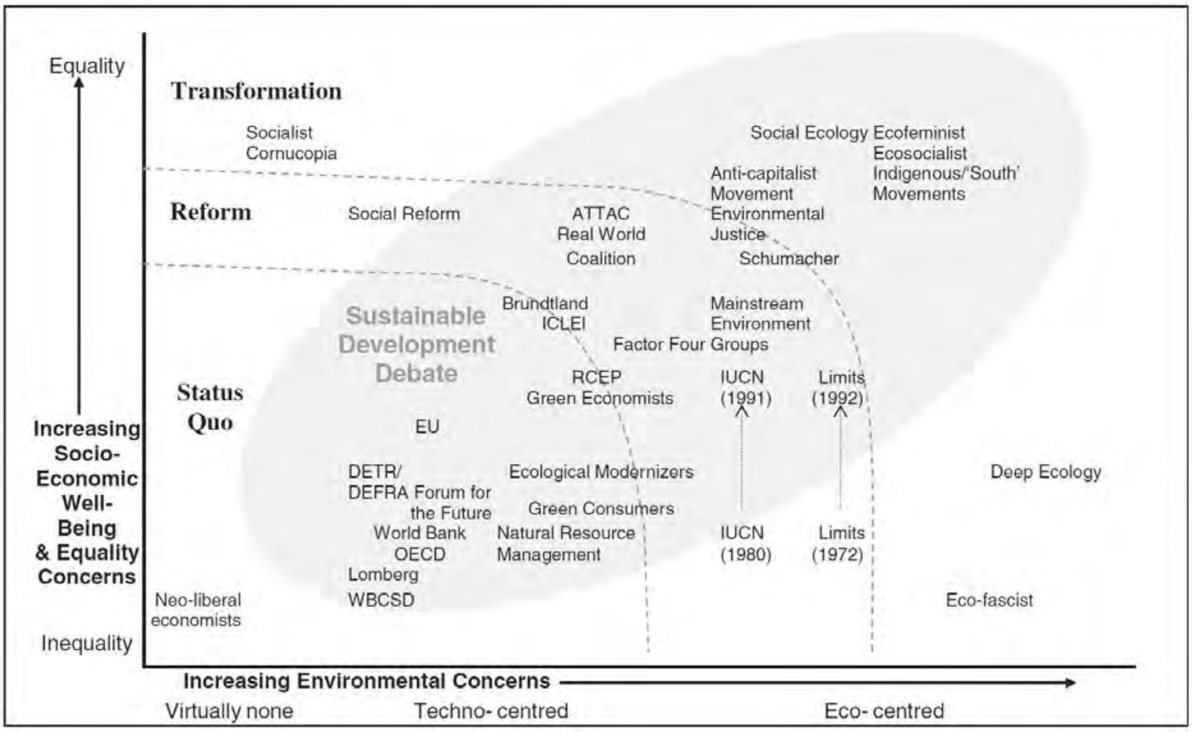


Figure 2-4: Mapping of views on sustainable development

An examination of the differing assertions regarding sustainability demonstrates that construction and moreover UUS is an essential medium for realising both economic growth and social progress (see Figure 2-5), this having been implied but not declared explicitly (Rogers, 2009). Nevertheless, realisation that both economic growth and social progress ought not to transpire at the expense of the environment (e.g. depletion of groundwater levels, river quality, air quality, and excessive carbon emissions), stresses the difficulty associated in wanting to realise sustainable construction. In actual fact, the economy cannot be present deprived of a society, and society cannot be existent devoid of an environment (Giddings et al., 2002), and for that reason the primary assessment for sustainable construction ought to justifiably be its environmental performance as understood when taking into account sustainable development as an embedded model (see Figure 2-4).

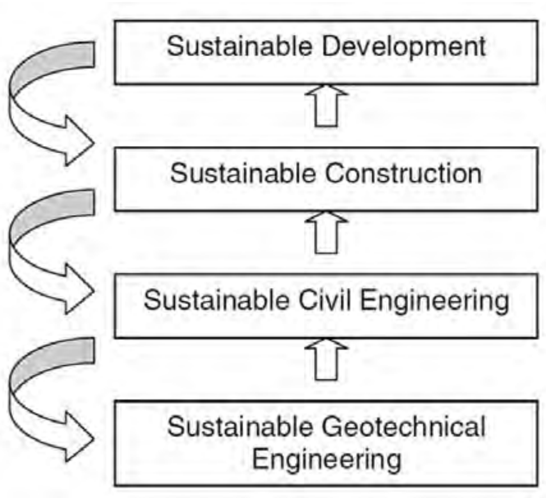


Figure 2-5: UUS (i.e. geotechnical engineering) in the construction chain (Abreu et al., 2008)

The effectiveness of the classical three-pillar model has been critiqued due to its limitations in particular circumstances to deliver a suitable equilibrium (see Figure 2-6); for instance, 'cultural vitality, good governance and political frameworks' (Hawkes, 2001) have been recommended for insertion. An appropriate illustration is Arup's SPeAR model (see Figure 2-21), which comprises 'natural resources' as the fourth pillar with extensive applications in civil engineering developments (McGregor & Roberts, 2003). In 2005, the UK Sustainable Development Strategy Framework indicators were amended to included resource expenditure (DEFRA, 2005).

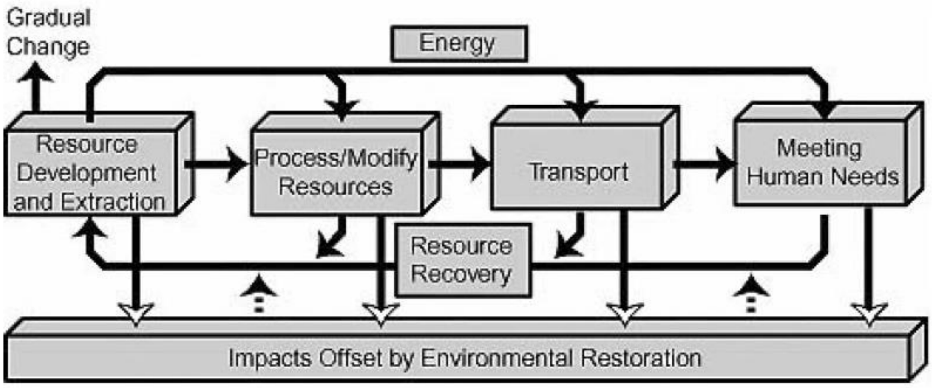


Figure 2-6: Elements of a sustainable system for humankind which include resource expenditure (Roberts, 1996)

Nevertheless, whatever model is implemented, it is vital to pursue a coherent broad definition for sustainable development. Brundtland (1987) is the most frequently cited explanation which is: '*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (ecological integrity, equity between nations, the individuals and the generations, and economic efficiency). Several other 'operational' definitions of sustainable development were suggested since, but none can satisfy concurrently the justifiable requirements of all the individuals, the peoples, the companies or the organisations (Besner, 2002; Owens & Cowell, 2011) (see Figure 2-4). For one reason or another, the enduring acceptance of Brundtland' description is its convincing, intelligible foresight, and so far conformity to this definition has not been without it challenges as it necessitates an estimation of the future environment. A justifiable, yet fragile attitude would be to sidestep 'compromising the ability of future generations to meet their own needs' presuming that the existing state of affairs remains, but this would be to disregard our obligation to future generations and essentially contradict the essence of the definition (Hopwood et al., 2005; Rogers, 2009; Bettencourt & Kaur, 2011). The need to foresight the future environment was stressed by (Stephan A. Jefferis, 2008), who emphasised that the key is to conceptualise all of the points in question, and Clayton (2009) who raised Donald Rumsfeld's illustrious quote ('*there are known knowns, and known unknowns, . . .*') laying emphasis that it is the 'unknown unknowns' that cannot be neglected.

Porritt (2000) elucidation of sustainable development mentions 'capacity for continuance into the long-term future' and, it occasions yet again, that we must foresight (i.e. employing scenarios) the long-term future when realising sustainable development. Foresighting the future can encapsulate many permutations and combinations and is dependent on the epoch in question, but the mechanisms that permit us to make use of foresights are advancing, e.g. see Hunt, Lombardi, Atkinson, et al. (2012);

Rogers et al. (2012). Thoughts that tend in this direction are suitable; bearing in mind the differing perspectives (in addition to time perspectives) permits us to make judicious judgements, irrespective of the chosen action, and the perspectives of different futures are integral to this process (Rogers et al., 2012); many would have an influence on underground engineering (UUS) and would be accounted for in designs if they were identified and quantifiable impacts (Hunt et al., 2011).

2.4 SUSTAINABILITY AND UNDERGROUND SPACE FACILITIES

UUS services facilitate sustainable development as they benefit from certain natural features. Sterling et al. (2012) asserts that facilities housed in UUS provide the definitive 'green roof'. Facilities located entirely in UUS (when built) prohibit trauma or shocks to above ground structures besides providing natural landscape surfaces and vegetation that preserve the natural ecological exchanges of the hydrological cycle (see Figure 2-7).

Figure 2-7: Underground school facility, Arnhem, the Netherlands (Admiraal, 2006)

In point and fact, the contrast between above ground and below ground facilities remains considerably more problematic as a result of the broad range of categories and functions of underground facilities that prevail; see for example Bobylev (2009a); Rogers (2009). Furthermore, since underground facilities have to be built from above ground and merge with above ground for entrance/ exit and several systems of facility services (e.g. maintenance access, waste removal, ventilation etc.), full detachment from above ground impacts to UUS is not possible. A summary of the advantages (benefits) and disadvantages (drawbacks) of underground facilities is presented below in Table 2-1.

Table 2-1: Benefits and drawbacks of underground facilities (Carmody & Sterling, 1993, p. 26)

Major Issues	Subcategory	Potential Benefits	Potential Drawbacks
Physical and Institutional Issues	Location	Proximity Lack of surface space Service provision Status	Unfavourable geology Uncertain geology
	Isolation	Climatic thermal, severe weather, fire, earthquake Protection noise, vibration, explosion, fallout, industrial accident Security limited access, protected surfaces Containment	Climatic thermal, flooding Communication Human issues psychological acceptability, physiological concerns, fire safety, personal safety

Major Issues	Subcategory	Potential Benefits	Potential Drawbacks
		hazardous materials, hazardous processes	
	Preservation	Aesthetics visual impact, interior design Environmental natural landscape, ecology, run-off Materials	Aesthetics visual impact, building services, skilful design Environmental site degradation, drainage, pollution
	Layout	Topographic freedom 3-dimensional planning	Ground support Span limitations Access limitations Adaptability Sewage removal
	Institutional		Easement acquisition Permits Building code Investment uncertainty
Life Cycle Cost	Initial Cost	Land cost savings Construction savings no structural support, weather independent, scale Sale of excavated materials or minerals Savings in specialised design features	Confined work conditions Ground support Limited access Ground excavation, transportation, and disposal Cost uncertainty geological, contractual, institutional delays
	Operating Cost	Maintenance Insurance Energy use	Equipment/ material access Personnel access Ventilation and lighting Maintenance and repair
Societal Issues		Land use efficiency Transportation and circulation efficiency Energy conservation Environment/ aesthetics Disaster readiness national security Less construction disruption	Environmental degradation Permanent changes Embodied energy

It should be noted in reference to UUS facilities, that it is often very difficult to revert them back to a larger degree than surface facilities, to their pre-construction state, more so in UUS structures housed in rock caverns which cannot be returned to their original condition as geomechanical properties and surrounding ground water conditions would have likely changed forever. This observed phenomenon is significant in light of the aim of sustainable development to leave a positive legacy to future generations, who should also be able to meet their own needs. Consequently as soon as underground space is utilised even once to meet the needs of the present, it necessitates that it cannot be reverted to its original state, but provisions should be made to safeguard future utilisation for differing form or function. This limitation to usage of UUS can be in most cases moderately insignificant and in some limited cases of great significance (e.g. storage of hazardous substances for industry), but provision for long term planning in such cases is of the utmost importance so as to limit any barriers to future continued use of UUS. Several barriers exist that constrain one's ability to administer sustainable use of underground space (Hunt & Rogers, 2005), while by the same token, the same authors point out a corresponding set of enablers and refer to one of the most significant enablers of designs that achieves a happy medium of the functional issues as being the early participation of all stakeholders in the decision-making/ policy-making process. Hunt, Lombardi, Jefferson, et al. (2008) specify a framework for this purpose to optimise decision-making so as to mitigate future adverse impacts (see Figure 2-8). The authors propose that timely decisions have to be taken by decision-makers throughout a redevelopment of UUS infrastructure for utility services as 'windows of opportunity' exist that will either 'lock-in' or 'lock-out' choices; hence addressing the complexity of trade-offs in decision-making concerning a number of sustainable choices above ground and their requirement for UUS.

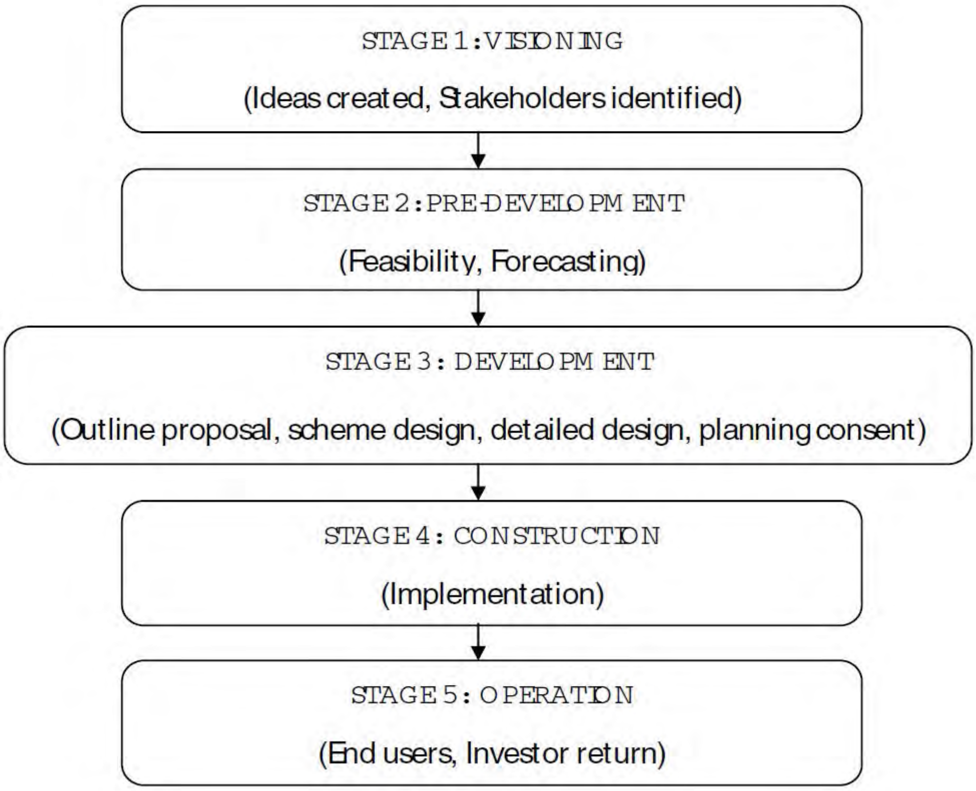


Figure 2-8: Overarching five-stage process of the development timeline framework (showing key activities) (Hunt, Lombardi, Jefferson, et al., 2008)

Subsequent to the above-mentioned premise, UUS use can be held to be proportional to the sustainability of urban environments, since utilisation of underground facilities has a bearing upon the degree to which anthropological use of land area on the above ground environment is possible (see Figure 2-9). For instance, use of UUS through utility service provision and a developed transport system that would be unworkable to house above ground, can change the economic circumstances in cities for the better. Use of underground facilities can also provide the added advantage of evading damaging effects to the local community of a city as soon as a considerable large-scale above ground infrastructure development intrudes into occupied districts. Nevertheless, it is essential to recognise that UUS is an environmental entity as well as a natural resource in its own right and thus is susceptible to alteration or damage by anthropological activities in the underground (e.g. mining, tunnelling and ground water abstraction) (Evans et al., 2009).

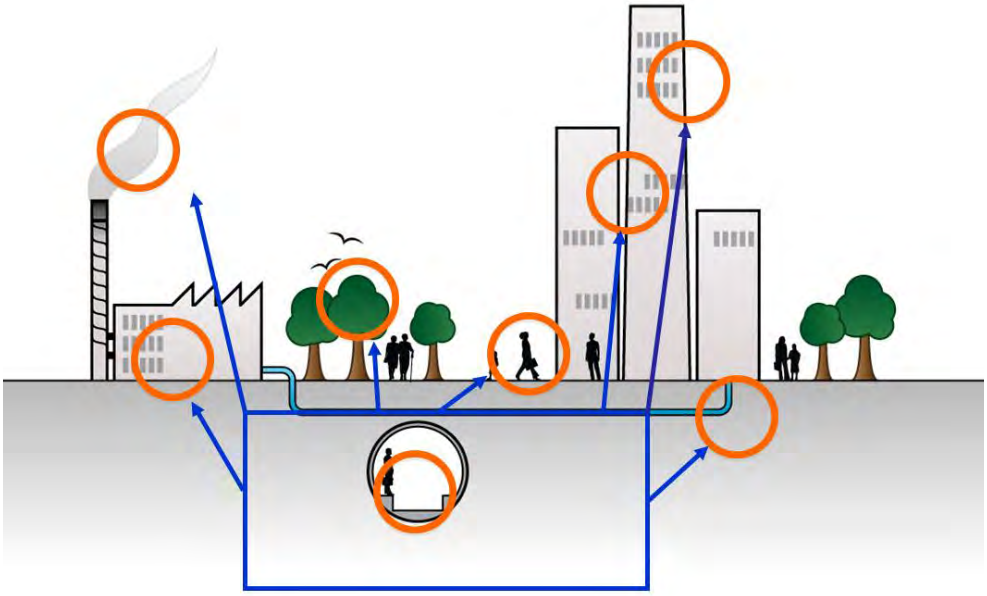


Figure 2-9: Different dimensions of urban sustainability that UUS impacts within the urban landscape (Lombardi et al., 2012)

Parriaux et al. (2007) classified the four basic functional elements that comprise the sub-surface environment by way of a resource as: space (i.e. for construction of urban systems & structures, heritage resources); geomaterials (i.e. the geomechanical properties of geologically derived materials); groundwater (i.e. underground aquifers), and geothermal energy. The important points in question for sustainability as pertaining to each element are outlined below:

(a) Space: Cities have transformed historically (agricultural centres to industrial centres) as have their land use planning programmes from commercial and populous land oriented development, to present day heavy-composite urban developmental planning (O'Sullivan, 2012). By means of increased urban development, space thus develops to an increasingly prized and scarce commodity. This phenomenon leads progressively to the locating underground of service facilities and additional facilities that do not need to be housed above ground. Despite the fact that anthropological excavation of underground cavities can reach in excess of 3000m in mining operations, merely the topmost stratums of the underground can be regarded as valuable for UUS functions. Nearly all utility and pedestrian functions compete for space in the top 0-6m from the surface, whilst selected transit tunnels and deep utilities might increase to the 50-80 m depth (excluding tunnels that pass through hills and mountains) (Evans et al., 2009). Although more space is required in urban areas, however additional land leasing is restricted, space hunting in urban environments is heading towards a three-dimensional trend.

(b) Geomaterials: Accessibility of raw materials has a significant influence on construction activities, above or below ground. Mining and quarrying zones are in recession, delivery of raw materials has grown to become a demanding endeavour. A eco-friendly material point of supply from construction excavation sites may well alleviate material supply deficits (Rochat et al., 2006). Meaningful characteristics of materials in UUS involve assessment of: the soil/rock structure within which excavation must take place, groundwater is retained, and facilities constructed; several valuable resources/ minerals that can be mined; besides any dangerous materials (natural or artificial) that require isolation (Sterling et al., 2012).

(c) Groundwater: Water is a crucial production element for agriculture, manufacturing and urban development. The utilisation of groundwater is in excess of 70% of the overall water consumption in the majority of the Eurozone urban areas, particularly for drinking water (Zektser & Lorne, 2004). Groundwater is a critical natural resource of the underground that is coupled to the local and global hydrological cycle; variations in groundwater conditions (e.g. through groundwater abstraction) could be capable of disturbing above ground structures.

(d) Geothermal Energy: Energy supply is a difficult undertaking for contemporary society's esp. in urban areas. Transport and building energy requirements account for over and above half the energy demand experienced. Energy as an underground resource group comprises geothermal resources that can be retrieved via active heat conversation with the ground (e.g. ground source heat pumps (GSHP) market is growing throughout the globe (Jacobs, 2010) employing mechanical systems, along with the reduction in heat exchange for facilities housed underground and the corresponding energy conservation opportunities.

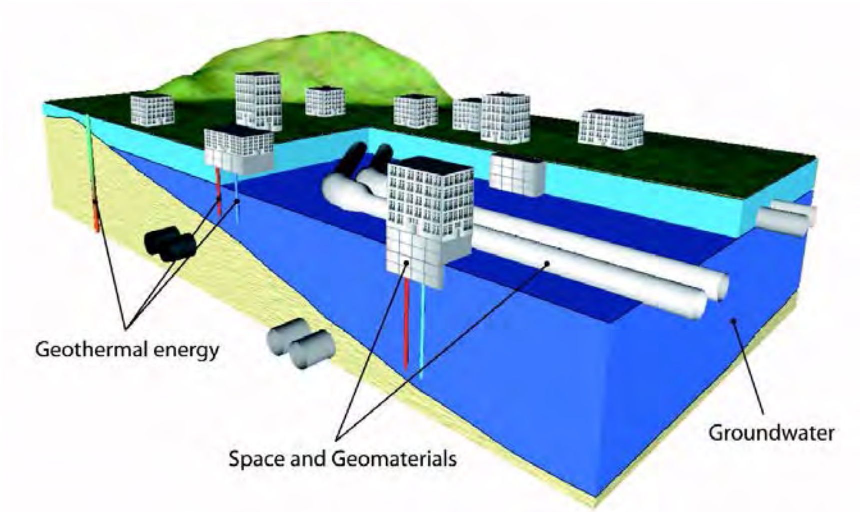


Figure 2-10: The four main resources of the urban underground (Parriaux et al., 2006)

Bobylev (2009a) contends that the 'ecosystem services', or else natural resources in their broadest sense that are offered by the underground space (see Figure 2-10) have been underestimated in terms of their value, which in turn has brought about the absence of adequate planning measures for UUS utilisation as a valuable resource (i.e. accounting for resilience in its broadest sense). Bobylev furthermore splits UUS resources into renewable vs. non-renewable services/ resources (see Figure 2-11); passive alongside active utilisation of services/ resources (e.g. groundwater supply for surface vegetation in contrast to drinking water supply); also the amount of 'competition' and/ or elimination of the utilisation of services/ resources (can various services coincide or does use of UUS for one prior service or resource prevent other potential uses of UUS; e.g. 'cultural heritage' which can prevent an area of unique geological value from being excavated). The following sections seeks to elucidate the manner in which such ecosystem services can be understood in the context of this thesis. It highlights just how the theoretical root of ecosystem services i.e. resilience, can be understood within sustainability science and suggests a typology that forms the basis for the present work i.e. a socio-ecological systems (SES), thereby clearly spelling out what conceptual structure resilience is to take in this thesis. This clear description affords the basis upon which both the operationalisation and application of resilience within sustainability science is can be realised in order to develop a socio-ecological systems evaluation framework (see Chapter 3).

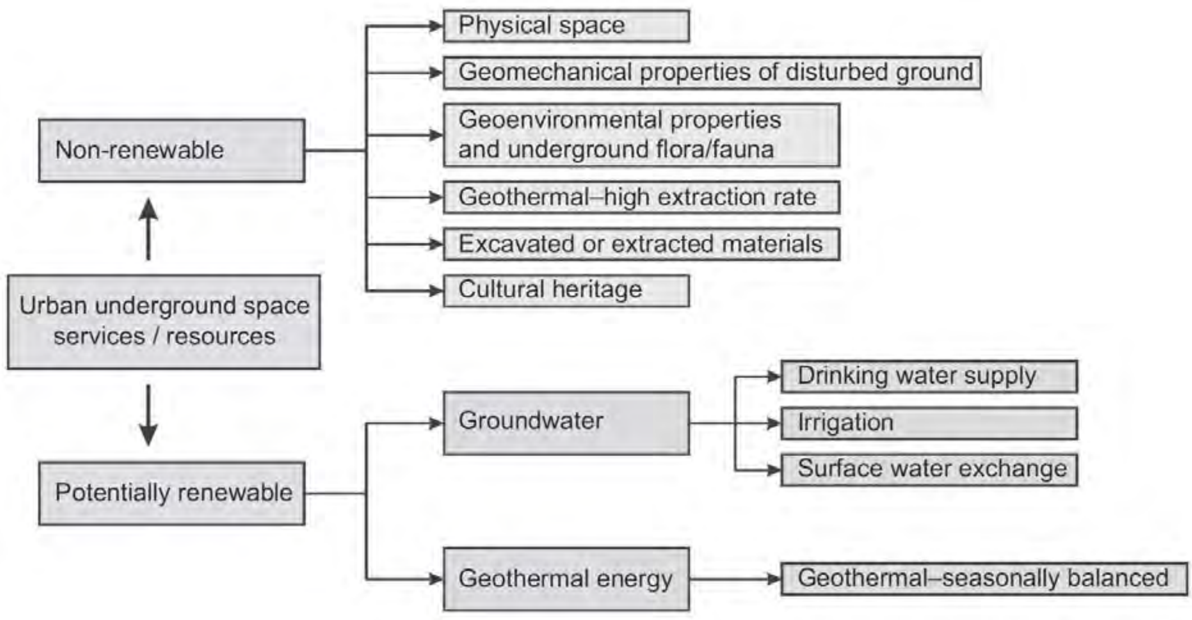


Figure 2-11: Renewable and non-renewable underground resources (Bobylev, 2009a)

2.5 RESILIENCE-THEORY IN SUSTAINABILITY-SCIENCE

The abstract concept of resilience is amongst the most significant research areas in the context of realising sustainability (Perrings, 1995; Kates et al., 2001; Foley et al., 2005). Resilience was first introduced as a descriptive ecological term (Holling, 1973), it has since that time undergone several redefinitions and extended with respect to normative, metaphorical and heuristic dimensions (e.g. Holling (2001); Ott and Döring (2004); Pickett et al. (2004); Hughes et al. (2005)). Meanwhile, resilience as a concept has been employed by a broad range of scientific disciplines as an approach to evaluate ecological along with socio-ecological systems (Anderies et al., 2006; Folke, 2006). As such, resilience stimulates research efforts amongst disciplines and between science and policy.

As a result over time of the extension of resilience through descriptive and normative aspects, it has suffered as regarding its conceptual clarity and practical applicability. To limit the current wide extension of the term resilience and its ambiguous use in general terms is important in this thesis. This assertion is made with the understanding that the successful application of the concept in stimulating research across sustainability science and resilience theory (as necessitated by the aims and objectives of this thesis) on the one side and the watering down of the descriptive core on the other hand, solicits the fundamental question, what conceptual structure of resilience is required as a basis for the current work.

Given this context, the result of analysis by Brand and Jax (2007), focusing on the meaning(s) of resilience (see Table 2-2), displays 3 categories, 10 classes, and correspondingly 10 definitions of resilience. It is important to note that the three categories reveal whether the definition aligns with either a genuinely descriptive concept (Category I), a hybrid concept, where descriptive and normative meanings are fused (Category II), or a truly normative concept (Category III). It also is noteworthy that Class 1–4 represents purely ecological definitions and Class 5–10, those that are employed in other fields (e.g. economy, sociology).

Table 2-2: Ten definitions of resilience with respect to the degree of normativity (Brand & Jax, 2007)

Categories and classes	Definitions	References
(I) DESCRIPTIVE CONEPT		
(Ia) ECOLOGICAL SCIENCE		
1) Original-ecological	Measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.	Holling 1973:14
2) Extended-ecological	The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour and	Gunderson and Holling 2002:4
	The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity	Walker et al. 2006:2
2a) Three characteristics	capacities i) to absorb disturbances, ii) for self-organization, and iii) for learning and adaptation	Walker et al. 2002
2b) Four aspects	1) latitude (width of the domain), 2) resistance (height of the domain), 3) precariousness, 4) cross-scale relations	Folke et al. 2004:573
3) Systemic-heuristic	Quantitative property that changes throughout ecosystem dynamics and occurs on each level of an ecosystem's hierarchy	Holling 2001
4) Operational	Resilience of what to what? and	Carpenter et al. 2001
	The ability of the system to maintain its identity in the face of internal change and external shocks and disturbances	Cumming et al. 2005
(Ib) SOCIAL SCIENCES		
5) Sociological	The ability of groups or communities to cope with external stresses and disturbances	Adger 2000:347

Categories and classes	Definitions	References
	as a result of social, political, and environmental change	
6) Ecological-economic	Transition probability between states as a function of the consumption and production activities of decision makers and	Brock et al. 2002:273
	The ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently	Perrings 2006:418
(II) HYBRID CONCEPT		
7) Ecosystem-services-related	The underlying capacity of an ecosystem to maintain desired ecosystem services in the face of a fluctuating environment and human use	Folke et al. 2002:14
8) Social-ecological system		
8a) Social-ecological	The capacity of a social-ecological systems to absorb recurrent disturbances (...) so as to retain essential structures, processes and feedbacks	Adger et al. 2005:1036
8b) Resilience-approach	A perspective or approach to analyse social-ecological systems	Folke 2006
(III) NORMATIVE CONCEPT		
9) Metaphoric	Flexibility over the long term	Pickett et al. 2004:381
10) Sustainability-related	Maintenance of natural capital in the long run	Ott and Döring 2004:213f

Holling (1973) provided in his seminal paper an ecologically focused definition of resilience and as illustrated in Table 2-2, it has since taken many forms. In the context of this present chapter, the need to understand resilience through the prism of sustainability science is necessitated because it is problematic and in some cases impossible to fully comprehend ecosystem dynamics and their capability to create services devoid of understanding the human dimension. To focus purely on the ecological side as a basis for evaluation and decision-making for sustainability is too simplistic and simplifies the reality to the extent the outcome of such a process becomes incomplete and the conclusions limited. As a result, the adoption of a socio-ecological systems definition of resilience (definition 8a & b as in Table 2-2) is necessary to permit understanding as necessitated the aim of this thesis, for an interdependent and constantly co-evolving dynamic of UUS evaluation (see Figure 2-9 and Chapter 3 & 5). Socio-ecological systems are not just related but truly interrelated as well as co-evolving across spatial and temporal scales. Given that socio-ecological systems are founded on the interconnection of sustainability science and resilience theory, it behoves us to understand how these two theoretical fields can be combined given their inherent differences.

2.5.1 UNDERSTANDING THE THEORETICAL BASIS OF SOCIO-ECOLOGICAL SYSTEMS

In reference to socio-ecological systems, sustainability science and resilience theory which underpins them have several objectives and elements in common and some inherent differences when it comes to their drive to comprehend system dynamics, improve strategic capabilities, and comprise wide-ranging viewpoints (Fiksel, 2006; Liu et al., 2007; Leach et al., 2010; Wiek et al., 2011); see Table 2-3 for a summary comparison.

Table 2-3: Contrasting elements of resilience and sustainability (Redman, 2014)

Resilience Theory Approach	Sustainability Science Approach
Change is normal, multiple stable states	Envision the future, act to make it happen
Experience adaptive cycle gracefully	Utilise transition management approach
Origin in ecology, maintain ecosystem services	Origin in social sciences, society is flawed
Result of change is open needed, emergent	Desired results of change are specified in advance
Concerned with maintaining system dynamics	Focus is on interventions that lead to sustainability
Stakeholder input focused on desirable system dynamics	Stakeholder input focused on desirable outcomes

Socio-ecological resilience is the capability of a system to encounter shocks whilst preserving function, structure, response capabilities, and consequently distinctiveness (Walker et al., 2006; Walker & Salt, 2006); see Figure 2-12. Resilience theory underscores that for socio-ecological systems, change is as normal as stability, and a system could subsist in several stable states (Fiksel, 2006). The objective is the implementation of a system that is responsive to changing conditions so that minimal losses are experienced by the system and to its core functioning. Extraneous shocks or growing stresses could prompt the changing condition by means of forcing the system above a tipping point.

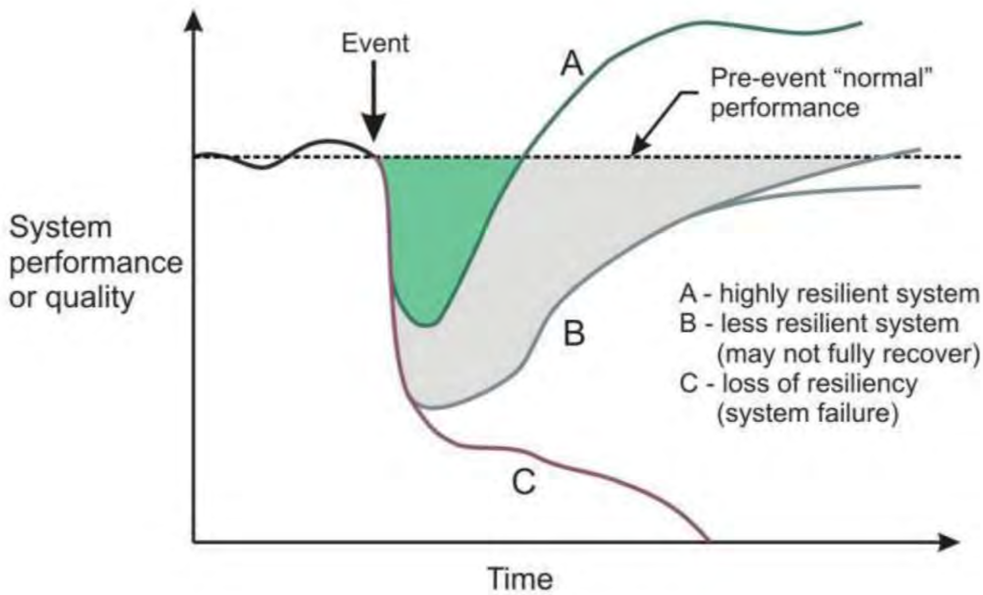


Figure 2-12: Conceptual Definition of Socio-Ecological Resilience - Performance Response Functions (Sterling & Nelson, 2013)

When a cycle of change is beginning, the system outcome is not predetermined and could in due course be similar to the system's previous conditions or not the same at all, i.e., regime modification. Since the end result of the system advancing via the adaptive cycle is not prearranged, the resilience theorist(s) is therefore obliged to take action on partial information of the consequence(s) of that action, and with determination that the resulting attributes of the new system will be beneficial. Through the link that exists between ecology and natural resource management to resilience theory, there has been in times past a trend to evaluate system outcomes that uphold conditions and services rendered via the previous system as a constructive outcome, even though it is acknowledged e.g. Fiksel (2006), that particular resilient systems are in an objectionable condition and may well be made better through modification. It is vital to formulate and put into action policies for improved resilience, because trends propose a significant growth in complexity for future urban systems (Allenby, 2005).

Sustainability science on the other hand strives to engage with the foremost of challenges confronting humankind, whilst making sure human welfare is retained holistically and the elemental structures of the Earth system continue to function. Brundtland (1987) proposed that sustainable development is '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'. To identify the route of preferred transformation wrought by Brundtland' definition, a sustainable pathway reflects one which human welfare is improved, social equity is increased, and environmental integrity is safeguarded (Leach et al., 2010). By way of the strong links to development, management, and politics (reference is made to Bettencourt and Kaur (2011) for a bibliometric examination of the discipline in the past thirty years), sustainability scientists lean towards being discontented by the present-day order and often campaign for basic and frequently extreme transformations to the system (Gibson, 2006; Leach et al., 2010; Smith & Stirling, 2010).

Transformation of the social order necessitates engagement with civic members and stakeholders to (1) identify what is meaningful to them by way of sustainability metrics, (2) develop pathways for their system, (3) determine preferable futures, and (4) devise changes that will bring about the preferred, sustainable results (Kates & Clark, 1999; Robinson, 2003; Wiek et al., 2012). Consenting to this schema, transition management facilitates a working model that gives emphasis to agency and power associations and follow-on changes that, design, encourage, and govern the pathway of change (Rotmans et al., 2001; Loorbach, 2010). Comparable to a resilience approach, sustainability evaluations take into account the bio-physical drivers and limitations on a systems future, nevertheless lay emphasis on and assess change in relation to human decisions, institutional dynamics, and collective approaches (reference is made to case studies in Wiek et al. (2012)). Generally, the size of change necessary to realise sustainability proposes a transformation of the system; related nomenclature infers that pursuing sustainable results is a journey (Kates & Clark, 1999) or pathway (Leach et al., 2010) and that it is optimistic and often necessitates a cycle of repetitive advances.

The strong point in utilising a sustainability approach is that it methodically evaluates future alternatives, allocates values to those alternatives by the use of indicators, and adapts its policies to realise those alternatives. It thoroughly incorporates normative values and pre-emptive rational within scientific architecture (Clark & Dickson, 2003; Swart et al., 2004). Compared to a sustainability approach, the strong suit of a resilience approach is that it cultivates adaptive capacity and/ or robustness into the system; as a result the system is able to smoothly withstand the unavoidable, nonetheless indeterminate, system shocks and stressors. The prediction of outcomes is not required when utilising a resilience approach; it develops social and natural capital and increases adaptive capacity to manage the future whatever that may be (Carpenter & Folke, 2006; Folke et al., 2010). To put it simply, resilience puts precedence on the process to outcome(s), sustainability puts precedence on outcome(s) of processes as part of a socio-ecological systems approach.

2.5.1.1 Adaptation and Transformation as Core Actions of Resilience and Sustainability

In order to further make a distinction between resilience and sustainability approaches in the context of socio-ecological systems, it is appropriate to compare adaptation and transformation (see Table 2-4), that display a number of differences in their attempt to reconcile the risks coupled by way of change and uncertainty (Leach et al., 2010; Brown & Westaway, 2011; Kates et al., 2012).

Table 2-4: Contrasting elements of adaptation and transformation (Redman, 2014)

Adaptation	Transformation
Incremental change	Major, potentially fundamental, change
Respond to shock	Action in anticipation of major stresses
Maintain previous order	Create new order, open ended
Build adaptive capacity	Reorder system dynamics
Emergent properties guide trajectory	Build agency, leadership, change agents

Adaptation pertains to the process of decision-making and actions carried out to regulate a system to future shocks, stresses, or additional varying circumstances in a way that preserves critical system functioning (Nelson et al., 2007). It generally is the case that the essential modifications to the system will be moderate and cumulative. Therefore, adaptive strategies remain fairly conventional: subject to the stresses of varying conditions, these strategies facilitate the system maintaining or returning to the prior order or one comparable to it. Adaptive strategies are frequently precise and restricted to an immediate area; they focus on a likely threat and related vulnerability and modify the system in proportion to that threat. A wider view as related to this strategy, akin to ordinary resilience, is one that is a proponent for efforts to increase the adaptive capacity of the system to withstand possible shocks and stresses that tend to be wide-ranging (Gunderson, 2001; Nelson et al., 2007; Chapin et al., 2009; Brown & Westaway, 2011). Certain resilience theorists have highlighted the parallels of this process to specific resilience (operational resilience; see Table 2-2), stressing that it be incumbent upon somebody to ask what conditions are resilient, in addition to what and for whom are they resilient (Folke et al., 2010).

Transformation hints at a more widespread and fundamental restructuring of the socio-ecological system. Nelson et al. (2007) outline transformation being a fundamental modification of a system when the present ecological, social, or economic circumstances turn out to be unsupportable or are unwanted (see also Walker et al. (2004); Walker and Salt (2006). Therefore, the transformation of system dynamics possibly will be necessary or preferred wherever a considerable threat is anticipated, for instance climate change, or wherever a system failure is identified, for instance the demographic shifts experienced in many cities in the developing world from an influx of poverty trap immigrants (Thapa, 2010; Kates et al., 2012). Transformatory planning often is brought about from a persistent and growing stress observed as approaching a limit or tipping point that might have terrible consequences for the system. Therefore, the device employed as a response to such phenomenon is to permit the system to reconstruct itself through inserting a different batch of dynamics that function within indicated desirable values into the distant future. Nonetheless, transformative undertakings include taking considerable risks, frequently are viewed as overpriced, and have more questionable results than most adaptive actions. Notwithstanding that transformative policies are targeted at precise system changes or outcomes, they hold a lot in common with sustainability science approaches for instance transitions management (Rotmans et al., 2001; Loorbach, 2010), wherein projecting pathways of change and creating suitable interventions are the goals. Several sustainability scientists propose that transformations are required to construct a pathway to sustainability (Hopwood et al., 2005; Leach et al., 2010; Wiek et al., 2011). On the other hand, to the extent those specifics regarding future conditions are elastic and increasing the robustness of the system and its administration is the objective, transformation actions could likewise be a part of a resilience approach (Olsson et al., 2006; Folke et al., 2010). The following sections of the chapter aim to explore issues related to UUS in light of both city resiliency and sustainable development.

2.6 RELATIONSHIP OF UNDERGROUND SPACE USE TO CITY RESILIENCY

2.6.1 GENERAL ASPECTS OF UNDERGROUND RESILIENCY

Resilience is predominantly essential for interdependent systems where a subsequent catastrophe in any part can rapidly spread to other parts of the system, as a result, producing system failure (Park et al., 2011). Several categories of UUS use can impact city resiliency, owing to the isolation offered through the covering soil or rock from catastrophic incidents that take place above ground. For instance, geo-structures normally afford an exceptional resistance to incidents such as terrorist threats, radiation, external blasts, tornados, external fires, hurricanes and earthquakes (H. W. Parker, 2008b). Resistance for instance to earthquakes has been proven time and again, counting the Loma Prieta earthquake in San Francisco at which point the transit system was examined and returned to functional service in less than half a day following initial seismic activity, while most of the city was crippled for several months (Seed, 1990; Ardekani, 1992). Nonetheless, geo-structures are not exempt to damage from catastrophic events, for instance, shallow underground utility systems in spite of their sheltered location, could possibly be impaired in a number of ways via large-scale natural catastrophes – a number of the major concerns, both advantages and disadvantages, of underground facilities with respect to catastrophic events are summarised in Table 2-5.

Table 2-5: General advantages and disadvantages of underground facilities with respect to catastrophic events (Sterling & Nelson, 2013)

Type of Event	Advantages or Mitigations	Disadvantages or Limitations
	Ground motions reduce rapidly below surface	Fault displacements must be accommodated
Earthquake	Structures move with the soil	Instability in weak materials or poor configurations
Hurricane, Tornado	Wind loadings have minimal impact on fully buried structures	Damage to shallow utilities from toppling of surface structures such as trees and power lines

Type of Event	Advantages or Mitigations	Disadvantages or Limitations
Flood, Tsunami	Ground provides protection from surge and debris flow	Extensive restoration time and cost if the structure is flooded
External Fire, Blast	Ground provides effective protection	Entrances and exposed surfaces are weaknesses
External Radiation, Chemical/ Biological Exposure	Ground provides additional protection	Appropriate ventilation system protections required
Internal Fire, Blast	Limited extent of damage with appropriate compartmentalization	Confined space increases internal damage and personnel risk
Internal Radiation, Chemical/ Biological Releases	Limited extent of damage with appropriate compartmentalization	Confined space increases internal damage and personnel risk

As specified in Table 2-5, in the event of floods and hurricanes, with the proviso that access points are properly secured and/ or sealed, the forces on geo-structures are clearly known and simply dealt with when weighed against the impact, flood and wind loadings for surface structures. On the other hand, the effect of an explosion or internal fire is normally more dangerous and life-threatening in an underground facility than in a surface structure (Canto-Perello & Curiel-Esparza, 2001; Canto-Perello & Curiel-Esparza, 2003; Curiel-Esparza & Canto-Perello, 2005).

2.6.2 UNDERGROUND INFRASTRUCTURE RESILIENCY

In densely populated urban centres, the underground space is littered with energy networks (gas, electricity) and water networks (wastewater (i.e. storm water and sanitary) and water distribution). Furthermore, a growing inclination subsists with respect to locating underground all service networks (including telecommunications, electricity and in some cases solid waste collection) (Rogers, 2009), whilst, in major capital cities across the world, transit systems (intercity, metro, road or highway networks) may well enjoy wide-spread underground mechanisms and connected facilities. Energy networks, water networks and transportation systems play a significant part in the long-term sustainability of a city, and in the event these core services stop functioning, the inevitable result experienced is a halt in routine commercial and social cycles (e.g. food supply, etc.).

Therefore, the capacity of a city to restrict loss and to recover speedily with respect to catastrophic events is intricately connected to the functional performance of these systems (see Figure 2-12). Several illustrations of these dependencies abound. For instance, during the Kobe Earthquake, water service pipes ruptured subsequently starting enormous fires that left the fire brigade powerless to contain (Chang et al., 2002). Another example is the sluggish reinstatement of water, power and waste water systems in New Orleans after Hurricane Katrina which was partly responsible for the work force deficiencies that impeded the restoration of normal life across the city (Allouche, 2006).

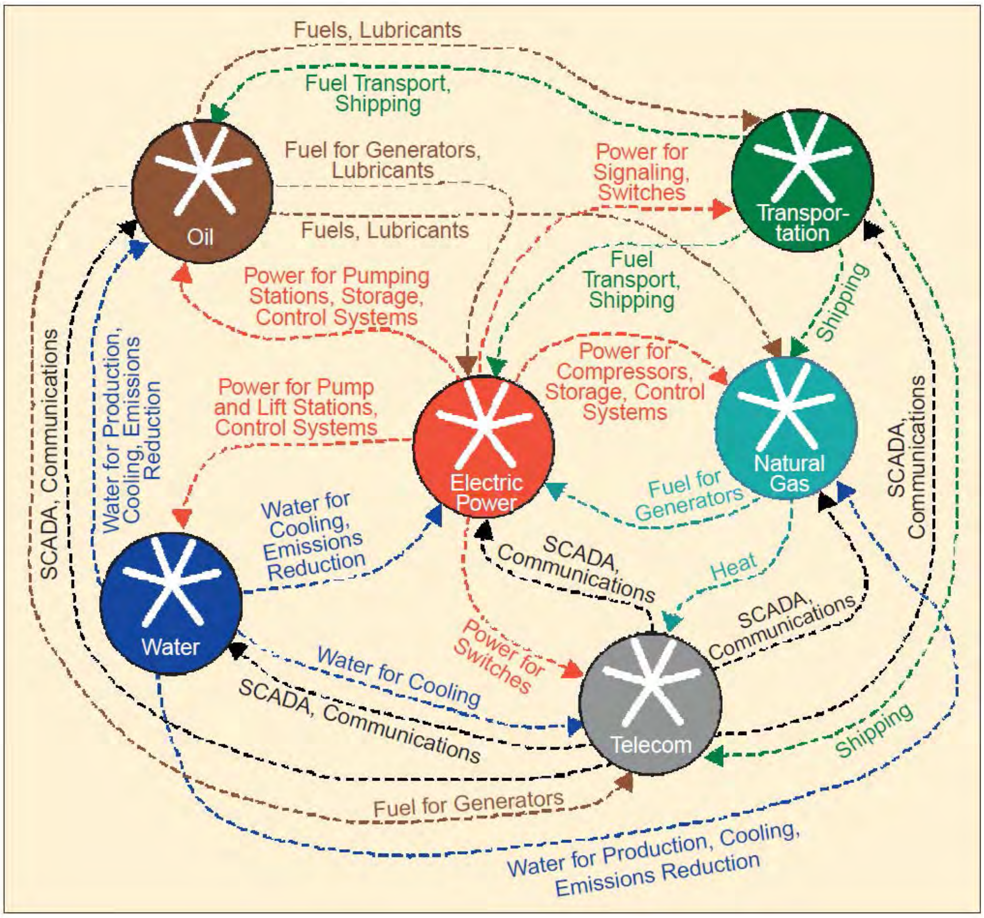


Figure 2-13: Examples of 'critical' infrastructure dependencies (Rinaldi et al., 2001)

Underground infrastructure nonetheless poses a singular and demanding set of circumstances: it not visible, nor is it readily interpreted from the surface; it has the implicit advantage of being sheltered from extreme events (see Table 2-5), but then again has revealed certain weaknesses under provincial and incident-related conditions faced in some recent hurricanes and flooding events that jolted heavily populated areas (Allouche, 2006; Leavitt & Kiefer, 2006). For instance, once impaired, it may well be problematic and slow to repair and the planning of repairs to many buried infrastructures below damaged streets can produce terrible scenarios of wasted resources and traffic congestion (Sterling & Nelson, 2013). Certain decision-making approaches aimed at engendering engineering resilience of infrastructure networks pay emphasis on time and/or cost to prevail on system actors to initiate the repair of network elements, so that the network system(s) can revert back to functional performance in the shortest space of time (see Figure 2-12). Such approaches do not always account for concessions built-in when repairing the elements of various infrastructures below a specific street in a harmonised way so that budgets are decreased. It often is the case that this phenomenon does not impact aerial infrastructure much, but is a major issue for buried infrastructure with the exception of multi-utility tunnels, for which considerable social disturbance of repair would be avoided (Rogers & Hunt, 2006). Permitting that engineering infrastructure design lives ought to be elastic and robust in order to counteract as many threats as possible; it remains quite challenging if not impossible, to design for engineering systems that are full-proof against all future threats. As a result, for engineering systems to be sustainable, it is required, if not necessary to make certain that the system in question is fundamentally competent of returning back to its previous functional state, regardless of the nature or size of stress or shock experienced; such systems typify socio-ecological systems. UUS structures tend to form important parts of 'critical' infrastructure systems for the reason that resilience must be embedded in geotechnical engineering designs to permit for 'critical' infrastructures to be resilient (see Figure 2-13) (Dueñas-Osorio et al., 2007; McDaniels et al., 2007).

Other observations to the multifaceted difficulties of resiliency produced through catastrophic events can be understood through a more precise examination of the Katrina Aftermath (Allouche, 2006; Leavitt & Kiefer, 2006; Colten et al., 2008). The hurricane produced selected, but not cataclysmic destruction. The actual catastrophe was triggered through flooding as a result of the levee system failing, thereby instigating a chain of malfunctions and wide-spread damage to physical and social systems which still subsist till this present day. As a result of the pumping station failing to function due to being exposed during the flooding, it required shutting down for dewatering before it could be utilised again to syphon water after rain and hurricane events. The failure of the pumping station also resulted in both houses and shallow buried infrastructure lines floating for the duration of the flooding, mostly leading to the splitting of connections to underground utility services (particularly water and gas) at the access sockets hooked on buildings. This brought about several leakages in water and gas supply networks and as a result the required distribution pressures failed and the piping systems overflowed with contaminated saline water. Damage to the water supply systems in turn hindered firefighting efforts and significantly delayed the restoration of standard living conditions in submerged areas. The low pressure gas supply system was submerged bringing about disintegration of stopcocks and meter gauges which necessitated large-scale replacement. Tree root systems especially those of mature trees significantly damaged shallow-buried utility lines when blown over in the course of the rainstorm. The absence of suitable and available records with respect to the utility asset catalogue, stopcocks, and the location of additional core infrastructure elements hindered utility response and crisis management services. Compounding this problem was the fact that several typical landmarks aimed at pinpointing facilities were destroyed by the storm damage. Consequently, a return for communities to pre-Katrina conditions was hindered through the damage to urban services (such as sanitation, fresh water, power etc.).

The significance of the robustness of singular infrastructure systems to long-term resilience is underscored by the preceding examples and to a greater degree, the interdependencies between whole systems of systems – thereby necessitating the implementation adaptive strategies through the prism of socio-ecological systems. Urban design therefore requires an integrated socio-ecological systems design approach in order to account for resilience by means of a multihazard approach to disaster management. The implementation of such an approach requires planning for the most probable (risk) scenarios and should incorporate ample elasticity to a make room for the unexpected - e.g. see National Research Council (2011). A cohesive and harmonised systems plan should contain the provision for critical redundancies within systems that, for instance, permit acceptable response and recovery once a section of a system fails. Underground and above ground infrastructure assets ought to be constructed and operated as combined integrated systems with lifecycle support, hazard, reliability, and instantaneous reaction in mind. Implementation of such approach for use of UUS and infrastructure significantly reduces the impact of extreme events; as a result, society is inclined to generally recognise UUS as a progressively dependable and fortified resource and an important segment of a sustainable society (see Figure 2-9).

2.7 CASES OF SOCIO-ECOLOGICAL RELATED URBAN UNDERGROUND SPACE ISSUES

In view of the Brundtland (1987) definition of sustainable development, underground infrastructure plays a crucial role in facilitating the sustainability of its surroundings in several ways: accounting for land, water and biodiversity, cutting greenhouse gases (e.g. Rogers (2009) shows this happens mostly in the transport sector as well as for underground sewage treatment facilities), protecting natural resources, and needless visual disturbances; making opportunities for a reduced amount of energy expenditure and waste generation (‘compact city’; see Gordon and Richardson (1997)); making geo-structures less affected through catastrophic events (e.g. earthquakes, tsunamis etc.); and improving by and large both environmental and landscape quality. Use of geo-structures permits a decrease in land area occupied by man-made structures. The density of urban services or lack of it usually has secondary effects such as altering transportation needs of local residents in addition to either enabling or inhibiting automobile usage. Therefore, if the density of UUS infrastructure is high, this characteristic aids to inhibit and fight urban sprawl, preserving the compactness of the urban community, thus redeeming natural sites and safeguarding the bio-physical environment.

In urban environments significant development of underground infrastructure constructs a self-regulating stratum of communication and services, containing critical underground facilities that improve a city’s congruence and resilience. It has been identified that systems having several substitute links between their components are more enduring (robust socio-ecology) as opposed to ones which have individual links in their performance sequences (Bobylev, 2009b). In the following sub-sections, various examples of clear-cut matters or else conflicts as regards to use of UUS are pointed out. These are not meant to be exhaustive but preferably to contribute context to the broad-spectrum of issues above.

2.7.1 ENVIRONMENTAL IMPACT AND UNDERGROUND SPACE USE

The shallow sub-surface (major zone of human interaction) often develops organically as a city grows. General uses comprise foundations (shallow (strip, pad), semi deep (caisson, cofferdam) and deep (piles, slurry walls) for buildings and underground stores and the considerable web of cables, pipes and tunnels that convey utilities and transportation services. Currently, the design decisions for each of these underground facilities are considered as separate development options/ scenarios, irrespective of their impact on the probable future use of UUS for other requirements. For instance, as exemplified in Figure 2-14, the selection of a foundation (shallow, semi-deep or deep) for a building has a substantial bearing on the capacity to employ UUS below or next to the building. A comparable concern applies to the usage of anchorage (horizontal tiebacks) meant for provisional/ permanent reinforcement of foundation walls (see Figure 2-14), particularly as soon as they spread out into the ground below public paths.

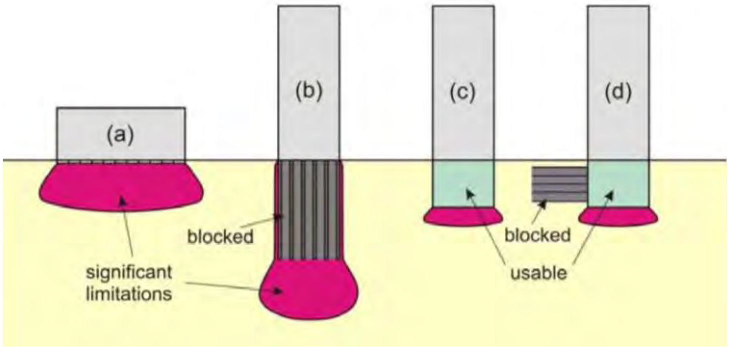


Figure 2-14: Typical underground space use implications of foundations types: (a) shallow spread footings; (b) deep pile foundation; (c) deep basement floating foundation; (d) deep basement floating foundation with tie back/ soil nail retaining walls (actual restrictions and design details) (Sterling et al., 2012)

UUS tunnel design typically ranges between a cut-and-cover tunnel and a bored tunnel option. Both options have considerable differences as to the consequences that follow their application from disruption in the course of construction; bored tunnels being superior in this concern. The European Union - EU (2004), states that the effect of what tunnel options is exercised has implications as far as the short and long term local economic and social conditions. The choice of tunnel also impacts as seen with building foundations the potential for current and future use of UUS for sub-structures in close proximity (e.g. cut-and-cover tunnels have support walls which can act as an obstacle for upcoming tunnels, besides the possibility of a severe impact on groundwater flow. Underground facilities increase proportionally with the growth of cities (stations, road tunnels, rail tunnels and transit tunnels) and are frequently driven to constantly deeper depths (see Figure 2-15, Tokyo metro line as an example). Because underground facilities located at deep depths are not as suitable for commuters and more costly to build, this concern only further highlights (putting a premium vis-à-vis UUS) the need to reduce the vertical UUS occupied by UUS facilities.

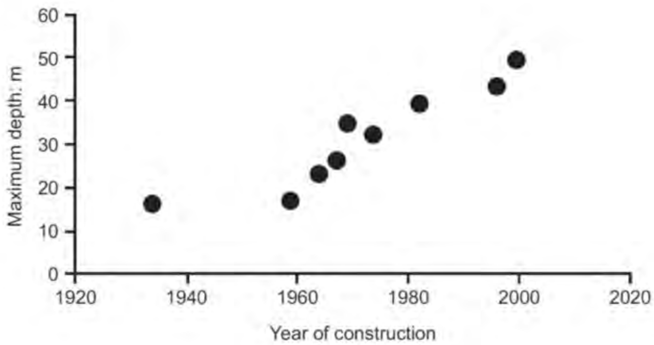


Figure 2-15: Evolution of the depth of Tokyo metro lines (Bobylev, 2009a)

Traditionally in many northern climates, direct heating using fuels or electrical resistance or air-source heat pumps have been employed for heat conversion from the ground in the course of the winter. In recent times, geothermal heat exchange systems have grown into the conventional method for ground heat conversion whilst providing a higher coefficient of performance. Some heat exchange systems are constructed on deep vertical boreholes whilst others are constructed on shallow ground rings (below the ground surface). Majority of these systems do not engage in groundwater abstraction to use in heat conversion, but rather, utilise a revolving fluid to convert heat directly through the soil. UUS interaction with such systems raises sustainability concerns ranging from the absorption of large volumes of UUS through a 'jungle' of vertical boreholes to the change in thermal conditions underground due to widespread use of ground heat conversion systems – the performance of such systems will reduce progressively except a system to seasonally balance the thermal input and output is instituted (Banks, 2009).

Although sub-surface facilities could reduce the total environmental shock caused by a facility in comparison to above ground facilities, they unavoidably modify the sub-surface environment marginally. It is vital to evaluate the extent to which these impacts are considerably unfavourable (e.g. groundwater quality decline, induced seismicity, induced sinkholes), slightly unfavourable (e.g. expected change in thermal distribution adjacent to the sub-structure), or, an advantage in one or fewer cases (e.g. when a ground heat extraction scheme can be installed in tandem with the rehabilitation of an earlier polluted zone (Admiraal, 2010)).

2.7.2 UTILITY SERVICE PROVISION INFRASTRUCTURE – MUT'S

UUS in cities worldwide have one constant feature in that virtually all the underground space down 2-3 meters beneath the street level is filled with urban utilities (see Figure 2-16). These urban utilities increase progressively as a city grows and in the future are already in place when further uses of UUS turn out to be important (subway systems; rail and pedestrian etc.). This concentration of urban utilities has been characterised as "*the spaghetti subsurface problem*" by urban engineers (Oude, 1992). Utility service provision is only increasing as a result of population density in urban areas (see Figure 2-1 and Figure 2-2), we cannot live without utilities (see Figure 2-13). For this very reason, the extensive use of UUS for utility service provision is by far its prime function to-date (Rogers & Hunt, 2006). It was noted as far back as 1987 by Carmody and Sterling (1993), that the total cost of urban utility systems in the western hemisphere was approximately $US25 billion/ year and this has only been increasing, making the shallows sub-surface (zone of human interaction) saturated and often difficulty is experienced in the maintenance of these utilities. Furthermore, trench digging to install new, or upgrade existing urban utility networks at times is hardly possible, and if possible, causes considerable traffic disruption (Legrand et al., 2004).

Figure 2-16: Congestion of UUS with utility infrastructure (ITA, 2002)

Oddly enough, at the beginning of the 21st Century, traditional methods of utility placement/provision through trenching (open-cut construction) are even now accepted within all major UK cities. Techniques used for the lacing of utilities are for the most part the same, apart from where trenchless machinations happen to be used, and therefore maintenance, siting, capability of enlargement of subsisting utility catalogues contained by city centres is very complicated and continues to be far from sustainable. Additionally, entitlements to access roadways (approximated to be 135 diverse businesses within the UK) on any occasion, has proliferated considerably ever since 1901. This has to an almost break-point situation of ever endless street works (the DfT (2003) reported that 1 million street works were documented in 2003) at the same time as escalation of direct and indirect costs (UKWIR (2005) reports that out of the approximately four million hovels excavated every 365 days within the UK's main roads besides sidewalks via utility businesses, costing in the region of one billion (direct costs) and an approximate indirect cost of £5.5 billion (J. Parker, 2008)). The manifold issues related with employing traditional open-cut construction are well documented in the literature; open-cut construction leads to additional traffic and road-user delays (Bayer, 2005; Jung & Sinha, 2007) estimated to cost the UK as a whole £5.5 billion per year (J. Parker, 2008), open-cut construction tends to cause increased noise and vibration (Jung & Sinha, 2007), open-cut construction is potentially dangerous due to excavations and mobile plant and vehicles (HSE, 2014a, 2014b), open-cut construction tends to have a negative impact on local residents (Jung & Sinha, 2007), open-cut construction tends to have a negative impact on local business (Laistner, 1997), open-cut construction tends to more often than not cause damage to the landscape (Jung & Sinha, 2007), open-cut construction costs more to maintain in the long-term as opposed to trenchless technologies (Rogers & Hunt, 2006; Hunt et al., 2014), open-cut construction tends to cause significant damage to roadways and pavements (Jung & Sinha, 2007), open-cut construction tends to require at times quite costly de-watering contingencies to manage groundwater levels (Najafi & Gokhale, 2005), and open-cut construction tends to cause damage to existing utilities in the course of putting in place otherwise maintenance of adjacent utilities (Hunt & Rogers, 2005; Woodroffe & Ariaratnam, 2008).

These phenomena have brought about a growing interest in Multi-Utility Tunnel (MUT)/ Utilidors (common galleries for utilities – see Figure 2-17 for example) systems as a means of engendering sustainable development of UUS, due to the increasing congestion of utilities within the shallow sub-surface. A MUT can be defined as "*any system of underground structure containing one or more utility service which permits the placement, renewal, maintenance, repair or revision of the service without the necessity of making excavations; this implies that the structure is traversable by people and, in some cases, traversable by some sort of vehicle as well*" (APWA, 1997). Rogers and Hunt (2006) make known in excess of 60 global cases of MUTs which differ in type of installation, size, shape, depth, material and category of utilities accommodated (see Appendix A). Tunnel accessibility offered within an MUT on the one hand can be searchable – permitting selective accessibility through removable lids – or visitable – permitting personnel entry throughout the length of the MUT (Cano-Hurtado & Canto-Perello, 1999; Curiel-Esparza et al., 2004).

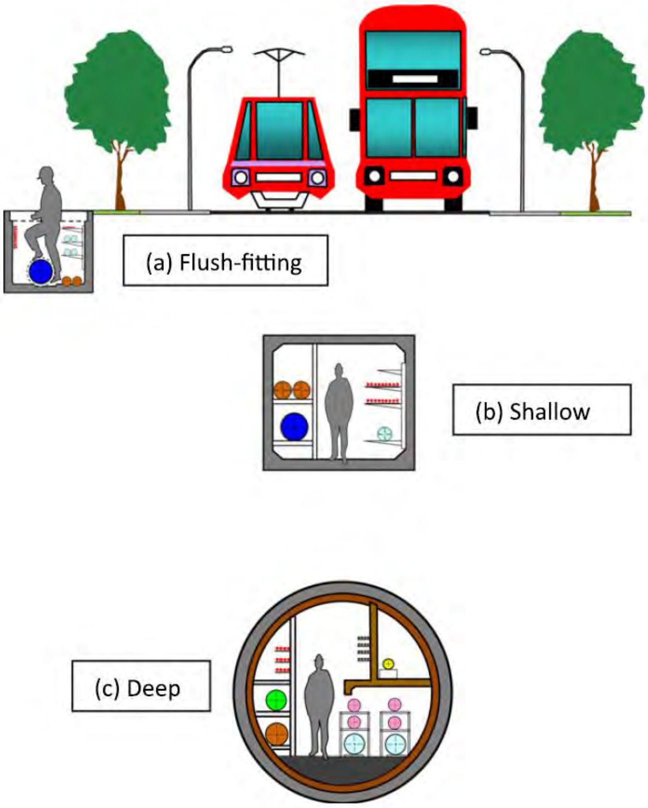


Figure 2-17: MUTs characterised in relation to their depth of placement (a) Flush-fitting MUT: 0.0m cover; (b) Shallow MUT: 0.5m-2.0m cover and (c) Deep MUT: 2-80m cover (Hunt et al., 2014)

MUTs in addition to trenchless technologies offer an alternative to trenching (i.e. open-cut construction) and are the best geo-engineering solution to achieve sustainable development of UUS as a socio-ecological system (Canto-Perello & Curiel-Esparza, 2003; Legrand et al., 2004; Curiel-Esparza & Canto-Perello, 2005; Hunt & Rogers, 2005; Canto-Perello & Curiel-Esparza, 2006; Hunt, Jefferson, Drinkwater, et al., 2012; Laistner & Laistner, 2012; Hunt et al., 2014) as opposed to open-cut trenching, which remains the greatest, extensively used solution for lacing utilities underneath the ground in the UK (Rogers & Hunt, 2006). As a consequence of using MUTs, saturation of UUS falls, zoned planning of UUS is more effective, maintenance is easier, traffic interruption stops and the addition of new urban services can take place without disruption to the public highway (Cano-Hurtado & Canto-Perello, 1999; Hunt & Rogers, 2005; Rogers & Hunt, 2006; Hunt, Jefferson, Drinkwater, et al., 2012).

Nevertheless, MUTs are more expensive when compared to traditional solutions (open-cut excavation – trenching) in the short term (see Figure 2-18). They however provide significant long-term savings when compared to open-cut trenching (see Figure 2-19) i.e. the more times the road has to be dug up to upgrade/maintain utilities, the more cost-effective MUTs become. For the reason that decision-makers decide principally on economic criteria (mono-criteria vs. multicriteria), MUTs in this day and age are rarely a first choice for decision makers as a solution for sustainable use of UUS (Legrand et al., 2004; Rogers & Hunt, 2006; Hunt, Jefferson, Drinkwater, et al., 2012), this being one of the many barriers that prevents it uptake in the UK (see Table 2-6). The following sub sections will deconstruct the barriers, enablers and decision-making mechanisms with respect to MUTs.

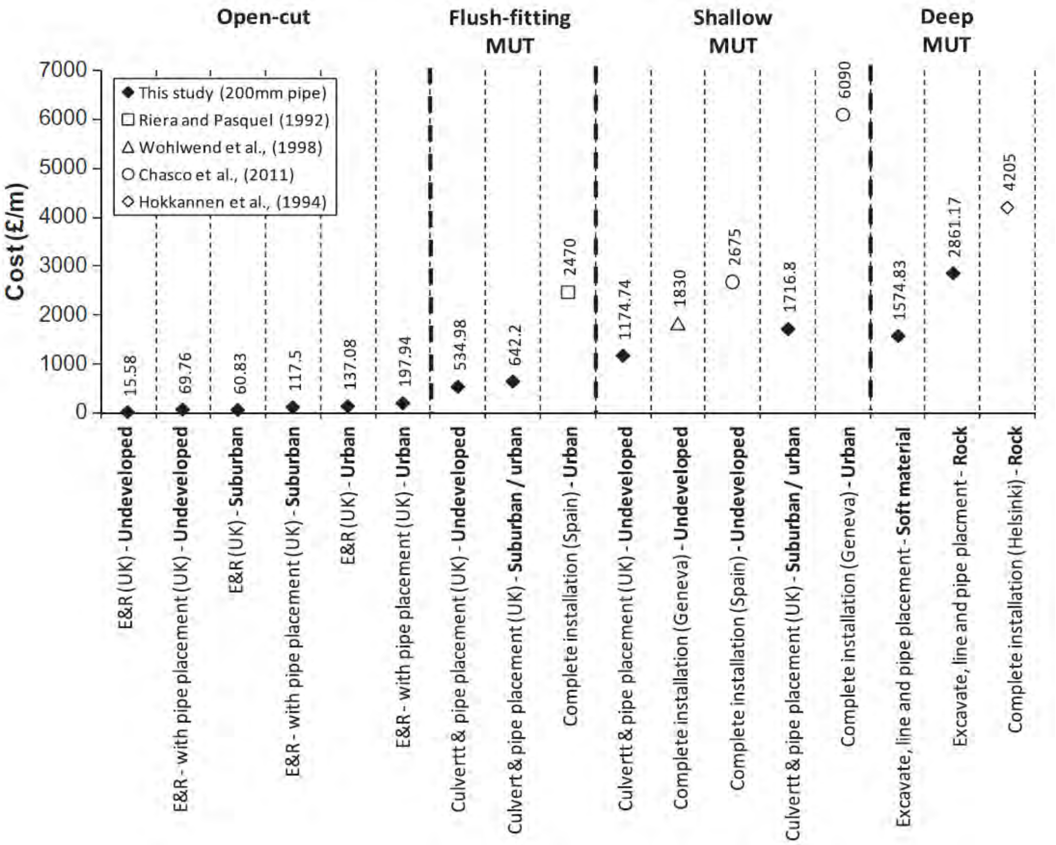


Figure 2-18: Urbanisation and the short-term cost of MUT installation (Hunt et al., 2014)

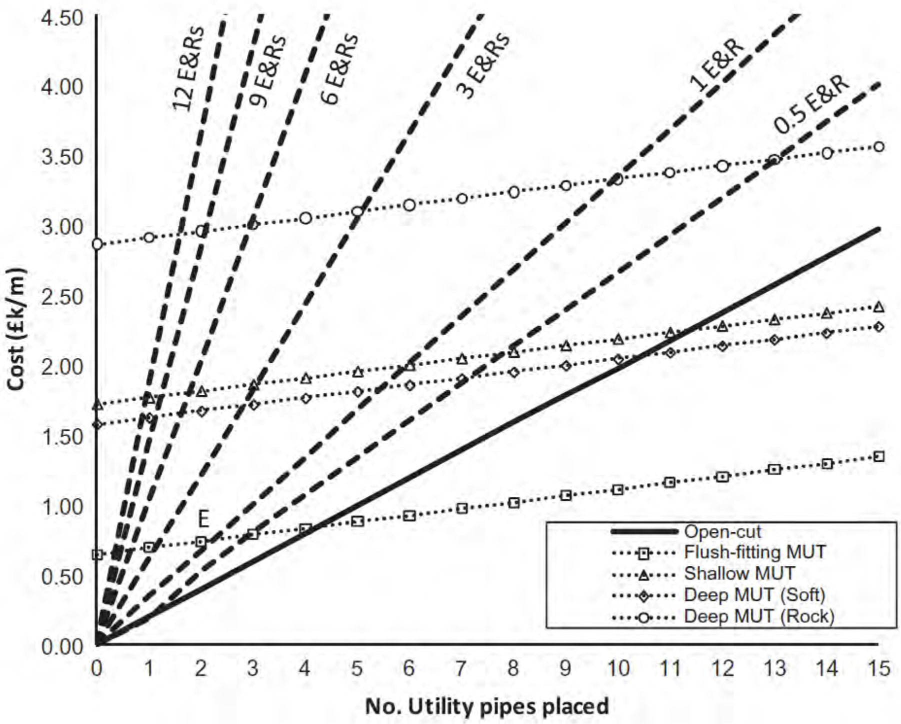


Figure 2-19: MUT costs versus open-cut costs with and without yearly E&Rs (200 mm pipe, urban) (Hunt et al., 2014)

Table 2-6: Barriers to the implementation of MUTs (Hunt & Rogers, 2005)

Barrier	Details
Lack of knowledge	† How and where can it be done? † Lack of uptake in UK † Lack of visible information or research in UK
Piecemeal approach to utilities	† Trenching is a short-term, relatively flexible technique that can be carried out in small areas/on a small scale
† No universal standards for MUTs † Risk aversion	† MUTs are not well known in the UK
No value is placed on underground space or open space	† Financial drivers are lacking
High costs	† Initial outlay expected to be high † Who pays for construction? † Who maintains the tunnel?
Lack awareness	† The problems are not visible Contractor does not ask for MUTs
Lack of powers to intervene inherited system	† Voluntary codes of practice † Too difficult to retrofit, i.e. moving existing utilities into tunnels would require an essentially new installation
Incompatibility problems	† Utility companies are unwilling to house gas and electricity supply cables together
Coordination of utility companies	† Utility companies have different drivers
Utility tunnel ownership	† Who owns the tunnel?
† Previous bad experiences with utility tunnels † Reduced flexibility	† The MUT would be difficult and expensive to move
Security Issues	† Preventing unwanted access to one or more of the utilities is more difficult

There exist several ways of overcoming the barriers to MUT uptake in the UK. MUT schemes (flush-fitting, shallow or deep) tend to be more economical for densely populated areas with a high concentration of utility infrastructure (i.e. city-centre-based as opposed to street-based developments) where multiple excavation and reinstatements of utilities are needed (see Figure 2-19) (Legrand et al., 2004) and where open-cut trenching could as a rule be avoided. The impetus to institute MUT schemes will be brought to realisation by policies that place a premium on UUS and ecosystem services it can provide to present and future generations (see Table 2-7).

Table 2-7: Enablers of implementation of MUTs (Hunt & Rogers, 2005)

Enabler	Details
Informed knowledge	*Promotion of case histories* † A database of international examples is required *Research* † Materials and internal tunnel structure † Position relative to highways and open space † Engineering requirements
Government policy changes	† Charge for roadwork's (e.g. Middlesbrough trial)

Enabler	Details
	† Introduce a no-dig policy in cities (e.g. Malaysia, India) † Utilities forming larger part of sustainability agenda † Enforced use, e.g. prior to planning permission for new developments † Stringent leakage reduction targets
Sustainable cost model	† Including social, economic and environmental costs † Whole-life costing (maintenance savings and leak detection and reduction)
Increase awareness and demand	† Public outcry caused by continued disruption of traffic, pedestrians and open space † Scheme designs and well-publicised pilot projects making MUTs a viable option
Reduce risk	† Research into economic and health comparisons for traditional and MUT schemes † Compartmentalise utilities
Payback periods	† Letting of space by council at guaranteed rates would allow economic cases to be made
Increased flexibility for future utility placement	† Future technologies † Future communications † Future fuel supplies (e.g. hydrogen)

The core of means of enabling majority of the enabling factors detailed in Table 2-7 is to highlight a means of evaluating the holistic sustainability of MUT implementation and provide more case studies of both evaluation and implementation of MUTs. Hunt, Jefferson, Drinkwater, et al. (2012) highlight a MUT refurbishment as a means of bridging the gap in regards to case study examples. These have been few and far between (Legrand et al., 2004) and are crucial in being able to aid in the uptake of MUTs by municipalities as a means of understanding how to account for MUTs in master planning for UUS under local conditions i.e. that is being able to systematically have a means to incorporate adaptive strategies for sustainable implementation of MUTs. MUTs are broadly documented to deliver effective expenditure of UUS and long-term sustainable maintenance, however decision-making in relation to their installation is highly debatable and are varied and complex (Nguyên & Gérard, 2005; Rogers & Hunt, 2006). It is worthwhile to re-examine customary utility installation procedures as a means of addressing long-term sustainability in urban areas (socio-ecological systems); a decision support tool/ framework to highlight the efficacy or otherwise of MUTs is yet to be devised as a means of evidenced based decision-making to support their ability to continue to deliver their function into the future, whatever that may be.

This knowledge gap with respect to a decision support tool/ framework to highlight the efficacy or otherwise of MUTs in socio-ecological systems is apparent in the literature. Merely the topmost stratums (zone of human interaction) of the underground can be regarded as valuable for UUS functions (see Figure 2-10 and Figure 2-16). Utilities harbour this space, and this is only set to increase especially in densely populated urban centres (see Figure 2-1). It has been suggested in the literature that multi-utility tunnels provide the best solution to engender sustainable use of underground space through sustainable utility placement (Cano-Hurtado & Canto-Perello, 1999; Curiel-Esparza et al., 2004; Legrand et al., 2004; Hunt & Rogers, 2005; Canto-Perello & Curiel-Esparza, 2006; Rogers & Hunt, 2006; Hunt et al., 2009; Curiel-Esparza & Canto-Perello, 2012; Hunt, Jefferson, Drinkwater, et al., 2012; Canto-Perello & Curiel-Esparza, 2013; Hunt et al., 2014). The first mention of a gap in the evidence base to make a case for multi-utility tunnels in the literature was by Legrand et al. (2004) who sought to address this gap by suggesting that a multicriteria decision-making approach would aid decision-makers get past a one dimensional - mono-criterion (economic criteria) approach to decision-making – which according to Legrand *Ibid*., was the reason why multi-utility tunnels were rarely chosen; the study did not present any data to this end.

Another study worthy of mention in regards to the state-of the-art, concerning evaluation of multi-utility tunnels is that conducted by Curiel-Esparza and Canto-Perello (2013). This study employed an analytical hierarchy process (multi-criteria, more specifically, multi-attribute approach to decision-making) in combination with the Delphi method (a multi-stage anonymous survey aimed at consensus building between experts) i.e. AHP-Delphi method, in an attempt to develop a decision-support-system to support civil engineers when selecting from different methods of utility placement (traditional trenching, common conduit, flat utility tunnel, shallow utility tunnel and deep utility tunnel) in urban underground engineering; the basis of their decision-support system is the generation of priority weights with regard to key relative measurements (quantification) of the intangibles that ought to, according to the authors, be accounted for in utility placement decision-making (urban environment, economic-financial, governance, maintenance requirements, security, liability and archaeological sites). The study, whilst useful has two key limitations that have been identified. Firstly, given that local priorities and conditions drive sustainable solutions, moreover, long term investments such as deep utility tunnels; it is difficult to see how the evaluation carried by the authors can be applied to a different context in addition to the priority weights identified. For instance, deep utility tunnels according to the expert feedback and pairwise comparisons were the most suitable method for utility placement; they however are quite a significant investment in economic terms (Hunt et al., 2014), and their use is again most likely to be driven by local priorities and conditions. Traditional trenching received the second highest overall priority result. It would stand to reason given the established literature with regard to the unsustainable nature of this utility placement technique (Laistner, 1997; Bayer, 2005; Najafi & Gokhale, 2005; Rogers & Hunt, 2006; Jung & Sinha, 2007; Woodroffe & Ariaratnam, 2008; HSE, 2014a, 2014b; Hunt et al., 2014) that the view held by experts surveyed unfortunately is based on the here-and-now, driven by an economic imperative, at the expense of environmental and social considerations. Secondly, the priorities for each of the alternatives are a reflection of the assessment in light of present-day conditions. They can however be utilised to validate as an evidence base the continued functional performance of the chosen utility placement technique; the significant point here being that decision(s) geared towards sustainability necessitate being founded upon rational judgments, and systematic, comprehensive appraisal(s) taking into account the multi-dimensional and multidisciplinary aspects of socio-ecological systems.

The study however was useful, in firstly providing evidence where it is sorely lacking at present, and represents a useful first step in demonstrating how priority weights could be generated using a multi-criteria approach, and secondly, demonstrating the efficacy of a multi-criteria approach to resolving the sustainability evaluation of MUTs; seconding the call by Legrand et al. (2004).

Hunt et al. (2014) represents another study worthy of mention, representing the stat-of-the-art with respect to evaluation of multi-utility tunnels; they sought to address the aforementioned evidence gap by assessing the economic viability of multi-utility tunnels vs. traditional trenching methods to establish precisely where the economic tipping point between the two methods subsists, even as they took under consideration various factors (utility type, pipe number (i.e. density), pipe diameter, number of excavation and reinstatement and (E&R) procedure avoided, location (i.e. urban, suburban and undeveloped areas) and the choice of MUT being adopted (i.e. flush-fitting, shallow and deep)). The study established that multi-utility tunnels can afford a more economically sustainable (economically resilient) technique of utility placement in all three local contexts, with the tipping points taking place where street works are possibly more common and/ or where utility density is high. The limitation of the study was that it assessed sustainability through a mono-criterion (economic considerations) and did not account for the holistic nature of global sustainability which requires that social, economic and environmental considerations (socio-ecological perspective) be accounted for. However at present, there is no literature in the state-of-the-art that can demonstrate the efficacy or otherwise of these claims in relation to multi-utility tunnels being the most suitable utility placement technique when taking account of global sustainability (social, economic and environmental considerations) - will multi-utility tunnels continue to deliver their proposed function (resilience) into the future whatever that may be. This knowledge gap should be addressed.

2.7.3 LIFE-CYCLE FACILITY ISSUES

It takes energy and resources to construct facilities above or below ground. Effects of such activities are wide-ranging, but in relation to socio-ecological systems, the energy contribution to construction that is resource intensive, necessitates the need for decision-makers to find a happy medium between continuing to safe guard resources, and examination as to the viability of continuing investments based on resources (renewable vs. non-renewable). Sub-surface construction is characteristically an energy intensive process with usage of heavy concrete structures with high levels in generated power and ground movement. Be that as it may, bored tunnels and trenchless technologies use considerably lower resources than traditional methods (e.g. O'Sullivan (2012)).

Underground facilities commonly last a long time (see Table 2-8) – chiefly as a result of exclusion to harsh environmental conditions, but also due to the large dead weight of underground facilities that are essential in withstanding ground compressions. Even though they change slowly, underground structures do degrade over time and may have need for repair. However, the changing of certain urban service systems could be problematic or implausible unless the delivery of urban service infrastructure is brought to a stop. Parker and Reilly (2009) carried life-cycle cost analysis which established that several underground facilities possess a lesser (or at any rate competitive) life-cycle cost when weighed against above ground facilities.

Table 2-8: Urban change processes (Wegener & Fürst, 1999, p. 43)

Urban change processes	Examples
Very slow change	*Networks* (e.g., transport networks, communications networks): are the most permanent elements of cities *Land use*: distribution is often stable, changes are incremental

Urban change processes	Examples
Slow change	*Workplaces* (e.g., warehouses, office buildings, shopping centres): exist much longer than the firms or institutions that occupy them *Housing*: exist longer than the households that live in it
Fast change	*Employment*: refers to firms that open, close, expand, or relocate *Population*: refers to households that form, grow, decline, dissolve, or relocate
Immediate change	*Goods transport*: adjusts quickly to changes in demand *Travel*: adjusts quickly to changes in traffic conditions

Underground facilities/ structures normally offer exceptional protection to disastrous events for example radiation, external blasts, tornados, external fires, hurricanes, earthquakes and terrorist actions (H. W. Parker, 2008b). Seismic protection by underground structures has been verified for instance, Sterling et al. (2012) state that Loma Prieta earthquake in San Francisco where subsequent to tremors, the underground transit system was examined and returned to full operation in less than half a day, while most of the city was crippled for several months. In circumstance of floods and hurricanes, provided that the access points to underground structures are secure and watertight, the compressive forces they experience are comfortably handled in comparison to aboveground structures (e.g. flood, wind and impact loads). Nonetheless, the significance of an explosion or fire is characteristically quite severe in an underground structure than in an aboveground structure.

The ingress of ground water and/ or high moisture levels can be very damaging to an underground structures performance and aesthetics, irrespective of its structural integrity (ITA, 1991c). Water ingress is possibly the most significant aspect regarding prospective maintenance and repair needs for an underground facility and could potentially be quite problematic to resolve if not effectively accounted for when first constructed (Hunt, Jefferson, Drinkwater, et al., 2012). A correlation between groundwater levels relative to urban environments is important to note. Groundwater levels will raise and fall depending on water abstraction schemes, water supply leakages and drainage or sewer pipes; this can place underground structures at greater risk (Lerner & Barrett, 1996).

2.8 CURRENT ASSESSMENT OF SUSTAINABILITY IN UNDERGROUND PROJECTS

Evaluating global sustainability or rating different design otherwise development options towards their sustainability in socio-ecological systems ought to comprise applicable measures. In relation to underground space use projects, the above mentioned sustainability measures are thus far inadequately specified (Roberts, 1996; Sterling, 1996b; Chow et al., 2002; ITA, 2002; Godard, 2004; Parker, 2004; Matsumoto, 2005; Admiraal, 2006; Jefferson et al., 2006; Parriaux et al., 2006; Blunier et al., 2007; Parriaux et al., 2007; Reeves & West, 2009; Rogers, 2009; Admiraal, 2010; Holt et al., 2010b; Price et al., 2010; Hunt et al., 2011; Admiraal, 2012; Nelson & Sterling, 2012; Sterling et al., 2012; Canto-Perello & Curiel-Esparza, 2013; Sterling & Nelson, 2013). Sterling et al. (2012) highlight examples of factors that should be considered when assessing overall sustainability of underground space use projects:

(a) The volume actually occupied by a particular use against the volume effectively reserved or sanitised by that use (Bobylev, 2010; He et al., 2012);

(b) The ability to coexist with other adjacent uses (e.g. underground facilities creating vibrations may cause interference with nearby surface or underground facilities);
(c) The potential for damaging releases into the environment, the ability to detect those releases if they occur and the ability to contain or clean up the releases;
(d) The potential for underground construction to either damage historical and archaeological heritage or, as a positive attribute, to make it accessible for public access (Bobylev, 2010);
(e) An underground that conforms to and reinforces the economic and social goals for the urban area (Chen & Wang, 2005; Shu, 2005; Tong, 2005; He et al., 2012);
(f) The opportunity for underground facilities to maintain liveability or redress past problems of infrastructure provision or surface developments (Godard & Sterling, 1995; Godard, 2004);
(g) Measures that address social equity problems – for example those caused when surface or overhead infrastructure systems degrade quality of life for those next to the infrastructure, but without associated benefit; such problems often fall disproportionally on the poor or politically weak (Godard & Sterling, 1995; Rönkä et al., 1998);
(h) Avoidance of severance of neighbourhoods by major highways and rail lines; this has been shown to degrade the quality of life in those areas and to turn previously viable neighbourhoods into a downward social trend (ITA, 1987).

The assessment of sustainability in underground (geotechnical engineering) projects and current evaluation frameworks for this purpose is explored in the following sub-section.

2.8.1 Review of Studies Related to Sustainable Geotechnical Engineering (UUS)

In this section, the current studies pertinent to geosustainability (i.e. evaluation tools utilised by the profession to evaluate UUS, a socio-ecological system) of UUS are examined given the backdrop of the concept and system of socio-ecological systems approach above-mentioned. The application of the concept of 'sustainability' as well as 'resilience' in civil and geotechnical engineering vernacular and its numerous variants has developed into a commonplace feature, and usually are incorrectly ascribed to simply carbon emissions or environmental impact. It is essential to acknowledge that socio-ecological systems approach is multifaceted and as such, the resulting review will evaluate the validity of these studies in the context of the multifaceted nature of socio-ecological systems. Numerous geotechnical engineering studies and industrial projects have been carried out in recent times that can be viewed as advancing sustainable development. The extent and range of these studies and projects reside within the eight categories (see Figure 2-20). A huge number of these studies are centred on the collective thinking of sustainability such as use and reuse of substitute materials, technologies, resources and recycling. Nonetheless, whether such novel methods in reality facilitate suitable solutions within socio-ecological systems or otherwise have to be examined thoroughly. For instance, Clift and Wright (2000) probed into the economic and environmental sustainability of reusing and recycling of harmful materials; they contended the objective that drives for only the removal of harmful materials, whilst harming the environment as a result of poor end-of-life management should be stopped, and through the application of reverse logistics on studies in both the UK and Sweden, showed that the benefits accrued through recycling are offset to a large degree by the environmental impact of transporting back recycled materials; and the practice is not viable sustainably (economically and environmentally) for small cost, low reusability materials. Accordingly, a comprehensive sustainability evaluation framework is needed for geotechnical engineering projects to establish the relative merits or otherwise of alternative options presented for a project both now and into the future (see Figure 2-20).

Bearing in mind the above, this review sub-section examines the current tools and evaluation frameworks pertaining to geotechnical engineering (UUS). The appraisal is constrained to this area of geotechnical engineering, since it is deemed the most appropriate to sustainable development of the socio-ecological system of UUS; moreover, aids to realise the overarching aim of the present research work that seeks to address facilitating a novel method for sustainable and resilience evaluation of UUS physical utility infrastructure (see Figure 2-20).

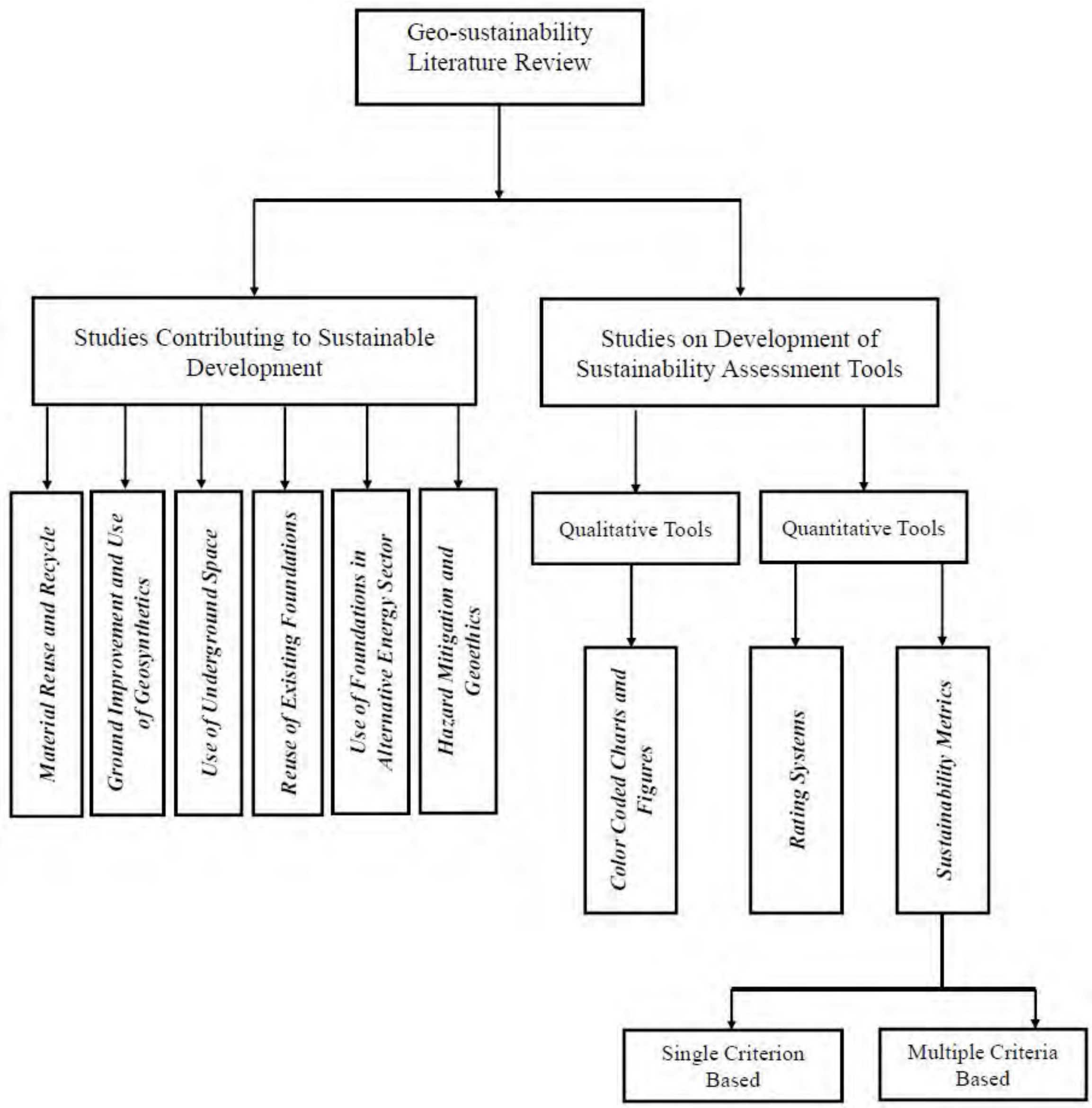


Figure 2-20: Summary of geosustainability literature (Basu et al., 2014)

2.8.1.1.1 Sustainability Evaluation Tools in Geotechnical Engineering (UUS)

In spite of the singular way in which geotechnical engineering (UUS) contributes with respect to the sustainable construction agenda (see Figure 2-5), up till now there exists no customary strategy or plan of action at beck and call to classify, evaluate and tackle sustainability within geotechnical projects (Holt et al., 2010b). There exist assortments of approaches that address this gap, which will be discussed further down. Thus far, there happens to be a small amount of detailed guidance on how to apply the principles of sustainability into geotechnical engineering, let alone in accounting for socio-ecological systems, especially with regard to accounting for complex geology, mainly because there is no proven tool or indicator system to this end (Stephan A Jefferis, 2008). Even supposing some suitable indicators for the routine steps of geotechnical engineering works can be acquired from different higher level systems, they can be challenging to classify and may well disappear amidst the selection of alternative indicators (Stephan A Jefferis, 2008). In the absence of such a framework to direct geotechnical engineers, majority of the decisions taken during a design process are still largely centred on budget restrictions, previous experience, and the engineers own beliefs and views (which varies from person-to-person and company-to-company), and therefore an absence of objectives aimed at sustainability for the duration of the design decision-making process is even now evident (Braithwaite, 2007; Holt et al., 2010b). Due to the fact that uncertainties related with geotechnical socio-ecological systems are frequently considerably larger than those experienced through other engineered systems (Barends, 2005), an evaluation framework for sustainability to serve geotechnical engineers ought to take into account the reliability and resilience of the geo-structure in light of the geo-system, and afford elasticity to the user to identify local priorities (Hunt et al., 2011).

Environmental impact as a means of comparing and contrasting competing options in geotechnical engineering, is often evaluated by means of quantitative environmental metrics such as embodied energy (Chau et al., 2006; Simpson & Tatsuoka, 2008; Soga et al., 2011), probability of global warming (Storesund et al., 2008), carbon critical design (Clarke, 2010b, 2010a), embodied carbon dioxide (Chau et al., 2008; Egan & Slocombe, 2010), and a mixture of emissions and embodied energy (nitrous oxide, methane, sulphur oxides, carbon dioxide and nitrogen oxides) (Inui et al., 2011). However, evaluating the sustainability of a geotechnical project centred just on metrics such as probability of global warming or embodied carbon dioxide contains ad hoc assumptions, thereby placing excessive importance on environmental attributes, and thus fails to take into account a holistic slant that necessitates the inclusion of economic, social and technical aspects (Holt et al., 2010a; Steedman, 2011). Carpenter et al. (2007) pointed out that for any decision-making framework, a mixture of life-cycle-analysis (LCA) and local priorities (e.g. site and material specific factors) provides a stronger contextual baseline for decision-making as opposed to a singular metric. Jefferson et al. (2007) similarly pointed out that the utilisation of a singular metric to assess the sustainability of a geotechnical engineering project may not always be adequate; a comprehensive sustainability evaluation framework in geotechnical engineering that sustains the resilience of engineering solutions is needed – covering all aspects of sustainability not just environmental aspects (Parkin et al., 2003; Walton et al., 2005; Braithwaite, 2007; Elghali et al., 2008; Hurley et al., 2008).

The multifaceted nature of geosustainability is accounted for in most cases using evaluation tools, a range of these tools are qualitative and depict the performance of a geotechnical project on different indicators graphically. One such qualitative indicator system, identified as “S.G.E.M” (Sustainable

Geotechnical Evaluation Model), was developed by Jiminez (2004) and is utilised for assessing the sustainability of various material options for slope stabilisation. The procedure of S.G.E.M aids to assess the sustainability of a geotechnical engineering development founded principally atop groupings of economic, social, environmental and raw material use, in addition to subgroups ranging from land use, water use and reusing of materials. By the same token, Holt et al. (2010b) developed "GeoSPeAR", an indicator system aimed at geotechnical construction, through the adaptation of "SPeAR" (Sustainable Project Appraisal Routine) developed by ARUP (see Figure 2-21), comprising a seven step process (including a pre-assessment to ensure communication amongst all parties involved in the process) of: (i) Step 1: setting up of boundaries for the assessment; (ii) Step 2: data collection from the project for different indicators; (iii) Step 3: A baseline assessment using GeoSPeAR; (iv) Step 4: detecting areas of sustainability concern; (v) Step 5: carrying out LCA to evaluate impact of different design options; (vi) Step 6: Re-examination of possible improvements for changes in design option (if necessary), and (vii) Step 7: repetition of steps 5-6 to realise the expected level of improvement. SPeAR employs a graphic – rose shaped, which is colour coded to evaluate a project on account of four principal measures: social, economic, environmental and natural resources – with a subsequent twenty sub-criteria as a sub-text to the principal measures of sustainability. Within the SPeAR circle, the functioning of a development is evaluated in a specific sub-criterion through hatching respective divisions with its individual colour (Ranging from: optimum = 1, to, worst case = 7). The nearer the hatched section is to the centre of the circle, the more sustainable the project is in connection with the specific sub-criterion. GeoSPeAR adapted and substituted 11 indicators from the master planning accompanying indicators of SPeAR (e.g. Social responsibility which measures contribution to the community, health and well-being which measures the provision of crèche facilities and other support facilities, and water discharge which measures utilisation of on-site organic process treatment facilities etc.) with 8 specific geotechnical related indicators (e.g. Sensible use of materials and resources, energy utilisation, site investigation, cost-effectiveness in design and recycling and reuse of existing substructures). GeoSPeAR furthermore comprises an elective delivery for life cycle assessment of a project to generate clarity to the important sustainability indicators (e.g. CO^2 emanations and noise etc.) besides narrowing the interpretation of the results, and in so doing verify the impacts of the design choice upon resource expenditure and the environment (Holt et al., 2010b).

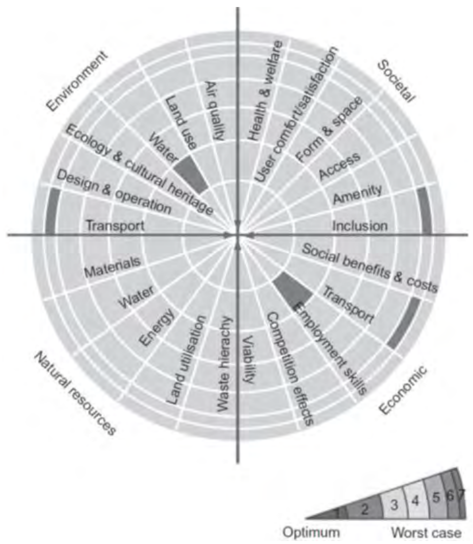


Figure 2-21: An example of the SPeAR template (Holt et al., 2010b)

The next group of multifaceted evaluation frameworks utilised in geotechnical engineering comprises of quantitative and life-cycle based tools. Dam and Taylor (2011) state that a LCA of geotechnical processes and products should be part of any geosustainability evaluation framework and ought to: (i) Safeguard social sustainability through fostering of resource budgeting and limiting the shift of the environmental load of a specific stage to areas later down the line; (ii) Ensure financial well-being of the stakeholders, and (iii) Apply sound engineering design and maintenance. Life-cycle-costing (LCC) has been utilised in aiding the decision-making process by identifying the best economical option among various choices. Examples of where LCC has been utilised in geotechnics can be found for instance in pavement design (Reigle & Zaniewski, 2002; Praticò et al., 2011; Zhang et al., 2011). LCC by its very nature lays emphasis on the social and environmental impacts by adapting them to represent a monetary net present value. Zhang et al. (2008) for instance, utilised a blend of LCC and LCA to evaluate the sustainability of pavements. Pittenger (2011) formulated a performance metric labelled as 'GAPI' (Green Airport Pavement Index) for evaluating the sustainability of alternative airport pavement options – GAPI merges the capacity for functioning of a pavement treatment option in the categories of LCC, resource use and project management through utilising relative weight measures to compute the metric. Lee, Edil, Tinjum, et al. (2010) merged LCA and LCC to quantitatively evaluate the benefit of utilising recycled materials in pavements – their empirical investigation demonstrated that significant savings in the categories of energy consumption, water consumption, hazardous waste production and global warming potential can be made once recycled materials are employed in construction. Lee, Edil, Benson, et al. (2010) adapted the evaluation framework formulated by Lee, Edil, Tinjum, et al. (2010) to include a LCA based rating system 'BE^{2}ST in-Highways' (Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways). BE^{2}ST in-Highways is chiefly aimed at projects where recycled materials are utilised, and in this system consensus from project stakeholders is required at the commencement of the project to decide on the impact categories and reduction targets in those categories. Points are subsequently given to projects based on how close they are to the set reduction target value; the reduction target vales are settled on in connection with the impact that could potentially be produced if virgin materials were utilised as an alternative to recycled materials. Torres and da Gama (2006) formulated 'ISA' (Environmental Sustainability Index) for quantifying the environmental sustainability in underground mining and geotechnical works. ISA reflects impacts grouped into the three pillars of sustainability ranging from, economic (e.g. salary incomes, assessment and landmarks etc.), social (e.g. relations with community, direct and indirect employment etc.), and environmental (e.g. atmosphere quality, geotechnical and water quality, waste and environmental incidents etc.). Misra (2010) and Misra and Basu (2012) formulated a multicriteria based quantitative framework aimed at evaluating the sustainability of geotechnical projects (specifically piles) – the framework takes into account environmental impacts, resource consumption and socio-economic value of a project over its whole life cycle. Embodied energy is employed to account for the use of resources, whilst the impact of emissions released is evaluated using 'EIA' (Environmental Impact Assessment), and finally the socio-economic impact on the project is evaluated by means of a 'CBA' (Cost Benefit Analysis). The result is the derivation of three indicators from the three metrics which are merged through aggregate weighting to compute the 'SI' (Sustainability Index) for the various alternatives offered for the project.

The final group of sustainability evaluation methods as pertaining to geotechnical engineering are point-based rating systems, which offer an appraisal relative to points gained in alternative yet related classifications. Jefferson et al. (2007) put forward a point-based indicator system named 'EGI' (Environmental Geotechnics Indicators). EGI comprises a set of 76 'generic indicators' utilised to evaluate the sustainability of any geotechnical project and a set of 32 additional 'technology specific' indicators utilised to evaluate the sustainability of specific techniques for treating contaminated land. EGI can be applied to a case site for ground improvement purposes by applying its points score system (1 (harmful) to 5 (significantly improved)). The EGI system was formulated by utilising existing construction sector indicators (SIGMA, SPeAR, BREEAM, Eco-points, CEEQUAL and KPI's) and by adapting them to be appropriate for the specific characteristics of ground improvement projects. The EGI system does not divide the indicators set into the various pillars of sustainability (economic, social and environmental) in a bid curb the chance of an end-user concentrating on the economic pillar alone. Laefer (2011) formulated a points-based scoring system to supplement SPeAR, aimed at aiding the evaluation of foundation reuse projects. In transportation geotechnics, a range of points-based rating systems have been formulated of late to address infrastructure assessment, these systems have shaped the direction of on-going research on alternative geo-materials. These systems comprise Greenroads (Muench & Anderson, 2009), I-LAST (Knuth & Fortmann, 2010), MTO – Green Pavement Rating System (Chan & Tighe, 2010), and GreenLITES (McVoy et al., 2010). The best possible use of natural resources in a project is one of the categories these rating systems assign points to and as such these systems provide a stimulus into researching of alternative sustainable geo-materials.

2.9 IMPLEMENTING SOCIO-ECOLOGICAL UNDERGROUND SPACE USE

Discussions to this point have addressed an assortment of important concerns in the evaluation of underground structures with above ground structures, and the prudent use of UUS as a resource in its own right. It is vital to take into account how issues raised could be governed for in the planning and design for UUS in urban areas. Table 2-9 from Bobylev (2009a) summarises by what method to incorporate socio-ecological issues for UUS into master planning activities and a number of points are examined below.

Table 2-9: Mainstreaming urban underground space (UUS) into a master plan (Bobylev, 2009a)

Nature of action	Action	Explanation, specifics	Methods and tools
Understanding state-of-the-art techniques, or the baseline	Three-dimensional map of a city, including UUS	Geological modelling, survey of existing structures, historic records of subsurface cultural heritage, existing services and users of UUS	Survey, modelling, GIS
Prospective planning	Three-dimensional map of a city, including UUS, and a time perspective (e.g. 25, 50, 100 years)	Needs for surface structure development; Needs for subsurface structure development; Identify prospective services	Planning, cost–benefit analysis
Assessment and analysis	Vulnerability assessment	Analyse UUI performance in critical situations (e.g. natural disasters)	Analysis, modelling
	Scenarios for development of selected UUS services	Reservation of space for different scenarios	Analysis, modelling

Nature of action	Action	Explanation, specifics	Methods and tools
	Check for broader UUS services and potential users	Other uses, interests (military, civil defence)	Analysis
	Sustainability component assessment	Environmental and social impacts	Environmental impact assessment, strategic environmental assessment, sustainability analysis
Decision-making	Integrated assessment	Identification of existing or potential conflicts in the issues listed above and establishing priorities	Multiple criteria decision analysis

2.9.1 EXISTING CONDITIONS

A very important constituent in the effective management of UUS in urban environments is a thorough comprehension of existing conditions as well as the local geological conditions i.e. a catalogue of existing underground structures/ assets and reference (baseline) figures that bring together significant characteristics of the underground urban environment. This composite information can then be aggregated relative to the strategic planning, design and construction consequences in the disparate geological formations and further necessitate that they are made clear and logical to decision-makers whose duties are to direct planning and urban policy (ITA, 1991b; H. W. Parker, 2008a; Hunt et al., 2009; Price et al., 2010).

The tangible indication of anthropogenic pursuits and their residual deposits in underground space is denoted using material categorised by the British Geological Survey (BGS) as 'Artificial Deposits' (Powell et al., 1999; Price et al., 2004; Ford et al., 2010). These deposits are classified by means of field surveys, borehole analysis and historic map and aerial photography evaluation and have been incorporated on 1:10 000 scale geological maps. Culshaw (2005) acknowledged the necessity for better-quality techniques of classification concerning artificial ground (cavities in addition to deposits) for enhanced risk and urban planning appraisals. The extensive growth and expansion of 3D geological modelling through the BGS utilising GSI3D software and approaches (Hinze et al., 1999; Sobisch & Bombien, 2003; Kessler et al., 2008; Kessler et al., 2009) has allowed 3D geological models to be visualised and explored. The models comprise superficial, and bedrock deposits.

The formulation of approaches to model UUS in 3D has facilitated a way to augment geological models through incorporating artificial deposits and high resolution soils. Nevertheless, the classification of UUS furthermore comprises archaeological structures, foundations and infrastructure and utilities (within the zone of human interaction). This brings about a substantial challenge for the construction of useful 3D models of UUS (Rosenbaum, 2003). The construction of 3D ground models for the classification of variability in UUS comprising artificial deposits in urban environments greatly improves support for sustainable land use planning.

The information regarding what has been previously constructed in the UUS (principally in relation to the utility asset catalogue) is really inadequate in nearly all cities and is difficult to gather a complete account of previous UUS uses, moreover ecosystem services (Rosenbaum, 2003; National-Research-Council, 2006; Parriaux et al., 2006; Sterling et al., 2012; National Research Council, 2013; Sterling &

Nelson, 2013). The accession of three-dimensional geographical information systems (GIS) as well as survey-grade global positions systems v(GPS) are allowing the development of detailed underground usage databases, but data quality, precision and dependability continue to persist for the present (Metje et al., 2007; Sterling et al., 2009; Baiden et al., 2014).

2.9.2 OPPORTUNITIES FOR NEW CONSTRUCTION OR REUSE

Existing structures, their arrangements and types are important as they influence the simplicity with which construction of underground facilities can take place and their combination with, or detachment from, existing facilities. The examination of possible infill sites can govern usability and prospective value of the sites. China is presently undertaking extensive development of UUS; for instance, see Shi (2009) for Beijing. In general, these developments comprise comprehensive modernisation of enormous urban sites (see Figure 2-22) and include a combined use of UUS as a segment of the development strategy. Extensive development or redevelopment zones provide the possibility for construction economies as well as the ability to operationally increase the present surface level to deliver all-round improvements without the need of underground construction. Instances of this last methodology are the La Defense and Seine Rive Gauche developments in Paris and the Tsukuba Science City in japan (Sterling et al., 2012).

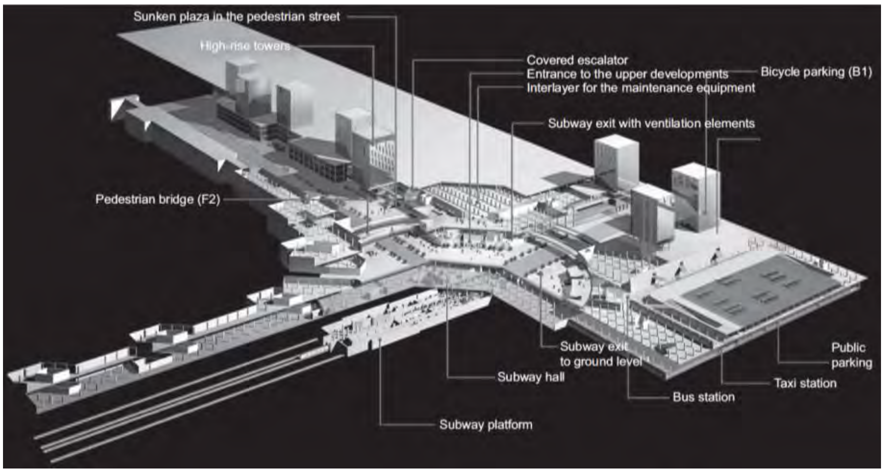


Figure 2-22: Underground space integrated design and use: Guogongzhuang Station of Metro Line 9, Beijing, China – comprising 200 000 m^2 of underground space (Sterling et al., 2012)

The sustainability of underground structures also hinges on the ability to evaluate them for structural rehabilitation or functional change as they approach functional obsolescence. On the whole, underground facilities can be potentially reused for different functions (Rogers & Hunt, 2006), but this generally hinges on their existing spans (longer is better) and greater free heights within the primary structural element. For instance, underground parking structures with smaller free heights offer limited reuse options even though property prices can cause this to be desirable.

2.9.3 PLANNING AND LEGAL FRAMEWORK

Master planning that meaningfully addresses underground facilities and UUS are small in number throughout the world. Instances of cities that have taken an active approach to this end, and have carried out planning activities previous, and/ or have existing plans comprise: Minneapolis (Subspace, 1990) and Helsinki (Vähäaho, 2009) and Singapore (Singapore-Government, 2010). Logically, it is difficult to understand why such a significant part of urban growth is not clearly recognised in urban master plans generally. On the other hand, from a practical perspective, the scarcity of data and inadequate understanding of the substantive problems and lack of accessible control processes frequently result in such planning requirements being overlooked and/ or the results appearing unsatisfactory. The majority of current illustrations originate from settings where geological conditions or space restrictions offer distinct problems to be resolved (Working Group Number 13-ITA, 2004).

Lack of legislative measures to incentivise, or compel utility service providers into MUT galleries or to permit public use tunnels to cut across - deep underneath private lands (see Figure 2-3), means that UUS uses will continue to be dotted and limited and probably less effective as a means of supporting the comprehensive socio-ecological well-being of an urban area (see Figure 2-9). Current legislative provisions in a selection of countries were assessed by the ITA in 1990 (ITA, 1991a). An amendment in legislation that stands as a good example explicitly aimed at encouraging more effective UUS growth is the deep underground usage law in Japan (Matsumoto, 2005) (see Figure 2-3). This legislative amendment allows ‘deep’ underground space to be utilised for public infrastructures. Kobe in Japan is utilising the deep underground space law, and building a new transmission line for drinking water. The law significantly streamlines the compromises in the middle of preferred tunnel position, besides legal/ economic barriers due to private property concerns. Finnish law specifies that the titleholder of a property has control to regulate and modify the underground portion of the property, while the vertical limit is not explicitly laid out in law (Narvi et al., 1994). Whilst deducing the degree of possession, the lower limit of a property is constrained to the depth to which it can be officially used. Practically speaking, this means a working depth of 6m from the lowermost point of the property building. This permits the erection of publicly owned underground facilities beneath this depth (6m) without expense on the public purse for utilisation of the said space (Vähäaho, 2009).

Jefferson et al. (2006) address the issue that even when sustainability objectives and underground issues are incorporated in master plans and policy documents, the necessity remains as to how decision makers can both recognise and exercise these objectives into local and regional policymaking processes (see Table 2-9). A ground-breaking project in this respect has been the Eastside Sustainability Research Project in Birmingham, UK (Hunt & Rogers, 2005). The goal of this research project has been to investigate in what way sustainability is delivered in practice for the duration of the regeneration policymaking/ decision-making process, and evaluate the sustainability performance of solutions through a development timeline framework, enabling the practitioner to optimise decision-making in development programmes in Birmingham’s Eastside, alongside specified sustainability indicators and objectives (Hunt, Lombardi, Rogers, et al., 2008).

Underground space is often designed for and constructed by Geotechnical engineers who naturally work using lengthy design lives, equally planners of underground space use by extension (Rogers, 2009). A generalisation of future developments does not, inevitably result in designs that are fit for purpose in the far future and their attendant socio-ecological systems, whatever that may be; circumstances could possibly be very different to those referred to now. A large body of literature has grown on work pertaining to future scenarios (e.g. see Raskin and Monks (2005)), and this approach has been broadened to the study of the probable future value of underground space use by advancing four distinctive and extreme, yet plausible, alternative futures and examining the usefulness of today's engineering solutions, which are by and large proposed in the name of sustainability, in those futures (Hunt et al., 2011). If the engineering solutions are suitable and deliver their intended function no matter what the future, then the designs can be considered resilient; otherwise, at that point modification of the designs might be considered to safeguard their value if the future turns out to be different to forecasts grounded on present-day socio-ecological trends.

2.9.4 RECOGNITION AND ACCEPTANCE OF UNDERGROUND SPACE IN THE PLANNING PROCESS

Methodologies for underground planning are contingent on local circumstances. Urban areas should individually classify the categories of underground utilisation to their city. The choice of options for underground facilities and their reservation guidelines that may be suitable will subsequently be restricted. For instance, the city of Helsinki's underground planning requirements pertain to rock outcropping and near surface rock cavern possibilities. Figure 2-23 displays a section of the Helsinki underground space master plan. The complete master plan of Helsinki's underground comprises the entire city and suburbs (please refer to (Vähäaho, 2009)). It is generated and sustained by through the City of Helsinki, City Planning Department. Both current and scheduled underground spaces (reserved spaces exhibited two-dimensionally in the master plan) and tunnels are indicated in the underground master plan. The master plan furthermore comprises rock resources earmarked for future underground usage (as needs arise), with the intention of classifying suitable sites for functions appropriate to locate underground, dispersing the pressure placed in exhausting its rock resources at the city centre for underground developments. The appropriateness of rock zones for different functional purposes will be considered during preparation of the town plan.

Figure 2-23: City of Helsinki underground space master plan. Circled figures indicate approximate floor elevations. Existing vital access links to underground technical maintenance spaces/tunnels are shown on the map with triangles. Grey = planned underground spaces and tunnels; dark grey = existing underground spaces and tunnels; light grey = rock resources reserved for the construction of as yet unnamed underground facilities; lightest grey = rock surface less than 10 m below ground surface (Sterling et al., 2012)

In cities such as Tokyo, Amsterdam and Shanghai a disparity exists in comparison to Helsinki as planning pertains to high groundwater levels, flat topography and ground conditions where soft soils dominate in the low to medium depths of the underground (Sterling et al., 2012).

For planning purposes, the growth of 'up-and-coming' cities or extensions to current cities, the setting aside of underground transportation strips and the formation of future growth levels for foot travellers, road and rail inside high-density zones should be carried out where possible (for example Joondalup, near Perth in Western Australia, see Sterling (1996a)). Such policies that withhold suitable sites for specific functions can limit utility clashes for future tunnelling to the present degree of difficulty; can side-step the locating of subtle facilities next to transportation corridors, and can make available a harmonised but not entirely planned urban development inside the region covered through the plan (e.g. Helsinki, (Vähäaho, 2009)). Occasions when major developments are taking place can be utilised to incorporate underground construction or entrance for such facilities in a way that is not probable in isolated sites. The widespread city centre underground pedestrian networks in both Toronto and Montreal were instigated by means of major redevelopment projects (Boivin, 1991; Bélanger, 2007).

Developmental proposals that are multi-purpose and allow effective resource and space usage should be recognised and supported. MUTs integrate several utility services into a solitary sustainable facility. This type of consolidation and collocation of utility service provision is in sharp contrast to current trends (as a result of deregulation), where utility service providers (esp. telecommunication companies) have numerous suppliers installing separate cables in public rights-of-way to deliver a functional service to the same consumers. For example, in Kuala Lumpur a innovate method through the use of a 'Smart' tunnel for merging functions within a solitary underground infrastructure section, in addition to flood relief with a tunnel to reduce traffic congestion throughout non-flood periods is being used (Rieker, 2006). Orly Airport in Paris has also put forward a proposal under consideration for a multi-purpose underground development (Duffaut & Labbé, 2008).

Energy delivery heat conversion systems may be combined with utility or structural elements of a project (e.g. joined piling and geothermal heat conversion, see Kentaro et al. (2005)). On the whole, the significant point for the appropriate use of UUS as a complex socio-ecological system is for planners and policy makers alike to develop awareness of UUS as part of the urban planning process, and approving suitable methods for development of UUS in light of key geological opportunities identified in the policy/decision-making process.

2.10 REMARKS ON THE STATE-OF-THE-ART: IDENTIFICATION OF KNOWLEDGE GAPS

This chapter has highlighted the broad spectrum of UUS use in urban environments and has demonstrated that UUS has clear advantages for the formulation and/ or preservation of functional, sustainable and resilient cities (socio-ecological system). However, underground construction even now poses challenges and difficulties under various urban and geological conditions and brings about some of its own risks to the group of people that it serves. Underground services, especially for infrastructure elements, frequently allow clear minimisation of above ground environmental impacts when weighed against surface facilities, and as such can advance urban sustainability through safeguarding the above ground environment at the same time improving access and service delivery for lasting economic viability. Even so, underground structures as a result of their often high initial cost and perpetual modification of the underground environment place a distinctive insistence on long-term planning efforts which take into account life-cycle advantages and the adoption of projects that afford the greatest impact to urban sustainability as opposed to ad hoc solutions for a singular need. The significant point is that urban professionals and policy makers need to understand how UUS use as a socio-ecological system, can strengthen the sustainability through resilience approach of cities and for this to develop into a deliberate segment of the urban planning process to engender the preservation of favourable circumstances for urban development by posterity.

Sustainability related studies in geosustainability essentially reside in one of two groups: the first group contribute to global sustainability by way of employing alternative materials and innovative engineering; the second group contributes to global sustainability through development of sustainability assessment frameworks (see Figure 2-20). A critical review of the relevant research studies as pertaining to sustainability assessment frameworks has been provided for the purpose of mapping the scope of current geotechnical practice. Not all the knowledge gaps identified will be relevant to the aims of this research, and as such statements to that effect will be limited to those that impact the aims of this research. Allowing for this context, the identified gaps of knowledge are defined as follows:

- A substantial knowledge gap identified in the literature, which impacts significantly on the aims of this research, is that though the sustainability assessment tools reviewed in the previous section serve the profession well, <u>none</u> of these assessment frameworks consider resilience in both design and assessment of geo-structures i.e. a socio-ecological approach. They do not address the issue of performance of the geo-structure which resilience demands i.e. will the geo-structure continue to deliver its intended function into the future, whatever that may be? This demands that the temporal dimension of shifting socio-ecological system objectives be accounted for and quantified which <u>none</u> of the current assessment frameworks provide. Marley (2001) highlights Michael Wegener's statement that "*Everything that happens, happens somewhere in space and time*"; every major concern has a time scale: disasters (days), infectious disease (weeks), economic meltdown (months), climate tipping points (years), and climate change (decades). This calls for spatial literacy i.e. the capacity to make sense of problems and their solutions in spatial terms. The Urban Futures Method (Rogers et al., 2012) relevant to urban development, which has been developed recently, has a wider and comprehensive scope in the assessment of sustainability solutions through a resilience approach (with accompanying socio-ecological future scenarios) to planning and offers the best opportunity to account for the holistic and temporal nature of socio-ecological system; in the context of this thesis, UUS. There exists useful literature which may provide an opportunity for the development of such a system aimed at geotechnical engineering to address this gap, particularly that of Hunt et al. (2011) with the aid and combination of other tools (see Table 2-9) (e.g. Geographical Information Systems (Including '*Fuzzy*' GIS), Multicriteria Decision Analysis etc.).
- By carrying out the literature review, a knowledge gap with respect to the sustainability assessment of multi-utility tunnels has been identified. There is no literature that can demonstrate the efficacy or otherwise of these claims in relation to multi-utility tunnels being the most suitable utility placement technique when taking account of global sustainability

(social, economic and environmental considerations) i.e. from a socio-ecological systems perspective- will multi-utility tunnels continue to deliver their proposed function (resilience) into the future whatever that may be. The novel socio-ecological systems evaluation framework that is to be developed (see Chapter 3) will evaluate the use of MUTs in Birmingham Eastside (see Chapter 5) and therefore address this gap in knowledge as a proof of concept.

- A further knowledge gap worthy of note is that none of the current assessment frameworks offer guidance on how to account for complex geology in the decision-making process when assessing underground projects. Geological spatial features are key aspects greatly impacting the use and cost of underground space and include aspects of rock and soil properties (Working Group Number 13-ITA, 2004). This should be accounted for when evaluating use of underground space (Hunt et al., 2011).

CHAPTER 3: DEVELOPMENT OF THE SUURE DECISION SUPPORT SYSTEM

3.1 INTRODUCTION

The previous chapter highlighted an absence of evaluation frameworks that account for SESs in UUS through the prism of resilience in geotechnical engineering. The evolving consensus on the nature of this challenge in SESs is that many of our environmental and resource challenges in the 21st century are seen as complex systems problems (Levin, 1999); UUS is a complex system that involves complexity of interfaces concerning natural and social systems. This complexity by its very nature creates a significant challenge for the current disciplinary approaches as evidenced in chapter 2 (see Section 2.8.1) for geotechnical engineers. UUS phenomena whose functional physical infrastructure are multiple (see Figure 2-13), varied and spread out cannot be understood, let alone managed as well as organised, through the current traditional scientific approaches in geotechnical engineering. A hybrid systems thinking definition of resilience (see Table 2-2: Class 8, 8a and 8b) as evidenced in SESs is thus deemed necessary as core objective of the present work, looking at sustainability as a process as opposed to just being an end product, it is viewed in the present work as a dynamic process that necessitates adaptive capacity for UUS to deal with change. It is fundamental to the proposed SUURE framework, its theoretical foundations and accompanying operational model given this context, that rather than assuming stability and explaining change, which is often the case, change is here assumed and stability is what is explained. To state explicitly for the purpose of the present work, sustainability indicates preserving the capacity of ecological systems that aid in the maintenance of social and economic systems. Maintaining this capacity necessitates analysis in addition to understanding of feedbacks and, by and large, the changing aspects (in space and time) of the interrelations concerning ecological systems and social systems (the economy being a by-product of the social construct in question). It is on this basis that the current chapter puts forward a complete description of the proposed '*Sustainable Underground Use Resilience Evaluation*' (SUURE) framework, a novel DSS framework and accompanying operational model for evaluation of UUS sustainability through the prism of resilience i.e. to quantify the spatial and temporal impacts of today's urban development and regeneration solutions on their subsurface environments (UUS) in light of future change. The chapter begins by providing an ontological narrative on the basis of the SUURE framework and makes known its components and the way in which they are organised.

3.2 DEVELOPMENT OF THE SOCIO-ECOLOGICAL SYSTEMS EVALUATION FRAMEWORK - SUURE

It is important to note in the context of this thesis that sustainability science by its structure, content and associated methodologies, differs fundamentally from most science as we know it. The existing traditional sustainability approaches in geotechnical engineering (UUS) to its hypothesis and testing as evidenced in Chapter 2 (see Section 2.8 - 2.8.1) fall short because of nonlinearity, complexity as well as the lengthy time horizons concerning actions (in the name of sustainability) and consequences. Further difficulties arise from the recognition that humans cannot stand outside the UUS-society system. Figure 3-1 illustrates the main aim of enquiry and associated fundamental thinking behind the SUURE framework. It is considered in the present work that change as well as the influence of change remain universal givens. The SES of UUS as illustrated through Figure 3-1 is impacted by change and copes with it as a function of its capacity to adapt to change (SES resilience) and shape it. The SUURE framework is developed as a means of identifying, categorising and systematising effective ways of analysing the phenomenon of change as experienced in UUS and how to respond to change and in turn mitigating potential loss of future developmental options. At its core, the SUURE framework seeks to evaluate UUS (a SES) adaptability to meet novel urban regeneration opportunities without compromising sustainability. The approach employed in this thesis is novel in that the focus is not merely on social change or on environmental change (see Chapter 2, Section 2.8.1), but alternatively on SES change (UUS). In adopting a resilience approach (see Chapter 2, Section 2.5 for rationale) to the present work, USS as a complex SES can be (the *(UUS)* systems we encounter and manage are complex, but not *infinitely* complex Holling (1973)) understood through integrating the two streams of thought social system complexity and ecological systems complexity, both underpinned and propped through the use of a resilience approach as an organising concept and scoping device. Thus, the SUURE framework reconciles the issue of change and adaptation via the lens of resilience, which the rest of this chapter will seek to draw out.

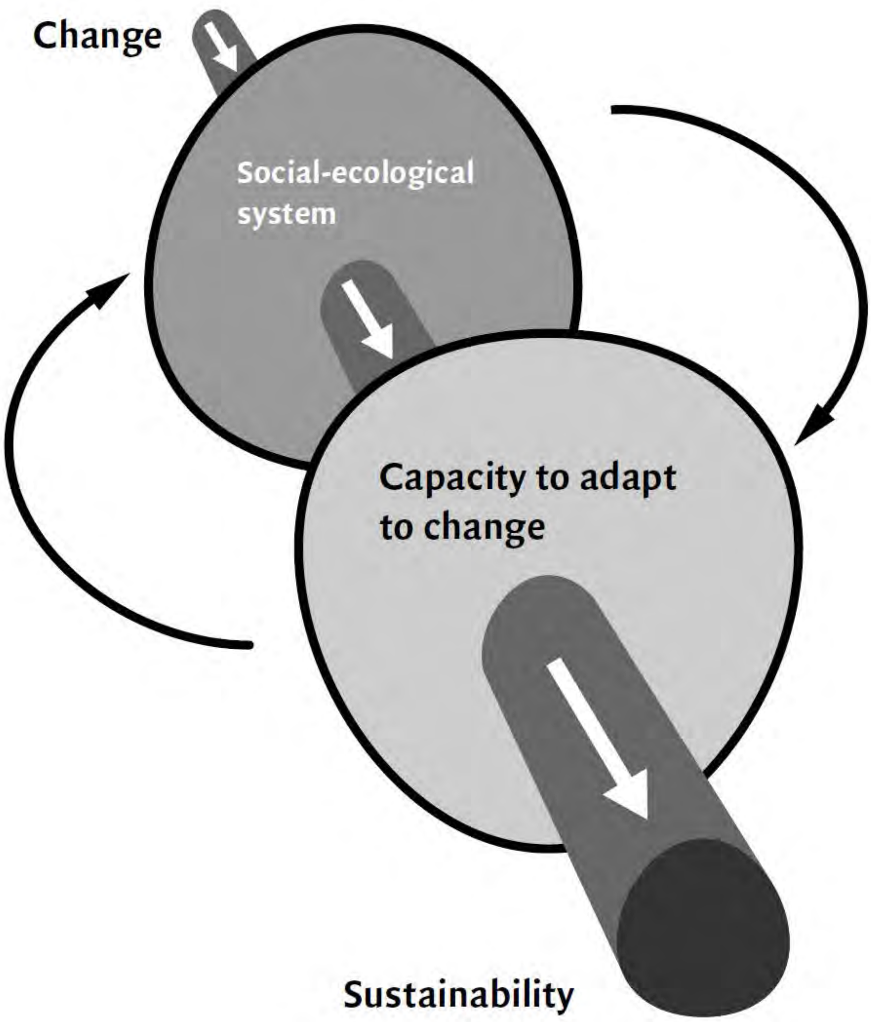


Figure 3-1: The focus on adaptive capacity for sustainability of UUS that underlies SUURE. Sustainability is viewed as a process, rather than an end-product, a dynamic process that requires adaptive capacity in resilient social–ecological systems to deal with change (Berkes et al., 2002)

Resilience as the core approach to the SUURE framework and accompanying operational model, in the process of realising sustainable engineering solutions, has been progressively regarded as a perspective, a way of thinking to evaluate interconnected socio-ecological systems (Folke, 2006). This different approach in the present work is put forward to address the clear limitations of engaging sustainability science in isolation (see for example Redman (2014)). Current efforts (see for example Folke (2006); Ostrom (2007, 2009a); Folke et al. (2010); Binder et al. (2013); Redman (2014)) to truly understand mutually dependant SESs are still largely in an exploratory stage, providing great scope for new creative methodologies and perspectives; the present work aims to contribute to this on-going line of inquiry through the formulation of the SUURE framework.

Many researchers employ the terms 'framework', 'theory' and 'model' almost interchangeably, but a more precise distinction is made in this thesis amongst these terms as articulated Ostrom (2009b), with a view to make the new way thinking and processes presented in this thesis clear . A framework affords the elementary lexis of concepts and words that could be utilised to assemble the kinds of causative explanations expected of a theory (e.g. resilience theory). Frameworks arrange diagnostic, explanatory and prescriptive inquiry. A theory advances precise causative relationships between core variables. Contrary to this, an operational model establishes more detailed manifestations of general theoretical phenomena as relating to the functional relationships between independent and dependent variables vis-à-vis UUS (see Figure 3-14 for the SUURE operational model). The SUURE framework presented in Figure 3-2 puts forward the metatheoretical language that is employed to compare the theories employed in the SUURE framework. It identifies clearly the universal elements that any subsequent theory utilised in future research endeavours, applied to the similar phenomena (in the context of this thesis UUS utility infrastructure: see Chapter 5) would need to include.

The SURRE framework (SESEF) presented in Figure 3-2 was designed to categorise the basic working parts and analytical connections amongst the essential elements that are essential to think through when studying UUS as a resource (which is a SES). It moreover affords the basis to address the overarching aim of this thesis (through objective 3) which is to '*quantify the spatial and temporal impacts of today's urban development and regeneration solutions on their sub-surface environments, in light of future change, whilst measuring their long term sustainability*'. Through this framework (see Figure 3-2), the specific assumptions that are necessary to understand the SUURE framework are presented, aiding to explicitly understand phenomena, explain processes as well as predict the outcomes of SUURE evaluation through the accompanying operational model. The diverse theories employed are all compatible with the SUURE framework and are discussed in the following section in detail (see Section 3.3). This chapter begins here in presenting the framework of SURRE, principally because of the number of varied processes happening in SUURE. It is important from the onset that the reader be able to grasp the nature of the framework, before the theories behind it, in addition to an operational model are presented later in this chapter. Confronting the constantly growing complexity of UUS as described in Chapter 2 (density of building stock, population increase, urbanisation, technological development, uncertainties concerning underground development etc.), it is crucial to move past a one-dimensional "steady state" model of sustainability as a fundamental research priority, and to the development of decision-making approaches that provide a basis for dynamic, adaptive management of UUS, contrasted with static optimisation. This necessitates approaches for understanding the full spatial consequences of different decisions whatever the future may be, and their comparative appeal in terms of strengthening UUS system resilience, and as a result city resilience, and thus sustainability development at large. Why this is important is brought about principally in relation to how SUURE evaluation purposes impacts the way we view the future with respect to planning and design of geo-structures.

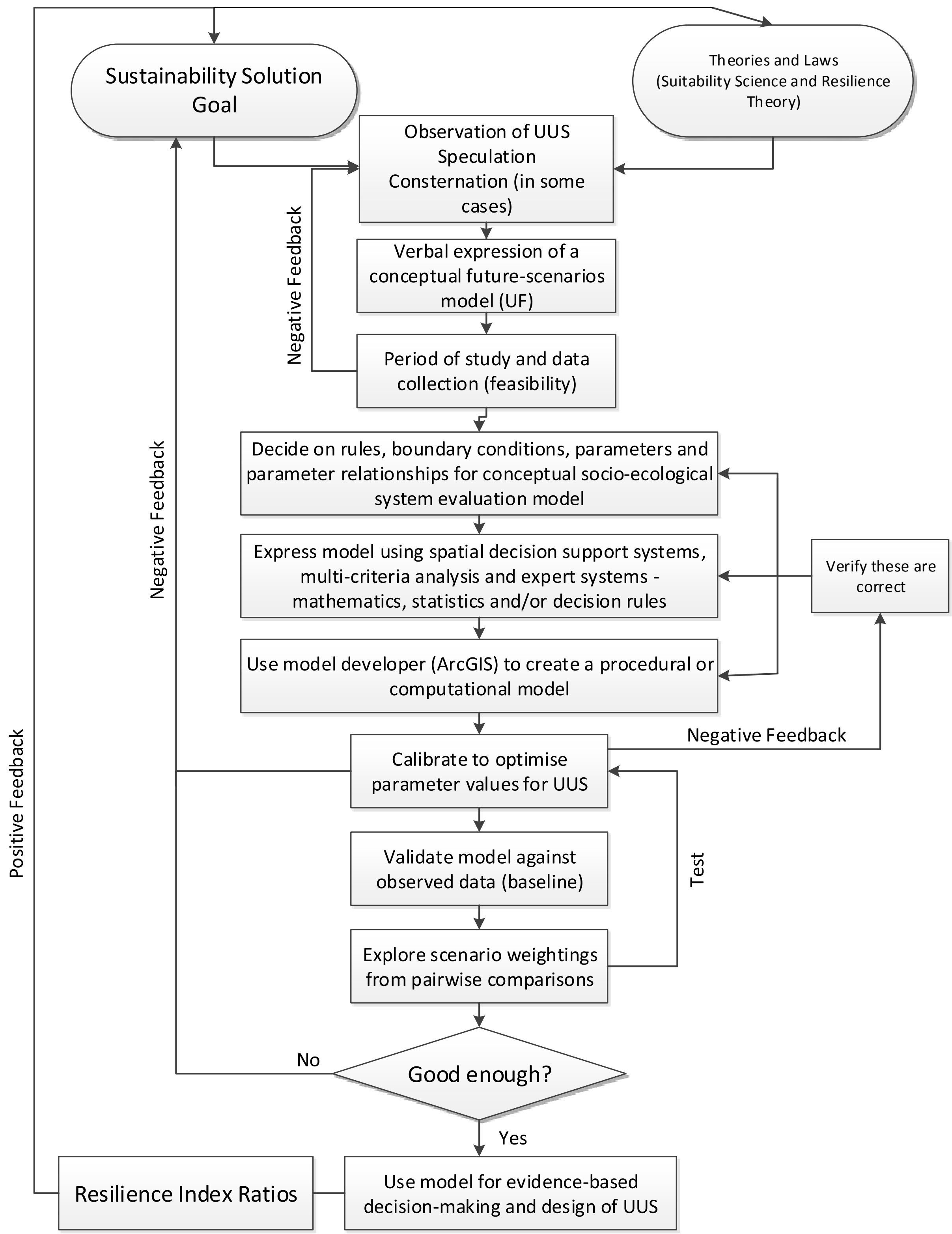


Figure 3-2: Schematic outline of the SUURE Framework

3.3 CORE COMPONENTS OF THE SUURE FRAMEWORK – A BASIS FOR SUURE 'OPERATIONAL MODEL' DEVELOPMENT

3.3.1 A SCENARIO-BASED APPROACH TO SOCIO-ECOLOGICAL SYSTEMS EVALUATION IN THE SUURE OPERATIONAL MODEL

The need to account for change and adaptability (see Figure 3-1) in the SESs i.e. UUS through SUURE, is fundamentally based on how one looks at the future. The need to account for the future is essential when taking account of planning and urban design pursuits (Conroy, 2006). Both these specialities interface with design and policy approaches that are utilised for managing the growth in urbanisation and the progressive changes in demographic, social and economic conditions. Planning as a pursuit consists of decision-making, and as Abbott (2005) notes, "*the notion of a decision implies the future is not predetermined*". By way of explanation, planning constitutes a speciality wherein decisions are carried out to guide pathways to the future with the aim of governing spatial changes to a degree that can sustain society's needs. The process is thus multifaceted and in some cases quite complex due to decision-makers having little scope in the management of external factors. For instance, at a local authority panning level, long term developmental frameworks can be slowed down and in some cases halted due to decisions taken by central government (e.g. changes to the national planning policy on climate change) (Bulkeley & Betsill, 2005; Bulkeley & Kern, 2006; Wilson, 2006).

Expounding on the navigation of multiple-path levels for change and adaptability through use of strategic planning, Hillier (2011) makes known the planning approach of various '*trajectories or visions of the distant future*' versus a future envisaged as an extension of present conditions, or as a path-dependent duplication of times past , which in majority of cases is at the core of traditional planning (see Table 3-1) (Berkhout & Hertin, 2002; Virdis, 2003; Shearer, 2005; Börjeson et al., 2006; Mander et al., 2008); he makes the case for a 'cartographic method' to advance planning that can explore different scenarios, and map the interrelationships of different forces at play . The ensuing maps can strengthen decision making and strategic planning and in essence represent scenarios of how the present can develop. Myers and Kitsuse (2000) arrive at a similar deduction, and state that scenarios have the capacity to 'unmask' the future through decreasing complexity at the same time contributing several viewpoints for contemplation. In essence, scenarios represent a helpful approach that can supplement the existing planning tools identified in Chapter 2 for SESs evaluation of UUS. Besides forecasting and backcasting, scenario analysis (foresighting) can be utilised to consider the impact of different decisions, whatsoever the future may be (Makropoulos et al., 2008).

Table 3-1: Approaches to the future with respect to planning - Adapted from (Timms et al., 2014)

	Forecasting	Foresighting (Scenarios)/ Exploratory Futures	Backcasting/ Visioning
Definition	Two principal types of forecast: *Do-minimum* forecast: an extrapolation of current trends to the future. *Do-something* forecast: the	Exploratory futures are Typically constructed as sets of differing possible futures (which might or might not be desirable). Such	A *vision* is defined as an image of a desirable future', with *visioning* being the construction of such images. Frequently, a vision is considered to

	Forecasting	**Foresighting (Scenarios)/ Exploratory Futures**	**Backcasting/ Visioning**
	prediction of the impact of implementing a specific geotechnical policy (or set of geotechnical policies), against a background in which current trends are extrapolated.	sets are usually defined as global alternatives that are 'out of the control' of any particular organisation. In some cases these futures are accompanied by a storyline describing how the future unfolds.	be a type of goal. *Backcasting* is defined as the construction of one or more pathways for attaining a vision.
'Starting point'	The present.	The future.	The future.
Examples of methods for construction	'Traditional' geotechnical modelling exercises carried out in a large number of planning exercises since the 1950s. Whilst not essential to the approach, most forecasts in geotechnical planning are made using computerised modelling software packages.	Research carried out by environmentally oriented organisations; 'foresight' workshops; studies commissioned by governmental and international organisations; academic research exercises.	Local authority policy formulation; participatory planning exercises; academic research exercises; creative exercises by individual writers.

Scenario analysis cannot express an outcome of change in SESs (see Figure 3-1) in advance due to fluctuations in the time-space-continuum i.e. the future, but can assist decision-makers to cultivate sensitivity to them and to structure programmatically for adaptation due to SES changes as an important segment of project/programme management, for both current pursuits and future strategies to land use planning vis-à-vis UUS. Scenario analysis methods are time and again used for planning purposes, although at no time have they become conventional tools in practice, particularly to test urban regeneration at small and medium scales (Rogers et al., 2012). The use of scenarios at regional and national levels is more common in order to explore, for instance, urban change with respect to the region or province in question (Ravetz, 2000; Chakraborty, 2010); and can be included in advanced GIS databanks, or even electronic voting strategies (Chakraborty, 2010). Scenario analysis has the benefit of facilitating dialogue regarding any solution to a particular challenge, allowing for a contextual narrative that can combine diverse features of the same problem (Virdis, 2003); consequently permitting the inter-disciplinary and multifaceted nature of SESs to be investigated along various dimensions. This holistic approach can aid to overcome the prevailing tendency to compartmentalisation inherent in planning, and by consequence, compartmentalisation tends to be plagued with up-and-down progress and difficulties negotiating differing stakeholder views (Lichfield, 2009), and a considerable portion of current research is evaluating the sustainability of these compartmentalised actions (Fenner et al., 2006; Cooper et al., 2009; Leach et al., 2010; Moncaster et al., 2010; Lombardi, Porter, et al., 2011).

The subsequent section seeks to clarify selected applications of scenario-based techniques in the development of a SUURE operational model. It furthermore offers justification for the preference from among choices of assortment socio-ecological scenarios derived in the 'Urban Futures' project, which form the basis of the SUURE framework methodology and accompanying operational model and are utilised here to evaluate the implementation of urban underground physical infrastructure (MUTs) in the case study area of Birmingham Eastside (see Chapter 5).

3.3.2 THE URBAN FUTURES (UF) METHODOLOGY: APPLICATION OF A SCENARIO-BASED APPROACH FOR THE SUURE OPERATIONAL MODEL

The traditional approach to SESs planning (including geotechnical engineering), considers the advantages of current solutions and in what manner things could develop owing to current trends and predictions (see Table 3-1 and Figure 3-7). Even though this is a traditional and valid engineering approach, what if the future changes from what we expect? The inevitability of change, uncertainty and volatility in the future are, possibly, what we can be certain off as regards the future (Alexander, 2009, p. 6). Is it possible that we can implement robust decisions (solutions-driven-engineering) to realise the grand goals of SESs whilst strictly not being aware of how the future may transpire? Flexible design approaches are one probable way of dealing with this challenge, however, to realise this necessitates that we include change and adaptability within the decision-making process, and also within strategic thinking concerning urban regeneration and into our evaluation of it (du Plessis & Cole, 2011); vis-à-vis the SUURE operational model.

The 'Urban Futures' (UF) methodology endeavours to better this decision-making. The UF project as stated by Rogers et al. (2012) sought to establish a range of alternative socio-ecological urban futures, test present day urban design solutions within those alternative future scenarios i.e. engineering implementation and performance, refine the results of evaluation through a sensitivity analysis of the alternative socio-ecological futures taking into account capacity to adapt and change processes – thereby allowing the sustainability solution to perform in as many of the alternative socio-ecological futures as possible, and provide the basis for diffusion of evidence-based intelligence to stakeholders, especially policy and decision-makers.

This section describes the UF approach and its underlying thinking, and seeks to establish how the UF methodology enables a transition from patchy decision-making, to integrated whole system thinking (Reed, 2007) which is vital if comprehensive SES goals through a resilience approach are to be realised, and more importantly the realisation of singular sustainability goals are not to be hindered (Lombardi, Caserio, et al., 2011). Such an approach is apt to provide the basis for addressing the knowledge gaps identified in Chapter 2, and in the context of this research work the UF methodology is deemed suitable because:

1. The academic strength of the UF method:
    a. The methodology was formulated by a multi-disciplinary research team, funded by the EPSRC through collaboration between Birmingham, Exeter, Lancaster, Birmingham City and Coventry Universities. The methodology has been developed across disciplinary boundaries, incorporating perspectives from civil engineering, biodiversity, air quality, urban studies, regional planning, urban design, geography and industrial ecology - thus generating a sui generis frame of reference to the 'alternative socio-ecological future scenarios' facets of design decision-making by addressing different fundamental assumptions and priorities with respect to SESs;
    b. The method employs an extensive body of work generated over the span of 20 years by the Global Scenario Group (GSG) (Hunt et al., 2010; Hunt, Lombardi, Atkinson, et al., 2012) – this being the basis on which the UF socio-ecological scenarios were formulated;
    c. The efficacy of the methodology is demonstrated by its numerous applications to various case study sites, and by application goes beyond current priorities and geographical locations, addresses issues regardless of scale – examples of its efficacy are demonstrated by several publications which comprise but are not limited to: (Boyko & Cooper, 2012; Brown & Barber, 2012; Caputo et al., 2012; Farmani et al., 2012; Hale & Sadler, 2012; Hunt, Lombardi, Farmani, et al., 2012; Lombardi et al., 2012; Pugh et al., 2012; Rogers et al., 2012);
2. The method is relevant to urban development and regeneration (specifically UK urban situations), and can be employed at a variety of scales. This permits the evaluation of UUS (capacity to change and adapt) for urban underground physical infrastructure (MUTs) in alternative socio-ecological future scenarios and will represent the first application of its kind (evaluation in both space and time) on both a national and international level (see Chapter 5);
3. The method tests socio-ecological solutions in the face of future change and their capacity to adapt, a socio-ecological scenario-based systems approach;
4. The method permits for the inclusion of both qualitative and quantitative information for evaluation purposes;
5. The method can be used at various stages of decision-making, and such flexibility and elasticity allows for isolated or integrated use with different disciplines and different foci of solutions/ tools (e.g. BREEAM, GIS etc.).

3.3.3 Introduction to the Urban Futures Socio-Ecological Scenarios and Derivation of the Methodology for Implementation in the SUURE Operational Model

The UF methodology evaluates and optimises the resilience - the capacity of a SES to encounter shocks (changing circumstances) whilst retaining function (capacity to adapt to change), of decisions made in the present day in the name of sustainability ('sustainability solutions') through evaluating them in various yet likely socio-ecological future scenarios. It achieves this through outlining the necessary conditions for the intended sustainability solution to transmit its intended benefit(s) and investigates whether these necessary conditions are likely to occur in the alternative future scenarios. The extensive review of future scenarios literature carried out by Hunt et al. (2010) highlighted critical dimensions that the socio-ecological scenarios formulated should account for: (i) UK context; (ii) Urban setting;

(iii) Regeneration focus; (iv) Sustainability (economic, social and environmental, along with governance), and (v) Realistic time horizon (40-50 years thus permitting the impact of present-day developmental decisions to fully mature, however not so far into the future therefore detaching from present-day conditions), leading to 2050.

The selected socio-ecological scenarios by the UF project and subsequent methodology had to comprise an adequate selection of probable futures to include an assortment of likely conceivable developments. On the occasion that the selected socio-ecological scenarios were too similar in their diagnostic components, then they possibly will produce similar results and miss the mark in being able to deliver an adequately robust test. A final and crucial forethought was the aspiration of the UF project to formulate socio-ecological scenarios that were well researched (Hunt et al., 2010; Hunt, Lombardi, Atkinson, et al., 2012) and adaptable, thus permitting other end users to build upon the methodology. Moreover, the UF methodology scenarios embody eight core themes covering the scope of topics to be tackled in the urban environment: (i) Ecology and biodiversity; (ii) Air quality; (iii) Water and wastewater; (iv) Subsurface built environment, infrastructure and utility service provision, as well as waste and resource reuse; (v) Surface built environment and open spaces, as well as urban design and place making; (vi) density and design decision making; (vii) Economy, organisational behaviour and innovation, and (viii) Social needs, aspirations, and planning policy. Although not a comprehensive list, they are characteristic of the occupational pursuits engaged in urban design stretching from geosphere (including the biosphere) to the atmosphere. Generally, the themes covered by the UF project map onto the Egan wheel, which is generally estimated to be among the most extensive tabulations in the UK in consideration of sustainable communities (see Table 3-2).

Table 3-2: Mapping of urban futures research themes on to the Egan wheel (ODPM, 2004) – cited from (Rogers et al., 2012)

Egan wheel components of sustainable communities	Urban futures research themes
Governance	Design decision-making Planning policy
Transport and connectivity	Air quality
Services	Water and wastewater Utility service provision, waste and resource reuse
Environmental	Ecology and biodiversity Air quality
Economy	Economy and innovation
Housing and the built environment	Surface built environment and open spaces Subsurface built environment, infrastructure Density and design decision making
Social and cultural	Social needs and aspirations Organisational behaviour

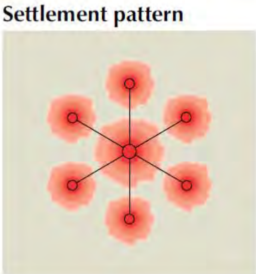
Consequently the UF project resulted in the emergence of four well-defined archetypes that mapped onto four future socio-ecological worlds advanced by Raskin (2005): (i) New sustainability paradigm (NSP); (ii) Policy reform (PR); (iii) Market forces (MF), and (iv) Fortress world (FW). These four scenarios arose out of substantial mounting evidence by the Global Scenarios Group across a 20-year span (Gallopin et al., 1997; Raskin et al., 1998; Raskin et al., 2002; GSG, 2014), are plausible (i.e. can be readily identified in various parts of the world in this present-day), academically comprehensive and containing an internal logical consistently. The scenarios are explained by drawing in , with accompanying descriptios for a typical OECD country (Electris et al., 2009; Raskin et al., 2010).

It should be noted that the four socio-ecological scenarios put forward by the UF project are not prophetic, but rather explorative (Börjeson et al., 2006). The scenarios do not try to forecast the future (For example - using trend analysis), rather they foresight (see Figure 3-3). More accurately, the internal logical consistently contained in the different scenarios can be employed to deal with 'what if' questions, for example 'what if there was a rise in urban population (would this necessitate use of MUTs)'? The UF socio-ecological scenarios are built with reference to the definitive drivers of power structure and culture, knowledge and understanding, values and needs, with fluctuations to these drivers giving rise to different reactions out of periphery drivers: population, economy, technology and governance (Raskin et al., 2002). Out of the descriptions of the four scenarios (see Figure 3-4) postulated by the GSG, the UF project team formulated a comprehensive list of indicators (such as use of underground space, population, technological innovation, land use, urban population density, total water demand). This was achieved by firstly referring to the UK sustainability indicators (DEFRA, 2007), and those concluded to be essential for comprehending urban regeneration and sustainability were drawn out. Secondly, key questions were devised (from the various disciplinary viewpoints) seeking to describe the sustainability performance of the scenario in question. For instance, as stated by Hunt et al. (2011), the key questions relating to land use underground were as listed below:

Q1. How is underground space being used, i.e. what variety of end-uses have been adopted?
Q2. How many types of utilities are located below ground, where are they located and how are they placed?
Q3. In what condition are the utilities and how is maintenance being carried out?
Q4. Are assets replaced on schedule consistent with life expectancy?

New Sustainability Paradigm (NSP) — **Key driver: Equity and sustainability**

Settlement pattern

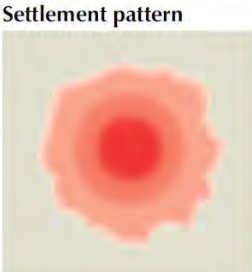


Description
An ethos of 'one planet living' facilitates a shared vision for more sustainable living and a much improved quality of life. New socio-economic arrangements result in changes to the character of urban industrial civilisation. Local is valued but global links also play a role. A sustainable and more equitable future is emerging from new values, a revised model of development and the active engagement of civil society.

Philosophy
The worldview of the *New Sustainability Paradigm* has few historical precedents, although John Stuart Mill, the nineteenth century political economist, was prescient in theorising a post-industrial and post-scarcity social arrangement based on human development rather than material acquisition (Mill, 1848).

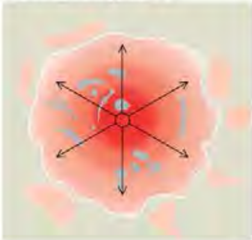
Policy Reform (PR) — **Key driver: Economic growth with greater equity**

Settlement pattern



Description
Policy Reform depends on comprehensive and coordinated government action for poverty reduction and environmental sustainability, negating trends toward high inequity. The values of consumerism and individualism persist, creating a tension with policies that prioritise sustainability.

Philosophy
In *Policy Reform*, the belief is that markets require strong policy guidance to address inherent tendencies toward economic crisis, social conflict and environmental degradation. John Maynard Keynes, influenced by the Great Depression, is an important predecessor of those who hold that it is necessary to manage capitalism in order to temper its crises (Keynes, 1936).

Market Forces (MF)		Key driver: Competitive, open global markets
Settlement pattern	**Description**	**Philosophy**
	*Market Forces* relies on the self-correcting logic of competitive markets. Current demographic, economic, environmental, and technological trends unfold without major surprise. Competitive, open and integrated markets drive world development. Social and environmental concerns are secondary.	The *Market Forces* bias is one of market optimism, the faith that the hidden hand of well-functioning markets is the key to resolving social, economic and environmental problems. An important philosophic antecedent is Adam Smith (1776), while contemporary representatives include many neo-classical economists and free market enthusiasts.

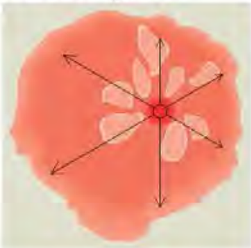
Fortress World (FW)		Key driver: Protection and control of resources
Settlement pattern	**Description**	**Philosophy**
	Powerful individuals, groups and organisations develop an authoritarian response to the threats of resource scarcity and social breakdown by forming alliances to protect their own interests. Security and defensibility of resources are paramount for these privileged rich elites. An impoverished majority exists outside the fortress. Policy and regulation exist but enforcement may be limited. Armed forces act to impose order, protect the environment and prevent a societal collapse.	The *Fortress World* mindset was foreshadowed by the philosophy of Thomas Hobbes (1651), who held a pessimistic view of the nature of man and saw the need for powerful leadership. While it is rare to find modern Hobbesians, many people believe, in their resignation and anguish, that some kind of a *Fortress World* is the logical outcome of the unattended social polarisation and environmental degradation they observe.

Figure 3-3: A summary of the four UK scenarios used in the Urban Futures methodology - descriptions derive from Raskin et al. (2002):– cited from Lombardi et al. (2012)

These types of questions provided the rational as to the selection of indicators and, essentially, permitted recognition of those indicators necessary to tackle its critical elements that were not accounted for in the futures characterised by the GSG or in the UK sustainability indicators. Metrics for individual indicators were established, present-day baselines of performance were determined (where feasible), and the performance of individual indicators was characterised in NSP, PR, MF and FW (as a result generating an extensive list of characteristics for each of the four scenarios (Boyko et al., 2012)). Rogers et al. (2012) assert that indicator performance assessment for the four different scenarios was established upon one or more of the subsequent sources:

1. The performance of the indicator exactly as described in the Global Scenarios Group literature;
2. The performance of the indicator derived from the Global Scenarios Group literature and adapted to the UK scale;
3. The performance of the indicator as deduced from the performance of other indicators.

The ensuing list of characteristics (see Figure 3-4) is a vital resource for putting into effect the UF methodology as it permits comparisons to be effortlessly derived across the four socio-ecological future scenarios. The list furthermore permits elevated analysis and/or an in-depth, deeper analysis by employing the arrows to specify the performance of indicators combined with additional comprehensive characteristic descriptions. Significantly, the characteristics list was designed to be flexible and adjustable. Relevant indicators can be inserted (either by way of the GSG or drawn out from existing characteristics) and new-fangled socio-ecological future scenarios may be included.

	Indicators/ descriptors	Measure (where applicable)	UK (near present)	Comments (including research needs)	NSP	NSP UK characteristic – urban
Demography	Population	Million	61·8 (2009 base)	The GSG methodology is based directly on UN high, medium and low variance predictions for 2050 (see http://esa.un.org/unup/). Here the growth rates for Western Europe have been applied to the UK. http://www.statistics.gov.uk/cci/article.asp?id=2615. http://www.statistics.gov.uk/statbase/product.asp?vlnk=6303	⇩	Total UK population decreases by 11% as compared to 2010 values (UK: 55 002k). Assuming a growth rate of –0·1% per annum from 2010 to 2025 and –0·4% per annum from 2025 to 2050
	Age distribution	% over 65	16 (2009 base)	http://www.statistics.gov.uk/cci/article.asp?id=2615	⇧	Ageing population
	Life expectancy	Years	77·7 (males), 81·9 (females) (2007–2009 base)	http://www.statistics.gov.uk/cci/nugget.asp?id=168	⇧	Increases generally for population
	Average household size	People/ household	2·4	UK stats indicate a growing trend toward smaller household sizes, down from 3·1 in 1961	⇧	Although population is ageing, strong social and environmental drivers mean co-housing and living with extended family or in multiple family units is commonplace

Figure 3-4: Sample of the urban futures characteristics list for the new sustainability paradigm future scenario (Rogers et al., 2012)

3.3.3.1 Future Analysis: Application of the Urban Futures Methodology

Figure 3-5 outlines the key steps in the UF method and it application and affords a schematic of the in terms of its underlying thinking and how this can be embedded in SUURE. The key steps to the UF method are as follows:

Step 1: Identify a Sustainability Solution and Define its Intended Benefit

In the event that more than one intended benefit is identified for a proposed sustainability solution, the full UF method analysis ought to be carried out for every respective intended benefit.

<u>Output of STEP 1</u>: One sustainability solution-intended benefit pair identified for analysis.

Step 2: Identify the Necessary Conditions

In this step, the conditions that permit/enable the sustainability solution to continue delivering its intended function have to be identified. Deliberations to this end should be accompanied by an appraisal of the full characteristics list for any indicators that correlate to the sustainability solutions application and function operation (see Figure 3-4).

<u>Output of STEP 2</u>: All conditions necessary for the identified solution to deliver the prescribed intended benefit are identified.

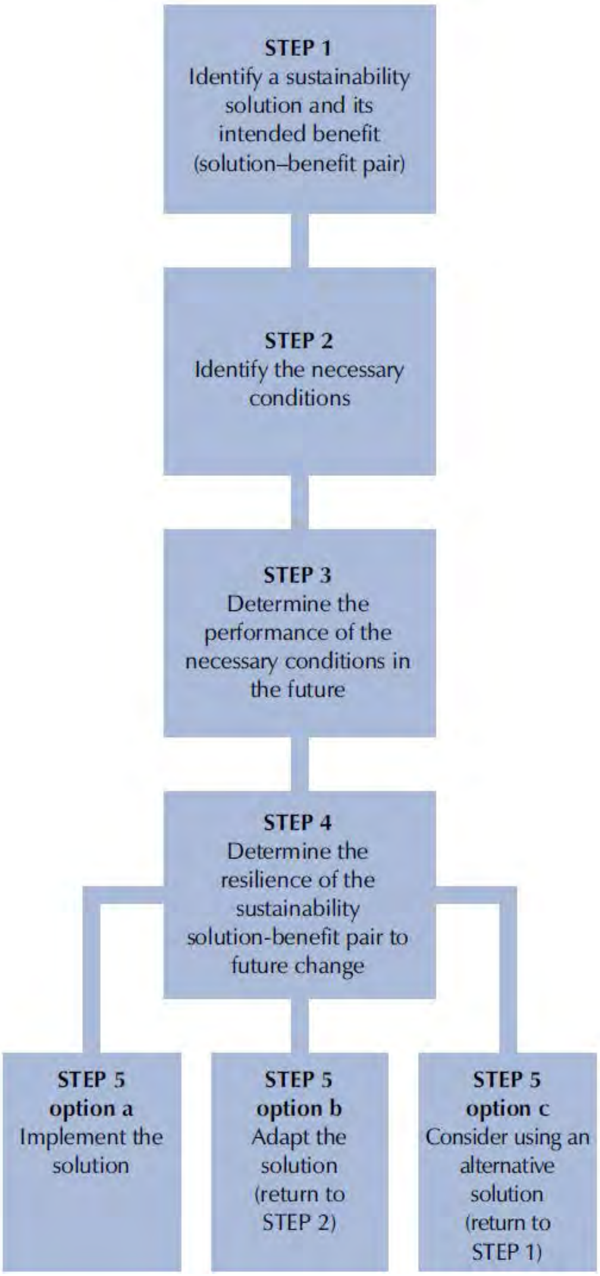


Figure 3-5: The Urban Futures method, a test for resilience using a scenario-based approach (Lombardi et al., 2012)

Step 3: Assess the Necessary Conditions against Scenario Characteristics

Evaluating whether the proposed sustainability solutions necessary conditions are likely to be present in each future scenario (see Figure 3-5) is carried out through employing the characteristics list, following Rogers et al. (2012):

1. For each necessary condition scan the indicators for those that are relevant;
2. For each relevant indicator review the performance of that indicator in each scenario (the characteristic);
3. Using this information to assess the impact of the characteristics upon the necessary condition to answer the question: ‘will the necessary condition continue to exist in each future?’;

4. Combine the responses to this question for all the solution's necessary conditions to answer the question: 'is the solution expected to continue to deliver its intended benefit?'

Table 3-3 by way of demonstration, makes available an assessment of the necessary conditions across the four future worlds for the example of multi-utility tunnels (the contextual narrative for analysis can be found in Hunt et al. (2011)) to promote sustainable use of urban underground space.

Output of STEP 3: The performance of necessary condition in each of the four future scenarios is assessed.

	Indicators/ descriptors	Measure (where applicable)	UK (near present)	Comments (including research needs)
Urban form	Settlement pattern (city scale)		(Planning policies tend to promote) Tendency to compact urban form	Current planning policies recommend dwelling densities in new urban development, that lead to thrifty use of land. They also recommend reduced car use and responsible use of resources. These principles correspond to an urban model of a compact city, which is considered sustainable. It is clearly difficult to capture the complexity of urban patterns in a quantitative measure. However, for the purpose of this list dwelling density, and the spatial configuration determined by land allocation for buildings (compact, fragmented, etc.) are used to connote the urban form. 'To ensure that outputs are maximised whilst resources used are minimised. For example, by building housing at higher densities on previously developed land, rather than at lower densities on greenfield sites'; 'local planning authorities should [encourage] patterns of development which reduce the need to travel by private car' (DCLG, 2005) 'Local Planning Authorities may wish to set out a range of densities across the plan area rather than one broad density range although 30 dwellings per hectare (dph) net should be used as a national indicative minimum to guide policy development and decision-making, until local density policies are in place' (DCLG, 2006).
	Settlement pattern (neighbourhood scale)			

Figure 3-6: Scanning the indicators to identify those that are relevant (Rogers et al., 2012)

Table 3-3: Assessment of the performance of multi-utility tunnels to promote the collocation and coordination of utilities for sustainable use of urban underground space – the synthesis is colour coded to specify whether the necessary condition will be: (i) Present and robust; (ii) Vulnerable, and (iii) Not present

Necessary Conditions	New Sustainability Paradigm (NSP)	Policy Reform (PR)	Market Forces (MF)	Fortress World (FW)
Likelihood of third party damage must exist	Third party damage is likely relatively low: Utility operations are less frequent (assets are well managed and life is extended through rehabilitation); Asset location facilitates repair/replacement (assets are located according to best practice and mapping is thorough and detailed)	Third party damage is likely high – Utility operations are frequent (assets are continually replaced consistent with design life, policy requires swift adoption of more city infrastructure networks, e.g. CHP, district heating, non-potable water, PWC); Asset location data, required through policy, is poor.	Third party damage is likely very high – Utility operations are frequent (ageing assets require reactive management, i.e. patching. In addition city infrastructure is used over and above its operating capacity). Asset location is relatively unknown (mapping is rare and detection technologies are poor).	Third party damage is likely high to very high – Outside the fortress conditions match MF with the additional risk of 3rd party damage through illegal tapping and vandalism. Inside the fortress conditions match closely PR, the main driver for new networks is 'security of supply' rather than policy enforcement.

Necessary Conditions	New Sustainability Paradigm (NSP)	Policy Reform (PR)	Market Forces (MF)	Fortress World (FW)
MUT must be a viable solution when costs are considered	Viability based on three pillar costs - Adoption of MUTs is considered using equal weighting of three pillar long-term costing (economic, social and environment). Road works via trenching is considered unacceptable and unsustainable.	Viability based on policy – Policy imposes fines for occupancy of highways; 'No-Dig' policies are implemented in places considered high 'public realm' value. Uptake of MUTs is not enforced as viable alternatives (e.g. trenchless) are favoured.	Viability based on economic costs alone - Adoption of MUTs is considered on a short-term economic basis alone. Acceptance of an inherited infrastructure and road works via trenching are all assumed necessary evils of modern city living.	Viability based on security of supply measures - Both inside and outside the fortress viability of MUTs is uncertain. There are trade-offs between ease of access for good (i.e. maintenance, leakage detection) and bad (i.e. arson, terrorism).
MUT must be owned and maintained	MUT jointly owned and maintained – Utility operators and city councils jointly fund, operate and maintain MUTs.	MUT owned and maintained by a third party – who rents out MUT space to recoup investment costs.	Lack of ownership – an unwillingness to fund, operate or maintain an MUT (exceptions include military barracks and Universities).	MUT owned and maintained by the elite – who are willing to invest in intelligent infrastructure only within fortress walls.
Acceptability of utility collocation and coordination of utility works	Complete collocation and coordination – All utilities are housed together, gas is compartmentalised to avoid risk. Daily work schedules are accepted.	Some collocation and coordination – All utilities, except gas, are housed together. Works are coordinated but tensions exist between utility companies.	Refusal to collocate and lack of coordination – Utility operators will not risk collocation and coordination is remiss; >150 companies can dig up roads at any time.	Complete collocation and coordination - only within fortress walls.

PRESENT AND ROBUST | VULNERABLE | NOT PRESENT

Step 4 and 5: To Implement or to Modify Solutions?

Determine whether to employ the sustainability solution, adapt it to render it more resilient to future change or substitute it completely. The ultimate decision is dependent on an appraisal regarding the comparative significance of risks identified in the four futures.

<u>Output of STEP 4</u>: The solution-benefit pair's capacity to convey its intended benefit in the future is determined

<u>Output of Step 5</u>: Next action is determined: (a) implement; (b) adapt (and go to STEP 2), or (c) Consider an alternative solution (and go to STEP 1)

Equipped with the results of analysis, the sustainability solution can still be employed being cognisant that is does not provide its functional performance in all four futures. Supplementary factors, for instance economic viability, political will as well as client demands and corresponding factors could take precedence over the consideration regarding the UUS assets long-term performance. The advantage of the UF methodology is that if such a sustainability solution is employed, it is carried out with the knowledge that there exists a possibility of failure and with an understanding of why it could fail (lack of capacity to adapt and change). Conversely, the result of evaluation could also be utilised to alter a solution to cause it to be more robust to future change. In this respect, the altered solution can be analysed by means of the UF methodology to establish its prospective functional performance i.e. robustness. (If adaptation of the solution is extensive, the option is available to begin again with a new solution); re-analysis from then on is, most certainly, possible. Engaging in this process offers a dual benefit, firstly, a refined and improved engineering solution, but secondly and more importantly, a broadened and deeper thought process on the part of the designer such that any future design will be embarked upon with insight regarding its probable vulnerabilities and long-term functional performance.

By the same token, the UF methodology as evidenced has been employed on sustainability solutions – to be precise, solutions that attempt to render the urban environment more sustainable, at the same time acknowledging the context specific nature of sustainability criteria and sustainability priorities for any given solution. For instance, the methodology could be employed to test grey water recycling or use of underground space. The point of emphasis being that any urban solutions can be evaluated to establish their retention of functional performance in the long-term – to be exact, their resilience undeterred by stresses to the system; the UF methodology is a 'sui generis' tool as regarding evaluation of robustness with respect to investment decisions made presently.

3.3.3.2 Limitations of the Urban Futures Method to SUURE Operational Model Development

The UF methodology tackles the question: will present-day sustainability solutions retain their functional performance (retention of intended socio-ecological benefits after a cycle of change) whatever the future turns out to be? The methodology makes available a structured process that can be simply repeated - to evaluate the functional performance of a sustainability solution in the future, through employing a qualitative resilience approach to analysis. It is important to note that the method has certain limitations as highlighted by Rogers et al. (2012) in light of the aims of this research, namely:

1. The UF method does not comprise means of accounting for a spatial component, thus making sense of problems and their proposed sustainability solutions in spatial terms.
2. The UF method does not define the local sustainability priorities, which shape and are shaped by the local context.
3. The UF method does not evaluate the performance of sustainability solutions in the present (i.e. current realities – see Figure 3-7); neither does it deal with present-day obstacles to implementation.
4. The UF method does not evaluate the present-day validity of the proposed sustainability solution to deliver sustainability benefits today, as performance is to a great extent context specific i.e. driven by local priorities.
5. The UF method has no inherent means of quantifying proposed sustainability solutions in both spatial and temporal terms (now and in the future).

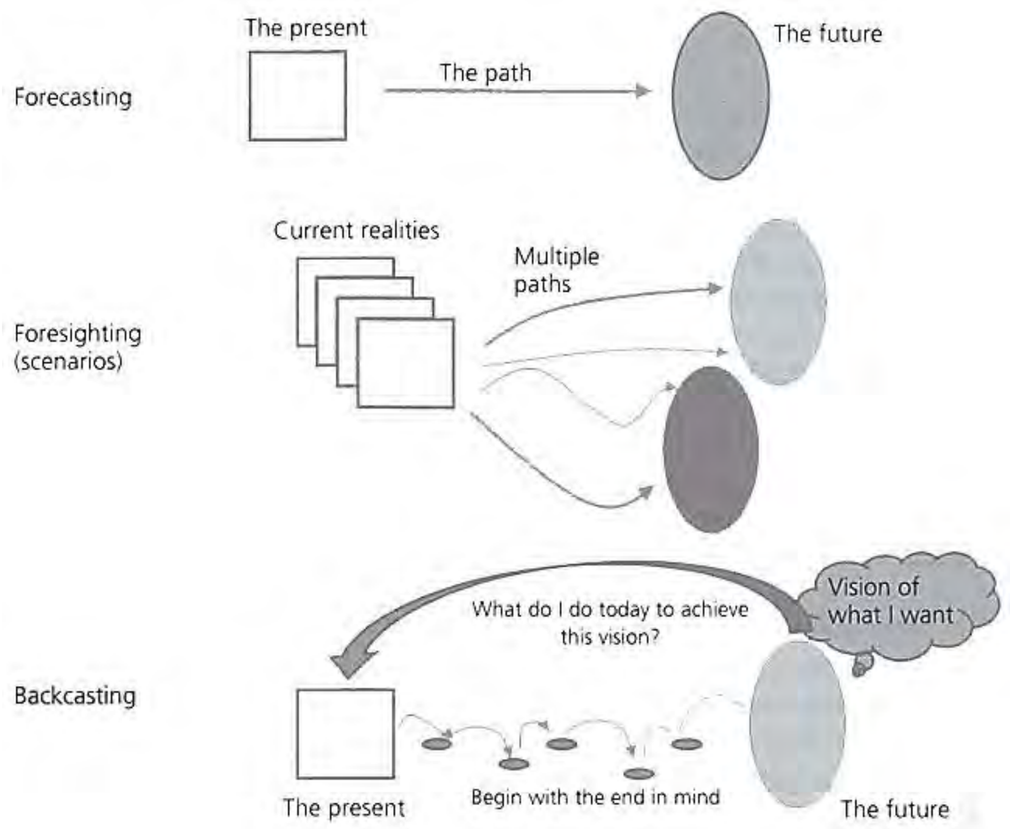


Figure 3-7: Forecasting, foresighting and backcasting compared (Ainger & Fenner, 2014)

3.3.3.3 Addressing the Limitations of the UF Method as Part of SUURE Operational Model Development

The adoption of a "*Multi-Criteria Spatial Decision Support System*" (MC-SDSS) in the present research work addresses with reference to SUURE operational model development:

1. *Limitation 1*: It facilitates a means of incorporating and accounting for the spatial component in decision-making.
2. *Limitation 2*: It facilities through the use of Analytical Network Process (ANP) multicriteria analysis, the means to define local sustainability priorities.
3. *Limitation 5*: It facilitates a means of quantifying scenarios (NSP, PR, MF and FW) through the use of pairwise comparisons (yielding weights for alternative sustainability solution options, ranging from 0-1) that can be subsequently utilised in overlay analysis to produce a representative scenario resilience ratio.

3.3.3.3.1 Multi-Criteria Decision Support System as Part of SUURE Operational Model Development

Decision-making by its very nature is a process consisting of the assessment of alternatives and the selection of the most desirable from them. For a decision-maker to make the "suitable" decision necessitates selecting such an alternative from a set of feasible options, in which, by making an allowance for the varied factors and conflicting requirements, an overall value is optimised (Pospelov

& Pushkin, 1972); to be precise, it will facilitate the best possible socio-ecological scenario to realise the sustainability goal pursued to the greatest degree feasible.

For several centuries, individuals took decisions through making allowance for one or two factors, while disregarding others that were deemed to be negligible to the core of the problem encountered; they subsisted in a world where variations in the environmental settings (social and economic) were small in number and new phenomena came into being 'in turn' but not concurrently (Pedrycz et al., 2011).

In the present-day (UUS a SES), this set of circumstances has altered. A sizable number of problems, or possibly the bulk of them, are multicriteria in nature, where it is essential to make allowances of several factors. Faced with such problems, a decision-maker has to assess an array of stimuli, benefits, and outcomes which typifies decision alternatives. Making an allowance for this typical decision-making scenario, it is essential to emphasise the acknowledgement of the element of subjectivity of a decision-maker in the course of decision-making clashes with the elementary methodological postulate of operational research (Simon, 1959; Yager, 1978; Zimmermann & Zysno, 1980; Jacquet-Lagreze & Siskos, 1982; Arrow & Raynaud, 1986; Bell et al., 1988; Grabisch, 1996): the pursuit for an objectively optimum outcome. Appreciation of the definitive entitlement of a decision-maker in the subjectivity of decisions is an indication of the emergence of a new theory of multicriteria decision-making (Kuhn, 1962). Nevertheless, decision-making that involves multi-criteria necessitate that an objective element continually subsists. Typically, this element comprises varied sorts of constraints enforced through the environment on probable decisions (accessibility of resources, ecological constraints, social circumstances, temporal constraints, etc.). A sizeable portion of psychological research studies make evident that decision-makers, devoid of supplementary analytical support, employ simplistic and, occasionally, inconsistent decision rules (Slovic et al., 1977).

Decision support involves supporting a decision-maker in the process of decision-making. For example, this support may well consist of as stated by Trachtengertz (2001):

- Supporting a decision-maker in the examination of an objective element *(UUS a SES)*, to be exact, in the comprehension and assessment of the current state of affairs enforced by the surrounding area;
- Bringing to light decision-makers preferences, to be exact, uncovering and ranking priorities, bearing in mind the uncertainty in decision-maker approximations, and determining the resultant preferences;
- Producing viable solutions, to be exact, generating a list of ready for use alternatives;
- Assessing feasible alternatives, bearing in mind decision-maker preferences and limitations by the environment;
- Examining the results of decision-making;
- Selecting the best alternative, from the decision-makers perspective.

An individual decision-maker makes elementary, habitual decisions readily, often in an instinctive and latent fashion, rarely being subjected to an exhaustive thought process. Nevertheless, on numerous occasions, alternatives are interrelated with complex conditions which are typified by an inconsistency of demands and multiple criteria, uncertainty of meaning in assessing conditions, miscalculations in the choice of priorities, and others. Altogether these varied elements considerably make difficult the process of taking decisions. The ambiguity of goals in decision-making is vital indicator of ambiguity that concerns the multi-criteria make-up of numerous problems met in UUS (see Chapter 2, Section 2.7 – complex system) planning, operation, and control. Multi-criteria decision-making is concerned with taking decisions in the face of multiple and conflicting criteria. Multicriteria decision-making problems could span from commonplace decision problems, for instance the procurement of a house, to those touching entire countries, as in the sensible utilisation of currency (monetary and fiscal policy) to maintain national well-being (Lu et al., 2007). Nonetheless, given the prevailing variation of multi-criteria decision-making problems, they all have the following shared attributes as stated by Hwang and Yoon (1981):

- **Multiple criteria**: every problem comprises multiple criteria, which can be objectives or attributes;
- **Conflicting criteria**: conflicts subsist between the multiple criteria;
- **Incommensurable units**: the multiple criteria tends to have differing units of measurement;
- **Design/ selection**: proposed resolutions to multi-criteria decision-making problems are either to design the optimal alternative(s) otherwise select the best option from the formerly identified finite alternatives.

Bearing in mind the above, criteria is differentiated into two types: objectives and attributes. Along these lines, multi-criteria decision-making problems can be categorised into two broad groups:

1. Multi-objective decision-making;
2. Multi-attribute decision-making.

The major distinction concerning these two classes is that multi-objective decision-making focuses on continuous decision spaces and multi-attribute decision-making concentrates on problems discrete decision spaces (Pedrycz et al., 2011). Expounding thus on the two above mentioned classes, some fundamental concepts phraseology are given below. These are in line with the written remarks described in the literature (Hwang et al., 1979; Hwang & Yoon, 1981; Belton & Stewart, 2002; Figueira et al., 2005; Lu et al., 2007).

Criteria outline the basis for judgement otherwise guidelines to assess suitability. Within the multi-criteria decision-making literature, they designate attributes and/or objectives.

Objectives reflect the aspiration of the decision-maker(s) and specify the direction on which decision-maker(s) intend to focus on. Multi-objective decision-making problems, consequently, comprise the design of alternatives that optimise or else at a minimum fulfil the objectives of the decision-makers.

Goals are objects preferred by decision-maker(s) and articulated with respect to explicit circumstance(s) in space and time. Hence, whereas objectives provide the preferred direction, goals provide a preferred (or target) level to realise.

Attributes are the attributes, traits, or performance specifications of alternatives. Multi-attribute decision-making problems comprise the choosing of the "optimum" alternative from a selection pool of pre-selected alternatives referred to with respect to their attributes.

Multi-objective decision-making is identified through it characteristic of being a continuous type of multi-criteria decision-making, and its foremost features are that decision-maker(s) have to realise multiple objectives despite the fact that these objectives are non-commensurable and clash with each other. A multi-objective decision-making configuration comprises a vector of decision factors, objective functions which define the respective objectives, and constraints (if any). Decision-maker(s) endeavour in practice to make the most of or curtail the objective functions.

Multi-attribute decision-making is identified through its characteristic of being concerned with making an optimum decision (to be precise, appraisal, choice, ranking, and/or ordering of rank) with regards to the presented selection options that are typified by multiple, often contradictory attributes. The major unique feature embodied by multi-attribute decision-making problems is that there are commonly a small number of pre-selected alternatives, which are related with the aim of realising the attributes. Depending on the attributes, the ultimate decision is taken by the decision-maker(s). The present research work adopted a multi-attribute approach as part of the SUURE operational model and is intended for use in discrete decision spaces.

3.3.3.3.1.1 Multi-Attribute Decision-Making: The Analytical Network process (ANP) and GIS as Part of SUURE Operational Model Development

The evaluation of UUS utilising a SESs resilience approach can be considered a multifaceted multicriteria decision-making problem that necessitates an all-encompassing assessment process of the probable underground zones for development and other criteria as diverse as social, technological, economic, environmental, political or legal issues (Geneletti, 2010).

With respect to the gaps identified in Chapter 2 (MUT global sustainability assessment and evaluation tool that accounts for SESs sustainability solution evaluations), evaluating the socio-ecological use of MUTs for sustainable utility placement is a challenging task for the reason that several interconnected and conflicting parameters of socio-ecological importance should be considered. Given this frame of reference, suitable provision is offered through a particular genus of Decision Support Systems [DSS; Burstein and Holsapple (2008)], termed Multicriteria Spatial Decision Support Systems [MC-SDSS; Malczewski (1999)], which is founded upon the combination of Multicriteria Decision Analysis (MCDA) and Geographic Information Systems (GIS) (Figueira et al., 2005; Bouyssou et al., 2006). MCDA is commonly defined as "*a decision-aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often conflicting, in order to guide the decision maker towards a judicious choice*" (Roy, 1996).

The utilisation of maps in decision-making processes was highlighted by McHarg (1969), this being one of the first mentions of its kind, where the fundamental theories that would in due course be established in Geographic Information Systems (GIS) (Charlton & Ellis, 1991) are stated. Even though Decision Support Systems (DSS) as well as GIS can operate separately to resolve straightforward decision challenges, numerous multifaceted conditions require them to be combined with the aim of delivering improved results (Li et al., 2004). Given this frame of reference, the evolution and expansion of Spatial Decision Support Systems (SDSS) is necessitated principally to address complex, un-structured, 2D/3D evaluation queries (Densham & Goodchild, 1989). Major growth and expansion of

SDSS's took place principally in the 1990s (Densham, 1991; Armstrong, 1993; Goodchild, 1993). The field has since matured and extended to take account of optimisation (Aerts et al., 2003; Church et al., 2004), expert systems (Leung, 1997), multicriteria assessment approaches (Janssen & Rietveld, 1990; Carver, 1991; Pereira & Duckstein, 1993; Jankowski & Richard, 1994; Laaribi et al., 1996; Eastman et al., 1998; Malczewski, 1999; Thill, 1999; Feick & Hall, 2004), online assessment of geographic information (Bédard et al., 2001), simulation (Wu, 1998), in addition to chromatic-critical information examination (Andrienko et al., 2003), aimed at the development, assessment and numerical calculation of trade-offs concerning choice options. On the subject of SDSS, the complete spectrum of methods and uses in recent times is comprehensively documented and examined by Malczewski (2006), and also most recently by Ferretti (2011a).

Bobylev (2011) stands as an example to the utilisation of a multicriteria (ANP) approach to UUS use decision-making by conducting a proportional-relative examination of the environmental impacts of different underground construction technologies (open cut, conventional tunnelling, and microtunnelling). Bobylev (2011) did not however utilise GIS and was limited to identifying current solutions for current realities aimed squarely at environmental assessment. There is an absence of literature as regarding MC-SDSS applications aimed squarely at UUS use resilience evaluation.

Table 3-4: Reasons for needing an ANP multicriteria decision methodology to examine the environmental concerns associated with UUS construction technology choice (Bobylev, 2011)

Consideration	Description
Booming urban underground space development	The need for and ability to develop UUS has resulted in ever increasing underground construction in urban areas.
Variety of UCT available	Recent technological advances have resulted in a great variety of UCT, e.g. automatic tunnelling, diaphragm walls, and horizontal directional drilling.
Significant environmental concerns about using UCT in urban settings	The most significant adverse environmental impacts include disturbance in the lithosphere (uneven settlements adjacent to construction site structures) and the hydrosphere (water pollution, groundwater level and mode changing).
Variety of environmental impacts	Use of alternative UCTs may have positive (e.g. remediation) as well as negative (e.g. air pollution) environmental impacts. Comparative analysis of direct and indirect environmental benefits and costs is needed.
Uncertain relationships between UCT choice, construction costs, and the environmental impacts	Every UUS development project is unique, and its technological, economic, and environmental performance should be considered in a comprehensive and systematic way.
Improvement of the urban environment as a primary goal of UUS development	There are a growing number of urban development initiatives, including underground construction projects, which are focused on

Consideration	Description
	improving the environment and its sustainability. Examples: replacing open car parking in city centres with underground garages and green areas, installation of underground rainwater storage tanks for combined sewerage systems.

***UCT = Underground Construction Technology**

The challenge faced in regulating use of UUS has progressively developed to an acute state at this time. Urban trends will only exacerbate this movement (United-Nations, 2010), and the installation of underground facilities has grown to be conflict-ridden (see Figure 3-8). Given this frame of reference, decision-makers must then be capable of qualifying their decisions with respect to the selected use of UUS through a methodical, clear and documented process.

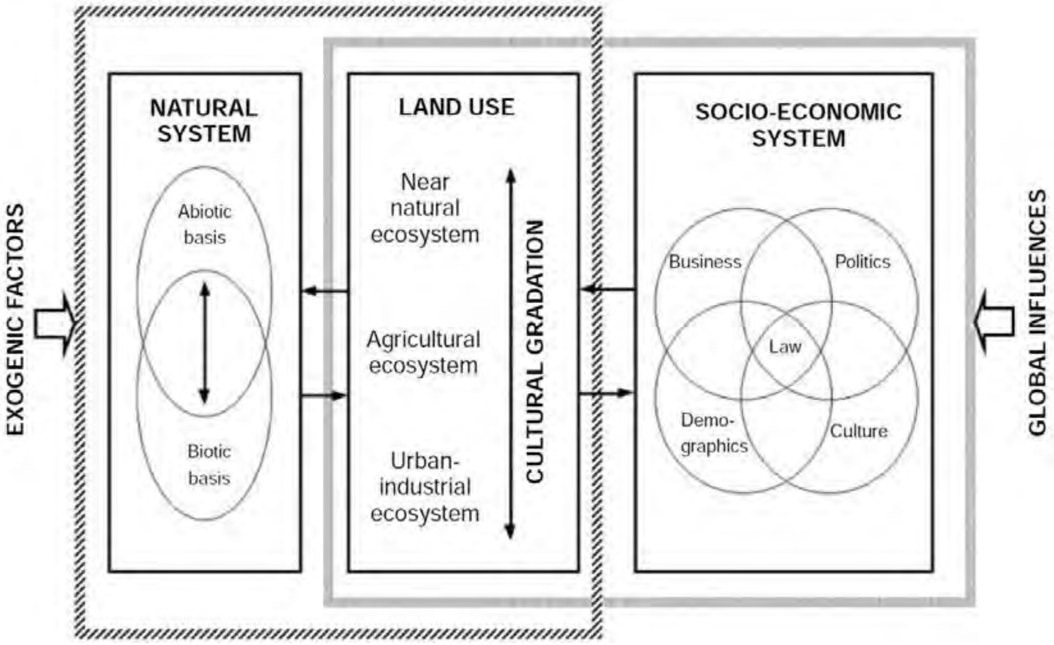


Figure 3-8: Socio-ecological push and pull forces that impact the planning, design and use of UUS (Brimicombe, 2010)

From a methodological perspective the development of the SUURE operational model to address the gap identified in Chapter 2 and account for socio-ecological resilience in both space and time as a means of evaluating the sustainability of geo-solutions, the present application recommends the formulation of an MC-SDSS (combination between GIS and the ANP) for evaluating UUS. The evaluation of socio-ecological resilience use of UUS is subject to an escalating range of issues, regulations and an enormous quantity of spatial information has to be assessed as well as managed. Even though GIS is an appropriate tool for use in complex multicriteria problems, it does not have the capacity to identify an optimal solution unless an optimisation procedure is built in (Bobylev, 2011). In the initial phase, the use of GIS usually includes exercising a group of criteria to permit the classification of an area under examination into distinct categories through generating bumper regions near terrestrial structures designated for safeguarding (Chang et al., 2008). Subsequently, the set of map strata is subsequently aggregated so that the resultant combined map categorises the zones under evaluation into suitable (i.e. resilient: the sustainable solution is continuing to deliver its function) and unsuitable ones (i.e. not resilient: the sustainable solution is not continuing to deliver its function).

The principal justification for combining MCDA and GIS is that they both offer singular capabilities that supplement each other. What is more, GIS contains an immense capacity for gathering, storing, handling, evaluating and visualising geospatial information essential for the policy/ decision-making process. In contrast, MCDA makes available an assortment of strategies, methods and algorithms designed for configuring decision problems, also planning, assessing then ranking choice options (Malczewski, 1999).

The ANP (Saaty, 2005) serves as a generalisation of the familiar AHP (Saaty, 1980), which permits the consideration of interdependencies (feedback) amongst decision elements (see Figure 3-9). Both techniques employ practitioner views as intakes aimed at assessing choice dynamics. Nevertheless, the ANP permits by design a network pattern configuration that remains highly advantageous as a tool to reflect existing interdependencies amongst practical components. The elements which impact the socio-ecological use of UUS resources stand case and point as an exemplar of this phenomenon (see Figure 3-8).

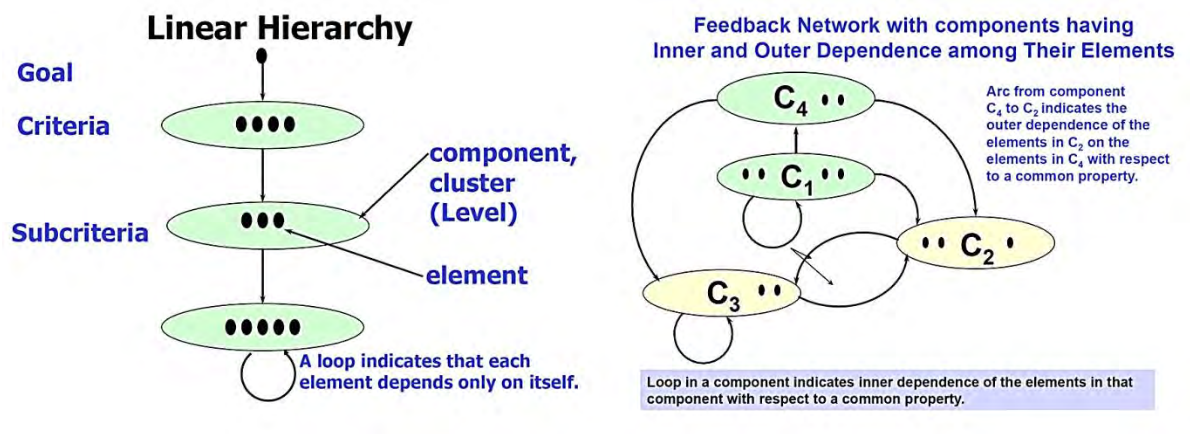


Figure 3-9: Structural Difference between a Linear (AHP) and a Nonlinear Network (ANP) (Saaty, 2005)

The ANP methodology is differentiated with respect to the AHP as the ANP integrates the effects, as well as connections between the components of the network structure in question (elements besides possible choices), being understood by the decision-maker, assembling the elemental components into network clusters. Several choice conundrums are incapable of being structured hierarchically for the reason that they consist of connections and dependencies of the top-level elements contained hierarchically atop the bottom-level ones. Furthermore, the response networks contained in the ANP approach make it possible to account for the significance of the alternatives with respect to the significance of the criteria, the latter being more prominent in this case, whilst the traditional hierarchy contained in the AHP approach only permits deliberation regarding the significance of criteria upon the significance of decision choices (Saaty, 2003).

An extensive besides established volume of MCDA published works subsists wherein identification of suitable techniques for various applications in light of the wide range available is easily achievable (Figueira et al., 2005). In relation to the AHP and ANP methodologies, the seminal work in their development is the literature production by Thomas L. Saaty, beginning commencement in 1980. In the matter of literature specific to ANP, it is more contemporary and various publications lie in different disciplines. With the goal of providing a snapshot of the heterogeneity of the manifold implementations of ANP in various disciplines, reference can be to a selection of these in the realm of transportation roads (Tuzkaya & Önüt, 2008), ecological appraisal of local variations (Bottero et al., 2008; Liu & Lai, 2009), economics and finance (Niemira & Saaty, 2004), excess administration (Khan & Faisal, 2008; Aragonés-Beltrán et al., 2010), civil engineering (Neaupane & Piantanakulchai, 2006), strategic policy planning (Ulutaş, 2005) and underground construction technology (Bobylev, 2011).

Despite the fact that traditional multicriteria methods remain mostly non-spatial, by means of typical or overall impacts that are considered suitable concerning the being examined, MC-SDSS retain capacity to combine the dimensions of both SESs at the same time allowing a systematic approach capable to demonstrate the significance of space (where), time (when) and geography (what). Spatial MCDA is an operational method that merges and changes geographical data (the input) into a decision (the output) (Ferretti, 2011b). This method contains processes that include the use geographical data and the priorities of the decision maker and the exploitation of information and priorities in keeping with definite decision rules (Sharifi & Retsios, 2004; Malczewski, 2006). This method benefits from the capacity of geographical information systems ability in handling and managing spatial data, besides the elasticity of multicriteria assessment to merge real physical data (e.g. geo-infrastructures, soil type, water depth, topography etc.) in addition to value-based evidence (e.g. quality standards, professional views etc.) (Geneletti, 2010). As a matter of fact, several choice conundrums consist on spatial-temporal terms (Farahani et al., 2010).

The justifications for employing an ANP-based SMCDA methodology in the development of the SUURE model, and application to UUS, are as follows:

1. The evaluation of UUS (a SES) is a multicriteria decision problem (Bobylev, 2011);
2. The identification of relevant criteria stresses emphasis on local priorities;
3. There exist dependencies between groups of criteria which necessitate evaluation in both space and time;
4. The need to quantify the baseline can be incorporated using this approach by employing and incorporating AI approaches (e.g. expert systems such as fuzzy concepts or artificial neural networks) – in the context of this present research work fuzzy concepts are deemed the most suitable as a result of their seamless integration into ANP-based SMCDA;
5. The simple way in which UF socio-ecological scenarios (foresighting) can be included in the analysis through pairwise comparisons (utilising the consistency ratio $CR = \frac{CI}{RI} < 0.1$ (see Section 3.4.2.2) with respect to their relative importance to the overall sustainability goal, in light of the contextual narrative offered by the scenarios themselves and performance indicators of the criteria in the different socio-ecological futures) of different yet plausible socio-ecological future scenarios; thus allowing a simple yet powerful method of quantifying temporal impacts of decisions made today in the name of sustainability in SESs (UUS);
6. The comprehensive examination of the interrelationships amongst clusters compels the decision-maker(s) to judiciously consider their development precedence method, in addition to the decision-making problem (sustainability solution) itself; consequently leading to a superior

grasp of the query (sustainability solution) and subsequently an evidence-based decision support for planners and policy makers alike.

7. For the reason that the complexity inherent in evaluating sustainability of UUS (a SES) is multi-criteria in nature, and with the goal of identifying the most important characteristics contained in the sustainability solution, the ANP system utilised in the present research work has been formulated in accordance to a simple network structure (*to be precise, a free-modelling method, which is not propped using any model otherwise pre-planned edifice. It is made up of clusters and elements, in addition to interrelations between elements*). Reference ought to be made aimed at the alternative option of constructing the ANP choice query in line with multipart network structure (Saaty, 2005), typically built on four sub-networks – BCOR (*Benefits, Costs, opportunities and Risks*). This BCOR structure uses a single simple network structure for each of the 4 sub-networks for the representative decision. The BCOR structure was deemed to be beyond the scope of the present research work and would in most cases be part of future research endeavours.

Functional uses of the ANP, which is especially suited to treating multifaceted choice quandaries that are typified as a result of interrelationships between the elements under consideration, are rather limited (Neaupane & Piantanakulchai, 2006; Levy et al., 2007; Nekhay et al., 2009). The application of the ANP-GIS based scenario choice assessment methodology as part of the SUURE operational model, signifies the first application of its kind on both a national and international level i.e. moving beyond a sensitivity analysis of the ANP model based on the variation of weights (*simulation scenarios - user defined forecasts, and in most cases lack rigour in varying quantitatively the components and parameters of the model; this generally lacks meaning and does not to tend to add depth to the study, neither verify its stability*) to one where a scenarios based approach to planning is implemented (*scenarios – well documented and defined can be used to carry out pairwise comparisons driven by a contextual narrative that are both plausible and contain an internal logical consistency*), by this means allowing the spatial and temporal impacts to be quantified (Delgado & Sendra, 2004; Malczewski, 2006; Ferretti, 2011a); in this novel way, SESs evaluation of UUS use can be carried out in both space and time – explicitly addressing the gaps identified in Chapter 2.

3.3.3.4 Addressing UF Limitations: Fuzzy Concepts – Evaluating Baseline Resilience Performance as part of the SUURE Operational Model

The adoption of a "*Fuzzy Concepts*" in the present research work addresses the ability to conduct a baseline evaluation of UUS as part of the UF approach by:

1. *Limitation 3 and 4*: It facilitates a means of assessing the present-day performance of the proposed sustainability solution i.e. its present ability to continue to deliver its function into the future whatever that may be. Thus permitting a means of validating the ability of the proposed sustainability solution to retain its functional performance as a baseline ratio that can permit comparisons of current conditions with respect to future conditions under alternative scenarios (NSP, PR, MF and FW).
2. *Limitation 5*: It facilitates a means of quantifying the baseline performance of a sustainability solution through the use of fuzzy logic (yielding weights for alternative sustainability solution

options by employing fuzzy membership functions, ranging from 0-1) that can be subsequently utilised in fuzzy overlay analysis baseline performance resilience ratio.

The reminder of this sub-section makes known the details of fuzzy concepts and the manner in which they address the short comings of the UF method as highlighted above, as a part of the SUURE model development process.

3.3.3.4.1 Baseline Conditions - Identification for the SUURE Operational Model

Baseline conditions could be attributed to as the UUS environmental setting, existing conditions, and several other similar expressions. The baseline conditions are the social, economic, natural, biochemical, physical, and cultural setting wherein the planned development is to be situated, and where local impacts (good and bad) may possibly take place.

These conditions are the benchmark that forms the basis for comparative analysis when taking into account different project alternatives and their corresponding future conditions (scenario analysis). The characterisation and description of the baseline conditions is essential for decision-makers, analysts, and all relevant stakeholders who are unacquainted with the project site and neighbouring environment. Regrettably, there exist a small number of published directions or guidelines on how to utilise the details of baseline conditions (Heuvelink, 1998; Noble, 2000; Shepard, 2005; Wathern, 2013). To appreciate and understand why the accounting of baseline conditions, moreover, correct analysis and instructions or procedures for end users are required, necessitates examination of what functions the baseline conditions perform in the evaluation of SESs.

All evaluations of sustainability and resilience are (or else, as a minimum, ought to be) carried out with reference to a benchmark: the present-day environment of the area wherein the planned development is to be situated. The baseline conditions typically take account of factors in the wide-ranging classifications of socio-economic, physical, bio-physical, and chemical factors. Considerations in defining baseline conditions are:

1. What classifications are to be taken account of or left out?
2. By what means will the required data be gathered and analysed?
3. By what means can the baseline conditions be accurately and impartially contrasted with future conditions under alternative scenarios?

3.3.3.4.2 Baseline Condition Use for the SUURE Operational Model

The representation of the baseline environment is ordinarily a report supplemented using tables, charts, diagrammatic illustrations and comprehensive technical appendices describing how the data was obtained (Shepard, 2005; Wathern, 2013). The manner in which the description is commonly utilised to evaluate sustainability using the different alternatives is factor-by-factor. This differs to the abstraction of SESs, where factors are combined on multi-levels and impact the functionality both en masse and on each other, not in seclusion. SESs are combined on multi-levels and their underlying forces cannot be comprehended through examination of individual factors out of context with other systemic factors. According to Wathern (2013) there exists a twofold defect with the manner in which majority of conventional reports represent baseline conditions:

1. They restrict quantitative comparisons of current conditions with respect to future conditions under alternative socio-ecological scenarios;
2. They restrict the expression of value (or "impact") of the project site and surrounding environmental area with regards to the larger environmental setting otherwise the values of different stakeholder and other special-interest groups.

These shortcomings provide un-wanted opportunities to contest: (i) What was done; (ii) How it was done, and (iii) By what method the conclusive decision was arrived at. As such, it is common to find that the textual portrayal of the baseline conditions boasts no expression of impact ("significance"). To be precise, there is no defined scale of global SESs against which present-day values can be weighed. This twofold deficiency necessitates removal with regards to the overall aim of this research project, and the method by this will be achieved (thus addressing UF methodology limitation 3, 4 and 5) is in the quantitative approach described in the following section.

3.3.3.4.3 From Baseline Subjectivity to Objectivity – Fuzzy Concepts

To fully comprehend how fuzzy sets, fuzzy logic, and approximate reasoning can rise above the limitations documented in the present chapter – Section 3.5 with respect to the UF method, specifically limitation 3, 4 and 5, and comprehend how to utilise fuzzy system models most effectively in carrying out a baseline performance evaluation (in space and time) as part of the SUURE operational model, some context is necessary. The mathematics that will be presented herein will be fundamental in nature, thus making available the basic comprehension of principles, methods and language that govern their utilisation in carrying out a baseline resilience performance evaluation with improved objectivity, mathematical rigor, and soundness. The following sections are not an exhaustive account of fuzzy sets, fuzzy logic, or fuzzy system models, for more insight and completeness see general texts on fuzzy sets (Berkan & Trubatch, 1997; Harris & Stöcker, 1998; Cox, 1999; Mendel, 2001; Zimmermann, 2001).

Fuzzy sets and their accompanying logic were initially postulated as a concept by Zadeh (1965) to quantify linguistic concepts i.e. words that possess 'significance' nonetheless are characteristically imprecise, unclear or fuzzy. On any occasion where uncertainty or fuzziness (lack of precise boundaries) is the word utilised instead of the resulting event, that uncertainty or fuzziness can be tackled using fuzzy logic. Fuzzy logic is not logic that is fuzzy; on the other hand it is logic that is utilised to express fuzziness. Instances of linguistic fuzziness are the concepts of 'very sustainable', 'SES' 'highly resilient', otherwise 'steep slope'. This fuzziness mirrors the vagueness of human thinking when viewpoints and interpretations are conveyed (Zimmermann & Zysno, 1980; Zimmermann, 1992). Several linguistic variables emerge in baseline performance evaluations, comprising concepts of population, topography, ground water level, distance, size, sustainability, resilience, acceptability amongst others. Whereas quantifiable measures of the first five are probable, the significance of that measurement in the context of baseline performance evaluation is not at all objective. Incalculable concepts for instance sustainability, resilience, and acceptability replicate the benefit of a natural system element by various stakeholders and interest groups and are not directly quantifiable. The subjective complexion of 'significance', the lack of ability to collate sizable data sets on baseline conditions, and the inherent uncertainties regarding future conditions underlying a set of developmental/regeneration alternatives for UUS, are all justifications why conventional approaches (traditionally applied within geotechnical engineering practice (see Section 2.7.3.1) and present-day environmental impact assessment) ought to be substituted with fuzzy logic that utilise advances in mathematics, the greater than before power of office computer systems, and established aspects of artificial intelligence.

Every fuzzy set is classified through a membership function that is utilised to compute and quantify the grade of membership, and these sets are thoroughly engineered utilising the instruments of fuzzy logic. Although conventional mathematics and logic have presupposed exact symbols with similarly exact meanings, fuzzy sets and its accompanying logic are utilised to designate categories of inexact objects. As a consequence, despite the fact that Boolean logic counts on a binary (0, 1) (designated 'crisp), fuzzy sets possess a continuum of membership. Given that inexactly defined categories are a central constituent in human thinking (Zadeh, 1997), fuzzy sets have been applied to mimetically reflect this phenomenon in cognitive psychology (Nowakowska, 1986), engineering (Blockley, 1979; Brown & Yao, 1983), linguistics (Zadeh, 1972; Kaufmann, 1975; Lakoff, 1975; Gupta et al., 1979), environment (Ayyub & McCuen, 1987) and knowledge engineering (Kaufmann, 1975; Graham & Jones, 1988).

As described by (Brimicombe, 2010), a fuzzy set allocates levels of membership μ in a range [0, 1] for each element of x in a set $\boldsymbol{A}$ in a universe $\boldsymbol{U}$:

$$\forall x \in \mathbf{U}, \{x|\mu_A\} \qquad 0 \geq \mu_A(x) \leq 1 \qquad \textbf{Eq 3-1}$$

Therefore for intervals of x of 0.1 in the range [0, 1], set $\boldsymbol{A}$ is characterised by:

$$\boldsymbol{A} = \{0|\mu_0, 0.1|\mu_{0.1}, 0.2|\mu_{0.2}, 0.3|\mu_{0.3}, \dots., 0.8|\mu_{0.8}, 0.9|\mu_{0.9}, 1|\mu_1\} \qquad \textbf{Eq 3-2}$$

where μ_0 designates no support for membership of $\boldsymbol{A}$ and μ_1 designates full support for membership in $\boldsymbol{A}$. Therefore the conventional binary (0, 1) can be regarded as crisp sets in the form:

$$\neg\boldsymbol{A} = \{0|\mu_1\} \qquad \boldsymbol{A} = \{1|\mu_1\} \qquad \textbf{Eq 3-3}$$

(where ¬ is Boolean NOT) and can therefore be regarded as a distinctive case of fuzzy set. Crisp and fuzzy sets are exhibited graphically in Figure 3-10. Fuzzy sets can be merged in Boolean operations and conventionally can be managed in a much more straightforward manner then probabilities:

Intersection (∩) $\boldsymbol{A}$ AND $\boldsymbol{B}$:

$$\forall x \in \mathbf{U}, \quad \mu_{A\cap B} = \mathrm{MIN}(\mu_A\,(x), \mu_B\,(x)) \qquad \textbf{Eq 3-4}$$

Union (∪) $\boldsymbol{A}$ OR $\boldsymbol{B}$:

$$\forall x \in \mathbf{U}, \quad \mu_{A\cup B} = \mathrm{MAX}(\mu_A\,(x), \mu_B\,(x)) \qquad \textbf{Eq 3-5}$$

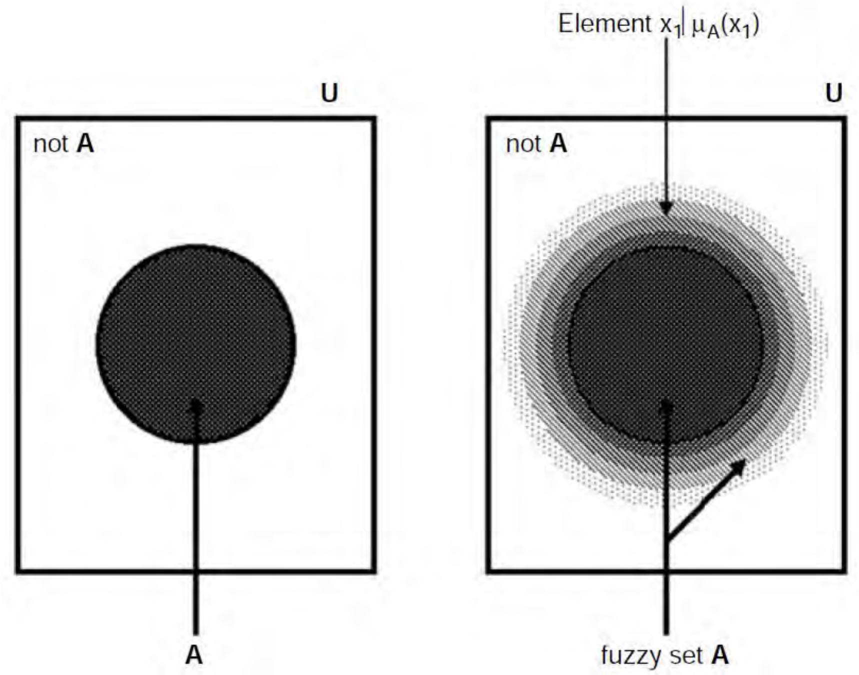


Figure 3-10: An illustration of crisp and fuzzy sets (Brimicombe, 2010)

Strictly speaking, for an intersection (AND) the least possible (MIN) membership of its respective elements x are accounted for and in the union (OR) the largest (MAX) membership of all respective elements are accounted for. This phenomenon has notable similarities with formulae **Eq 3-6** and **Eq 3-7**.

Boolean AND:

$$P[\bar{E}_C] = \prod_{i=1}^{n} P\,[\bar{E}_i] \qquad \textbf{Eq 3-6}$$

Boolean OR:

$$P[\bar{E}_C] = 1 - \prod_{i=1}^{n} P\,[E_i] \qquad \textbf{Eq 3-7}$$

where $P[\bar{E}_C]$ = composite map accuracy, $P[\bar{E}_i]$ = the accuracy of a given layer as a part suitably classified, $P[E_i]$ = the error of a given layer such that $P[\bar{E}_i] = 1 - P[E_i]$.

Fuzzy sets can therefore be effectively diffused in the course of analysis characteristic of those performed in a GIS where overlay is integrated with Boolean selection (see Figure 3-11 and Table 3-5). Fuzzy set operations and the multitude of ways in which they can be utilised in a geographical context have been examined by Macmillan (1995) and geographical spatial context by Burrough and Frank (1996). The expression 'fuzzy' is employed into GIS for managing uncertainty yet generally it has been proximately utilised to each and every non-binary usage of data for instance probabilities. But significant disparities exit between fuzzy sets and probabilities. To begin with, probabilities in the manner in which they are strictly classified are nevertheless crisp numbers. In the second place, probability of A and $\neg A$ ought to amount to unity, as opposed to fuzzy sets where there can be a resultant unknown otherwise un-quantified residual. As a result fuzzy sets, given this frame of reference, are simpler to utilise than probabilities.

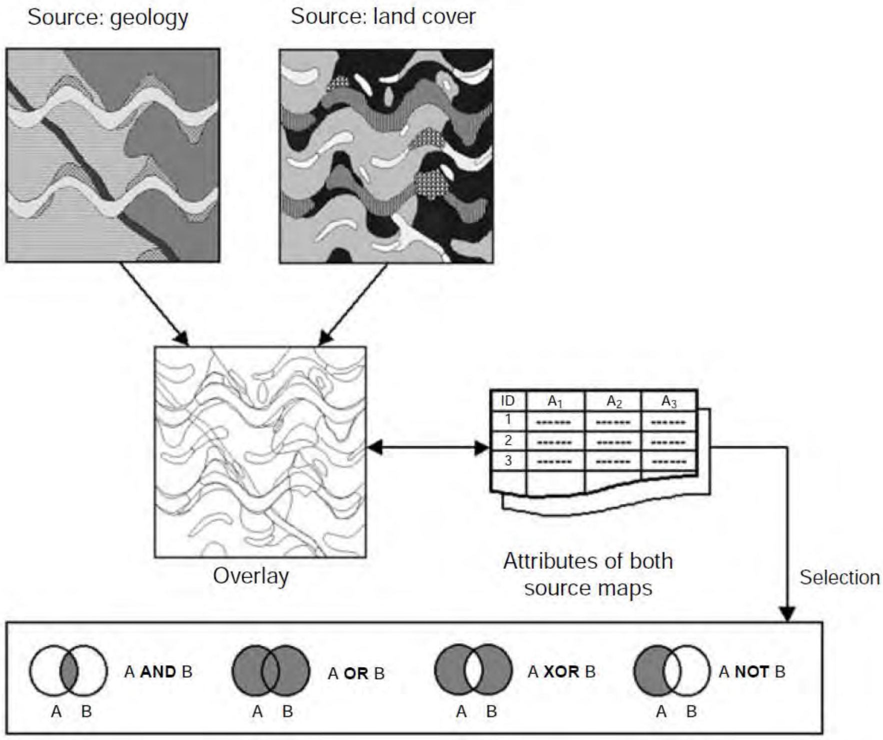


Figure 3-11: Examples of cartographic processing: overlay with Boolean selection of pertinent combinations of vector polygon attributes or an input raster (Brimicombe, 2010)

Boolean **AND**	Performs a Boolean 'AND' operation on the cell values of two input rasters. If both input values are true (non-zero), the output value is **1**. If one or both inputs are false (zero), the output is **0**.
Boolean **OR**	Performs a Boolean 'OR' operation on the cell values of two input rasters. If one or both input values are true (non-zero), the output value is **1**. If both input values are false (zero), the output is **0**.
Boolean **XOR**	Performs a Boolean exclusive 'OR' operation on the binary values of two input rasters. If one input value is true (non-zero) and the other false (zero), the output is **1**. If both input values are true and both are false, the output is **0**.
Boolean **NOT**	Performs a Boolean 'NOT' (complement) operation on the cell values of the input raster. If the input values are true (non-zero), the output value is **1**. If the input values are false (zero), the output is **0**.

Table 3-5: Different types of Boolean operators as shown in Figure 3-11 – Adapted from (Bhowmick et al., 2014)

One area of functional use in GIS has been the 'fuzzification' of data, databank queries and classification methods owing to the utilisation of fuzzy membership functions (rules) (see Figure 3-12), through this medium prevailing over the uncertainty contained in the binary management of data (Kollias & Voliotis, 1991; Burrough et al., 1992; Guesgen & Albrecht, 2000). An added area of implementation has been to quantify oral evaluations of data quality derived out of image explicators and as a result of expert assessments (Hadipriono et al., 1991; Gopal & Woodcock, 1994; Brimicombe, 1997, 2000). Utilisation of fuzzy numbers aimed at logging and disseminating geometric uncertainty is communicated in Brimicombe (1993, 1998). The most recent GIS applications comprise but are not limited to landslide susceptibility (Ercanoglu & Temiz, 2011; Oh & Pradhan, 2011; Pradhan, 2013), soil salinity (Giordano & Liersch, 2012), groundwater vulnerability index (Pathak & Hiratsuka, 2011), renewable energy (Charabi & Gastli, 2011), geochemical data mapping (Cheng et al., 2011) and geological prediction of coal bed methane (Cai et al., 2011). The theoretical monotony of fuzzy sets (aforesaid) can be anthropomorphised (brought to life) and demonstrated by way of a GIS example (see Chapter 5). In other words, fuzzy sets and its accompanying fuzzy logic are ideally suited to be a basis for a modern approach to baseline performance evaluation. Put another way, fuzzy sets are concerned with formal models of reasoning under linguistic (i.e. criterion) uncertainty (Zadeh, 1997).

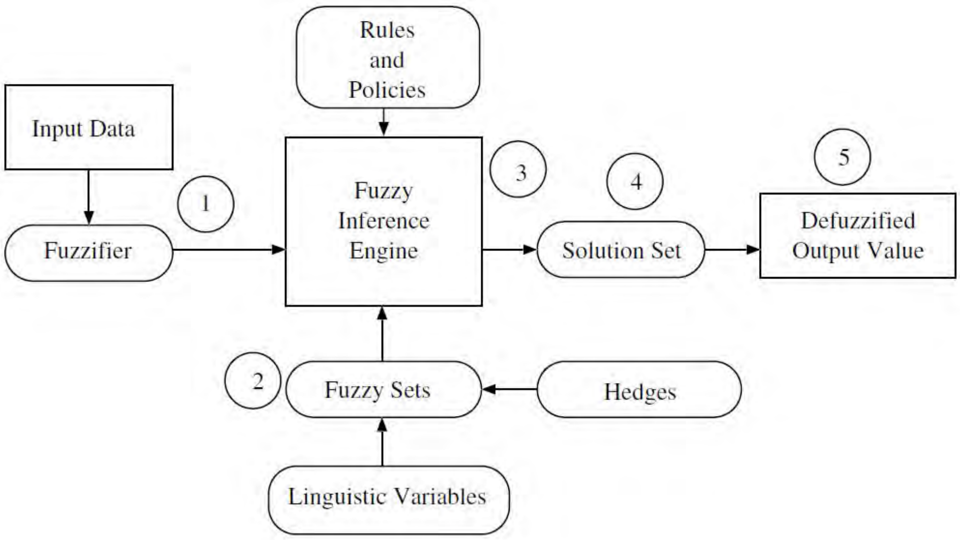


Figure 3-12: The major components of an approximate reasoning fuzzy expert system model and flow of processing through the components (Brimicombe, 2010)

3.4 GUIDANCE FOR APPLYING THE SUURE FRAMEWORK – AN OPERATIONAL MODEL OF THE FRAMEWORK AS A DSS

Whilst the SUURE Operational Model will consist of variable components and a specification of interactions amongst them, from the perspective of a decision-making model and its variable components, the SUURE Operational Model encapsulates the following three core mechanisms of the SUURE Framework: a measure of preferences in light of UUS decision objectives, available UUS decision options, and a measure of uncertainty (afforded by socio-ecological future scenarios) over the necessary conditions influencing the sustainability goal and capacity to adapt to change. The formalisation and decomposition of these different components (see Section 3.2; see Figure 3-2) into an interactive-computing environment is termed ‘modelling’. Modelling facilitates identifying an abstract representation of UUS that simplifies as well as assumes as much as possible about UUS, whilst preserving the essential relationships of UUS, and omitting unnecessary detail. Making decisions concerning UUS (e.g. the use MUTs as a sustainable method for utility service provision) a complex SES, is in most cases beyond the cognitive ability of one individual. It is this desire that necessitates a modelling approach to allow UUS evidence-based decisions as a reflection of the limitation experienced by human decision-makers. Badiru and Cheung (2002) highlight the limitations as experienced by human decision-makers as: (1) Human expertise is very scarce; (2) Humans get tired from physical or mental workload; (3) Humans forget crucial details of a problem; (4) Humans are inconsistent in their day-to-day decisions; (5) Humans have limited working memory; (6) Humans are unable to comprehend large amounts of data quickly; (7) Humans are unable to retain large amounts of data in memory; (8) Humans are slow in recalling information stored in memory; (9) Humans are subject to deliberate or inadvertent bias in their actions; (10) Humans can deliberately avoid decision responsibilities, and (11) Humans lie, hide, and die. These limitations only illustrate that human instinctive reasoning and decision-making can be far from optimal, complexity and stress only make this worsen. In order for the SUURE framework to be a decision support system (DSS) that can utilised, it necessitates distillation of the different elemental parts of the 'framework' into an "*Operational Model*" that can be utilised computationally to aid decision-makers (e.g. policy makers, urban planners etc.).

Operational models (interactive computational programs/environments) in recent times have been formulated through a conglomeration of a variety of techniques originating from artificial intelligence, information science and cognitive psychology, often taking form in one of two options: (1) An integrated computing environment aimed at complex decision making; (2) A stand-alone tool. These integrated computing environments are often termed as modelling decision support systems (DSSs) (Marakas, 2003). The conception of a DSS is very broad as well as the multiple definitions that it affords, subject to the authors perspective. To avoid any misunderstanding in light of the work presented in this thesis, DSSs are defined as interactive computer-based systems that assist their users in judgment and choice activities (Figueira et al., 2005). Knowledge-based systems are another synonym employed for DSSs, thus denoting the attempt to formalise domain knowledge so that it is agreeable to mechanised reasoning. The importance of a computer-based tool i.e. SUURE operational model, relevant to decision-making is at the core of the SUURE framework translating to a DSS, that directly supports modelling decision problems and ultimately aids to identify the best alternatives (in the case of SUURE a result of resilience index ratios).

As stated by Sage (1991), there exist three fundamental components of modelling DSSs:

1. Decision Database Management System (DDBMS): A DDBMS acts as a data repository for the DSS. It retains sizable quantities of data that are pertinent to the type of decision-making problems for which the DSS *(SUURE Operational Model)* has been designed and makes available coherent data structures (set against physical data structures) with which the decision-maker (user) interact. A DDBMS detaches the users' interaction from the physical facets of the decision database structure as well as processing. It ought to by necessity be capable of informing the decision-maker (user) of the types of data that are required.
2. Model-Base Management System (MBMS): The MBMS has a functional role comparable to that of the DDBMS. It seeks to primarily afford independence amongst the specific methodological approaches that are employed in the DSS *(SUURE Operational Model)* from the applications that utilise them. The MBMS seeks to transform data from the DDBMS into information that can be utilised in the decision-making process. Because many of the decision-making problems that the user of the DSS will have to deal with may be unstructured, the MBMS ought to be able to assist the user through a structured modelling process.

3. Dialog Generation and Management System (DGMS): The DSS ought to afford the decision-maker some level of insight that was not previously available. As such, users of DSSs are often non-technical managerial staff who are not computer-trained; DSSs need to be set up with intuitive as well as user-friendly interfaces. The user-friendly interface is crucial for model interaction and allows the DGMS to improve the capacity of the model user (decision-maker) to use and benefit from the DSS. For the remainder of this thesis, *user interface* (the broader term) will be utilised as opposed to DGMS.

Despite the fact that a variety of DSSs exist (Sage, 1991; Alavi & Leidner, 2001; Marakas, 2003; Bonczek et al., 2014), the aforementioned three fundamental components can be found in several DSSs and perform a key functions in their structure. The interaction of the three fundamental components of modelling DSSs with reference to the SUURE Operational Model is illustrated in Figure 3-13. In essence, the decision-maker interacts with the SUURE Operational Model (DSS) through the DGMS. This communicates via the DDBMS and MBMS, which shield the decision-maker and the user interface from the physical specifics of the SUURE Operational Model Base as well as database operation.

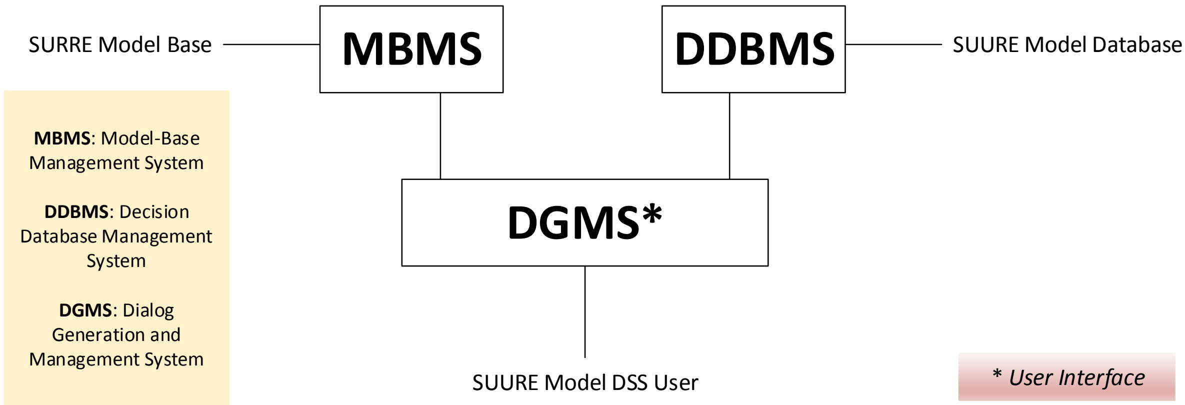


Figure 3-13: The architecture of the SUURE Operational Model DSS

The SUURE Operational Model analysis process is not a one-shot process (see Figure 3-2). The *model* as exemplified by the *framework* includes tools (see Section 3.2) for examining UUS resources (a SES) and classifying its most sensitive sections, which can be afterward expanded in greater detail. A user interface is the means of expression for the SUURE Operational Model construction and for investigating the results. Deprived of understanding, the decision-maker(s) may accept or reject a models guidance for all manner of reasons. To counter this as much as practicable, a good user interface for the SUURE Operational Model should make the SUURE Framework on which the Operational Model is based transparent to the decision-maker. The importance of the user interface cannot be understated, in as much as it affords insight into the decision problems faced vis-à-vis UUS and sustainability goals for UUS resource use. Any decision-making process follows a logical path. The abstraction of the rational decision-making process followed by individuals in society was put forward by Simon (1960). Simon's model postulated that decision-making follows a clear path by the decision-maker of (contextualised to the SUURE Operational Model): (i) Intelligence: This phase consists of finding, identifying and formulating the sustainability solution (goal); (ii) Design: This is the phase where alternatives to the sustainability solution (goal) are developed; (iii) Review: In this phase the sustainability solution (goal) is evaluated, both in the here and now (baseline), and the far future whatever that may be (UF socio-ecological scenarios) ; (iv) Choice/Implementation: In this last phase, evaluation of the alternatives is presented (resilience index ratios), with the decision to implement, adapt or mitigate the sustainability solution (goal) evaluated. It is assumed in the case and context of the SUURE Operational Model, that a decision-maker will follow Simons abstraction of the decision-making process; the abstraction put forward by Simon (1960) is still to this day the consensus approach to rational decision-making (Pettigrew, 2014).

Insight into the SUURE Operational Model can be greatly increased for the decision-maker at the user interface level by way of an illustrative diagram representing the interactions amongst the three fundamental components (MBMS, DDBMS and DGMS) of the SUURE Operational Model, with reference to the different methodological approaches reviewed to be embedded in the SUURE Operational Model (see Section 3.3). This diagram is presented in Figure 3-14.

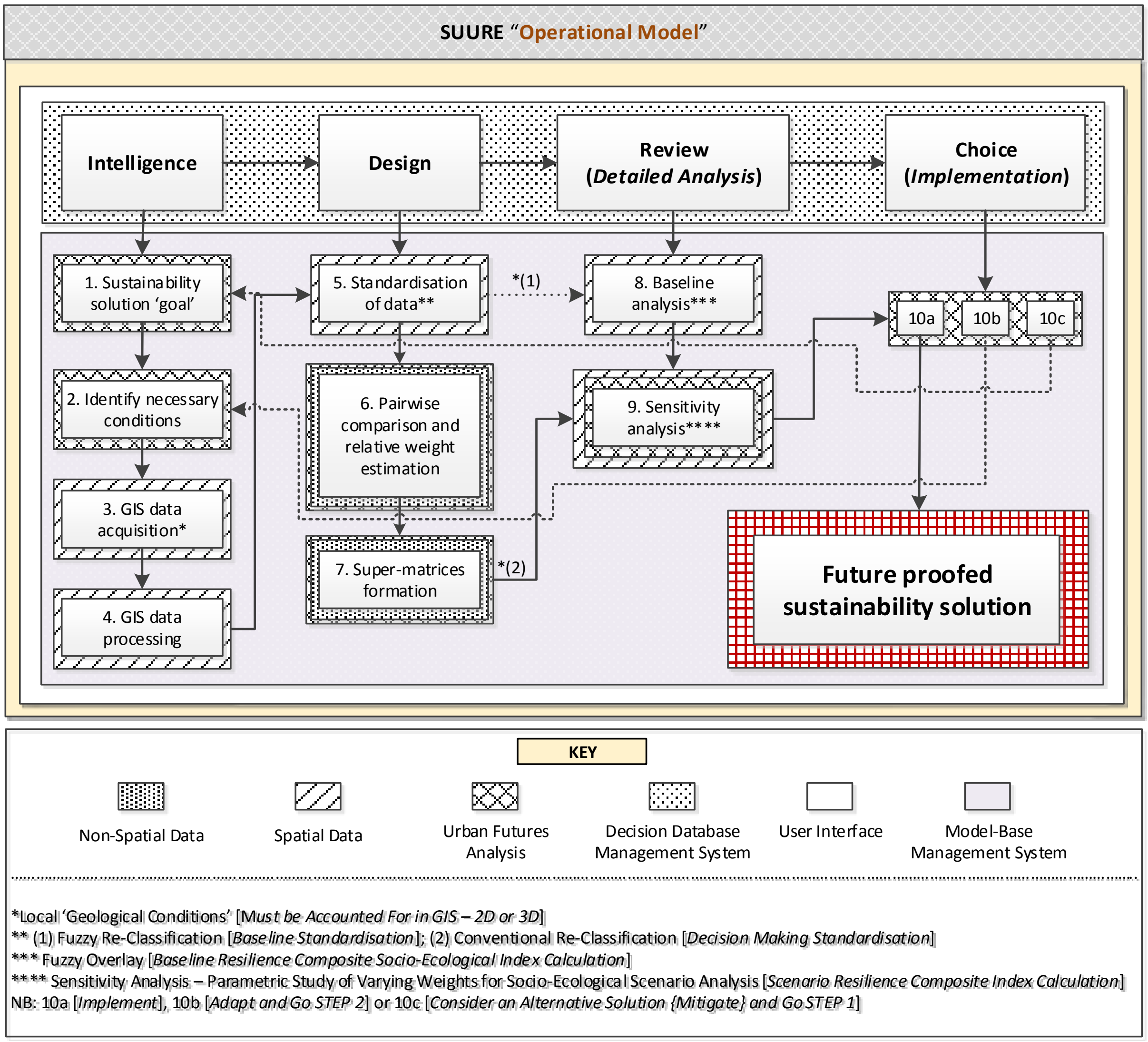


Figure 3-14: Sequence of activities and components of the SURRE "Operational Model"

The following sections will deconstruct and explain the structural process of the SUURE Operational Model as shown in Figure 3-14.

3.4.1 INTELLIGENCE

3.4.1.1 Step 1: Sustainability Solution 'Goal'

Given that the SUURE operational model utilises a multi-attribute (multi-criteria) decision-making approach, the goal, in this case the 'sustainability goal', needs to be stated as a first step to decomposing into a network model (ANP), thereby defining the overarching transformative goal.

3.4.1.2 Step 2: Identify Necessary Conditions

Once the 'sustainability goal' has been defined, the next step is to identify the necessary conditions (criteria) that would engender the ANP model development, categorising groups or 'clusters' founded by varied elements ('nodes') that impact the decision. Given that ANP is a multi-attribute decision-making problem approach, criterion is either restrictive (constraints) or non-restrictive (factors). Each element in the decision network edifice can be linked in various means as the ANP network structure can integrate responses besides multipart interrelationships contained by as well as amid clusters, consequently making available precision within the modelling of complex urban settings of UUS (a SES). The building of the ANP network structure signifies a vital and especially creative stage in the SUURE Operational Model sustainability goal evaluation sequence and the correct regard of the criteria, connections as well as responses included in the overarching transformative goal is the required proviso for effective evaluation.

3.4.1.3 Step 3 and 4: GIS Data Acquisition and Processing

In Step 3 raw data acquisition is carried out so that construction of a thematic map (map showing information regarding one characteristic of the UUS area under consideration) for each categorised factor and constraint can be produced (see Figure 3-15). The basic data model to facilitate overlay functions in the present work is through 'raster' data as opposed to 'vector' data. The SUURE operational model calls for the accounting of 'local geology' (addressing the knowledge gap identified in Chapter 2), and in the present research work this is achieved through the utilisation of GSI3D (see Chapter 4).

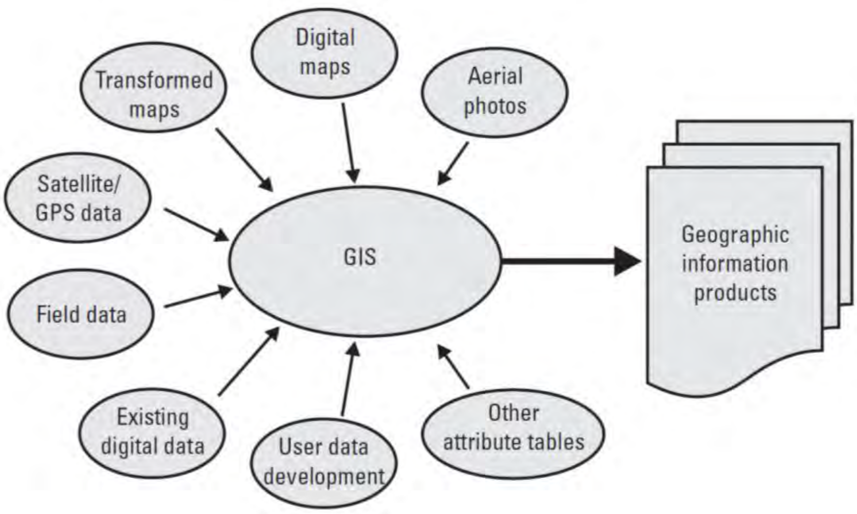


Figure 3-15: Inputs for thematic maps (Galati, 2006)

In Step 4 the constructed maps are computed via basic GIS operations (spatial queries, distance measurements, buffering, thematic map overlay etc.) – see Figure 3-16 and Figure 3-17.

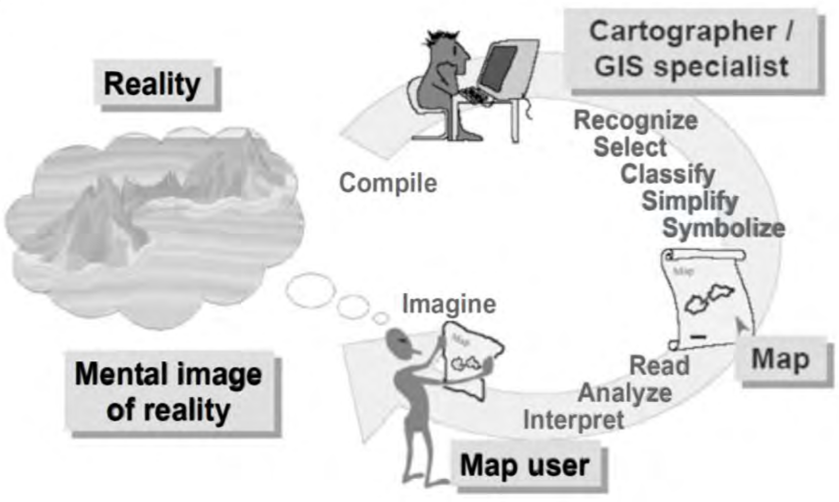


Figure 3-16: Different stages of information transfer in GIS (Fazal, 2008)

A container of maps in digital form	the general public
A computerized tool for solving geographic problems	decision makers, planners
A spatial decision support system	managers, operations researchers
A mechanized inventory of geographically distributed features	utility managers, resource managers
A tool for revealing what is otherwise invisible in geographic information	scientists, investigators
A tool for performing operations on geographic data that are too tedious if performed by manual methods	resource managers, planners, GIS experts

Figure 3-17: Definitions of GIS and the groups who find them useful (Fazal, 2008)

3.4.2 DESIGN

3.4.2.1 Step 5: Standardisation of Data

Step 6 has two separate standardisation procedures. This process transforms the incommensurable units for each thematic input map to dimensionless entity, and determines the partial appeal of every pixel of the thematic maps as regards each criterion. The first is fuzzy standardisation (reclassification) through the use of fuzzy membership functions to a scale of (0-1). The second is conventional standardisation (reclassification) to a common scale (0-1). In so doing, the baseline sustainability 'resilience' performance evaluation and the scenario sustainability 'resilience' performance evaluation stages permit mutually comparable value judgments through a common scale.

3.4.2.1.1 Fuzzy Standardisation

Step 4 (fuzzy standardisation) involves assigning the appropriate membership function to the linguistic variable i.e. the factors (non-restrictive necessary conditions) in the clusters in preparation for the baseline performance analysis in Step 8.

NB: the fuzzy membership functions presented herein correlate with those found in ArcGIS 10.2, the platform on which SUURE Operation Model analyses will be carried out on.

Table 3-6: Summary of fuzzy membership functions implemented in the Fuzzy Membership tool in ArcGIS 10.2: In addition, there are two hedges (Somewhat and Very) that qualify the membership. These functions have been found most useful in spatial modelling problems. The first five membership functions produce a sigmoid shape of the membership, which is used commonly in many fuzzy logic applications. Experience with these functions can be gained rapidly by implementing them in a spread sheet and adjusting the parameters – adapted from (Raines et al., 2010)

Membership Function	Description	Definition
Linear	A linear increasing or decreasing membership between two inputs. A linearized sigmoid shape.	$\mu(x) = 0\ if\ x < min, \mu(x) = 1 if\ x > max,$ $otherwise\ \mu(x) = \frac{(x - min)}{(max - min)}$ where min and max are user inputs
Large	Sigmoid shape where large inputs have large membership	$\mu(x) = \frac{1}{1 + (\frac{x}{f2})^{-f1}}$ where user inputs f_1 is the spread and f_2 is the midpoint.
Small	Sigmoid shape where small inputs have large membership	$\mu(x) = \frac{1}{1 + (\frac{x}{f2})^{f1}}$ where user inputs f_1 is the spread and f_2 is the midpoint.
MS Large	Sigmoid shape defined by the mean and standard deviation where large inputs have large memberships.	$\mu(x) = 1 - \frac{bs}{x - am + bs}\ if\ x > am,$ $otherwise\ \mu(x) = 0$ where *m* =mean, *s* = standard deviation, and *b* and *a* are multipliers provided by the user.
MS Small	Sigmoid shape defined by the mean and standard deviation, where small inputs have large memberships.	$\mu(x) = \frac{bs}{x - am + bs}\ if\ x > am,$ $otherwise\ \mu(x) = 1$ where *m* =mean, *s* = standard deviation, and *b* and *a* are multipliers provided by the user.
Near	A curved peak of membership over an intermediate value.	$\mu(x) = \frac{1}{1 + f1 * (x - f2)^2}$ where user inputs f_1 is the spread and f_2 is the midpoint.

Membership Function	Description	Definition
Gaussian	A Gaussian peak of membership over an intermediate value.	$\mu(x) = e^{-f1*(x-f2)^2}$ where user inputs f_1 is the spread and f_2 is the midpoint
Table of Contents (TOC)	The experts can visualize the membership values displayed on the map.	Membership is defined based on the classes in the symbolization in the Map document table of contents.
Categorical	Each named class is assigned a membership value by the expert.	Membership is defined by entering the values times a multiplier into a reclassification table.
Somewhat	Applied to slightly adjust a membership function.	$\sqrt{\mu_A(X)}$ Square root of membership.
Very	Applied to slightly adjust a membership function.	$[\mu_A(X)]^2$ Membership squared.

3.4.2.1.2 Conventional Standardisation

The evaluation of alternatives is generally communicated in accordance with different scales (ration, ordinal, and interval). Nevertheless, several multicriteria methods (comprising almost all the utility function-based approaches) necessitate that all their criteria be conveyed through a common scale. Standardising the criteria enables the use of a graduated system that rescales all the evaluation criteria magnitudes between 0 and 1. This enables within, in addition to between criteria comparisons with the baseline fuzzy 'membership' standardisation which also rescales evaluation criteria magnitudes between 0 and 1. There are an abundance of standardisation techniques available (Freudenberg, 2003; Saisana et al., 2005). In all these techniques, standardisation begins with an initial vector $(g_j(a_1), g_j(a_2), \ldots., g_j(a_m))$ to get a standardised vector $(r_{1j}, r_{2j}, \ldots.., r_{mj})$ using $0 \leq r_{ij} \leq 1; \forall_j \in F$ and $i = 1, \ldots, n$ (n is the number of alternatives). The standardisation technique that is most widely used in GIS-based multicriteria decision-making is the *linear transformation technique* (Malczewski, 2006; Ferretti, 2011a). It connects through respective alternative a_i and for respective criterion g_j the percentage of the maximum over all alternatives:

$$r_{ij} = \frac{g_j(a_i)}{max_i g_j(a_i)}, i = 1, \ldots.., n; j \in F \qquad \textbf{Eq 3-8}$$

3.4.2.2 Step 6: Pairwise Comparison and Relative Weight Estimation

Step 6 entails the comparative weight estimation that enables the classification of relative importance of each criterion concerning others, so that the level of contribution from each respective criterion is identified relative to the 'sustainability goal'. When carrying out the pairwise comparisons, the component in the comparison is the lesser one, whilst the larger element acts as a compound of the smaller element relative to the criterion being assessed. The first ANP pairwise comparison is at the cluster, the second at the node level. These pairwise comparisons are carried out utilising Saaty's

fundamental scale, a ratio scale of 1-9 (see Table 3-7) in order to liken whichever two elements (see Figure 3-18).
Saaty (1980) outlines the mathematical computations of ANP pairwise comparison:

$$A \times W = \lambda_{max} \times W \qquad \textbf{Eq 3-9}$$

where A is the matrix of the pairwise comparison, w is the eigenvector, and λ_{max} is the big eigenvalue of A.

Saaty (1980) further presents the manner in which the numerical pairwise comparison matrices are computed, by following:

$$\widetilde{w}_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \qquad \textbf{Eq 3-10}$$

where $\widetilde{w}_i$ is the eigenvector from the matrix of the pairwise comparison, a_{ij} is the element from the pairwise comparison matrix.

$$w_i = \frac{\widetilde{w_i}}{\sum_{i=1}^{n} \widetilde{w_i}} \qquad \textbf{Eq 3-11}$$

the equation above normalises w_i.

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(Aw)_i}{nw_i} \qquad \textbf{Eq 3-12}$$

λ_{max} is the eigenvalue.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \textbf{Eq 3-13}$$

$$CR = \frac{CI}{RI} \qquad \textbf{Eq 3-14}$$

$CR =$ the consistency ratio, $CI =$ consistency index and $RI =$ the average random consistency index

CR is utilised to test the consistency when a pairwise comparison is executed. Satisfactory consistency is achieved when pairwise comparison matrix results in a $CR < 0.1$. In the present research work the pairwise comparison is to be conducted through using Super Decisions 2.2.6 © – Software (Saaty & William, 2004).

Table 3-7: The fundamental scale of absolute numbers (Saaty, 2005)

Intensity of Importance	Definition	Explanation
1	**Equal importance**	Two activities contribute equally to the objective
2	Weak	

Intensity of Importance	Definition	Explanation
3	**Moderate importance**	Experience and judgment slightly favour one activity over another
4	Moderate plus	
5	**Strong importance**	Experience and judgment strongly favour one activity over another
6	Strong plus	
7	**Very strong or demonstrated importance**	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	**Extreme importance**	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	**If the activity *i* has one of the nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i***	A reasonable assumption
Rationals	**Ratios arising from the scale**	If consistency were to be forced by obtaining n numerical values to span the matrix

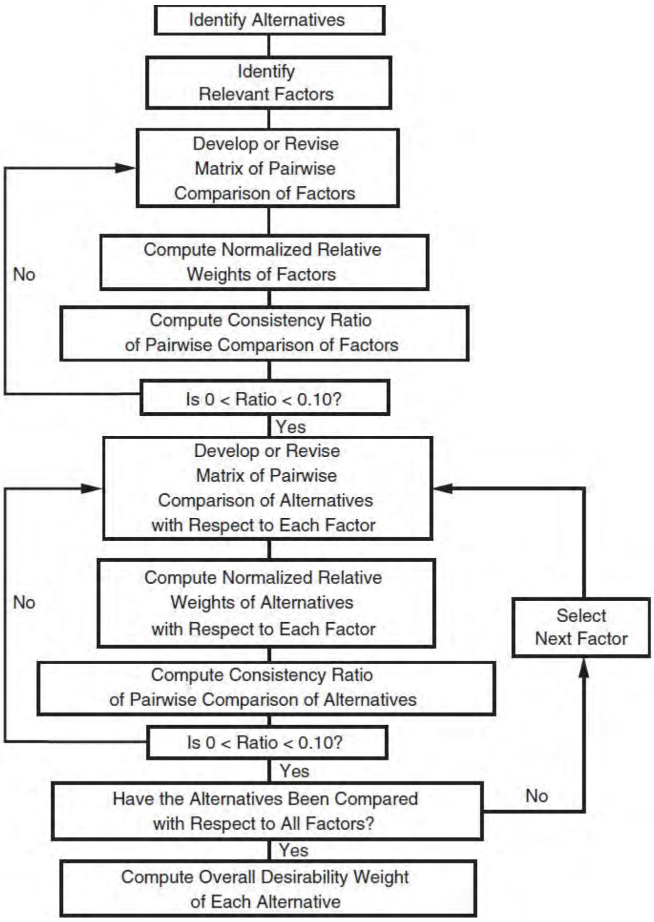


Figure 3-18: Flow-chart of the pairwise comparison process – adapted from (Badiru & Cheung, 2002)

3.4.2.3 Step7: Super-Matrices Formation

Step 7 involves the formation (step-by-step) of the three different types of super matrices (initial, unweighted and finally weighted); the final matrix formulated from the super matrices is the limit matrix, and provides the weights from the pairwise comparisons. All the eigenvectors produced by the pairwise comparisons matrices are contained within the unweighted supermatrix. This then feeds into initial supermatrix (eigenvectors from the cluster level comparison), as regards the 'sustainability solution goal', being applied as a cluster weight, resulting in the weighted supermatrix. The elements contained within the supermatrix permit a resolution to be observed with reference to the interdependencies that subsist between the elemental parts of the network structure.

$$W = \begin{array}{c} C_1 \begin{matrix} e_{11} \\ e_{12} \\ \vdots \\ e_{1n_1} \end{matrix} \\ C_2 \begin{matrix} e_{21} \\ e_{22} \\ \vdots \\ e_{2n_2} \end{matrix} \\ \vdots \\ C_N \begin{matrix} e_{N1} \\ e_{N2} \\ \vdots \\ e_{Nn_N} \end{matrix} \end{array} \overset{\begin{matrix} C_1 & C_2 & \cdots & C_N \\ e_{11}e_{12}\cdots e_{1n_1} & e_{21}e_{22}\cdots e_{2n_2} & & e_{N1}e_{N2}\cdots e_{Nn_N} \end{matrix}}{\begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix}}$$

Eq 3-15

The supermatrix is shown above – cited from (Saaty, 2005)

$W_{ij}\ Component\ of\ Supermatrix$

$$W_{ij} = \begin{bmatrix} W_{i_1}^{(j_1)} & W_{i_1}^{(j_2)} & \cdots & W_{i_1}^{(j_{nj})} \\ W_{i_2}^{(j_1)} & W_{i_2}^{(j_2)} & \cdots & W_{i_2}^{(j_{nj})} \\ \vdots & \vdots & & \vdots \\ W_{in_i}^{(j_1)} & W_{in_i}^{(j_2)} & \cdots & W_{in_i}^{(j_{nj})} \end{bmatrix}$$

Eq 3-16

the supermatrix of a network and detail of a component in it is shown above – cited from (Saaty, 2005)

3.4.3 REVIEW AND DETAILED ANALYSIS – OVERLAY ANALYSIS

Overlay analysis necessitates that two or more thematic map layers are overlaid or merged to create a new, composite map (see Figure 3-11).

3.4.3.1 Step 8: Baseline Analysis

Step 8 involves assigning the appropriate fuzzy combination operators (overlay type) executed in the fuzzy overlay tool in ArcGIS 10.2. Fuzzy overlay analyses are computed to quantify the baseline resilience index ratio. The equations for the different functions are:

$Fuzzy\ OR$ $$\mu(x) = Max(\mu_i)$$ **Eq 3-17**

$Fuzzy\ AND$ $$\mu(x) = Min(\mu_i)$$ **Eq 3-18**

$Fuzzy\ Product$	$\mu(x) = \pi_{i=1}^{n}\mu_i$	**Eq 3-19**
$Fuzzy\ Sum$	$\mu(x) = 1 - \pi_{i=1}^{n}(1-\mu_i)$	**Eq 3-20**
$Gamma$	$\mu(x) = (FuzzySum)^{\gamma} * (FuzzyProduct)^{1-\gamma}$ where γ is a user input	**Eq 3-21**

$x = memebrship\ value\ for\ crisp\ measurment$
$I = Specifies\ each\ of\ the\ (n) evidence\ layers$

NB: the fuzzy baseline overlay combination operators presented herein correlate with those found in ArcGIS 10.2, the platform on which SUURE Operational Model analyses will be carried out on.

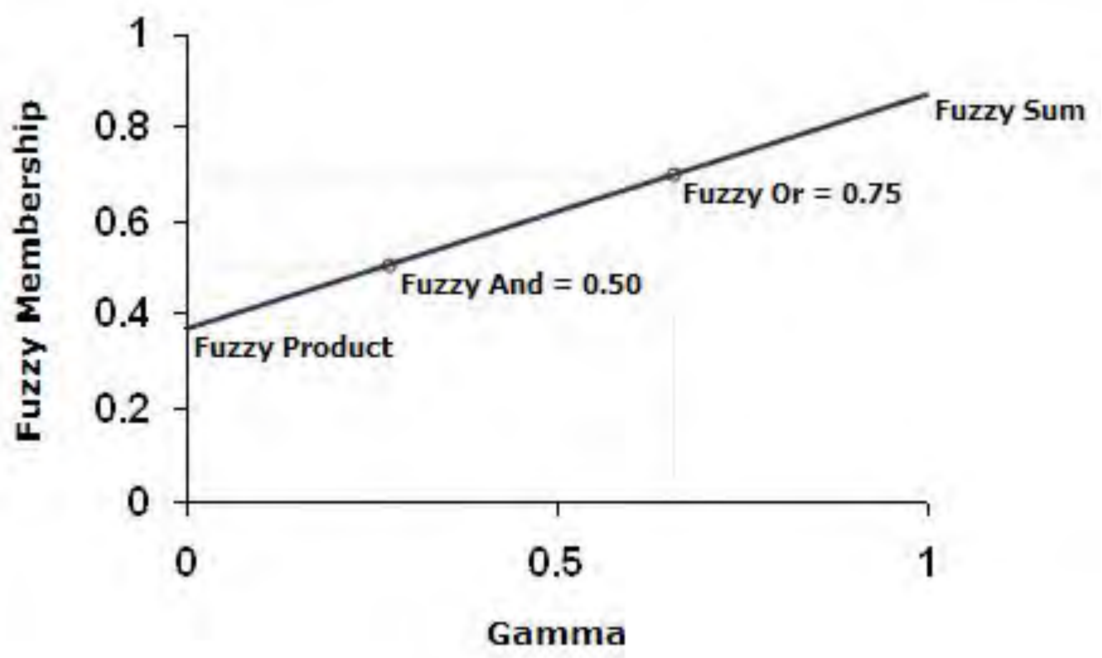


Figure 3-19: Relationship of Fuzzy Gamma to other fuzzy relationship types (ArcGIS 10.2, 2013)

3.4.3.2 Step 9: Sensitivity Analysis (Scenario-based)

In Step 9 the varying weights from the pairwise comparisons with respect to different future scenarios (NSP, PR, MF and FW) are applied to the overlay analysis and computed to quantify the scenario resilience index ratio. An overall characteristic Boolean multi-criteria evaluation is computed by:

$$S = \sum_{i=1}^{n} W_i X_i \times \prod_{j=1}^{m} C_j \qquad \textbf{Eq 3-22}$$

where S = suitability for resilience, W_i = weight of factor i, X_i = the criterion score of factor i, and C_j = the constraint j.

Bonissone and Decker (2013) notes that this weighted overlay operator represents neither an ‘AND’ (minimum) or ‘OR’ (maximum) operator (see Figure 3-11 and Table 3-5); it lies somewhere in between.

3.4.4 CHOICE: IMPLEMENTATION

3.4.4.1 Step 10: Choice and Implementation

In this final Step 10, the decision-maker can decide to implement, adapt or consider an alternative sustainability solution through the evidence base provided by the computed resilience index ratios of alternative options available i.e. do they have the capacity to adapt to change.

3.5 CHAPTER SUMMARY - OUTLINE OF THE SUURE FRAMEWORK DEVELOPMENT PROCESS

Ultimately, the results of the SUURE 'operational model' analysis (founded on the SUURE 'framework') conducted in the course of this research will be utilised in Chapter 5 to advance the existing evaluation methods for use of UUS reported in Chapter 2 (MUTs). The purpose more specifically of the SUURE operational 'model' is to make available and enable complex systems analysis, simulation, and their comprehension and governance with respect to UUS resources. From this viewpoint, and with regards to the insights postulated in Chapter 2 - Section 2.3, the principles of the SESs approach i.e. combining resilience theory and sustainability science are implemented in this framework (see Chapter 5, Section 5.4). The general approach utilised in the SUURE framework is straightforward. The SUURE framework is decomposed into subsystems, and an ANP-based SMCDA system is used to study them. This chapter has also shown how both fuzzy GIS and a scenario planning approach can be incorporated within an ANP-based SMCDA system, a novel method to enable a SESs approach, and thus quantification of both spatial and temporal impacts of today's urban development and regeneration solutions on their subsurface SES environments. Artificial deposits by means of a combined GSI3D (see Chapter 4) – ESRI GIS methodology provides a basis for modelling the anthropogenic landscape evolution of Birmingham Eastside and its impact (now and in future conditions under alternative scenarios) on the spatial variability on the subsurface ground conditions. The operational 'model' was subsequently found to be a robust operational decision-making tool for evaluating UUS resource (space for utility infrastructure) use during this research. There may be scope for axillary exploration into the application of the SUURE 'model' when taking into account the standardisation procedures (described in Section 3.8.2), for both the fuzzy baseline (fuzzy membership functions) and pairwise comparison criteria standardisation (standard deviation, geometrical interval, quantile, defined interval etc.).

For the analysis carried out using the SUURE Operational 'model', pairwise comparison - standardisation for socio-ecological scenario analysis was conducted through the implementation of a *linear transformation system*. The author is aware, nonetheless, that the effect of changing the standardisation system may result in slightly different weights on which the scenario analysis relies, and as such different values for the resilience ratio. Be that as it may, this was beyond the period of time of this research project and could be given due consideration with respect to future research. The parametric nature of the investigation necessitated the utilisation of 2D geo-spatial modelling (in preference to 3D – even though the geological model of Birmingham Eastside in Chapter 4 is in 3D) with the aim of making progression to the planning and management of UUS resources through SUURE. The application of full 3D analysis would have necessitated a computational ontogenesis of a robust system for vector overlay analysis (fuzzy and weighted) within ArcScene '3D Analyst' or any other commercial GIS package that can provide a platform to carry out this analysis. In addition to this the ability to implement a Digital Elevation Model (DEM) for the purpose of 3D overlay analysis, which can account for a 3D geological model would have also been required. Both of these approaches would have demanded a lot of time to execute. The shortage of computing power at that juncture in the research process would also have led to long run times for analysis. In spite of this, with current headways in computing power, the utilisation of this form of modelling could at the present time be plausible and the use of 3D geospatial modelling (specifically overlay analysis) may well be carried forward in any future research endeavour. A summary of the SUURE framework, its theoretical basis and accompanying operation model development would typically be a long winding road, but one which nevertheless amply rewards with reference to our understanding of phenomena and how we could govern them. The process of how the SUURE framework and its accompanying operational model was developed and its application dependably is, as evident from this chapter, a multi-stage methodology with its constructive and unconstructive feedback loops (see Figure 3-2).

CHAPTER 4: CASE STUDY AREA: BIRMINGHAM EASTSIDE

4.1 INTRODUCTION

The present chapter provides a present-day account on the underground construction carried out thus far, and subsequent promising opportunities that were not utilised, within a £6bn regeneration project, branded citywide as ‘Birmingham Eastside’. The ‘Birmingham Eastside’ redevelopment programme (a city centre brownfield site) was during its execution, one of the biggest regeneration schemes being embarked on within the UK (Porter & Hunt, 2005; Jefferson et al., 2006). It sought to transform a hundred and thirty hectare (four hundred and twenty acre) zone of Birmingham into the district’s leading ‘sustainability quarter’, as soon as it came to completion circa 2010 (Birmingham-City-Council, 2003a). A significant chunk of the development programme within Birmingham Eastside included the knocking down of existent buildings structures, alteration and expansion of existent infrastructure systems and the establishment of a redesigned and renewed urban landscape (i.e. a contemporary city park, retail outlets, offices, hotels, residential areas and grandiose underground parking). The chapter firstly seeks to both examine and explore the complexities (operational obstacles) that were encountered during the redevelopment programme in facilitating sustainable underground construction within Eastside, and focuses principally on the sustainable delivery of underground space development within Eastside by outlining sustainability elements for consideration with respect to the provision of utility infrastructure (comprising energy provision, water provision as well as utility placement). As a final point, the present chapter reports on the development of a 3D geological model of Birmingham Eastside using ‘Geological Survey and Investigation in 3 Dimensions’ (GSI3D), the flagship software of the British Geological Survey (BGS), a methodology and related software tool designed for 3D geological modelling of the shallow subsurface (artificial deposits). The development of the 3D geological model firstly seeks to address explicitly the knowledge gap identified in Chapter 2 as regards accounting for complex geology in sustainability evaluation tools/frameworks, and secondly to enable the embedding of the 3D geological model, albeit in 2D (attributed geo-spatial model of Birmingham Eastside), for SES evaluation using the SUURE Operational Model as regards the efficacy or otherwise of MUT placement (flush-fitting, shallow and deep) within Birmingham Eastside (see Chapter 5).

4.2 BIRMINGHAM EASTSIDE: A BRIEF DEVELOPMENTAL HISTORY

The city of Birmingham is the UK’s second largest city, acknowledged both nationally and globally for its leading sporting, commercial, industrial, business and entertainment facilities, in addition to its patrimonial legacy of being the birthplace of the steam engine - invented by James Watt and Matthew Boulton. Birmingham also stands in contrast to any other UK city as the leading centre with regards to its diverse ethnic makeup (in excess of 50%) (Phillimore, 2011). The expanse of Birmingham Eastside crosses over some 130 hectares (420 acres) as well as the zonal extents of Digbeth, besides the Aston triangle, altogether situated in the northern quadrant of Birmingham city centre contained by the Nechells Ward (see Figure 4-2 – exhibited by a dense dashed outline). The developmental genesis of Eastside can be traced back to 1996, when Birmingham City Council (BCC) tasked a team, albeit diminutive in size, of urban architects, besides engineers to enlarge the city centre in the direction of - through to the Eastside area. The preliminary master plan, prepared by HOK (a global design, architecture, engineering and planning firm), portrayed spaces for development (i.e. residential, retail and commercial) in the interior of a new Quarter centred upon the motifs of Learning, Technology as well as Cultural Tradition (HOK, 1996). The initial phase of the plan comprised the abolition of Masshouse Circus, a raised segment of the bypass built during the antecedent part of the 1960's, the time between Birmingham's motor city years. This ring road (named the 'concrete collar', exhibited in Figure 4-2 as a slender dashed line) covered the borderline of Eastside producing both a noticeable and operational obstacle to development which prohibited outer growth of the city into contiguous zones. This sizable obstacle thus drove planners to focus developmental activities on western districts of Birmingham (e.g. Broad Street and Brindley Place) rather than the east, in so doing instigating a reduction in environmental quality, social welfare and economic success for the area. BCC set out a developmental programme termed 'Objective 2', which pursued and got European funds for structural elimination of the 'concrete collar' in 2002, bringing about significant infrastructure modifications to enable future development.

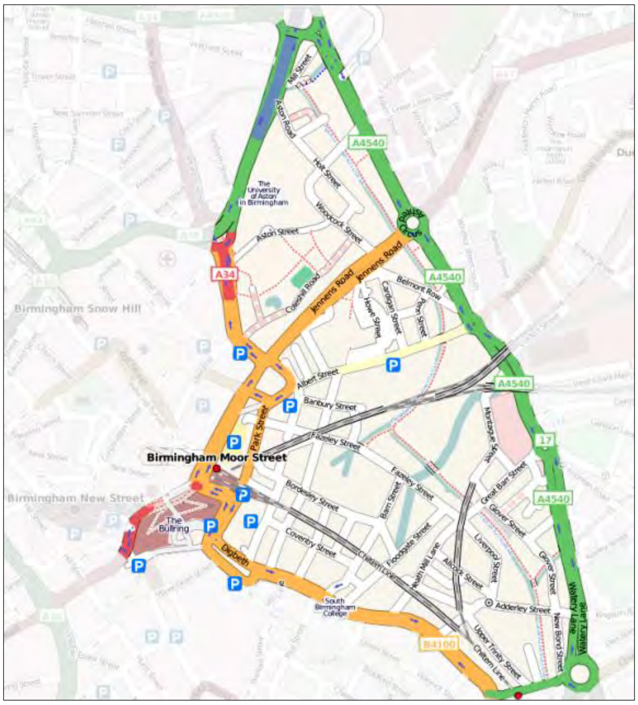


Figure 4-1: Birmingham Eastside

Consequently a number of development areas produced through the eradication of the roadway were flogged to market by BCC, with the monetary returns facilitating state-of-the-art developmental projects. On the whole, eight development sites (designated as Sites 1-8) even though two sites were abandoned (i.e. 1 and 2), and afterwards design schemes for sites 3-7 were prepared with reference to the guidance rules on urban design for BCC. The overarching goal of these new developments was that they would make certain the formation of an eye-catching and sustainable quarter that would make available areas and localities that would improve the overall condition of living for its inhabitants (GVA-Grimley, 2002). Masshouse (see Figure 4-2 – Sites 3 and 7) was designed such that it would embed sustainable regeneration as it chief motif (Mcleans, 2002) in line with the '*Sustainable Eastside: A Vision for the Future*' report inscribed via the Eastside Sustainability Advisory Group (ESAG), an autonomous consultative consortium aimed the regeneration scheme (Earth, 2002). City Park Gate

(Sites 4-6) was developed by Countryside Properties who also incidentally developed the Greenwich Millennium Village. The bid for the development by Countryside properties was won principally on the basis of their design approach and delivery, which significantly reduced adverse environmental impacts by implementing innovative technologies (e.g. heat retrieval, grey rainwater reprocessing, low energy systems and photovoltaics). City Park Gate upon completion comprises of a food store, offices and residential facilities. The final site (Site 8), designated 'New Library Site' was planned as ground zero for the newly designed city library for Birmingham by Richard Rogers (GVA-Grimley, 2004) supplanting a subsisting outmoded library located at Paradise Circus that was built in the 1970's. These plans for new library were quashed following a review, and Birmingham now has a new library situated in Centenary Square, Broad Street that opened in 2013 (Freeman, 2013).

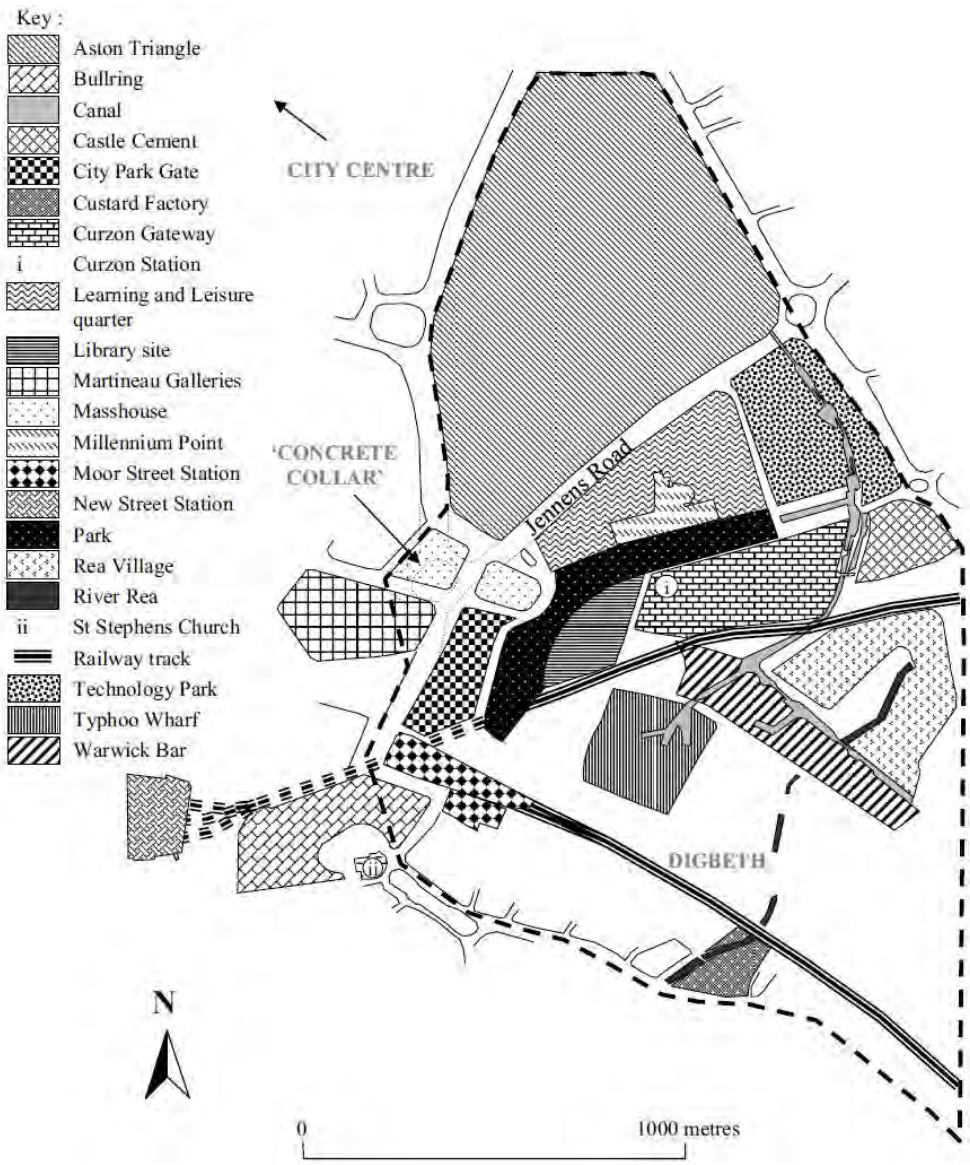


Figure 4-2: Sites for re-development in Birmingham Eastside (Jefferson et al., 2006)

In the course of these wide-ranging developmental pursuits, Advantage West Midlands (AWM), the resident agency tasked with redevelopment in the region, pursued obligatory acquisition of land neighbouring Millennium Point (Home to the Millennium project that opened in 2000), which has since been developed to include a leisure centre, new technology park and learning facilities for Birmingham City University (Lewis, 2013). The vision at the time by AWM was that Eastside would act as a model of sustainable design, and in turn facilitate the creation of circa 5000 jobs; thereby significantly impacting the economic pillar of sustainable development (Brown et al., 2010). Majority of the remaining sites were developed into residential properties (e.g. Curzon Gateway and Castle Cement Works) through the Eastside Partnership (a consortium of private equity investors).

Eastside' heritage area lies to the south of the railway tracks and Rea Village situated in this area was selected as a demonstrator project with regards to sustainable design through utilising the natural features of the environment (Birmingham-City-Council, 2001, 2003a). Two other developments also reside in this heritage area, Warwick Bar and Typhoo Wharf, both of which border the canal systems, and have both since been refurbished. Other refurbishments in the same vicinity also include the Custard Factory, which now houses small to medium size enterprises and budding artists. To the western front of Eastside is the flagship building of Birmingham, the 'Bullring', which opened in 2003. Such is its popularity that in 2004 it only lagged behind London and Glasgow as the third most visited shopping centre with well over 36 million visitors (Emery, 2006). The economic windfall brought about through the opening of the Bullring has been significant with over 8000 jobs created, this being a key regeneration driver for the area. Figure 4-2 contains the relevant aforementioned developments. By 2011 Eastside had further been developed and had to the North Corridor of Millennium Point (please refer to Figure 4-2) new transport infrastructure that consists of a bus route with embedded cycle network, new road network, upgraded foot-traveler amenities besides improved avenues to communal transportation systems as well as the inland waterways; thus fulfilling BCC vision of a economically viable and sustainable urban environment (Birmingham City Council 2003a).

4.3 SUSTAINABLE USE OF UNDERGROUND SPACE WITHIN EASTSIDE

Sustainability as discussed in Chapter 2 is a broad comprehensive agenda. Sustainability when viewed through an embedded socio-ecological model (i.e. the economy being a by-product of the social construct, and as such both work within the confines of the environment) is multifaceted and several commentators may well argue that construction, by definition, can under no circumstances be strictly sustainable. Despite the fact that the sustainable tokens (most apparent being environmental performance) of the man-made environment are readily noticeable and quantifiable subsequent to construction, those for UUS (a SES) are not. The greater than before demand for utility service provision, brought about by the wide-ranging redevelopment of Eastside to the present-day will and has undoubtedly placed larger requirements on Eastsides underground space. Sustainable development cannot be achieved unless due consideration is given to sustainable underground construction (see Figure 2-5), thus safeguarding the general well-being for present and future inhabitants of Eastside.

The basic building block of construction projects (building, city, town, and roads) is appropriate underground construction (e.g. foundations, basements etc.). This essential first step has a significant impact in terms of Birmingham Eastside realising a genuinely 'sustainable quarter'. More often than not, underground construction comprises utilities provision (i.e. communications, energy and water), shallow and deep basements, foundations and tunnelling (water and transport). The sustainable tokens of above ground space, especially concerning the built environment, are readily observable after construction, and more often than not, ecological efficiency can be appraised with comparative simplicity throughout as well as after erection of an edifice (e.g. Eco-points and BREEAM in the England, see Dickie and Howard (2000)). In spite of this construction relating to sustainability given a socio-ecological perspective is not required and thus enforced, therefore such phenomenon remains the exception instead of the rule (for instance, previous to August 2003 - merely three thousand four hundred constituents out of a hundred projects were endorsed with reference to the eco-homes scheme – see Ends-Report (2003)). The state of affairs with regard to underground space is not any better, in fact in most cases far worse, granting this can partially be attributed to the properties of underground space which are not easily visible, neither readily interpretable to decision-makers; exclusively inside the UK, the sustainable credentials of underground space have been largely ignored (Rogers, 2009). As discussed in Chapter 2, the increase in building stock densities above ground as a result of growing population densities inevitably necessities the exploitation of underground space, especially in urban areas (Singapore, Norway, Japan, Montreal, Denmark, Hong Kong are just some examples of where this phenomenon has brought about significant changes to UUS use). In Denmark for instance, the impetus to develop UUS comprise: spatial functional form, quality of environment and resourceful utilisation of space – see Monnikhof et al. (1998). To all intents and purposes, by building sizeable portions of all structures underground (i.e. those sections of a facility that lend themselves to this: car parks, utility systems, goods delivery, entertainment centres and shops) greater building stock concentrations inside municipalities are realised (Horvat et al., 1998). The polices thus pursued by these various countries acts to escape effecting a bequest of increased economic, social and environmental overheads in lieu of posterity, to some degree, Eastside strove to emulate this approach in its regeneration pursuits (Earth, 2002).

4.3.1 BIRMINGHAM EASTSIDE: UTILITY INFRASTRUCTURE

4.3.1.1 Utility Placement

Utility service provision is a vital and inevitable first course of action for all regeneration schemes. Its ability to be further expanded and thus account for expected future growth in demand (increased capacity required by e.g. increase in population density) will determine whether a forward-looking development, in this case Birmingham Eastside, can be sustained. Despite the fact that guidance for utility service provision exists (see Figure 4-3) and utility placement via traditional trenching methods is governed by legislation (Traffic-Management-Act, 2004), they are not compulsory mechanisms. With regard to the utility infrastructure situated in Birmingham Eastside, communications, street lighting, gas, water and electricity (includes low voltage (LV) and high voltage (HV) lines) was put in place and completed in late 2004. As illustrated in Figure 4-4, the manner in which utilities were placed within one of Eastside's pedestrian footpaths (2m wide diameter) was via traditional trenching (open-cut) practices. It is undoubtedly clear that best practice with reference to NJUG (2003) was not carried out, thereby most definitely leaving an unsustainable legacy (e.g. for the inevitable scenario where utility repair and maintenance, capacity enlargement and in some cases asset location will be required) by posterity, who will reside as well as toil within Eastside.

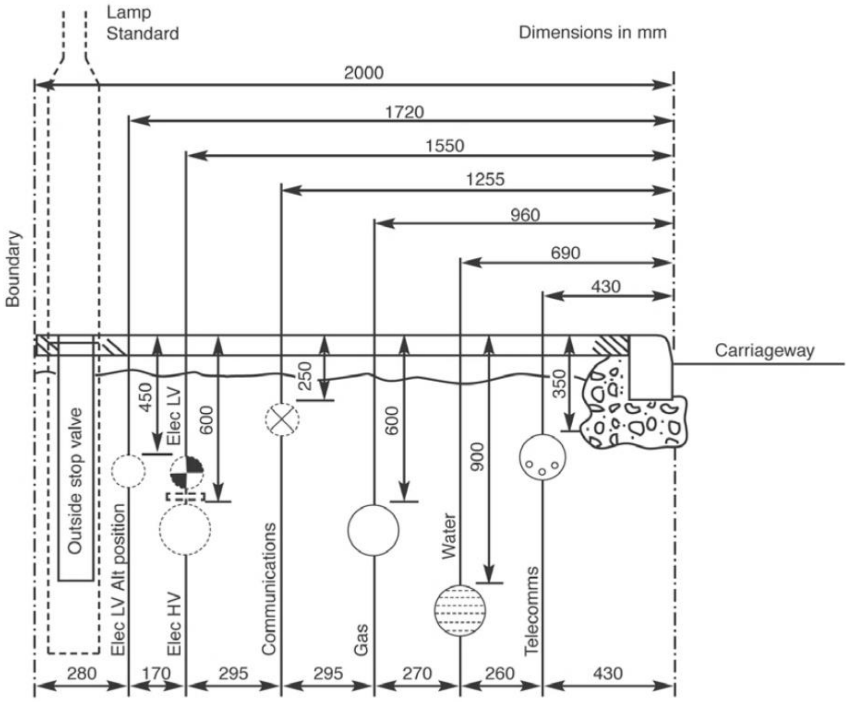


Figure 4-3: NJUG guidelines for utility installation in the UK (NJUG, 2003)

Figure 4-4: Utility placement within one of Eastside's 2m wide pedestrian walkways (Jefferson et al., 2006)

Figure 4-5: Pavement with high quality finish in Eastside (Jefferson et al., 2006)

It therefore begs the question as to why for a regeneration scheme of this magnitude in the UK and one touted to being a self-styled 'sustainable quarter', is trenching (open-cut construction) used. The foremost explanations for such phenomena comprise to a large extent the legacy of previous utility systems and an unawareness of available alternatives, in some case more sustainable techniques by gate keepers concerning Eastside and further afield in the sphere of the UK, where this understanding of improved methods subsists there is unwillingness to make changes to present-day practice (i.e. deep-rooted behavioural decision-making on the economic mono-criterion). Nonetheless, the principal concern for Eastside portends to the issue that pavement cuts are resurfaced (see Figure 4-5), the underlying disarray as illustrated in Figure 4-4 is not visible.

Utilities for the most part continue to be a hidden segment of the built environment and as such are relatively insignificant visibly to inhabitants of Birmingham Eastside. Phenomenon of this nature will subsist until which time the existing utility systems start to malfunction, otherwise at what time planned amounts aimed at distribution besides removal to Eastside go above allowable levels, and this crucially significant scenario will unquestionably have to be tackled by posterity. Intriguingly, despite the fact that there exist sustainability indicators that address the numerous processes of tradition utility placement through trenching (see Table 4-1), the technique has been branded by several authors to be fundamentally unsustainable (Cano-Hurtado & Canto-Perello, 1999; Canto-Perello & Curiel-Esparza, 2001; Canto-Perello & Curiel-Esparza, 2003; Curiel-Esparza et al., 2004; Hunt & Rogers, 2005; Canto-Perello & Curiel-Esparza, 2006; Rogers & Hunt, 2006; Canto-Perello et al., 2009; Hunt et al., 2009; Rogers, 2009; Curiel-Esparza & Canto-Perello, 2012; Hunt, Jefferson, Drinkwater, et al., 2012; Canto-Perello & Curiel-Esparza, 2013; Curiel-Esparza & Canto-Perello, 2013; Hunt et al., 2014) as a result of its intended and unintended consequences toward the surroundings (Giacomello & Trombetti, 2001), society (Iseley & Tanwani, 1990) and economy (Hunt et al., 2014).

Table 4-1: Sustainability Indicators for utilities (Rao et al., 2001)

Economic	Social	Environmental
Capital cost Whole life cost Efficiency Accessibility Research Risk Quality	Community disruption Training Health and safety Site security/safety	Material transport Aggregates Waste Leakage Materials Energy use Resource sharing Pollution control Packaging

As discussed in Chapter 2 (see Section 2.7.2), utilising MUT's as an alternative to traditional trenching practices would significantly aid towards the direction of sustainable underground construction as a result of sustainable utility placement (Hunt & Rogers, 2005; Rogers & Hunt, 2006; Hunt et al., 2009; Hunt et al., 2014). A MUT is defined as '*any system of underground structure containing one or more utility service which permits the placement, renewal, maintenance, repair or revision of the service without the necessity of making excavation ; this implies that the structure is traversable by people and, in some cases, traversable by some sort of vehicle as well*' (APWA, 1997). In the UK, MUTs have gathered relatively little attention a viable solution for utility placement and yet they offer a valid and consistent means for utility placement. Several instances of MUT usage exist globally (see Appendix A), yet the lack worldwide standards to their adoption (significant variations in type, installation, shape and material as evidenced in Appendix A) is indicative of the wide-ranging assortment of alternatives subsisting and are currently in operation. The sites of MUT placement also varies in depth depending on location, which can affect accessibility to the MUT i.e. flush-fitted MUT within or slightly below the pavement (see Figure 4-6) as an example, or having a different configuration, and being placed just underneath roadways otherwise other transport modes, which is applicable to Eastside (see Figure 4-7), or else subterranean Finland and Denmark (see Appendix A). Even as MUT's have several advantages (see for instance Hunt et al. (2009) or Curiel-Esparza and Canto-Perello (2012)), including minimal disturbance above ground and simplification of future utility maintenance by virtue of easier placement, several barriers to its wide-spread uptake subsist (e.g. see Hunt and Rogers (2005): lack of coordination between utility companies, expected high initial capital costs, lack of awareness of the problem, utility tunnel ownership, security access etc.). These are not limited to Birmingham Eastside and are experienced operationally across the whole of the UK (Hunt & Rogers, 2005). The initial high cost is often cited as a reason to why MUT's are not more widely adopted (see Figure 2-18), but this tends to be a barrier in the short term, whereas long-term it is more economically viable than traditional trenching methods both in Germany (Laistner, 1997) and in the UK (see Figure 2-19).

Figure 4-6: CHP pipes in a flush-fitting MUT at the University of Birmingham (Jefferson et al., 2006)

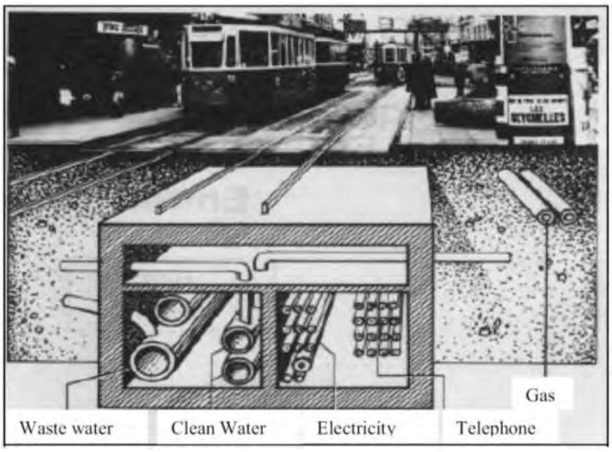


Figure 4-7: MUT under a tramway in Geneva (Pierre, 1977)

4.3.1.2 Energy Supply

The several developments in Eastside brought about an increase in energy demand (i.e. supply) and subsequently utility service provision infrastructure underground (Hunt et al., 2006). The Eastside regeneration scheme endeavoured to significantly reduce CO^2 emissions (climate change is benchmarked as headline metric to determine sustainable development or otherwise) and thus keep in line with UK policy and techniques being recommended by the government (DTI, 2003). One of the strategies implemented to this end was demand management and reduction of energy consumption by way of innovative design methods (e.g. augmented solar gain and natural air circulation), while a different one is the adoption of an extensive combined heat and power (CHP) system (at that time circa 2005, UK policy sought to implement 10 GWe of CHP capacity before 2010). That being said, decision-making for Eastside developments were piecemeal and seldom considered the holistic logistical challenges in planning and adopting CHP infrastructure across its utility service provision systems and consequently their impact on underground space development, requiring extensive retrofitting to be implemented. Such a case often seeks to emphasise the importance of considering alternative sustainable solutions with respect to energy provision during initial/primary periods in the choice selection activities; this sadly was not done till a late stage for Eastside due to funding restrictions (funding was won to carry out a feasibility study late in 2003 from the Carbon Trust). On the other hand, these problems may well be avoided totally if proposed combined heat and power geo-structure were to be charted as well as situated far as possible with regard to existing utilities, similarly if trenchless equipment (e.g. pipe jacking, horizontal auger boring, directional boring, pipe ramming, micro tunnelling, horizontal directional etc.) were utilised for utility placement the disturbance experienced from accompanying traditional trenching methods could be curtailed. This however would still not deal with the import issue of future asset location or maintenance, which can in most cases only be principally dealt with through the adoption and employment of MUTs aimed at accommodating combined heat and power, as well as additional utilities (see Figure 4-6). The CHP programme as luck would have it, acquired £1.3million worth of funding in mid-2005; this still left a funding gap of £2.8million.

The planned CHP infrastructure scheme on completion circa 2011, now delivers power via combined heat and power to 6 government owned office blocks. Two of these buildings remain situated inside Birmingham Eastside (Millennium Point, Aston University) and the rest are located contiguous to Eastside (Crown Courts, 1 Lancaster Circus, Children's Hospital and Victoria Law Courts). Millennium point houses the energy centre for the CHP system and is driven by two gas (1.5MWe) reciprocating engines with a global efficiency rating of 73%; 38% thermal and 35% electrical. In the course of a normal year's operation, this amounts to circa 41 GWhe of electricity and 45 GWhth of heat. The CHP system was constructed to have spare capability toward future inclusion of an additional 3MWe aimed at distribution of combined heat and power to subsequent new developments contained by the Birmingham Eastside regeneration programme (L'Induserielle, 2004).

Due to the CHP system being gas driven, demands for gas will inevitably go up considerably in Eastside. This is largely brought about as initially the main gas was utilised to produce electrical energy (replacing mains power). It is probable and yet to be observed whether or not the current CHP system (gas infrastructure) can handle the additional (unallocated) gas demand, if not, resulting in more alterations to existing underground utility service provision infrastructure. This scenario only further emphasises the need to engage with gate keepers on the primal stage possible in the regeneration agenda (i.e. master planning stage), presenting them with clear and unmistakable information for evidence-based decision-making for UUS (a SES).

The potential in Eastside also exists to extract from the underground strata overlying buildings, geothermal resources (i.e. warmth through central heating) that could be extricated by employing a typical GSHP submerged inside the underground strata (see Figure 4-11) and utilised in the interior of houses (Doherty et al., 2004) and bigger office blocks/apartments. Alternatively the same result can be achieved by attaching ground source heat pumps to the surface of piled foundations (Ryozo, 2006), a more state-of-the-art approach. It was proposed at the early stages of the Eastside redevelopment that the 'New Library' ought to comprise a geothermal system (GVA-Grimley, 2004). Nevertheless, the capital envisaged to roll this out hinged upon Birmingham winning the 'capital of cultures' bid, which in the end was won by Liverpool. Such an outcome only seeks to exemplify that sponsorship schemes comprise a vital role in (re)developmental choice selection processes, particularly as evidenced in Eastside, and can significantly impact the adoption and implementation of sustainable technologies (above or below ground) as opposed to traditional methods.

4.3.1.3 Water Supply and Waste Disposal

The hotels, retail outlets ad brand new offices within the Eastside regeneration scheme, subsequently placed huge new demands as regards the provision of water and excess water removal, that necessitated additional underground utility infrastructure. The water provision for Birmingham and consequently Birmingham Eastside was provided for by localised borehole abstraction (Knipe et al., 1993) up to finalisation of the Elan Valley reservoir in the beginning of the 1900's (Binnie, 1987). Due to the cessation in borehole abstraction, groundwater levels have risen to rebound levels i.e. pre-industrial (motor city) age (early 1800s) (Knipe et al., 1993; Powell et al., 2000). Facilitating underground construction would necessitate employing expensive dewatering schemes (temporary solutions as ground water levels rise over time on cessation of dewatering schemes).

Furthermore, the Birmingham Eastside area collects through rainfall approximately 819 Mega litres of water per calendar year. Water that infiltrates and percolates on porous ground surfaces in part permits for recharge of the sandstone aquifers (from Powell et al. (2000), Birmingham is underlain by a sizeable Sherwood Sandstone aquifer). To effectively manage rainfall and curtail unnecessary burdens to underground systems, Eastside's regeneration team rolled out a sizeable programme of sustainable urban drainage systems (SUDS), which by consequence permit significantly more water to infiltrate and percolate into the ground (see CIRIA (2001) and CIRIA (2000)) as opposed to heading for the combined storm sewer system. Paradoxically, urging such a practice of implementing SUDS could possibly not be the most suitable solution, particularly when designers (for UUS) are even now confronting challenges with sustainable underground construction. Such a situation simply underscores the need for such challenges of high water tables as in Eastside to be resolved through appropriate planning approached on a city scale. Such instances seek to exemplify the journey that Birmingham has undergone, in tandem with the learning faced by BCC with respect to sustainability and echoes the conclusions drawn by the PRESUD report (Birmingham-City-Council, 2003b). This elucidates further how crucial clear communication lines and knowledge exchanges networks within BCC and amongst decision-makers in various city councils. For example, Islington Borough Council, London, urges potential property developers via it sustainable planning guidance (SPG), to take into account borehole abstraction in order to lower ground water levels when assessing the feasibility of new development schemes (Islington-Council, 1999). This stands in contrast to Eastside's regeneration scheme, where such guidance was not presented to potential developers, and as such detracts from the sustainability agenda as a result of poor information. Masshouse development stands as the sole example of the Eastside regeneration scheme that accounted for installation of permanent boreholes for lowering water levels in the course of construction, and subsequently for cooling purposes throughout the operational phase (Gregory, 2004). This consideration however did not alter the decision-making process regarding Masshouse development as it surfaced too late within the process. This and obstacles with regards to financial liability of capital works if the scheme failed as result of the ground water issues resulted in traditional dewatering schemes (expensive) being adopted as a substitute (Hunt & Rogers, 2005).

The residual water settles on rooftops and roads. Typically large proportions of this (55-85%) is taken away by storm sewer gutters, which more often than not have a tendency to be overloaded simply in rainstorm swells, resulting in surface over flow. Paradoxically, over flow is a concern for zones postliminary of Birmingham Eastside. Despite the fact that that flooding in Eastside is unlikely given its topography, and additionally as a culvert exists on the River Rea, the challenges of flooding for Eastside do begin upstream. This exemplifies the need for dependable, consistent information and investigation, and could significantly impact the decision-making process from without and from within as regarding the capacity to achieve sustainable urban development on a scheme the size of Birmingham Eastside, subject to flawed information. Elevated decision-makers at the master planning level for BCC ought not to be facilitated with isolated sustainability solutions, devoid of due consideration objectively and holistically of the consequences that will come about from putting respective solutions it into practice. The current manner in which ad-hoc decision-making is conducted generally results in sustainable solutions not only implemented incorrectly; they in turn morph into problems of their own, unintentionally making them unsustainable, at the same time as opportunities for different sustainable solutions are being wasted. Over the course of its development, the Birmingham Eastside regeneration scheme has experienced a steady increase in demands for water, and early on water saving schemes were encouraged (rainfall harvesting- see City Park Gate development - Birmingham-City-Council (2003c) and GVA-Grimley (2004). Regarding disposal and supply of water in Birmingham Eastside, there unfortunately did not mature a holistic plan of action to address challenges concerning increasing ground water levels, precipitation abstraction, overflow reduction as well as water provision (Jefferson et al., 2006).

4.3.2 The Requirement for Adoption of Multi-Utility Tunnels within Birmingham Eastside

There exists a commonly held view (presupposition) that the most significant barrier confronting the realisation of sustainable utility infrastructure in the sphere of the UK remains the legacy of inherited utility systems, some more than 100 years old. Paradoxically, whereas this may be factual in the present-day, particularly with regards to traditional utility placement via trenching, the challenges have been experienced worldwide, thus far passed over, for decades. The earliest recognition of this phenomenon appears to be have been as early as 1901, during the course of New York's transit subway construction, when it was acknowledged that there was an window of opportunity to facilitate large scale and efficient delivery aimed at the numerous gas, electrical energy cables as well as H_2O plumbing contained by MUTs located beside the transit underpass (see Figure 4-8).

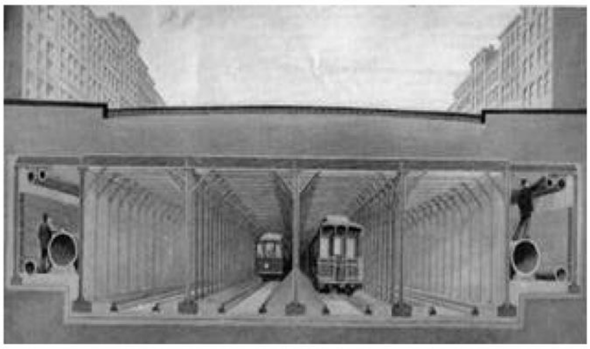


Figure 4-8: New subway for MRT (Scientific-America, 1901b)

Figure 4-9: MRT in 1901 (Scientific-America, 1901a)

Despite the fact that this form of utility placement satisfied the engineers of the day (given its relative simplicity engineering requirements and limited barriers with reference to utility infrastructure legacies) the pipe galleries were in time discarded in support of traditional trenching methods (see Figure 4-9). It was reported by (Scientific-America, 1901a) that the principal reason for this shift was as a result of semi-political pressures proffered consequent to the Railroad Commission. The subsequent ending paragraph was printed during this epoch: "*The present interruptions to traffic, the interminable and absolutely stupid way in which our choicest streets are dug up, re-laid and dug up again, is a perpetual and obtrusive nuisance, which would not be tolerated in any provincial town, and cannot be too soon removed from the streets of the second greatest city in the world*" (Scientific-America, 1901a).

Nevertheless, paradoxically, at the beginning of the 21st Century traditional methods of utility placement/provision through trenching (open-cut construction) are even now accepted within all major UK cities, and Birmingham Eastside is no different. Techniques used for the lacing of utilities are for the most part the same, apart from where trenchless machinations happen to be used, and therefore maintenance, siting, capability of enlargement of subsisting utility catalogues contained by city centres is very complicated and continues to be far from sustainable. Additionally, entitlements to access roadways (approximated to be 135 diverse businesses within the UK) on any occasion, has proliferated considerably ever since 1901. This has to an almost break-point situation of ever endless street works (the DfT (2003) reported that 1 million street works were documented in 2003) at the same time as escalation of direct and indirect costs (UKWIR (2005) reports that out of the approximately four million hovels excavated every 365 days within the UK's main roads besides sidewalks via utility businesses, costing in the region of one billion (direct costs) and an approximate indirect cost of £5.5 billion (J. Parker, 2008)). The manifold issues related with employing traditional open-cut construction are well documented in the literature; open-cut construction leads to additional traffic and road-user delays (Bayer, 2005; Jung & Sinha, 2007) estimated to cost the UK as a whole £5.5 billion per year (J. Parker, 2008), open-cut construction tends to cause increased noise and vibration (Jung & Sinha, 2007), open-cut construction is potentially dangerous due to excavations and mobile plant and vehicles (HSE, 2014a, 2014b), open-cut construction tends to have a negative impact on local residents (Jung & Sinha, 2007), open-cut construction tends to have a negative impact on local business (Laistner, 1997), open-cut construction tends to more often than not cause damage to the landscape (Jung & Sinha, 2007), open-cut construction costs more to maintain in the long-term as opposed to trenchless technologies (Rogers & Hunt, 2006; Hunt et al., 2014), open-cut construction tends to cause significant damage to roadways and pavements (Jung & Sinha, 2007), open-cut construction tends to require at times quite costly de-watering contingent on groundwater levels (Najafi & Gokhale, 2005) and open-cut construction tends to cause damage to existing utilities in the course of putting in place otherwise maintenance of adjacent utilities (Hunt & Rogers, 2005; Woodroffe & Ariaratnam, 2008).

As urban populations continue to expand rapidly (see Figure 2-1), previously declining provisions of H2O in addition to power resources will be exhausted at an even greater speed, even as the utility systems that transmits worsens, resulting in an increased loss of services within the system. This only makes worse the existing situation as OFWAT (2004) reported that in England and Wales between 2002/2003 water abstractions were in the range of forty billion litres/24hrs set against corresponding losses projected to be four billion litres/24hrs.

At present within the Eastside regeneration scheme as reported by Jefferson et al. (2006), the opportunity for providing complete, as opposed to singular instances of, sustainable underground construction looks as if they have been wasted, somewhat as a result of different utility infrastructure being dealt with in seclusion. In putting an end to this substantial obstacle to underground construction the resolution could most certainly be addressed through the adoption of MUT's in Eastside (see Figure 4-10), integrated systems which comprise all, as opposed to some, of the subsequent infrastructure necessities:

- Water provision/cache and removal;
- Waste removal;

- Energy supply/storage;
- Every added utility infrastructure.

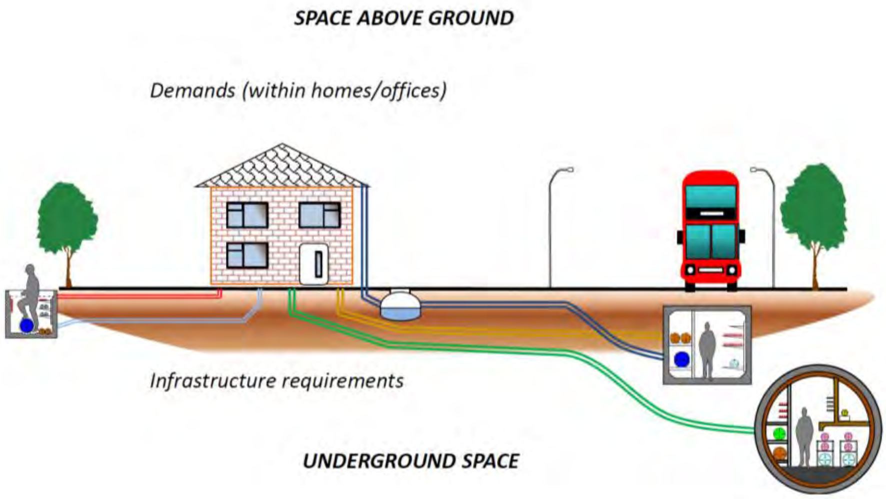


Figure 4-10: Different dimensions of potential MUT placement (flush-fitting – 0.0m cover, shallow 0.5m-2m cover and deep 2m-80m cover) within Birmingham Eastside (Hunt, Jefferson, & Rogers, 2012)

As an expected consequence of employing MUTs in Birmingham Eastside - saturation of UUS (topmost zone of human interaction) would decrease, zoned planning of UUS would be more effective, maintenance of utility systems would be easier, traffic interruption due to open-cut street works would significantly drop and the addition of new urban services can take place without disruption to the public highway (Cano-Hurtado & Canto-Perello, 1999; Hunt & Rogers, 2005; Rogers & Hunt, 2006; Hunt, Jefferson, Drinkwater, et al., 2012). The efficacy or otherwise of MUT placement in the geographical region of Birmingham Eastside will be evaluated in Chapter 5, utilising the SUURE Operational Model (see Figure 3-14).

4.4 THE APPLICATION OF 3D MODELS TO THE DEVELOPMENT OF AN INTEGRATED SOCIO-ECOLOGICAL SUBSURFACE MANAGEMENT SYSTEM

The geo-governance of UUS (a SES) and provision of valuable geo-environmental information in support of UUS development has two principal objectives. To begin with, the need to make certain that potentially problematic ground conditions are detected and mitigated against during engineering design and construction. Problematic ground conditions could consist of voids, contaminated soils and patchy geotechnical properties that could give rise to ground instability risks. Applied 3D geological modelling to this end, purposes to make available relevant ground information to decrease doubt in the course of ground investigations and successive above or below ground development. Secondly, ground information is necessary to facilitate the means to quantify the spatial and temporal impacts of large scale development(s). The latter takes account of the evaluation of probable contamination processes, decontamination of subsurface resources and the effects of the installing utilities and geo-structures into the ground and its immediate ecological unit (part of the SES).

The utilisation and management of geo-environmental data and information to assist the process of urban development and regeneration with reference to legislation is articulated by (Ellison et al., 1997;

Smith & Ellison, 1999; Hough et al., 2003; Culshaw, 2005) amongst others. The proliferation in the development and use of 3D geological models have made available innovative methods of visualising and using geo-environmental data aimed at applications in land use planning (above and below ground). Notably, 3D dissemination tools for instance the Subsurface Viewer (see for example (Terrington et al., 2009) let inexpert users interrogate and visualise 3D underground models on-the-fly.

The three-dimensional spatial irregularity contained by the UUS environment can be examined through visualising the 3D ground model, otherwise by way of developing additional 3D or 3D spatial outputs by implementation of computational geospatial probes. This can be realised considering that geological units contained in 3D models are configured as volumes embodied by their topmost and base boundaries. These volumes are utilised to compute and calculate the dispersion, thickness and structure of geological deposits. Accounting for the variability experienced in physical and chemical properties of respective geological units during the modelling process can be realised as a result of their classification, concentrated on the scope of geochemical, geotechnical and hydrogeological property values. The combination of geotechnical property data to facilitate the attribution (e.g. geotechnical, hydrogeological and confidence data) of 3D geological models has the capacity to be utilised as an analytical decision-support tool; thus identifying solutions to problems preceding physical development with respect to ground engineering. Geotechnical property attribution of 3D geological models as a decision-support tool to assess the variability in ground conditions as a means of determining sustainable use of underground space in urban and peri-urban environments, has been applied in the formerly heavily industrialised cities of NW England and Northern Ireland, see Price et al. (2010).

The construction of 3D geological models of the shallow subsurface that are attributed can thus make available the framework for the classification and sustainable utilisation of underground space. Nevertheless, it should be recognised that the shallow geological environment, within the zone of human interaction contains more than just geological (counting artificial deposits) constituents, but also additional man-made geo-structures comprising but not limited to underground facilities, foundations, utilities and basements (see Figure 4-11). It should be noted in the subterranean subsurface (80+ meters), petroleum and groundwater abstraction in addition to mining activities ought to be accounted for as being within the zone of human interaction, where anthropogenic pursuits have interacted with the geo-sphere. The UUS environment, its resources (space, geomaterials, groundwater and geothermal energy) and the processes that function within UUS (see Figure 4-11), necessitate being utilised in a sustainable and resilient way. The ability to combine 3D geological and geotechnical models with subsurface infrastructure, archaeological deposits and utilities makes available a powerful platform to manage UUS by way of land use planning.

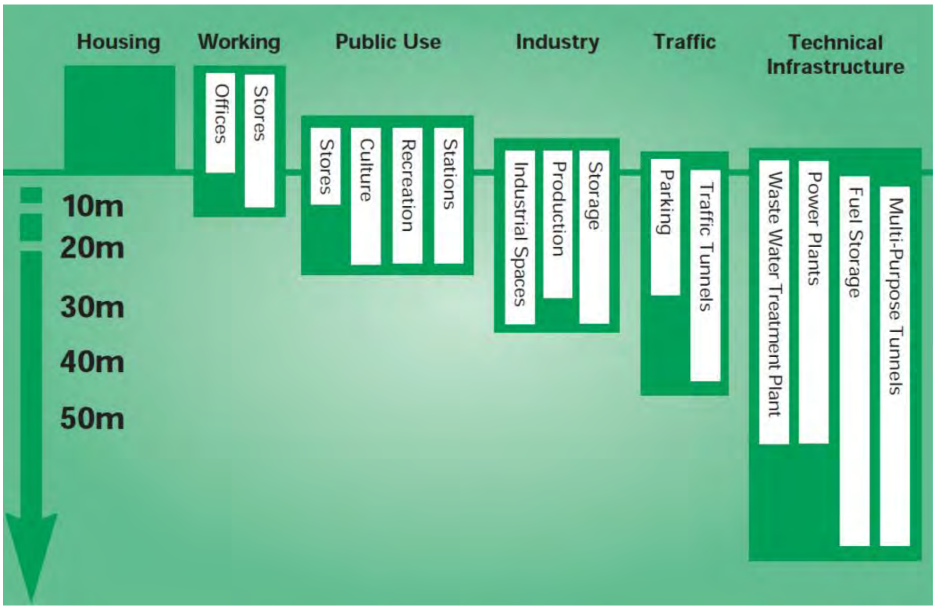


Figure 4-11: Feasible depths for underground space use (Evans et al., 2009)

4.5 THE GSI3D SOFTWARE AND METHODOLOGY SOLUTION: BIRMINGHAM EASTSIDE

Recent developments in computational techniques and the growing repository and digitisation of geological data by the British Geological Survey (BGS) now permit (geo-scientists, geotechnical engineers) to generate meaningful 3D geo-spatial models of the underground space (shallow sub-surface) in urban areas. Currently GSI3D can be used as a practicable mapping tool for categorising underground geology, in addition to properties associated with engineering , e.g. compressibility, shrink-swell characteristics and rock strength, and hydrogeology, e.g. permeability, porosity, thickness of the unsaturated zone or the likelihood of perched water tables (Royse et al., 2009).

GSI3D is reported to be one of the leading 3D geological modelling platforms in the world (Berg et al., 2011); this is primarily for the reason that in utilising GSI3D, the GIS analyst is able to access the BGS' extensive data set (UK mainland only) on the underground space; the quality of the model depends on the quality (density) of the data; due to the UK-centric nature of this present research work, the use of GSI3D to map the urban geology is the best platform available (see Appendix D). The benefit offered by employing GSI3D can be summed up as qualitative judgement based on fact (borehole/ legacy records); in essence the provision of physical data onto a platform that then can produce a qualitative judgement. This firmly puts the practitioner (geologist; engineer; engineering geologist) in the driving seat as the observation of geological phenomena can be embedded tacitly into the constructed 3d geological model.

The subsequent section explains the different baseline datasets employed in the modelling operational framework of the software – GSI3D at the BGS, relevant to the present research work.

Table 4-2: Scales of investigation using GSI3D (Kessler et al., 2009)

Type of survey or investigation	Overview	Systematic	Detailed Site Specific
Section spacing	Several kilometres	0.5-1.5 km	<500m
Section length	Tens of kilometres	5-10 km	<5km
Density of coded boreholes	Less than 1/km^2	Commonly 5-10/km^2	Often hundreds per square kilometre
Mapping level	Major groups and formations only	Formations and members, big lenses	Members and thin individual beds and lenses, artificial ground
Modelling speed excluding data preparation)	Up to hundreds of square kilometres a day	Up to 20 km^2 a day	<2km^2 a day
Scale	Compatible with 1:250 K of 1:50 K geological linework	Compatible with 1:50 K or 1:10 K geological linework	Compatible with detailed site plans at larger scales than 1:5 K
Modelling output	Often just sections and an open fence diagram	Computation of geological objects and surfaces for export to GIS	Computation of geological objects and surfaces for export to GIS
Users	Useful for education, visualisation and overviews (e.g. catchment characterisation), first-pass assessments	Builds a 3D model stack for interrogation in site selection, route planning, resource assessment, recharge and aquifer studies, etc.	Detailed 3D model for analysis of thickness, volumes, flow paths providing bed-by-bed stratigraphy for use in urban and quarry planning, and site investigations
Minimum unit thickness (m)	5	1	0.1

4.6 DATA FORMATS UTILISED IN GSI3D FOR BIRMINGHAM EASTSIDE

4.6.1 DIGITAL TERRAIN MODELS AND MAPS

GSI3D permits the geological modeller to import raster geo-registered images (JPEG's) in the form of air photos, satellite, and topographic base maps. Current elevation models, for instance digital terrain models (land surface), watertables, irregularities, rockhead, or bathymetry can be inserted using typical ASCII grid files.

4.6.2 BOREHOLES CATEGORISED LITHOLOGICALLY AND DECODED STRATIGRAPHICALLY

The corporate databases of the BGS, namely Borehole Geology (BoGe) and Single Onshore Borehole Index (SOBI) permit the extraction of digital borehole data (data is extracted as two clear-cut tab-divided ASCII files; although held in PDF format) (see Table 4-3).The borehole data extracted requires coding in preparation of computational geological modelling. Stratigraphic lexicons and various trade dictionaries are customary for coding boreholes. The BGS's report IR/05/123 titled "*A revised scheme for coding unlithified deposits*", see Cooper et al. (2006), presents the BGS coding system as a logging standard (based on BS5930: British-Standard (1999)) that enables the input of borehole logs and other engineering information. The coding scheme is limited to 6 characters by the Rock Classification Scheme (RCS) code due to database design, and as such designates each lithology (accounting for majority of 'granular' deposits) with one character, and utilises a combination of these characters to designate and classify more complex mixed lithologies. The abbreviations for the BGS coding system are:

CLAY:	C
SILT:	Z
SAND:	S
GRAVEL:	V*
COBBLES:	L
BOULDERS:	B
PEAT:	P

(V* utilised for gravel as 'G' is extensively employed, combined with other letters in RCS code e.g. Gabbro etc. This would inevitably cause a clash; V has no conflicts).

When the borehole index file is extracted from SOBI (see Table 4-3 for a sample of Birmingham Eastside borehole index), holding the distinctive borehole ID, position in x and y; and in the context of this research work with regard to the British National Grid plus, start height in reference to the UK Ordinance Datum. GSI3D by default presents bore records corresponding to individual start heights, whereas GSI3D modeller(s) have the choice, thus permitting all borehole records to be appended onto the digital terrain model if desired.

Table 4-3: Sample of boreholes of Birmingham Eastside

Unique Borehole ID	Easting (x)	Northing (y)	Start (collar) height (z)
SP08NE303.	407790	288130	106.2
SP08NE305.	407650	288180	106.8
SP08NE308.	407540	287920	113.8
SP08NE203.	407590	287930	113.2
SP08NE201.	407810	287980	108.2
SP08NE127.	407630	287830	114.3
SP08NE202.	407830	287900	109.6

The borehole log file (structured into tab-separated columns) presented in Table 4-4 holds data regarding the depth to base down the borehole of the individually classified geological units. Information can be extracted from (BoGE) or additional borehole databases to prepare a borehole log file. It is vital that the log be completed from the top to bottom and not alternating; breaks with an information deficit are coded as missing data not left empty.

Table 4-4: Sample borehole of Birmingham Eastside

Unique Borehole ID	Depth to the base of the unit (metres)	Lithostratigraphic unit code (BGS Lexicon)	Lithology (BGS rock classification)
SP08NE136.	1.71	MGR-UNDIFF	ARTDP
SP08NE136.	2.44	RTD1-XSV	SV
SP08NE136.	4.27	RTD1-XSV	S
SP08NE136.	4.96	BMS-SDST	SDST

4.6.3 GEOLOGICAL MAP INFORMATION

The British Geological Survey at this present time stores all its geological chart records in bespoke ESRI format. As a result of this, points, lines, and polygons are imported into GSI3D as ESRI shape files (Kessler et al., 2009). Considering that GSI3D at present can only handle shallow as well as unfaulted substratum settings, multifaceted physical dimensions are not currently incorporated, nevertheless, GSI3D is presently in the process of both augmentation and adaptation to permit the modelling of such complex environments besides inclusion of the required structural information.

4.6.4 SECTIONS

Geo-referenced sections situated in a plane – both horizontally and vertically (known as 'slices' within GSI3D) are combined, and are designed for conventional visualisation; on a functional basis this is achieved through the cross-section grid as well as the physical geological model contained by the window and/or with the lithological/ stratigraphical data matrix in the section window. Available data to this end is stored in the BGS repository, and comprises every digitally copied notes arising out of printed chart pages in addition to geophysical records, for example, ground penetrating radar readings, electric mapping etc.

4.6.5 COLOUR AND SYMBOL LEGEND

Colours and textures for coded lithologies/stratigraphy (borehole logs, correlated sections and map polygons) are assigned by a legend file (GLEG) in GSI3D (see Table 4-5). This tab-separated ASCII text file consists of an RGB (red, green and blue) colour model denomination designed for respective program utilised in the Generalised Vertical Sequence (GVS) see Table 4-6. The incidence with regard to the chroma arrangement contained in the legend file is not only helpful, but furthermore permits the modeller to easily and speedily visualise any inconsistencies in their correlation.

Table 4-5: The legend file of boreholes in Birmingham Eastside

Legend ID	Red	Green	Blue	Transparency	Texture Link
MGR-UNDIFF	128	128	128	255	TEXTURES/black.jpg
MGR-ROAD	90	128	128	255	TEXTURES/black.jpg
ALV-XCZ	253	253	50	255	TEXTURES/black.jpg
RTD1-XSV	255	135	255	255	TEXTURES/black.jpg
GLLD-C	255	130	21	255	TEXTURES/black.jpg
STLL-DMTN	64	255	255	255	TEXTURES/black.jpg
GFDU-XSV	255	249	158	255	TEXTURES/black.jpg
MMG-MDST	255	117	148	255	TEXTURES/black.jpg
BMS-SDST	255	201	84	255	TEXTURES/black.jpg
WRS-SDST	255	201	84	255	TEXTURES/black.jpg

4.6.6 NUMERICAL POINT MEASUREMENTS

Geo-registered geometric spot quantities, for instance, geotechnical investigations and biochemical analysis are also available for insertion into GSI3D by way of ASCII text files which remain generated by the modeller in wide-ranging commercial software's on or after data measurement(s) capture. This data is often imported as well as displayed concurrently through borehole charts in addition to cross-sections.

4.6.7 GEOLOGICAL GUIDELINES – MATHEMATICAL PROPERTIES

The Generalised Vertical Sequence file regulates the position where the geological unit can materialise in addition to dismissing any interactions sketched within sections that does not match up to the pre-set sequence (see Table 4-6). This tab-separated ASCII text GVS file is configured to be the mainstay of any GSI3D task. It generally is created via GSI3D analyst, and develops during the course of the project with the ease of instant revision subject to new data; ultimately it will house the all the geological divisions inside their proper and singular ranking group. The super-position of the geological units remains important as it outlines the 'stack' which will compute, and consequently generate the final 3D geological model. The fundamental components of the GVS files are as follows:

Table 4-6: Generalised vertical sequence (GVS) for the 3D geological model Birmingham Eastside

Name	ID	Stratigraphy	Lithology	Genesis	Free text
DTM	0	DTM	-	-	DTM for the site
MGR-UNDIFF	1	MGR-UNDIFF	ARTDP	Artificial Deposit	Fill
MGR-ROAD	2	MGR-ROAD	ARTDP	Artificial Deposit	Made ground
ALV	10	ALV-XCZ	XCZ	Quaternary	Alluvium
RTD1	11	RTD1-XSV	XSV	Quaternary	River terrace deposits
GLLD	15	GLLD-C	C	Quaternary	Glaciolacustrine deposits
STLL	20	STLL-DMTN	DMTN	Quaternary	Sandy till
GFDU	25	GFDU-XSV	XSV	Quaternary	Glaciofluvial deposits
MMG	100	MMG-MDST	SDST	Triassic	Mercia mudstone group
BMS	110	BMS-SDST	SDST	Triassic	Bromsgrove sandstone formation
WRS	120	WRS-SDST	SDST	Triassic	Wildmoor sandstone foundation

Name: Holds the model code which is responsible for the connection to the correlation lines as well as the geological units within the 'stack'; this has to be different for each layer. The final order first-last necessitates the stratigraphic sequential arrangement of the whole prototypical map domain.

ID: This field is utilised basically to outline the stratigraphic order of geological entities in addition to intersecting sections.

Stratigraphy: This column, in addition to successive columns in it, subsists to make available a connection to the legend file. The colour of the model (stratigraphy) can be decided through selection from any of these fields. The modeller can also include a discretionary additional column to the GVS for geological unit descriptions, notes or free text (as shown).

4.7 SOFTWARE METHODOLOGY

The programming language employed to encode GSI3D is Java 'script' and functions within a graphical user interface with four windows, to be precise borehole log window, map, cross-section ad 3D (see Figure 4-13). The graphical user interface in GSI3D is programmed dynamically, such that a change in one of the four windows (for example borehole log or section window) results in immediate revision and streamlining of all the additional windows.

The philosophical foundation that underpins the GSI3D tool and methodology, is firstly singular and furthermore straightforward – the building and development of geological subsurface models necessitates comprehension regarding the geological sequence as well as probable geomorphological progression of a site under examination (see Fookes (1997)).

The progressions which shape and fashion respective geological elements as well as resultant structures are unable to at present be reproduced precisely using computational means. Therefore, these geomorphological progressions are only capable of being annexed through the reasonable assembly of geological boundaries supported by competent and knowledgeable geologists; especially where data remains scarce otherwise of poor quality (Lemon & Jones, 2003; Wu et al., 2005; Kaufmann & Martin, 2008). The geologist sketches the limits in question founded upon an extensive occupational proficiency and observation (Kessler & Mathers, 2004, 2006). Tacit knowledge employed to this end has been documented and acknowledged as essential in lieu of model assembly by Varnes (1974); Fookes (1997); Turner (2003); Jones et al. (2004); Turner and Gable (2007).

The history of geology (Gohau, 1990) draws out the two established, yet elementary approaches, which have been employed to display geological relationships – cross-sections and maps, the pair each portraying a depiction concerning geological subsurface layout. The GSI3D approach replicates these conventional modes of working through affording the engineering geologist with initially an implement aimed at sketching and outlining cross-sections as well as one aimed at the distribution envelope with regard to all geological units contained by the GVS (see Figure 4-29). Completion of this allows the 3D geological model to be computed through triangulation. By tradition geologists give preference to fence drawings that allow illustration of multifarious subsurface compositions (Mathers & Zalasiewicz, 1985; Sobisch & Bombien, 2003).

Several quaternary and alluvial settings can only be correlated geometrically in regard to their discrete entities once the superficial charting, log records and terrain happen to be observed with respect to one another in the sphere of a 3D environment. This phenomenon happens for the reason that superficial deposits, for instance fluvial, coastal and glacial deposits, are seldom discernible owing to fossils otherwise distinctive lithological indicators. Environments such as these cannot for practical purposes be rendered in three dimensions deprived of a cross-section methodology.

GSI3D compels the modeller with exceptional success, toward examining the many crossing-points (intersections) in the middle of cross-sections to generate a correctly linked and inwardly consistent structure. Simultaneously, the model maintains complete consistency with the superficial and subcrop mapping of the modeller. Model calculation requires that the generalised vertical sequence (GVS) as well as the digital terrain model subsist. An additional benefit of this sequence of modelling in GSI3D is that if the generalised vertical sequence and the digital terrain model are present, the cross-sections show the progressive development of 3D geology straightaway.

Interpolation of middle points in the x-y-z nodules and the full length of sections as well as those along the boundaries of the envelopes of individual units generates an array of triangulated irregular networks (TINS), collectively matching substratum concerning relevant geological entities under consideration. The utilisation of TIN edifices that one may designate geological entities is described by Turner (2003). GSI3D utilises a custom-built Delaunay-triangulation dependent upon a Quad-edge algorithm (Green & Sibson, 1978). The formulation with regard to three dimensional constructs, tops (volume) as well as base (shells) combined, is at that moment basically realised computationally through annexing the base(s) of the nearby superimposing units, otherwise the digital terrain model that contains the outcrop of the unit under consideration. In the event that units spread out past the project boundary perpendicular partitions are put in place to complete the 3D entity. The subsequent entity is tantamount to a polygon depicting geological entities appearing in two-dimensions.

GSI3D uses its own custom-built TIN-sculpting set of rules to effect immediate computations of each crop and subcrop, thus permitting the developing model to be computed incrementally and assessed during the course of model development. By the same token, a swift TIN-TIN junction algorithm permits the computation of projected outcrop arrangements utilising finely detailed digital terrain models.

Similarly, the completed model can be swiftly adjusted in consideration of up-to-date data or insight. As a result, the importance of retaining the completed model is lowered; on the other hand merely the saving of the four constituents from which it is computed: i.e. generalised vertical sequence, digital terrain model, cross-sections and envelopes in xml format is required. Computerised simplification to generate lower resolution models remains feasible through utilisation of Boolean operative functions on envelopes and correlation lines, once specification in GVS file of collective unit sets is complete.

In a nutshell, the advantages of GSI3D are that it straightforwardly supersedes current analogue operational methods employed by geologists with buttons in a computer program, thus making it more straightforward to teach and prepare individuals to utilise the computer program, a precedent to extensive recognition, acceptance, and utilisation as exhibited by operators at the British Geological Survey to facilitate a powerful tool and methodology to aid planning and decision-making (Mathers & Kessler, 2010; Royse et al., 2010). Moreover, GSI3D is encoded to swift and dynamic functionality, permitting its inclusion as an elemental constituent of a systematic, iterative and explanatory review process.

4.8 GEOLOGICAL HISTORY OF BIRMINGHAM

A general and brief geological history of Birmingham (relevant to Birmingham Eastside) is concisely summarised and given in this short introductory account based on the latest survey of the area (see Powell et al. (2000)), supplemented by a thorough examination of obtainable borehole and geophysical data (see Table 4-7). Birmingham experienced an industrial revolution in the 18th and 19th centuries, which had a significant impact on its landscape; large-scale made ground deposits as well as quarry pits are indicative to the significance of minerals (e.g. limestone, foundry sand, brick clay, ironstone, fireclay, coal and aggregate) in the geological genesis to date of the area (see Figure 4-12). These wide-ranging deposits resulted in a legacy of contamination and undermining that ought to be considered in contemporary planning and development.

The Sherwood Sandstone Group (a concentrated succession of Triassic Rocks) was deposited in fluvial settings, filling the space left by the very quickly abating basin. Over time, slenderer and smaller successions were deposited atop the contiguous formations. The Mercia Mudstone Group (superimposed) was deposited in fluvial and lacustrine environments; this evidence of a semi-arid climate is indicated through gypsum and desiccation attributes. In the latter part of the Triassic epoch a vast transgression took place; this is indicated by fossiliferous mudstones and limestones proceeding from the Penarth Group, which en masse including the overlying coastal Jurassic rocks truncate (crop) out in a bantam faulty-bounded outlier. The following epoch, namely, the Quaternary resulted in deposits chiefly offshoots of the Anglian glaciation (sand, till, clay and gravel), in addition to periglacial deposits that overlie a big portion of the region; plasmic-rich Hoxnian interglacial deposits have been evidenced in boreholes, see Powell et al. (2000). The resulting bedrock contains Palaeovalleys (interred canals), permeated with assorted glacigenic and interglacial deposits. Puerile drift deposits, comprising bulk headway deposits, are pervasive in the district.

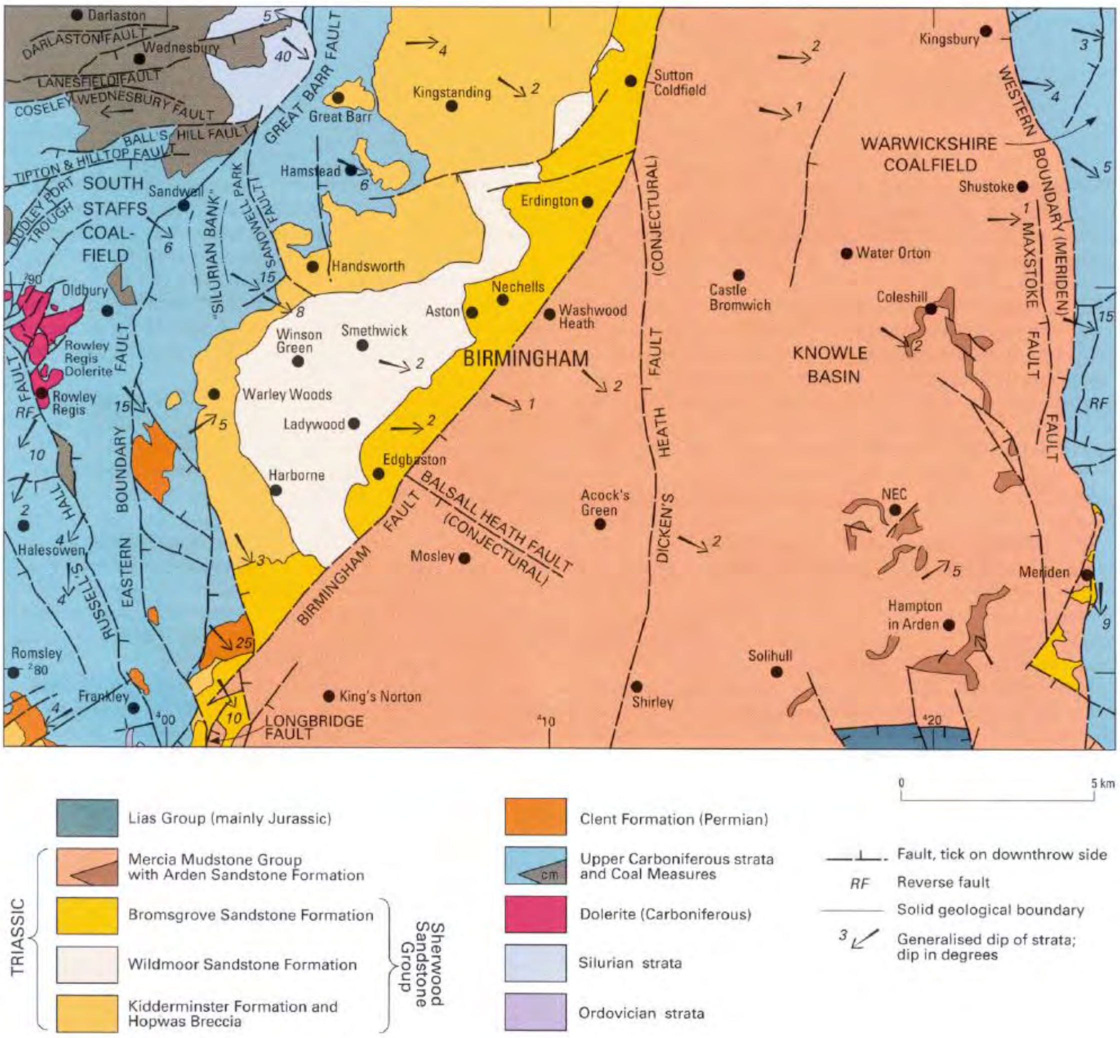


Figure 4-12: Sketch map of the solid geology of the Birmingham Area (Powell et al., 2000)

Table 4-7: Summary of geological succession of the Birmingham Area (relevant to Birmingham Eastside) – Adapted from (Powell et al., 2000)

<table>
<tr><td>Quaternary (Holocene and Pleistocene)</td><td>Anglian to Flandrian</td><td colspan="2">Postglacial
Artificial (man-made) ground, head, landslip, peat, lacustrine deposits, alluvium, river terrace deposits</td><td>Glacial and Interglacial
Glaciofluvial deposits, glaciolacustrine deposits, interglacial deposits[1], till and sandy till</td><td>Approx. thickness (m)</td></tr>
<tr><td rowspan="2">Jurassic</td><td rowspan="2">Hettangian</td><td rowspan="2">Lias Group</td><td rowspan="2">Blue Lias Fm</td><td>Saltford Shale Member: dark grey, calcareous, fissile mudstone with sparse thin limestone beds</td><td>20</td></tr>
<tr><td>Wilmcote Limestone Member: mudstone, siltstone and thin limestone beds</td><td>8-10</td></tr>
<tr><td rowspan="8">Triassic</td><td rowspan="3">Rhaetian</td><td rowspan="2">Penarth Group</td><td>Lilstock Fm</td><td>Cotham Member; grey-green, calcareous mudstone with sparse limestone beds</td><td>6</td></tr>
<tr><td>Westbury Fm</td><td>Dark grey, fissile mudstone and minor siltstone beds</td><td>7</td></tr>
<tr><td rowspan="2">Mercia Mudstone Group</td><td>Blue Anchor Fm</td><td>Pale green mudstone and siltstone</td><td></td></tr>
<tr><td>Ladinian-Norian</td><td>Undivided, except for Arden Sandstone Fm</td><td>Red-brown, locally gypsiferous mudstone with thin, green-grey siltstones (‘skerries’): Arden Sandstone Formation, 0-10m thick, locally present: green-grey mudstone, siltstone and cross-bedded sandstone</td><td>365</td></tr>
<tr><td>Anisian</td><td rowspan="4">Sherwood Sandstone Group</td><td>Bromsgrove Sandstone Fm</td><td>Red-brown, miscaceous, calcareous sandstone with pebble conglomerate lenses, and subordinate mudstone</td><td>84-180</td></tr>
<tr><td rowspan="3">Induan-Olenekian</td><td>Wildmoor Sandstone Fm</td><td>Orange-red, fine-to medium-grained, miscaceous, feldspathic (mottled) sandstone with red-brown mudstone</td><td>0-120</td></tr>
<tr><td>Kidderminster Fm</td><td>Red-brown and yellow-brown, feldspathic, pebbly sandstone with beds and lenses of pebble/ cobble conglomerate, particularly in the lower part</td><td>45-120</td></tr>
<tr><td>Hopwas Breccia</td><td>Red-brown sandstone, pebbly in part, with minor mudstone</td><td>0-10</td></tr>
<tr><td>Lower Permian?</td><td></td><td></td><td>Clent Formation</td><td>Breccia with red-brown and purple mudstone matrix, in south; pebbly with sandstone and mudstone in north</td><td>c, 100</td></tr>
</table>

--------- unconformity; **Fm** formation; **U** Upper; **M** Middle; **L** Lower; [1]does not crop out, proved in boreholes; **nfp** not fully proved

4.9 GEOLOGY OF BIRMINGHAM EASTSIDE

This section provides a summary of the coded boreholes (see Appendix C).

4.9.1 AVAILABLE INFORMATION

The major repository of obtainable printed information on the geology of Birmingham Eastside is from geological maps dating as far back as the early 1900s to the late 1980s, held by the British Geological Survey. Descriptions of the geological succession and survey of the area have been covered by a range of memoirs (Barrow et al., 1919; Eastwood et al., 1925; Whitehead & Eastwood, 1927) and in the works of (Wills, 1970, 1976), the most recent being the work of (Powell et al., 2000). Geological descriptions with respect to a sizeable portion of boreholes and wells in the district of Birmingham are provided by Butler and Lee (1946).

To enhance and improve on the published data, and to make available a comprehensive account of the present geology, especially in fault-finding areas, and for a sounder understanding of the superficial deposits for 3D geological modelling using GSI3D, borehole investigation records were collated and abstracted from 178 non-confidential boreholes within Birmingham Eastside: Boreholes SP08NE (26, 30, 32, 33, 35, 38-47, 79, 80, 97-100, 124-137, 140, 147-153, 163, 165, 171-177, 187, 198-208, 214 (A-F) – 217, 229, 230 (A-B), 231, 232, 269, 297, 298 (A-B) – 310, 316 – 319, 332, 334, 343, 345, 348 – 352, 356 – 375, 382 – 386, 389, 391, 432, 434, 435, 451, 452, 456, 457, 491 – 498, 527 – 532, 606 – 608, 613 – 623, 644, 645, 667, 668, 682 – 684).

4.9.2 GENERAL GEOLOGY

Birmingham Eastside is mainly underlain by solid strata of Triassic age (Sherwood Sandstone Group and Mercia Mudstone Group, see Jackson and Lloyd (1983)) as well as an uneven covering of glacial and fluvioglacial deposits and large extents of made ground.

Table 4-8: Geological succession (genesis) of Birmingham Eastside – Adapted from (Knipe et al., 1993)

			Thickness (m)
Quaternary (Holocene and Pleistocene)	Made ground		up to 20
	River alluvium		up to 6
	Terrace and fluvioglacial sands and gravels Glacial till, sands and gravels, lake clays	))	up to 40
Triassic	Mercia Mudstone Group (Keuper Marl) including Arden Sandstone		up to 300
	Sherwood Sandstone Group		
	Bromsgrove Sandstone (Keuper Sandstone)		25 – 120
	Wildmoor Sandstone (Upper Mottled Sandstone)		0 – 90

4.9.3 MADE GROUND: BIRMINGHAM EASTSIDE

Widespread portions of Birmingham Eastside are overlain in fill deposits. The made ground differs from 1-5m or more, rarely up to 20m in aged marl quarries, with a global average wherever fill is present of circa 2m (Knipe et al., 1993; Powell, 1993). Noticeably denser areas of fill constituents exist:

- On the Eastside boundary of the Birmingham Fault where several infilled brick clay pits within Mercia Mudstones subsist. It is commonplace to find fill of greater than 10m there;
- As assorted surface dumps of spoil, railway embankments, and infilled canal arms and mill ponds.

4.9.4 QUATERNARY AND RECENT DEPOSITS: BIRMINGHAM EASTSIDE

The geological genesis with respect to quaternary deposits (glacial and post-glacial) is complicated and the sequence of deposits differs swiftly both vertically and horizontally. A number of geologists/ engineering geologists have investigated detailed areas within the Birmingham, particularly Duigan and Godwin (1956); Pickering (1957); Kelly (1964); Horton (1974, 1975); Old (1991); Powell (1993), nevertheless no complete depiction of the genesis occurs in the published literature. The glacial fill was deposited on an asymmetrical anterior superficial surface; however, there exists a weak connection concerning the form of the sub-drift surface the current topography. The deposits illustrate merely the abrade leftovers of previous, more widespread sequences. Land (1966) put forward that approximately one quarter of the sandstone outcrop is concealed by drift, but the analysis carried in this present study on the great quantity of site investigation borehole legacy records implies that the drift cover is considerably more extensive than hitherto documented.

Broadly speaking there are evidently quite a few periods of deposition (see Table 4-9 which outlines their four broad lithological types). Both Mitchell (1973) and Powell et al. (2000) put forward a general sequence for the local glacial deposits to be:

1. Upper group of overlying tills - three stages of glacial deposits with a period of ice-dammed deposition between each.
2. Glacial lake deposits;
3. Lower glacial deposits - sands, gravel and till.

Table 4-9: Outline of the classification of glacial and associated interglacial deposits of the district (Powell et al., 2000)

Lithology	Deposit	Landform	Environment of deposition
Till and sandy till (clay diamicton, and sandy diamicton)	Till and sandy till (boulder clay)	Degraded undulating terrain; also present in palaeovalleys	Subglacial (lodgement till) and superglacial (melt-out and flow tills)
Sand and gravel (clayey, in part)	Glaciofluvial deposits (undifferentiated)	Broad, degraded undulating spreads, elongate ridges (eskers); also present in palaeovalleys	Superglacial, englacial and Subglacial streams; outwash plains; proglacial braided rivers, and ice-marginal streams

Lithology	Deposit	Landform	Environment of deposition
	Glaciofluvial terrace deposits	Flat-topped spreads	Proglacial rivers or ice-marginal streams
Clay, silt and sand (mostly laminated)	Glaciolacustrine deposits	Broad, flat spreads; also present in palaeovalleys	Shallow, impounded lakes fed by proglacial streams
Organic-rich silt and clay, and peat	Interglacial deposits	Present in palaeovalleys (proved in boreholes)	Colonisation of shallow lakes and depressions by plants during temperate stages; deposition of organic matter in shallow lakes

4.9.5 BEDROCK STRATA: BIRMINGHAM EASTSIDE

The Mercia Mudstone Group (previously designated as the Keuper Marl) is mainly made up of equivalent to 300m (Birmingham wide) of largely red marls as well as a number of green and grey bands and intermittent strips of greenish or grey sandstone (skerries). Roughly 30-50m beneath the peak of the formation prevails the Arden (previously designated Upper Keuper) Sandstone and near the bottom of the formation is a soaring quantity of inter-bedded sandstones. On the whole, the Mercia Mudstones can be considered for the most part impermeable.

The Bromsgrove Sandstone (previously designated as the Lower Keuper Sandstone) is the more elevated group of the Sherwood Sandstone Group. It outlines a thin outcrop next to the western boundary of the Birmingham fault, however rests broadly beneath the Mercia Mudstones to the eastern boundary of the fault with an upper limit thickness of 120m, otherwise more. The formation comprises mainly of fully buttressed red and brown sandstones besides red and blue marl, a number of which are quite considerable in thickness. The Wildmoor Sandstone (previously designated Upper Mottled Sandstone) outcrops beneath a considerable portion of western Birmingham. The formation comprises mainly of thickly bedded bright red sandstones (uniform and soft), besides breakups and slender strips of marl, and its upper limit being 90m.

The Kidderminster Sandstone (previously designated as Bunter pebble Beds) includes up to 110-125m of mainly brown-reddish, medium to coarse-grained pebbly sandstones in addition to conglomerates near the bottom. They differ from crumbly and weakly cemented to very cemented and sturdy.

The Hopwas Breccia covers basically small outcrops at the westward trim of the study area that encompass not more than 10m thickness of coarse quartzite breccias (oblique stones).

4.10 APPLICATIONS: BUILDING THE GEOLOGICAL MODEL OF BIRMINGHAM EASTSIDE USING GSI3D

The geological modelling of the geological succession in the study area, Birmingham Eastside was carried out utilising GSI3D modelling software (Kessler et al., 2008). The software tool and its operational method as previously mentioned, permit the modeller to develop 3D geological models through integrating interpreted digital borehole data, digital geological maps and digital terrain models (DTMs) to build an interconnecting grid of cross-sections. From the resultant chain of interconnecting grid cross-sections, the top and bottom of individual geological units is subsequently characterised and the ensuing geological model is calculated to obtain the 3D distribution, geometry and elevation of each geological deposit. This section will provide an outline of the process undertaken in the formulation of the 3D geological model of Eastside, and the interested reader is directed to the GSI3D user manual (Mathers et al., 2011) for more detail with respect to the steps undertaken in the construction of the 3D geological model.

4.10.1 GRAPHICAL USER INTERFACE OF GSI3D

On starting up GSI3D, the following is the graphical user interface that one would encounter:

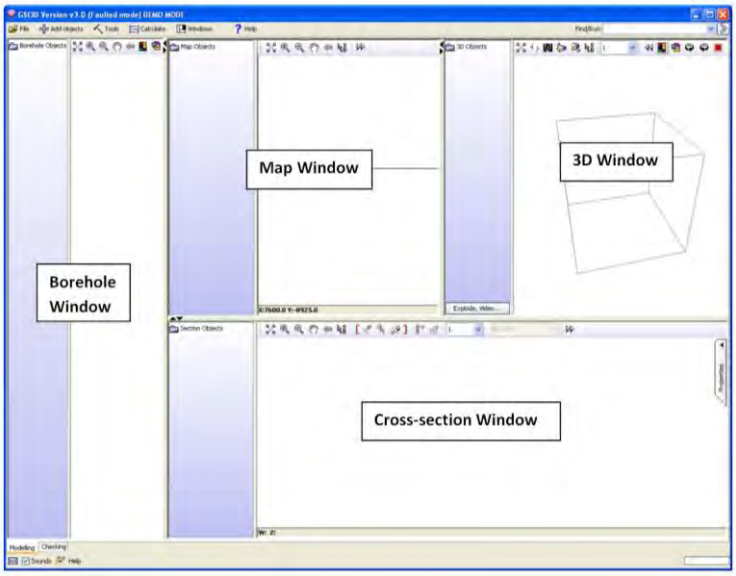


Figure 4-13: The graphical user interface of GSI3D

As can be seen from the figure above, GSI3D has four principal windows:

1. Borehole window: this is utilised to view boreholes with depths and attribute information;
2. Map window: this is utilised to view the topological maps, air photos, geophysical maps and surface geology. Furthermore, it also acts to delineate location of lines of section;
3. Cross-section window: borehole and geophysical sections (if any) are here utilised to correlate the geological structure. It should be noted that a digital map or 2D geological object distribution can be utilised to constrain the area of geological units;
4. 3D window: this is utilised for viewing the digital terrain models (DTMs), map drapes and model in 3D.

4.10.2 STEP 1: IMPORT THE GVS, GLEG AND TERRAIN MODEL

Step 1 is to insert into the GSI3D workspace (map window) the GVS file (see Table 4-6), the GLEG file (see Table 4-5) and the digital terrain/elevation model (see Figure 4-14). For the present application, the Digital Terrain Model (10m cell size) was downloaded from BGS corporate DTM "Bald Earth Model". This DTM is derived from 5m NEXTMAP DTM (Intermap) which was then combined with Ordnance Survey Landform Profile to remove trees, woodlands and human artefacts such as buildings. Figure 4-15 below shows the pull-down menu for loading data from prepared files and/or alternative projects into the GSI3D project.

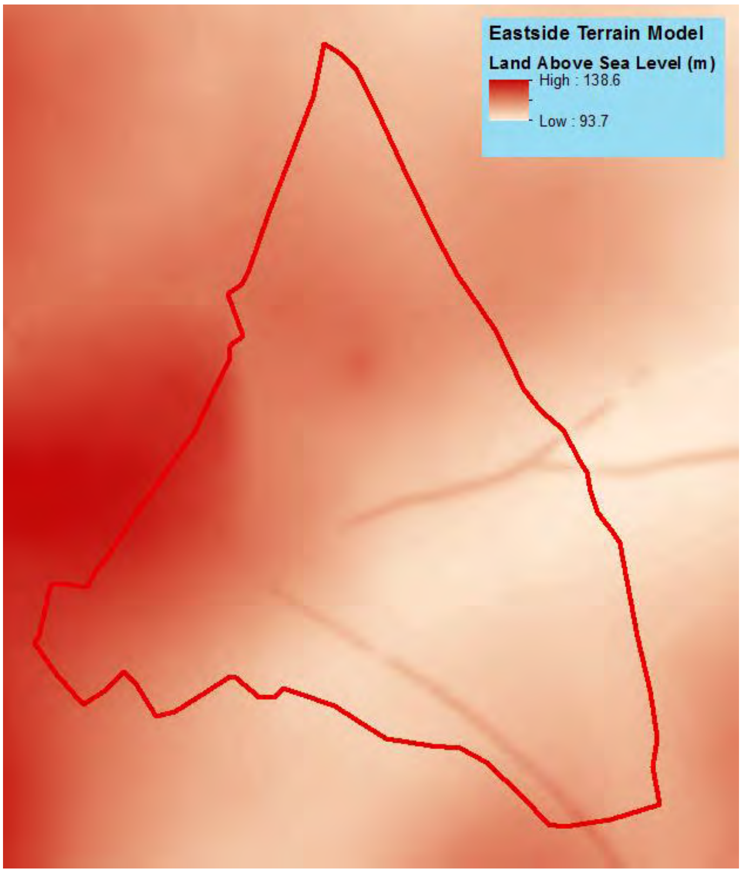


Figure 4-14: Digital terrain model of Birmingham Eastside

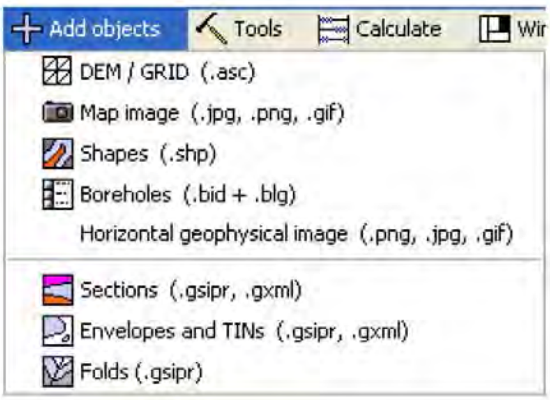


Figure 4-15: GSI3D add objects menu

4.10.3 STEP 2: IMPORT BOREHOLE DATA

Step 2 is to insert the borehole index (*.bid) and borehole downhole interpretation (*blg) file (see Figure 4-16). The boreholes were coded using the BGS lithology lexicon, see Cooper et al. (2006). The bulk of the labour required with boreholes is carried out outside the GSI3D software and comprises the compiling of the ‘bid’ and ‘blg’ files employing a text editor. Uniformity of borehole coding and the formation of relevant codes for lithology, stratigraphy etc. is all a vital component of constructing a GSI3D model. Mathers et al. (2011) point out that despite the fact that borehole information is considered necessary in modelling it is not a prerequisite and several acceptable and suitable models have been built with no boreholes (requires an experienced geologist/ geological modeller to carry out). Below is an excerpt from both the borehole index and the borehole interpretation file; reference is made to Appendix B for the complete BID file and Appendix C for the complete BLG file of Birmingham Eastside:

Table 4-10: Excerpt of the borehole index file for Birmingham Eastside

Unique Borehole ID	Easting	Northing	Start Height
SP08NE100.	406880	286330	125.4
SP08NE124.	408150	287800	112.9
SP08NE125.	407600	287750	116.3
SP08NE126.	407570	287630	118.9
SP08NE127.	407630	287830	114.3
SP08NE128.	407950	287180	106.8
SP08NE129.	407950	287250	109.5
SP08NE130.	407370	286850	122.7
SP08NE131.	407440	286930	120
SP08NE132.	407300	287090	130.7
SP08NE133.	407340	287160	129.8
SP08NE134.	407470	287120	117.8
SP08NE135.	407110	286470	118.5
SP08NE136.	407060	286440	119.4
SP08NE137.	407620	286350	101.8
SP08NE139.	406820	286260	129
SP08NE140.	406790	286340	129.9
SP08NE147.	406850	286810	132.8
SP08NE148.	406870	286770	131.9
SP08NE149.	406920	286400	123.9
SP08NE150.	406930	286330	123.2
SP08NE151.	406970	286360	121.4
SP08NE1517.	408408	286398	105.5
SP08NE1518.	408402	286309	108.34
SP08NE152.	406980	286430	122
SP08NE153.	407000	286470	122

Table 4-11: Excerpt of the borehole interpretation file for Birmingham Eastside

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE38.	3.96	MMG-MDST	SDST	Hard sandstone
SP08NE38.	6.58	MMG-MDST	CZ	Hard marl
SP08NE38.	80.16	WRS-SDST	SDST	Hard sandstone
SP08NE38.	86.14	WRS-SDST	SDST	Sandstone
SP08NE39.	5.49	MGR-ROAD	ARTDP	Made ground
SP08NE39.	8.23	RTD1-XSV	V	Gravel
SP08NE39.	10.36	STLL-DMTN	DMTN	Running sand
SP08NE39.	12.19	MMG-MDST	SDST	Sandstone
SP08NE39.	17.07	BMS-SDST	SDST	Red sandstone
SP08NE39.	62.79	BMS-SDST	SDST	Sandstone
SP08NE39.	64.62	BMS-SDST	SAMDST	Sandstone and marl
SP08NE39.	70.1	BMS-SDST	SDST	Sandstone
SP08NE39.	76.2	WRS-SDST	SAMDST	Sandstone and marl
SP08NE41.	1.52	MGR-ROAD	ARTDP	Made ground
SP08NE41.	2.44	RTD1-XSV	S	Sand
SP08NE41.	5.18	STLL-DMTN	LB	Large ballast
SP08NE41.	7.32	MMG-MDST	SCZ	Sandy marl
SP08NE41.	8.84	MMG-MDST	CZ	Red marl
SP08NE41.	9.75	MMG-MDST	C	Light blue clay
SP08NE41.	11.58	WRS-SDST	SDST	Sand and stones
SP08NE41.	14.63	WRS-SDST	SDST	Hard sand stone
SP08NE41.	15.54	WRS-SDST	SDST	Light sand stone
SP08NE41.	17.68	MMG-MDST	CZ	Red marl
SP08NE41.	21.03	MMG-MDST	SDST	Red sandstone
SP08NE41.	21.34	MMG-MDST	B	Grey stone
SP08NE41.	33.83	WRS-SDST	SDST	Hard sandstone
SP08NE41.	36.27	MMG-MDST	CZ	Red marl
SP08NE41.	46.33	BMS-SDST	SDST	Fine sandstone
SP08NE41.	53.95	BMS-SDST	SDST	Coarse sandstone
SP08NE41.	57.91	MMG-MDST	CZ	Red marl
SP08NE41.	74.68	BMS-SDST	SDST	Sandstone
SP08NE41.	76.2	WRS-SDST	SDST	Hard sandstone
SP08NE43.	1.83	MGR-ROAD	ARTDP	Made ground
SP08NE43.	4.15	MMG-MDST	CL	Red and blue clay and pebbles
SP08NE43.	15.73	MMG-MDST	CZ	Red and blue marl
SP08NE43.	20.73	MMG-MDST	CZ	Red and blue marl and pebbles
SP08NE43.	30.48	MMG-MDST	CZ	Hard blue and red marl
SP08NE44.	37.79	MMG-MDST	CZ	Red and blue marl
SP08NE44.	39.32	MMG-MDST	SDST	Red sandstone
SP08NE44.	41.45	MMG-MDST	SCZ	Red sandy marl
SP08NE44.	60.05	BMS-SDST	CZ	Red marl
SP08NE44.	62.18	BMS-SDST	SDST	Red sandstone
SP08NE45.	27.13	STLL-DMTN	DMTN	Sand
SP08NE45.	28.04	STLL-DMTN	LB	Ballast
SP08NE45.	43.46	MMG-MDST	CZ	Marl

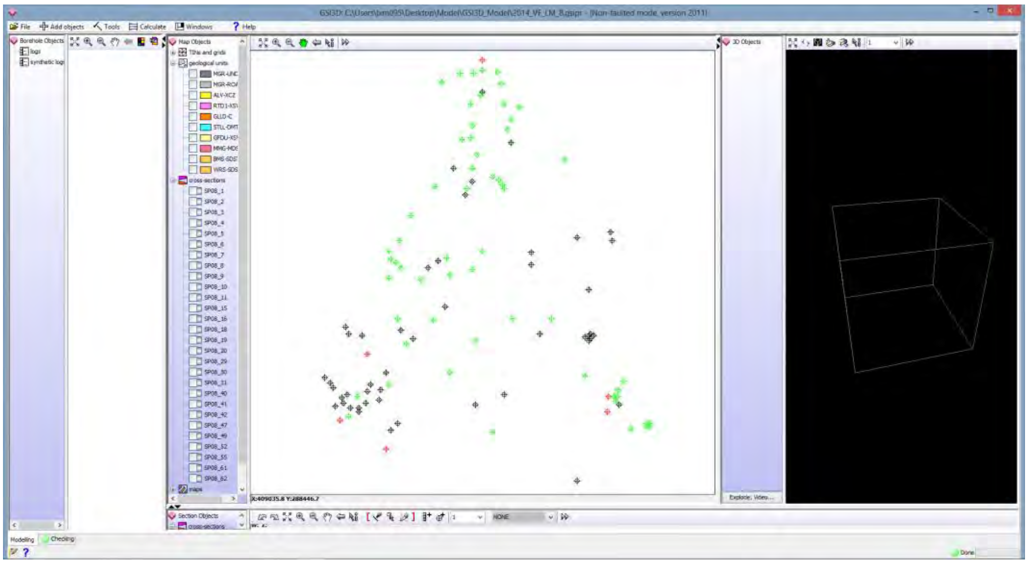


Figure 4-16: Borehole points loaded in the map window

Note: Boreholes with the colour red are not suitable for modelling and simply hold location details. Boreholes with the colour black or green (depending on their total depth, black deep and green shallow) are suitable for modelling.

4.10.4 STEP 3: LOAD GEOLOGICAL MAP

Step 3 is to insert DigMap Geology (UK general geology, downloaded from BGS repository). This is a 10k (see Table 4-2) artificial deposits, superficial deposits and bedrock map (see Figure 4-17 and Table 4-6).

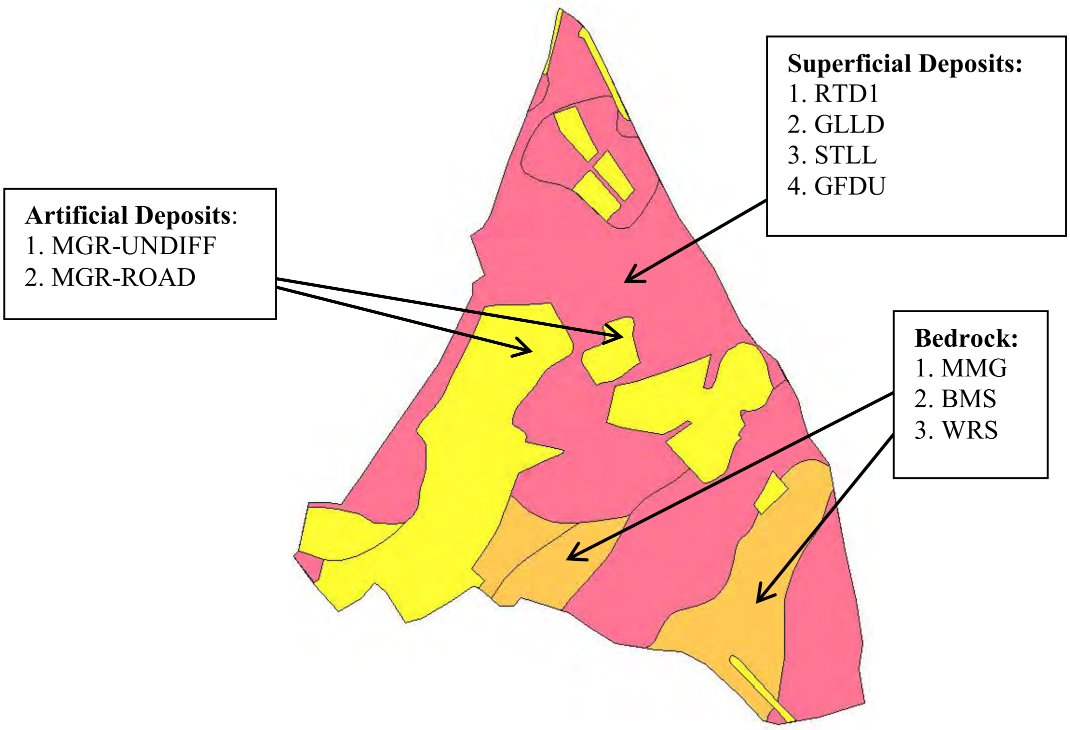


Figure 4-17: DigMap geology of Birmingham Eastside

Once the digital (DigMap) geology is loaded, the use of the 'info' tool needs to be employed, by selecting the polygon (either artificial, superficial or bedrock) in order to ascertain the relevant information (attribute table) of the geology in the bottom of the map window. These maps are principally employed as a means of initiating and guiding section and cross-section construction, and subsequently the construction of geological units (see Step 6).

4.10.5 STEP 4: BUILD AND CORRELATE SECTIONS

In Step 4 the construction of the cross-sections takes place. GSI3D principally requires the use of a fence diagram (see Figure 4-18) and in addition has three types of sections that can be employed in model construction: (i) Helper sections: short sections utilised to model linear deposits (e.g. alluvial tracts) and isolated outcrops (e.g. outliers in a dissected landscape); (ii) Docker sections: utilised to digitise lines to track more asymmetrical boundaries for instance watersheds or city limits, and necessitates the use of a larger digital terrain model; (iii) Digitised sections from rasters: these are employed by digitising over geo-registered vertical sections that are put on view in the section window as rasters. At which time the fence diagram is completed as illustrated in Figure 4-18 (cross-sections showing network linking boreholes), individual sections can now be drawn in conjunction with borehole logs (clicking on the borehole in the map window so it appears in the borehole window as shown in Figure 4-18). The draping of the geological maps (DigMap polygons) onto the cross-sections are utilised to constrain the outcrop extents of the geology, and the modeller ought to utilise perspectives in the window command tools to change screen to Map and Section. This process of section construction is an iterative process of snapping correlation lines to other sections, of checking and rechecking to ensure the ideal situation of having all correlation lines between boreholes and knick points, snapped to their outcrop and/or subcrop positions within the section (see Figure 4-19) using the draw line button and GVS selector drop down menu. This process proceeds until the section is completed through consistency with snapping of map linework to other sections (see Figure 4-20 and Figure 4-21 for example sections), and it should be noted that if necessary the GVS should be displayed to explain the super-positional order of units. Throughout this process it is possible to send cross-sections to 3D (ensuring that the log thickness is reduced to 10-15m) for checking of consistency in correlations until finally deemed suitable (see Figure 4-22).

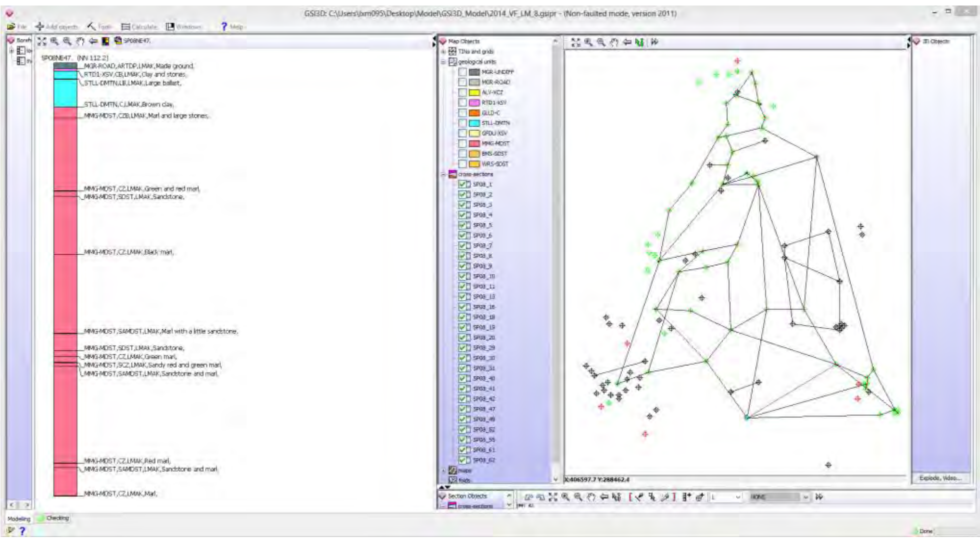


Figure 4-18: The fence (sections) diagram of Birmingham Eastside

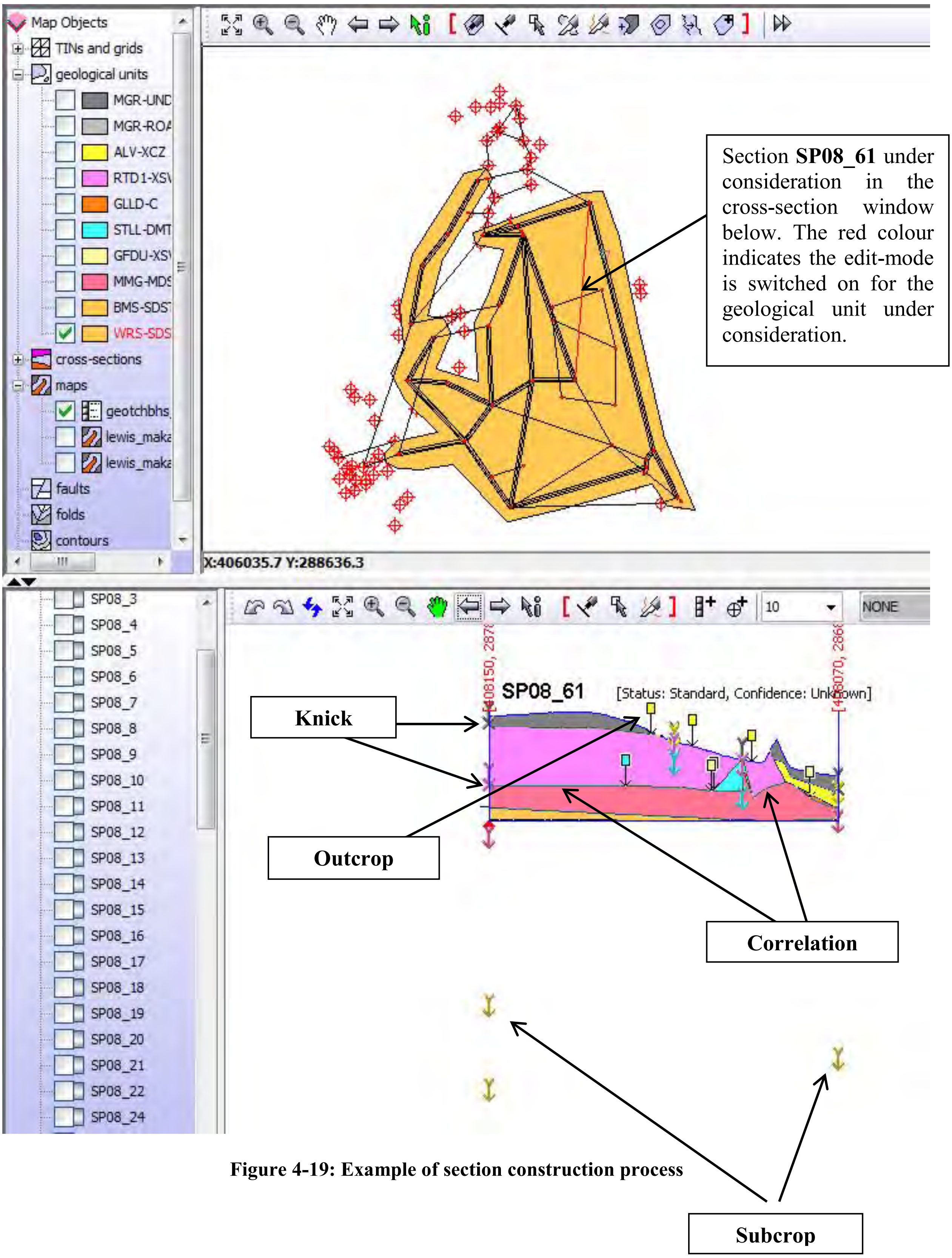


Figure 4-19: Example of section construction process

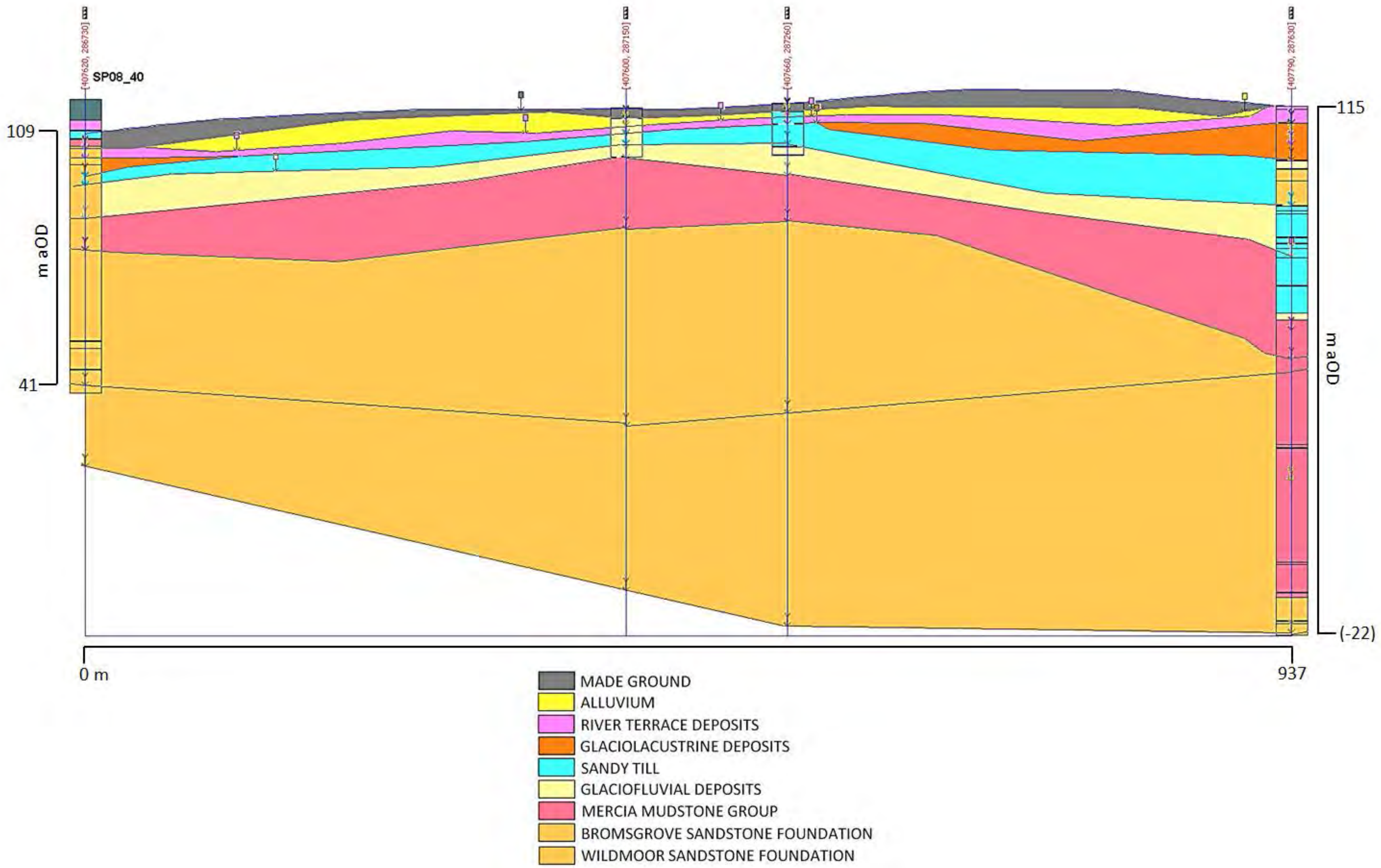


Figure 4-20: Example of a hand-correlated cross-section used to construct the 3D geological model, the column of each borehole identifies the lithostratigraphy

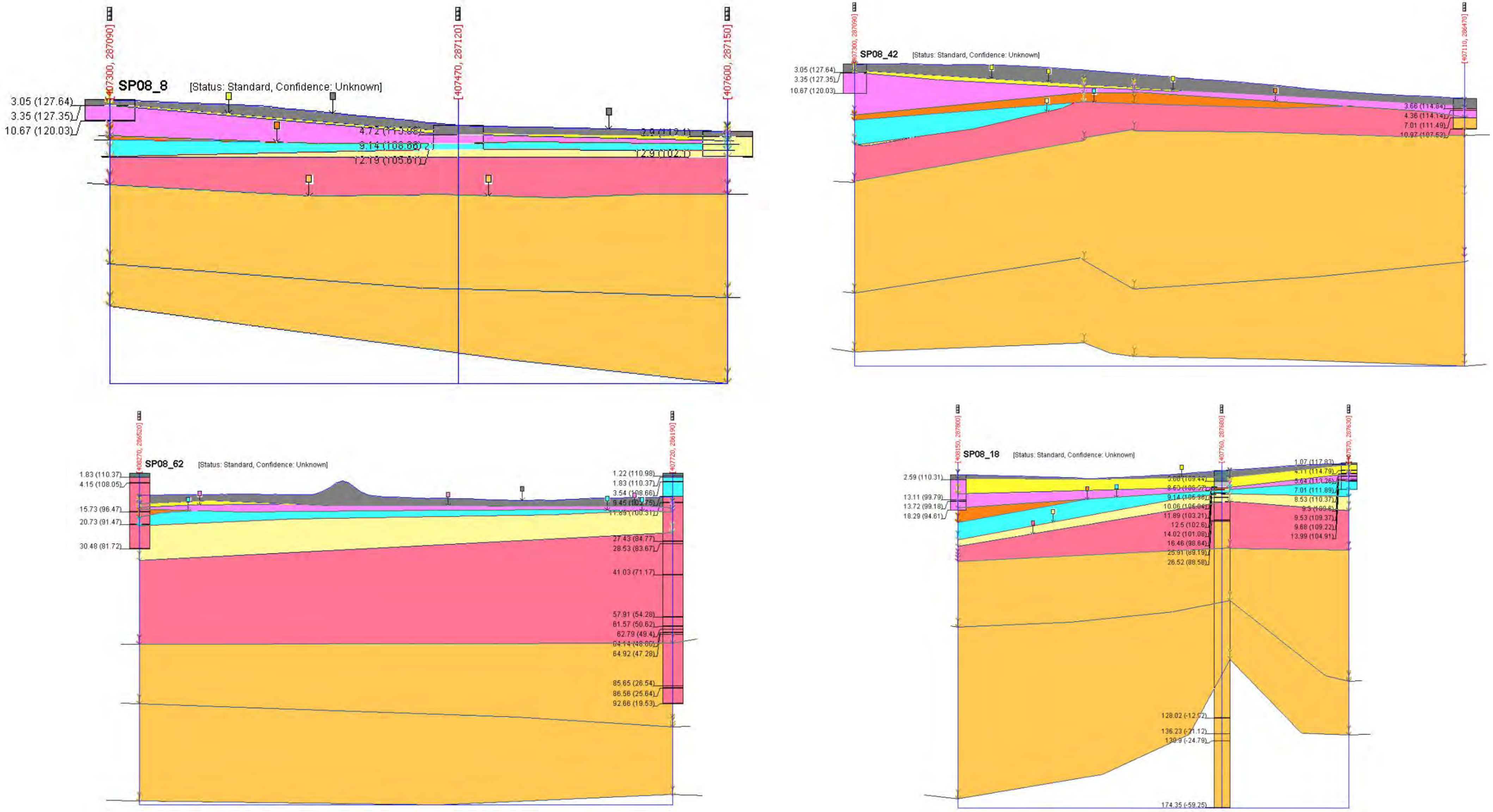


Figure 4-21: Further examples of hand correlated sections of the 3D geological model for Birmingham Eastside

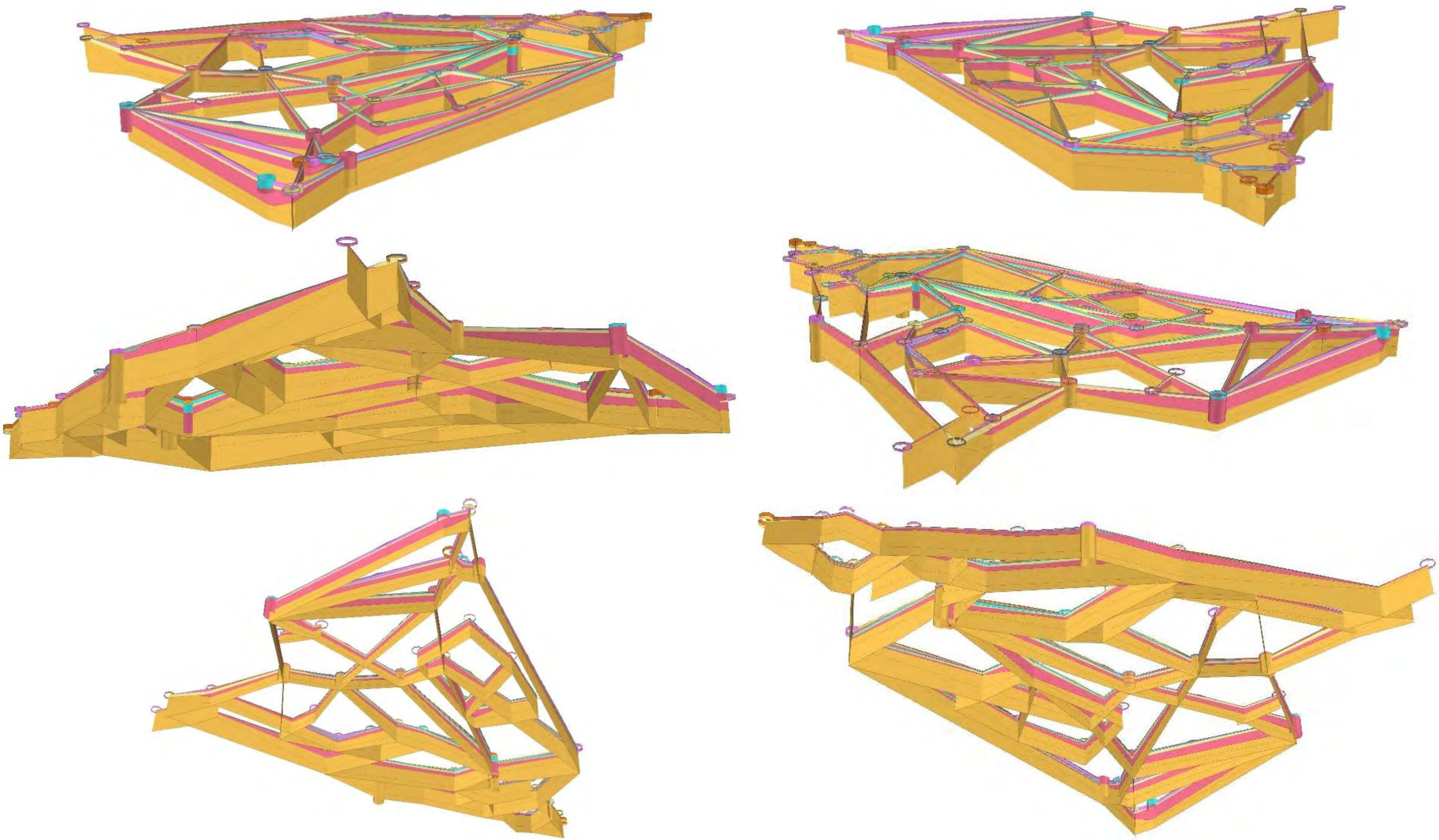


Figure 4-22: Different views of the complete cross-sections fence diagram sent to 3D in GSI3D of Birmingham Eastside

4.10.6 STEP 5: CONSTRUCT GEOLOGICAL UNIT ENVELOPES

In Step 5 the geological envelopes (9 in this case – see Figure 4-20) are drawn. For the made ground and the superficial deposits, construction of their envelopes can be essentially drawn from the surface geological linework. For the bedrock data, a combination of surface outcrop information and data from sections and boreholes facilitates the construction of the simple bedrock geology encountered in Birmingham Eastside. Once the model is calculated, the triangulated top/base as well as volumes is confined inside the singular geological envelope unit entry in the table of contents in the map window. The general procedure described here (selection of the geological unit to illustrate this procedure is the Wildmoor Sandstone Formation) follows the directive set out by Mathers et al. (2011): (i) Switch on edit, and the Wildmoor Sandstone Formation selection turns to red in the table of contents; (ii) Go to the polygon attribute table as in Figure 4-23, and select and insert all entries with respect to the WRS, returning to the map window to inspect the WRS polygons; (iii) Switch off edit, followed by right clicking on the unit (*extra functions* > *calculate* > *calculate unit as non-faulted unit*). Bring up-to-date the nodes for the base geological unit on hand for calculation, after switching on edit on the geological unit again; (iv) The iterative process of updating the map window employing the cross-section fence diagram and borehole logs, revising the polygon(s) as necessary (see Figure 4-24), and (v) Switch off edit and save the workspace. The envelope construction of all the geological units is presented in Figure 4-25.

Table

Eastside_10k_Bedrock

FID	Shape *	LEX	LEX_D	LEX_RCS	RCS	RCS_X	RCS_D	RANK	BED_EQ	BED_EQ_D	MB_EQ	MB_EQ_D
0	Polygon	BMS	BROMSGROVE SANDSTONE FORMATION	BMS-SDST	SDST	SDST	SANDSTON	FORMATIO	NotAp	Not Applicable	NotAp	Not Applicable
1	Polygon	MMG	MERCIA MUDSTONE GROUP	MMG-MDST	MDST	MDST	MUDSTONE	GROUP	NotAp	Not Applicable	NotAp	Not Applicable
2	Polygon	WRS	WILDMOOR SANDSTONE FORMATION	WRS-SDST	SDST	SDST	SANDSTON	FORMATIO	NotAp	Not Applicable	NotAp	Not Applicable

Figure 4-23: Eastside 10K Bedrock shape attribute table (excerpt) from the DigMap

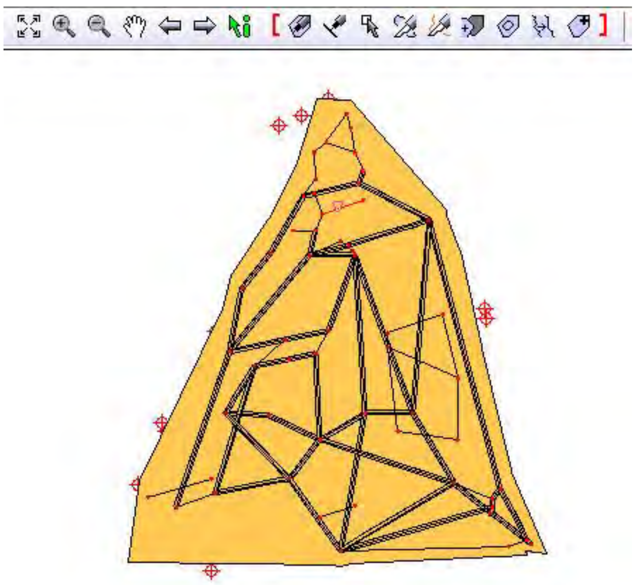


Figure 4-24: The redrawn Wildmoor Sandston Formation polygon to include all of the area covered by the model - since the WRS occurs under the whole area of Birmingham Eastside

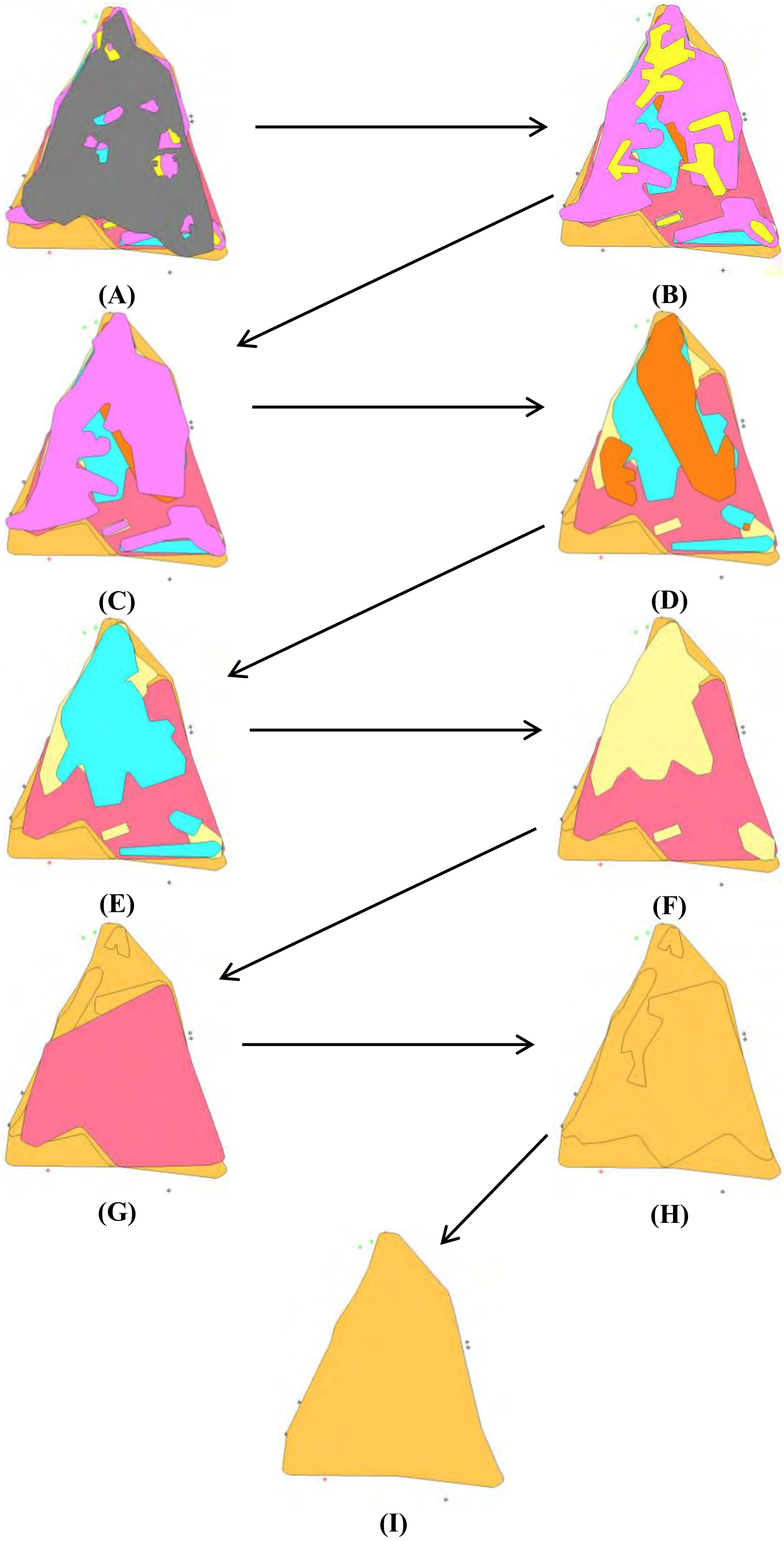


Figure 4-25: The order of envelope construction showing the top to bottom envelope: (A) Made Ground; (B) Alluvium; (C) River Terrace Deposits; (D) Glaciolacustrine Deposits; (E) Sandy Till; (F) Glaciofluvial Deposits; (G) Mercia Mudstone Group; (H) Bromsgrove Sandstone Foundation; (I) Wildmoor Sandstone Foundation

4.10.7 STEP 6: CALCULATE MODEL

Step 6 is simply the calculation of the 3D geological model (see Figure 4-26) from the sections and envelopes prepared. This process in GSI3D utilises a custom-built Delaunay-triangulation dependent upon a Quad-edge algorithm (Green & Sibson, 1978). Please refer to Figure 4-28 for various views of the final calculated model of Birmingham Eastside, and Figure 4-29 for a summary of the GSI3D workflow for modelled area of Birmingham Eastside.

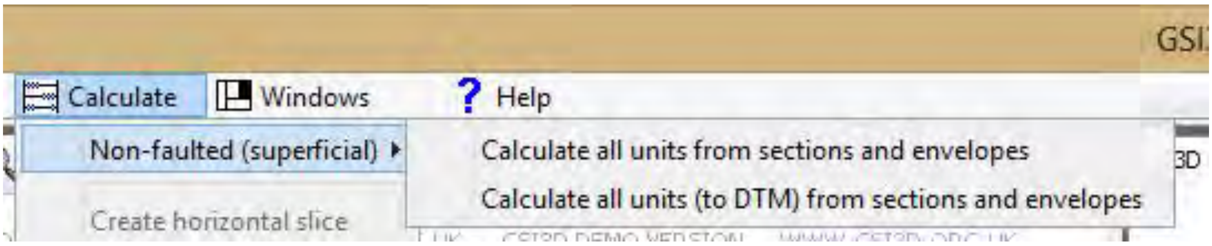


Figure 4-26: GSI3D model calculation option

4.10.8 STEP 7: EXPORT 3D GEOLOGICAL MODEL

Step 6 involves the exporting of relevant data (GSI3D enables the user to save the top, base and thickness of the constructed model, and are saved as ASII or surfer grids otherwise a single ESRI shape file) that can then permit the 3D geological model of Birmingham Eastside to be utilised in the decision-making process by utilisation of the SUURE Operational Model in ArcGIS (see Chapter 5). Figure 4-27 below illustrates the process by which one exports from GSI3D. It is important to note that the appropriate cell size and grid extent must be inputted as shown below, thereby corresponding to other raster data for analyse purposes.

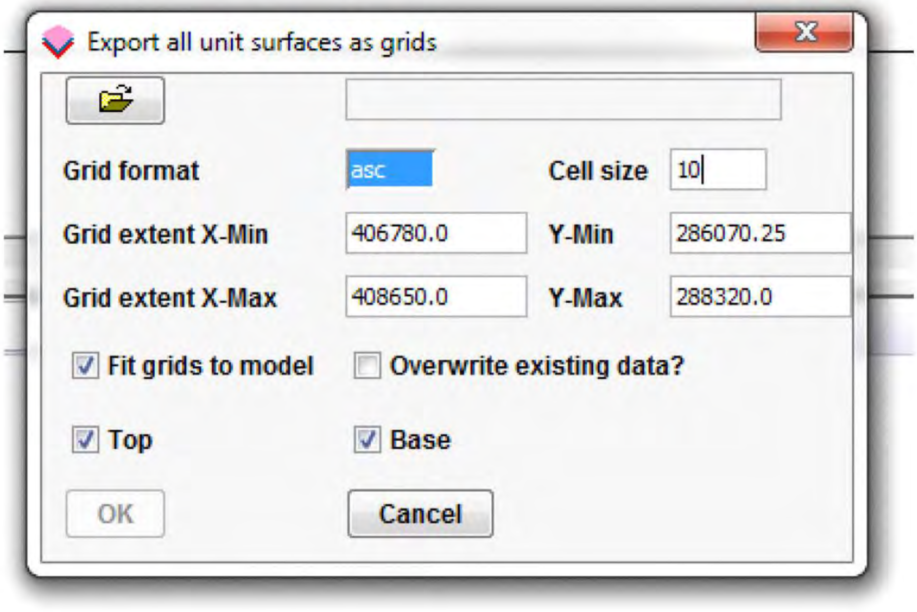


Figure 4-27: Exporting of all unit surfaces as grids for use in ArcGIS for the 3D geological model of Birmingham Eastside

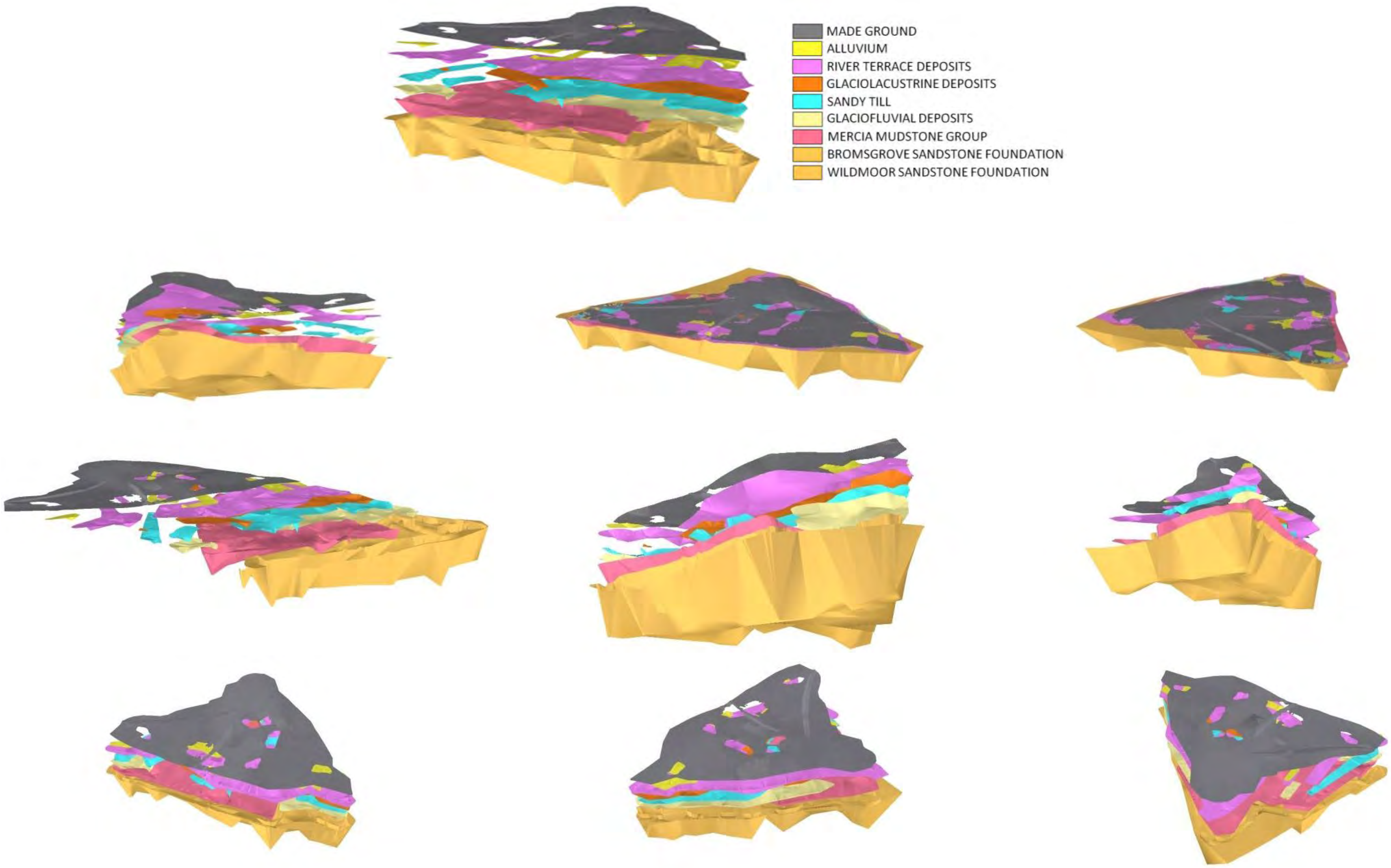
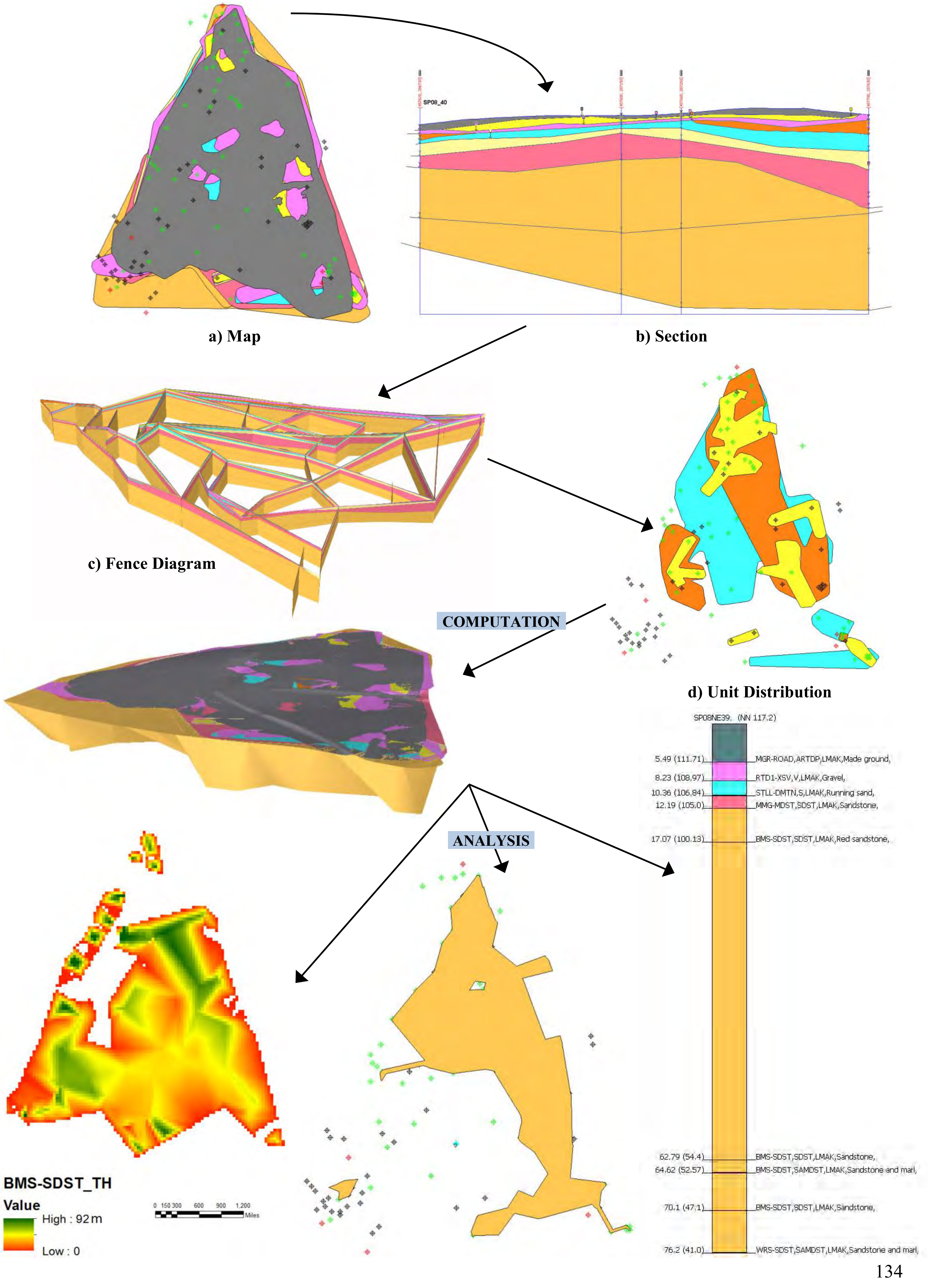


Figure 4-28: Different view-points (normal and exploded) of the final 3D geological model of Birmingham Eastside

Fig 4-29: The GSI3D workflow for Birmingham Eastside



f) Thickness Grid

g) Ground sliced at -10m OD

h) Synthetic Borehole

4.11 UNCERTAINTY IN THE GSI3D GEOLOGICAL MODEL

The three-dimensional model of Birmingham Eastside utilising GSI3D represents the state-of-the-art with regards to the geological comprehension of the region that can be utilised to support planning and decision-making for UUS, for example see Mathers and Kessler (2010) and Royse et al. (2010). What's more, end users of such geological models may well have need of measures of uncertainty, for instance the uncertainty of the geological model provided by the construction of the channel tunnel (Blanchin & Chilès, 1993). The objective of the channel tunnel engineers was to remain inside the Chalk Marl, circumventing both the primary Gault Clay and the covering, distorted and raptured, Grey Chalk. The analysis of several borehole downhole investigations (penetration examinations to the top of the Gault Clay) using geo-statistics, permitted engineers to calculate projected tunnel pathways and the corresponding risk involved of tunnelling into the Gault, thereby fine-tuning their scheme designs to decrease this risk to tolerable levels. The final 3D geological model of Birmingham Eastside (see Figure 4-29) consequently comprises closed 3D entities which match up to the stratigraphic units characterised in the cross-sections and geological succession of the area under examination. Pre-set stages of GSI3D model development are constrained to the final triangulations, and consequently are not founded on a statistical model. In practical terms, contrary to the output of an entirely geostatistical algorithm, there exists at this present time no model-derived measure of uncertainty with respect to GSI3D 3-D geological models (Lark et al., 2013). Lelliott et al. (2009) put forward a system to enable a structured approach to the measurement of uncertainty in 3D geological models which integrates information on various factors that, independent of experience, are believed to be partly responsible for the uncertainty of a 3D geological model. These comprise: (i) Local geological complexity, and (ii) Distances from the site under examination to neighbouring boreholes. Their methodology specifies by what means the uncertainty of a 3D geological model could be estimated to fluctuations spatially, and it was made known that the approach yielded results coherent with geologists' expectations. The expectation that Lelliott et al. (2009) postulated with reference to the distance to boreholes accounting for any disparities in size of differences in 3D geological model error, were refuted by Lark et al. (2013) who found no evidence of this in their study into the uncertainty inherent in 3D geological models using controlled experiments with a team of modellers at the BGS; their proposed approach is however limited to quantification (confidence intervals – commonly 95%) of uncertainty relative to different expert modeller elicitation relative to the geologists own understanding of uncertainty in the model. This attempt to establish an operational method to quantify, using statistical prediction, the magnitude of uncertainties in 3D geological models is an on-going work (Bond et al., 2011; Bond et al., 2012; Lark et al., 2013). Lark (2014) states that the study conducted by Lark et al. (2013) which represents the state-of-the-art in the field at this present time, was never intended as a means of providing methods that could be simply used as an operational method. The starting point was that, while various expert views on sources of uncertainty have been provided, there was no independent statistical evidence for how good 3D models are or how their uncertainty varies in space; thus representing an on-going work to try to move towards an operational procedure, based on benchmarking studies to quantify uncertainty in different settings, and work to see how factors like distance to borehole along the interpreted cross section controls cross section error which then propagates into the 3D volume. In addition to this, Lark (2014) states that work has been carried out in the BGS on simple confidence indices to summarize sources of uncertainty in geological models, particularly relevant to models built from boreholes and seismic data; this however is still under peer review and is not yet in a form that can simply be passed on to GSI3D users (similar to the Lelliott et al. (2009) procedure). Lark (2014) lastly relates that at present the BGS takes the view that the best way to engage with the model user on uncertainty is to make clear what data support the model (so having maps which show (in 2D) the location of boreholes which prove the contacts of interest); this immediately shows the user where the model is supported by local cross-sections and where the surface is subject to least control by hard data. As a result of this, a summary of the type and sum of site investigation locations that completely accessed each geological deposit, together with a description of each deposit relative to the borehole logs surveyed for Birmingham Eastside, is given in Table 4-12. In addition to this, Figure 4-30 illustrates Table 4-12 in graphical form, permitting an understanding of where the boreholes reside within Birmingham Eastside. Figure 4-31 - Figure 4-33 show the contacts of interest and their relative distribution for the modelled geological unit surface, thus making it very clear what data supports the 3D geological model of Birmingham Eastside.

Table 4-12: Lithostratigraphic descriptions and site investigation summary of Birmingham Eastside

Lithostratigraphic unit	Number of investigation point type fully penetrating deposit				Description
	CP_1	TP	CP_2	Total**	
Made ground	7	36	3	46	Variable composition. Man-made superficial deposit (generic).
Alluvium	2	15	-	17	Normally soft to firm consolidated, compressible silty clay, but can contain layers of silt, sand, peat and basal gravel. A stronger, desiccated surface zone may be present.
River terrace deposits	7	31	4	42	Sand and gravel, locally with lenses of silt, clay or peat.
Glaciolacustrine deposits	2	14	2	18	Silt and clay, laminated, commonly rich in organic matter, locally with interbedded peat; of glaciolacustrine origin.
Sandy till	5	15	3	23	Sandy, silty, pebbly clay, locally with sand and gravel lenses (Diamicton).
Glaciofluvial deposits	2	15	1	18	Sand and gravel, locally with lenses of silt, clay or organic material; of glaciofluvial origin.
Mercia mudstone group	7	13	6	26	Dominantly red, less commonly green-grey, mudstones and subordinate siltstones with thick halite-bearing units in some basinal areas. Thin beds of gypsum/anhydrite widespread; sandstones are also present.
Bromsgrove sandstone foundation	2	7	4	13	Sandstones, red, brown and grey, commonly pebbly or conglomeratic at the bases of beds, interbedded with red and brown siltstones and mudstones.
Wildmoor sandstone foundation	2	1	5	8	Sandstones, generally silty or argillaceous, fine- to medium-grained, bright orange-red to dark brick-red, with subordinate siltstone and mudstone; pebbles rare.

CP_1, cable percussion; **TP**, trial pit; **CP_2**, cable percussion and SPT
**Total boreholes (55)

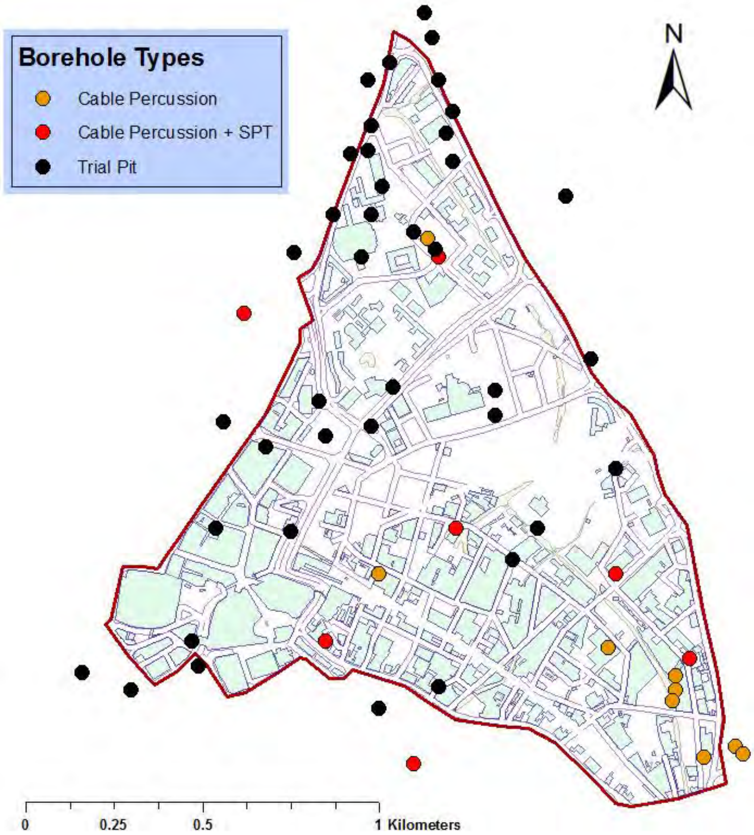


Figure 4-30: Borehole investigation type and distribution within the geographically modelled area of Birmingham Eastside

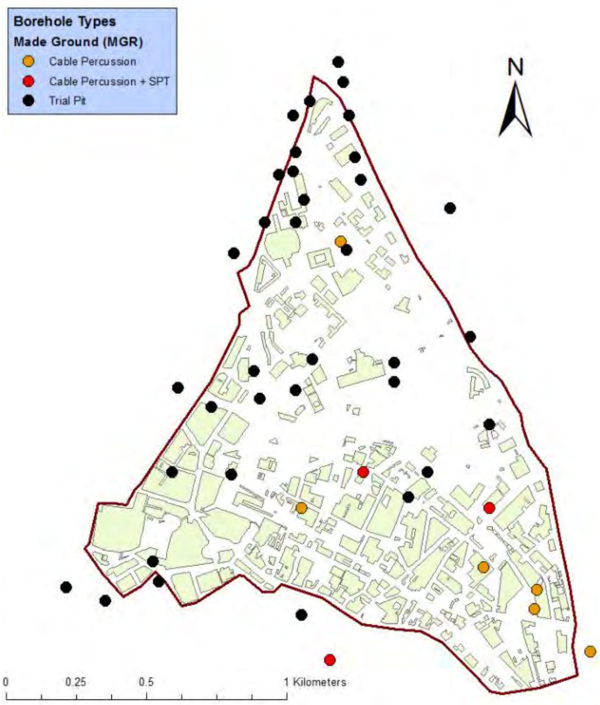


Figure 4-31: Boreholes showing the contacts of interest and their relative distribution for the modelled geological unit surface at Birmingham Eastside: Made Ground

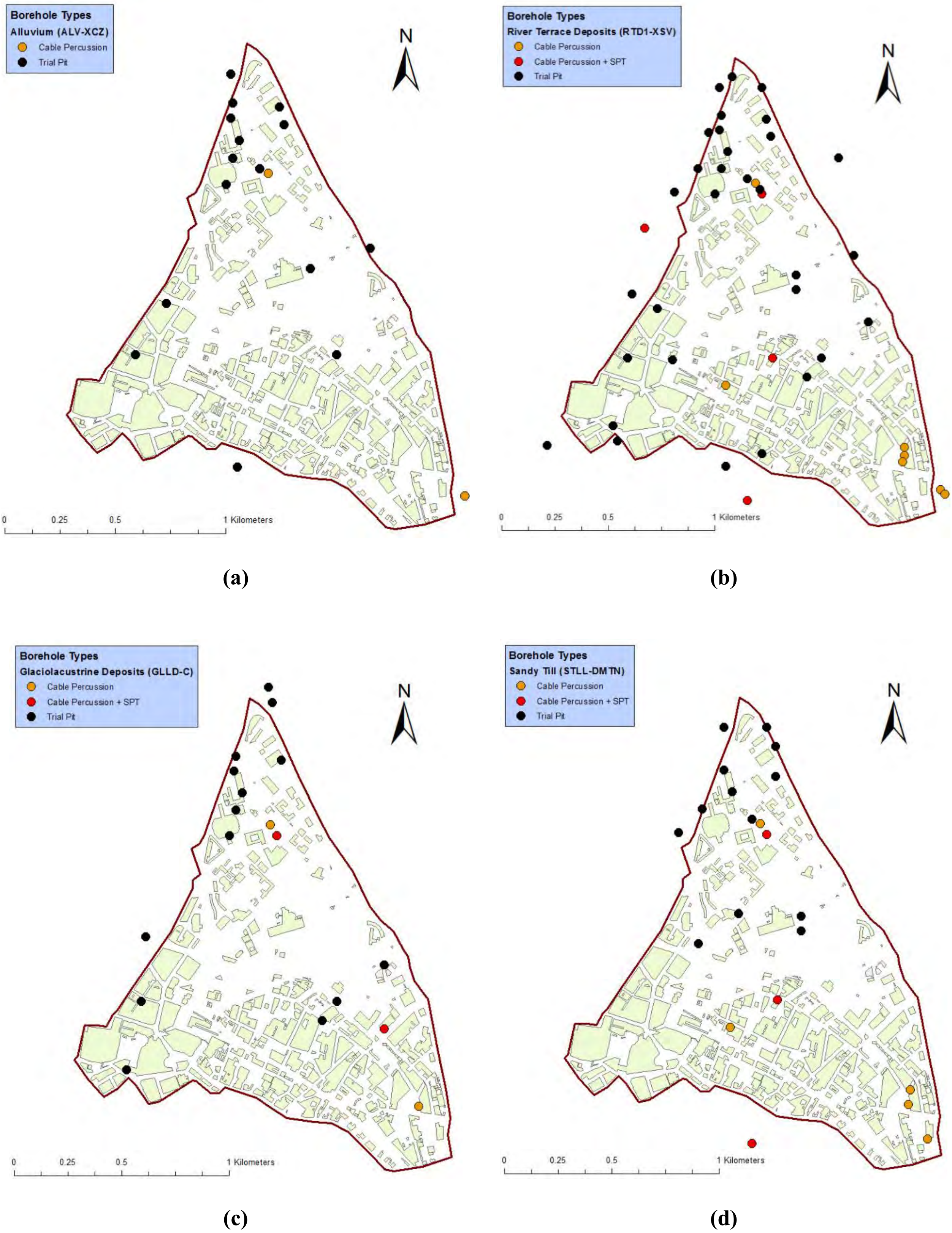


Figure 4-32: Boreholes showing the contacts of interest and their relative distribution for the modelled geological unit surfaces at Birmingham Eastside: (a) Alluvium; (b) River Terrace Deposits; (c) Glaciolacustrine Deposits; (d) Sandy Till

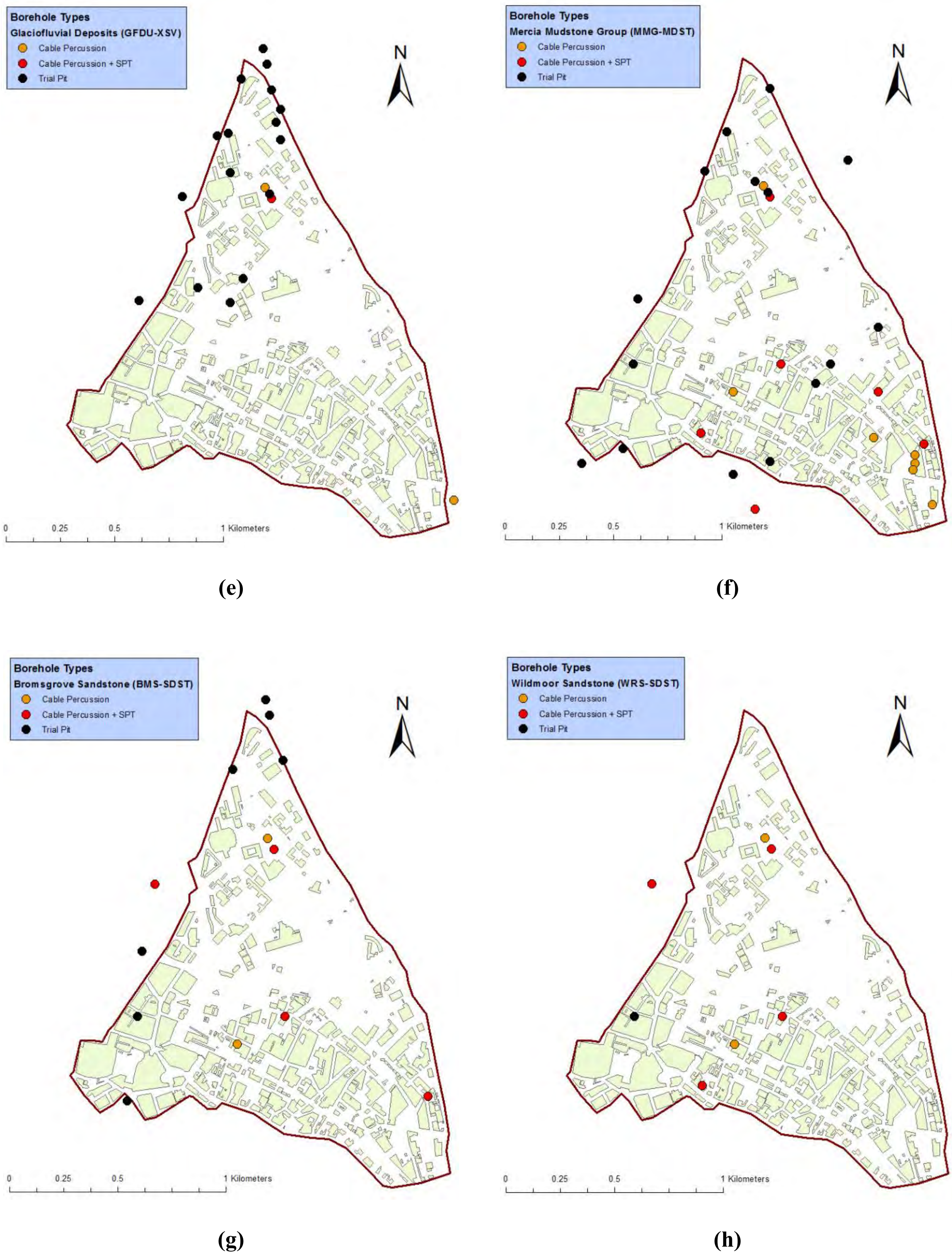


Figure 4-33: Boreholes showing the contacts of interest and their relative distribution for the modelled geological unit surfaces at Birmingham Eastside: (e) Glaciofluvial Deposits; (f) Mercia Mudstone Group; (g) Bromsgrove Sandstone Foundation; (h) Wildmoor Sandstone Formation

4.12 CHAPTER SUMMARY

Birmingham Eastside has achieved several sustainability successes to-date and continues, notwithstanding its short comings, to be exemplified as a model ‘sustainability quarter’ in Birmingham as part of BBC’s ‘Big City Plan’. It however has missed a step with regard to use of its urban underground space (a SES). The manner in which utilities are laced in Eastside is wholly unsuited to serve the needs of future generations in a sustainable manner i.e. when taking into account the socio-ecological influences of UUS on the urban landscape (see Figure 2-9). The adoption of MUTs would go a long way to improving the sustainable use of UUS through sustainable utility placement in Birmingham Eastside. The question therefore stands; would MUTs if placed in Birmingham Eastside in the name of sustainability, continue to deliver their function into the future whatever that may be? Such an investment no doubt has to be evaluated, evidence gathered and sorted to this end i.e. do MUTS’s have the capacity to adapt to future socio-ecological changes. As part of the evaluation of MUTs in Eastside, the geology of the district undeniably plays a significant part, without which the possibility of quantifying the spatial and temporal impacts of infrastructure developments on UUS would limited in value. The 3D geological model presented in this chapter of Birmingham Eastside (see Figure 4-28) developed using GSI3D, will facilitate through its inclusion (see Chapter 5) an improved socio-ecological evaluation of underground space use, by thus permitting for the spatial variability of infrastructure and geology to be evaluated in light of a proposed sustainability (UUS utility service provision) solution. The following chapter seeks to address the question of whether MUTs would suffice as a means of sustainable use of UUS in Eastside, through a SUURE Operational Model evaluation.

CHAPTER 5: SUURE EVALUATION OF MUT'S IN BIRMINGHAM EASTSIDE

5.1 INTRODUCTION

The sixth and seventh objective of this research work is to make evident the efficacy of employing the developed SUURE Operational Model (see Chapter 3) by testing it on different regeneration solutions against longer term sustainability criteria. In Chapter 2, it was shown that decision-making regarding UUS (a SES) is a multifaceted endeavour, comprising a complex set of economic, social, environmental and technical issues. In this chapter, the SUURE Operational Model (see Figure 5-2) will be demonstrated in its fullness as a means of improved decision-making, through evaluating the utilisation of MUT's (flush-fitting, shallow and deep) in Birmingham Eastside (proof of concept) as an alternative utility placement technique to the present methodology used as evidenced in Chapter 4 of traditional trenching (open-cut construction). This application seeks to bridge the knowledge gap identified in Chapter 2, through evaluating the sustainability credentials of MUT's in the here and now in Birmingham Eastside, and in the future, and is the first application of its kind on both a national and international level with reference to the evaluation of MUT's (as part of a SES) in both space and time. Thus such an application extends the use of the proposed SUURE Operational Model to sensitivity in decision-making processes in both space and time, that permits decision-makers to plan for SES resilience (retention of functional performance) as a key part of strategic operational decisions tending towards sustainability of engineering solutions, besides accounting for complex geology (see Chapter 4) in relation to urban underground physical infrastructure. Planning decisions taken in this fashion (considerate of resilience of SESs) which are squarely centred on an evidence base that determines the robustness of sustainability solutions into the far future whatever that maybe (NSP, PR, MF and FW – extreme-yet-plausible futures) allow decision-makers to have confidence that the investment in MUT's, specifically in Birmingham Eastside, are being made wisely through application of the SUURE Operational Model that encourages broadening of processional thinking geared towards geo-professionals, urban planners and policy makers as opposed to providing another tool that simply stipulates an outcome. In this chapter it is demonstrated that the knowledge gaps identified in Chapter 2 for decision-support frameworks that serve underground professionals may be addressed through application of the SUURE Operational Model. The case study area of Birmingham Eastside introduced in the previous chapter was presented in order to apply the SUURE Operational Model. Thus, the present chapter is devoted to the discussion of the acquired results of the SUURE Operational Model evaluation of MUT's for the case study region of Birmingham Eastside. Data and evaluation results of data modelling, fuzzy overlay (baseline performance), and weighted (scenario sensitivity – retention of functional performance) analysis, impact evaluation and decision generation are discussed.

5.2 OVERVIEW OF UTILITY INFRASTRUCTURE IN BIRMINGHAM EASTSIDE

In Chapter 4, the need for MUT's as a means of sustainable utility placement in Birmingham Eastside was discussed. Urban underground spaces in cities worldwide have one constant feature in that virtually all the underground space down 2-3 meters beneath the street level (zone of human interaction) is filled with urban utilities. This concentration of urban utilities has been characterised as "*the spaghetti subsurface problem*" by urban engineers (Oude, 1992), and this is no different presently in Birmingham Eastside (see Figure 4-4). Utility service provision is only due to increase in Birmingham Eastside as a result of expected increase in population density (a key driver) in urban areas (see Figure 2-1) over time, and also considering that the proposed HS2 high speed train line terminal from London to Birmingham is planned to be located in the heart of Eastside at Curzon Street (Forster, 2010; Chen, 2012). It stands to reason that we cannot live without utilities, and both people and the natural environment in Birmingham Eastside are materially affected by urban utility systems in a significant way.

For this very reason, the extensive use of UUS for utility service provision is by far its prime function to-date in Birmingham Eastside. This phenomenon in Birmingham Eastside has brought about a growing interest in Multi-Utility Tunnel (MUT) systems as a means of engendering sustainable development of UUS as reported by Hunt and Rogers (2005) and Jefferson et al. (2006), due to the increasing congestion of utilities within the zone of human interaction (i.e. shallow sub-surface) both now and into the future. MUTs offer an alternative to open-cut excavation that is currently being used in Birmingham Eastside i.e. trenching and open-cut construction is the most used methodology for lacing utilities below the ground currently in the UK. It is well documented that MUT's when implemented reduce saturation of UUS, improve zonal planning of UUS, allow for easier and streamlined maintenance of existing utilities, significantly reduce traffic disruption and permit the addition of new urban services without disruption to the public highway.

5.3 APPLICATION OF THE SUURE OPERATIONAL MODEL

The SUURE Operational Model (see Figure 5-2) will be utilised thus to evaluate (synthesising available data in the decision options/alternatives) the efficacy or otherwise of MUT's as a proposed sustainability solution (investment) to engender sustainable utility placement, and by consequence, sustainable use of UUS in Birmingham Eastside.

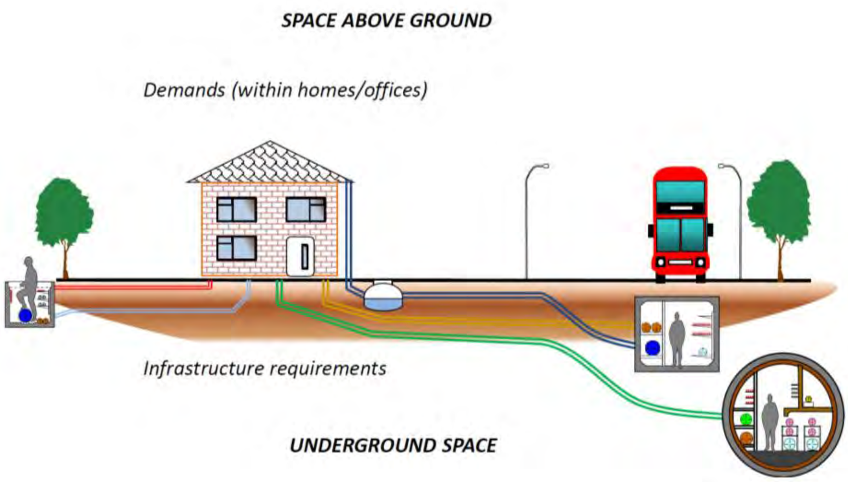


Figure 5-1: Different dimensions of potential MUT placement (flush-fitting – 0.0m cover, shallow 0.5m-2m cover and deep 2m-80m cover) within Birmingham Eastside (Hunt, Jefferson, & Rogers, 2012)

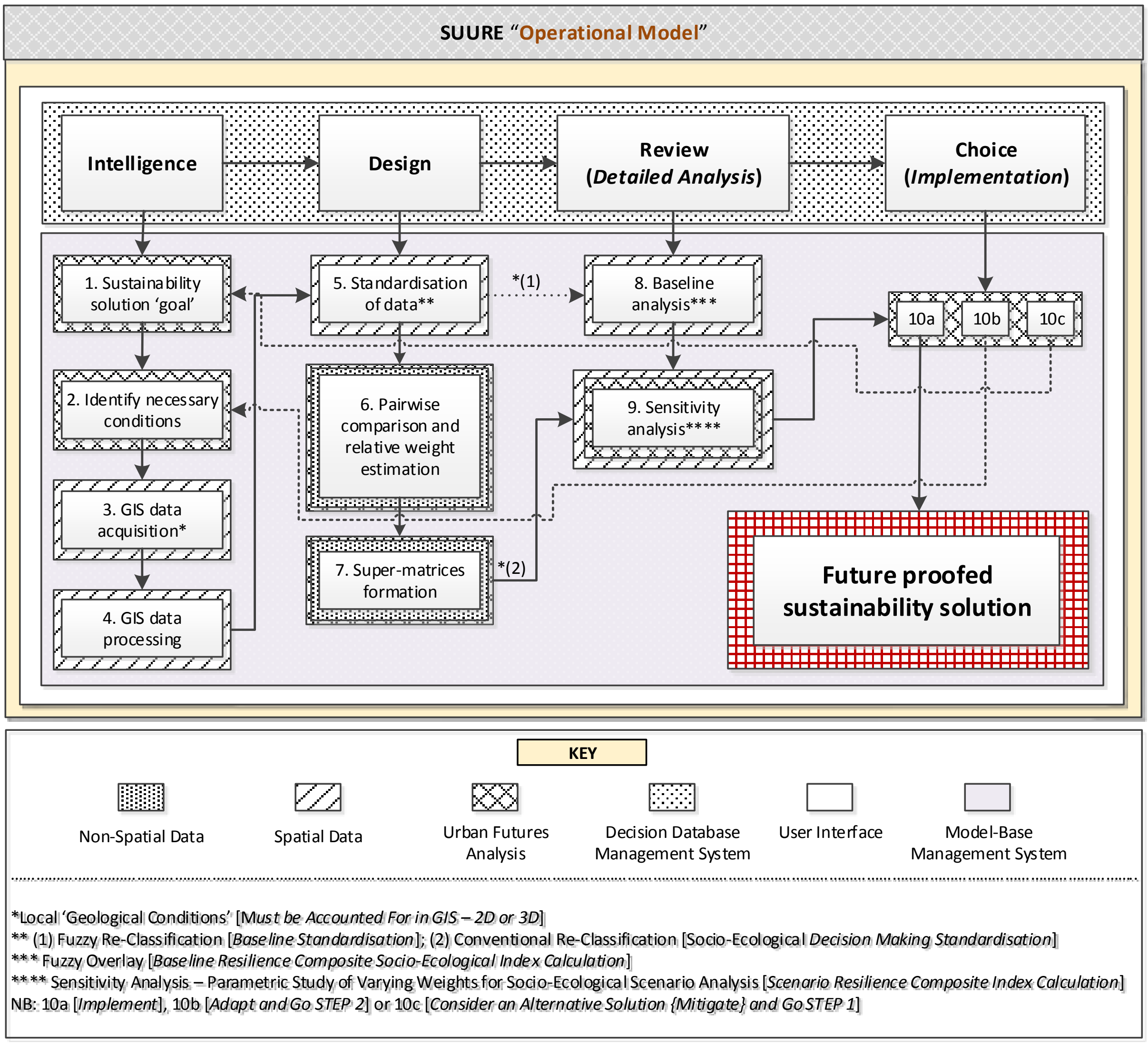


Figure 5-2: Sequence of activities and components of the SURRE "Operational Model"

5.3.1 SYSTEM CHARACTERISATION: INTELLIGENCE AND DESIGN

5.3.1.1 SUURE Operational Model: Step 1

The first step in the SUURE Operational Model is the identification of the sustainability solution 'goal'. The 'goal' identified for the present research in light of the contextual state of utility infrastructure (see Chapter 4, section 4.3) in Birmingham Eastside is:

Goal: MUT placement for collocation and coordination of utilities for sustainable use of UUS.

5.3.1.2 SUURE Operational Model: Step 2

The 'goal' necessitates the identification of the necessary conditions to put in place MUTs in Birmingham Eastside. These necessary conditions will facilitate the evaluation of capacity to adapt to change for MUTs in the SES of UUS. The placement of an MUT (flush, shallow and deep) is a MCDA problem that necessitates taking into account a wide-ranging array of socio-ecological criteria. Beginning with the goal in mind, the necessary conditions that replicate the relevant attributes for MUT placement in Birmingham Eastside were identified (see Figure 5-3). It is essential to underscore that criteria identified as illustrated in Figure 5-3, were carefully chosen from appropriate published engineering articles (ITA, 1987; Godard & Sterling, 1995; Haasnoot et al., 1997; Edelenbos et al., 1998; Rönkä et al., 1998; ITA-WG4, 2000; NJUG, 2003; Butler & Davies, 2004; Godard, 2004; Legrand et al., 2004; Chen & Wang, 2005; Hunt & Rogers, 2005; Canto-Perello & Curiel-Esparza, 2006; Bélanger, 2007; Foster et al., 2007; NJUG, 2007; Duffaut & Labbé, 2008; Canto-Perello et al., 2009; Yang et al., 2010; He et al., 2012; Sterling et al., 2012; Curiel-Esparza & Canto-Perello, 2013; Hunt et al., 2014) that highlight the full-range of necessary conditions (indicators) that require consideration for the placement of an MUT irrespective of the case study area under examination. Further elaboration as to the significance of each criterion to the goal and case study area under examination (Birmingham Eastside) is described in Table 5-3.

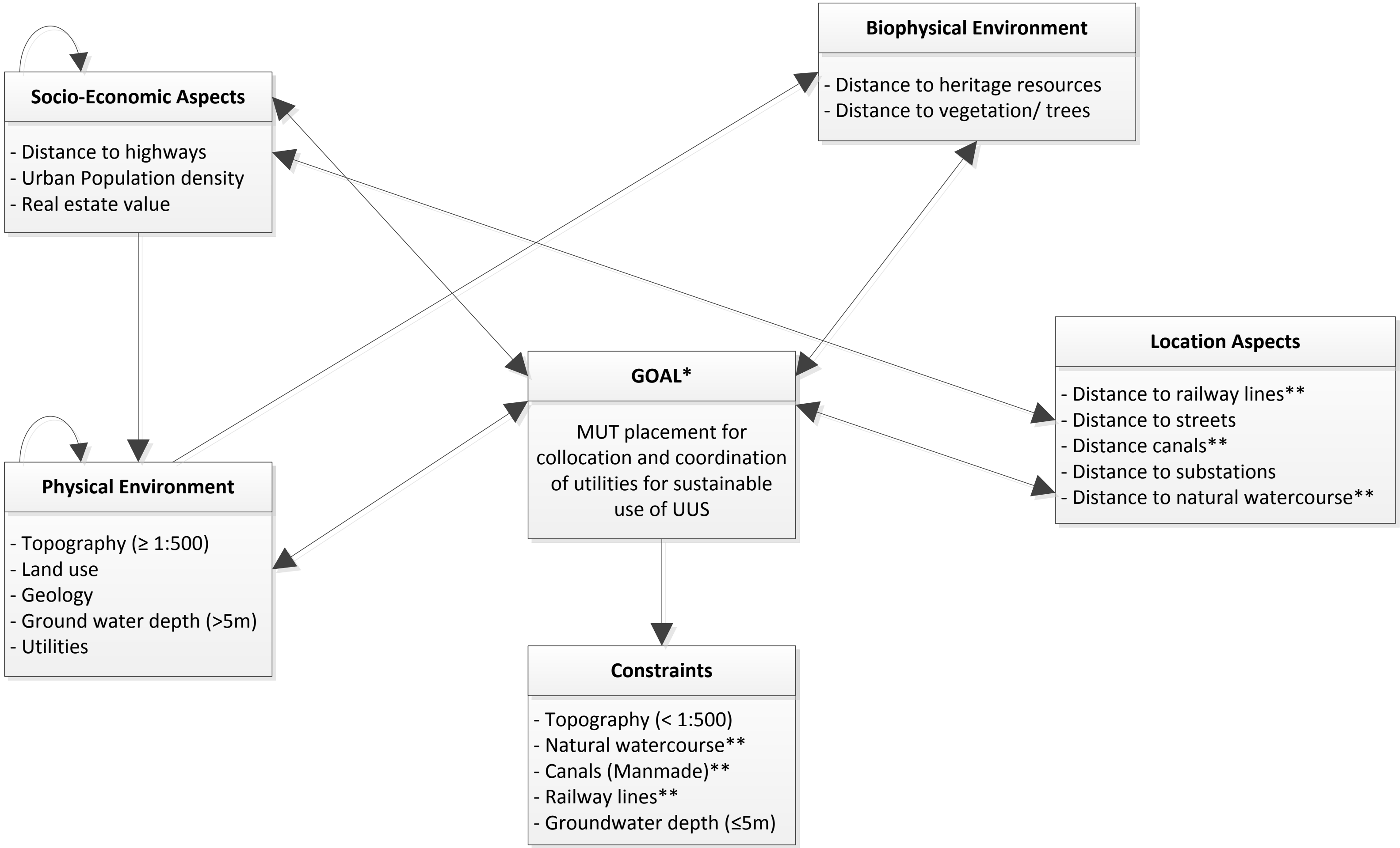
The identified socio-ecological criteria (necessary conditions) are classified in two groups: constraints and factors. The constraints identified can either be a Boolean true, or Boolean false (see Figure 3-11 and Table 3-5); thus restricted in Birmingham Eastside to particular zones (areas to be included and excluded in the analysis – (i) baseline; (ii) scenario), in addition assessment measures regulate the scale of socio-ecological resilience (functional performance) for all feasible alternatives (flush-fitting, shallow or deep MUT). The factor criteria that impact analysis by compensation, weighs in to some measure as regards the goal (functional resilience of MUT's), which can either be - (i) cost criteria: contributes negatively to the goal or (ii) benefit criteria: contributes positively to the goal. Set against constraints, that will not transpire nullification, inferior functional performance of compensatory criteria under consideration can be nullified through suitable functional performance of a different factor. Employing compensatory decision guidelines, for instance a weighted sum, the resultant overlay analysis can nevertheless produce a suitable overall functional performance in the composite resilience index ratio map. In the present study, 20 criteria were included in the evaluation method, differentiated by way of compensatory (15) as well as non-compensatory (5). As illustrated in Figure 5-3, the criteria for the case study area of Birmingham Eastside are grouped in five principal clusters comprising factors affecting the biophysical environment, location aspects, constraints, factors affecting the physical environment and socio-economic aspects (see Figure 5-3). Reference is made to the need to have a dedicated cluster that accounts for location aspects unique to the case study area under examination as these aspects impact the potential placement or otherwise of MUTs.

The ANP grid arrangement for the case study area of Birmingham Eastside (see Figure 5-3) was developed as specified by Miller (1956), with a decision-maker(s) limitation in mind, whereby the clusters modelled ought not to contain too many elements for comparison by way of the enunciation of relative judgements, for the reason that the network structure is not intended to be viewed as an algorithm that has the inherent ability to mechanically produce the desired solution, on the other hand, it ought to preferably support the decision-maker(s) who have to undertake a methodical analysis of the alternative sustainability solutions (flush-fitting, shallow or deep MUT) and who is/are entirely in authority of the final choice (implement, don't implement, or mitigate). To achieve consistency in the structuring of the ANP network, exacting care was taken for resultant clusters to be readily practicable. In the construction of the network model, small and proportional clusters have as a result been well-though-out to represent the state of affairs. This is especially significant when taking into account a cognitive viewpoint, for the reason that consensus in the literature draws attention to the proclivity that decision-maker(s) tend to have in giving greater weight towards parts that are defined using a greater amount of elements in the network structure (Simon, 1960; Saaty, 1980). In some case this is unavoidable and to a large extent is determined by the sustainability solution under examination.

In keeping with the ANP approach, as soon as the network structure is constructed, the influences that exist between the respective elements have to be expressed accordingly. Subsequently, individual criterion are analysed with respect to the effect that other relevant criteria exert upon it; this step acts to facilitate Step 6 and 7 in the SUURE Operational Model, where the corresponding pairwise comparisons for different future socio-ecological scenarios (NSP, PR, MF and FW) matrices of each criteria with respect to the goal will be carried out, thus generating the corresponding eigenvectors and priority vectors (factor weights for each of the necessary conditions). The approach to forming relevant cluster and node relationships for case study area under examination in the present research work begins with the goal in mind i.e. all the elements are intended to have an effect on the overall goal. Additional cluster relationships are successively determined with reference to the probable influences between the elements of each cluster. These relationships thus replicate the real-world environmental underlying forces upon MUTs, where link and interface arteries occur among singular independent elements that can desirably or undesirably influence respective independent elements. For example, 'utilities' are influenced by 'urban population density' as well as the 'real estate value', and 'distance to vegetation/tress' is influenced by 'land use' (see Figure 5-3). The directional configurations of the arrows in Figure 5-3 specify the interdependence connection(s) that subsist with regard to the factors (necessary conditions). The dominance exerted by one factor to another is signified by a solitary directional arrow. Arrows that are bi-directional signify reciprocal influence concerning the factors. The cluster loops specify inner dependencies in the elemental node(s).

5.3.1.3 SUURE Operational Model: Step 3 and 4

In Step 3 raw data acquisition was carried out for the case study area so that construction of a thematic map (map showing information regarding one characteristic of the area under consideration) for each categorised factor and constraint could be produced in Step 4. The case study area GIS model was discretised utilising a maximum grid cell size (based on largest raster map in the GIS database) of 20mx20m. Table 5-1 tabulates the evaluation criteria (constraints and factors) for the case study area under examination, and makes available for every respective criterion the data source and scale, the source map utilised to portray them as well as the derived maps generated for Birmingham Eastside. As can be observed from Table 5-1, a sizeable chunk of the resulting maps are distance maps. These maps are generated by a Euclidean distance calculation that produces a resultant raster map where every pixel contains distance values equivalent against the distance derived at source pixels within the prototype source map. These thematic maps (see Table 5-1) form the basis on which the quantification of the spatial and temporal impacts of MUTs on the underground space in Eastside in light of future socio-ecological change, can be carried out using the SUURE Operational Model. These steps (3 and 4) are crucial and if not completed will halt any possibility of the successful application of the SUURE Operational Model.



Key:

***** MUT options: (**a**) Flush-fitting MUT: 0.0m cover; (**b**) Shallow MUT: 0.5m-2.0m cover and (**c**) Deep MUT: 2-80m cover

****** These criteria are unique to Birmingham Eastside and would otherwise not be considered when evaluating the benefits or otherwise of MUT placement for collocation and coordination of utilities for sustainable use of UUS

Figure 5-3: The ANP network structure for the case under examination – MUT placement in Birmingham Eastside

Table 5-1: Maps used to represent the criteria for MUT placement in Birmingham Eastside

	Criteria	Data source and scale	Source map	Derived map
Constraints	Topography (< 1:500)	µ, 1:50000	Map of topography	Map of topography
	Natural watercourse	β, 1:10000	Map of heritage resources	Map of heritage resources
	Canals (manmade)	β, 1:10000	Map of the existing canals	Map of the existing canals
	Railway lines	β, 1:10000	Map of existing railway lines	Map of existing railway lines
	Ground water depth (≤ 5m)	∂, 1:10000	Map of groundwater depth	Map of groundwater depth
Criteria	Topography (> 1:500)	µ, 1:50000	Map of topography	Map of topography
	Land use	µ, 1:10000	Land use map	Map of land use classes
	Geology	Δ, 1:10000	Map of lithostratigraphic arrangement of the soil	Map of lithostratigraphic arrangement of the soil
	Ground water depth (> 5m)	∂, 1:10000	Map of groundwater depth	Map of groundwater depth
	Utilities		Map of existing utilities	map of existing utilities
	Urban population density	≯, 1:10000	Urban population density values	Map of urban population density values
	Real estate value	Ω, 1:10000	Real estate values	Map of real estate values
	Distance to highways	µ, 1:10000	Map of existing highways	Distance map
	Distance to heritage resources	Ʊ, 1:10000	Map of existing heritage resources	Distance map
	Distance to vegetation/ trees	µ, 1:50000	Map of existing vegetation/ trees	Distance map
	Distance to railway lines	β, 1:10000	Map of existing railway lines	Distance map
	Distance to streets	µ, 1:10000	Map of existing streets	Distance map
	Distance to canals	β, 1:10000	Map of existing canals	Distance map
	Distance to substations	β, 1:10000	Map of existing substations	Distance map
	Distance to natural watercourse	µ, 1:10000	Map of existing natural watercourses	Distance map

***µ:** Ordnance Survey UK
****β:** Open Street Map
*****Δ:** British Geological Survey (Borehole Records + GSI3D)
******∂:** British Geological Survey (National Well Archive)
*******≯:** Office of National Statistics UK (ONS)
********Ω:** Birmingham City Council
*********Ʊ:** English Heritage

Projection Coordinate System:

British National Grid
WKID: 27700 Authority: EPSG
Projection: Transverse Mercator
False Easting: 400000.0
False Northing: -100000.0
Central Meridian: -2.0
Scale Factor: 0.9996012717
Latitude of Origin: 49.0
Linear Unit: Meter (1.0)

5.3.1.4 SUURE Operational Model: Step 5

Step 5 employed two separate standardisation procedures as shown in the SUURE Operational Model. This process transformed the incommensurable (different) units for each thematic input map to standardised dimensionless entities (range: 0, worst – 1, best), and determined the partial appeal of every pixel of the thematic maps as regards each criterion for the case study area under examination i.e. for standardised maps (baseline and scenarios), the colour green represents high suitability in the area in question of SES resilience, whilst red represents low suitability in the area in question of SES resilience.

Fuzzy standardisation (reclassification) was carried out through the use of fuzzy membership functions to a scale of (0, worst - 1, best). Table 5-2 below shows the appropriate fuzzy membership functions used to reclassify the criteria to the linguistic variable i.e. the factors (non-restrictive necessary conditions) in the clusters in preparation for the baseline performance analysis in Step 8 following the procedure outlined in the schematic in Table 5-2. The process of assigning fuzzy membership functions served the purpose of replicating the present-day conditions of each of the alternative MUT options with respect to each criterion (see Figure 5-4). The ‘MSLarge’ and ‘MSSmall’ membership functions were deemed appropriate as a means of replicating present-day conditions due to the fact that they both are defined by the mean and standard deviation of dataset contained by the thematic map as a means of assigning the sigmoid membership shape, in addition to the hedges: ‘somewhat’ and ‘very’ that are used to fine tune the fuzzy membership functions.

MSLarge membership function:

$$\mu(x) = 1 - \frac{bs}{x - am + bs} \; if \; x > am, \qquad \textbf{Eq 5-1}$$

$$otherwise \; \mu(x) = 0$$

MSSmall membership function:

$$\mu(x) = \frac{bs}{x - am + bs} \; if \; x > am, \qquad \textbf{Eq 5-2}$$

$$otherwise \; \mu(x) = 1$$

where *m* =mean, *s* = standard deviation, and *b* and *a* are multipliers provided by the user (in this case from the data contained in the thematic map).

‘Somewhat’ hedge:

$$\sqrt{\mu_A(X)} \qquad \textbf{Eq 5-3}$$

produces a square root of the membership and consequently marginally modifies a membership function.

‘Very’ hedge:

$$[\mu_A(X)]^2 \qquad \textbf{Eq 5-4}$$

produces a squared membership function and consequently marginally modifies a membership function

Other membership functions were deemed more problematic to apply (except the 'linear' membership function) as they necessitate a 'user defined' midpoint; this would have necessitated a lengthy analysis process to qualify each criterion with respect to the appropriate midpoint value for suitable fuzzy membership of the SES of UUS (MUTs), which was deemed beyond the scope of the present research work, nonetheless, noteworthy as a basis for future research endeavours.

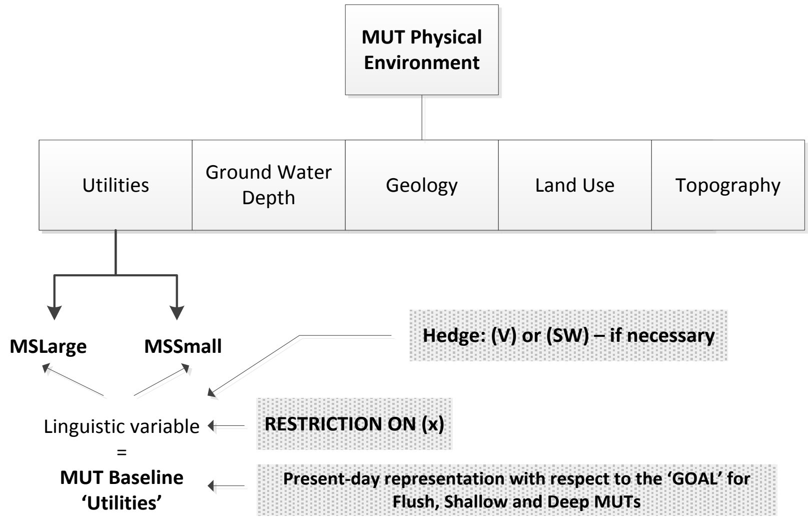


Figure 5-4: Example of assignment of linguistic values to criterion in the case study area under examination (see Figure 5-3), corresponding to the reclassification tabulated in Table 5-2

The second reclassification was conventional standardisation to a common scale similar to that of the fuzzy reclassification (0, worst – 1, best). In so doing, the baseline 'resilience' performance evaluation and the scenario 'resilience' performance evaluation stages permit mutually comparable value judgments through a common scale. The basis for standard reclassification was through application of a linear transformation as shown in Table 5-3 and presupposes the existence of a linear association between the reclassified values and the supposed importance of the reclassified criterion values with respect to the 'goal'; thus consistency was maintained between the original measurements and the standardised vales through connecting the respective alternative a_i and for respective criterion g_j the percentage of the maximum over all alternatives:

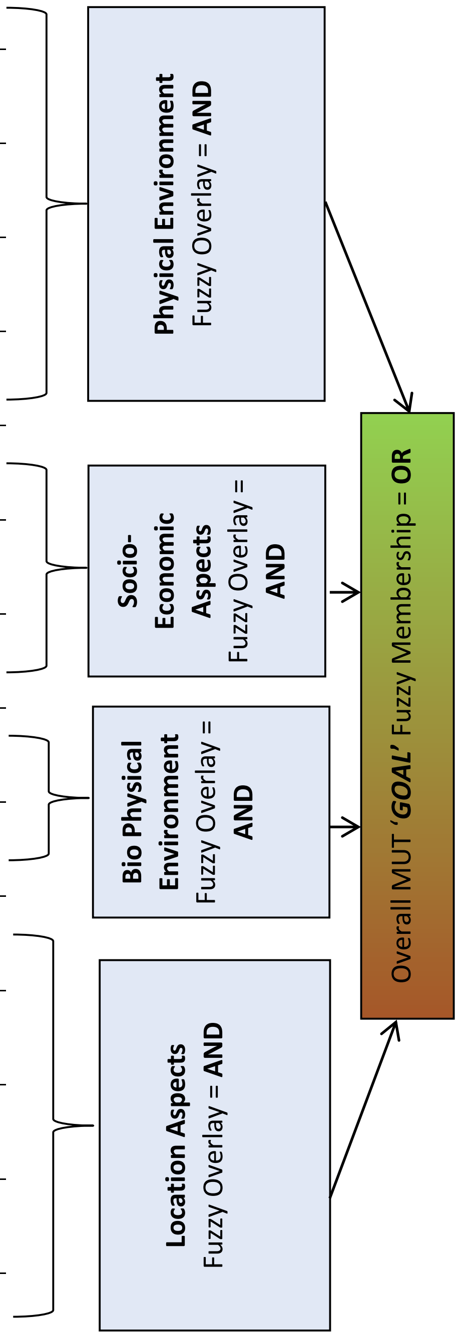
$$r_{ij} = \frac{g_j(a_i)}{max_i g_j(a_i)}, i = 1, \ldots\ldots, n; j \in F \qquad \textbf{Eq 5-5}$$

Table 5-3 explains the linear transformation of the evaluation criteria (constraints and factors) for the case study area under examination. The resulting maps (source and standardised) are illustrated in Figure 5-5 - Figure 5-6 (the rest of the resulting maps can be found in Appendix E).

The completion of Step 5 firstly permits the fuzzy reclassification (see Table 5-2) to straightway be utilised in baseline performance evaluation in Step 8. Secondly, the reclassified evaluation criteria as shown in Table 5-3 necessitates Step 6 and 7 of the SUURE Operational Model in addition to the conventional standardised map data in Step 5 to be primed for scenario resilience evaluation in Step 9.

Table 5-2: Criteria description and fuzzy standardisation/reclassification for baseline analysis

	Criteria	Fuzzy Membership Function	Fuzzy Overlay Function
***CONSTRAINTS**	See Table 5-1		
FACTORS	Topography (≥ 1:500)	F: MSSmall S: MSSmall D: MSSmall	
	Land use	F: MSSmall S: MSLarge D: MSLarge (*SW*)	
	Geology	F: MSSmall S: MSLarge D: MSLarge (*SW*)	
	Ground water depth	F: MSSmall S: MSSmall (*SW*) D: MSLarge	
	Utilities	F: MSSmall S: MSLarge D: MSLarge (*SW*)	
	Urban population density	F: MSSmall S: MSLarge D: MSLarge	
	Real estate value	F: MSSmall S: MSLarge D: MSLarge (*SW*)	
	Distance to highways	F: MSSmall S: MSSmall D: MSSmall	
	Distance to heritage resources	F: MSSmall S: MSSmall (*SW*) D: MSLarge	
	Distance to vegetation/ trees	F: MSLarge S: MSSmall D: MSSmall (*V*)	
	Distance to railway lines	F: MSSmall (*SW*) S: MSSmall D: MSSmall (*V*)	
	Distance to streets	F: MSLarge S: MSLarge D: MSLarge	
	Distance to canals	F: MSSmall S: MSSmall D: MSSmall	
	Distance to substations	F: MSSmall (*SW*) S: MSLarge (*V*) D: MSLarge	
	Distance to natural watercourse	F: MSLarge S: MSLarge (*V*) D: MSSmall	



***Constraints** = *these are the same as illustrated in Table 5-1 and Figure 5-3*
***F** (*Flush-fitting MUT*); **S** (*Shallow MUT*); **D** (*Deep MUT*)
***AND** = *the minimum of the fuzzy memberships from the input rasters*
***OR** = *the maximum of the fuzzy memberships from the input rasters*
***MSLarge** = *defines a fuzzy membership through a function based on the mean and standard deviation, with the larger values having a membership closer to 1*
***MSSmall** = *defines a fuzzy membership through a function based on the mean and standard deviation, with the smaller values having a membership closer to 1*
***SW** (*somewhat*) = *this hedge increases the fuzzy membership functions*
***V** (*very*) = *this hedge decreases the fuzzy membership functions*

Table 5-3: Criteria description and standardisation/reclassification for scenario analysis

	Criteria	Description	Standardisation
CONSTRAINTS	Topography (< 1:500)	Sewerage is topographically oriented because the grade requirement is usually adopted; 1:500 is the allowable limit, anything flatter than this should be avoided as it will be difficult to construct accurately (Butler & Davies, 2004).	Areas with topography < 1:500 are standardised to NODATA (0); the remaining areas are characterised to DATA (1).
	Natural watercourse	Areas with natural watercourses are omitted from evaluation, with a buffer zone of 5m.	Areas with natural watercourses are standardised to NODATA (0); the remaining areas are characterised to DATA (1).
	Canals (manmade)	Areas with canals are omitted from evaluation, with a buffer zone of 5m.	Canal areas are standardised to NODATA (0); the remaining areas are characterised to DATA (1).
	Railway lines	Areas with railway lines are omitted from evaluation, with a buffer zone of 10m.	Railway line areas are standardised to NODATA (0); the remaining areas are characterised to DATA (1).
	Ground water depth (GWD)	Areas with GWD 0- 5m are omitted from evaluation.	Depth ≤ 5m are standardised to NODATA (0); the remaining areas are characterised to DATA (1).
FACTORS	Topography (≥ 1:500)	Generally, sewers should follow the slope of the as far as possible to minimise excavation (Butler & Davies, 2004; Canto-Perello & Curiel-Esparza, 2006; Canto-Perello et al., 2009). The criterion maps the topography within the area under analysis.	Linear standardisation (the greater the topography (≥ 1:500), the bigger the SES resilience ratio).

Criteria	Description	Standardisation
Land use	The criterion classifies the area under analysis into four land classes: industrial, commercial, educational and natural (Legrand et al., 2004; Hunt, Jefferson, Drinkwater, et al., 2012; Hunt et al., 2014).	Linear standardisation (the greater the urbanised area i.e. less natural (Canto-Perello & Curiel-Esparza, 2013; Hunt et al., 2014), the bigger the SES resilience ratio).
Geology	The criterion classifies the area under analysis into 9 stratigraphical divisions corresponding to the make-up of the soil. Geological features are an important part of UUS evaluation (ITA, 1987; Haasnoot et al., 1997; Edelenbos et al., 1998; Rönkä et al., 1998; ITA-WG4, 2000; Godard, 2004; He et al., 2012; Sterling et al., 2012).	Linear standardisation (the greater the clay percentage, the bigger the SES resilience ratio; (Curiel-Esparza et al., 2004).
Ground water depth	The criterion maps the groundwater level below ordinance datum within the area under analysis. Given the Sherwood Sandstone aquifers in the area under examination, aquifer protection i.e. groundwater depth with respect to MUT placement is an important consideration (Foster, 1987; Butler & Davies, 2004).	Linear standardisation (the lower the depth after >5m, the bigger the SES resilience ratio).
Utilities	The criterion maps existing utility service provision in the area under analysis. These include sewerage, water supply, electric power, gas and telecommunications. MUT's provide a more economical sustainable method for utility placement where utility density is high (Hunt & Rogers, 2005; Rogers & Hunt, 2006; Canto-Perello et al., 2009; Hunt et al., 2014).	Linear standardisation (the greater the density of utilities, the bigger the SES resilience ratio).
Urban population density	The criterion maps the maps the urban population density within the area under analysis. MUT's share the common feature of being population orientated (Canto-Perello & Curiel-Esparza, 2006; Duffaut & Labbé, 2008; Canto-Perello et al., 2009).	Liner standardisation (the greater the population density is, the bigger the SES resilience ratio).

Criteria	Description	Standardisation
Real estate value	Real estate accessibility and prices frequently determine utility network location and provision (Godard, 2004; Chen & Wang, 2005; Canto-Perello & Curiel-Esparza, 2006; Bélanger, 2007; He et al., 2012). The criterion assigns to each land parcel used a real estate value expressed in (£ Million/ acre; Foster et al. (2007), so that real estate property prices are represented.	Linear standardisation (the bigger the real estate prices, the bigger the SES resilience ratio).
Distance to highways	City arteries are intended to circumvent high-populated zones in-so-far as is feasible, and are typically built after major utility networks are already established (ITA, 1987; Canto-Perello & Curiel-Esparza, 2006). The criterion charts the distance to the current highways in/near Birmingham Eastside.	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).
Distance to heritage resources	The criterion maps the distance to the existing heritage resources (areas of archaeological interest and listed buildings) within the area under analysis. Protecting heritage must in no case be neglected when assessing the placement of MUT's (Godard, 2004; Ping et al., 2009; Yang et al., 2010). Sustainable urban underground space policies, which include MUT's, help protect archaeological sites (Curiel-Esparza & Canto-Perello, 2013).	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).
Distance to vegetation/ trees	The criterion maps the distance to existing vegetation/ trees within the area under analysis. A prohibited zone of 1m from the tree trunk needs to be observed (NJUG, 2007).	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).
Distance to railway lines	The criterion maps the distance to existing railway lines within the area under analysis (ITA, 1987).	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).

Criteria	Description	Standardisation
Distance to streets	The criterion maps the distance to streets within the area under analysis; 2m sidewalks boundary (NJUG, 2003). Good arrangement placement for MUTs would be below sidewalks, street edges, or front part street division strips; utility networks coincide at the local street level (Canto-Perello & Curiel-Esparza, 2006).	Liner standardisation (the lower the distance, the bigger the SES resilience ratio).
Distance to canals	The criterion maps the distance to the canals within Birmingham Eastside.	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).
Distance to substations	The criterion maps the distance to substations (transmission; with the exception of one for generation) within the area under analysis *(Canto-Perello and Curiel-Esparza, 2006)*.	Liner standardisation (the lower the distance, bigger the SES resilience ratio).
Distance to natural watercourse	The criterion maps the distance to the natural watercourses within Birmingham Eastside.	Liner standardisation (the greater the distance, the bigger the SES resilience ratio).

The figures below (Figure 5-5 and Figure 5-6) illustrate the standardisation process detailed in the table above (the remaining maps can be found in Appendix E). As can be observed by the topographical standardisation (see Figure 5-5), the source map contains units of slope percentage. The incommensurable units of slope percentage are then standardised to a scale of (0, worst – 1, best). The standardised map colour set is quite simple and easy to understand. The green colour represents areas of high suitability for MUT resilience in UUS of Birmingham Eastside, with respect to topography. The red colour represents areas of low suitability for MUT resilience in UUS of Birmingham Eastside, with respect to topography. Figure 5-6 is a second illustration of the standardisation process, displaying the source and standardised map for the factor 'urban population density'. The incommensurable units of person/ha are then standardised to a scale of (0, worst – 1, best). The standardised map colour set follows the same rational as that of the topography. The green colour represents areas of high suitability for MUT resilience in UUS of Birmingham Eastside, with respect to urban population density. The red colour represents areas of low suitability for MUT resilience in UUS of Birmingham Eastside, with respect to urban population density. All the thematic standardised maps once developed form the basis of analysis in STEP 8 and 9 of the SUURE Operational Model.

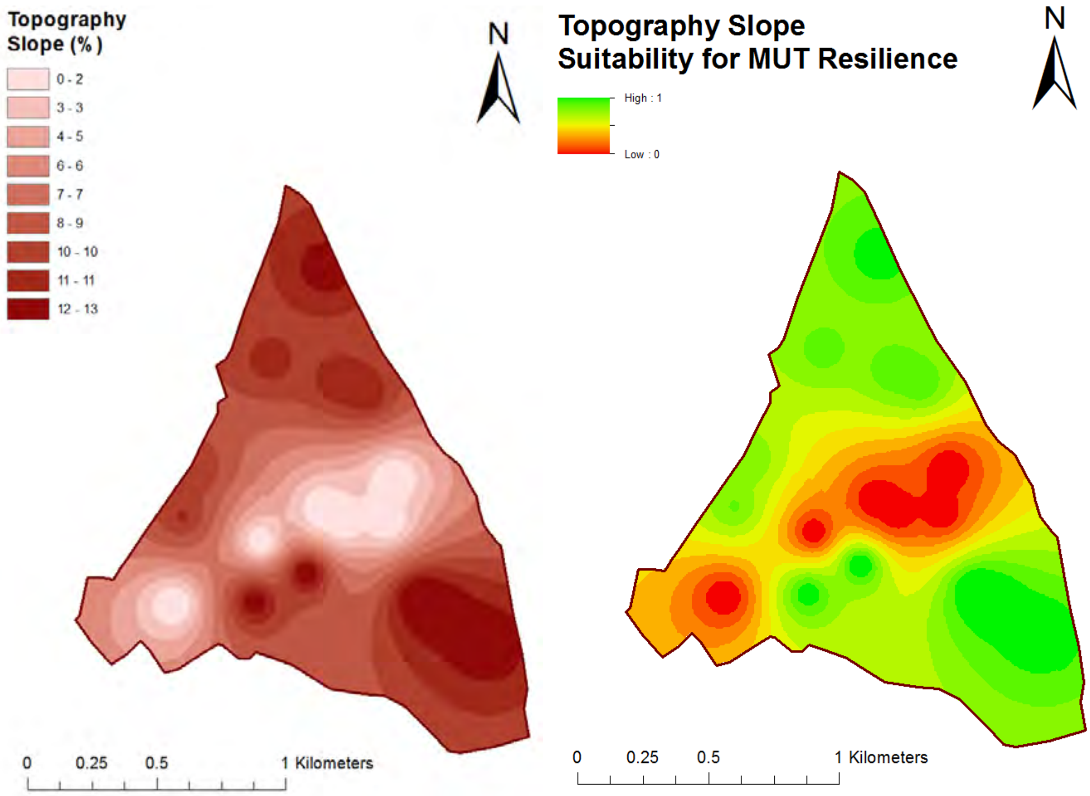


Figure 5-5: Source map and standardised/ reclassified map for the factor 'Topography (≥ 1:500)'

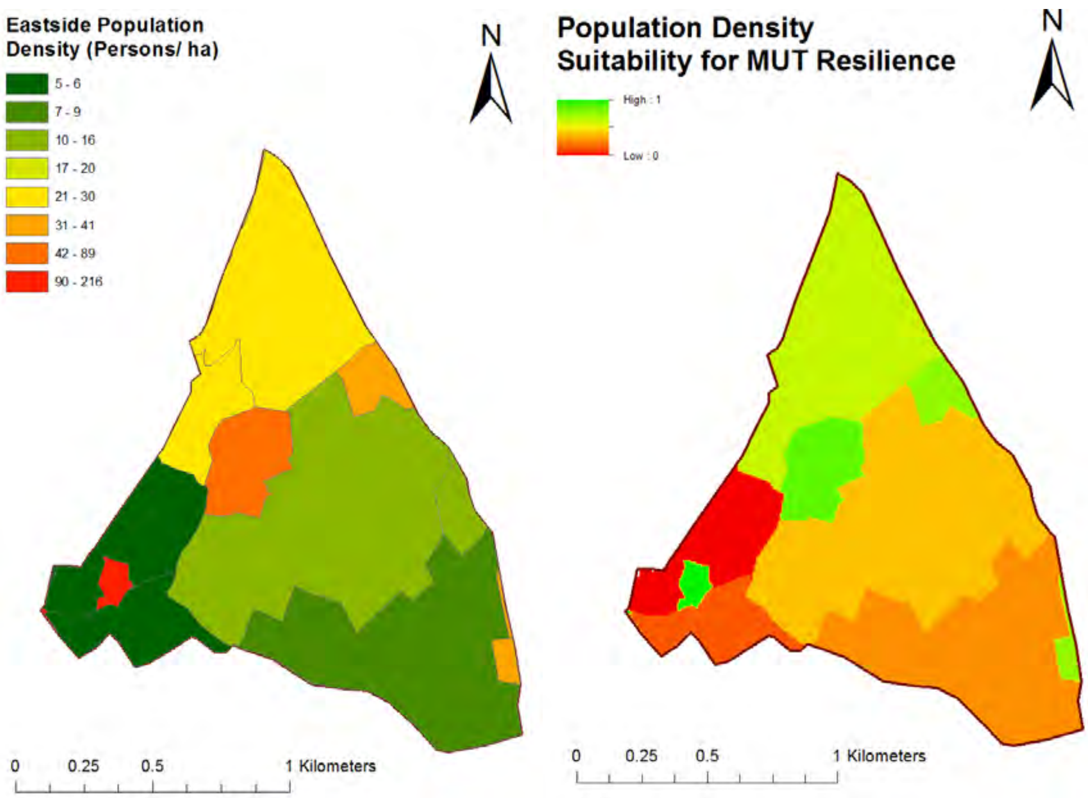


Figure 5-6: Source map and standardised/ reclassified map for the factor 'Urban population density'

5.3.1.5 SUURE Operational Model: Step 6

Step 6 in the SUURE Operational Model necessitates the use of the contextual narrative of the future scenarios (NSP, PR, MF and FW – see) from Rogers et al. (2012) (see Figure 3-3), and more specifically the contextual narrative of the scenarios with respect to the future use of urban underground space provided by Hunt et al. (2011) and summarised below in Table 5-4, to establish the relative functional performance of each criterion (see Table 5-3) to the analysis (overall goal) in each of the different future scenarios as mapped in the ANP network structure (see Figure 5-3) for the case study area under examination, thus permitting the correct use of pairwise comparisons to establish the relative priority weights in different future scenarios. Mention should be made to the application of Super Decisions version 2.2.6 © (Saaty & William, 2004) that was utilised in the present research work to simulate the ANP network structure (see Figure 5-3), and subsequently automatically by design generates the list of pairwise comparison(s) required to run the pairwise analysis.

Table 5-4: Sustainability indicator performance for general underground space use in Future (UK) Scenarios (Hunt et al., 2011)

Sustainability Indicators	Performance in Future (UK) Scenarios				
	MF	PR	NSP	FW_{R*}	FW_{P*}
ENERGY DEMAND					
Thermal (kWh/p/day)	↑	↓	↓↓	↑	↓↓
Electrical (kWh/p/day)	↑	↓	↓	↑	↓↓
Total (kWh/day)	↑↑	↑	↔	↑	↓
EMISSIONS					
CO_2 (Tonnes/p/day)	↑	↓	↓↓	↑	↓
WATER SUPPLY					
Domestic (L/p/day)	↑	↓	↓↓	↑	↓↓
Total (L/day)	↑↑	↔	↓	↑	↓
Leakage (L/day)	↑	↓	↓↓		↑↑
WATER DISPOSAL					
Wastewater (L/day)	↑↑	↑	↓	↑	↓
Stormwater (L/day)	↑↑	↑	↓	↑	↓
WASTE DISPOSAL					
Solid waste (kg/p/day)	↑↑	↓	↓↓	↑	↓

*R – Focus on rich, **P** – Focus on poor
Key: ↑↑ Significant increase, ↑ Increase, ↔ Little/ no change, ↓ Decrease, ↓↓ Significant decrease

At this stage the UF method was used in conjunction with its accompanying characteristic list (see Figure 3-4) to perform a qualitative (coarse analysis) as illustrated in Table 5-4 above, for the evaluation criteria of the case study area under examination (see Table 5-5). One of the limitations that could potentially be experienced during this step is the complexity of evaluating the criteria (necessary conditions) with respect to the many scenario characteristics available. Depending on the sustainability solution under examination, it may well be the case that no direct characteristic can be identified to match a particular criterion. For example, the evaluation criterion of, see Table 5-5, 'Distance to canals' may be well not have a direct matching characteristic. It however can be still be appraised by proxy i.e. utilising an appropriate global characteristic from the UF characteristic list, or creating a characteristic as denoted by the UF method to account for the different future scenarios; for the evaluation criterion 'Distance to canals', the characteristic deemed suitable as a means of conducting the coarse analysis was 'Urban water bodies: amount'. Table 5-5 also shows (in brackets under the criterion) the corresponding UF characteristic utilised in establishing the performance for each of the evaluation criteria in Table 5-3.

Table 5-5: Performance of evaluation criteria with respect to the overall goal in different future scenarios for the case study area under examination – a UK centric perspective of 2050

Sustainability Criteria	Metric (where applicable)	UK (near present)	Performance in Future (UK) Scenarios				
			NSP	PR	MF	FW$_{R*}$	FW$_{P*}$
PHYSICAL ENVIRONMENT							
Land use [*Land use*]	% built up	6 %	↓	↔	↑↑	↑	↑
Geology [*N/A*]	Stratigraphy	varies	↔	↔	↔	↔	↔
Ground water depth [*Total water demand*]	Depth from surface (m)	varies	↑↑	↑	↔	↓	↑
Utilities** [*Use of underground space – urban form*]	Density (m^3/m^2)	varies	↑	↑	↑	↑	↔
Topography [*N/A*]	Elevation (m)	varies	↔	↔	↔	↔	↔
SOCIO-ECONOMIC ASPECTS							
Distance to highways [*Road and parking characteristics*]	(m)	varies	↓	↓	↑	↔	↔
Urban population density [*Urban population density*]	Person/ha	40.3	↑	↔	↓	↓↓	↑
Real estate value [*Need for affordable housing*]	Value of land (£ Million/ acre)	varies	↓	↓	↑↑	↓	↑
LOCATION ASPECTS							
Distance to substation [*Total primary energy demand*]	(m)	varies	↑	↑	↓	↔	↔
Distance to streets [*Road and parking characteristics*]	(m)	varies	↓	↓	↑	↔	↔
^Distance to canals [*Urban water bodies: amount*]	(m)	varies	↑	↑	↓	↔	↓
^Distance to railway lines [*Passenger rail travel*]	(m)	varies	↑	↓	↓	↑	↑
^Distance to natural water courses [*Urban water bodies: amount*]	(m)	varies	↑	↑	↓	↔	↓
BIOPHYSICAL ENVIRONMENT							
Distance to vegetation/ trees [*Degree of maintenance for ecological features*]	(m)	varies	↑	↔	↔	↔	↓
Distance to heritage sources*** [*Quality of strategic planning for biodiversity conservation*]	(m)	varies	↑	↑	↔	↓	↓

Key: ↑↑ Significant increase, ↑ Increase, ↔ Little/ no change, ↓ Decrease, ↓↓ Significant decrease
MF – Market forces, **PR** – Policy Reform, **NSP** – New sustainability paradigm, **FW** – Fortress World
***R** – Focus on rich, **P** – Focus on poor
** All utilities, except gas, are house together in Policy Reform (**PR**)
*** Areas of archaeological interest and listed buildings
[xx] Shows corresponding UF characteristic for the evaluation criterion
^ These criteria are unique to Birmingham Eastside and would otherwise not be considered when evaluating the benefits or otherwise of MUT placement for collocation and coordination of utilities for sustainable use of UUS

The execution of pairwise comparisons permits the performance indicators (see Table 5-5) in tandem with the ANP network structure (see Figure 5-3) to transform these value functions to mathematical representations of human judgement in decision-making regarding the placement of MUTs in Birmingham Eastside. Consequently, this step in the SUURE Operational Model purposes at constructing a judgement approach all through the case study under examination, through transforming the performance indicator of a criterion into an explicit value score (weight). The resulting criterion value score (oscillating between 0, worst -1, best) thus denotes the degree to which the overall goal of the evaluation is realised. Since the SUURE Operational model is a multi-attribute framework i.e. more than one criterion expresses the degree of satisfaction with respect to the overall goal; these have to be combined to perform Step 9 of the SUURE Operational Model (socio-ecological scenario performance resilience ratio). It is important to note that all pairwise comparisons undertaken (for NSP, PR, MF and FW) had to have a consistency ratio of less than 0.1 ($CR = \frac{CI}{RI} < 0.1$) according to Saaty (1980), if not revision is deemed necessary in order to better measurement accuracy (see Table 5-9, and).

[$CR =$ the consistency ratio, $CI =$ consistency index and $RI =$ the average random consistency index]

This makes certain that relative weight estimation for the 'Goal' (see Figure 5-3) and its alternatives (flush-fitting, shallow and deep MUTs) under alternative futures (NSP, PR, MF and FW) maintained an ordered consistency with respect to the transformation of the value function. This is important as the evaluation criterion varied markedly in some cases with respect to the 'Goal' and their differing relative importance in the future scenarios. The use of pairwise comparisons permits a simple and seamless process that can capture the essence of the contextual narrative with respect to different criteria (value functions) under plausible-yet-different future socio-ecological scenarios (NSP, PR, MF and FW). It is important to note that the constraints identified in case study area under examination (see Figure 5-3) are not subject to the pairwise comparison process, this is only for the factors which are then subsequently allocated appropriate weighing as a result of the pairwise comparison process (see Step 7 of the SUURE Operational Model below). Table 5-6 and Table 5-7 display the questions that form part of the pairwise comparison process for the case study area examination, and Table 5-8 displays the 9-point scale for pairwise comparisons (for Table 5-6 and Table 5-7) in ANP for evaluation (see Figure 5-3) with respect to the case study area under examination.

Table 5-6: Questionnaire to evaluate main criteria – Cluster Level

Cluster comparisons with respect to the Overall Goal	
Q1	How important are Socio-Economic Aspects when compared to the Physical Environment
Q2	How important are Socio-Economic Aspects when compared to the Bio-Physical Environment
Q3	How important are Socio-Economic Aspects when compared to Location Aspects
Q4	How important is the Physical Environment when compared to the Bio-Physical Environment
Q5	How important is the Physical Environment when compared to Location Aspects
Q6	How important is the Bio-Physical Environment when compared to Location Aspects

Cluster comparisons with respect to Socio-Economic Aspects	
Q7	How important are Socio-Economic Aspects when compared to the Physical Environment
Q8	How important are Socio-Economic Aspects when compared to Location Aspects
Q9	How important is the Physical Environment when compared to

Cluster comparisons with respect to the Physical Environment	
Q10	How important is the Physical Environment when compared to the Bio-Physical Environment

Table 5-7: Questionnaire to evaluate main criteria – Nodal Level

Comparisons with respect to Ground Water Depth node in Physical Environment Cluster	
Q11	How important are Utilities when compared to Geology

Comparisons with respect to Overall Goal node in Socio-Economic Aspects Cluster	
Q12	How important is Distance to Highways when compared to Real Estate Value
Q13	How important is Distance to Highways when compared to Urban Population Density
Q14	How important is Real Estate Value when compared to Urban Population Density

Comparisons with respect to Overall Goal node in Physical Environment Cluster	
Q15	How important is Geology when compared to Ground Water Depth
Q16	How important is Geology when compared to Land Use
Q17	How important is Geology when compared to Topography
Q18	How important is Geology when compared to Utilities
Q19	How important is Ground Water Depth when compared to Land Use
Q20	How important is Ground Water Depth when compared to Topography
Q21	How important is Ground Water Depth when compared to Utilities
Q22	How important is Land Use when compared to Topography
Q23	How important is Land Use when compared to Utilities
Q24	How important is Topography when compared to Utilities

Comparisons with respect to Overall Goal node in Bio-Physical Environment Cluster	
Q25	How important is Distance to Heritage Resources when compared to Distance to Vegetation

Comparisons with respect to Overall Goal node in Location Aspects Cluster	
Q26	How important is Distance to Canals when compared to Distance to Natural Watercourse
Q27	How important is Distance to Canals when compared to Distance to Railway Lines
Q28	How important is Distance to Canals when compared to Distance to Substations
Q29	How important is Distance to Canals when compared to Distance to Substations
Q30	How important is Distance to Natural Watercourse when compared to Distance to Railway Lines
Q31	How important is Distance to Natural Watercourse when compared to Distance to Substations
Q32	How important is Distance to Natural Watercourse when compared to Distance to Substations
Q33	How important is Distance to Railway Lines when compared to Distance to Substations
Q34	How important is Distance to Railway Lines when compared to Distance to Substations
Q35	How important is Distance to Streets when compared to Distance to Substations

Comparisons with respect to Real Estate Value node in Location Aspects Cluster	
Q36	How important is Distance to Canals when compared to Distance to Railway Lines
Q37	How important is Distance to Canals when compared to Distance to Substations
Q38	How important is Distance to Railway Lines when compared to Distance to Substations

Comparisons with respect to Urban Population Density node in Physical Environment Cluster	
Q39	How important is Ground Water Depth when compared to Land Use
Q40	How important is Ground Water Depth when compared to Utilities
Q41	How important is Land Use when compared to Utilities

Table 5-8: 9-point scale for pairwise comparisons in ANP for evaluation, linguistic terms and their meaning

Notation	Meaning	Intensity of Importance
EP	A criterion or alternative is **extremely preferred** to another	9
EP-VP	A criterion or alternative **is extremely to very strongly preferred** to another	8
VP	A criterion or alternative is **very strongly preferred** to another	7
VP-MP	A criterion or alternative is **very strongly to moderately preferred** to another	6
MP	A criterion or alternative is **moderately preferred** to another	5
MP-SP	A criterion or alternative is **moderately to slightly preferred** to another	4
SP	A criterion or alternative is **slightly preferred** to another	3
SP-QP	A criterion or alternative is **slightly to equally preferred** to another	2
QP	A criterion or alternative is **equally preferred** to another	1
SN-QP	A criterion or alternative is **slightly to equally non-preferred** to another	1/2
SN	A criterion or alternative is **slightly non-preferred** to another	1/3
MN-SN	A criterion or alternative is **moderately to slightly non-preferred** to another	1/4
MN	A criterion or alternative is **moderately non-preferred** to another	1/5
VN-MN	A criterion or alternative is **very strongly to moderately non-preferred** to another	1/6
VN	A criterion or alternative is **very strongly non-preferred** to another	1/7
EN-VN	A criterion or alternative is **very strongly to extremely non-preferred** to another	1/8
EN	A criterion or alternative is **extremely non-preferred** to another	1/9

The results of the pairwise comparisons are displayed in Table 5-9 for the flush-fitting MUT. The results for the shallow and deep MUTs can be found in Appendix F. As can be observed, each of the questions (see Table 5-6 and Table 5-7) were answered assuming the role of the decision maker i.e. placement of MUTs in Birmingham Eastside, under the premise of priorities *n* (flush-fitting, shallow or deep – see Figure 5-3) based on *m* criteria (see Table 5-5). Table 5-9 summarises the result of each question with reference to the MUT type (flush-fitting, shallow or deep) being potentially instituted, against each of the different socio-ecological future scenarios performance indicators for *m* criteria (see Table 5-5). The performance of the criteria changes relative to the characteristics of the socio-ecological scenarios and this is reflected in the manner in which the 9-point scale for pairwise comparison in ANP evaluation is carried out as shown in Table 5-8. The intensity of importance (*W*) is paired against the future scenario it is evaluated in, with the consistency ratio (*CR*) having to be less than 0.1 (signifying a consistency in judgement). Table 5-9 is the basis on which Step 7 of the SUURE Operational Model is carried out i.e. the formulation of priority weights (supermatrix) for each of the sustainability criteria in the different future scenarios and for each of the alternative MUT options (flush-fitting, shallow and deep).

Table 5-9: Evaluation results of the pairwise comparisons with respect to Flush-fitting MUT in different future scenarios

Key: W = Intensity of Importance for Pairwise Comparisons (see Table 5-8), CR = Consistency Ratio, NSP - PR - FW_R - FW_P - MF = Socio-Ecological Future Scenarios

Pairwise Criteria	Results for different future scenarios									
	NSP - W	**NSP- CR**	**PR - W**	**PR - CR**	**MF - W**	**MF - CR**	**FW_R - W**	**FW_R - CR**	**FW_P - W**	**FW_P - CR**
Q1	SP-QP	0.04288	SP-QP	0.04288	VP-MP	0.06395	SP-QP	0.04288	VP-MP	0.06395
Q2	VP-MP	0.04288	VP-MP	0.04288	VP-MP	0.06395	VP-MP	0.04288	VP-MP	0.06395
Q3	EP-VP	0.04288	EP-VP	0.04288	EP-VP	0.06395	EP-VP	0.04288	EP-VP	0.06395
Q4	MP	0.04288	MP	0.04288	MP-SP	0.06395	MP	0.04288	MP-SP	0.06395
Q5	VP	0.04288	VP	0.04288	SP-QP	0.06395	VP	0.04288	SP-QP	0.06395
Q6	SP	0.04288	SP	0.04288	QP	0.06395	SP	0.04288	QP	0.06395
Q7	SP-QP	0.03112	SP-QP	0.03112	MP-SP	0.06852	SP-QP	0.03112	MP-SP	0.06852
Q8	VP	0.03112	EP-VP	0.03112	EP	0.06852	VP	0.03112	EP	0.06852
Q9	VP-MP	0.03112	VP-MP	0.03112	MP	0.06852	VP-MP	0.03112	MP	0.06852
Q10	VP	0.0	VP	0.0	EP	0.0	VP	0.0	EP	0.0
Q11	MN-SN	0.0	SP	0.0	SN	0.0	MN	0.0	VN-MN	0.0
Q12	MN	0.05156	SN	0.05156	MN-SN	0.0	VN	0.07348	SN	0.07069
Q13	MN	0.05156	SN	0.05156	MN-SN	0.0	EN-VN	0.07348	MN-SN	0.07069
Q14	SP-QP	0.05156	SP-QP	0.05156	QP	0.0	SP-QP	0.07348	SN	0.07069
Q15	MP-SP	0.08963	MP	0.09351	QP	0.00222	SP	0.08945	QP	0.00134
Q16	MN-SN	0.08963	SN	0.09351	QP	0.00222	MN	0.08945	QP	0.00134
Q17	MN-SN	0.08963	SN	0.09351	QP	0.00222	MN	0.08945	QP	0.00134
Q18	VN-MN	0.08963	SN	0.09351	MN-SN	0.00222	VN	0.08945	MN	0.00134
Q19	MN	0.08963	MN	0.09351	QP	0.00222	VN-MN	0.08945	QP	0.00134
Q20	SN	0.08963	SN-QP	0.09351	QP	0.00222	MN-SN	0.08945	QP	0.00134
Q21	MN	0.08963	MN-SN	0.09351	SN	0.00222	VN-MN	0.08945	MN-SN	0.00134
Q22	SP-QP	0.08963	SP	0.09351	QP	0.00222	SP-QP	0.08945	QP	0.00134
Q23	SN-QP	0.08963	QP	0.09351	SN	0.00222	SN	0.08945	MN-SN	0.00134
Q24	MN-SN	0.08963	SN	0.09351	SN	0.00222	MN	0.08945	MN-SN	0.00134
Q25	MN-SN	0.0	SN	0.0	QP	0.0	VN-MN	0.0	SN	0.0

Pairwise Criteria	**Results for different future scenarios**									
	NSP - W	**NSP- CR**	**PR - W**	**PR - CR**	**MF - W**	**MF - CR**	**FW_R - W**	**FW_R - CR**	**FW_P - W**	**FW_P - CR**
Q26	MP-SP	0.03543	MP	0.05205	QP	0.0	SP	0.03651	QP	0.0
Q27	SP	0.03543	MP-SP	0.05205	QP	0.0	SP-QP	0.03651	QP	0.0
Q28	VN-MN	0.03543	MN	0.05205	QP	0.0	VN	0.03651	QP	0.0
Q29	MN-SN	0.03543	SN	0.05205	QP	0.0	MN	0.03651	QP	0.0
Q30	SN-QP	0.03543	QP	0.05205	QP	0.0	SN	0.03651	QP	0.0
Q31	EN	0.03543	EN-VN	0.05205	QP	0.0	EN	0.03651	QP	0.0
Q32	EN-VN	0.03543	VN	0.05205	QP	0.0	EN	0.03651	QP	0.0
Q33	EN-VN	0.03543	VN	0.05205	QP	0.0	EN	0.03651	QP	0.0
Q34	VN	0.03543	VN-MN	0.05205	QP	0.0	EN-VN	0.03651	QP	0.0
Q35	SP-QP	0.03543	SP	0.05205	QP	0.0	QP	0.03651	QP	0.0
Q36	MP-SP	0.05156	MP	0.06239	QP	0.0	SP	0.02795	SP-QP	0.05156
Q37	MN-SN	0.05156	SN	0.06239	SN	0.0	MN	0.02795	SN-QP	0.05156
Q38	EN-VN	0.05156	VN	0.06239	SN	0.0	EN	0.02795	SN-QP	0.05156
Q39	MN-SN	0.07348	SN	0.01759	SN-QP	0.05156	MN	0.06033	MN-SN	0.02365
Q40	VN	0.07348	VN-MN	0.01759	SN-QP	0.05156	EN	0.06033	MN	0.02365
Q41	MN-SN	0.07348	SN	0.01759	SN-QP	0.05156	MN-SN	0.06033	SN-QP	0.02365

5.3.1.6 SUURE Operational Model: Step 7

In Step 7, at the completion of the pairwise comparisons (see Table 5-9 and Appendix F), the formation of matrices (initial, weighted and super matrix) from the pairwise comparisons formed the basis for computation of related priority vectors (scenario for each criterion). The unweighted supermatrix represents the pairwise comparisons at the node level. The multiplication of the unweighted supermatrix with the cluster level weighted matrix thus produces the weighted supermatrix. The weighted supermatrix is then raised to a limiting power (see Eq 5-8), with the intention of focalising, therefore getting a perennial constant set of weights that characterises the ultimate priority vector(s) of the elements contained within the ANP network structure for Birmingham Eastside. This is an important step as it permits the capture of transmission of influence down every probable (decision-making) pathway of the supermatrix.

According to Saaty (2005) the priorities vector has the following structure:

$$[w_{1,1}, w_{2,1}, w_{4,1}]^T$$ **Eq 5-6**

Before its introduction into the supermatrix this vector has to be completed with 0s:

$$[w_{1,1}, w_{2,1}, 0, w_{4,1}]^T$$ **Eq 5-7**

According to Saaty (2005) the limit supermatrix is computed by:

$$\lim_{k\to\infty} \frac{1}{N} \sum_{k=1}^{N} W^k$$ **Eq 5-8**

where W^k k=1, 2,…. represents the influence sequence of a matrix, its square, its cube, etc.

As stated by Sylvester (1867); (Sylvester, 1884) the entire function of the above (diagonalisable) matrix W whose distinctive roots are discrete can be denoted as:

$$f(W) = \sum_{i=1}^{n} f(\lambda_i) Z(\lambda_i)$$ **Eq 5-9**

where

$$Z(\lambda_i) = \frac{\prod_{j\neq i}(\lambda_j I - W)}{\prod_{j\neq i}(\lambda_j - \lambda_i)}$$ **Eq 5-10**

According to Saaty (1980) $Z(\lambda_i)$ can be shown to be complete idempotent matrices of W, having the properties:

$$\sum_{i=1}^{k} Z(\lambda_i) = I, Z(\lambda_i)Z(\lambda_j) = 0, i \neq j, Z^2(\lambda_i) = Z(\lambda_i),$$ **Eq 5-11**

where *I* and *0* are the identity and null matrices, in that order.

Table 5-10: Supermatrix of 'Flush-fitting MUT – NSP'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Flush MUT (NSP) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.08875	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.55907	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.35219	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.08551	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.04919	0.00000	0.00000	0.07543	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.25894	0.00000	0.00000	0.22905	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.16568	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.44067	0.00000	1.00000	0.69552	1.00000	0.80000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.10952	0.00000	0.22273	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.03529	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.05128	0.00000	0.07015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.48594	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.31797	0.00000	0.70712	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.04610	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29402	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.18296	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.02904	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.01671	0.00000	0.00000	0.02824	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.08793	0.00000	0.00000	0.08575	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05626	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.14964	0.00000	0.83370	0.26039	1.00000	0.80000	0.87500	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.01888	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.07554	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00510	0.00000	0.03704	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00164	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00239	0.00000	0.01167	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02261	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01480	0.00000	0.11759	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.025570	0.224562	0.101473	0.018531	0.012130	0.057468	0.031204	0.406357	0.010474	0.049080	0.011144	0.000911	0.003943	0.012541	0.034613

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table 5-10 above summarises the process of supermatrix creation (initial, weighted and limiting) for a flush-fitting MUT in the socio-ecological scenario of NSP. From the original priorities vector amongst clusters the initial unweighted supermatrix is formulated. The original supermatrix has to become a matrix by stochastic columns. That way it can converge when raising it to successive powers that being the central reason why the cluster priorities are needed to formulate the weighted supermatrix. Having formulated the weighted matrix, raising the weighted supermatrix to limiting powers until all the entries converge. At the end, all the columns are the same and their values show the global priority of each element of the ANP network. From the limiting supermatrix, its values are normalised with reference to the alternatives and the criteria separately to obtain the priority weights (see Table 5-11),

The model builder tool in ArcGIS 10.2 © provides the ability to utilise a number of different approaches with respect to the application of weights gained in Step 7, which are applied to the weighted overlay analysis to be carried out in Step 9 (scenario resilience performance ratio). Input of weights can be through a ranking order, direct method or pairwise comparison at any level in the model tree built. The present research work utilised the direct method as all the priority weights had been computed from the ANP network structure model and could therefore be attributed to their corresponding factor raster map under analysis. The tables showing initial unweighted, weighted and limiting matrices of the alternatives MUT placement options under various future scenarios (NSP, PR, MF and FW) are shown in Table 5-10 (an example) and the rest in Appendix G. The resultant summarised priorities of elements and clusters (weights) measured in the investigation are shown below in Table 5-11 (an example) and the rest in Appendix H.

Table 5-11: Priorities (weights) of all elements considered in the network for 'Flush-fitting MUT – NSP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.351605)	
Distance to highways	0.025570
Urban Population Density	0.101473
Real Estate Value	0.224562
Physical Environment (0.525690)	
Topography (≥ 1:500)	0.031204
Land use	0.057468
Geology	0.018531
Ground water depth (>5m)	0.012130
Utilities	0.406357
Bio-Physical Environment (0.059554)	
Distance to heritage resources	0.010474
Distance to vegetation/ trees	0.049080
Location Aspects (0.063152)	
Distance to railway lines	0.003943
Distance to streets	0.012541
Distance to canals	0.011144
Distance to substations	0.034613
Distance to natural watercourse	0.000911

5.3.2 SUSTAINABILITY EVALUATION: REVIEW AND DETAILED ANALYSIS

As previously shown in Chapter 4, a 3D geological model was generated using the software GSI3D to reconstruct the geological spatial distribution of Birmingham Eastside. The 3D geological model was converted to a 2D raster, representing through pixels, the lithology and stratigraphical information of the 3D geological model (including Z – height to *top* and *bottom* surface of each geological layer) for use in the SUURE Operational Model. It was identified through the course of this research that a limitation exists when utilising the 2D model for analyses (baseline –Step 8 and scenario – Step 9) in the SUURE Operational Model in ArcGIS 10.2. For the *Physical Environment* cluster, *Socio-Economic Aspects* cluster as well as the *Overall Goal*, the analysis *(when including the 2D Geological Model)* was limited to areas where there was existing physical infrastructure (buildings, utilities etc.). The limitation as evidenced in this research is that the resultant maps for the *Physical Environment* cluster, *Socio-Economic Aspects* cluster as well as the *Overall Goal*, contain blank '*white areas*' that do not reflect any geometrical volume of the ground considered in the model for analysis. This unfavourable result does not deter from the novel methodology put forward by the SUURE Operational Model to include geological ground models (in the future, 3D models conditional on a computational ontogenesis) in a sustainability evaluation of UUS resources to support future UUS planning. The basis as to why the 2D raster geological model could not be accounted for in SUURE evaluation for the whole area under Eastside could not be established i.e. is it a limitation due to ArcGIS 10.2, GSI3D data conversion, or a limitation with reference to raster (fuzzy –baseline) multi-criteria evaluation, and was deemed beyond the scope of the current research exercise. It is noteworthy that for any future research with reference to the SUURE Operational Model, this discrepancy ought to be addressed to fully realise the objective purpose of the SUURE Framework. The user is alerted to the blank '*white areas*' in resultant GIS maps (for both Step 8 and 9 of the SUURE Operational Model, specifically the *Physical Environment* cluster, *Socio-Economic Aspects* cluster as well as the *Overall Goal*) do not reflect any result/meaning (resilience index ratio) as to the potential for MUT placement or otherwise and should be disregarded when reading the resultant GIS maps of Step 8 and 9 in the SUURE Operational Model.

5.3.2.1 SUURE Operational Model: Step 8

Step 8 is the fuzzy baseline resilience analysis. This step achieves two things:

1. It scales the input data on the defined scale (0-1);
2. It combines all the intelligence and design stages i.e. all the maps and the fuzzy membership functions (see Table 5-2); fuzzy overlay analyses are performed after the schema displayed in Table 5-2, which displays the definition of set classes and characteristics of the phenomenon as a representation of its modelling structure.

As a result of this step, the baseline resilience performance index ratios for the case study area under examination were generated for flush-fitting, shallow and deep MUTs. The analyses carried out was conducted in ArcGIS 10.2, and made use of the in-built model builder that permit a model to be synthesized to meet the analyses needs of the present research work (see Table 5-2).

5.3.2.2 SUURE Operational Model: Step 9

Step 9 is the scenario analysis. This step achieves two things:

1. It scales the input data on the defined scale (0-1);
2. It utilises the standardised data, and the priority weights gained from the pairwise comparisons as the basis for combination of and analysis of all the standardised map layers.

As a result of this step, the baseline resilience performance index ratios for the case study area under examination were generated for flush-fitting, shallow and deep MUTs. The analyses carried out was conducted in ArcGIS 10.2, and made use of the in-built model builder that permit a model to be synthesized to meet the analyses needs of the present research work (see Figure 5-3).

This step follows the weighted overlay formula:

$$S = \sum_{i=1}^{n} W_i X_i \times \prod_{j=1}^{m} C_j \qquad \textbf{Eq 5-12}$$

where S = suitability for resilience, W_i = weight of factor i, X_i = the criterion score of factor i, and C_j = the constraint j.

The weighted overlay assumes that the more favourable elements are (priority weights), the better the result. The weighted overlay is neither an 'AND' (minimum operator) or an 'OR' (maximum operator); it ranges between the two.

5.3.2.2.1 Baseline Analysis Results

At the completion of Step 8 of the SUURE Operational Model, the baseline analysis results for the case study area under examination were collated. It should be noted that as shown in Table 5-2, an 'AND' fuzzy overlay operator was selected for each of the cluster analyses, principally as it replicates the 'worst case scenario' approach to design i.e. it finds the minimum functional performance which would otherwise be lost if an 'OR' maximum fuzzy overlay function was used. However, subsequent to the cluster analysis as shown in Table 5-2, the 'OR' i.e. maximum function was used for the overall MUT baseline resilience analysis; this is principally because the 'OR' function finds the maximum - minimum values of the cluster analysis. The sections below review each MUT type with relation to their baseline results.

5.3.2.2.1.1 Flush MUT Baseline Results

Figure 5-7 shows the result of the fuzzy baseline analysis for the bio-physical environment. Majority of vegetation/trees in Birmingham Eastside are on the surface; in addition to the heritage resources classed as such i.e. listed buildings, etc. It would therefore explain why the performance for the bio-physical baseline resilience performance as shown by ranges from a resilience ratio maximum of 0.83, with a mean ratio of 0.16 and a standard deviation 0.23; and from Figure 5-7, the indication is that bio-physical environmental aspects for the flush-fitting MUT have to be resolved i.e. removal of vegetation/trees as a means of improving the resilience index ratio.

Figure 5-7 shows the result of the fuzzy baseline analysis for location aspects. Birmingham Eastside given its natural watercourses, canals and railway lines at the surface, represents a number of fuzzy obstacles for the placement of the flush-fitting MUT. This indicates why the performance for the location aspects baseline resilience performance as shown by ranges from a resilience ratio maximum of 0.54, with a mean ratio of 0.03 and a standard deviation 0.09. At this present time as shown by Figure 5-7, the location aspects are not suited towards flush-fitting MUT placement.

Figure 5-7 shows the result of the fuzzy baseline analysis for the physical environment. It indicates that at this present time, the physical environment can support the placement of flush-fitting MUT(s). This indicates why the performance for the physical environment baseline resilience performance as shown by Figure 5-7 ranges from a resilience ratio maximum of 1, a minimum of 0.18, with a mean ratio of 0.52 and a standard deviation 0.18.

Figure 5-7 shows the result of the fuzzy baseline analysis for socio-economic aspects. It indicates that at this present time, the socio-economic conditions can support the placement of flush-fitting MUT(s). This indicates why the performance for the socio-economic aspects baseline resilience performance as shown by Figure 5-7 ranges from a resilience ratio maximum of 1, a minimum of 0.16, with a mean ratio of 0.62 and a standard deviation 0.26.

The overall composite MUT fuzzy baseline analysis as shown in Figure 5-7 indicates that the flush-fitting MUT is suitable to place in Birmingham Eastside as a means of engendering sustainable use of underground space, through sustainable utility placement; Figure 5-7 shows its composite baseline resilience ratios range from a maximum of 1, a minimum 0.24, with a mean ratio of 0.74 and a standard deviation 0.20.

5.3.2.2.1.2 Shallow MUT Baseline Results

Figure 5-8 shows the result of the fuzzy baseline analysis for the bio-physical environment. Majority of vegetation/trees in Birmingham Eastside are on the surface; in addition to the heritage resources classed as such i.e. listed buildings, etc. It would therefore explain why the performance for the bio-physical baseline resilience performance as shown by ranges from a resilience ratio maximum of 1, a minimum of 0.17, with a mean ratio of 0.69 and a standard deviation 0.25; and from Figure 5-8, the indication is that bio-physical environmental aspects for the shallow MUT are suitable for MUT placement.

Figure 5-8 shows the result of the fuzzy baseline analysis for location aspects. Birmingham Eastside given its natural watercourses, canals and railway lines at the surface, represents a number of fuzzy obstacles for the placement of the shallow MUT. This indicates why the performance for the location aspects baseline resilience performance as shown by Figure 5-8 ranges from a resilience ratio maximum of 0.44, with a mean ratio of 0.02 and a standard deviation 0.07.

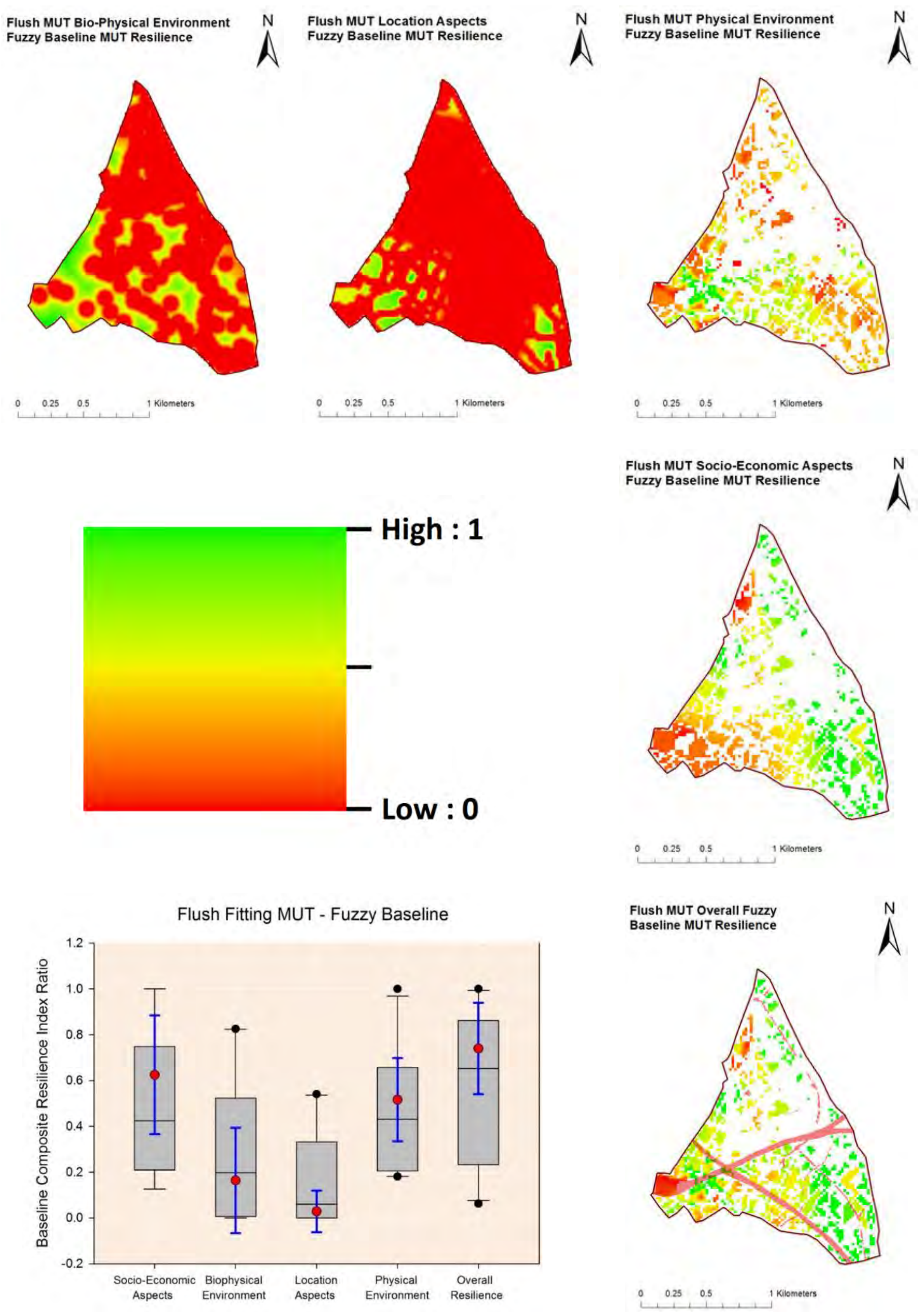


Figure 5-7: Derived maps of the fuzzy bio-physical environment, location aspects, physical environment and socio-economic aspects of the flush-fitting MUT resilience as well as overall fuzzy baseline flush-fitting MUT resilience. The bottom left shows the baseline composite resilience index ratios for flush-fitting MUT, showing the min, max, mean, range and the standard deviation

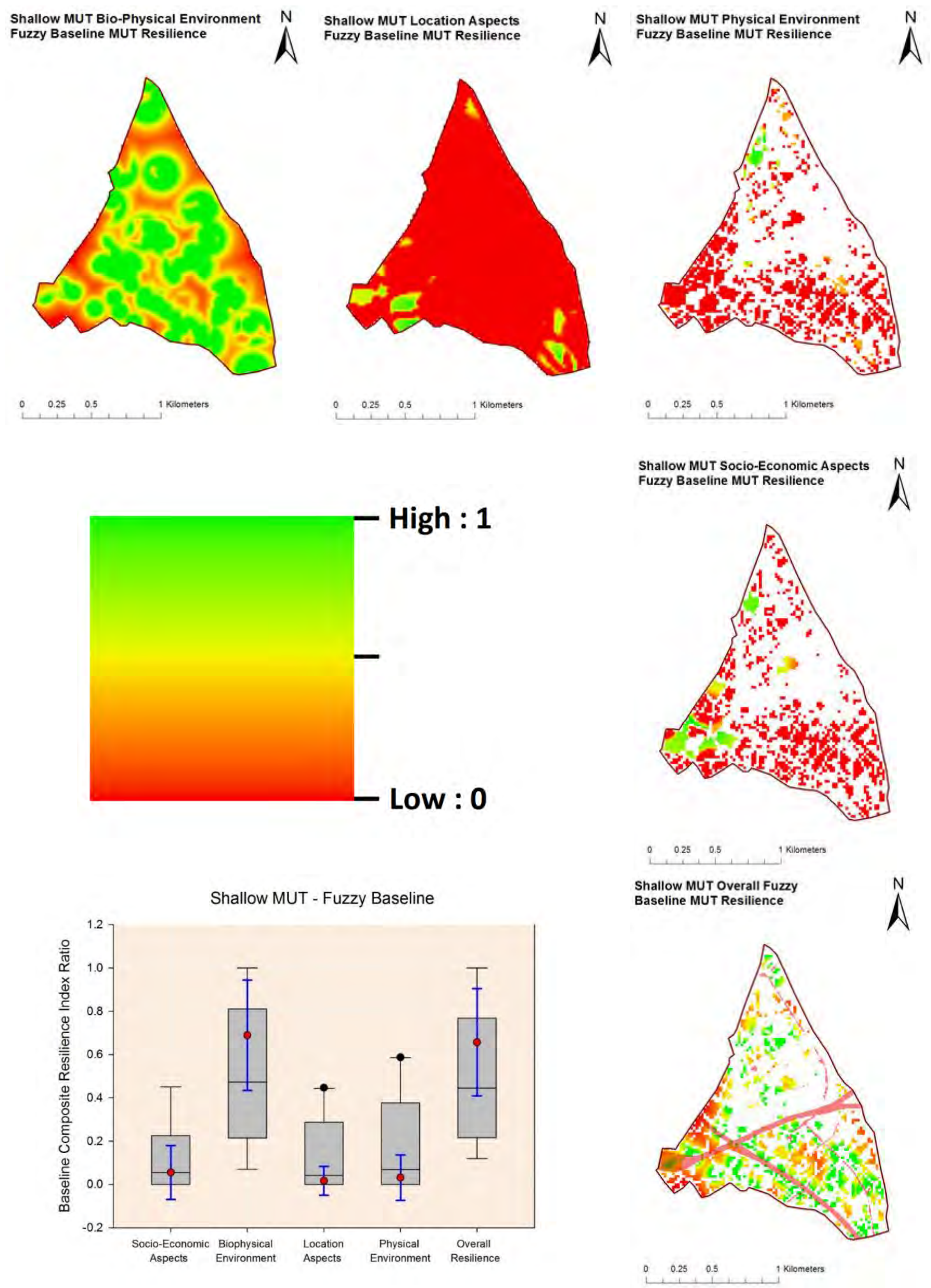


Figure 5-8: Derived maps of the fuzzy bio-physical environment, location aspects, physical environment and socio-economic aspects of the shallow MUT resilience as well as overall fuzzy baseline shallow MUT resilience. The bottom left shows the baseline composite resilience index ratios for shallow MUT, showing the min, max, mean, range and the standard deviation

Figure 5-8 shows the result of the fuzzy baseline analysis for the physical environment. It indicates that at this present time, the physical environment cannot support the placement of shallow MUT(s). This indicates why the performance for the physical environment baseline resilience performance as shown by Figure 5-8 ranges from a resilience ratio maximum of 0.58, with a mean ratio of 0.03 and a standard deviation 0.10.

Figure 5-8 shows the result of the fuzzy baseline analysis for socio-economic aspects. It indicates that at this present time, the socio-economic conditions cannot support the placement of shallow MUT(s). This indicates why the performance for the socio-economic aspects baseline resilience performance as shown by Figure 5-8 ranges from a resilience ratio maximum of 0.45, with a mean ratio of 0.05 and a standard deviation 0.12.

The overall composite MUT fuzzy baseline analysis as shown in Figure 5-8 indicates that the shallow MUT is suitable to place in Birmingham Eastside as a means of engendering sustainable use of underground space, through sustainable utility placement; Figure 5-8 shows its composite baseline resilience ratios range from a maximum of 1, a minimum 0.18, with a mean ratio of 0.66 and a standard deviation 0.25.

5.3.2.2.1.3 Deep MUT Baseline Results

Figure 5-9 shows the result of the fuzzy baseline analysis for the bio-physical environment. Majority of vegetation/trees in Birmingham Eastside are on the surface; in addition to the heritage resources classed as such i.e. listed buildings, etc. It would therefore explain why the performance for the bio-physical baseline resilience performance as shown by ranges from a resilience ratio maximum of 0.76, with a mean ratio of 0.17 and a standard deviation 0.22; and from Figure 5-9, the indication is that bio-physical environmental aspects for the deep MUT are mostly.

Figure 5-9 shows the result of the fuzzy baseline analysis for location aspects. Birmingham Eastside given its natural watercourses, canals and railway lines at the surface, represents a number of fuzzy obstacles for the placement of the deep MUT. This indicates why the performance for the location aspects baseline resilience performance as shown by Figure 5-9 ranges from a resilience ratio maximum of 0.55, with a mean ratio of 0.03 and a standard deviation 0.09.

Figure 5-9 shows the result of the fuzzy baseline analysis for the physical environment. It indicates that at this present time, the physical environment cannot support the placement of deep MUT(s). This indicates why the performance for the physical environment baseline resilience performance as shown by Figure 5-9 ranges from a resilience ratio maximum of 0.55, with a mean ratio of 0.02 and a standard deviation 0.10. Figure 5-9 shows the result of the fuzzy baseline analysis for socio-economic aspects. It indicates that at this present time, the socio-economic conditions cannot support the placement of deep MUT(s). This indicates why the performance for the socio-economic aspects baseline resilience performance as shown by Figure 5-9 ranges from a resilience ratio maximum of 0.62, with a mean ratio of 0.08 and a standard deviation 0.17.

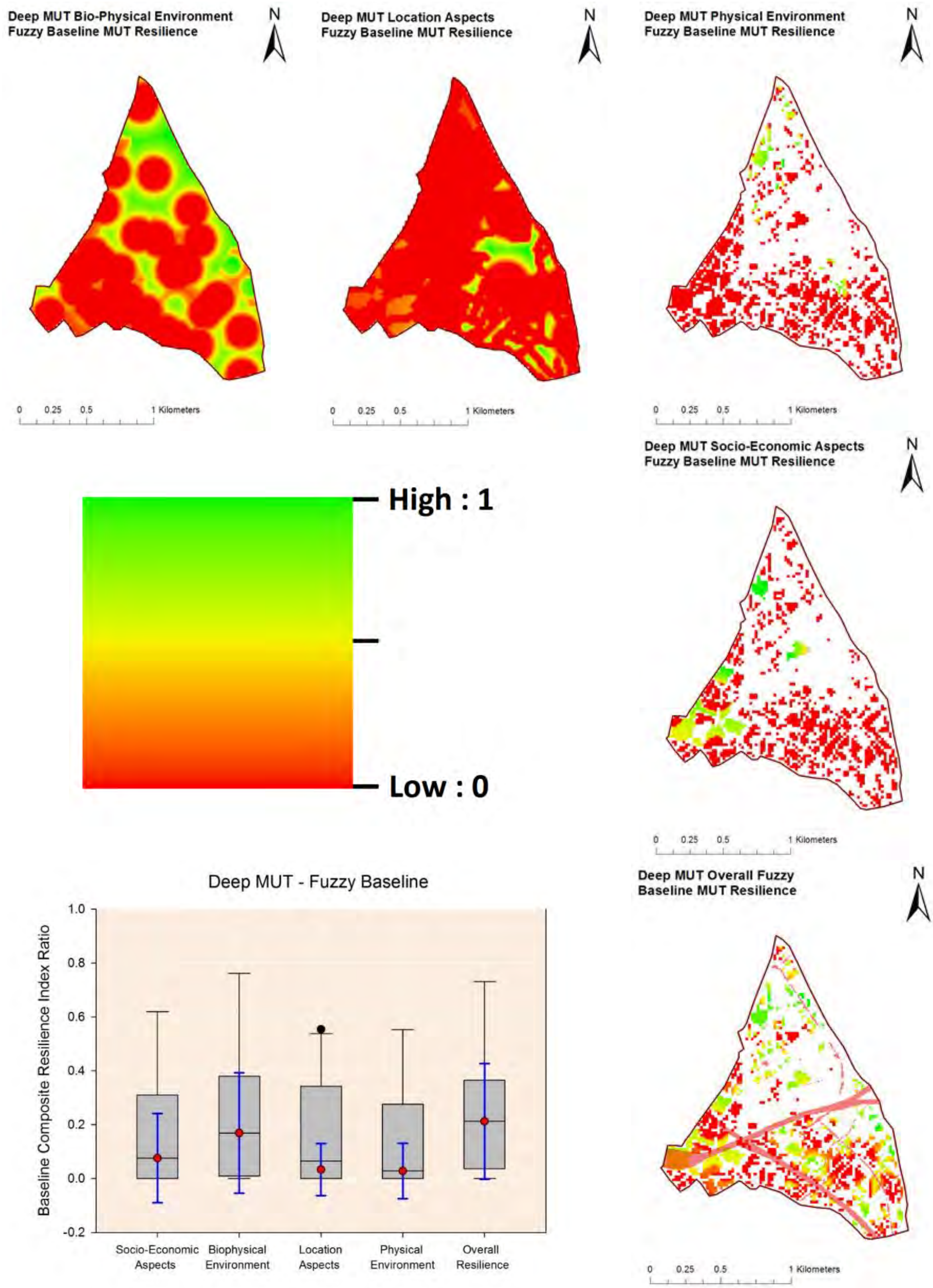


Figure 5-9: Derived maps of the fuzzy bio-physical environment, location aspects, physical environment and socio-economic aspects of the deep MUT resilience as well as overall fuzzy baseline deep MUT resilience. The bottom left shows the baseline composite resilience index ratios for deep MUT, showing the min, max, mean, range and the standard deviation

The overall composite MUT fuzzy baseline analysis as shown in Figure 5-9 indicates that the deep MUT is mildly suitable to place in Birmingham Eastside as a means of engendering sustainable use of underground space, through sustainable utility placement; Figure 5-9 shows its composite baseline resilience ratios range from a maximum of 0.73, with a mean ratio of 0.21 and a standard deviation 0.21. Either a strong political will or significant project e.g. HS2 terminal in Birmingham Eastside would propel the likelihood of deep MUT placement at this present time.

5.3.2.2.2 Sensitivity Analysis of Fuzzy Overlay Functions

Characterisation of the baseline conditions in Birmingham Eastside was carried out using fuzzy membership functions as shown in Table 5-2. Given the use of both the MSSmall and MSLarge membership functions (expert semantic descriptions – reflecting degrees of truth), and in some cases a hedge necessary to adjust the function to reflect present day conditions i.e. real-world phenomena, it was deemed important to conduct a sensitivity analysis to observe how these membership functions (given the criteria) operate under different overlay functions (how the evidence is combined), unlike the configuration illustrated in Table 5-2 (using fuzzy 'AND' and 'OR' operators). Different fuzzy overlay functions utilised were for the sensitivity analysis, accounting for all the clusters and overall goal were:

$Fuzzy\ OR$	$\mu(x) = Max(\mu_i)$	**Eq 5-13**
$Fuzzy\ AND$	$\mu(x) = Min(\mu_i)$	**Eq 5-14**
$Fuzzy\ Product$	$\mu(x) = \pi_{i=1}^{n}\mu_i$	**Eq 5-15**
$Fuzzy\ Sum$	$\mu(x) = 1 - \pi_{i=1}^{n}(1 - \mu_i)$	**Eq 5-16**
$Gamma$	$\mu(x) = (FuzzySum)^{\gamma} * (FuzzyProduct)^{1-\gamma}$ where γ is a user input	**Eq 5-17**

$x = memebrship\ value\ for\ crisp\ measurment$
$I = Specifies\ each\ of\ the\ (n) evidence\ layers$

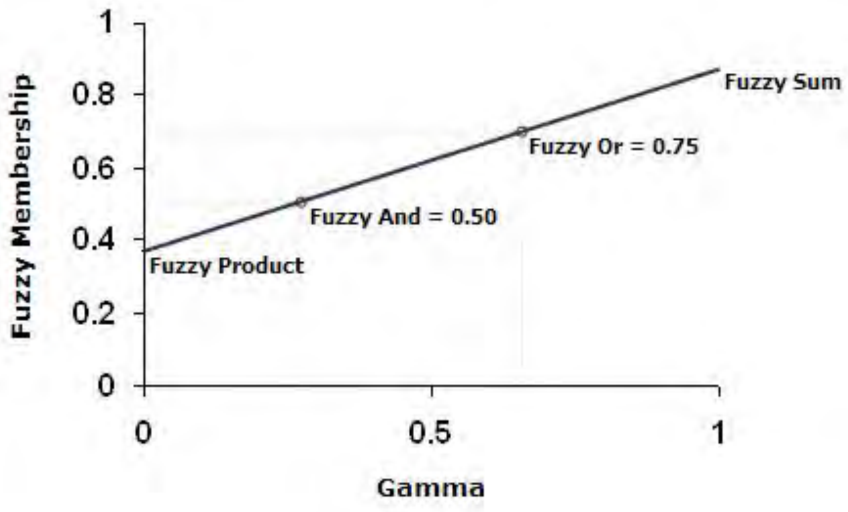


Figure 5-10: Relationship of Fuzzy Gamma to other fuzzy overlay relationship types (ArcGIS 10.2, 2013)

These fuzzy operators afford greater flexibility in contrast to weighted-overlay (utilised for the scenario analysis) as they can be adjusted accordingly with respect to how the criteria ought to interact

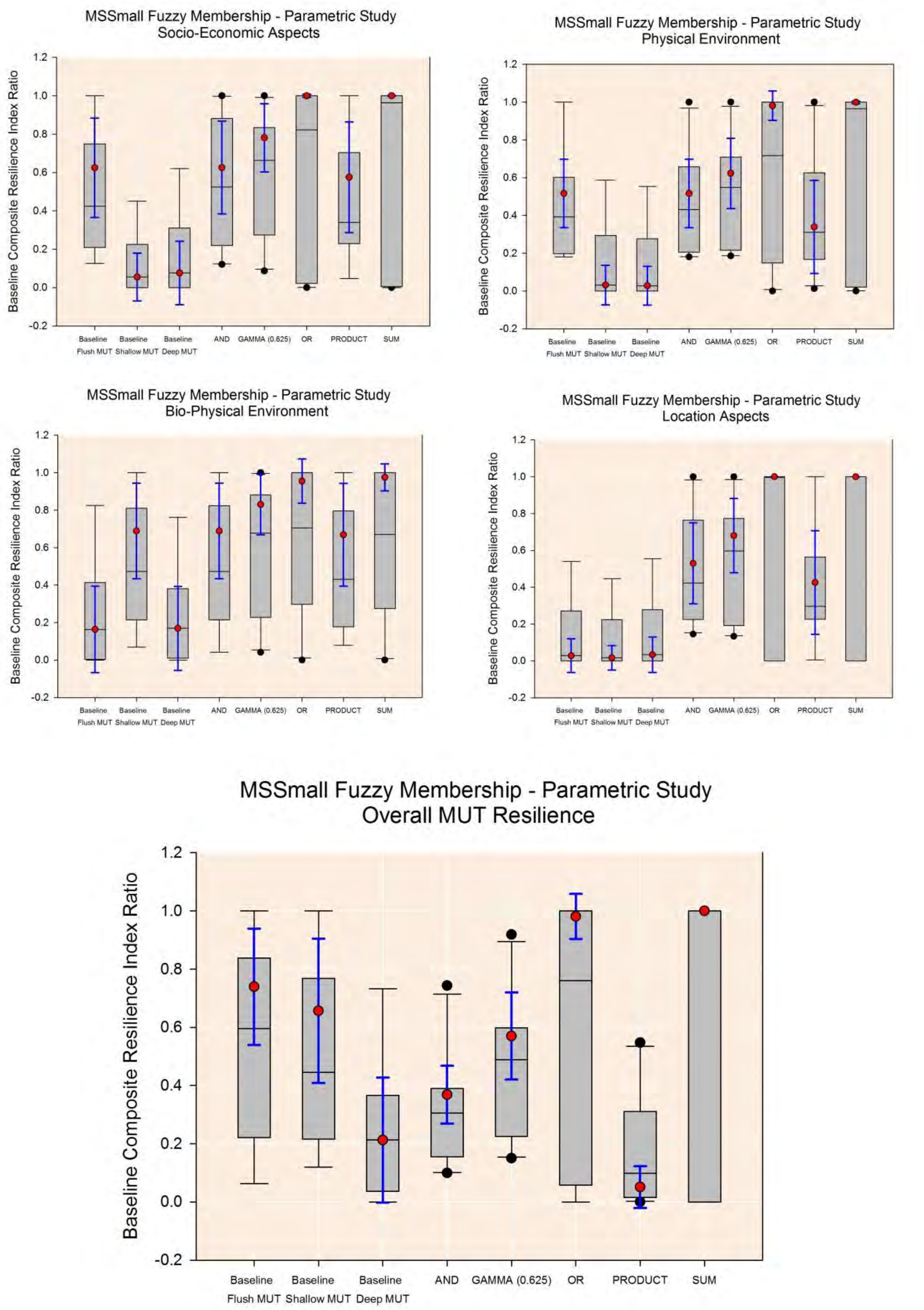


Figure 5-11: Sensitivity Analysis of Fuzzy Overlay Functions - MSSmall Fuzzy Membership Type, showing the min, max, mean, range and the standard deviation

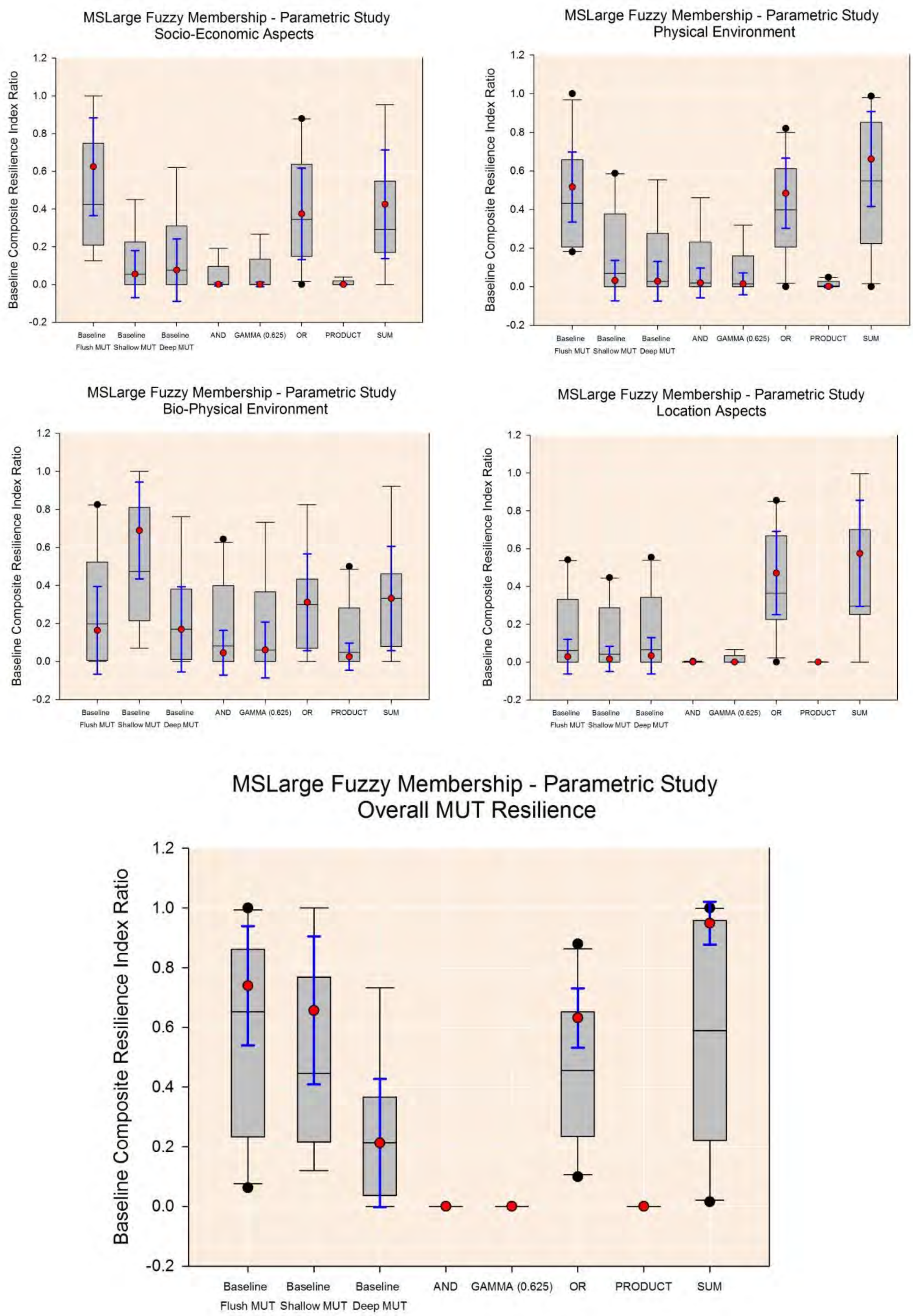


Figure 5-12: Sensitivity Analysis of Fuzzy Overlay Functions – MSLarge Fuzzy Membership type, showing the min, max, mean, range and the standard deviation

(membership value for crisp measurements). Selecting a fuzzy overlay function is relatively straightforward, but overlay functions tend to require some fine tuning to as a reflection of expert knowledge. Table 5-2 is an example of a simple fuzzy logic spatial model, appropriate to the case study area of Birmingham Eastside. As illustrated by the Figure 5-10 above, both the fuzzy sum and product are extreme functions and are rarely utilised in practice - help file, ArcGIS 10.2 (2013). The gamma overlay function necessitates the user to define algebraic value by which it is to be raised; if it is 1, then it corresponds to the fuzzy sum, if it is 0, then it corresponds to the fuzzy product. The fuzzy gamma is a function often utilised to represent relationships amongst multiple input criteria, with the caveat that it does not return the value of a single membership set, which both fuzzy 'AND' and 'OR' do. It however is often utilised to get values greater than the fuzzy product, but less than the fuzzy sum.

Figure 5-11 shows the results of the sensitivity analysis for 'MSSmall' membership function, under different fuzzy overlay operators for socio-economic aspects, the physical environment, the bio-physical environment, location aspects and overall baseline MUT resilience. Figure 5-12 shows the results of the sensitivity analysis for 'MSLarge' membership function, under different fuzzy overlay operators for socio-economic aspects, the physical environment, the bio-physical environment, location aspects and overall baseline MUT resilience. It is interesting to note for both sets of fuzzy membership functions that a change in the fuzzy overlay operator markedly impacts the computed fuzzy baseline resilience index ratio. The parametric studies, for both the 'MSSmall' and 'MSLarge' membership functions, with respect to different fuzzy operators, indicate very clearly that care has to be taken in the choice of appropriate overlay function in order to full reflect the manner in which the evidence interacts accurately.

5.3.2.2.3 Sensitivity Scenario Analysis Results

At the completion of Step 9 of the SUURE Operational Model, the scenario sensitivity analysis results were collated. The sections below review each MUT type with relation to their scenario (NSP, PR, MF and FW) results. Further GIS cluster (see Figure 5-3) generated maps can be found for the flush-fitting MUT (see Appendix I), shallow MUT (see Appendix J) and the deep MUT (see Appendix K).

5.3.2.2.3.1 Flush-fitting MUT Scenario Analysis Results

Figure 5-13 (see Appendix I for further results) shows the result of the scenario composite resilience index analysis for the socio-economic aspects under different future scenarios. The clear indication is that under all future scenarios, the socio-economic conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the flush-fitting MUT. Figure 5-13 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for socio-economic aspects.

Figure 5-13 (see Appendix I for further results) shows the result of the scenario composite resilience analysis for the physical environment under different future scenarios. The clear indication is that under all future scenarios, the physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the flush-fitting MUT. Figure 5-13 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for the physical environment.

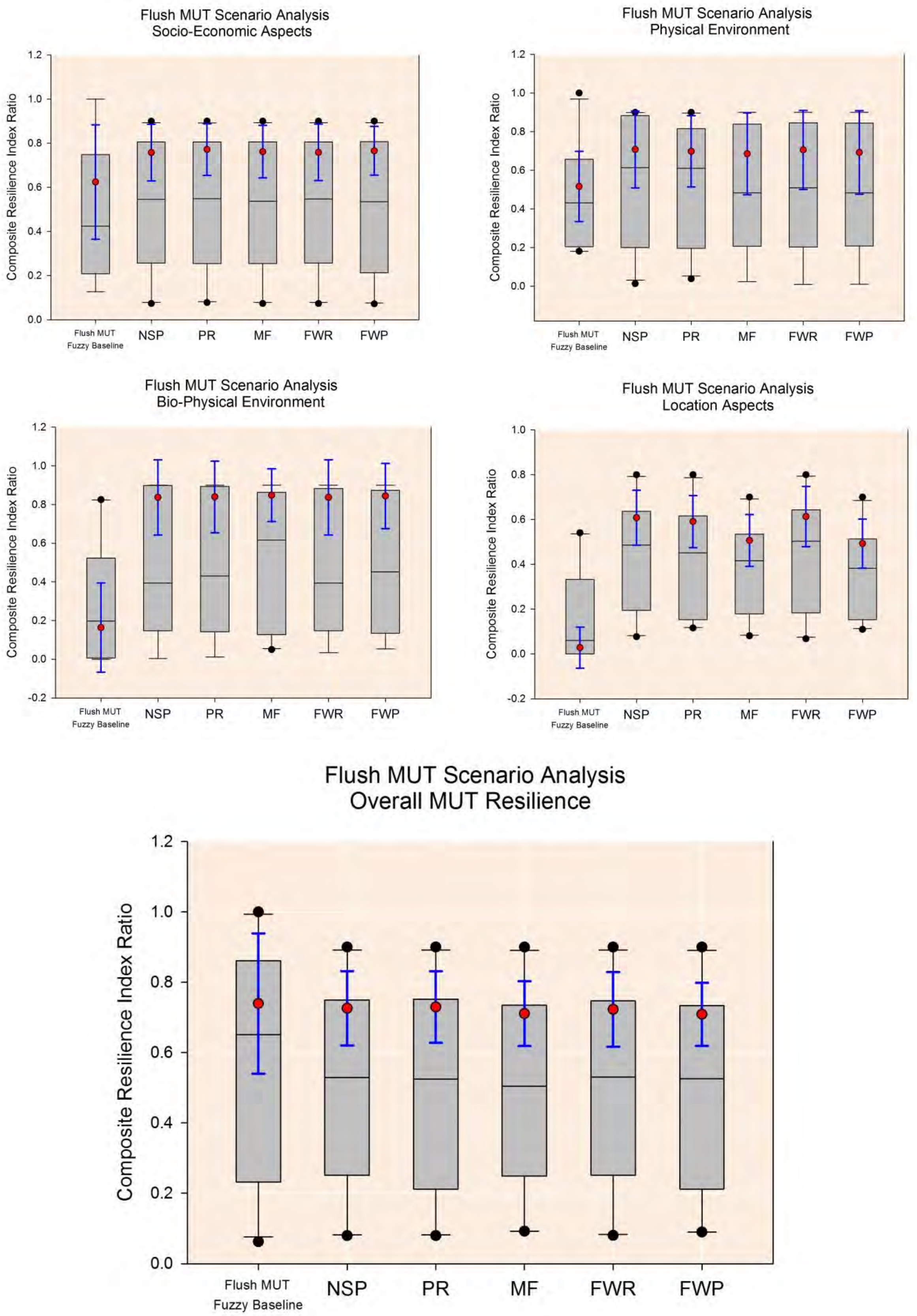


Figure 5-13: Resilience index ratios for flush-fitting MUT under different future scenarios, showing the min, max, mean, range and the standard deviation

Figure 5-13 (see Appendix I for further results) shows the result of the scenario composite resilience analysis for the bio-physical environment under different future scenarios. The clear indication is that under all future scenarios, the bio-physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the flush-fitting MUT. Figure 5-13 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for the bio-physical environment. A large contributor to this result is the expected increase in urbanisation, which would significantly reduce any trees/vegetation, in addition to the current grade 2 listed buildings (heritage resources) having been knocked down due to redundancy.

Figure 5-13 (see Appendix I for further results) shows the result of the scenario composite resilience analysis for the location aspects under different future scenarios. The clear indication is that under all future scenarios, the location aspects conditions unique to Birmingham Eastside, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the flush-fitting MUT. Figure 5-13 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for location aspects.

Figure 5-13 (see Appendix I for further results) shows the result of the scenario composite resilience analysis for the overall resilience suitability under different future scenarios. The clear indication is that under all future scenarios, the overall resilience, relative to the goal criteria (see Figure 5-3), would have retained ~90% of the characteristics essential for continued functional performance of the flush-fitting MUT. Figure 5-13 clearly illustrates that under all future scenarios, there is a comparatively similar composite scenario index ratio in contrast to the baseline performance index ratio for overall resilience.

5.3.2.2.3.2 Shallow MUT Scenario Analysis Results

Figure 5-14 (see Appendix J for further results) shows the result of the scenario composite resilience index analysis for the socio-economic aspects under different future scenarios. The clear indication is that under all future scenarios, the socio-economic conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the shallow MUT. Figure 5-14 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for socio-economic aspects.

Figure 5-14 (see Appendix J for further results) shows the result of the scenario composite resilience analysis for the physical environment under different future scenarios. The clear indication is that under all future scenarios, the physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the shallow MUT. Figure 5-14 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for the physical environment.

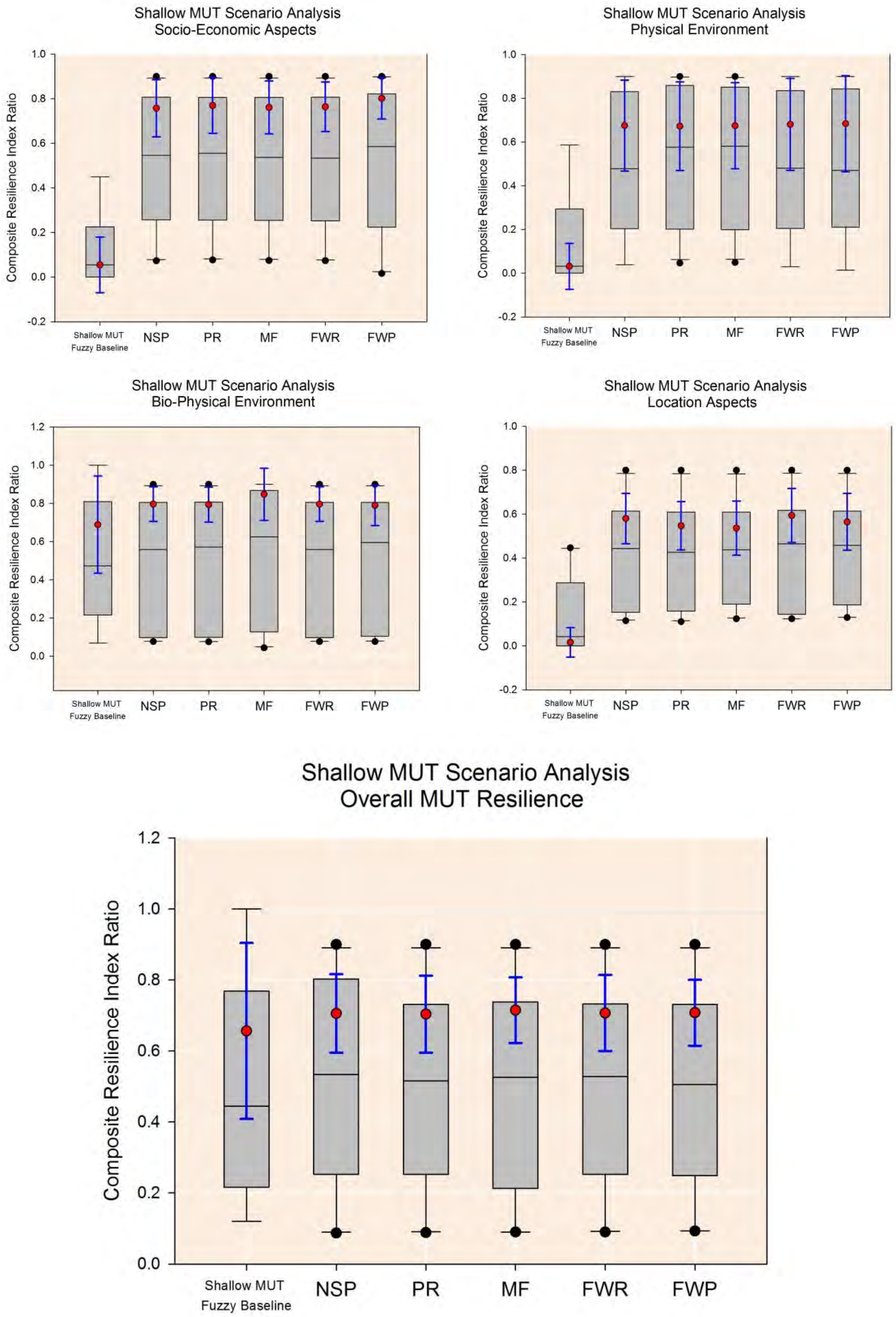


Figure 5-14: Resilience index ratios for shallow MUT under different future scenarios, showing the min, max, mean, range and the standard deviation

Figure 5-14 (see Appendix J for further results) shows the result of the scenario composite resilience analysis for the bio-physical environment under different future scenarios. The clear indication is that under all future scenarios, the bio-physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the shallow MUT. Figure 5-14 clearly illustrates that under all future scenarios, there is a comparatively similar composite scenario index ratio in contrast to the baseline performance index ratio for the bio-physical environment.

Figure 5-14 (see Appendix J for further results) shows the result of the scenario composite resilience analysis for the location aspects under different future scenarios. The clear indication is that under all future scenarios, the location aspects conditions unique to Birmingham Eastside, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the shallow MUT. Figure 5-14 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for location aspects.

Figure 5-14 (see Appendix J for further results) shows the result of the scenario composite resilience analysis for the overall resilience suitability under different future scenarios. The clear indication is that under all future scenarios, the overall resilience, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the shallow MUT. Figure 5-14 clearly illustrates that under all future scenarios, there is a comparatively similar composite scenario index ratio in contrast to the baseline performance index ratio for overall resilience.

5.3.2.2.3.3 Deep MUT Scenario Analysis Results

Figure 5-15 (see Appendix K for further results) shows the result of the scenario composite resilience index analysis for the socio-economic aspects under different future scenarios. The clear indication is that under all future scenarios, the socio-economic conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the deep MUT. Figure 5-15 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for socio-economic aspects.

Figure 5-15 (see Appendix K for further results) shows the result of the scenario composite resilience analysis for the physical environment under different future scenarios. The clear indication is that under all future scenarios, the physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the deep MUT. Figure 5-15 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for the physical environment.

Figure 5-15 (see Appendix K for further results) shows the result of the scenario composite resilience analysis for the bio-physical environment under different future scenarios. The clear indication is that under all future scenarios, the bio-physical environmental conditions, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the deep MUT. Figure 5-15 clearly illustrates that under all future scenarios, there is a comparatively similar composite scenario index ratio in contrast to the baseline performance index ratio for the bio-physical environment.

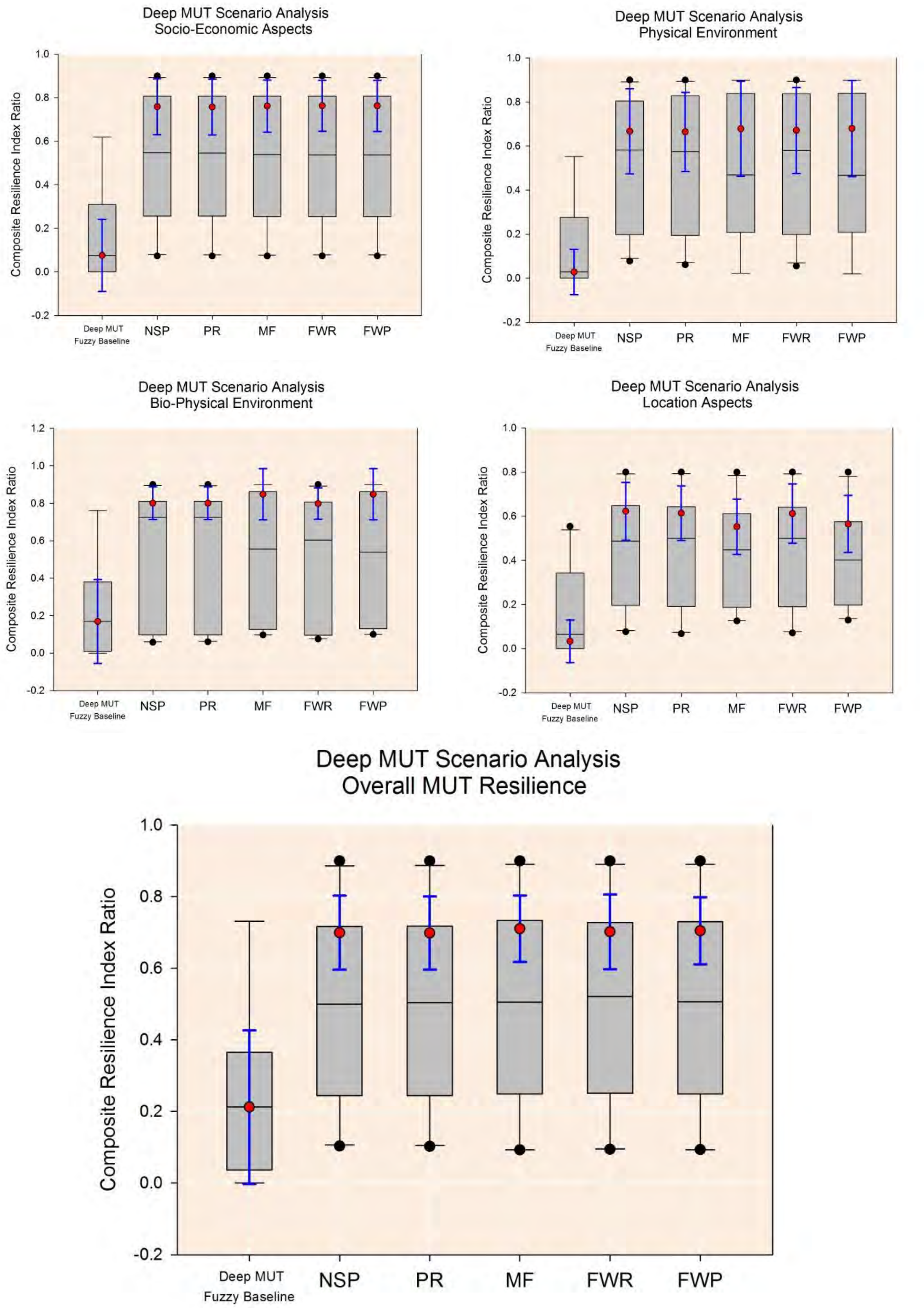


Figure 5-15: Resilience index ratios for deep MUT under different future scenarios, showing the min, max, mean, range and the standard deviation

Figure 5-15 (see Appendix K for further results) shows the result of the scenario composite resilience analysis for the location aspects under different future scenarios. The clear indication is that under all future scenarios, the location aspects conditions unique to Birmingham Eastside, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the deep MUT. Figure 5-15 clearly illustrates that under all future scenarios, there is an improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for the location aspects.

Figure 5-15 (see Appendix J for further results) shows the result of the scenario composite resilience analysis for the overall resilience suitability under different future scenarios. The clear indication is that under all future scenarios, the overall resilience, relative to the goal criteria (see Figure 5-3), would have retained characteristics essential for continued functional performance of the deep MUT. Figure 5-15 clearly illustrates that under all future scenarios, there is a significant improvement of the composite scenario index ratio in comparison to the baseline performance index ratio for overall resilience.

5.3.3 SYSTEM CAPACITY TO ADAPT TO CHANGE: CHOICE AND IMPLEMENTATION

5.3.3.1 SUURE Operational Model: Step 10

In Step 10 of the SUURE Operational Model armed with the results of analysis (see Table 5-12), the decision-maker chooses the appropriate course of action:

1. To implement the sustainability solution (MUT);
2. To adapt the sustainability solution (MUT) in response to vulnerabilities detected in the analyses;
3. To replace the sustainability solution (MUT) with an alternative solution.

5.3.3.2 Significance of the Results: Birmingham Eastside

As evidenced in Birmingham Eastside as well as further afield, utility services are there to serve society all the time. It is this ever present state of affairs, coupled with the increase in socio-ecological complexity that throws the spotlight on their resilience. This on-going challenge that seeks to establish - *What does it take to have resilient utilities?* – is at the core of SUURE evaluation of Eastside. Planning for UUS sustainable future comprises the ability to lessen the use of open-cut trenching as addressed in this thesis. A high degree of foresight in planning for MUTs is required through their entire life-cycle, and goes a long way to aid decision-maker(s) understand, manage and exploit the resilience (or risks identified in implementation) inherent to strategic programmes.

The results of evaluation (see Table 5-12) will at a strategic level firstly offer decision-maker(s) an evidence-base that is structured, that obtained, refined and analysed relevant digital (and other) information to inform and optimise the trade-off phases encountered of MUT life-cycles, through a scenario-led approach to planning in Eastside (even though their design and operational risks are not accounted for). This acts as a first step in understanding the resilience of the value-chain for MUTs (an alternative to open-cut trenching), promoting sound judgement that combines existing expert opinion, through accessible evidence and analysis.

MUTs are expected to have a long shelf life to justify their initial high first-cost; see Figure 2-18 and Figure 2-19. As such, a design life of a minimum of circa 50 years is quite reasonable for a reinforced concrete MUT geo-structure in Birmingham Eastside. Throughout this time, several alterations will take place in varieties of and volume of utilities, and settings of sources and services. It should be noted also that the underground space in Birmingham Eastside, or anywhere else for that matter, is a non-renewable resource. Once a geo-structure (e.g. facility, utility infrastructure, etc.) is located underground, the space utilised can never go back to its initial state and this further compounds the need for long term urban planning, which is demanded by sustainability, moreover, resilience through a socio-ecological systems perspective.

Table 3-3 highlights issues that have to be considered, with regard to the necessary conditions required so that an MUT can continue to deliver its function in Birmingham Eastside: (i) third party damage issues; (ii) initial capital cost; (ii) utility tunnel ownership, and (iv) awareness of the problem that MUTs address (Hunt & Rogers, 2005; Hunt et al., 2009). These form just a few of the wide-ranging considerations in light of present-day challenges, including others such as the lack of a knowledge base i.e. no universal design standard with regard to MUTs (Hunt et al., 2014), security access (Canto-Perello et al., 2013), potential hazards and risks (Curiel-Esparza & Canto-Perello, 2005), incompatibility problems (Canto-Perello et al., 2009), negative legacy – inherited systems (Hunt & Rogers, 2005), reduced flexibility (Canto-Perello & Curiel-Esparza, 2013), piecemeal approach to utilities (Hunt & Rogers, 2005; Jefferson et al., 2006; Hunt et al., 2009), etc. In light of these other barriers, the decision for implementation surpasses just the retention of functional capacity i.e. the capacity to adapt to change, albeit a very important and compelling basis for evidence based decision-making as evaluated by the SUURE Operational Model at a strategic level, and other systemic issues could undoubtedly prevent a sustainable solution being implemented in Birmingham Eastside as already underscored in Chapter 4. On this point, it would be worthwhile to extend the SUURE Operational Model (given its current limitation) to allow for a multiple solutions analysis i.e. multi-objective as opposed to the current multi-attribute single solution approach, this should be considered as part of any future research endeavour and would aid to analyse all the factors involved in decision-making concerning the sustainability solution(s) in both space and time. The SUURE Operational Model nonetheless represents a significant step towards understanding the socio-ecological dynamics of UUS physical infrastructure.

In support of a decision for the overall goal (MUT placement for collocation and coordination of utilities for sustainable use of UUS), the results obtained from the SUURE Operational Model evaluation indicate that at this present-time, the most appropriate and sustainable MUT placement technique for Birmingham Eastside would be the flush-fitting MUT. As can be seen from Table 5-12, the baseline resilience (retention of functional performance) of the flush-fitting MUT is the highest, the lowest being the deep MUT. It is clear that conditions to support both shallow and deep MUTs markedly improve in all the future scenarios (i.e. their capacity to adapt to change), signifying that the retention of functional capacity will indeed prevail i.e. resilient capacity in light of plausible yet divergent socio-ecological future scenarios.

However, it would be very difficult to implement either one of these two in Birmingham Eastside given their higher initial cost (see Figure 2-18), especially for the deep MUT, in addition to a lack of integration of utility companies which all act as separate entities presently It has been already argued by others (see Curiel-Esparza and Canto-Perello (2013) and Hunt et al. (2014)) that the current approach to utility service provision is the bottom line economic cost indicators that precipitate traditional trenching approaches to lacing utilities as opposed to more sustainable techniques such as MUTs. For both shallow and deep MUTs, these two key conditions (economic considerations as the prime bottom line driver for decision-making and an unregulated utilities industry with no utilities integration) amongst others that have been mentioned above, need to be overcome or else they will remain what they are at present an 'ideal', although they can clearly deliver their intended functions into the long term future (i.e. they have the capacity to adapt to socio-ecological change), whatever that may be. Policies even now could be put in place to enable the use of MUTs in Birmingham Eastside, such as charging for roadwork's, Birmingham City Council coming up with a sustainable cost model or introducing a no-dig-policy, thereby placing a higher premium on underground space, etc. The flush-fitting MUT would be viable both now and in the future (considering the auxiliary issues mentioned which require suitable procedures to address these complex issues that cannot be neglected) and is recommended for implementation as a result of SUURE Operational Model evaluation, with the basis of argument being the current approach to planning and decision-making that puts a strong emphasis on the most cost effective solution/investment (often neglecting social and environmental concerns), although the flush-fitting out performs the shallow and deep MUTs overall. It should be noted that in the scenario, for instance where Birmingham builds a terminal for HS2, such a development affords a once in a lifetime opportunity to put in place MUTS (flush-fitting, shallow or deep) with ease as opposed to having to reconcile the existing legacy of utilities in urban centres.

5.3.3.3 Validation of the SUURE Operational Results for Eastside

To measure the impact of the results of SUURE analysis for MUTs in Birmingham Eastside, a comparison is made in light of the work of Curiel-Esparza and Canto-Perello (2013) who carried out a survey of urban underground engineering practitioners. This represents the only other study currently that has attempted to establish the viability (SES resilience) of MUTs, the caveat being that it is from a practitioner's perspective (questionnaire survey). Their survey was instituted using an AHP-Delphi approach (meant for consensus building amongst decision-makers). The core of their hypothesis was that establishing future sustainable strategies in urban underground engineering consists of the ability to lessen the use of open-cut traditional trenching techniques. Their survey criterion in light of UUS as a SES was: (i) Consideration of the urban environment; (ii) Economic/financial consideration of different utility placement options; (iii) Governance of UUS; (iv) Maintenance requirements of the option in question; (v) The security of the chosen option; (vi) The liability on the undertaker (i.e. utility owner) for the chosen option, and (viii) The impact of the chosen option on archaeological sites. The overall outcome of the study was a set of global priorities for each of the alternatives to utility placement. The study did not however consider the prioritisation of the SES UUS criteria for different practitioners, but sought to aggregate the final global priority vector in light of their responses.

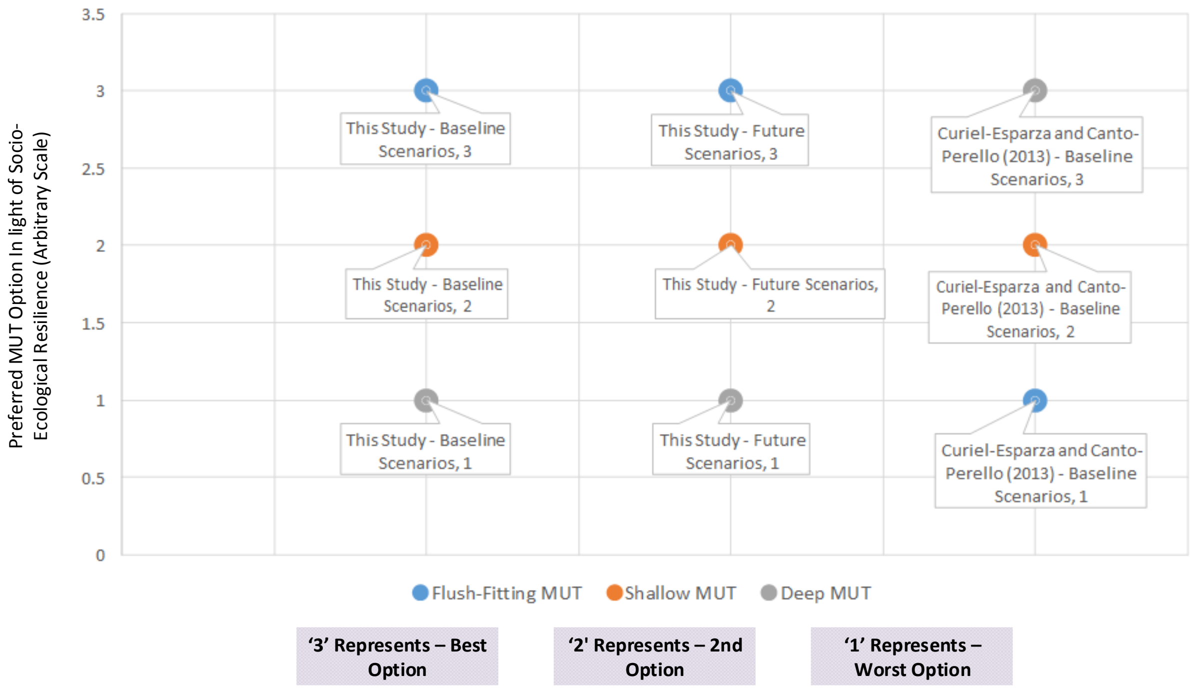


Figure 5-16: Comparison of MUT results - 'This Study' vs. Curiel-Esparza and Canto-Perello (2013)

As can be seen on the figure above, for both studies the shallow MUT ranked second for all scenarios (baseline vs. future). It was however the view of practitioners in the present day that the deep MUT would suffice as a better option for sustainable utility placement as opposed to the flush-fitting MUT (when compared to 'This Study'). It should be noted however that this discrepancy between 'this study' and 'Curiel-Esparza and Canto-Perello (2013)' in the view of the author, is principally a result of the criterion utilised as a means to evaluate the efficacy or otherwise of MUT placement. The focus of 'this Study' was on Birmingham Eastside, on solutions driven by local priorities. Whereas the 'Curiel-Esparza and Canto-Perello (2013) Study' was geared towards high level global indicators as the basis for formulation of global priority vectors for MUT options. The level of trade-off concerning local priority weights and global priority weights is calculated on or after (with the same weights and variables) the normal process of weight formulation in an ANDness multi-criteria evaluation model by:

$$ANDness(w) = \frac{1}{n-1}\sum\nolimits_r (n-r)w_r \qquad (where\ ORness = 1 - \ ANDness) \qquad \textbf{Eq 5-18}$$

$$TradeOff(w) = 1 - \left[\frac{n\sum_r (w_r - \frac{1}{n})^2}{n-1}\right] \qquad \textbf{Eq 5-19}$$

This phenomenon as observed in the Figure above necessitates further investigation in light of the placement of MUTs i.e. are local priorities more important in decision-making or global decision indicators in the formulation of priority weights? This would make a useful basis for future research endeavours in this line of work.

Table 5-12: Necessary conditions (resilience) for the continuing operation of the sustainability solution 'MUT placement for collocation and coordination of utilities for sustainable use of UUS', for the case study area of Birmingham Eastside, UK. The likelihood that each necessary condition will continue to be met in each future socio-ecological scenario is assessed in the right-most panels i.e. the capacity to adapt to change

Solution 'Goal'	Criteria Conditions	Baseline			Met in Future?														
					NSP			PR			MF			FWR			FWP		
		F	S	D	F	S	D	F	S	D	F	S	D	F	S	D	F	S	D
MUT Placement in Birmingham Eastside	Topography (≥ 1:500)	***1.000	***0.587	***0.553	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑
	Land use Geology	**0.516	**0.031	**0.028	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑
	Ground water depth Utilities	*0.180	*0.000	*0.000	↔	↑	↑	↔	↑	↑	↔	↑	↑	↔	↑	↑	↔	↑	↑
	Urban population density	***1.000	***0.451	***0.620	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑
	Real estate value	**0.624	**0.055	**0.076	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑	↑	↑↑	↑↑
	Distance to highways	*0.157	*0.000	*0.000	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑
	Distance to heritage resources	***0.825	***1.000	***0.761	↑	↔	↑↑	↑	↔	↑↑	↑	↔	↑↑	↑	↔	↑↑	↑	↔	↑↑
		**0.163	**0.689	**0.167	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑	↑↑	↔	↑↑
	Distance to vegetation/ trees	*0.000	*0.175	*0.000	↑	↔	↑	↑	↔	↑	↑	↔	↑	↑	↔	↑	↑	↔	↑
	Distance to railway lines Distance to streets	***0.541	***0.447	***0.554	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑	↑↑	↑↑
	Distance to canals Distance to substations	**0.028	**0.016	**0.033	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑
	Distance to natural watercourse	*0.000	*0.000	*0.000	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Overall goal	***1.000	***1.000	***0.732	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑
		**0.739	**0.656	**0.212	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑
		*0.244	*0.183	*0.000	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑	↔	↔	↑↑

*__Baseline__ = *'__min__' resilience composite index ratio, **'__mean__' resilience composite index ratio, ***'__max__' resilience composite index ratio

***F** (*Flush-fitting MUT*); **S** (*Shallow MUT*); **D** (*Deep MUT*)

*Future Scenarios: - **NSP** (*New Sustainability Paradigm*); **PR** (*Policy Reform*); **MF** (*Market Forces*); **FWR** (*Fortress World – Rich*); **FWP** (*Fortress World – Poor*)

Key: ↑↑ Significant increase, ↑ Increase, ↔ Little/ no change, ↓ Decrease, ↓↓ Significant decrease

Physical Environment (green) *Socio-economic Aspects* (orange) *Bio-physical Environment* (blue) *Location Aspects* (amber) *Overall Goal* (yellow)

5.4 SUURE: SUSTAINABILITY REALISATION – THE PATH FORWARD

The core theme of this thesis is that urban growth necessities redirection towards meeting future needs, and not just towards decreasing economic expense as much as is practicable. The ability to for decision-makers to realise this necessitates new approaches to metrics and formalism in sustainability evaluation. The SUURE Framework and accompanying Operational Model is one such attempt to bridge this gap, specifically with reference to UUS resources; the focus of this thesis being urban underground physical utility infrastructure systems (MUTs – flush-fitting, shallow and deep). The geotechnical engineering profession at present does not have a critical mass of engineers trained to cope with the future needs of complex systems management; new concepts and approaches to metrics and formalism require recalibration of management judgement. The ever growing attentiveness in the profession of both the value and the resilience of critical underground infrastructure systems necessitates a concerted effort to put forward new, interdisciplinary, approaches focused on long-term socio-ecological strategies (with a focus on resilient systems) toward the efficient, safe, secure, reliable, and sustainable planning, design, operation, and maintenance of UUS infrastructure systems.

The approach utilised in the SUURE Operational Model, with output in the form of resilience index ratios can be viewed as a kind of metamodel outcome that reflects the functional resilience of the SES (in the context of this thesis – UUS Utility Infrastructure). Constructing resilience index ratios as exemplified by SUURE Operational Model to assist decision-makers necessitates understanding of scale, aggregation, interfaces and interdependences as illustrated in the SUURE Framework. Conceptually, the resilience of socio-ecological systems such as UUS is a useful concept, but its practical application has several challenges. Data sets alone that can facilitate the broad range of socio-ecological resilience as evidenced in the course of this present work are difficult to procure (and in some cases cannot be obtained), and the evaluation of resilience for socio-ecological systems is not yet widely accepted nor utilised by the engineering profession. Social scientists and engineers are not yet thinking as one regarding representation of socio-ecological resilience, and land use professionals and planners are markedly missing from discussions on this subject matter. Any evaluation/measurement of socio-ecological resilience will be driven by local priorities i.e. the definition of the region and the necessary conditions that are needed to make the SES resilient – as evidenced in the present work, case study area Birmingham Eastside.

Local priorities and conditions dictate to a large extent the parameters for inclusion of spatial and temporal scales, boundaries of necessary condition(s) of the sustainability solution in question, and the level of detail or else granularity. Adopting a multi-criteria approach (in addition to expert systems – fuzzy logic), embedded in the SUURE Operational Model as case and point, is a very useful approach to capture the broad range of metrics for resilience of socio-ecological systems. A SUURE Operational Model approach to urban planning affords the basis to build a repository of spatially distributed information against several socio-ecological future scenarios, the variation and geography of a metric (resilience index ratio) could yield understanding about how the local region responds – ultimately laying the foundations towards a standardised form for prediction of comparative socio-ecological resilience amongst different communities and societies. When combined over space and time, the ensuing character of the resilience index ratios may indicate typical UUS resources functional performance aggregate ratios. If so, then the possibility exists to explore a new science of complex socio-ecological system analysis through resilience index ratios, in which an elementary comprehension of how metric functions (resilience index ratios) show a discrepancy as a function of spatial, temporal as well as concentration effects of regional boundaries. This would necessitate formulating an understanding about how resilience index ratios vary (or are the same) across scales, sectors as well as SESs. With such an interdisciplinary approach offered by the SUURE Operational Model (a tested to analyse complex SESs with interdependencies as well as anticipating performance and impacts of new tools and approaches) that captures attributes of the SES in a region, we can begin to answer important questions, comprising but not limited to:

- How can resilience index ratios help a decision-maker to understand when investment or adaptive management is warranted to improve the resilience of a SES (UUS) or interdependent systems?
- For SESs, how does resilience response develop, and what elements regulate or impact the development?
- Are there thresholds, tipping points in this process, state changes, or is it a continuous process of a SESs capacity to adapt to change?

SUURE at its core facilitates the understanding of time-dependant responses (through socio-ecological future scenarios) of SES (UUS) performance of geo-structures (context of this thesis) that is key to understanding and stress testing the log-term sustainability and functional socio-ecological resilience (UUS physical utility infrastructure - the focus of this thesis), and on a broader scale – all other resources encompassed by UUS (geomaterials, groundwater and geothermal energy) as part of future research endeavours in this line of work.

5.4.1 SIGNIFICANCE OF THE SUURE OPERATIONAL MODEL RESULTS

The present chapter has demonstrated the implementation of the SUURE Operational Model from start to finish as a means of emphasising adaptive strategies of socio-ecological capacity to both evaluate and manage the capacity to adapt to change in order to sustain core functionality in geo-structures, through evaluation models in different future socio-ecological scenarios. The framework in addition to its accompanying operational model provides many clear benefits for the geo-professional, urban planner, and policy-maker. The case study evaluation of Birmingham Eastside has resulted in an evaluation model of MUTs that provides an outline of the performance of different MUT types (flush-fitting, shallow and deep) within different future socio-ecological scenarios, inside the case study area, by assembling a large number of local criteria (necessary conditions for sustainability solution to continue delivering its function), processes and evidence base in a manner never previously achieved. In particular, the SUURE Operational Model maximises the use of future socio-ecological scenarios, by incorporating them as performance indicators at multiple levels in the system description. Nonetheless, this analysis is integrated into the broader context of all the sources of evidence that the geo-professional will wish to take into account (geology is fundamental) providing a useful and relevant sustainability evaluation tool, through the prism of socio-ecological resilience. The limitation that is evidenced (see Section 5.3.2) as regarding the inability of the current crop of commercial GIS platforms (ArcGIS 10.2 employed in the present work) to evaluate the entire case study area geology as part of the of SUURE Operational Model, necessitates a different approach (e.g. use of ‘R’ to write a be-spoke program) to afford the SUURE platform to fully realise its potential (currently the geology is evaluated/ constrained to areas under physical infrastructure). The accounting of geotechnical risk (design, below-ground contract risk and project management risk), in the context of SUURE - technical design risk through an attributed geological model of the case study area under examination as afforded by the best currently available UK Geological Modelling platform – GSI3D. The uncertainty of the geotechnical uncertainty and geological framework at this present time in GSI3D cannot be quantified and this limitation is currently being addressed as part of ongoing work at the British Geological Survey (Lark, 2014) and it would noteworthy to as part of future research endeavours to recalibrate the SUURE Operational Model when these limitations have been addressed.

The Table of merit (see Table 5-12) affords a clear representation of the range of functional performance in different future scenarios with respect to the placement of MUTs in the case study area under examination, in addition to uncertainty (with respect to the capacity to adapt to change) associated with the evaluated sustainability solution. This addresses objective 7 of this thesis through establishing the impact of different scenarios on the SES of urban underground utility service provision infrastructure. This functional performance is a reflection of the knowledge database contained with regard to the behaviour of the UUS physical utility service provision infrastructure system. The focus being specifically with reference to local conditions, driven by local priorities in the case study area of Birmingham Eastside. Further investigation can establish, any sources of uncertainty inherent, permitting the decision-maker to target resources more efficiently. The evaluation acting as a first step to help identify where resources, financial or otherwise, ought to be targeted strategically.

The SUURE Operational Model further provides a transparent and auditable mechanism for exploring, justifying and prioritising different types of investment decisions at all levels within a SES, with a clear focus at locally driven priorities and in turn solutions. Clearly some subjective judgments are required, but these are open to scrutiny and discussion (e.g. see Table 5-2 and Table 5-3). This affords a more auditable and transparent mechanism for geo-professionals and otherwise than is currently available, affording evidence-based policy formulation at a strategic level with reference to urban planning (see Figure 5-17).

The SUURE Operational Models approach to capturing and evaluating both present and long-term functional performance of a system (capacity to adapt to change) utilises process modelling i.e. project life cycle thinking within the framework and accompanying operational model. The graphical representation of performance from evaluation ought to prove attractive to decision-makers as it makes readily available a basis for decision-making devoid of the need to have a technical base to understand the implication(s) thereof, and additionally not needing to ingest and process a sizable amount of data (see Table 5-12).

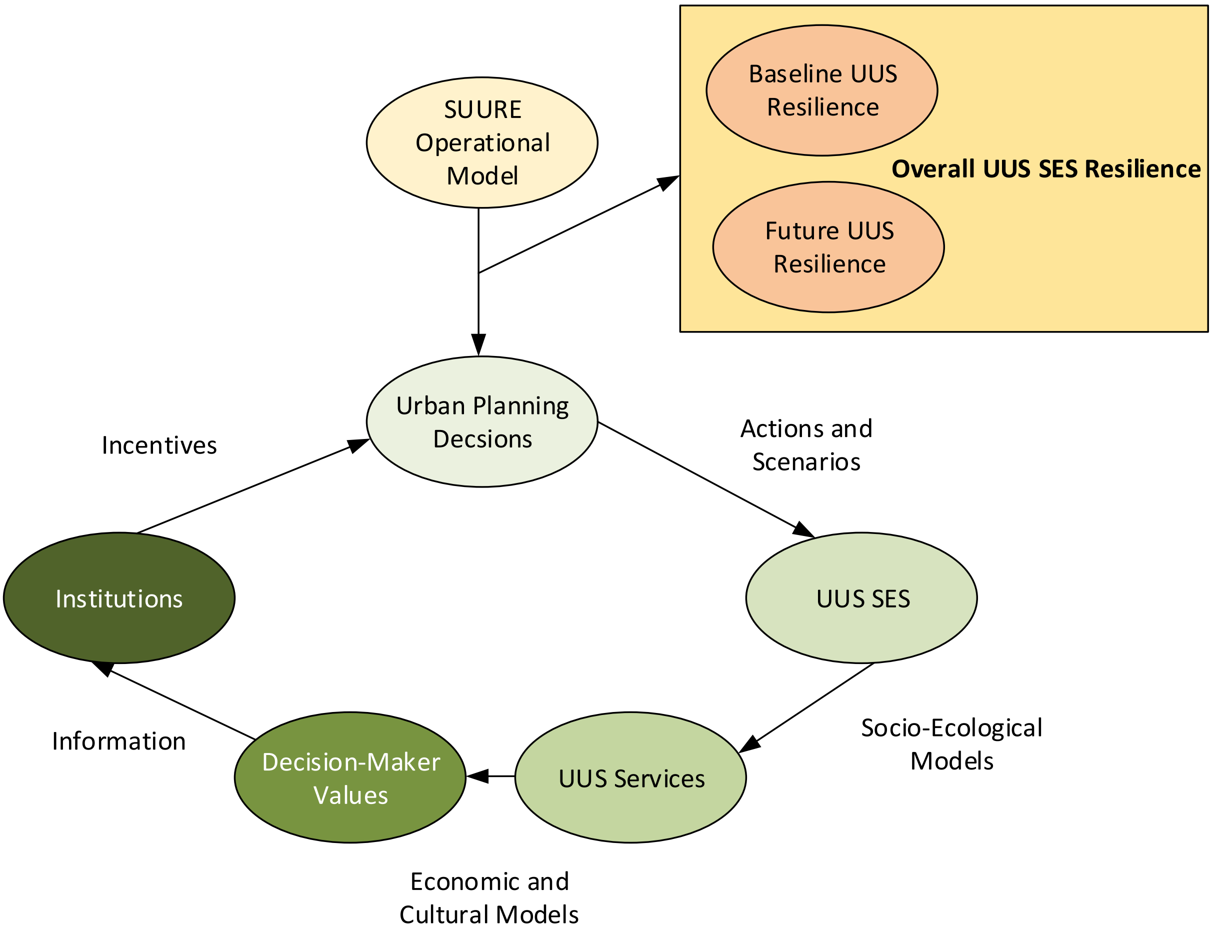


Figure 5-17: A framework illustrating how the SUURE Operational Model can be utilised to inform UUS ecosystem services decision-making at a macro level in the urban planning process. One may link any two ovals, in virtually any direction, this schematic presents the simplest version

As evidenced, the SUURE framework is straightforward to explain yet enables the complexity of the system and the richness of evidence to be captured in the operational model. A key benefit that could be gained through process thinking in evaluation as SUURE requires, is to facilitate communication between decision stakeholders focussed on different areas when needed with respect to the domain and SES being evaluated. It is often the case for the geo-professional that due consideration is given to only the effects of their decisions on a limited part of the SES, and as illustrated in Figure 2-5, are surprised that decisions they make can significantly influence the performance of different parts of the system (UUS).

Using the SUURE Operational Model, engineers can be able to communicate the importance of maintenance to the overall functional performance of a sustainability solution. Managers as a result of the SUURE Operational Model are thus provided with a holistic view of the sustainability solution (within its SES) under evaluation and are able to view the relative importance of sub-systems to its overall sustainability i.e. resilience – capacity of the SES under evaluation to adapt to change (change is afforded by diverse yet plausible socio-ecological scenarios).

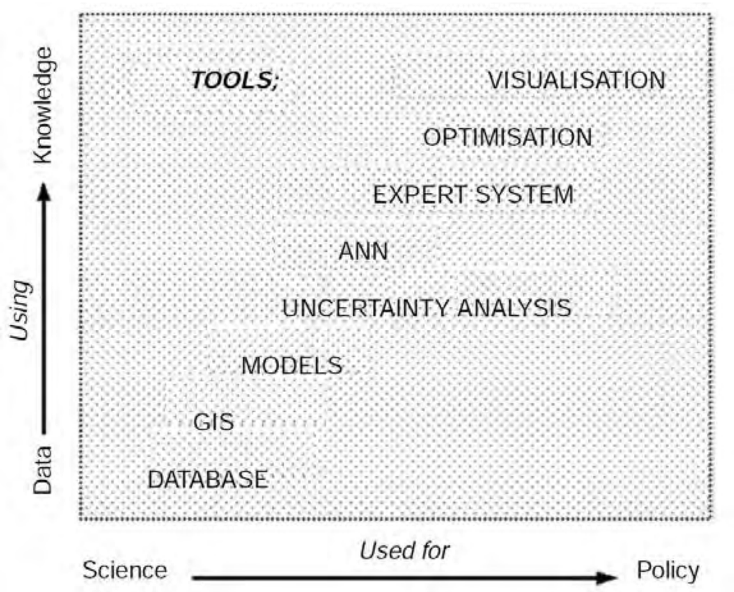


Figure 5-18: An assortment of tools relative to the SUURE Operational Model and their use in policy-making (Brimicombe, 2010)

Sceptical decision-makers may recognise the benefits of the SUURE approach (framework, embedded theoretical approaches and accompanying operational model), yet would most likely point out that evaluation model construction and maintenance signifies yet another time-consuming activity. The implementation of the methodology in the form of the be-spoke novel operational model constructed in ArcGIS software has helped to reduce this.

However, the balance between the cost (measured in time) and the benefit of SUURE evaluation will shift in favour as it becomes more integrated with data programmes for instance the 'Digital National Framework' (http://www.dnf.org/) aimed at building a common platform to support information sharing and facilitate improved decision-making, through the construction of a 'geographic spatial framework for the UK'. The key through such a platform would be for policy-makers to grasp how UUS resources use can contribute to the resiliency i.e. sustainability of cities (a SES) and for this way of thinking to become a deliberate approach to the urban planning process (see Figure 5-17 and Figure 5-18) Despite this, the very act of engaging in SUURE Operational Model evaluation of a SES (sustainability solution) provides immediate benefits in its own right as decision-makers are forced to think in a way they had not previously about the processes they and others enact, and the information that is available and its importance to facilitate through decision-making a greater capacity for a SES to adapt to future change.

CHAPTER 6: CONCLUSIONS

"*Life can only be understood backwards; but it must be lived forwards.*"

Søren Kierkegaard, 1843

6.1 INTRODUCTION

Resilience theory as a concept and its subsequent use in planning is an emerging field, still at a relatively early stage. The thesis attempts to decipher and translate this concept, exploring its use in systematic SES evaluation of the sustainability of urban systems, vis-à-vis the urban underground space utility service provision physical infrastructure (MUTs). The premise of this thesis is that sustainability is viewed as a process, rather than an end-product, a dynamic process that requires adaptive capacity in resilient social–ecological systems to deal with change, whatever that may be into the far future. This is more tangibly realised as an acceptance on the part of the decision-maker (engineer, policy-maker, urban planner) that changes are going to take place in the SES under evaluation, consequently sustainability evaluations ought to account for this whilst taking steps to support decision-makers to reduce and absorb vulnerabilities that urban systems have to encounter, therefore restructuring themselves through development of adaptive strategies to manage and cope with change, consequently improving functional performance capacity.

The aim of the thesis came about principally as a response to satisfy the knowledge gap identified through a critical review of geo-sustainability literature. Although at present many sustainability evaluation DSSs abound to serve geo-professionals, none of them however account for resilience, i.e. functional performance of the geo-structure in SESs. This gap necessitated the overarching aim of the research study, which was to develop a new DSS that would thus aid to quantify the spatial and temporal impacts of today's urban development and regeneration solutions on their sub-surface environments, in light of future socio-ecological change, whilst measuring their long term sustainability, whatever the future may be. The thesis through this aim, seeks to thereby make available an improved understanding of how the various 'key' contributing elements of urban underground space and its use for utility service provision infrastructure (MUTs), can contribute towards achieving a sustainable urban environment, and more importantly how their 'sustainability performance' can be measured through the prism of SES resilience, and as a result framed within the SUURE Operational Model to effectively support decision-making/makers. The SUURE (Sustainable Underground Use Resilience Evaluation) framework was proposed as a means of satisfying the overarching aim, in addition to addressing the other knowledge gaps identified through the critical literature review. The SUURE Operational Model acts as a platform for exploring potential investment decisions (with respect to UUS resources – the focus of this thesis being urban underground utility service provision physical infrastructure, MUTs - as an alternative to open-cut trenching, accounting for all aspects of sustainability) and their long term functional performance i.e. impacts on all levels of the SES. This has been demonstrated by the testing of potential MUT placement in Birmingham Eastside utilising scenarios developed from the UF project (NSP, MF, PR and FW); but other types of scenarios are capable of being both developed and included in the analysis as described in Chapter 3, Section 3.3.2.

6.2 OVERALL CONCLUSIONS AND SCIENTIFIC CONTRIBUTIONS

The SUURE DSS has been presented and discussed (see Chapter 3 and 5). The DSS is developed with the intention of enabling complex SES UUS systems analysis and simulation (see Chapter 2, 3 and 5), and to as a result of this, generate sets of composite resilience index ratios (baseline and scenario based) to aid geo-professionals, planners and policy makers alike in decision-making with regard to sustainable use of underground space, advantageously having a sensitive view of spatial and temporal impacts of alternative sustainability solutions. SUURE has the following stages: Intelligence, design, review - detailed analysis and choice-implementation. The contents of each of these stages and their place within the SUURE configuration and work flow have been explained and illustrated using the case study area of Birmingham Eastside as a proof of concept. The view-point with reference to geotechnical engineering, the manner in which SUURE supports decision-making and its computational execution has been outlined (see Chapter 3, 4 and 5).

The various interdisciplinary tools and methods utilised in the SUURE DSS have also been presented, examined and discussed (see Chapter 3). The SUURE framework contains a wide range of methods, including those for data preparation undertakings: data tidying, methods of data standardisation/reclassification and integration, for scenario knowledge discovery: ANP-based MCDA for estimation and result generation, methods of artificial intelligence and hybrid models through fuzzy logic and sets; overlay approaches for decision-making ratios: computer simulation and approaches of decision theory. The different methodological tools discussed (see Chapter 3) and incorporated into the SUURE framework (see Figure 3-2), and the choice rests upon their practical operation and efficiency, and affords support to all stages of the SUURE Operational Model (see Figure 3-14).

The other significant quality of the SUURE Operational Model rests on its integration possibilities: integration happens in quite a few dimensions: distally, end-to-end down the full pathway of the sequence of activities from identification of necessary conditions for the sustainability goal in question, to ultimate decision alternatives and choice; horizontally, across diverse sources that feed into circulation and products of GIS data mining processes; transversely through different logical levels; and temporally across diverse-yet-plausible socio-ecological time dimensions (NSP, PR, MF and FW) from analysis of foresights (future scenarios). The SUURE Framework and its accompanying Operational Model furthermore explicitly integrates and links conventional decision support methodologies with expert system (artificial intelligence through fuzzy logic and sets) approaches and knowledge discovery methods. What's more, it opens out to deal with more complex, multi-sectoral issues within the SES under evaluation (see Figure 5-3) and permits the user to produce evidence-based policies (see Table 5-12, Figure 5-17 and Figure 5-18).

The monograph is devoted en bloc to the examination and analysis of current sustainability evaluation frameworks and their corresponding decision-support-systems for underground projects, and brings together current approaches and techniques, putting forward a novel interdisciplinary adaptable DSS (SUURE) aimed at multifaceted, systematic SESs domains and evidence-policy formulation. As a whole, the motivation and objectives of the research are presented and discussed in Chapter 1.

Chapter 2 fulfils objectives 1 and 2 of the thesis. The critical review of the current state-of-the-art, as presented in Chapter 2, introduces the current challenges faced in urban centres with respect to planning, regulation, evaluation and use of underground space. Chapter 2 points to the fact that at present there is a knowledge gap with regard to utility installation procedures that employ MUTs as a means of addressing long-term sustainability in urban areas; a decision support tool/ framework to highlight the efficacy or otherwise of multi-utility tunnels as a sustainable SES (UUS) option was yet to be devised as a means of evidenced based decision-making. Chapter 2 also introduces an overview of comprehensive approaches for both sustainability and resilience in the field of geo-sustainability (see Figure 2-20). It highlights the current crop of sustainability evaluation frameworks/ tools with a particular emphasis on the problem of decision-making when faced with SES challenges. It is outlined that the problem rests in the subsistence of several frameworks and tools, which intend to manage UUS – a complex SES; however, even-so, they do not meet the necessary terms for integrated support in sustainability evaluation, both spatially and temporally. A further conclusion from this chapter relates to the need to formulate a new evaluation DSS, utilising a systems approach – by combining sustainability science and resilience theory for the decision-support-system creation as SES frameworks are, characteristically, the optimum means to study a system from a multi-focal viewpoint.

Chapter 3 fulfils objective 3 of the thesis. The novel SUURE DSS described in Chapter 3, is a combination of a systematic sequence of methodologies and tools that can be applied to evaluate sustainable and resilient use of underground space with respect to its SES properties (see Figure 3-14). The SUURE Framework is separated into sub-systems, highlighting the different forms of internal and external associations between the independent variables in the framework. The principal focus in the formulation of this framework was to centralise the capacity to cope with disturbances i.e. change in UUS (a SES), which is essential to introducing a new perspective to the conventional paradigm of sustainable development evaluation. The process involved in the development of a SES evaluation DSS along with its description are presented and discussed, and mention is made to the novel way in which sensitivity analysis, through use of contextual socio-ecological future scenarios is applied on a spatial multi-criteria decision analysis in the SUURE Operational Model.

Chapter 4 fulfils objectives 4 and 5 of the thesis. Chapter 4 provides an outline of the case study area of Birmingham Eastside. It describes the development of its underground space to date, focusing on utility infrastructure and current approach to utility placement through open-cut trenching. It is clearly evidenced that decisions taken during the course of the regeneration cycle within Birmingham Eastside did not engender sustainable use of underground space, moreover, have left a negative future legacy for posterity; bearing in mind that Eastside was and is to act as a demonstrator 'sustainable quarter'. Multi-utility tunnels are identified as a potential means of engendering sustainable use of underground space in Eastside, through sustainable utility placement, and this requires testing when making an allowance for the knowledge gap identified in Chapter 2. In addition, a description of the development of a 3D sub-surface geological model (within the zone of human interaction) of Birmingham Eastside is presented and discussed. The generated 3D geological model serves the explicit purpose of demonstrating the means by which complex geology can be accounted for in sustainability evaluation for underground projects through SUURE as demonstrated in Chapter 5. It was identified through the course of this research (see Chapter 5 – Section 5.3.2) that a limitation exists when utilising the 2D model for analyses (baseline –Step 8 and scenario – Step 9) in the SUURE Operational Model in ArcGIS 10.2. For the *Physical Environment* cluster, *Socio-Economic Aspects* cluster as well as the *Overall Goal*, the analysis *(when including the 2D Geological Model)* was limited to areas where there was existing physical infrastructure (buildings, utilities etc.). The limitation as evidenced in this research is that the resultant maps for the *Physical Environment* cluster, *Socio-Economic Aspects* cluster as well as the *Overall Goal*, contain blank '*white areas*' that do not reflect any geometrical volume of the ground considered in the model for analysis. This unfavourable result does not deter from the novel methodology put forward by the SUURE Operational Model to include geological ground models (in the future, 3D models conditional on a computational ontogenesis) in a sustainability evaluation of UUS resources to support future UUS planning. The basis as to why the 2D raster geological model could not be accounted for in SUURE evaluation for the whole area under Eastside could not be established i.e. is it a limitation due to ArcGIS 10.2, GSI3D data conversion, or a limitation with reference to raster (fuzzy –baseline) multi-criteria evaluation, and was deemed beyond the scope of the current research exercise. It is noteworthy that for any future research with reference to the SUURE Operational Model, this discrepancy ought to be addressed to fully realise the objective purpose of the SUURE DSS, thereby accounting for the full spatial variability in 3D, the SUURE Operational Model would thus be able to observe the changes in ground conditions, from resulting maps of analyses – in space and time.

Chapter 5 fulfils objectives 6 and 7 of the thesis. In Chapter 5, the SUURE Operational Model is employed to evaluate the use of MUTs within the case study area of Birmingham Eastside. This particular novel evaluation of MUTs through use of the SUURE Operational Model is the first of its kind on both a national and international level. The use and deliberation of associated socio-ecological future scenarios is a comparatively novel knowledge area within civil engineering as regards analysing future requirements and impact of urban underground infrastructure. In addition, the sequence of activities within the SUURE Operational Model and its implementation with respect to MUTs are presented and discussed in addition to the impact of different socio-ecological future scenarios on MUT placement in Birmingham Eastside. The results obtained from SUURE evaluation are shown. The characteristic nature of the initial information is discussed and information sources that were utilised for data retrieval and synthesis are presented. All the stages (1-10) in the SUURE Operational Model are demonstrated and exemplified. In addition, the means by which SUURE provides support to decision-making processes is presented and discussed. It is concluded that sustainable and resilient urban underground infrastructure solutions are not simply scenario specific, on the other hand are also location specific; by way of explanation, local priorities and conditions impact significantly sustainable and resilient evaluation outcomes.

Taking everything into account, the advantages of the SUURE DSS ought to be outlined. To begin with, it supports the universal typical flow of steps for a project life cycle. This feature renders the SUURE Operational Model suitable and wide-ranging for applications across a broad spectrum of complex SES domains. Second, the adaptability of the SUURE Operational Model and potential for simple modification to any domain of interest should be noted. The SUURE Operational Model is configured in such a way that the alteration of domain is achieved during the first stage of sustainability evaluation (i.e. sustainability goal identification), however all other procedures of data acquisition, processing and ultimate decision generation are carried out in a similar way, albeit for different domains. This feature adds adaptability to the SUURE Operational Model and extends its functional use to other areas besides geotechnical engineering.

Furthermore, the SUURE DSS employs recognised vocabulary and incorporates tools as well as approaches from different fields, taking full advantage of the strengths each has to offer. A key insight gained through the process of the research project, is that the possibility does exist, but with great difficulty i.e. the potential of formulating an elaborate and unified DSS aimed at particular and exact decision-support for SES evaluation of complex domains. This goal is problematic to realise, for the reason that the commonalities shared by different complex SESs, besides UUS, must be accounted for without mislaying their attributes. Nonetheless, the SUURE DSS through its Operational Model affords a flexible approach to explanation of sustainable and resilient solution SES applications. Its potential ought to be utilised for complex SES study, as it affords a platform to pool together an aggregate capacity of approaches and implements from different disciplines.

6.3 RECOMMENDATIONS FOR FURTHER WORK

With regard to the above-mentioned Section 6.1-6.2, it can be concluded that the aim and objectives of this present research work as specified in Chapter 1 have been addressed with the formulation of the SUURE DSS. Nevertheless, these assertions have been founded upon a number of model assumptions and simplifications. Notwithstanding these limitations, the SUURE Operational Model can be successfully utilised to assess use of urban underground space, for placement of urban underground utility infrastructure. Even so, the limitations that have thus been identified can only be resolved through further research, to sharpen up and better the proposed DSS. These are presented below:

- The SUURE DSS through its Operational Model, is a multi-attribute decision-making framework, and because of this is intended for use in discrete decision spaces. It evaluates one sustainability solution at a time. Whereas the built environment is tightly interwoven as evidenced with the evaluation of MUTs in Chapter 5 (see Figure 5-3), and sustainability evaluation of a SES to this end often necessitates simultaneous elements to be considered (see Table 3-3). Performing a SUURE evaluation as currently is for each consecutive element of a multiple solutions analysis as required (see Table 3-3), would most likely prove to be too lengthy and is practically unmanageable. Multi-objective decision-making problems, consequently, comprise the design of alternatives that optimise or else at a minimum fulfil the objectives of the decision-makers; as such, more than one objective (sustainability goal) can be evaluated at one go. The use of a multi-objective decision approach would be of scientific interest to incorporate into the SUURE DSS and accompanying Operational Model.
- The analyses for both baseline and scenario resilience evaluation was carried out in 2D overlay, limited only by computational power at the time of analyses. A very promising opportunity exists to apply the SUURE Operational Model in full 3D integration of not only the geology, but all related sustainability criteria, esp. underground utilities and infrastructure. This is increasingly important for two reasons. Firstly, the complete variability that exists presently must be accounted for. Secondly, through characterisation of the existing underground asset catalogue and full geology, thereby accounting for the full spatial variability in 3D, the SUURE Operational Model would thus be able to observe the changes in ground conditions, from resulting maps of analyses – in space and time. This novel application could prove to be a very promising line of research and would be the first application of its kind to blaze the trail into sustainable subsurface management. The principal area of focus in the present work as regarding UUS resources is with reference to space for UUI. UUS also encompasses geomaterials,

groundwater and geothermal energy. The SUURE DSS has scope to be extended to these other resources offered by UUS and this would be of scientific interest.

- The research data was stored, processed and analysed in raster data format. An opportunity to this end exists to store, process and analyse data using the alternative 'vector' data format. Although it presents challenges with respect to compiling correct geometry and projection of vector data on a medium-large scale SUURE Operational Model evaluation exercise, the advantage that could be gained in adopting this data format for the SUURE DSS is the ability to thus quite simply and effortlessly quantify the interrelationships that exist between different criteria in space and time, using spatial statistics tools such as exploratory regression, grouping analysis, geographically weighted regression, ordinary least squares, etc. which is not afforded by adopting a raster format. This could prove to be quite a promising line of research by being able to deconstruct the minutia of differences that exist in the different socio-ecological future scenarios used (NSP, PR, MF and FW).
- The ANP network structure employed in the present research work represents a simple network structure i.e. at one top-level concerning the control criteria (goal). It would be useful to include the use of the BOCR (benefits, opportunities, costs and risks) in the evaluation of a proposed sustainability solution i.e. a multiple top-level network. This application would comprehensively account for all factors that influence the control criteria (goal) – accounting for control criteria with respect to BOCR, and representing these in sub-networks for the high priority control criteria in clusters. Mention should be made to the high number of comparison matrices that would be generated employing this method in contrast to the approach employed in the present research work.
- Scenario resilience analyses carried out utilising SUURE, employed with respect to MUTs, data that had been reclassified using the conventional linear standardisation method. Different standardisation methods exist for the purpose of reclassifying data fit for contextual analysis, such as equal intervals, mean-standard deviation, quantiles, maximum breaks, natural breaks, etc. It would be of interest to include some of these different reclassification procedures as a means of identifying their impact on the resultant scenario resilience performance index ratio.
- Baseline performance resilience analyses carried out utilising SUURE, employed with respect to MUTs, fuzzy membership functions 'MSLarge' and 'MSSmall'. Other membership functions exist for the purpose of fuzzy standardisation such as linear, large, small, near and gaussian, etc. It would be of interest to include some of these different reclassification procedures as a means of identifying their impact on the resultant baseline resilience performance index ratio.
- A comparison of the results of SURRE MUT evaluation with the work of Curiel-Esparza and Canto-Perello (2013) highlighted a phenomenon worthy of exploration. This phenomenon as observed in Figure 5-16 necessitates further investigation in light of the placement of MUTs i.e. are local priorities more important or global decision indicators in the formulation of priority decision-making weights?

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APPENDIX A WORLD-WIDE EXAMPLES OF MUT'S

Country	City	Year	Length (km)	Depth (m)	Width (m)	Height (m)	Type	Installation	Shape	Material	Utility housed							
											Gas	Electric	Clean water	Sewerage/ rainwater	Communications	District cooling	District heating	Refuse collection
Belgium	Antwerp	1969	-	-	-	-	B	-	IV	-	N	Y	Y	Y	Y	N	N	N
	Brussels	1976	4.0	-	1.3	1.9	B	-	II	c	N	Y	N	N	Y	N	N	N
Denmark	Copenhagen	1980	1.6	35.0	-	-	-	-	IV	-	N	N	N	N	N	Y	Y	N
Finland	Helsinki	1982	40.0	80.0	5.0	7.0	B	-	II	f	N	Y	Y	N	Y	N	Y	N
France	Angers	1970	-	-	1.3	1.9	B	R	V	b	N	Y	Y	Y	Y	N	Y	N
	Besancon	1966	12.0	-	1.0	1.8	B	-	V	b	N	Y	Y	Y	Y	N	Y	N
	Dijon	1977	-	-	2.2	3.4	B	-	II	b	N	N	Y	Y	N	N	N	N
	Epinay-sous	1976	2.0	-	2.0	2.0	B	P	V	b	N	Y	Y	Y	Y	N	N	N
	Grenoble	1970	1.5	1.5	7.2	4	B	R	II	b	N	Y	Y	Y	Y	N	Y	N
	Lyon	1984	-	-	2.1	2.9	B	P	II	c	N	Y	Y	Y	Y	N	Y	N
	Marne la Vallee	1972	-	-	2.0	2.4	B	-	II	-	N	Y	Y	Y	Y	N	N	N
	Metz	1972	-	0.5	2.5	3.2	B	R	II	c	Y	Y	Y	Y	Y	N	N	N
	Paris – *Rive Gauche*	1990	2.1	0.5	4.7	10.5	C	R	II	b	Y	Y	Y	Y	Y	N	N	N
	Paris – *La Defense*	1992	12.0	-	3.6	2.5	B	-	V	b	N	Y	Y	Y	Y	Y	N	N
	Rennes	1970	1.4	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	-
	Roen	1967	-	-	1.9	2.0	B	-	II	c	N	Y	Y	Y	Y	N	N	N
	Saint Ettienne	1972	0.4	--	1.5	1.9	B	-	II	c	Y	Y	Y	Y	Y	N	N	N
	Saint Germaine en laye	1971	1.3	-	2.1	3.0	B	-	V	b	N	Y	Y	Y	Y	N	Y	N
	Toulouse	1972	0.7	-	2.2	2.5	B	-	II	b	N	Y	Y	Y	Y	N	Y	N
	Tours	1945	3.8	-	1.5	2.0	B	-	-	-	N	Y	Y	Y	Y	N	N	N
	Villiers sur marne	1971	3.0	-	-	-	B	-	-	-	Y	Y	Y	Y	N	N	N	N
Germany	Fahrland	1994	0.3	-	2.0	2.0	B	-	IV	a	N	Y	Y	Y	N	N	N	N
	Lauchheim	1995	0.3	-	2.0	2.0	B	-	IV	d	N	Y	Y	Y	N	N	N	N
	Wachau	1992	4.0	-	2.0	2.0	B	-	IV	a	Y	Y	Y	Y	N	N	N	N
Japan	Tokyo – *Minato Mirai*	2000	25.0	-	14.0	7.7	C	-	II	b	Y	Y	Y	Y	Y	Y	Y	Y
	Tokyo – *Minato Mirai*	2000	25.0	-	15.6	9.1	C	-	VI	c	Y	Y	Y	Y	Y	Y	Y	Y
	Sato	1993	1.9	-	7.7	3.4	C	R	II	c	N	Y	Y	Y	Y	N	N	N
	Hiroshima Minami	1993	2.6	2.5	3.3	3.9	C	P	II	c	Y	Y	Y	Y	Y	N	N	N
Malaysia	Putrajaya	2003	15.0	1.0	8.0	5.0	C	R	II	b	Y	Y	Y	Y	Y	Y	N	N
Norway	Oslo	-	-	2.0	-	-	B	-	II	c	N	Y	Y	Y	Y	N	N	N
Russia	Kiev	1950	-	-	-	-	B	-	II	c	N	Y	Y	Y	Y	N	N	N
	Moscow	1943	100	-	2.0	3.0	B	-	II	b	N	Y	Y	Y	Y	N	N	N
Singapore	New Downtown	2004	20.0	-	12.0	4.0	C	R	II	b	Y	Y	Y	Y	Y	Y	Y	Y
Spain	Barcelona	1992	28.0	2.0	2.0	1.0	A	P	III	c	N	Y	Y	N	Y	N	N	N
	Madrid	1940	100	0.0	2.1	4.5	C	-	V	e	N	Y	Y	Y	Y	N	N	N
Switzerland	Basel	1980	-	-	-	-	C	-	II	b	N	Y	Y	Y	Y	N	N	N
	Geneva	1984	0.8	0.5	-	-	C	M	II	c	N	Y	Y	Y	Y	N	N	N
	Lugano	1963	10	-	-	-	-	-	IV	c	N	Y	N	N	Y	N	N	N
Taiwan	Taipei – *Civic Boulevard*	2000	11.0	-	-	-	C	P	II	c	N	Y	Y	Y	Y	N	N	N
	Taipei – *Betoi No. 15*	2000	0.5	0.5	1.7	1.4	B	P	II	c	N	Y	Y	Y	Y	N	N	N
	Taipei – *Xinyi MRT Line*	2011	0.8	-	-	-	B	-	II	c	N	Y	Y	Y	Y	N	N	N
	Taipei – *Nangang*	2010	1.7	-	-	-	B	-	II	c	N	Y	Y	Y	Y	N	N	N
UK	London – Holburn viaduct	1866	-	-	-	-	B	R	V	e	N	N	Y	Y	N	N	N	N
	London – Barbican	1957	4.5	-	-	-	B	-	II	b	N	Y	N	Y	Y	N	N	Y
	M6 Toll Road	2003	-	-	-	-	A	R	III	c	-	-	-	-	-	-	-	-
	Birmingham - University	2005	0.1	0.0	1.6	0.8	A	R	III	c	N	N	N	N	Y	N	Y	N
	Mersey tunnel	1972	-	-	-	-	A	R	IV	c	Y	Y	N	N	Y	N	N	N
USA	Alaska – *Cape Lisburn, Nome, Fort McPherson*	-	-	-	-	-	B	-	V	c	N	Y	Y	Y	Y	N	N	N
	Chicago	1992	-	-	-	-	B	-	V	c	N	N	N	N	Y	N	N	N
	Disney	1982	1.0	-	-	-	B	R	II	c	N	Y	Y	Y	Y	N	N	N
	Fairbanks – *University*	1938	1.0	1.8	0.9	-	B	R	V	c	N	Y	Y	Y	Y	N	N	N
	New York	-	-	-	-	-	B	-	IV	c	N	Y	Y	Y	Y	N	N	N
	Seattle - *University*	1940	-	-	-	-	B	R	II	c	N	Y	Y	Y	Y	N	N	N

Type, installation, shape and material of MUT

Type	Installation	Shape	Material
A. Searchable	R – Road	I. Trapezoid	a. High Density Polyethylene (PEHD)
B. Visitable	P – Pavement	II. Rectangular	b. Cast in-situ concrete
C. Compartmentalized	M - Metro	III. Rectangular with lid	c. Pre-cast concrete sections
		IV. Circular	d. Steel
		V. Ovoid with gutter	e. Brick and mortar
		VI. Double Oval	f. Sprayed concrete

Table adapted from Rogers and Hunt (2006)

APPENDIX B BOREHOLE INDEX FILE (*.BID)

Unique Borehole ID	Easting	Northing	Start Height
SP08NE100.	406880	286330	125.4
SP08NE124.	408150	287800	112.9
SP08NE125.	407600	287750	116.3
SP08NE126.	407570	287630	118.9
SP08NE127.	407630	287830	114.3
SP08NE128.	407950	287180	106.8
SP08NE129.	407950	287250	109.5
SP08NE130.	407370	286850	122.7
SP08NE131.	407440	286930	120
SP08NE132.	407300	287090	130.7
SP08NE133.	407340	287160	129.8
SP08NE134.	407470	287120	117.8
SP08NE135.	407110	286470	118.5
SP08NE136.	407060	286440	119.4
SP08NE137.	407620	286350	101.8
SP08NE139.	406820	286260	129
SP08NE140.	406790	286340	129.9
SP08NE147.	406850	286810	132.8
SP08NE148.	406870	286770	131.9
SP08NE149.	406920	286400	123.9
SP08NE150.	406930	286330	123.2
SP08NE151.	406970	286360	121.4
SP08NE1517.	408408	286398	105.5
SP08NE1518.	408402	286309	108.34
SP08NE152.	406980	286430	122
SP08NE153.	407000	286470	122
SP08NE163.	407210	286710	123.7
SP08NE165.	407170	287320	129.4
SP08NE171.	407560	287590	119.8
SP08NE172.	407490	287750	118
SP08NE173.	407600	287670	117.9
SP08NE174.	407380	287640	118.7
SP08NE175.	407110	287100	135
SP08NE176.	407160	286860	131.6
SP08NE177.	407050	286380	118.8
SP08NE187.	408220	287340	105.9
SP08NE198.	408220	285900	135.47
SP08NE199.	407780	287650	115.3

Unique Borehole ID	Easting	Northing	Start Height
SP08NE200.	407720	287700	115.5
SP08NE201.	407810	287980	108.2
SP08NE202.	407830	287900	109.6
SP08NE203.	407590	287930	113.2
SP08NE204.	407150	287190	132.3
SP08NE205.	407180	287160	132.7
SP08NE207.	407830	288040	106.8
SP08NE208.	407880	288110	106
SP08NE214A-F.	406980	286650	127.6
SP08NE215.	407600	287150	115
SP08NE216.	407450	287220	119.7
SP08NE217.	407660	287260	116.2
SP08NE229.	408290	287030	96.3
SP08NE230A.	408070	286860	97.1
SP08NE230B.	408070	286860	97.1
SP08NE231.	408000	286770	97.1
SP08NE232.	407790	286410	100.5
SP08NE269.	407760	287680	115.1
SP08NE298.	407660	288390	115.24
SP08NE299.	407660	288330	105.4
SP08NE300.	407610	288310	106.3
SP08NE301.	407750	288320	104.1
SP08NE302.	407770	288250	104.8
SP08NE303.	407790	288130	106.2
SP08NE304.	407660	288200	106.2
SP08NE305.	407650	288180	106.8
SP08NE306.	407590	288130	108.9
SP08NE307.	407600	288000	111.4
SP08NE308.	407540	287920	113.8
SP08NE309.	407420	288260	108.9
SP08NE310.	407530	288310	107.5
SP08NE316.	408650	286240	110.1
SP08NE317.	408650	286220	110.1
SP08NE318.	408630	286220	109.5
SP08NE319.	408630	286240	109.5
SP08NE332.	407790	287630	115.5
SP08NE334.	407240	287470	124.1
SP08NE348.	408460	286440	104.4
SP08NE349.	408440	286400	104.9
SP08NE350.	408460	286400	105
SP08NE351.	408470	286350	105.8

Unique Borehole ID	Easting	Northing	Start Height
SP08NE352.	408450	286370	105.3
SP08NE356.	407180	286790	127.7
SP08NE357.	407180	286790	127.7
SP08NE358.	407180	286790	127.7
SP08NE359.	407180	286790	127.7
SP08NE360.	407180	286790	127.7
SP08NE361.	407250	286740	123.4
SP08NE362.	407250	286740	123.4
SP08NE363.	407250	286740	123.4
SP08NE364.	407250	286740	123.4
SP08NE365.	407250	286740	123.4
SP08NE366.	407250	286740	123.4
SP08NE367.	406950	286760	131.7
SP08NE368.	406950	286760	131.7
SP08NE369.	406950	286760	131.7
SP08NE37.	407090	286090	114.6
SP08NE370.	406950	286760	131.7
SP08NE371.	406950	286760	131.7
SP08NE372.	406950	286760	131.7
SP08NE373.	406950	286760	131.7
SP08NE374.	406950	286760	131.7
SP08NE375.	406950	286760	131.7
SP08NE38.	407470	286540	115.5
SP08NE382.	406730	286510	132
SP08NE383.	406760	286480	130.4
SP08NE384.	406830	286390	127.4
SP08NE385.	406840	286360	127.2
SP08NE386.	406860	286410	126.4
SP08NE389.	406870	286280	126.1
SP08NE39.	407620	286730	117.2
SP08NE391.	406930	286310	123.1
SP08NE41.	407840	286860	115.5
SP08NE43.	408270	286520	112.2
SP08NE435.	407400	287200	125.9
SP08NE44.	408500	286490	112.2
SP08NE45.	408540	286210	115.5
SP08NE47.	407720	286190	112.2
SP08NE527.	408270	286750	98.4
SP08NE528.	408290	286760	98.2
SP08NE529.	408300	286770	98
SP08NE530.	408320	286760	98.4

Unique Borehole ID	Easting	Northing	Start Height
SP08NE531.	408300	286740	98.8
SP08NE532.	408290	286730	99
SP08NE613.	407120	287210	130.6
SP08NE614.	407110	287260	133.5
SP08NE615.	407120	286200	133
SP08NE616.	407160	286240	130.6
SP08NE667.	408420	287370	103.1
SP08NE668.	408430	287320	100.7
SP08NE98.	407090	286540	127.52
SP08NE99.	406780	286450	135.8

APPENDIX C BOREHOLE DOWNHOLE INTERPRETATION FILE (*BLG)

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE38.	3.96	MMG-MDST	SDST	Hard sandstone
SP08NE38.	6.58	MMG-MDST	CZ	Hard marl
SP08NE38.	80.16	WRS-SDST	SDST	Hard sandstone
SP08NE38.	86.14	WRS-SDST	SDST	Sandstone
SP08NE39.	5.49	MGR-ROAD	ARTDP	Made ground
SP08NE39.	8.23	RTD1-XSV	V	Gravel
SP08NE39.	10.36	STLL-DMTN	DMTN	Running sand
SP08NE39.	12.19	MMG-MDST	SDST	Sandstone
SP08NE39.	17.07	BMS-SDST	SDST	Red sandstone
SP08NE39.	62.79	BMS-SDST	SDST	Sandstone
SP08NE39.	64.62	BMS-SDST	SAMDST	Sandstone and marl
SP08NE39.	70.1	BMS-SDST	SDST	Sandstone
SP08NE39.	76.2	WRS-SDST	SAMDST	Sandstone and marl
SP08NE41.	1.52	MGR-ROAD	ARTDP	Made ground
SP08NE41.	2.44	RTD1-XSV	S	Sand
SP08NE41.	5.18	STLL-DMTN	LB	Large ballast
SP08NE41.	7.32	MMG-MDST	SCZ	Sandy marl
SP08NE41.	8.84	MMG-MDST	CZ	Red marl
SP08NE41.	9.75	MMG-MDST	C	Light blue clay
SP08NE41.	11.58	WRS-SDST	SDST	Sand and stones
SP08NE41.	14.63	WRS-SDST	SDST	Hard sand stone
SP08NE41.	15.54	WRS-SDST	SDST	Light sand stone
SP08NE41.	17.68	MMG-MDST	CZ	Red marl
SP08NE41.	21.03	MMG-MDST	SDST	Red sandstone
SP08NE41.	21.34	MMG-MDST	B	Grey stone
SP08NE41.	33.83	WRS-SDST	SDST	Hard sandstone
SP08NE41.	36.27	MMG-MDST	CZ	Red marl
SP08NE41.	46.33	BMS-SDST	SDST	Fine sandstone
SP08NE41.	53.95	BMS-SDST	SDST	Coarse sandstone
SP08NE41.	57.91	MMG-MDST	CZ	Red marl
SP08NE41.	74.68	BMS-SDST	SDST	Sandstone
SP08NE41.	76.2	WRS-SDST	SDST	Hard sandstone
SP08NE43.	1.83	MGR-ROAD	ARTDP	Made ground
SP08NE43.	4.15	MMG-MDST	CL	Red and blue clay and pebbles
SP08NE43.	15.73	MMG-MDST	CZ	Red and blue marl
SP08NE43.	20.73	MMG-MDST	CZ	Red and blue marl and pebbles
SP08NE43.	30.48	MMG-MDST	CZ	Hard blue and red marl
SP08NE44.	37.79	MMG-MDST	CZ	Red and blue marl
SP08NE44.	39.32	MMG-MDST	SDST	Red sandstone

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE44.	41.45	MMG-MDST	SCZ	Red sandy marl
SP08NE44.	60.05	BMS-SDST	CZ	Red marl
SP08NE44.	62.18	BMS-SDST	SDST	Red sandstone
SP08NE44.	65.23	BMS-SDST	CZ	Red marl
SP08NE44.	70.1	BMS-SDST	SDST	Red sandstone
SP08NE44.	83.52	BMS-SDST	CZ	Red marl
SP08NE44.	97.54	BMS-SDST	SDST	Red sandstone
SP08NE44.	98.76	WRS-SDST	CZ	Red marl
SP08NE44.	100.28	WRS-SDST	SAMDST	Red sandstone and marl in layers
SP08NE45.	27.13	STLL-DMTN	DMTN	Sand
SP08NE45.	28.04	STLL-DMTN	LB	Ballast
SP08NE45.	43.46	MMG-MDST	CZ	Marl
SP08NE47.	1.22	MGR-ROAD	ARTDP	Made ground
SP08NE47.	1.83	RTD1-XSV	CB	Clay and stones
SP08NE47.	3.54	STLL-DMTN	LB	Large ballast
SP08NE47.	9.45	STLL-DMTN	C	Brown clay
SP08NE47.	11.89	MMG-MDST	CZB	Marl and large stones
SP08NE47.	27.43	MMG-MDST	CZ	Green and red marl
SP08NE47.	28.53	MMG-MDST	SDST	Sandstone
SP08NE47.	41.03	MMG-MDST	CZ	Black marl
SP08NE47.	57.91	MMG-MDST	SAMDST	Marl with a little sandstone
SP08NE47.	61.57	MMG-MDST	SDST	Sandstone
SP08NE47.	62.79	MMG-MDST	CZ	Green marl
SP08NE47.	64.92	MMG-MDST	SAMDST	Sandstone and marl
SP08NE47.	64.14	MMG-MDST	SCZ	Sandy red and green marl
SP08NE47.	85.65	MMG-MDST	CZ	Red marl
SP08NE47.	86.56	MMG-MDST	SAMDST	Sandstone and marl
SP08NE47.	92.66	MMG-MDST	CZ	Marl
SP08NE98.	0.61	MGR-UNDIFF	ARTDP	Fill
SP08NE98.	1.68	RTD1-XSV	SCZ	Brown sandy clayey silt with some gravel
SP08NE98.	3.05	GLLD-C	ZCS	Medium brown silty clay with a little fine sand
SP08NE98.	5.79	GLLD-C	SDST	Medium brown soft sandstone with fine sand
SP08NE99.	2.29	MGR-UNDIFF	ARTDP	Fill
SP08NE99.	3.81	RTD1-XSV	CS	Brown clayey sand
SP08NE99.	5.49	RTD1-XSV	SZ	Reddish brown sand with some silt traces
SP08NE99.	7.32	RTD1-XSV	SZ	Clayey sand with silt
SP08NE99.	8.23	RTD1-XSV	S	Light brown fine sand
SP08NE100.	3.81	MGR-UNDIFF	ARTDP	Fill
SP08NE100.	4.57	RTD1-XSV	SC	Reddish brown sandy clay
SP08NE100.	8.53	RTD1-XSV	S	Reddish brown sand with silt traces
SP08NE124.	2.59	MGR-UNDIFF	ARTDP	Fill
SP08NE124.	13.11	RTD1-XSV	SV	Coarse brown sand and gravel
SP08NE124.	13.72	RTD1-XSV	SV	Reddish brown sand and gravel, trace of clay

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE124.	18.29	RTD1-XSV	SV	Reddish brown sand and gravel
SP08NE125.	0.76	MGR-UNDIFF	ARTDP	Fill
SP08NE125.	2.13	ALV-XCZ	CV	Brown clayey topsoil; gravel fill
SP08NE125.	3.51	ALV-XCZ	SV	Yellow and red sand with some gravel; clayey silt
SP08NE125.	5.94	RTD1-XSV	SZ	Medium brown soft sandy silt with a little gravel
SP08NE125.	6.17	RTD1-XSV	Z	Grey black silt with a little gravel
SP08NE125.	7.01	RTD1-XSV	ZSV	Brown medium silty sand with some gravel
SP08NE125.	7.62	GLLD-C	CZ	Brown clayey silt with some gravel and sand
SP08NE125.	8.84	GFDU-XSV	CZ	Brown clayey silt, some fine sand
SP08NE125.	9.91	GFDU-XSV	ZC	Brown silty clay and fine sand
SP08NE125.	11.43	GFDU-XSV	ZC	Medium brown silty clay
SP08NE125.	12.8	GFDU-XSV	SZ	Brown sand and silt
SP08NE125.	14.02	GFDU-XSV	Z	Brown silt conglomerate with some sandstone
SP08NE125.	14.94	GFDU-XSV	ZC	Brown silty clay with some sand
SP08NE125.	15.85	GFDU-XSV	CZ	Brown clayey silt with some small gravel
SP08NE126.	1.07	MGR-UNDIFF	ARTDP	Fill
SP08NE126.	4.11	ALV-XCZ	SZ	Brown medium sand with little silt; some fine gravel
SP08NE126.	5.64	ALV-XCZ	CZ	Red-brown clayey silt with pockets of fine sand; sandstone fine gravel
SP08NE126.	7.01	RTD1-XSV	ZV	Brown silt with some gravel; a little sand
SP08NE126.	8.53	RTD1-XSV	ZC	Brown silty clay; patches of fine sand & some fine gravel
SP08NE126.	9.3	RTD1-XSV	Z	Brown silt
SP08NE126.	9.53	GLLD-C	S	Brown sand
SP08NE126.	9.68	GLLD-C	CZ	Brown clayey silt
SP08NE126.	13.99	STLL-DMTN	DMTN	Brown medium sand; some silty lumps
SP08NE127.	2.44	MGR-UNDIFF	ARTDP	Fill
SP08NE127.	2.59	ALV-XCZ	SZ	Brown sandy silt with some gravel
SP08NE127.	3.31	ALV-XCZ	ZC	Firm red-brown silty clay, some gravel
SP08NE127.	10.52	RTD1-XSV	S	Medium brown sand with a little silt
SP08NE127.	13.11	RTD1-XSV	CZ	Dark brown clayey silt with a little fine sand, with some gravel
SP08NE127.	14.48	GLLD-C	SV	Brown sand with much gravel
SP08NE127.	15.62	GLLD-C	V	Clean gravel
SP08NE127.	16.23	STLL-DMTN	VZ	Clean gravel with silt and sands
SP08NE127.	17.37	STLL-DMTN	CZ	Red-brown clayey silt with fine sand
SP08NE127.	17.98	STLL-DMTN	SB	Rock sand
SP08NE128.	0.76	MGR-UNDIFF	ARTDP	Fill
SP08NE128.	3.05	RTD1-XSV	SV	Clean light brown medium sand with gravel
SP08NE128.	9.14	STLL-DMTN	SB	Brown medium grained soft rock sand
SP08NE129.	1.37	MGR-UNDIFF	ARTDP	Fill
SP08NE129.	1.75	ALV-XCZ	SV	Sandy soil with little gravel

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE129.	5.33	RTD1-XSV	CS	Medium brown clay sand in mixture of gravel
SP08NE129.	6.4	RTD1-XSV	PEAT	Black sandy clay with fibres (peat)
SP08NE129.	7.01	RTD1-XSV	S	Medium brown fine fairly clean sand
SP08NE129.	7.47	STLL-DMTN	SB	Medium brown fine rock sand
SP08NE130.	0.3	MGR-UNDIFF	ARTDP	Fill
SP08NE130.	5.18	RTD1-XSV	SV	Clayey sand and gravel with traces of silt
SP08NE130.	12.19	RTD1-XSV	SV	Reddish brown coarse sand with gravel and traces of silt and clay
SP08NE131.	2.44	MGR-UNDIFF	ARTDP	Fill
SP08NE131.	7.92	RTD1-XSV	SV	Medium to fine reddish brown sand with gravel and trace of silt and clay
SP08NE132.	3.05	MGR-UNDIFF	ARTDP	Fill
SP08NE132.	3.35	ALV-XCZ	ZCV	Silty clay and gravel
SP08NE132.	10.67	RTD1-XSV	SC	Medium to fine reddish brown sand with clay and silt traces
SP08NE133.	2.44	MGR-UNDIFF	ARTDP	Fill
SP08NE133.	8.53	RTD1-XSV	SC	Medium reddish brown sand with clay and silt traces
SP08NE134.	4.72	MGR-UNDIFF	ARTDP	Fill
SP08NE134.	9.14	RTD1-XSV	SV	Reddish brown sand and gravel with clay pockets
SP08NE134.	12.19	STLL-DMTN	SB	Reddish brown rock sand
SP08NE135.	3.66	MGR-UNDIFF	ARTDP	Fill
SP08NE135.	4.36	MMG-MDST	CZ	Red marl
SP08NE135.	7.01	RTD1-XSV	S	Compact medium red sand
SP08NE135.	10.97	BMS-SDST	SDST	Soft red sandstone
SP08NE136.	1.71	MGR-UNDIFF	ARTDP	Fill
SP08NE136.	2.44	RTD1-XSV	SV	Sand and gravel
SP08NE136.	4.27	RTD1-XSV	S	Compact medium red sand
SP08NE136.	4.96	BMS-SDST	SDST	Soft red sandstone
SP08NE137.	1.83	MGR-ROAD	ARTDP	Made ground
SP08NE137.	3.05	ALV-XCZ	LB	Ballast
SP08NE137.	3.66	RTD1-XSV	VC	Hoggin
SP08NE137.	5.49	MMG-MDST	CZ	Soft to firm marl
SP08NE137.	8.84	MMG-MDST	CZ	Hard marl
SP08NE140.	0.91	MGR-UNDIFF	ARTDP	Fill
SP08NE140.	5.49	STLL-DMTN	SC	Light brown medium sand with clay with traces to red-brown sand
SP08NE147.	2.74	MGR-ROAD	ARTDP	Made ground
SP08NE147.	5.12	STLL-DMTN	DMTN	Dry brown sand
SP08NE147.	6.1	BMS-SDST	SDST	Red sandstone
SP08NE147.	8.23	BMS-SDST	SDST	Sandstone, layered, fairly compact
SP08NE148.	0.91	MGR-ROAD	ARTDP	Made ground
SP08NE148.	2.44	ALV-XCZ	SDST	Dark brown sandstone
SP08NE148.	6.4	RTD1-XSV	SDST	Brown sandstone

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE148.	7.01	GLLD-C	C	Red clay
SP08NE148.	8.84	BMS-SDST	SDST	Red sandstone
SP08NE149.	5.49	MGR-UNDIFF	ARTDP	Fill
SP08NE149.	6.4	MMG-MDST	CZ	Red marl
SP08NE149.	10.97	BMS-SDST	SDST	Soft red sandstone
SP08NE150.	4.57	MGR-UNDIFF	ARTDP	Fill (composed of brick rubble, fill material and ashes)
SP08NE150.	5.18	MMG-MDST	CZ	Red marl with grey inclusions
SP08NE150.	5.79	BMS-SDST	ZS	Compact red silty fine sand
SP08NE150.	6.4	WRS-SDST	SDST	Soft red sandstone
SP08NE151.	3.43	MGR-UNDIFF	ARTDP	Fill
SP08NE151.	4.11	MMG-MDST	CZ	Soft to firm red marly clay
SP08NE151.	4.72	RTD1-XSV	S	Very compact fine and medium sand
SP08NE151.	5.33	BMS-SDST	SDST	Soft red sandstone
SP08NE152.	2.62	MGR-UNDIFF	ARTDP	Fill
SP08NE152.	4.15	ALV-XCZ	S	Moderately compact fairly coarse moist yellow brown sand
SP08NE152.	5.36	ALV-XCZ	SB	Very compact cemented sand; hardening to rock sand
SP08NE152.	5.67	ALV-XCZ	ZC	Hard red brown moist silty clay with greyish laminations
SP08NE152.	7.19	STLL-DMTN	SB	Hard rock sand
SP08NE153.	1.68	MGR-UNDIFF	ARTDP	Fill and soil
SP08NE153.	2.21	ALV-XCZ	CSV	Fairly loose cemented brown clayey sand with 40% gravel and few cobbles; more compact towards base
SP08NE153.	3.51	ALV-XCZ	ZS	Light red brown silty and fine sandy clay
SP08NE153.	3.81	ALV-XCZ	S	Compact red-brown medium sand with a few clayey pockets
SP08NE153.	4.34	ALV-XCZ	CZ	Firm red-brown clay; silty mudstones
SP08NE153.	4.54	RTD1-XSV	S	Compact fairly coarse moist light red brown sand
SP08NE153.	4.84	STLL-DMTN	SB	Fine grained brown rock sand
SP08NE163.	3.84	MGR-UNDIFF	ARTDP	Fill
SP08NE163.	6.1	ALV-XCZ	SC	Soft brown sandy clay and fine gravel
SP08NE163.	7.92	GFDU-XSV	SV	Dense brown fine to medium sand; some gravel
SP08NE163.	14.02	BMS-SDST	SDST	Weekly cemented red sandstone
SP08NE163.	15.73	MMG-MDST	ZC	Hard red silty clay (marl)
SP08NE163.	21.43	MMG-MDST	SAMDST	Weakly cemented red sandstone; marl layer
SP08NE165.	3.29	MGR-ROAD	ARTDP	Made ground
SP08NE165.	5.18	ALV-XCZ	CSV	Red clayey sand with gravel
SP08NE165.	5.36	ALV-XCZ	SZ	Red sand with thin layers of black silty sand
SP08NE165.	7.68	RTD1-XSV	S	Red brown sand
SP08NE165.	7.8	RTD1-XSV	SDST	Soft grey sandstone
SP08NE165.	7.92	GLLD-C	SC	Red brown sandy clay
SP08NE165.	9.45	STLL-DMTN	DMTN	Red sand

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE165.	9.68	MMG-MDST	SCZ	Red sand with marl
SP08NE165.	15.4	STLL-DMTN	S	Compact red sand
SP08NE165.	19.8	BMS-SDST	SDST	Red sandstone
SP08NE171.	0.91	MGR-UNDIFF	ARTDP	Fill
SP08NE171.	2.74	ALV-XCZ	SV	Clean compact sand and little gravel
SP08NE171.	3.44	RTD1-XSV	S	Compact dark sand
SP08NE171.	4.27	RTD1-XSV	S	Damp compact red sand, unstable when wet
SP08NE171.	5.76	MMG-MDST	SCZ	Sand with marl, unstable when wet
SP08NE171.	6.27	MMG-MDST	CZ	Stiff dry clayey marl
SP08NE172.	0.69	MGR-UNDIFF	ARTDP	Fill
SP08NE172.	1.98	RTD1-XSV	SV	Clean soft sand with little gravel
SP08NE172.	2.13	MMG-MDST	CZS	Marl and sand
SP08NE172.	5.49	STLL-DMTN	DMTN	Clean soft sand , unstable when wet
SP08NE172.	6.71	MMG-MDST	CZS	Compact marly sand, unstable when wet
SP08NE173.	0.91	MGR-UNDIFF	ARTDP	Fill
SP08NE173.	3.05	MMG-MDST	CZ	Fairly stiff marl with little sand and pebbles
SP08NE173.	3.81	MMG-MDST	SCZ	Sandy marl
SP08NE173.	4.75	GLLD-C	Z	Black silt
SP08NE173.	9.14	MMG-MDST	SCZ	Fairly compact sandy marl
SP08NE174.	2.44	MGR-ROAD	ARTDP	Made ground
SP08NE174.	4.57	RTD1-XSV	S	Medium coarse sand with fine medium coarse gravel
SP08NE174.	5.36	RTD1-XSV	ZS	Fine medium silty sand with sand with fine medium coarse gravel
SP08NE174.	8.53	STLL-DMTN	DMTN	Medium and coarse sand with some fine medium and coarse gravel
SP08NE174.	10.67	GFDU-XSV	VS	Medium and coarse gravel with some coarse sand
SP08NE175.	0.61	ALV-XCZ	S	Firm red sand
SP08NE175.	1.52	RTD1-XSV	SC	Sand and clay
SP08NE175.	2.41	RTD1-XSV	SCV	Firm red sand with clay + gravel
SP08NE175.	4.88	RTD1-XSV	SV	Red sand and gravel
SP08NE175.	5.33	RTD1-XSV	SCV	Firm red sand with clay + gravel
SP08NE175.	6.1	GFDU-XSV	SV	Firm red sand and gravel
SP08NE175.	8.84	BMS-SDST	SDST	Red sand stone
SP08NE175.	13.72	STLL-DMTN	DMTN	Brown firm sand
SP08NE176.	0.15	MGR-ROAD	ARTDP	Made ground (concrete)
SP08NE176.	1.52	ALV-XCZ	VS	Gravel and sand
SP08NE176.	3.05	ALV-XCZ	S	Sand
SP08NE176.	4.88	RTD1-XSV	SV	Sand and gravel
SP08NE176.	5.49	RTD1-XSV	CSV	Clayey sand and gravel
SP08NE176.	6.1	RTD1-XSV	VS	Gravel and sand
SP08NE176.	9.14	RTD1-XSV	S	Dense cemented sand
SP08NE176.	9.75	MMG-MDST	CZ	Firm red clay and marl

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE176.	11.28	RTD1-XSV	S	Dense cemented sand
SP08NE176.	12.04	GLLD-C	C	Firm red clay
SP08NE176.	12.19	MMG-MDST	CZ	Hard red marl
SP08NE176.	12.65	BMS-SDST	C	Firm red clay
SP08NE176.	12.8	BMS-SDST	ZC	Hard shaley marl
SP08NE176.	15.24	WRS-SDST	S	Dense cemented sand or soft sandstone
SP08NE177.	2.59	MGR-ROAD	ARTDP	Made ground – loose sand, brick and rubble, underlain by soft black sandy clay
SP08NE177.	3.35	ALV-XCZ	SC	Soft yellow-brown sandy clay, some fine and medium gravel
SP08NE177.	3.66	ALV-XCZ	SC	Brown fine and medium sand, with pockets of soft red clay
SP08NE177.	5.49	RTD1-XSV	CZS	Red clayey, silty fine sand
SP08NE177.	7.92	BMS-SDST	SDST	Sandstone and silty marl in alternating bands (lower kemper sandstone)
SP08NE187.	1.22	MGR-UNDIFF	ARTDP	Fill
SP08NE187.	1.83	ALV-XCZ	SV	Brown medium to fine sand; a little gravel
SP08NE187.	2.44	ALV-XCZ	CS	Compact clayey yellow-brown sand with silt pockets
SP08NE187.	2.62	ALV-XCZ	S	Compact medium fine brown sand
SP08NE187.	3.43	RTD1-XSV	S	Ditto, pockets of silt and clayey sand
SP08NE187.	3.59	RTD1-XSV	ZC	Brown silty clay
SP08NE198.	2.13	MGR-UNDIFF	ARTDP	Fill
SP08NE198.	2.54	MMG-MDST	CZ	Firm green-grey clay with some small hard shaley pieces
SP08NE198.	4.51	MMG-MDST	CZ	Firm red-brown marl with some grey veins
SP08NE199.	5.18	MGR-UNDIFF	ARTDP	Fill
SP08NE199.	6.1	RTD1-XSV	CSZ	Soft dark grey and brown clayey sand and silt with some gravel
SP08NE199.	6.4	RTD1-XSV	SZC	Firm brown sandy silty clay
SP08NE199.	10.06	GFDU-XSV	CZ	Brown clay with fine silt lamination
SP08NE199.	13.72	GFDU-XSV	SZC	Brown sandy and silty clay with some fine gravel
SP08NE199.	16.95	GFDU-XSV	SVL	Compact sand with gravel and cobbles
SP08NE199.	21.34	MMG-MDST	SCZ	Fine red sandy marl
SP08NE200.	3.96	MGR-UNDIFF	ARTDP	Fill
SP08NE200.	4.42	ALV-XCZ	SC	Brown sandy clay
SP08NE200.	5.12	ALV-XCZ	CV	Red clay with some gravel
SP08NE200.	9.75	ALV-XCZ	C	Stiff brown clay with some fine silt
SP08NE200.	10.82	RTD1-XSV	Z	Brown silty clay with some fine silt lamination
SP08NE200.	13.11	STLL-DMTN	SZC	Brown sandy and silty clay with gravel
SP08NE200.	15.85	STLL-DMTN	SV	Compact sand with gravel cobbles
SP08NE200.	21.34	MMG-MDST	CZ	Compact firm red marl
SP08NE201.	2.51	MGR-UNDIFF	ARTDP	Fill
SP08NE201.	3.43	ALV-XCZ	CZ	Mottled brown clayey silt, with sand
SP08NE201.	4.8	ALV-XCZ	CZV	Ditto, with gravel

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE201.	4.95	ALV-XCZ	SDST	Broken sandstone and gravel
SP08NE201.	5.33	RTD1-XSV	ZSV	Brown silty sand and gravel
SP08NE201.	6.25	RTD1-XSV	S	Gravel and sand
SP08NE201.	7.24	RTD1-XSV	S	Yellow-brown clean sand
SP08NE201.	7.47	GLLD-C	ZC	Brown silty clay with coarse sand and gravel
SP08NE201.	11.66	GFDU-XSV	SV	Brown sand and gravel
SP08NE202.	2.29	MGR-UNDIFF	ARTDP	Fill
SP08NE202.	3.96	ALV-XCZ	CZ	Brown/ grey clay with a little silt; sand
SP08NE202.	4.88	RTD1-XSV	ZC	Brown silty clay
SP08NE202.	6.1	RTD1-XSV	ZC	Ditto with some gravel
SP08NE202.	7.32	STLL-DMTN	DMTN	Brown medium to fine clean sand
SP08NE202.	8.23	GFDU-XSV	SV	Ditto with some gravel
SP08NE202.	9.45	GFDU-XSV	SV	Coarse sand and gravel
SP08NE203.	1.3	MGR-UNDIFF	ARTDP	Fill
SP08NE203.	1.6	ALV-XCZ	S	Hard orange brown sand
SP08NE203.	2.36	RTD1-XSV	VS	Compact gravel and yellow brown sand
SP08NE203.	5.26	RTD1-XSV	SC	Compact yellow-brown sand red-brown medium to coarse sand, sometime clayey
SP08NE203.	5.64	GLLD-C	CZ	Soft brown very clayey silt
SP08NE203.	7.47	GLLD-C	SCZ	Loose coarse brown sand with clayey firm sand-silt
SP08NE203.	8	STLL-DMTN	DMTN	Compact red-brown medium sand
SP08NE203.	8.31	GFDU-XSV	SZ	Soft red-brown clayey fine sand and silt
SP08NE203.	9.68	GFDU-XSV	SV	Coarse dark sand with a little gravel
SP08NE203.	10.29	MMG-MDST	CS	Coarse red-brown clayey sand
SP08NE203.	11.05	MMG-MDST	CZ	Firm red-brown marly clay
SP08NE204.	0.3	MGR-UNDIFF	ARTDP	Fill
SP08NE204.	3.05	RTD1-XSV	SV	Red and light brown medium to coarse sand, trace of gravel
SP08NE204.	3.51	RTD1-XSV	CS	Soft to firm red clay; sand pockets
SP08NE204.	6.55	BMS-SDST	SDST	Compact red fine to medium sand (very soft sandstone)
SP08NE204.	7.16	MMG-MDST	ZC	Hard red silty marl
SP08NE204.	11.58	BMS-SDST	SDST	Soft red to medium sandstone
SP08NE205.	2.82	MGR-UNDIFF	ARTDP	Fill
SP08NE205.	5.33	RTD1-XSV	SV	Compact red/ brown medium to coarse sand, trace of gravel
SP08NE205.	5.79	RTD1-XSV	SV	Compact medium brown sand and gravel
SP08NE205.	6.1	GLLD-C	SC	Red sandy clay, silty at base
SP08NE205.	7.77	GFDU-XSV	S	Compact red-brown medium sand
SP08NE205.	10.06	GFDU-XSV	S	Compact red and light brown; medium sand
SP08NE205.	10.97	MMG-MDST	CZ	Hard red marl
SP08NE205.	14.33	BMS-SDST	SDST	Soft red brown medium sandstone
SP08NE207.	1.22	RTD1-XSV	ZC	Dirty coarse silty clay
SP08NE207.	3.35	RTD1-XSV	SCZ	Brown sandy marl

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE207.	3.96	STLL-DMTN	SV	Medium and coarse brown sand; gravel
SP08NE207.	4.57	STLL-DMTN	SV	Medium and coarse brown sand and gravel with clay and silt
SP08NE207.	5.79	STLL-DMTN	DMTN	Fine and medium brown sand
SP08NE207.	9.75	STLL-DMTN	DMTN	Fine, medium and coarse brown sand with little fine gravel
SP08NE207.	10.67	GFDU-XSV	CZ	Reddish brown marly clay
SP08NE207.	11.89	BMS-SDST	SDST	Red/ brown soft sandstone
SP08NE208.	3.66	MGR-ROAD	ARTDP	Made ground
SP08NE208.	4.07	ALV-XCZ	ZCS	Silt, clay and sand
SP08NE208.	6.1	ALV-XCZ	S	Fine and medium sand with little silt and clay
SP08NE208.	8.53	ALV-XCZ	S	Fine medium and dense sand, little clay and silt
SP08NE208.	10.97	RTD1-XSV	SV	Sand and gravel
SP08NE208.	12.19	RTD1-XSV	SC	Sand and red clay with little silt
SP08NE214A.	0.15	MGR-UNDIFF	ARTDP	Fill
SP08NE214A.	3.05	RTD1-XSV	S	Red sand
SP08NE214A.	3.96	RTD1-XSV	SV	Sand and gravel
SP08NE214A.	4.72	STLL-DMTN	DMTN	Red sand
SP08NE214A.	8.99	BMS-SDST	SDST	Red sandstone
SP08NE214A.	9.3	BMS-SDST	CZ	Red marl
SP08NE214B.	2.13	MGR-UNDIFF	ARTDP	Fill
SP08NE214B.	3.51	RTD1-XSV	SV	Brown sand and gravel
SP08NE214B.	6.25	RTD1-XSV	S	Dense red sand
SP08NE214B.	7.62	RTD1-XSV	SV	Sand and gravel with clayey marl
SP08NE214B.	7.77	GLLD-C	CZV	Red marl and gravel
SP08NE214B.	9.3	BMS-SDST	SDST	Red-brown sandstone
SP08NE214C.	1.37	MGR-UNDIFF	ARTDP	Fill
SP08NE214C.	1.68	ALV-XCZ	VCZ	Gravel and marl
SP08NE214C.	3.05	ALV-XCZ	CZV	Red clay marl and gravel
SP08NE214C.	8.69	BMS-SDST	SDST	Red sandstone
SP08NE214C.	9.14	GLLD-C	CZ	Red marl
SP08NE214C.	9.45	BMS-SDST	SDST	Red sandstone
SP08NE215.	2.9	MGR-UNDIFF	ARTDP	Fill
SP08NE215.	12.9	GFDU-XSV	S	Firm reddish brown sand with traces of silt
SP08NE216.	1.22	MGR-UNDIFF	ARTDP	Fill
SP08NE216.	4.57	GFDU-XSV	CSV	Brown clayey sand and gravel
SP08NE216.	12.19	GFDU-XSV	SV	Brown sand with gravel and traces of silt and clay
SP08NE217.	2.29	MGR-UNDIFF	ARTDP	Fill
SP08NE217.	5.49	STLL-DMTN	SL	Medium brown sand, small pebbles, black silt traces
SP08NE217.	11.28	STLL-DMTN	SL	Medium sand, small pebbles, black silt traces
SP08NE217.	11.43	GFDU-XSV	SC	Sandy clay
SP08NE217.	13.56	GFDU-XSV	VS	Gravel and sand

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE229.	2.03	MGR-ROAD	ARTDP	Made ground
SP08NE229.	2.74	RTD1-XSV	S	Soil
SP08NE229.	3.99	RTD1-XSV	V	Gravel
SP08NE229.	4.88	GLLD-C	CB	Clay and stones
SP08NE229.	5.79	MMG-MDST	CZ	Red marl
SP08NE229.	7.24	MMG-MDST	CZ	Hard marl
SP08NE230A.	3.81	MGR-ROAD	ARTDP	Made ground
SP08NE230A.	6.17	RTD1-XSV	VC	Gravelly clay
SP08NE230A.	7.62	RTD1-XSV	V	Gravel
SP08NE230A.	8.08	MMG-MDST	CZ	Marl
SP08NE230A.	8.41	STLL-DMTN	C	Blue clay
SP08NE230A.	9.19	MMG-MDST	CZ	Marl
SP08NE230A.	9.45	BMS-SDST	SDST	Skerry band
SP08NE230A.	11.33	WRS-SDST	SAMDST	Marl with thin skerry bands
SP08NE230B.	3.81	MGR-ROAD	ARTDP	Made ground
SP08NE230B.	6.17	ALV-XCZ	VC	Gravelly clay
SP08NE230B.	7.62	ALV-XCZ	V	Gravel
SP08NE230B.	8.08	ALV-XCZ	CZ	Marl
SP08NE230B.	8.41	GLLD-C	C	Blue clay
SP08NE230B.	9.19	MMG-MDST	CZ	Marl
SP08NE230B.	9.45	MMG-MDST	SDST	Skerry band
SP08NE230B.	11.33	MMG-MDST	CZ	Marl with thin skerry bands
SP08NE231.	1.93	MGR-UNDIFF	ARTDP	Fill
SP08NE231.	2.54	RTD1-XSV	CZ	River marl
SP08NE231.	3.81	RTD1-XSV	LB	River ballast
SP08NE231.	4.17	GLLD-C	C	Red clay
SP08NE231.	4.52	GLLD-C	C	Blue clay
SP08NE231.	5.82	MMG-MDST	CZ	Red marl
SP08NE231.	7.39	MMG-MDST	CZ	Marl with thin skerry bands
SP08NE232.	1.88	MGR-ROAD	ARTDP	Made Ground
SP08NE232.	3.89	RTD1-XSV	V	Gravel
SP08NE232.	7.32	MMG-MDST	CZ	Red marl (hard)
SP08NE269.	5.66	MGR-ROAD	ARTDP	Made ground
SP08NE269.	8.53	ALV-XCZ	CZ	Red marl
SP08NE269.	9.14	RTD1-XSV	V	Gravel
SP08NE269.	10.06	GLLD-C	CZ	Red marl and boulders
SP08NE269.	11.89	STLL-DMTN	V	Large gravel
SP08NE269.	12.5	GFDU-XSV	S	Sand
SP08NE269.	14.02	GFDU-XSV	V	Gravel
SP08NE269.	16.46	GFDU-XSV	S	Sand
SP08NE269.	25.91	MMG-MDST	SDST	Sandstone
SP08NE269.	26.52	MMG-MDST	CZ	Marl
SP08NE269.	128.02	BMS-SDST	SDST	Sandstone

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE269.	136.23	WRS-SDST	SDST	Conglomerate
SP08NE269.	139.9	WRS-SDST	SDST	Sandstone
SP08NE269.	174.35	WRS-SDST	SDST	Conglomerate
SP08NE297.	2.13	MGR-ROAD	ARTDP	Ash, sand, gravel etc.
SP08NE297.	3.05	RTD1-XSV	V	Gravel and cobbles in some silty clay
SP08NE297.	5.79	RTD1-XSV	V	Gravel, cobbles and boulders with some sand
SP08NE297.	6.4	RTD1-XSV	SC	Sandy clay
SP08NE297.	7.62	ALV-XCZ	S	Dense medium red sand
SP08NE297.	9.75	RTD1-XSV	ZS	Fine reddish silty sand (very dense)
SP08NE297.	15.24	STLL-DMTN	DMTN	Dense red sand
SP08NE298A.	1.22	MGR-UNDIFF	ARTDP	Ash, brick, general rubbish etc., fill.
SP08NE298A.	2.44	ALV-XCZ	SC	Yellow brown sandy clay
SP08NE298A.	3.34	ALV-XCZ	SC	Stiff red sandy clay
SP08NE298A.	4.57	RTD1-XSV	S	Yellow sand
SP08NE298A.	5.12	RTD1-XSV	Z	Pale brown silt
SP08NE298A.	5.79	RTD1-XSV	ZC	Red silty clay
SP08NE298A.	8.84	STLL-DMTN	DMTN	Pale brown sand
SP08NE298A.	10.06	STLL-DMTN	Z	Pale brown silt
SP08NE298A.	11.89	GFDU-XSV	S	Brown sand
SP08NE298A.	14.33	GLLD-C	ZS	Silty sand (reddish)
SP08NE298A.	15.85	GLLD-C	SC	Silt and brown clay
SP08NE298A.	23.01	MMG-MDST	SV	Red sand with some gravel
SP08NE298A.	26.06	BMS-SDST	SDST	Dense red sand to weak sandstone
SP08NE298B.	0.61	MGR-UNDIFF	ARTDP	Brick fill
SP08NE298B.	3.51	RTD1-XSV	SCV	Pale brown sandy clay with gravel
SP08NE298B.	7.62	GLLD-C	CS	Pale brown slightly clayey sand
SP08NE298B.	8.53	GLLD-C	SC	Brown sandy clay
SP08NE298B.	13.72	GFDU-XSV	SV	Pale brown sand with occasional gravel
SP08NE299.	1.22	RTD1-XSV	SC	Brown silty sandy clay
SP08NE299.	2.13	RTD1-XSV	S	Loose/ compact red medium sand
SP08NE299.	6.86	STLL-DMTN	DMTN	Pale, reddish-brown medium sand; compact/ dense
SP08NE299.	9.75	STLL-DMTN	DMTN	Red brown silty sandy clay, firm to soft
SP08NE299.	10.97	GFDU-XSV	SV	Sand fine to coarse, gravel and cobbles very dense
SP08NE299.	12.5	BMS-SDST	SDST	Dense red sand becoming weakly cemented sandstone
SP08NE300.	0.61	RTD1-XSV	S	Asphalt sand becoming weakly cemented sandstone surfacing on sand, gravel and ash
SP08NE300.	5.12	RTD1-XSV	S	Compact red sand, becoming dense
SP08NE300.	6.4	GLLD-C	ZSC	Red-brown silty sandy clay
SP08NE300.	9.45	STLL-DMTN	SV	Sand, gravel, cobbles and boulders
SP08NE300.	12.19	BMS-SDST	SDST	Weak to medium hard red sandstone
SP08NE301.	2.74	MGR-UNDIFF	ARTDP	Ash, brick, gravel, clay etc. fill

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE301.	8.23	GLLD-C	ZC	Pale brown sandy silty clay with occasional fragments of coal, becoming very sandy
SP08NE301.	17.68	GLLD-C	ZC	Pale brown silty clay with occasional fragments of coal
SP08NE301.	26.21	GFDU-XSV	SV	Sand and gravel (coarse)
SP08NE301.	28.96	BMS-SDST	SDST	Weak red sandstone
SP08NE302.	1.83	MGR-ROAD	ARTDP	Asphalt surfacing as ash, slag, brick, gravel etc.
SP08NE302.	8.23	GLLD-C	ZC	Soft red to red brown and yellow mottled silty clay, becoming firm and then stiff towards the base
SP08NE302.	9.45	GFDU-XSV	CV	Stiff red clay with gravel
SP08NE302.	13.11	BMS-SDST	SDST	Weak, red sandstone, poorly cemented
SP08NE303.	0.3	MGR-UNDIFF	ARTDP	Ash fill
SP08NE303.	1.22	RTD1-XSV	SV	Pale brown sand and gravel
SP08NE303.	2.13	RTD1-XSV	SC	Red-brown sandy-clay
SP08NE303.	4.27	MMG-MDST	CZ	Red marly clay
SP08NE303.	10.36	GFDU-XSV	SV	Sand and fine to coarse rounded gravel
SP08NE303.	10.67	MMG-MDST	CZ	Red marl
SP08NE303.	13.72	STLL-DMTN	DMTN	Dense red sand becoming weakly cemented
SP08NE304.	5.72	MGR-UNDIFF	ARTDP	Ash and topsoil, ash brick concrete glass etc. with gravel
SP08NE304.	7.47	RTD1-XSV	SV	Reddish sand and gravel; very dense
SP08NE304.	8.76	BMS-SDST	SDST	Weak red sandstone
SP08NE305.	2.44	MGR-UNDIFF	ARTDP	Brick fill
SP08NE305.	5.94	RTD1-XSV	CV	Red-brown clay with gravel
SP08NE305.	9.45	RTD1-XSV	SV	Sand and gravel
SP08NE305.	10.82	STLL-DMTN	SC	Pale brown sandy clay
SP08NE305.	12.19	GFDU-XSV	SV	Brown sand with occasional gravel
SP08NE306.	1.07	MGR-UNDIFF	ARTDP	Topsoil, ash, gravel, asphalt etc.
SP08NE306.	2.44	ALV-XCZ	C	Soft/ firm reddish-brown clay
SP08NE306.	7.92	RTD1-XSV	CV	Red-brown clay with fine to coarse gravel
SP08NE306.	11.89	RTD1-XSV	SV	Coarse sand and fine to very coarse gravel with occasional cobbles
SP08NE306.	12.19	STLL-DMTN	DMTN	Dense red sand
SP08NE307.	0.61	MGR-UNDIFF	ARTDP	Asphalt surfacing and brick hard-core (fill)
SP08NE307.	2.13	ALV-XCZ	SCV	Brown sandy clay with gravel, soft to firm
SP08NE307.	4.72	ALV-XCZ	SV	Brown sand and gravel
SP08NE307.	6.1	RTD1-XSV	SC	Soft/ firm brown sandy clay
SP08NE307.	6.71	RTD1-XSV	V	Gravel
SP08NE307.	10.06	GLLD-C	CS	Brown clayey sand
SP08NE307.	11.73	GLLD-C	SC	Reddish-brown sandy clay
SP08NE307.	15.24	BMS-SDST	SDST	Dense red sand (weathered sandstone)
SP08NE308.	1.52	MGR-UNDIFF	ARTDP	Sand, gravel, brick etc. - fill
SP08NE308.	5.12	RTD1-XSV	SV	Sand, fine to very coarse gravel and cobbles, very dense

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE308.	10.97	RTD1-XSV	S	Red medium, to coarse sand; extremely dense
SP08NE308.	12.34	GFDU-XSV	SCV	Firm/ stiff reddish brown very sandy clay with fine to coarse gravel and cobbles
SP08NE309.	3.05	MGR-ROAD	ARTDP	Ash and brick fill
SP08NE309.	5.12	RTD1-XSV	SV	Sand and fine to very coarse rounded gravel
SP08NE309.	6.71	RTD1-XSV	SV	Sand gravel and cobbles
SP08NE309.	10.06	BMS-SDST	SDST	Dense red sand becoming weakly cemented sandstone
SP08NE310.	0.3	MGR-UNDIFF	ARTDP	Ash and brick fill
SP08NE310.	2.74	GLLD-C	C	Firm to stiff brown clay
SP08NE310.	3.66	GLLD-C	CS	Clayey sand and fine to coarse gravel
SP08NE310.	6.71	GFDU-XSV	SV	Sand and fine to very coarse rounded gravel
SP08NE310.	7.32	MMG-MDST	SAMDST	Red mudstone and red sandstone
SP08NE310.	10.36	BMS-SDST	SDST	Weakly cemented red sandstone
SP08NE316.	1	MGR-UNDIFF	ARTDP	Fill-soft to firm, dark brown, very sandy, silty clay and fine to medium gravel. Brick and coal fragments
SP08NE316.	1.5	ALV-XCZ	CZ	Fill-dark brown, slightly clayey silty, fine to coarse sand, and fine to coarse gravel
SP08NE316.	2	ALV-XCZ	SZC	Medium dense fill-soft to soft to firm, dark brown, very sandy, silty clay, and fine to medium gravel. Brick and coal traces
SP08NE316.	3	ALV-XCZ	CZS	Fill-brown, clayey, silty, fine to coarse sand. Fine gravel traces
SP08NE316.	3.5	RTD1-XSV	ZS	Dense fill-dark brown, silty, fine to coarse sand, and fine to coarse gravel. Brick and coal traces
SP08NE316.	6.5	RTD1-XSV	CZS	Very dense, brown, becoming reddish brown at 5.5m, clayey, silty, fine to coarse sand, and fine to medium gravel. Clay content varies
SP08NE316.	15	RTD1-XSV	CZS	Medium dense (dense 8.5m to 9.0m) reddish brown, clayey, silty, sandy, fine to coarse gravel. Slightly clayey form 12.5m
SP08NE316.	18	RTD1-XSV	ZS	Medium dense, reddish brown, silty, fine to coarse sand, with some fine to coarse gravel
SP08NE317.	1.8	MGR-UNDIFF	ARTDP	Loose fill, brown sand, brick rubble, gravel
SP08NE317.	4.5	ALV-XCZ	SV	Loose fine to medium brown sand, and mixed gravel
SP08NE317.	11.8	RTD1-XSV	VS	Medium dense, becoming dense with depth, mixed rounded gravel, some mixed brown sand
SP08NE317.	12.2	RTD1-XSV	SZC	Brown-very sandy silty clay
SP08NE318.	3	MGR-ROAD	ARTDP	Loose fill, clayey brown sand, ash, brick rubble
SP08NE318.	9	RTD1-XSV	SV	Medium dense fine to medium brown sand, gravel traces
SP08NE318.	12	RTD1-XSV	SV	Medium dense fine to medium, brown sand, gravel traces
SP08NE318.	15	RTD1-XSV	SV	Medium dense fine to medium red sand, some mixed rounded gravel
SP08NE319.	2	RTD1-XSV	SV	Fill, dirty brown sand, ash, brick rubble, gravel
SP08NE319.	5	GFDU-XSV	S	Medium dense fine to medium reddish brown sand

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE319.	17	GFDU-XSV	SV	Medium dense fine to medium reddish brown sand, little mixed rounded gravel
SP08NE332.	0.91	RTD1-XSV	C	Clay
SP08NE332.	4.57	RTD1-XSV	S	Sand
SP08NE332.	14.2	GLLD-C	C	Clay
SP08NE332.	16.34	GFDU-XSV	SV	Sand and gravel
SP08NE332.	19.39	BMS-SDST	SDST	Soft sandstone
SP08NE332.	25.91	BMS-SDST	SDST	Hard red sandstone
SP08NE332.	27.13	STLL-DMTN	B	Fine red rock
SP08NE332.	28.04	STLL-DMTN	CZ	Red marl
SP08NE332.	34.14	STLL-DMTN	B	Red rock
SP08NE332.	35.66	STLL-DMTN	CZ	Red marl
SP08NE332.	36.88	STLL-DMTN	B	Red rock
SP08NE332.	39.32	STLL-DMTN	CZ	Red and grey marl
SP08NE332.	46.63	STLL-DMTN	B	Red rock
SP08NE332.	53.64	STLL-DMTN	B	Finer and lighter red rock
SP08NE332.	55.47	GFDU-XSV	SZC	Loamy red bed
SP08NE332.	87.78	MMG-MDST	B	Fine light red rock
SP08NE332.	88.7	MMG-MDST	ZC	Red shaley marl
SP08NE332.	118.26	MMG-MDST	B	Fine light red rock
SP08NE332.	118.87	MMG-MDST	CZ	Red marl
SP08NE332.	126.19	MMG-MDST	SDST	Light red sandstone
SP08NE332.	127.41	MMG-MDST	CZ	Red marl
SP08NE332.	133.5	BMS-SDST	SDST	Light red sandstone
SP08NE332.	134.11	WRS-SDST	SDST	Darker red sandstone
SP08NE332.	137.16	WRS-SDST	B	Coarse dark rock with pebbles
SP08NE334.	16.76	RTD1-XSV	SV	Sand and gravel
SP08NE334.	132.89	BMS-SDST	SDST	Sandstone
SP08NE334.	148.44	BMS-SDST	SDST	Fine sandstone
SP08NE334.	149.04	BMS-SDST	SDST	Very fine hard sandstone
SP08NE334.	150.88	BMS-SDST	SDST	Conglomerate sandstone
SP08NE334.	151.79	WRS-SDST	SDST	Soft sandstone
SP08NE334.	152.7	WRS-SDST	SAMDST	Marl sandstone
SP08NE334.	155.45	WRS-SDST	SDST	Soft red sandstone
SP08NE334.	163.68	WRS-SDST	SDST	Very fine hard sandstone
SP08NE348.	2.44	MGR-ROAD	ARTDP	Made ground – furnace ashes, brick ends
SP08NE348.	3.96	RTD1-XSV	SV	Sand and gravel
SP08NE348.	14.63	STLL-DMTN	SB	Yellow sand, free of stones and runs with water at 4.57m
SP08NE348.	15.54	STLL-DMTN	SB	Compact sand with mixed stones
SP08NE348.	17.68	MMG-MDST	CZ	Layers of hard and soft marl
SP08NE348.	18.29	MMG-MDST	SCZ	Hard sandy marl
SP08NE349.	2.13	MMG-MDST	CZ	Hard marl
SP08NE349.	2.44	RTD1-XSV	SV	Sand and gravel

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE349.	14.94	RTD1-XSV	S	Running sand, very much alive with water
SP08NE349.	20.73	MMG-MDST	CZ	Hard marl
SP08NE350.	2.13	MMG-MDST	CZ	Hard marl
SP08NE350.	2.44	RTD1-XSV	SV	Sand and gravel
SP08NE350.	14.94	RTD1-XSV	S	Running sand, very much alive with water
SP08NE350.	20.73	MMG-MDST	CZ	Hard marl
SP08NE351.	3.66	MGR-ROAD	ARTDP	Made ground
SP08NE351.	4.27	ALV-XCZ	SZC	Black loam
SP08NE351.	5.49	STLL-DMTN	LB	Large fragmented ballast, very compact
SP08NE351.	6.1	GFDU-XSV	SV	Dry compact sand and gravel
SP08NE352.	2.44	MGR-ROAD	ARTDP	Made ground, some clay
SP08NE352.	2.74	RTD1-XSV	SV	Sand and gravel
SP08NE352.	18.29	GLLD-C	S	Drift sand (free of tones)
SP08NE352.	18.89	STLL-DMTN	LB	Sand and ballast (this is very compact)
SP08NE352.	21.03	MMG-MDST	CZ	A clean hard marl
SP08NE356.	2.74	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE356.	5.49	STLL-DMTN	S	Sand
SP08NE356.	7.32	GFDU-XSV	SC	Sand and clay
SP08NE356.	12.19	MMG-MDST	V	Gravel
SP08NE356.	12.8	MMG-MDST	VCZ	Gravel and marl
SP08NE356.	14.63	MMG-MDST	CZ	Marl
SP08NE356.	17.07	BMS-SDST	SDST	Soft brown sandstone
SP08NE356.	18.99	BMS-SDST	SDST	Red sandstone
SP08NE357B.	1.83	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE357B.	5.18	RTD1-XSV	S	Sand
SP08NE357B.	8.53	GLLD-C	C	Clay
SP08NE357B.	11.58	BMS-SDST	SDST	Soft brown sandstone
SP08NE357B.	12.19	BMS-SDST	SDST	Red sandstone
SP08NE357C.	1.4	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE357C.	2.62	ALV-XCZ	C	Clay
SP08NE357C.	4.88	RTD1-XSV	S	Sand
SP08NE357C.	6.71	GLLD-C	C	Clay
SP08NE357C.	7.92	GFDU-XSV	V	Gravel
SP08NE357C.	10.97	BMS-SDST	SDST	Soft brown sandstone
SP08NE357C.	11.58	BMS-SDST	SDST	Red sandstone
SP08NE358B.	1.83	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE358B.	5.18	RTD1-XSV	S	Sand
SP08NE358B.	8.53	GLLD-C	C	Clay
SP08NE358B.	11.58	BMS-SDST	SDST	Soft brown sandstone
SP08NE358B.	12.19	BMS-SDST	SDST	Red sandstone
SP08NE358C.	1.4	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE358C.	2.62	ALV-XCZ	C	Clay
SP08NE358C.	4.88	RTD1-XSV	S	Sand

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE358C.	6.71	GLLD-C	C	Clay
SP08NE358C.	7.92	GFDU-XSV	V	Gravel
SP08NE358C.	10.97	BMS-SDST	SDST	Soft brown sandstone
SP08NE358C.	11.58	BMS-SDST	SDST	Red sandstone
SP08NE359.	1.22	MGR-ROAD	ARTDP	Rubble (made ground)
SP08NE359.	2.62	ALV-XCZ	C	Clay
SP08NE359.	5.79	RTD1-XSV	S	Sand
SP08NE359.	6.4	GLLD-C	SC	Sand and clay
SP08NE359.	7.01	GLLD-C	C	Clay
SP08NE359.	8.23	GFDU-XSV	V	Gravel
SP08NE359.	10.67	BMS-SDST	SDST	Soft brown sandstone
SP08NE359.	11.28	BMS-SDST	SDST	Red sandstone
SP08NE360.	0.7	MGR-ROAD	ARTDP	Sand (made ground)
SP08NE360.	1.83	MGR-ROAD	ARTDP	Concrete (made ground)
SP08NE360.	4.88	ALV-XCZ	C	Clay
SP08NE360.	6.71	GLLD-C	SC	Sand and clay
SP08NE360.	7.92	MMG-MDST	CZ	Marl
SP08NE360.	8.53	BMS-SDST	SDST	Soft brown sandstone
SP08NE360.	9.45	BMS-SDST	SDST	Red sandstone
SP08NE361.	1.22	MGR-ROAD	ARTDP	Concrete and made ground
SP08NE361.	2.13	ALV-XCZ	SDST	Light yellow sandstone
SP08NE361.	3.66	ALV-XCZ	SAMDST	Loamy red sandstone
SP08NE361.	4.27	ALV-XCZ	SDST	Red sandstone
SP08NE361.	5.67	RTD1-XSV	S	Running sand
SP08NE361.	7.32	STLL-DMTN	CL	Brown clay, small pebbles
SP08NE361.	8.23	STLL-DMTN	SCL	Hard sandy clay and pebbles
SP08NE361.	9.14	MMG-MDST	SAMDST	Light red loamy sandstone
SP08NE361.	10.55	STLL-DMTN	SB	Brown sand and stones
SP08NE361.	11.43	STLL-DMTN	SB	Light brown sand, stones and pebbles
SP08NE362.	1.83	MGR-ROAD	ARTDP	Mage-ground, loamy sand, stones, lumps of concrete, lumps of tar and stones mixed, metal etc.
SP08NE362.	2.74	ALV-XCZ	S	Dark grey coarse sand with stones down to small pebbles
SP08NE362.	2.93	ALV-XCZ	S	Light grey coarse sand
SP08NE362.	4.88	RTD1-XSV	SZ	Dark grey sand with traces of red loamy sand
SP08NE362.	5.67	GLLD-C	SC	Sandy clay mixture
SP08NE362.	6.98	GLLD-C	C	Stiff brown clay
SP08NE362.	7.19	GLLD-C	C	Reddish brown and dark brown clay with stones
SP08NE363.	2.74	MGR-ROAD	ARTDP	Made ground
SP08NE363.	2.93	ALV-XCZ	S	Light brown coarse sand
SP08NE363.	3.35	ALV-XCZ	S	Dark grey sand stones and pebbles
SP08NE363.	3.75	RTD1-XSV	S	Dark grey fine sand

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE363.	4.94	RTD1-XSV	S	Light brown fine sand
SP08NE363.	5.36	GLLD-C	SC	Brown sand and traces of mixed sandy clay
SP08NE363.	6.4	GLLD-C	SC	Dark and light brown sandy clay
SP08NE363.	6.71	GLLD-C	C	Reddish brown clay mixture with odd pebbles
SP08NE363.	7.71	GLLD-C	C	Dark brown clay with odd pebbles
SP08NE363.	7.89	STLL-DMTN	SB	Sand, stones, pebbles and traces of clay
SP08NE364.	2.44	MGR-ROAD	ARTDP	Made ground, concrete, bricks, metal etc.
SP08NE364.	2.62	MGR-ROAD	ARTDP	Cellar floor, concrete and bricks
SP08NE364.	2.93	RTD1-XSV	S	Light brown coarse sand, odd pebbles
SP08NE364.	3.66	RTD1-XSV	S	Dark grey sand, and stones down to pebbles
SP08NE364.	4.45	GLLD-C	SC	Reddish brown sandy clay
SP08NE364.	5.06	MMG-MDST	SZC	Reddish brown loamy sand
SP08NE364.	6.4	MMG-MDST	SZC	Light brown loamy sand and stones
SP08NE364.	7.62	BMS-SDST	C	Stiff brown clay
SP08NE365.	0.3	MGR-ROAD	ARTDP	Made ground
SP08NE365.	1.4	ALV-XCZ	S	Black sandy soil, dark sand mixture
SP08NE365.	2.44	ALV-XCZ	S	Light brown sand
SP08NE365.	3.63	RTD1-XSV	S	Light brown coarse sand and small pebbles
SP08NE365.	4.88	RTD1-XSV	S	Reddish brown sandy clay mixture, occasional pebbles
SP08NE365.	5.36	STLL-DMTN	SZ	Dark grey fine sand, traces of black shale stones and traces of soft black silt
SP08NE365.	6.37	STLL-DMTN	SL	Dark grey sand, pebbles and pockets of sandy clay
SP08NE365.	7.19	STLL-DMTN	SV	Dark grey sand, gravel, small pockets of black silt
SP08NE365.	7.35	GFDU-XSV	SC	Brown sand and clay mixture
SP08NE365.	8.53	GFDU-XSV	SC	Chocolate brown sandy clay with small pebbles and coal traces
SP08NE365.	8.93	GFDU-XSV	SC	Brown sandy clay
SP08NE365.	9.11	GFDU-XSV	S	Brown sand
SP08NE366.	0.58	MGR-ROAD	ARTDP	Made ground
SP08NE366.	1.1	ALV-XCZ	SC	Sandy clay mixture and some stones
SP08NE366.	4.15	RTD1-XSV	S	Light brown coarse sand
SP08NE366.	4.57	RTD1-XSV	S	Dark grey sand
SP08NE366.	6.1	GLLD-C	S	Fine brown sand
SP08NE366.	6.28	GLLD-C	SC	Mixed sandy clay
SP08NE366.	7.8	GLLD-C	C	Brown stiff clay
SP08NE367A.	2.32	MGR-ROAD	ARTDP	Made ground, concrete brick rubble, ashes etc. (loose)
SP08NE367A.	2.74	STLL-DMTN	BS	Brick base, on sand and cinders
SP08NE367A.	5.18	GFDU-XSV	S	Brown sand; dry
SP08NE367A.	6.1	MMG-MDST	SAMDST	Red sandstone, inclined to be loamy
SP08NE367A.	8.23	BMS-SDST	SDST	Sandstone, layered, fairly compact
SP08NE367B.	1.4	MGR-ROAD	ARTDP	Made ground, concrete, brick, hard core

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE367B.	1.71	MGR-ROAD	ARTDP	Made ground, ashes and loam
SP08NE367B.	4.57	RTD1-XSV	S	Brown sand; dry
SP08NE367B.	5.36	MMG-MDST	SAMDST	Red sandstone, some loam
SP08NE367B.	7.92	BMS-SDST	SDST	Red sandstone, layered, fairly compact
SP08NE368A.	2.32	MGR-ROAD	ARTDP	Made ground, concrete brick rubble, ashes etc. (loose)
SP08NE368A.	2.74	MGR-ROAD	ARTDP	Brick base, on sand and cinders
SP08NE368A.	5.18	STLL-DMTN	DMTN	Brown sand; dry
SP08NE368A.	6.1	MMG-MDST	SAMDST	Red sandstone, inclined to be loamy
SP08NE368A.	8.23	BMS-SDST	SDST	Sandstone, layered, fairly compact
SP08NE368B.	0.91	MGR-ROAD	ARTDP	Made ground, concrete, brick, hard core
SP08NE368B.	1.71	MGR-ROAD	ARTDP	Made ground, ashes and loam
SP08NE368B.	4.57	STLL-DMTN	S	Brown sand; dry
SP08NE368B.	5.36	MMG-MDST	SAMDST	Red sandstone, some loam
SP08NE368B.	7.92	BMS-SDST	SDST	Red sandstone, layered, fairly compact
SP08NE369C.	0.91	MGR-ROAD	ARTDP	Made ground, concrete, brick, hard core
SP08NE369C.	1.71	STLL-DMTN	SZC	Sand – loamy and some pebbles
SP08NE369C.	3.96	STLL-DMTN	DMTN	Brown sand; dry
SP08NE369C.	4.57	MMG-MDST	SAMDST	Red sandstone, some loam
SP08NE369C.	7.62	WRS-SDST	SDST	Red sandstone, layered, fairly compact
SP08NE369D.	0.49	MGR-ROAD	ARTDP	Concrete on brick rubbles
SP08NE369D.	1.22	MGR-ROAD	ARTDP	Brick and concrete ‘footing’
SP08NE369D.	2.62	MMG-MDST	SAMDST	Red sandstone, loamy
SP08NE369D.	4.88	BMS-SDST	S	Brown sand; dry
SP08NE369D.	5.49	BMS-SDST	SDST	Red sandstone, some clay
SP08NE369D.	7.92	WRS-SDST	SDST	Red sandstone, layered
SP08NE370C.	0.91	MGR-ROAD	ARTDP	Made ground, concrete, brick, hard core
SP08NE370C.	1.71	ALV-XCZ	SZC	Sand – loamy and some pebbles
SP08NE370C.	3.96	STLL-DMTN	DMTN	Brown sand; dry
SP08NE370C.	4.57	MMG-MDST	SAMDST	Red sandstone, some loam
SP08NE370C.	7.62	WRS-SDST	SDST	Red sandstone, layered, fairly compact
SP08NE370D.	0.49	MGR-ROAD	ARTDP	Concrete on brick rubbles
SP08NE370D.	1.22	MGR-ROAD	ARTDP	Brick and concrete ‘footing’
SP08NE370D.	2.62	MMG-MDST	SAMDST	Red sandstone, loamy
SP08NE370D.	4.88	BMS-SDST	S	Brown sand; dry
SP08NE370D.	5.49	BMS-SDST	SDST	Red sandstone, some clay
SP08NE370D.	7.92	WRS-SDST	SDST	Red sandstone, layered
SP08NE371E.	0.27	MGR-UNDIFF	Unknown	Concrete and bricks
SP08NE371E.	2.13	MMG-MDST	SZC	Red loamy sand
SP08NE371E.	2.93	BMS-SDST	SDST	Yellow sandstone
SP08NE371E.	4.27	BMS-SDST	SDST	Light brown flaky sandstone
SP08NE371E.	6.58	BMS-SDST	SDST	Dark brown sandstone and clay
SP08NE371E.	8.53	BMS-SDST	SDST	Very dark brown sandstone and clay

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE371E.	8.84	BMS-SDST	SDST	Dark red sandstone
SP08NE371F.	0.91	MGR-ROAD	ARTDP	Made ground
SP08NE371F.	1.52	BMS-SDST	SDST	Dark brown sandstone
SP08NE371F.	2.44	BMS-SDST	SDST	Very dark brown sandstone
SP08NE371F.	6.4	BMS-SDST	SDST	Brown sandstone
SP08NE371F.	7.01	BMS-SDST	C	Red clay
SP08NE371F.	8.84	BMS-SDST	SDST	Red sandstone
SP08NE372E.	0.27	MGR-UNDIFF	ARTDP	Concrete and bricks (FILL)
SP08NE372E.	2.13	MMG-MDST	SZC	Red loamy sand
SP08NE372E.	2.93	BMS-SDST	SDST	Yellow sandstone
SP08NE372E.	4.27	BMS-SDST	SDST	Light brown flaky sandstone
SP08NE372E.	6.58	BMS-SDST	SDST	Dark brown sandstone and clay
SP08NE372E.	8.53	BMS-SDST	SDST	Very dark brown sandstone and clay
SP08NE372E.	8.84	BMS-SDST	SDST	Dark red sandstone
SP08NE372F.	0.91	MGR-ROAD	ARTDP	Made ground
SP08NE372F.	1.52	BMS-SDST	SDST	Dark brown sandstone
SP08NE372F.	2.44	BMS-SDST	SDST	Very dark brown sandstone
SP08NE372F.	6.4	BMS-SDST	SDST	Brown sandstone
SP08NE372F.	7.01	BMS-SDST	C	Red clay
SP08NE372F.	8.84	BMS-SDST	SDST	Red sandstone
SP08NE373G.	0.79	MGR-ROAD	ARTDP	Made ground
SP08NE373G.	1.71	ALV-XCZ	SC	Red sandy clay
SP08NE373G.	2.44	BMS-SDST	SDST	Brown sandstone
SP08NE373G.	3.84	BMS-SDST	SDST	Dark brown sandstone
SP08NE373G.	7.32	BMS-SDST	SDST	Light brown sandstone
SP08NE373G.	7.92	BMS-SDST	C	Red brown clay
SP08NE373H.	0.49	MGR-ROAD	SC	Brown sandy clay and pebbles
SP08NE373H.	1.1	ALV-XCZ	SC	Dark brown sandy clay
SP08NE373H.	1.52	MMG-MDST	SAMDST	Dark brown loamy sandstone
SP08NE373H.	3.35	MMG-MDST	SAMDST	Light brown loamy sandstone
SP08NE373H.	6.58	BMS-SDST	SDST	Light red sandstone
SP08NE373H.	7.19	BMS-SDST	SC	Brown sandy clay
SP08NE373H.	8.84	BMS-SDST	SDST	Red sandstone
SP08NE374G.	0.79	MGR-ROAD	ARTDP	Made ground
SP08NE374G.	1.71	ALV-XCZ	SC	Red sandy clay
SP08NE374G.	2.44	BMS-SDST	SDST	Brown sandstone
SP08NE374G.	3.84	BMS-SDST	SDST	Dark brown sandstone
SP08NE374G.	7.32	BMS-SDST	SDST	Light brown sandstone
SP08NE374G.	7.92	BMS-SDST	C	Red brown clay
SP08NE374H.	0.49	ALV-XCZ	SC	Brown sandy clay and pebbles
SP08NE374H.	1.1	GLLD-C	DC	Dark brown sandy clay
SP08NE374H.	1.52	MMG-MDST	SAMDST	Dark brown loamy sandstone
SP08NE374H.	3.35	MMG-MDST	SAMDST	Light brown loamy sandstone

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE374H.	6.58	BMS-SDST	SDST	Light red sandstone
SP08NE374H.	7.19	BMS-SDST	SC	Brown sandy clay
SP08NE374H.	8.84	BMS-SDST	SDST	Red sandstone
SP08NE375.	3.35	MGR-ROAD	ARTDP	Made ground, brick wall
SP08NE375.	5	MMG-MDST	SDST	Light red sandstone
SP08NE375.	5.79	MMG-MDST	SDST	Fine red sandstone
SP08NE375.	6.28	MMG-MDST	SAMDST	Soft dark brown loamy sandstone
SP08NE375.	6.71	MMG-MDST	SC	Dark brown sandy clay
SP08NE375.	8.84	MMG-MDST	SCZ	Dark red sandy marl
SP08NE382.	1.22	MGR-ROAD	ARTDP	Brick, mortar and ash
SP08NE382.	2.59	MGR-ROAD	ARTDP	Bricks and fine red sand
SP08NE382.	3.93	RTD1-XSV	S	Fine red sand, grey and black silt traces
SP08NE382.	4.36	RTD1-XSV	S	Light brown fine rock sand
SP08NE383.	2.23	MGR-UNDIFF	ARTDP	Brick, mortar, mixed sand
SP08NE383.	2.32	ALV-XCZ	SC	Brown sandy clay
SP08NE383.	2.41	ALV-XCZ	S	Fine red sand
SP08NE383.	3.78	ALV-XCZ	SC	Brown sandy clay
SP08NE383.	4.85	RTD1-XSV	S	Fine reddish brown sand
SP08NE383.	4.97	RTD1-XSV	S	Fine brown sand, black silt traces
SP08NE383.	5.12	GLLD-C	SC	Sandy clay, grey silt traces
SP08NE383.	5.24	GLLD-C	S	Fine reddish brown sand
SP08NE383.	5.49	STLL-DMTN	BS	Fine light brown rock sand
SP08NE383.	7.32	STLL-DMTN	BS	Fine light brown rock sand, clay traces
SP08NE383.	7.96	STLL-DMTN	BS	Fine light brown rock sand
SP08NE384.	1.4	MGR-UNDIFF	ARTDP	Bricks, mortar and sand
SP08NE384.	1.92	ALV-XCZ	SL	Medium grey sand, small pebbles
SP08NE384.	2.44	ALV-XCZ	SZ	Fine reddish brown sand, grey silt bands, clay traces
SP08NE384.	3.93	RTD1-XSV	SC	Sandy clay, grey silt bands
SP08NE384.	3.99	RTD1-XSV	Z	Light brown silt, grey silt traces
SP08NE384.	4.45	RTD1-XSV	S	Fine reddish brown sand
SP08NE384.	5.97	STLL-DMTN	BS	Fine rock sand, clay traces
SP08NE384.	6.28	STLL-DMTN	DMTN	Fine reddish brown rock sand, grey rock sand traces
SP08NE384.	8.5	STLL-DMTN	DMTN	Fine rock sand, clay traces
SP08NE384.	8.53	STLL-DMTN	BS	Coarse brown rock sand
SP08NE385.	3.93	MGR-UNDIFF	ARTDP	Brick, mortar sand and stones
SP08NE385.	4.57	RTD1-XSV	SC	Sandy clay
SP08NE385.	4.75	RTD1-XSV	S	Fine sand
SP08NE385.	8.41	GLLD-C	SZ	Fine rock sand, grey silt and clay traces
SP08NE386.	4.02	MGR-ROAD	ARTDP	Sand, silt, bricks and stones (made ground)
SP08NE386.	8.23	GLLD-C	SZ	Fine rock sand, grey silt and slight clay traces
SP08NE389.	1.46	MGR-ROAD	ARTDP	Clay, sand and stones (made ground)
SP08NE389.	3.54	MGR-ROAD	ARTDP	Bricks, mortar and sand (made ground)

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE389.	4.02	ALV-XCZ	S	Medium sand, clay traces
SP08NE389.	4.21	ALV-XCZ	C	Brown clay
SP08NE389.	7.01	RTD1-XSV	BS	Medium rock sand
SP08NE389.	7.28	GLLD-C	C	Brown plastic clay, grey silt traces
SP08NE389.	8.11	GLLD-C	C	Brown friable clay, grey silt traces
SP08NE389.	10.03	GLLD-C	SC	Hard friable sandy clay, grey silt traces
SP08NE389.	11.28	GLLD-C	BS	Medium rock sand
SP08NE389.	11.49	GLLD-C	C	Brown clay
SP08NE389.	12.8	STLL-DMTN	DMTN	Fine rock sand
SP08NE391.	2.44	MGR-UNDIFF	ARTDP	Bricks, sand stones
SP08NE391.	2.99	RTD1-XSV	S	Medium brown sand
SP08NE391.	3.05	RTD1-XSV	CS	Clay and sand mixed
SP08NE391.	4.69	RTD1-XSV	SC	Brown sandy clay, grey silt traces
SP08NE391.	5.36	RTD1-XSV	S	Fine brown sand
SP08NE391.	8.41	GLLD-C	SB	Fine rock sand
SP08NE391.	8.5	GLLD-C	C	Brown clay
SP08NE391.	8.69	STLL-DMTN	SB	Medium rock sand
SP08NE391.	8.78	STLL-DMTN	C	Brown clay
SP08NE391.	9.14	GFDU-XSV	SB	Medium rock sand, slight clay traces
SP08NE435.	0.15	MGR-UNDIFF	ARTDP	Made ground
SP08NE435.	0.65	MGR-UNDIFF	ARTDP	Mod compact and brick fill
SP08NE435.	2.6	MGR-ROAD	SZ	Mod compact reddish brown sandy and silty fill with sand, gravel, pieces of concrete, clinker, tile and brick
SP08NE435.	4.3	ALV-XCZ	ZS	Compact yellowish brown silty fine grained sand with traces of silt
SP08NE435.	5.65	RTD1-XSV	CS	Compact brown clayey fine to medium grained sand with occasional fine to coarse gravel and traces of clay
SP08NE435.	6.6	GLLD-C	ZC	Soft to firm reddish brown poorly laminated silty clay with occasional fine to coarse gravel and carbonaceous inclusions
SP08NE435.	9.3	STLL-DMTN	ZS	Very dense brown slightly silty medium grained sand
SP08NE527.	0.15	MGR-UNDIFF	ARTDP	Fill – ash and clay
SP08NE527.	0.45	MGR-UNDIFF	Unknown	Concrete
SP08NE527.	0.65	MGR-UNDIFF	ARTDP	Fill – dense sand and gravel
SP08NE527.	1.6	MGR-ROAD	ARTDP	Fill – loose wet dark grey brown ashy sandy silt, gravel, brick, concrete, silty clay
SP08NE527.	2.9	MGR-ROAD	ARTDP	Fill – very loose dark brown and a little orange brown ashy slightly clayey sandy silt with ash, gravel and siltstone
SP08NE527.	3.3	GFDU-XSV	SV	Firm brown sandy gravelly silty clay
SP08NE527.	6.5	MMG-MDST	ZC	Firm becoming stiff with depth friable red brown with traces of light grey very silty clay with clayey silt horizons and fragments of siltstone

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE528.	0.2	MGR-UNDIFF	CB	Firm – clay and bricks
SP08NE528.	2.2	MGR-ROAD	ARTDP	Fill – loose to very loose dark grey brown ashy slightly silty soily sand with inclusions of brick, concrete, ash, metal and gravel
SP08NE528.	2.6	STLL-DMTN	SZC	Firm yellow brown sandy silty clay with traces of gravel
SP08NE528.	3.2	STLL-DMTN	SZC	Firm to stiff red brown sandy silty clay with traces of gravel
SP08NE528.	6.5	BMS-SDST	Z	Firm to stiff becoming very stiff with depth red brown with traces of light grey very silty clay with clayey silt horizons and bands of very weak weathered siltstone
SP08NE529.	1	MGR-UNDIFF	ARTDP	Fill – large fragments of concrete and brick in ashy sand matrix
SP08NE529.	2.3	MGR-UNDIFF	ARTDP	Fill – loose ash, slag, bricks and traces of gravel in an ashy silty sand matrix
SP08NE529.	2.7	STLL-DMTN	SZC	Firm yellow and light red brown very sandy silty clay with a little gravel
SP08NE529.	3.6	STLL-DMTN	SZC	Firm to stiff red brown with traces of light grey sandy silty clay with traces of gravel and small sand pockets
SP08NE529.	6.05	BMS-SDST	Z	Stiff becoming very stiff with depth red brown, brown and light grey very silty clay with horizons of clayey silt and bands of very weak weathered siltstone
SP08NE530.	1.7	MGR-UNDIFF	ARTDP	Fill – loose brown slightly silty sandy ash with inclusions of brick, glass, coal, gravel and concrete
SP08NE530.	2.7	ALV-XCZ	SZ	Firm to stiff friable orange red and brown slightly sandy silty clay with a little grey silty clay, traces of gravel and black carbonaceous matter
SP08NE530.	6	RTD1-XSV	ZC	Firm to stiff red brown slightly friable silty clay with traces of light grey silty clay and a few slightly sandy horizons – also traces of siltstone
SP08NE531.	1.8	MGR-UNDIFF	ARTDP	Fill – loos brown sandy ash with fragments of brick, concrete, sandstone, twigs, gravel and timber
SP08NE531.	2.5	WRS-SDST	SZ	Stiff yellow and red brown/ grey sandy very silty clay with some gravel and cobbles
SP08NE531.	6.5	WRS-SDST	ZC	Stiff becoming stiffer with depth red brown friable very silty clay with some clayey silty horizons and traces of light green grey silt and siltstone fragments
SP08NE532.	0.15	MGR-UNDIFF	ARTDP	Fill – ash and clay
SP08NE532.	0.8	MGR-UNDIFF	Unknown	Concrete
SP08NE532.	1.6	MGR-UNDIFF	ARTDP	Fill – very loose dark grey ash, brick, glass, gravel, burnt shale and very soft sandy clay and clayey silt
SP08NE532.	2.3	GLLD-C	CS	Medium dense brown silty slightly clayey sand with some gravel and a few sandstone fragments
SP08NE532.	2.7	GLLD-C	SZC	Firm red brown sandy silty clay

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE532.	6	MMG-MDST	ZC	Firm to stiff becoming very stiff with depth friable red brown very silty clay and clayey silt with traces of light grey green clayey silt
SP08NE613.	0.2	MGR-UNDIFF	Unknown	Topsoil
SP08NE613.	2	MGR-UNDIFF	ARTDP	Fill – very dense sandy topsoil, soft grey silty clay, gravel and brick rubble
SP08NE613.	4.9	RTD1-XSV	V	Medium dense becoming very dense red brown and orange brown silty gravelly fine to medium sand
SP08NE613.	6.2	BMS-SDST	SDST	Hard red brown very silty clay with lithorelicts and thin bands of sandstone
SP08NE613.	10.28	BMS-SDST	SDST	Very weak improving to moderately weak with depth uncemented fine red sandstone (rock sand)
SP08NE614.	3.1	MGR-UNDIFF	ARTDP	Fill – brick rubble, concrete, brickwork, reinforcement, steel sheets, metal pipes and timber – excavated out in advance by mechanical excavator and casing placed in pit
SP08NE614.	3.6	MGR-ROAD	B	Concrete floor slab
SP08NE614.	5.55	RTD1-XSV	Z	Loose improving to medium dense with depth red brown silty slightly gravelly medium sand
SP08NE614.	8.3	GFDU-XSV	ZV	Dense red brown silty slightly gravelly fine to medium sand with horizons of firm clayey sand
SP08NE614.	12.55	BMS-SDST	SDST	Weak uncemented fine red sandstone
SP08NE615.	4	MGR-ROAD	ARTDP	Fill – backfill to trial pit (soily sand and masonry)
SP08NE615.	5.6	RTD1-XSV	VS	Loose to medium dense reddish brown slightly gravelly fine to medium sand
SP08NE615.	6.8	RTD1-XSV	SZ	Stiff red brown sandy silty clay and clayey silty sand with traces of gravel
SP08NE615.	8.55	STLL-DMTN	ZS	Medium dense red brown silty fine to medium sand with traces of gravel and isolated clayey sand lenses
SP08NE616.	1.8	MGR-UNDIFF	ARTDP	Fill – medium dense dirty sand with fine to coarse gravel fragments of coke, ash, bricks and boulder size fragments of dolerite and sandstone
SP08NE616.	4.65	STLL-DMTN	SV	Dense becoming very dense orange brown grading into brown fine to medium sand – gravelly at some horizons
SP08NE616.	5.9	BMS-SDST	ZC	Hard red brown very silty clay
SP08NE616.	10	BMS-SDST	SDST	Moderately weak uncemented fine to coarse sandstone
SP08NE667.	0.5	MGR-UNDIFF	Unknown	Concrete
SP08NE667.	0.8	MGR-ROAD	ARTDP	Fill – loose brown and dark grey, silty ash, with gravel, brick fragments and slag
SP08NE667.	1.5	ALV-XCZ	ZS	Loose red brown slightly silty sand with some gravel
SP08NE667.	3	RTD1-XSV	SZC	Firm orange brown becoming light grey sandy silty clay with orange brown sand
SP08NE667.	4	RTD1-XSV	ZC	Stiff red brown occasionally light grey silty clay becoming more silty

Borehole ID	Base of Unit	Stratigraphy	Lithology	Unit Description
SP08NE667.	5	GLLD-C	ZS	Medium dense light greyish brown silty fine sand
SP08NE667.	6.5	GLLD-C	ZC	Firm to stiff friable red brown very silty clay with siltstone fragments becoming stiff to hard
SP08NE667.	8.05	GLLD-C	CZ	Very weak red brown clayey siltstone becoming weak
SP08NE668.	0.4	MGR-UNDIFF	ARTDP	Tarmac over cobble stones and concrete
SP08NE668.	2.5	MGR-ROAD	ARTDP	Fill – soft red brown sandy silty clay in parts soily becoming gravelly with coal fragments and occasional cobbles
SP08NE668.	2.95	ALV-XCZ	ZS	Firm light brown slightly silty sand
SP08NE668.	5	GLLD-C	CZ	Firm friable red brown occasionally light grey clayey silt
SP08NE668.	9	GLLD-C	CZ	Firm friable brown and occasionally light grey clayey silt becoming hard with fine sand in parts
SP08NE668.	9.6	GLLD-C	CZ	Very weak red friable brown clayey siltstone

APPENDIX D EXAMPLES OF PROGRAMMES AND TOOLS FOR 3D SUBSURFACE MODELLING

This table is adapted from De Mulder et al. (2012):

- = less suitable; + = more suitable; + + = extensively used; in-between brackets: uncertain. Suitability for all-purpose modelling of underground excavations is based on the experience of the author, supplemented by public information from the developers and suppliers, and literature references. Suitability may change as programs are regularly updated and new features may make programs less suitable in 2012 to become very suitable in the future. The table is not conclusive as software development is very versatile (e.g. new programs, changes of name or ownership, programs are split in different or combined to new packages, same program may be available under different names). All programs (if not mentioned otherwise) are or claim to be 3D (or 4D) programs; however, some may not possess a full 3D (or 4D) database structure. Geophysical, fluid (groundwater) flow, and mechanical programs have only been included if options for geological modelling are included. Most names of software packages, companies, and consortia are registered trademarks ©. Only the leader is included for the products developed by a consortium.

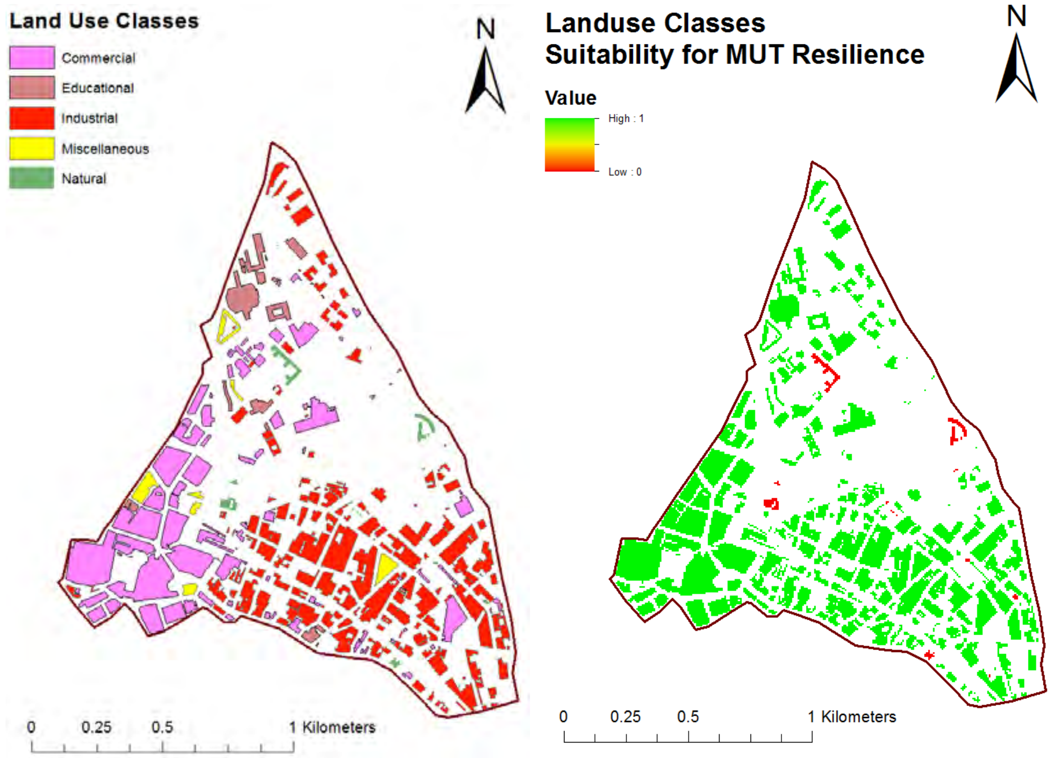
Program	*Suitability for all-purpose modelling of underground excavations*	*Remarks*	*Developer/ supplier/ consortium leader*	*Web-site*
2/3/4D Move	+	Family of 2D-4D programs for oil & gas, mining, geology	Midland valley Exploration Ltd., UK	http://www.mve.com/
Amine	+	AutoCAD based geological modelling & mining system. Used for geotechnical, environmental and geochemistry modelling	Flairbase, Canada	http://www.flairbase.com/WEBSITE/EN/amine.html
ArcGIS 3D Analyst	+	3D extension of the popular ArcGIS cartographic software	ESRI, USA	http://www.esri.com/
AutoCAD	-/+	CAD system, not a 3D modelling program, but with add-ons used for subsurface modelling	Autodesk, USA	http://usa.autodesk.com/
Cadsmine	+	CAD based geology, mining & geotechnical modelling	Gijima, South Africa	http://graphicmining.com/node/178
CoViz 4D	(+)	4D visualisation	Dynamic Graphics, Inc., USA	http://www.dgi.com/coviz/cvmain.
Datamine	+	mining, geology, mine planning, geotechnical & environmental modelling	Datamine International Ltd., UK	http://www.datamine.co.uk/
Deep Exploration	(-)	Conversion & integration software	Right Hemisphere, USA	http://www.rightemisphere.com/products/
EarthModel	-	Oil & gas, geology & seismic modelling	Fugro jason	http://www.fugro-jason.com/overview.htm
EarthVision	-	Oil & gas, geology & seismic modelling	Dynamic Graphics, Inc., USA	http://www.dgi.com/earthvision/evmain.html
EVS/MVS	++	Mining, geology, geotechnical & environmental (ESRI program environment)	C Tech Development Corporation, USA	http://www.ctech.com/
FEFLOW	(-)	3D Fluid flow (groundwater) & geothermal modelling	DHI-WASY GmbH, Germany	http://www.feflo.info/
FEHM	(-)	3D Fluid flow (groundwater) & modelling	Los Alamos National Laboratory (LANL), USA	http://fehm.lanl.gov/

Program	*Suitability for all-purpose modelling of underground excavations*	*Remarks*	*Developer/ supplier/ consortium leader*	*Web-site*
FLAC3D/ 3DEC/ PFC3D	(-)	3/ 4D mechanical modelling programs (only some basic geology modelling)	Itasca, USA	http://www. itascacg.com/home.php
FracSIS	++	Mining, geological, geophysical, geomechanical, environmental & geotechnical modelling	FracSIS, Australia	http://www. fractaltechnologies.com/hoome.36. html
Geoblock	+	Mining, geology, geotechnical environment (open source)	Contact: Getos Ltd., distributer: Sourceforce	http://geoblock.sourceforge.net/geoblock.htm & hhtp://getos.chat.ru/#Presentation
Geocap GIM and Oil & Gas	-	Oil & gas, geology & seismic modelling	Geocap AS, Norway	http://www.geocap.no/
GEOL_DH & KAI-2001	-/+	Mining, geology (AutoCad tools)	Alexei Deridovich	http://geol-dh.narod.ru/en_index.html
Geomodeller 3D	++	Oil & gas, mining, geology, geophysical, geothermal, carbon capture & sequestration (CSS), hydrogeology, geotechnical & environmental modelling	Basins Consortium/ Intrepid Geophysics, GeoIntrepid, Australia & BRGM (Bureau de Recherches Geologiques et Minieres) France	http://www.geomodeller.com/geo/index.php?lang=EN&menu=homepage&BRGM: http://www.brgm.fr/index.jsp
Geosoft (Oasis montaj)	-	Mining, borehole interpretation, geophysical & geochemistry modelling. Linked to the ARCGIS software of ESRI	Geosoft, Canada	http://www.geosoft.com/
GoCad	+	Geology, oil & gas, mining & geophysical modelling	GoCad, France	http://www.gocad.org/
GrADS	(+)	4D visualisation & 5D analysis tool	COLA, USA	http://grad.iges.org/grads/head.html
GRASS GIS	++	Oil & gas, mining, geology, geotechnical & environmental (open source)	Open Source Geospatial Foundation (OSGeo)	http://grass.osgeo.org/
GSI3D	++	Oil & gas, mining, geology, geophysical, geothermal, archaeological, flood risk management & environmental modelling	British Geological Survey, UK & INSIGHT GmbH, Germany (formerly also: Geological Survey of Lower Saxony, Germany)	http://www.gsi3d.org.uk/
Jewel Suite	-	Oil & gas, geology & seismic modelling	JOA Group	http://www.jewelsuite.com/
Leapfrog mining	++	Mining, geology, geophysical, geochemical & geotechnical modelling	ARANZ Geo Limited, New Zealand	http://www.leapfrog3d.com/mining/solutions
Lynx	++	Mining, geology, environmental & geotechnical modelling	Lynx Geosystems S.A. (Pty) Ltd., South Africa	http://www.lynxgeo.com/
MathLad	(-/+)	Mathematical program, many tools from third	Mathworks, USA	http://www.mathworks.com/products/

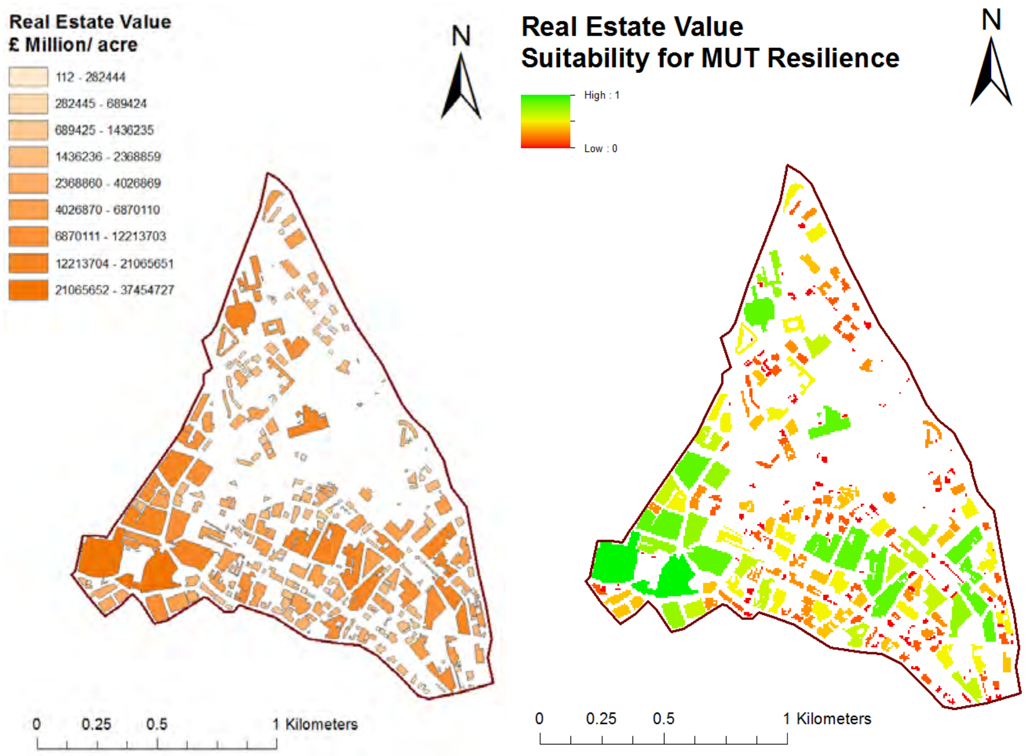
Program	*Suitability for all-purpose modelling of underground excavations*	*Remarks*	*Developer/ supplier/ consortium leader*	*Web-site*
		party developers for geological data handling		
Micromine	++	Mining, geology & geotechnical modelling	Micromine, Australia	http://www.micromine.com/
Micromodel	+	Mining, geology, geotechnical & environmental	RKM mining Software, USA	http://www.rkmminingsoftware.com/
Microstation	-/+	CAD system, not a 3D modelling program, but with add-ons used for subsurface modelling	Bentley, USA	http://www.bentley.com/en-US/Products/MicroStation/
MineGeo	++	Mining, geology 7 geotechnical modelling (directed to mining)	Cad Cam Slutions Australia Pty. Ltd., Australia	http://www.minegeo.com/index.html
MineSight	++	Mining, geology 7 geotechnical modelling (directed to mining)	MineSight, USA	http://www.minesight.com/index.php
MODFLOW	(-)	3D Fluid flow (groundwater), with many add-ons	USGS	http://water.usgs.gov/nrp/gwsoftware/modflow.html
Petrel	-	oil & gas, geology & geophysical modelling	Schumberger	http://www.slb.com/services/software/geo/petrel.aspx
Plaxis	(-)	3/ 4D mechanical modelling program (only some basic geological modelling)	Plaxis	http://www.plaxis.nl/
Promine	+	CAD based geology, mining & geotechnical modelling	Promine, Canada	http://www.promine.com/
RockWorks	++	Software tools for geology & related subjects, including 3D modelling program. Extensively used in oil & gas, mining, environmental, geotechnical and groundwater modelling	Rockware, USA	http://www.rockware.com/
Roxar IRAP RMS Suite	-	Oil & gas, geology & geophysical modelling	Emerson Process Management	http://www2.emersonprocess.com/en-US/brands/roxar/pages/Roxar.aspx
StrataExplorer	-	interpretation tool for boreholes & strata/ unit definition (not a full 3D modelling program)	GAEA Technologies Ltd., Canada	http://www.gaeatech.com/index.html
Surpac	++	Mining, geology, geotechnical & environmental modelling	Gemcom, Australia	http://www.gemcomsoftware.com/products/surpac
Techbase	++	Geology, environmental, geotechnical, groundwater, oil & gas & mining modelling	Techbase, USA	http://www.techbase.com/index.html
Vulcan	++	Mining, geology, geotechnical & environmental modelling	Maptek, Australia	http://www.maptek.com/products/vulcan/index.html
WinFence	-	Tool for fence diagram interpretation (not a full 3D modelling program)	GAEA Technologies Ltd., Canada	http://www.gaeatech.com/index.html

Program	*Suitability for all-purpose modelling of underground excavations*	*Remarks*	*Developer/ supplier/ consortium leader*	*Web-site*
ZOOMQ3D	(-)	3D Fluid flow (groundwater)	OO models, University of Birmingham, Environment Agency, British Geological Survey (BGS)	http://www.oomodels.info/pmwiki/pmwiki.php & http://www.bgs.ac.uk/science/3Dmodelling/zoom.html

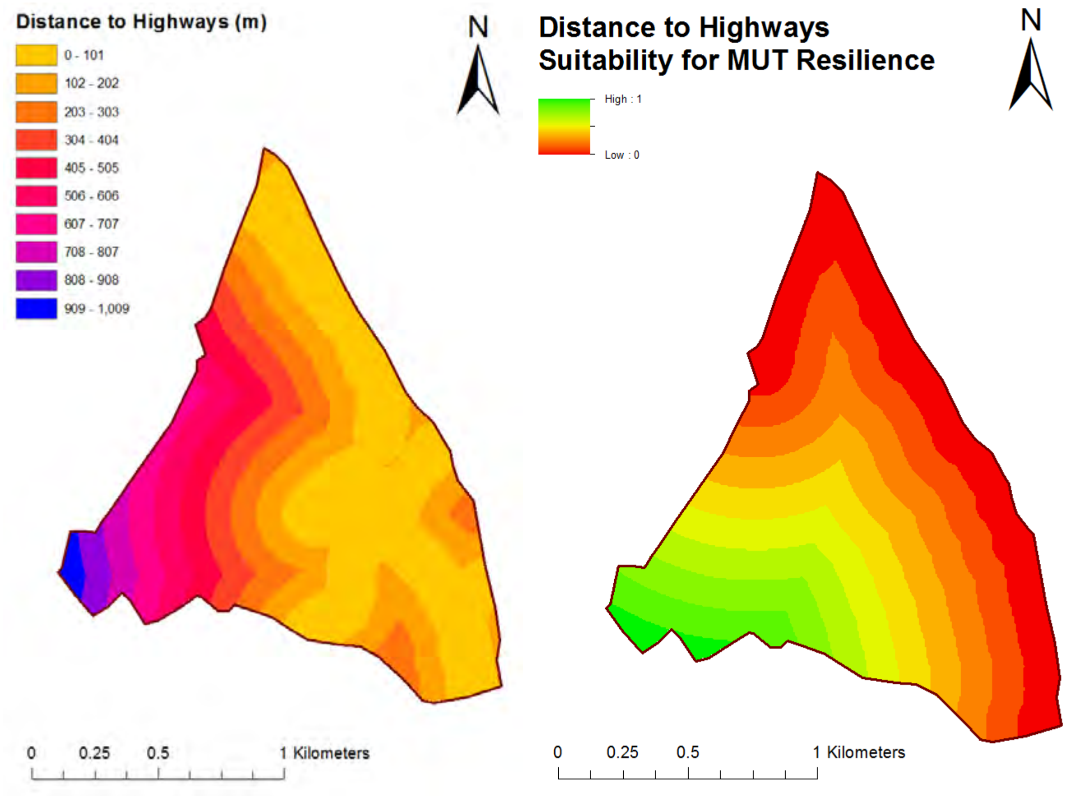
APPENDIX E MAPS – SOURCE MAP AND STANDARDISED MAP OF MUT FACTORS



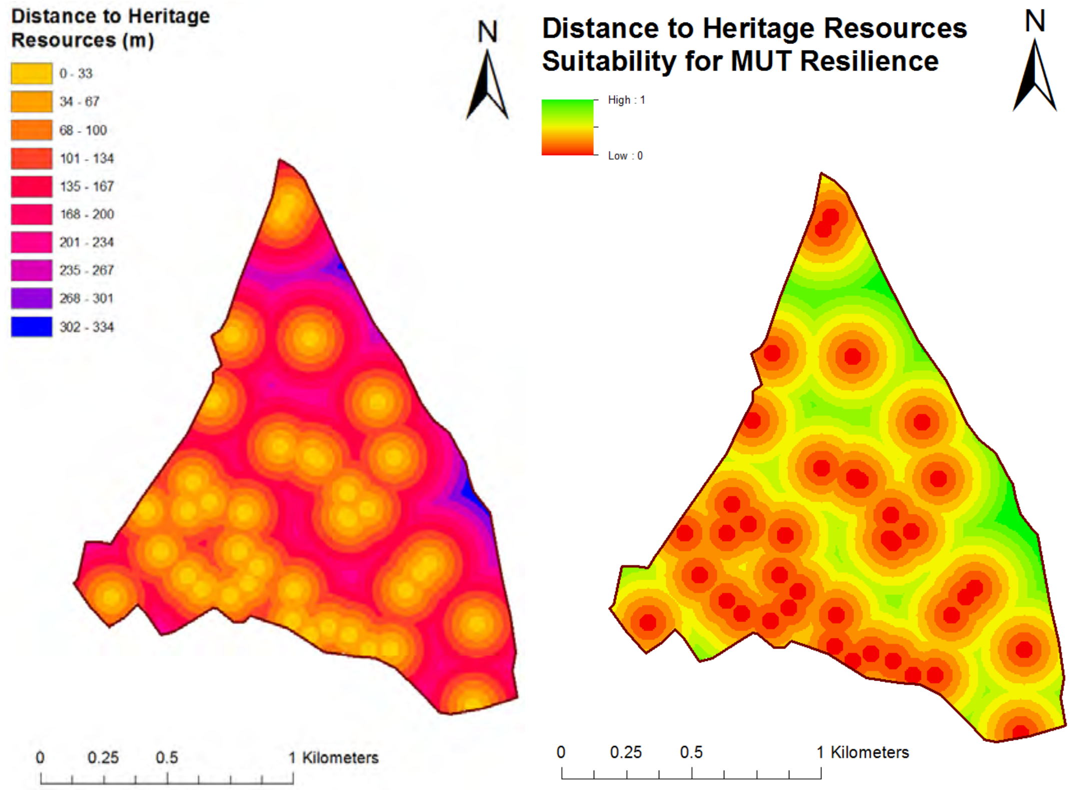
Source map and standardised/ reclassified map for the factor 'Land-use Classes'



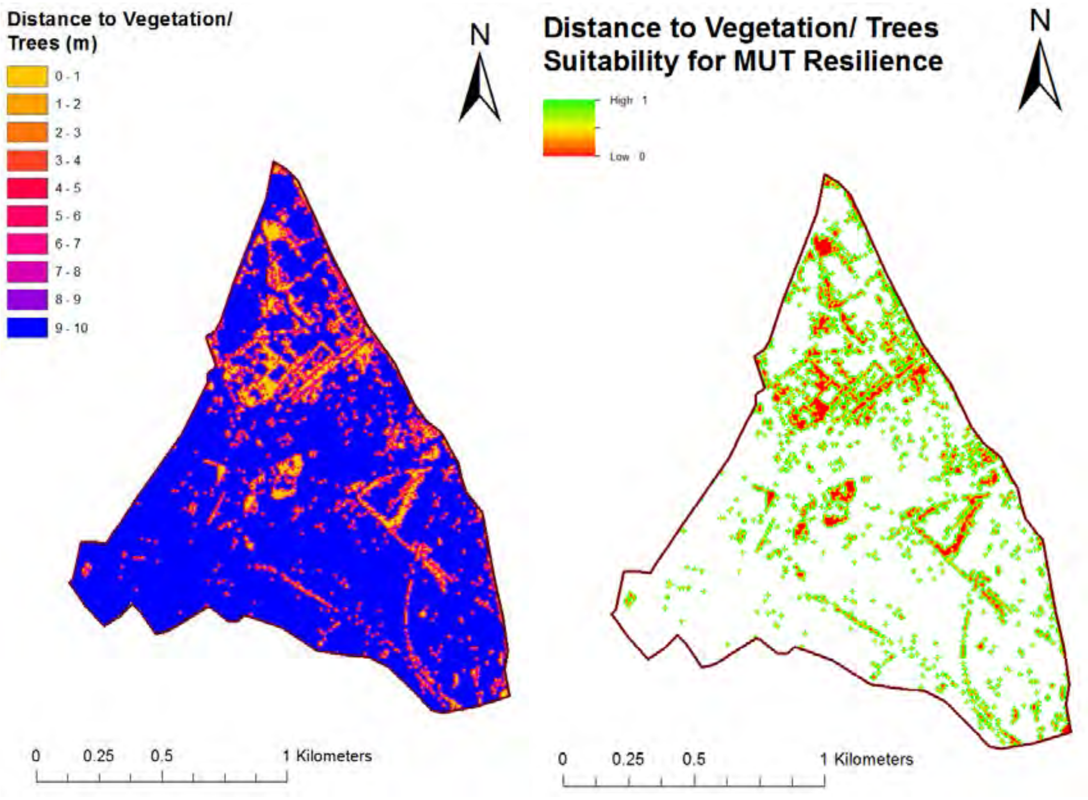
Source map and standardised/ reclassified map for the factor 'Real estate value'



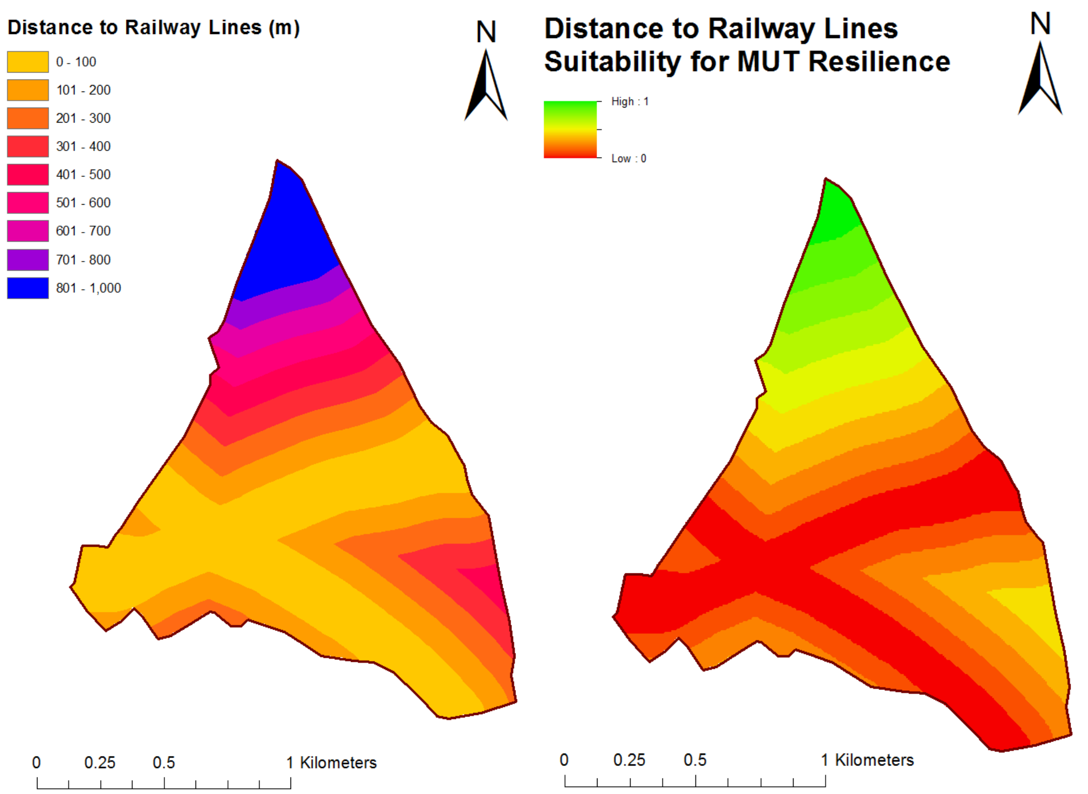
Source map and standardised/ reclassified map for the factor 'Distance to highways'



Source map and standardised/ reclassified map for the factor 'Distance to heritage resources'

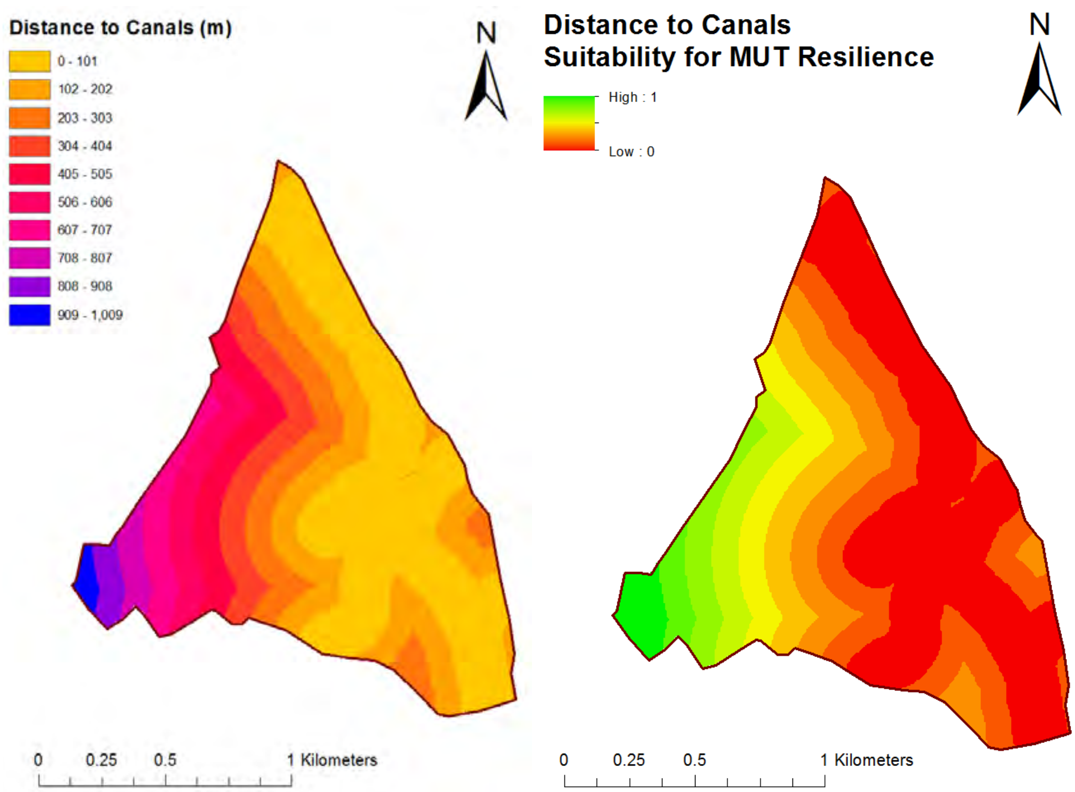


Source map and standardised/ reclassified map for the factor 'Distance to vegetation/ trees'

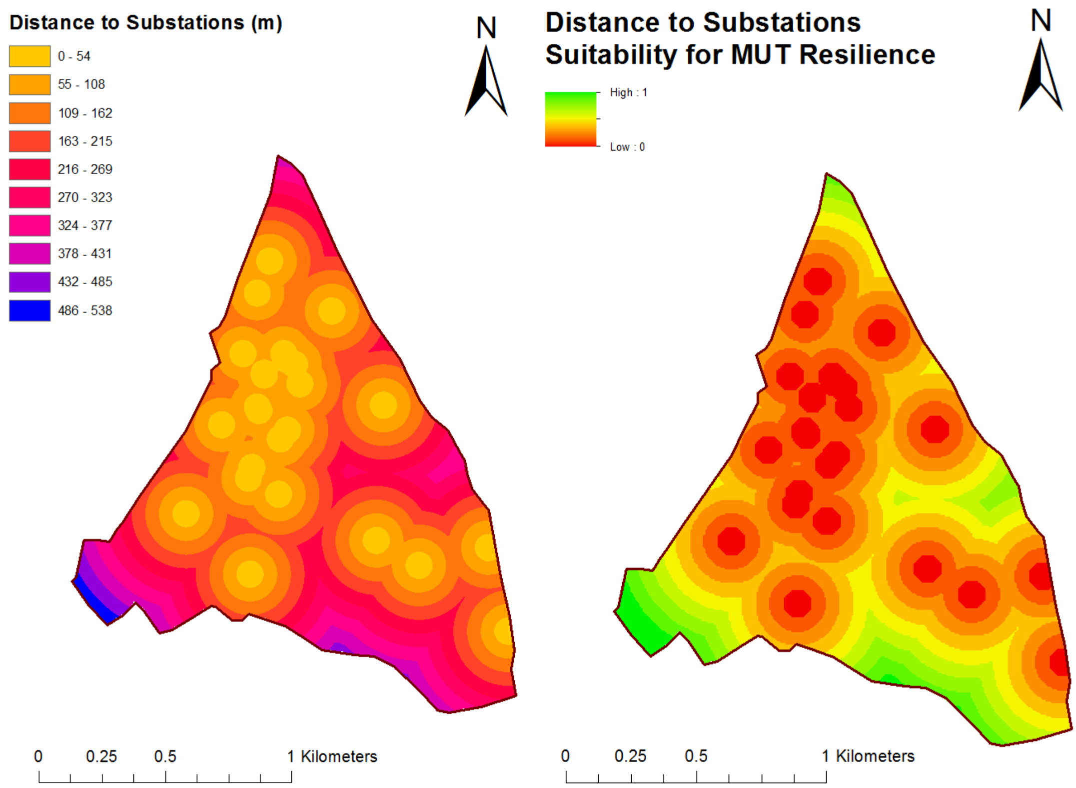


Source map and standardised/ reclassified map for the factor 'Distance to railway lines'

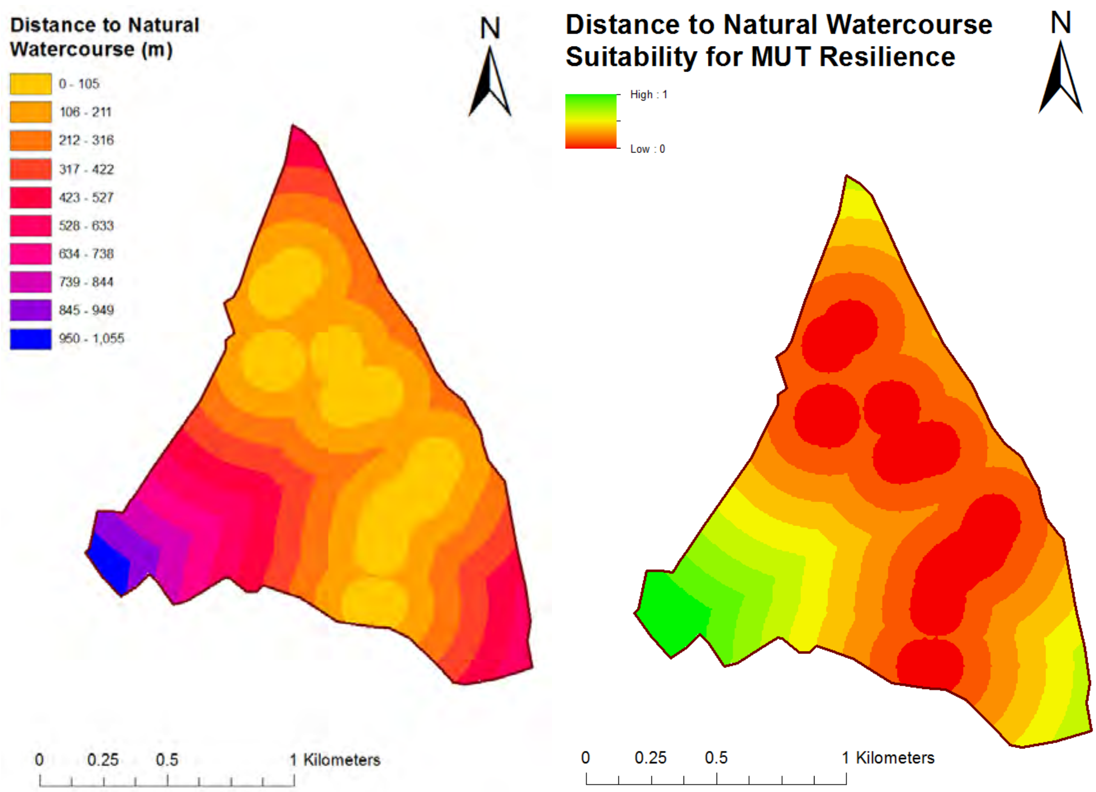
Source map and standardised/ reclassified map for the factor 'Distance to streets'



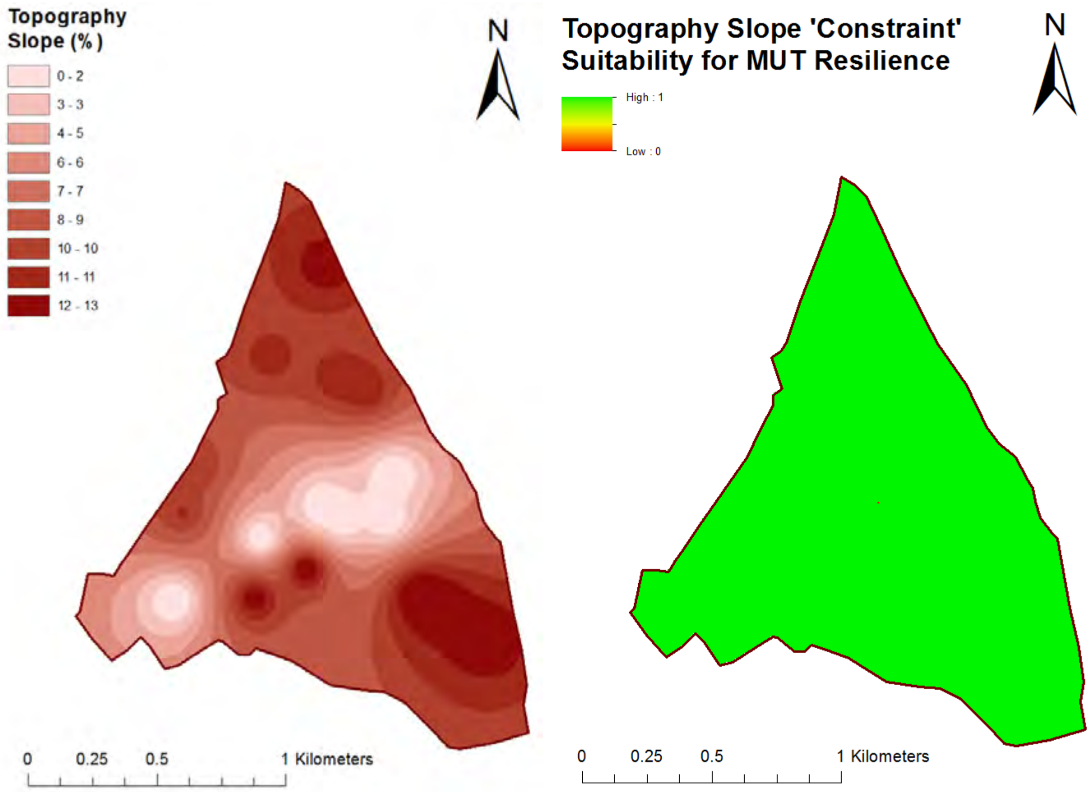
Source map and standardised/ reclassified map for the factor 'Distance to canals'



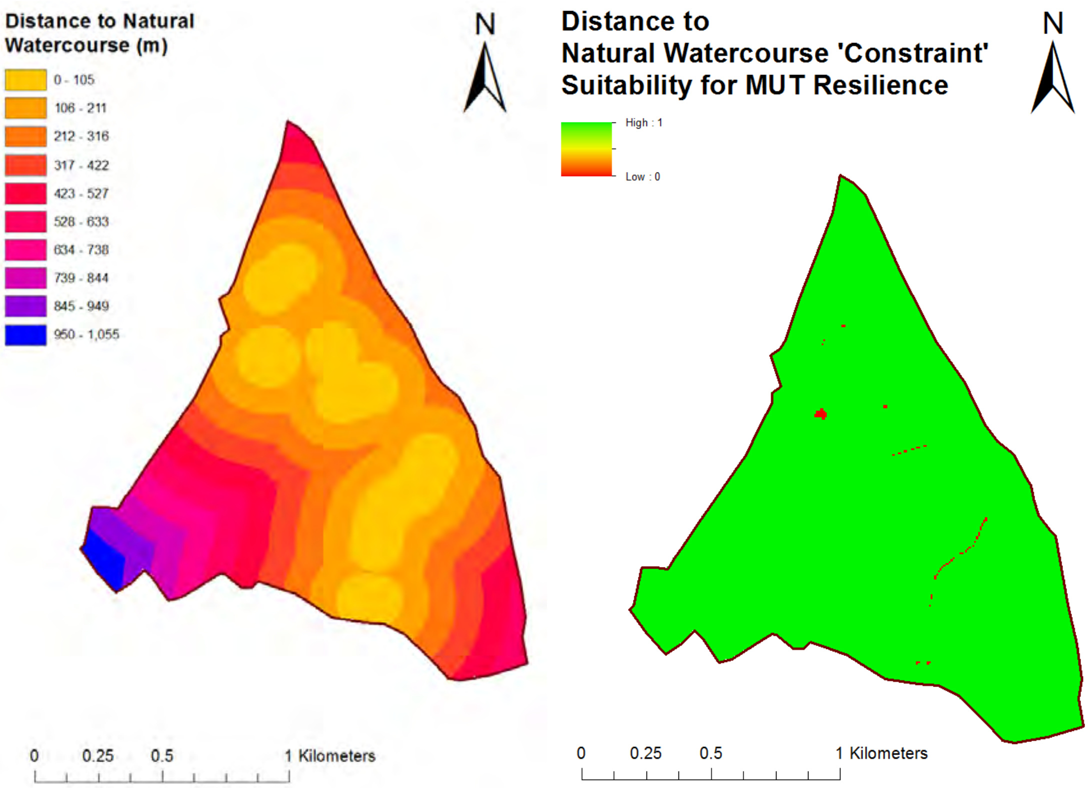
Source map and standardised/ reclassified map for the factor 'Distance to substations'



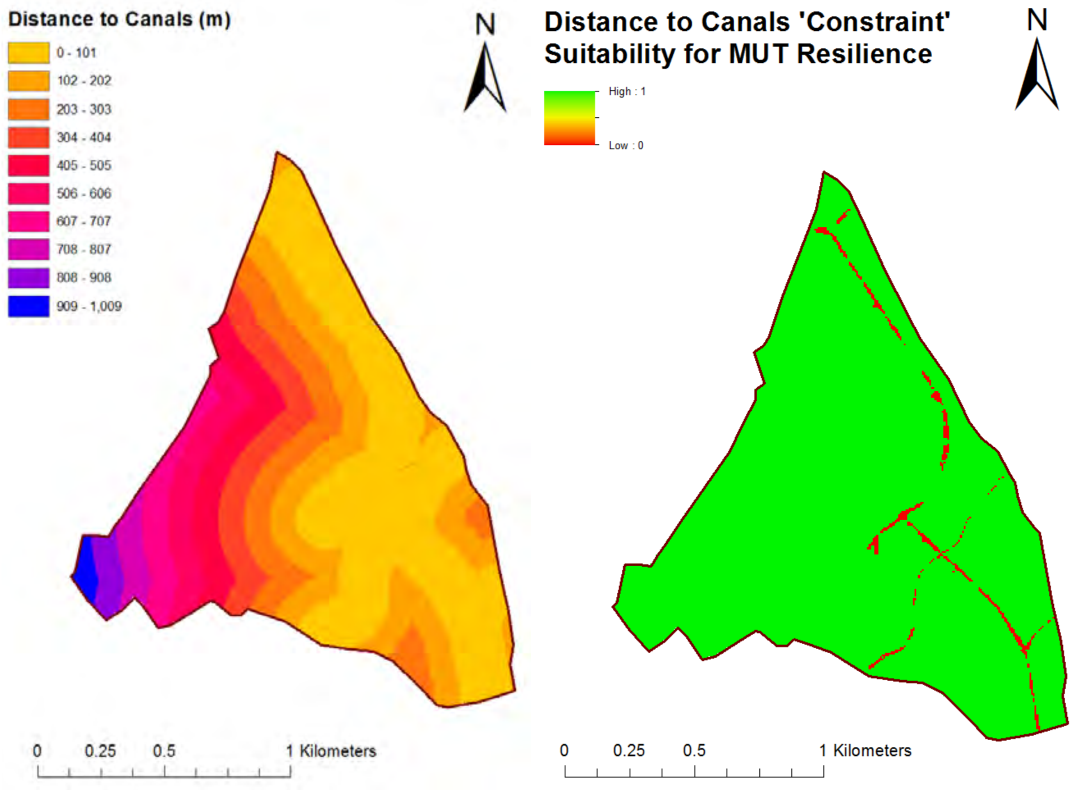
Source map and standardised/ reclassified map for the factor 'Distance to natural watercourse'



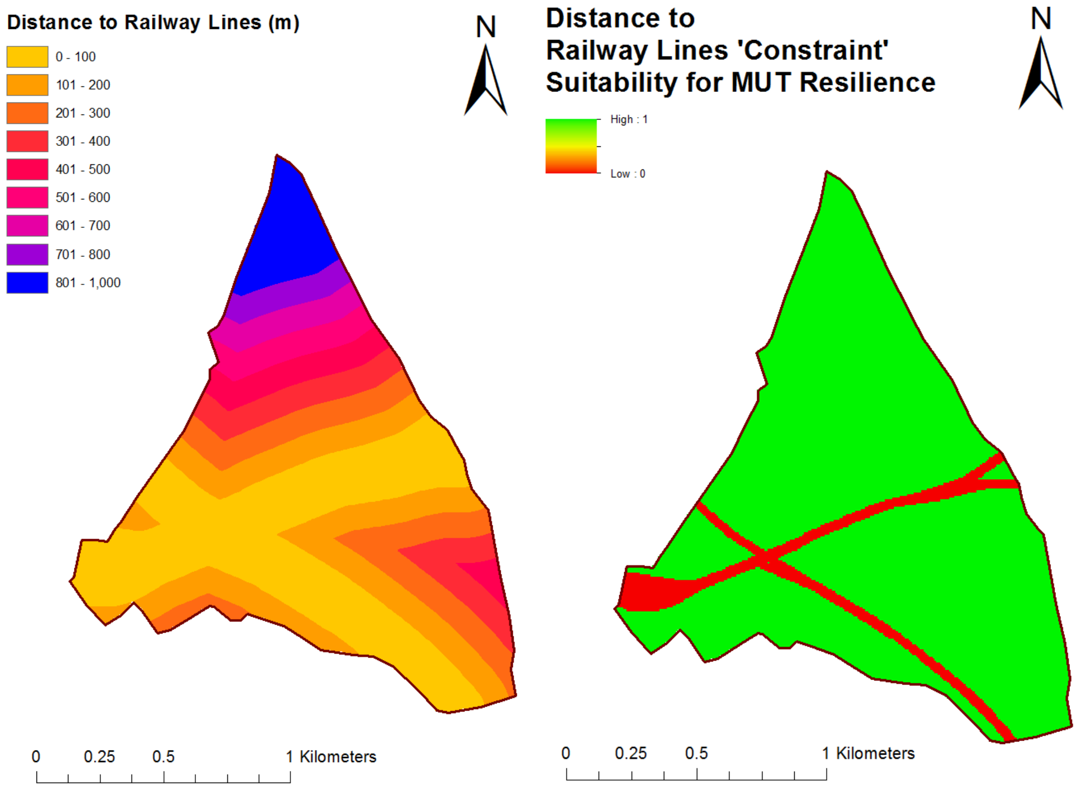
Source map and standardised/ reclassified map for the constraint 'Topography (≤ 1:500)'



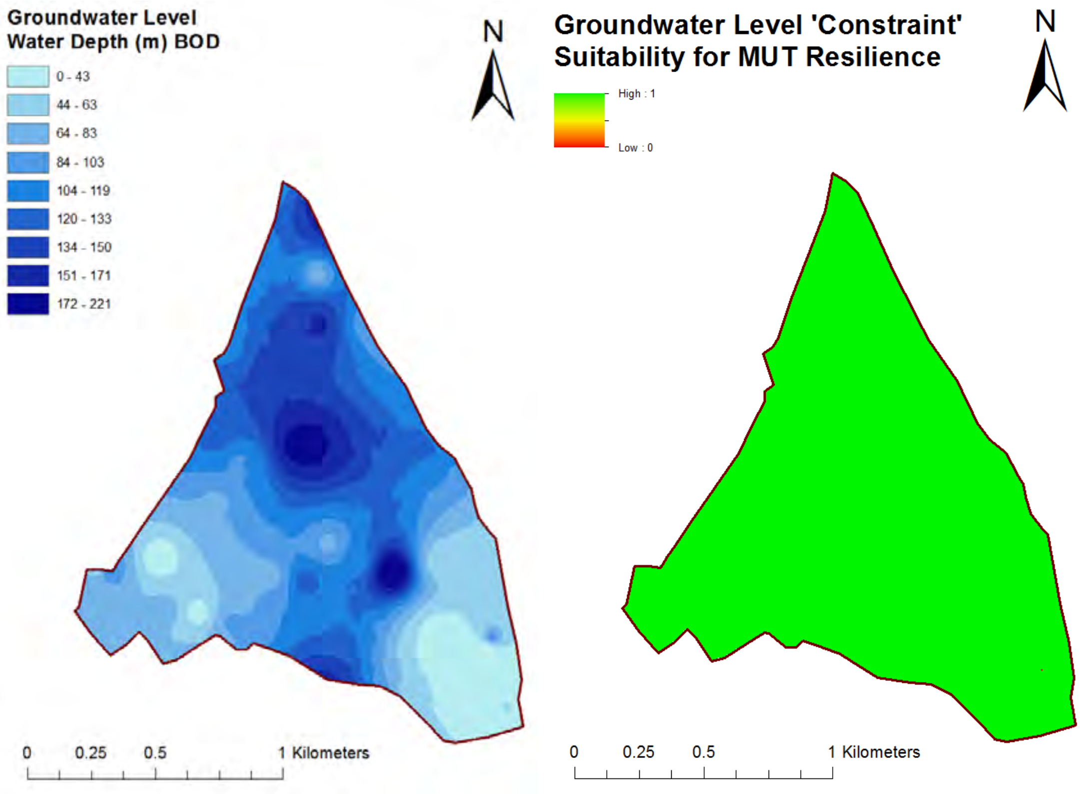
Source map and standardised/ reclassified map for the constraint 'Natural watercourse'



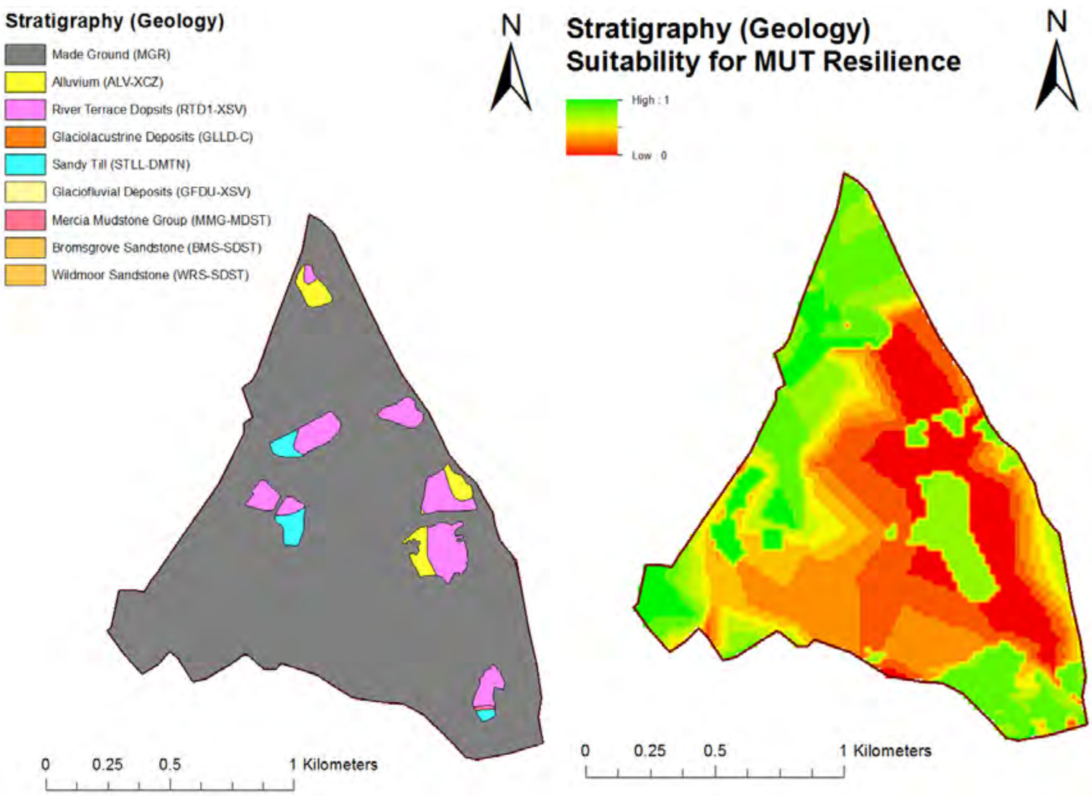
Source map and standardised/ reclassified map for the constraint 'Canals (man-made)'



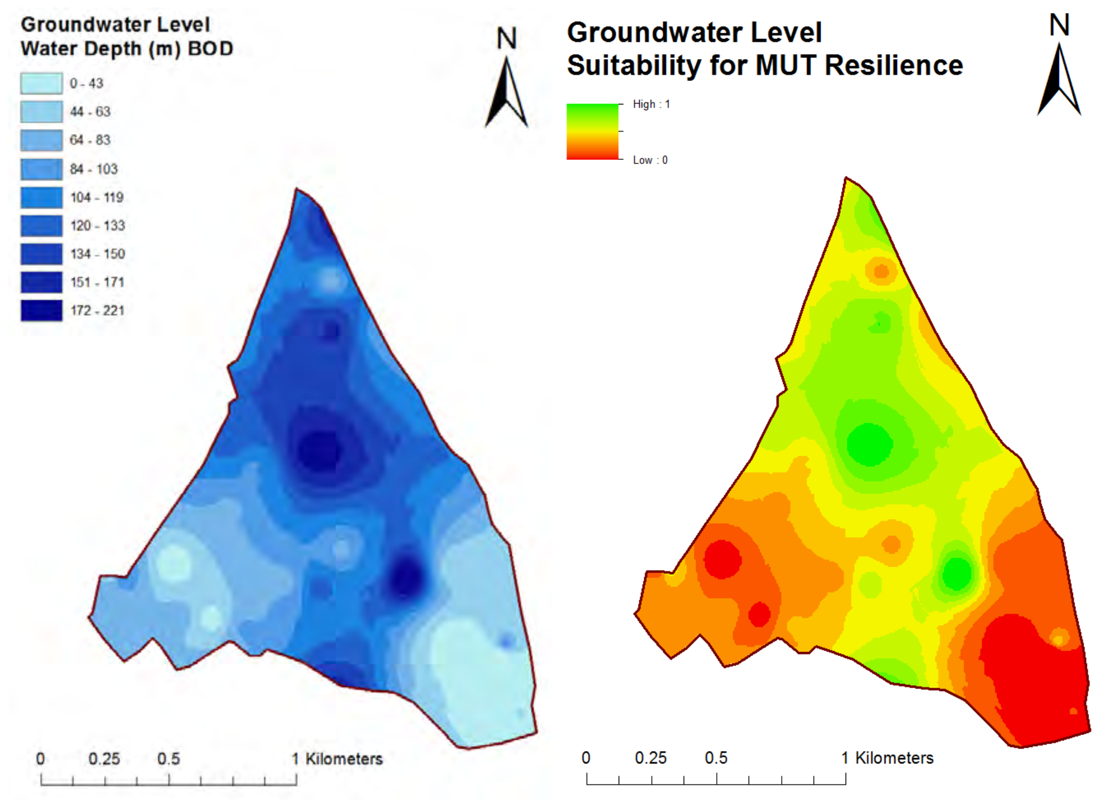
Source map and standardised/ reclassified map for the constraint 'Railway lines'



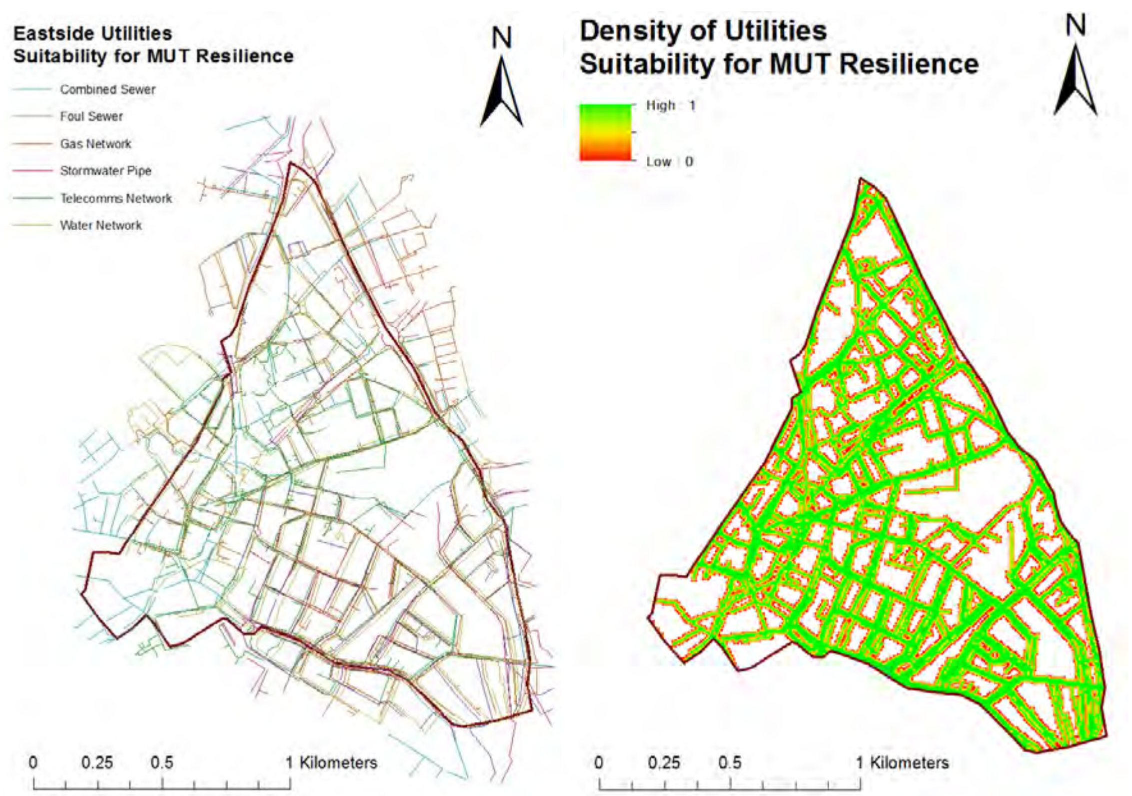
Source map and standardised/ reclassified map for the constraint 'Groundwater depth'



Source map and standardised/ reclassified map for the factor 'Geology'



Source map and standardised/ reclassified map for the factor 'Groundwater depth'



Source map and standardised/ reclassified map for the factor 'Utilities'

APPENDIX F MUT RESULTS OF SCENARIO PAIRWISE COMPARISONS

Table: Evaluation results of the pairwise comparisons with respect to Shallow MUT in different socio-ecological future scenarios

Pairwise Criteria	Results for different future scenarios									
	NSP - W	NSP- CR	PR - W	PR - CR	MF - W	MF - CR	FW_R - W	FW_R - CR	FW_P - W	FW_P - CR
Q1	SP-QP	0.04288	SP-QP	0.04288	VP-MP	0.06395	SP-QP	0.04288	VP-MP	0.06395
Q2	VP-MP	0.04288	VP-MP	0.04288	VP-MP	0.06395	VP-MP	0.04288	VP-VP	0.06395
Q3	EP-VP	0.04288	EP-VP	0.04288	EP-VP	0.06395	EP-VP	0.04288	EP-VP	0.06395
Q4	MP	0.04288	MP	0.04288	MP-SP	0.06395	MP	0.04288	MP-SP	0.06395
Q5	VP	0.04288	VP	0.04288	SP-QP	0.06395	VP	0.04288	SP-QP	0.06395
Q6	SP	0.04288	SP	0.04288	QP	0.06395	SP	0.04288	QP	0.06395
Q7	SP-QP	0.03112	SP-QP	0.03112	MP-SP	0.06852	SP-QP	0.03112	MP-SP	0.06852
Q8	VP	0.03112	VP	0.03112	EP	0.06852	VP	0.03112	EP	0.06852
Q9	VP-MP	0.03112	VP-MP	0.03112	MP	0.06852	VP-MP	0.03112	MP	0.06852
Q10	VP-MP	0.0	VP-MP	0.0	EP	0.0	VP-MP	0.0	EP	0.0
Q11	MP-SP	0.0	SN	0.0	MP-SP	0.0	MN	0.0	MN	0.0
Q12	VN	0.05156	MN	0.02365	SN	0.0	EN-VN	0.05156	MN	0.00532
Q13	VN	0.05156	MN-SN	0.02365	SN	0.0	EN-VN	0.05156	MN-SN	0.00532
Q14	SP-QP	0.05156	SP-QP	0.02365	QP	0.0	SN-QP	0.05156	QP	0.00532
Q15	MN-SN	0.08764	SN	0.08001	SP-QP	0.04401	MN	0.07664	SN-QP	0.04263
Q16	SP-QP	0.08764	SP	0.08001	SP-QP	0.04401	QP	0.07664	SP-QP	0.04263
Q17	QP	0.08764	SP-QP	0.08001	SP-QP	0.04401	SN-QP	0.07664	SN-QP	0.04263
Q18	MN-SN	0.08764	SN	0.08001	MN-SN	0.04401	MN	0.07664	VN-MN	0.04263
Q19	SP	0.08764	MP-SP	0.08001	SP-QP	0.04401	SP-QP	0.07664	SP-QP	0.04263
Q20	MP-SP	0.08764	MP	0.08001	SP-QP	0.04401	SP	0.07664	SP-QP	0.04263
Q21	VN-MN	0.08764	MN	0.08001	SN	0.04401	VN	0.07664	SN	0.04263
Q22	SP-QP	0.08764	SP-QP	0.08001	QP	0.04401	QP	0.07664	QP	0.04263
Q23	VN	0.08764	VN	0.08001	SN	0.04401	EN-VN	0.07664	MN-SN	0.04263
Q24	VN	0.08764	VN-MN	0.08001	SN	0.04401	EN-VN	0.07664	MN	0.04263
Q25	SP	0.0	MP-SP	0.0	QP	0.0	SP	0.0	QP	0.0
Q26	MP-SP	0.05474	MP	0.06013	SP-QP	0.01732	SP	0.05864	SP-QP	0.06498
Q27	SP	0.05474	MP-SP	0.06013	SP-QP	0.01732	SP-QP	0.05864	SP	0.06498
Q28	VN-MN	0.05474	MN	0.06013	QP	0.01732	VN	0.05864	QP	0.06498
Q29	MN-SN	0.05474	SN	0.06013	SN-QP	0.01732	MN	0.05864	SN-QP	0.06498
Q30	SN	0.05474	SN-QP	0.06013	QP	0.01732	MN-SN	0.05864	SP-QP	0.06498
Q31	EN	0.05474	EN-VN	0.06013	QP	0.01732	EN	0.05864	SN-QP	0.06498

Pairwise	Results for different future scenarios									
Criteria	NSP - W	NSP- CR	PR - W	PR - CR	MF - W	MF - CR	FW_R - W	FW_R - CR	FW_P - W	FW_P - CR
Q32	VN	0.05474	VN-MN	0.06013	SN-QP	0.01732	EN-VN	0.05864	SN-QP	0.06498
Q33	EN-VN	0.05474	VN	0.06013	QP	0.01732	EN	0.05864	MN-SN	0.06498
Q34	VN	0.05474	VN-MN	0.06013	SN-QP	0.01732	EN-VN	0.05864	SN-QP	0.06498
Q35	SP-QP	0.05474	SP	0.06013	SN-QP	0.01732	QP	0.05864	SN	0.06498
Q36	MP-SP	0.02365	MP	0.00532	QP	0.0	SP	0.01759	QP	0.00355
Q37	SN-QP	0.02365	QP	0.00532	MN-SN	0.0	SN	0.01759	VN-MN	0.00355
Q38	MN	0.02365	MN-SN	0.00532	MN-SN	0.0	VN-MN	0.01759	MN	0.00355
Q39	SN-QP	0.01361	QP	0.01759	QP	0.05156	SN	0.07069	SP-QP	0.01759
Q40	VN	0.01361	VN-MN	0.01759	SN-QP	0.05156	EN-VN	0.07069	SN	0.01759
Q41	MN	0.01361	MN-SN	0.01759	QP	0.05156	VN-MN	0.07069	MN-SN	0.01759

Key: W = Intensity of Importance (see Table 5-8); CR = Consistency Ratio

Table: Evaluation results of the pairwise comparisons with respect to Deep MUT in different socio-ecological future scenarios

Pairwise	Results for different future scenarios									
Criteria	NSP - W	NSP- CR	PR - W	PR - CR	MF - W	MF - CR	FW_R - W	FW_R - CR	FW_P - W	FW_P - CR
Q1	SP-QP	0.04288	SP-QP	0.04288	VP-MP	0.06395	SP-QP	0.04288	VP-MP	0.06395
Q2	VP-MP	0.04288	VP-MP	0.04288	VP-MP	0.06395	VP-MP	0.04288	VP-MP	0.06395
Q3	EP-VP	0.04288	EP-VP	0.04288	EP-VP	0.06395	EP-VP	0.04288	EP-VP	0.06395
Q4	MP	0.04288	MP	0.04288	MP-SP	0.06395	MP	0.04288	MP-SP	0.06395
Q5	VP	0.04288	VP	0.04288	SP-QP	0.06395	VP	0.04288	SP-QP	0.06395
Q6	SP	0.04288	SP	0.04288	QP	0.06395	SP	0.04288	QP	0.06395
Q7	SP-QP	0.03112	SP-QP	0.03112	MP-SP	0.06852	SP-QP	0.03112	MP-SP	0.06852
Q8	VP	0.03112	VP	0.03112	EP	0.06852	VP	0.03112	EP	0.06852
Q9	VP-MP	0.03112	VP-MP	0.03112	MP	0.06852	VP-MP	0.03112	MP	0.06852
Q10	SP	0.0	SP	0.0	EP	0.0	SP	0.0	EP	0.0
Q11	SP	0.0	SN-QP	0.0	MP-SP	0.0	MN-SN	0.0	VN-MN	0.0
Q12	EN-VN	0.05156	VN-MN	0.05156	MN	0.0	EN	0.05156	VN-MN	0.05156
Q13	EN-VN	0.05156	VN-MN	0.05156	MN	0.0	EN	0.05156	VN-MN	0.05156
Q14	SP-QP	0.05156	SP-QP	0.05156	QP	0.0	SN-QP	0.05156	SN-QP	0.05156
Q15	SN	0.05802	SN-QP	0.05765	SP	0.05173	MN-SN	0.05950	MP-SP	0.06330
Q16	VP	0.05802	EP-VP	0.05765	SP	0.05173	VP-MP	0.05950	MP-SP	0.06330
Q17	MP-SP	0.05802	MP	0.05765	SP	0.05173	SP	0.05950	MP-SP	0.06330
Q18	SN	0.05802	SN-QP	0.05765	MN	0.05173	MN-SN	0.05950	MN-SN	0.06330
Q19	EP-VP	0.05802	EP	0.05765	SP-QP	0.05173	VP	0.05950	SP	0.06330

Pairwise Criteria	Results for different future scenarios									
	NSP - W	**NSP- CR**	**PR - W**	**PR - CR**	**MF - W**	**MF - CR**	**FW_R - W**	**FW_R - CR**	**FW_P - W**	**FW_P - CR**
Q20	VP	0.05802	EP-VP	0.05765	SP-QP	0.05173	VP-MP	0.05950	SP	0.06330
Q21	SN-QP	0.05802	QP	0.05765	MN-SN	0.05173	SN	0.05950	MN	0.06330
Q22	SP-QP	0.05802	SP	0.05765	QP	0.05173	QP	0.05950	QP	0.06330
Q23	VN	0.05802	VN-MN	0.05765	MN	0.05173	EN-VN	0.05950	VN-MN	0.06330
Q24	EN	0.05802	EN-VN	0.05765	MN	0.05173	EN	0.05950	VN	0.06330
Q25	VP	0.0	EP-VP	0.0	QP	0.0	VP-MP	0.0	QP	0.0
Q26	SP-QP	0.05136	SP	0.07854	SP	0.06744	QP	0.08215	SN	0.05853
Q27	VP-MP	0.05136	VP-MP	0.07854	SP	0.06744	MP-SP	0.08215	SN	0.05853
Q28	EN	0.05136	EN-VN	0.07854	QP	0.06744	EN	0.08215	QP	0.05853
Q29	MN-SN	0.05136	SN	0.07854	SN-QP	0.06744	MN	0.08215	SP-QP	0.05853
Q30	QP	0.05136	SP-QP	0.07854	QP	0.06744	SN-QP	0.08215	SP-QP	0.05853
Q31	EN	0.05136	EN-VN	0.07854	QP	0.06744	EN	0.08215	QP	0.05853
Q32	EN	0.05136	EN-VN	0.07854	SN-QP	0.06744	EN	0.08215	SP-QP	0.05853
Q33	EN	0.05136	EN-VN	0.07854	SN	0.06744	EN	0.08215	QP	0.05853
Q34	EN	0.05136	EN-VN	0.07854	SN-QP	0.06744	EN	0.08215	SP	0.05853
Q35	SP-QP	0.05136	SP	0.07854	SN	0.06744	QP	0.08215	SP-QP	0.05853
Q36	SN	0.02795	SN-QP	0.0	QP	0.0	MN-SN	0.09040	QP	0.05156
Q37	EN	0.02795	EN-VN	0.0	MN	0.0	EN-VN	0.09040	MN-SN	0.05156
Q38	MN	0.02795	MN-SN	0.0	MN	0.0	MN	0.09040	SN-QP	0.05156
Q39	EP-VP	0.03548	EP	0.00148	QP	0.0	VP	0.07721	MN-SN	0.00885
Q40	SN-QP	0.03548	QP	0.00148	SN	0.0	SN	0.07721	VN-MN	0.00885
Q41	EN	0.03548	EN-VN	0.00148	SN	0.0	EN	0.07721	SN-QP	0.00885

Key: W = Intensity of Importance (see Table 5-8); CR = Consistency Ratio

APPENDIX G SUPERMATRIX TABLES UNDER DIFFERENT FUTURE SCENARIOS

Table: Supermatrix of 'Shallow MUT – NSP'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Shallow MUT (NSP) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.06504	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.57361	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.36135	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.09034	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.20660	0.00000	0.00000	0.09381	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.07148	0.00000	0.00000	0.16659	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05908	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.57251	0.00000	1.00000	0.73959	1.00000	0.80000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.75000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.11048	0.00000	0.33307	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.03425	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.05768	0.00000	0.09739	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.48481	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.31278	0.00000	0.56954	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.03379	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29798	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.18771	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.03068	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.07015	0.00000	0.00000	0.03512	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.02427	0.00000	0.00000	0.06237	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.02006	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.19440	0.00000	0.83370	0.27689	1.00000	0.80000	0.85714	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.07082	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.02361	0.00000	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00514	0.00000	0.05539	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00159	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00268	0.00000	0.01620	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02256	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01455	0.00000	0.09471	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.018960	0.233126	0.105343	0.025828	0.043069	0.020191	0.011258	0.421470	0.039742	0.016132	0.015798	0.000894	0.005282	0.012659	0.030248

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Deep MUT – NSP'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Deep MUT (NSP) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.05738	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.57831	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.36431	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.17043	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.31943	0.00000	0.00000	0.35684	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.04690	0.00000	0.00000	0.05404	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.03733	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.42592	0.00000	1.00000	0.58913	1.00000	0.75000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.87500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.12500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.09422	0.00000	0.07042	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.04141	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.03600	0.00000	0.17818	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.51385	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.31452	0.00000	0.75140	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.02981	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.30042	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.18925	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.05787	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.10847	0.00000	0.00000	0.13359	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01592	0.00000	0.00000	0.02023	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01268	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.14463	0.00000	0.83370	0.22056	1.00000	0.75000	0.75000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.08262	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.01180	0.00000	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00438	0.00000	0.01171	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00193	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00168	0.00000	0.02963	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02391	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01464	0.00000	0.12496	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.015977	0.224502	0.101446	0.048945	0.071693	0.010588	0.006794	0.404517	0.044288	0.008974	0.004979	0.001033	0.007550	0.012816	0.035898

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Flush-fitting MUT – PR'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Flush MUT (PR) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.13965	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.52784	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.33252	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.12637	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.05726	0.00000	0.00000	0.09534	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.33291	0.00000	0.00000	0.24986	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.16113	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.32234	0.00000	1.00000	0.65481	1.00000	0.75000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.75000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.13699	0.00000	0.27895	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.04129	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.04555	0.00000	0.07193	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.50637	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.26980	0.00000	0.64912	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.07254	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.27420	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.17274	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.04291	0.00000	0.00000	0.00000	0.00000	0.250000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.01944	0.00000	0.00000	0.03569	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.11304	0.00000	0.00000	0.09354	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05471	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.10946	0.00000	0.83370	0.24515	1.00000	0.75000	0.87500	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.02361	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.07082	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00637	0.00000	0.04639	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00192	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00212	0.00000	0.01196	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02356	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01255	0.00000	0.10795	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.039995	0.210751	0.095232	0.027186	0.014118	0.071231	0.030165	0.389660	0.013014	0.047947	0.013291	0.001059	0.003689	0.012990	0.029671

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Shallow MUT – PR'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Shallow MUT (PR) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.09739	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.56954	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.33307	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.12623	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.23031	0.00000	0.00000	0.13539	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.06425	0.00000	0.00000	0.15498	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05256	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.52665	0.00000	1.00000	0.70963	1.00000	0.75000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.13844	0.00000	0.46647	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.03785	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.05310	0.00000	0.10050	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.50603	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.26459	0.00000	0.43303	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.05059	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29586	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.17302	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.04286	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.07821	0.00000	0.00000	0.05069	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.02182	0.00000	0.00000	0.05802	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01785	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.17883	0.00000	0.83370	0.26567	1.00000	0.75000	0.85714	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.07554	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.01888	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00644	0.00000	0.07757	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00176	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00247	0.00000	0.01671	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02355	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01231	0.00000	0.07201	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.028448	0.227231	0.097290	0.036329	0.048907	0.017912	0.010036	0.414243	0.042476	0.013178	0.021249	0.000990	0.005187	0.013240	0.023286

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Deep MUT – PR'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Deep MUT (PR) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.07507	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.56746	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.35748	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.22217	0.00000	0.00000	0.00000	0.00000	0.33333	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.36003	0.00000	0.00000	0.48145	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.05337	0.00000	0.00000	0.05564	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.03486	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.32958	0.00000	1.00000	0.46291	1.00000	0.66667	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.88889	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.11111	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.11371	0.00000	0.09091	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.04700	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.03292	0.00000	0.18182	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.53974	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.26664	0.00000	0.72727	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.03900	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29478	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.18570	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.07544	0.00000	0.00000	0.00000	0.00000	0.33333	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.12225	0.00000	0.00000	0.18024	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01812	0.00000	0.00000	0.02083	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01184	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.11191	0.00000	0.83370	0.17330	1.00000	0.66667	0.75000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.08393	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.01049	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00529	0.00000	0.01512	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00219	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00153	0.00000	0.03024	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02511	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01241	0.00000	0.12094	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.020378	0.214763	0.097045	0.066550	0.081379	0.011492	0.006185	0.389958	0.043862	0.008356	0.006012	0.001143	0.007294	0.013124	0.032458

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Flush-fitting MUT – MF'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Flush MUT (MF) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.11111	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.44444	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.44444	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.13270	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.14014	0.00000	0.00000	0.19580	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.14014	0.00000	0.00000	0.31081	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.14014	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.44689	0.00000	1.00000	0.49339	1.00000	0.75000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.20000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.20000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.20000	0.00000	0.60000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.07458	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29831	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.29831	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.02353	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.02485	0.00000	0.00000	0.04816	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.02485	0.00000	0.00000	0.07646	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.02485	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.07925	0.00000	0.79303	0.12137	1.00000	0.75000	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.01554	0.00000	0.04140	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.01554	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.01554	0.00000	0.04140	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01554	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01554	0.00000	0.12418	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.037922	0.266060	0.151687	0.016952	0.019943	0.024234	0.012637	0.336060	0.018755	0.021178	0.018914	0.007901	0.018914	0.007901	0.040941

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Shallow MUT – MF'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Shallow MUT (MF) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.42857	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.42857	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.19728	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.15550	0.00000	0.00000	0.25992	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.10149	0.00000	0.00000	0.32748	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.10149	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.44424	0.00000	1.00000	0.41260	1.00000	0.20000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.22079	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.14280	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.14280	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.16454	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.32908	0.00000	0.66667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.09588	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.28766	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.28766	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.03499	0.00000	0.00000	0.00000	0.00000	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.02758	0.00000	0.00000	0.06394	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01800	0.00000	0.00000	0.08056	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01800	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.07878	0.00000	0.79303	0.10149	1.00000	0.20000	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.01715	0.00000	0.03450	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.01109	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.01109	0.00000	0.03450	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01278	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.02557	0.00000	0.13798	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.048695	0.256234	0.146084	0.036444	0.023345	0.020908	0.009140	0.327108	0.018731	0.020822	0.017550	0.005634	0.014473	0.006492	0.048339

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Deep MUT – MF'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Deep MUT (MF) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.09091	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.45454	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.45454	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.21001	0.00000	0.00000	0.00000	0.00000	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.11621	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.07238	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.07238	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.52902	0.00000	1.00000	0.60000	1.00000	0.20000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.24190	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.12551	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.10242	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.18367	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.34650	0.00000	0.71429	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.06102	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.30509	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.30509	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.03724	0.00000	0.00000	0.00000	0.00000	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.02061	0.00000	0.00000	0.04920	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01284	0.00000	0.00000	0.04920	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01284	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.09382	0.00000	0.79303	0.14759	1.00000	0.20000	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.01879	0.00000	0.02957	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00975	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00796	0.00000	0.02957	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01427	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.02692	0.00000	0.14784	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.030782	0.269960	0.153910	0.033164	0.017969	0.014047	0.006475	0.340007	0.018607	0.020011	0.017463	0.004919	0.011996	0.007199	0.053491

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Flush-fitting MUT – FWR'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Flush MUT (FW-R) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.06137	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.56590	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.37272	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.06263	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.04167	0.00000	0.00000	0.06033	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.23793	0.00000	0.00000	0.23115	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.15875	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.49901	0.00000	1.00000	0.70852	1.00000	0.83333	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.85714	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.08537	0.00000	0.17818	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.03343	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.05762	0.00000	0.07042	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.43391	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.38969	0.00000	0.75140	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.03188	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.29398	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.19362	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.02127	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.01415	0.00000	0.00000	0.02259	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.08079	0.00000	0.00000	0.08654	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05391	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.16945	0.00000	0.83370	0.26526	1.00000	0.83333	0.87500	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.01349	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.08094	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00397	0.00000	0.02963	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00156	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00268	0.00000	0.01171	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02019	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01813	0.00000	0.12496	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.017682	0.230225	0.107385	0.013508	0.010273	0.054101	0.029897	0.413705	0.007481	0.051650	0.009025	0.000863	0.004183	0.011198	0.038825

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of ‘Shallow MUT – FWR’

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Shallow MUT (FW-R) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.05738	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.36431	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.57831	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.06122	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.17489	0.00000	0.00000	0.07261	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.06941	0.00000	0.00000	0.16623	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.07541	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.61908	0.00000	1.00000	0.76116	1.00000	0.83333	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.75000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.08559	0.00000	0.24986	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.03299	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.06356	0.00000	0.09534	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.43437	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.38349	0.00000	0.65481	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.02981	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.18925	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.30042	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.02079	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.05939	0.00000	0.00000	0.02718	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.02357	0.00000	0.00000	0.06223	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.02561	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.21022	0.00000	0.83370	0.28496	1.00000	0.83333	0.85714	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.07082	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.02361	0.00000	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00398	0.00000	0.04155	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00153	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00296	0.00000	0.01585	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02021	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01784	0.00000	0.10889	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.016154	0.204436	0.162821	0.017369	0.036612	0.022907	0.013878	0.412160	0.038382	0.016066	0.010653	0.000832	0.004844	0.010954	0.031933

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Deep MUT – FWR'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Deep MUT (FW-R) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.05133	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.36665	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.58202	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.13249	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.28951	0.00000	0.00000	0.28974	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.03963	0.00000	0.00000	0.05490	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.04383	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.49454	0.00000	1.00000	0.65536	1.00000	0.80000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.85714	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.08156	0.00000	0.06754	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.04501	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.04632	0.00000	0.19907	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.44394	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.38317	0.00000	0.73338	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.02666	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.19047	0.00000	0.00000	0.62562	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.30235	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.04499	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.09831	0.00000	0.00000	0.10847	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01346	0.00000	0.00000	0.02055	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.01488	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.16793	0.00000	0.83370	0.24535	1.00000	0.80000	0.75000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.08094	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.01349	0.00000	0.00000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.00380	0.00000	0.01123	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.00209	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00215	0.00000	0.03311	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.02066	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01783	0.00000	0.12196	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.013896	0.197840	0.157568	0.037111	0.068324	0.010252	0.007756	0.398331	0.042179	0.009593	0.004200	0.001092	0.007673	0.010765	0.033420

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of ‘Flush-fitting MUT – FWP’

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Flush MUT (FW-P) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.11722	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.26837	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.61441	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.11757	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.12271	0.00000	0.00000	0.09739	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.12271	0.00000	0.00000	0.33307	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.12271	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.51431	0.00000	1.00000	0.56954	1.00000	0.85714	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.75000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.20000	0.00000	0.31081	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.20000	0.00000	0.19580	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.20000	0.00000	0.49339	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	**(1)**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.07868	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.18013	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.41239	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.02085	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.02176	0.00000	0.00000	0.02396	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.02176	0.00000	0.00000	0.08193	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.02176	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.09121	0.00000	0.79303	0.14010	1.00000	0.85714	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.01844	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.05532	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.01554	0.00000	0.06433	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.01554	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.01554	0.00000	0.04052	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01554	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.01554	0.00000	0.10212	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.038610	0.240985	0.202372	0.012450	0.015527	0.027259	0.010679	0.325191	0.009050	0.029875	0.023128	0.007625	0.017391	0.007625	0.032234

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Shallow MUT – FWP'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Shallow MUT (FW-P) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.10050	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.46647	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.43303	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.10022	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.18734	0.00000	0.00000	0.23849	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.09211	0.00000	0.00000	0.13650	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.11621	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.50413	0.00000	1.00000	0.62501	1.00000	0.83333	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.21282	0.00000	0.12972	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.13116	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.08559	0.00000	0.13785	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.21789	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.35254	0.00000	0.73243	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.06745	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.31309	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.29065	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.01777	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.03322	0.00000	0.00000	0.05867	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01633	0.00000	0.00000	0.03358	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.02061	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.08940	0.00000	0.79303	0.15375	1.00000	0.83333	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	00.01653	0.00000	0.02685	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.01019	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.00065	0.00000	0.02853	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01693	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.02739	0.00000	0.15159	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.034662	0.273505	0.149356	0.013439	0.025834	0.013409	0.010590	0.343427	0.018953	0.020294	0.015840	0.005236	0.011220	0.008699	0.055536

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspects

Table: Supermatrix of 'Deep MUT – FWP'

Super Matrix	Cluster	Goal	Socio-Economic Aspects			Physical Environment					Bio-physical Environment		Location Aspects				
	Node	Deep MUT (FW-P) (1)	Distance to highways (2)	Real estate value (3)	Urban population density (4)	Geology (5)	Ground water depth (>5m) (6)	Land use (7)	Topography (>1:500) (8)	Utilities (9)	Distance to heritage resources (10)	Distance to vegetation/ trees (11)	Distance to canals (12)	Distance to natural watercourse (13)	Distance to railway lines (14)	Distance to streets (15)	Distance to substations (16)
Initial Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.07507	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.35748	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.56746	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.24288	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.11638	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.05649	0.00000	0.00000	0.32339	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.05410	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.53016	0.00000	1.00000	0.58763	1.00000	0.85714	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.50000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.13766	0.00000	0.18400	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.30809	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.24967	0.00000	0.23183	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.20833	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.09625	0.00000	0.58417	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Weighted Supermatrix	(1)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(2)	0.05038	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(3)	0.23994	0.00000	0.00000	0.75401	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(4)	0.38088	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(5)	0.04307	0.00000	0.00000	0.00000	0.00000	0.14286	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(6)	0.02064	0.00000	0.00000	0.02189	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(7)	0.01002	0.00000	0.00000	0.07955	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(8)	0.00959	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(9)	0.09402	0.00000	0.79303	0.14455	1.00000	0.85714	0.90000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(10)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(11)	0.03688	0.00000	0.00000	0.00000	0.00000	0.00000	0.10000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(12)	0.01070	0.00000	0.03808	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(13)	0.02394	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(14)	0.01940	0.00000	0.04798	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(15)	0.01619	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	(16)	0.00748	0.00000	0.12091	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Limiting Supermatrix	N_i^T	0.000000	0.024770	0.259143	0.187246	0.023210	0.014245	0.019820	0.004717	0.336772	0.018132	0.020114	0.015127	0.011767	0.021970	0.007957	0.035009

Note: N_i stands for any of the 14 nodes involved in the four clusters including; (1) Socio-economic aspects; (2) Physical environment; (3) Bio-physical environment and (4) Location Aspect

APPENDIX H PRIORITY (SUPERMATRIX) WEIGHT TABLES

Table: Priorities (weights) of all elements considered in the network for 'Deep MUT – NSP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.341925)	
Distance to highways	0.015977
Urban Population Density	0.101446
Real Estate Value	0.224502
Physical Environment (0.542537)	
Topography (≥ 1:500)	0.006794
Land use	0.010588
Geology	0.048945
Ground water depth (>5m)	0.071693
Utilities	0.404517
Bio-Physical Environment (0.053262)	
Distance to heritage resources	0.044288
Distance to vegetation/ trees	0.008974
Location Aspects (0.062276)	
Distance to railway lines	0.007550
Distance to streets	0.012816
Distance to canals	0.004979
Distance to substations	0.035898
Distance to natural watercourse	0.001033

Table: Priorities (weights) of all elements considered in the network for 'Flush-fitting MUT – PR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.345978)	
Distance to highways	0.039995
Urban Population Density	0.095232
Real Estate Value	0.210751
Physical Environment (0.532360)	
Topography (≥ 1:500)	0.030165
Land use	0.071231
Geology	0.027186
Ground water depth (>5m)	0.014118
Utilities	0.389660
Bio-Physical Environment (0.060961)	
Distance to heritage resources	0.013014
Distance to vegetation/ trees	0.047947
Location Aspects (0.060700)	
Distance to railway lines	0.003689
Distance to streets	0.012990
Distance to canals	0.013291
Distance to substations	0.029671
Distance to natural watercourse	0.001059

Table: Priorities (weights) of all elements considered in the network for 'Shallow MUT – NSP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.357429)	
Distance to highways	0.018960
Urban Population Density	0.105343
Real Estate Value	0.233126
Physical Environment (0.521816)	
Topography (≥ 1:500)	0.011258
Land use	0.020191
Geology	0.025828
Ground water depth (>5m)	0.043069
Utilities	0.421470
Bio-Physical Environment (0.055874)	
Distance to heritage resources	0.039742
Distance to vegetation/ trees	0.016132
Location Aspects (0.064881)	
Distance to railway lines	0.005282
Distance to streets	0.012659
Distance to canals	0.015798
Distance to substations	0.030248
Distance to natural watercourse	0.000894

Table: Priorities (weights) of all elements considered in the network for 'Shallow MUT – PR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.352969)	
Distance to highways	0.028448
Urban Population Density	0.097290
Real Estate Value	0.227231
Physical Environment (0.527427)	
Topography (≥ 1:500)	0.010036
Land use	0.017912
Geology	0.036329
Ground water depth (>5m)	0.048907
Utilities	0.414243
Bio-Physical Environment (0.055654)	
Distance to heritage resources	0.042476
Distance to vegetation/ trees	0.013178
Location Aspects (0.063952)	
Distance to railway lines	0.005187
Distance to streets	0.013240
Distance to canals	0.021249
Distance to substations	0.023286
Distance to natural watercourse	0.000990

Table: Priorities (weights) of all elements considered in the network for 'Flush-fitting MUT – MF'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.455669)	
Distance to highways	0.037922
Urban Population Density	0.151687
Real Estate Value	0.266060
Physical Environment (0.409826)	
Topography (≥ 1:500)	0.012637
Land use	0.024234
Geology	0.016952
Ground water depth (>5m)	0.019943
Utilities	0.336060
Bio-Physical Environment (0.039933)	
Distance to heritage resources	0.018755
Distance to vegetation/ trees	0.021178
Location Aspects (0.094571)	
Distance to railway lines	0.018914
Distance to streets	0.007901
Distance to canals	0.018914
Distance to substations	0.040941
Distance to natural watercourse	0.007901

Table: Priorities (weights) of all elements considered in the network for 'Deep MUT – PR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.332186)	
Distance to highways	0.020378
Urban Population Density	0.097045
Real Estate Value	0.214763
Physical Environment (0.555564)	
Topography (≥ 1:500)	0.006185
Land use	0.011492
Geology	0.066550
Ground water depth (>5m)	0.081379
Utilities	0.389958
Bio-Physical Environment (0.052218)	
Distance to heritage resources	0.043862
Distance to vegetation/ trees	0.008356
Location Aspects (0.060031)	
Distance to railway lines	0.007294
Distance to streets	0.013124
Distance to canals	0.006012
Distance to substations	0.032458
Distance to natural watercourse	0.001143

Table: Priorities (weights) of all elements considered in the network for 'Shallow MUT – MF'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.451013)	
Distance to highways	0.048695
Urban Population Density	0.146084
Real Estate Value	0.256234
Physical Environment (0.416945)	
Topography (≥ 1:500)	0.009140
Land use	0.020908
Geology	0.036444
Ground water depth (>5m)	0.023345
Utilities	0.327108
Bio-Physical Environment (0.039553)	
Distance to heritage resources	0.018731
Distance to vegetation/ trees	0.020822
Location Aspects (0.092488)	
Distance to railway lines	0.014473
Distance to streets	0.006492
Distance to canals	0.017550
Distance to substations	0.048339
Distance to natural watercourse	0.005634

Table: Priorities (weights) of all elements considered in the network for 'Deep MUT – MF'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.454652)	
Distance to highways	0.030782
Urban Population Density	0.153910
Real Estate Value	0.269960
Physical Environment (0.411662)	
Topography (≥ 1:500)	0.006475
Land use	0.014047
Geology	0.033164
Ground water depth (>5m)	0.017969
Utilities	0.340007
Bio-Physical Environment (0.038618)	
Distance to heritage resources	0.018607
Distance to vegetation/ trees	0.020011
Location Aspects (0.095068)	
Distance to railway lines	0.011996
Distance to streets	0.007199
Distance to canals	0.017463
Distance to substations	0.053491
Distance to natural watercourse	0.004919

Table: Priorities (weights) of all elements considered in the network for 'Shallow MUT – FWR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.383411)	
Distance to highways	0.016154
Urban Population Density	0.162821
Real Estate Value	0.204436
Physical Environment (0.502926)	
Topography (≥ 1:500)	0.013878
Land use	0.022907
Geology	0.017369
Ground water depth (>5m)	0.036612
Utilities	0.412160
Bio-Physical Environment (0.054448)	
Distance to heritage resources	0.038382
Distance to vegetation/ trees	0.016066
Location Aspects (0.059216)	
Distance to railway lines	0.004844
Distance to streets	0.010954
Distance to canals	0.010653
Distance to substations	0.031933
Distance to natural watercourse	0.000832

Table: Priorities (weights) of all elements considered in the network for 'Deep MUT – FWR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.369304)	
Distance to highways	0.013896
Urban Population Density	0.157568
Real Estate Value	0.197840
Physical Environment (0.521774)	
Topography (≥ 1:500)	0.007756
Land use	0.010252
Geology	0.037111
Ground water depth (>5m)	0.068324
Utilities	0.398331
Bio-Physical Environment (0.051772)	
Distance to heritage resources	0.042179
Distance to vegetation/ trees	0.009593
Location Aspects (0.057150)	
Distance to railway lines	0.007673
Distance to streets	0.010765
Distance to canals	0.004200
Distance to substations	0.033420
Distance to natural watercourse	0.001092

Table: Priorities (weights) of all elements considered in the network for 'Flush-fitting MUT – FWR'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.355292)	
Distance to highways	0.017682
Urban Population Density	0.107385
Real Estate Value	0.230225
Physical Environment (0.521484)	
Topography (≥ 1:500)	0.029897
Land use	0.054101
Geology	0.013508
Ground water depth (>5m)	0.010273
Utilities	0.413705
Bio-Physical Environment (0.059131)	
Distance to heritage resources	0.007481
Distance to vegetation/ trees	0.051650
Location Aspects (0.064094)	
Distance to railway lines	0.004183
Distance to streets	0.011198
Distance to canals	0.009025
Distance to substations	0.038825
Distance to natural watercourse	0.000863

Table: Priorities (weights) of all elements considered in the network for 'Flush-fitting MUT – FWP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.481967)	
Distance to highways	0.038610
Urban Population Density	0.202372
Real Estate Value	0.240985
Physical Environment (0.391106)	
Topography (≥ 1:500)	0.010679
Land use	0.027259
Geology	0.012450
Ground water depth (>5m)	0.015527
Utilities	0.325191
Bio-Physical Environment (0.038925)	
Distance to heritage resources	0.009050
Distance to vegetation/ trees	0.029875
Location Aspects (0.088003)	
Distance to railway lines	0.017391
Distance to streets	0.007625
Distance to canals	0.023128
Distance to substations	0.032234
Distance to natural watercourse	0.007625

Table: Priorities (weights) of all elements considered in the network for 'Shallow MUT – FWP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.457523)	
Distance to highways	0.034662
Urban Population Density	0.149356
Real Estate Value	0.273505
Physical Environment (0.406699)	
Topography (≥ 1:500)	0.010590
Land use	0.013409
Geology	0.013439
Ground water depth (>5m)	0.025834
Utilities	0.343427
Bio-Physical Environment (0.039247)	
Distance to heritage resources	0.018953
Distance to vegetation/ trees	0.020294
Location Aspects (0.096531)	
Distance to railway lines	0.011220
Distance to streets	0.008699
Distance to canals	0.015840
Distance to substations	0.055536
Distance to natural watercourse	0.005236

Table: Priorities (weights) of all elements considered in the network for 'Deep MUT – FWP'

Elements of the network	Normalised priorities
Socio-Economic Aspects (0.471159)	
Distance to highways	0.024770
Urban Population Density	0.187246
Real Estate Value	0.259143
Physical Environment (0.398764)	
Topography (≥ 1:500)	0.004717
Land use	0.019820
Geology	0.023210
Ground water depth (>5m)	0.014245
Utilities	0.336772
Bio-Physical Environment (0.038246)	
Distance to heritage resources	0.018132
Distance to vegetation/ trees	0.020114
Location Aspects (0.091830)	
Distance to railway lines	0.021970
Distance to streets	0.007957
Distance to canals	0.015127
Distance to substations	0.035009
Distance to natural watercourse	0.011767

APPENDIX I FLUSH-FITTING MUT SCENARIO ANALYSES RESULTS

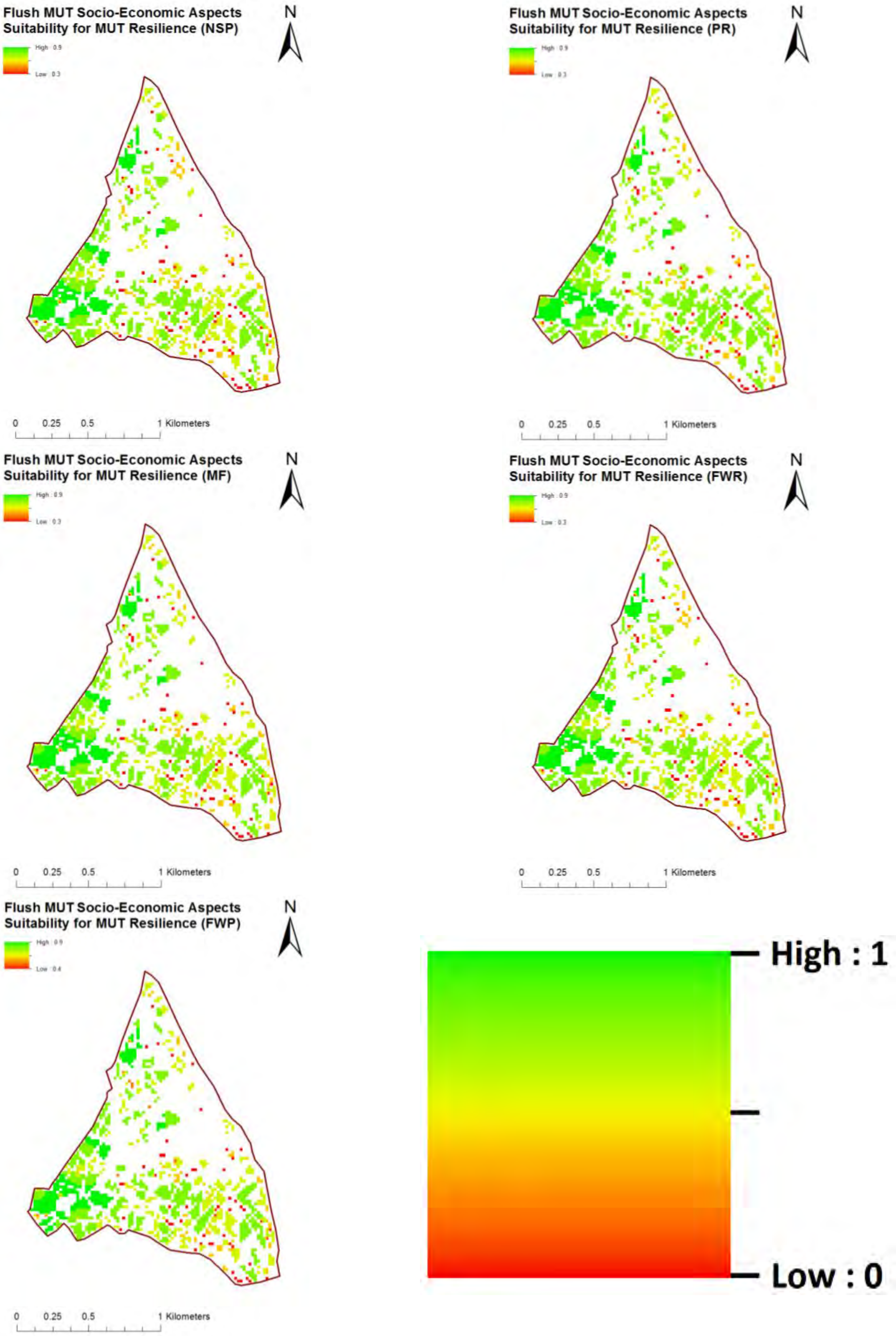


Figure: Derived scenario resilience maps of physical environment for flush-fitting MUT under different future scenarios

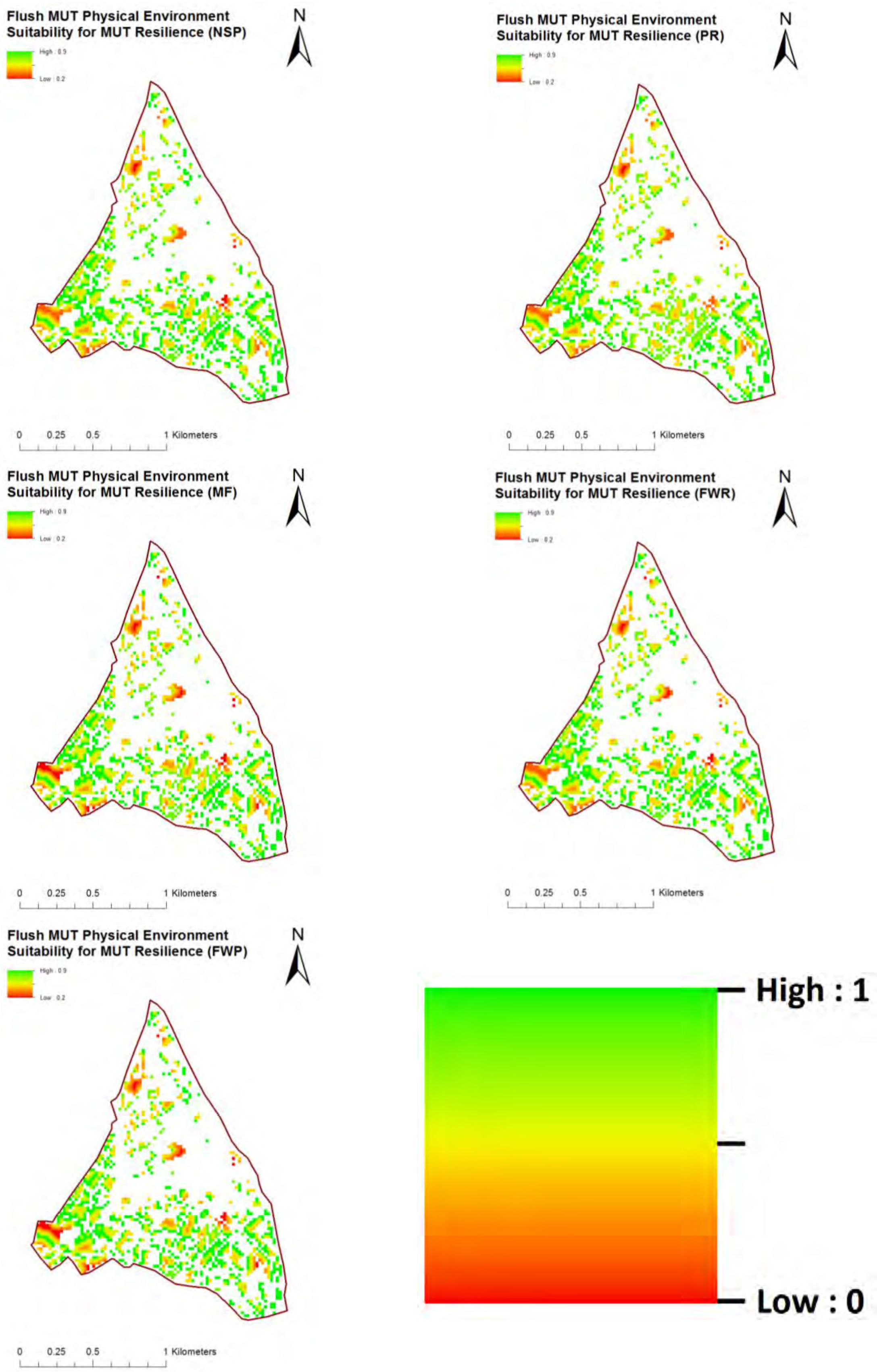


Figure: Derived scenario resilience maps of physical environment for flush-fitting MUT under different future scenarios

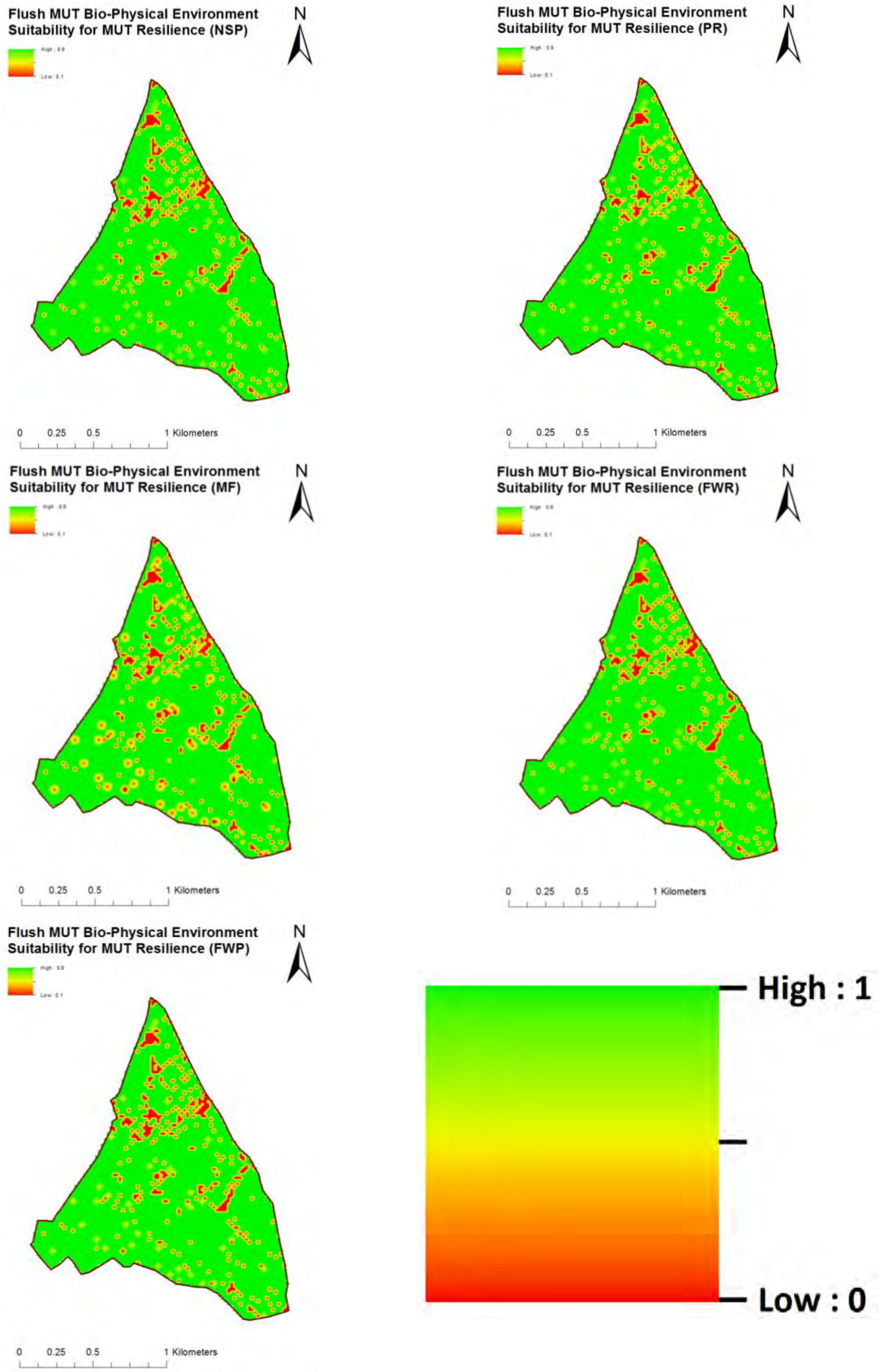


Figure: Derived scenario resilience maps of bio-physical environment for flush-fitting MUT under different future scenarios

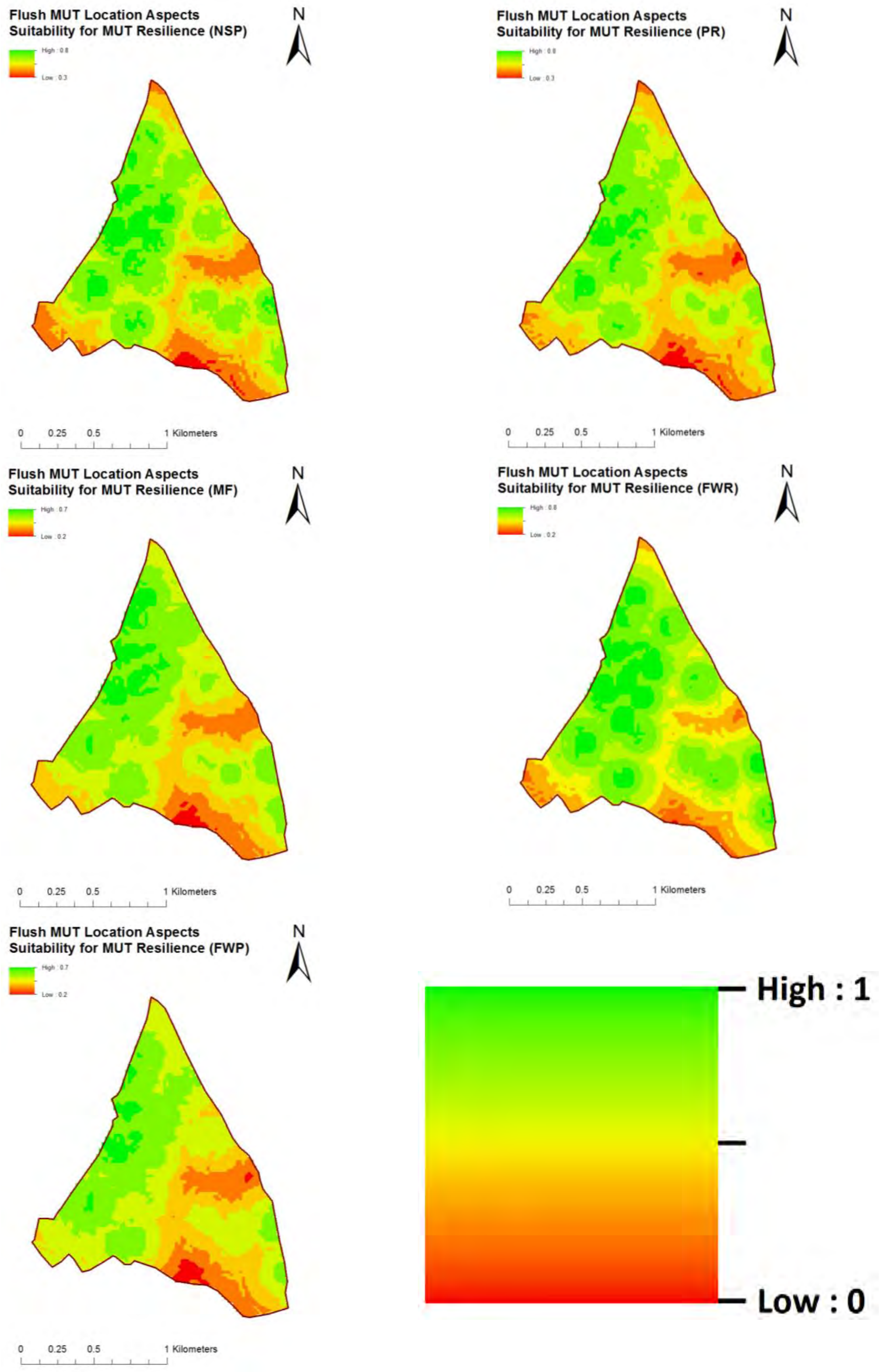


Figure: Derived scenario resilience maps of location aspects for flush-fitting MUT under different future scenarios

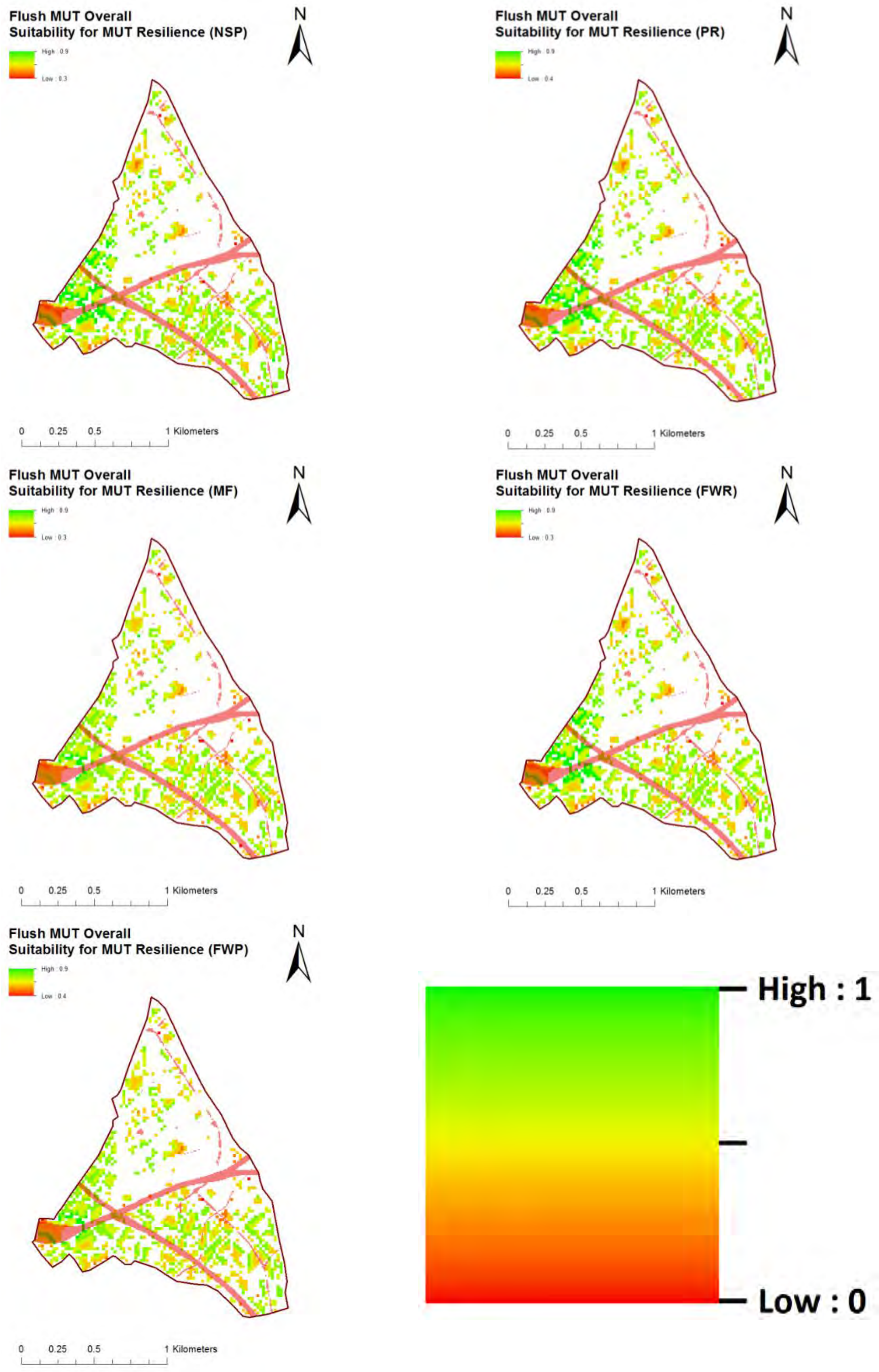


Figure: Derived scenario resilience maps of overall resilience suitability for flush-fitting MUT under different future scenarios

APPENDIX J SHALLOW MUT SCENARIO ANALYSES RESULTS

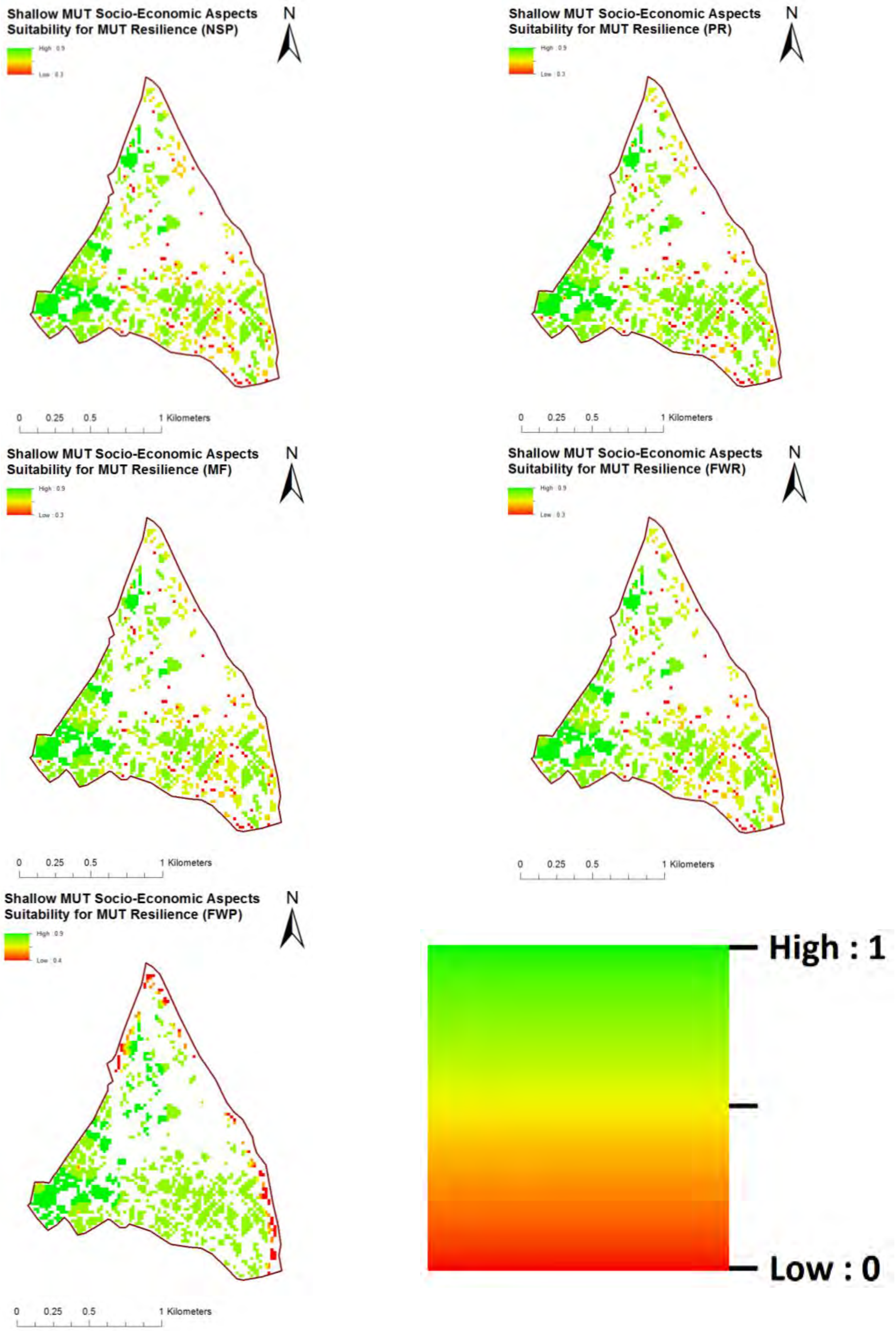


Figure: Derived scenario resilience maps of socio-economic aspects for shallow MUT under different future scenarios

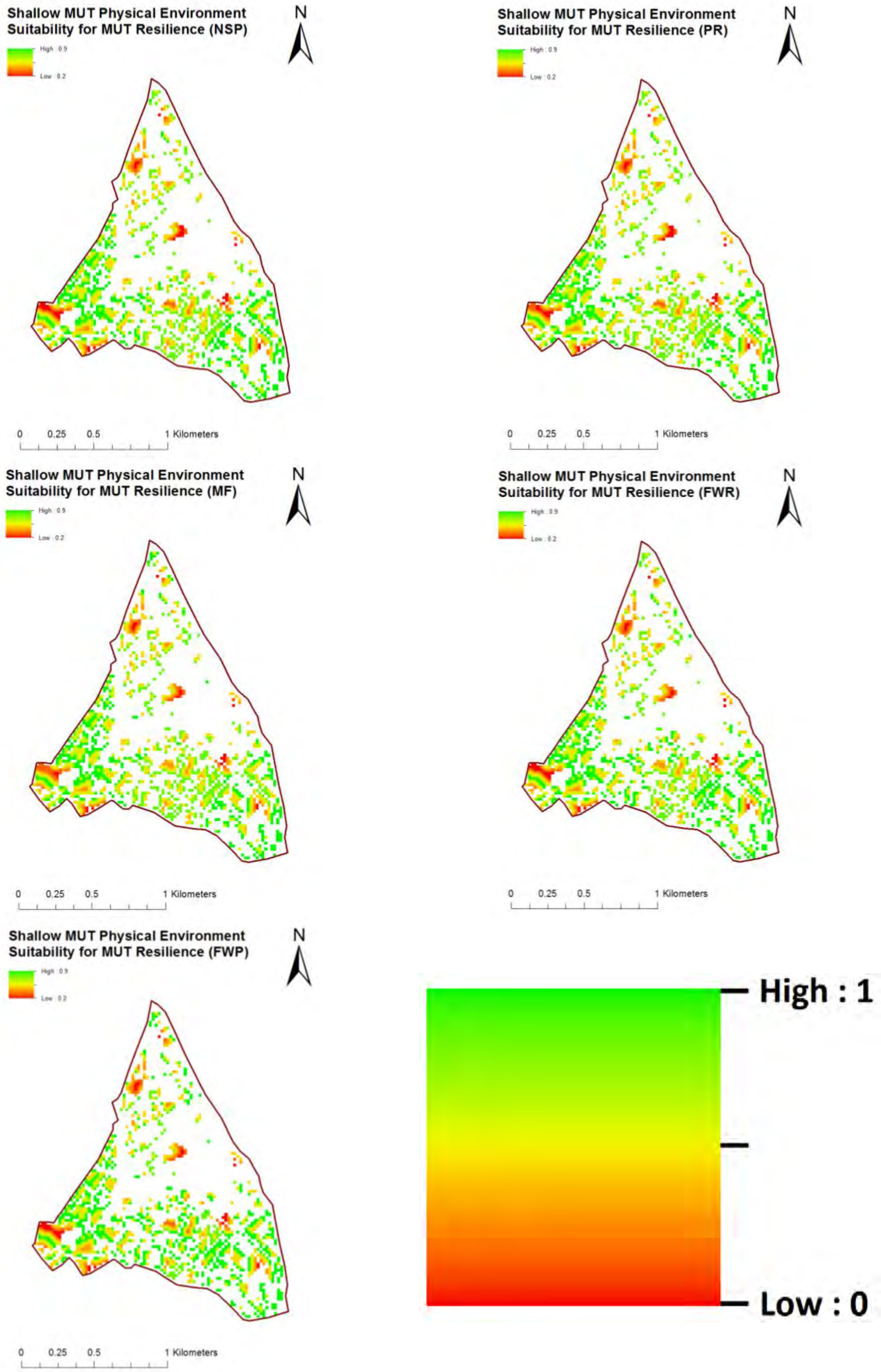


Figure: Derived scenario resilience maps of physical environment for shallow MUT under different future scenarios

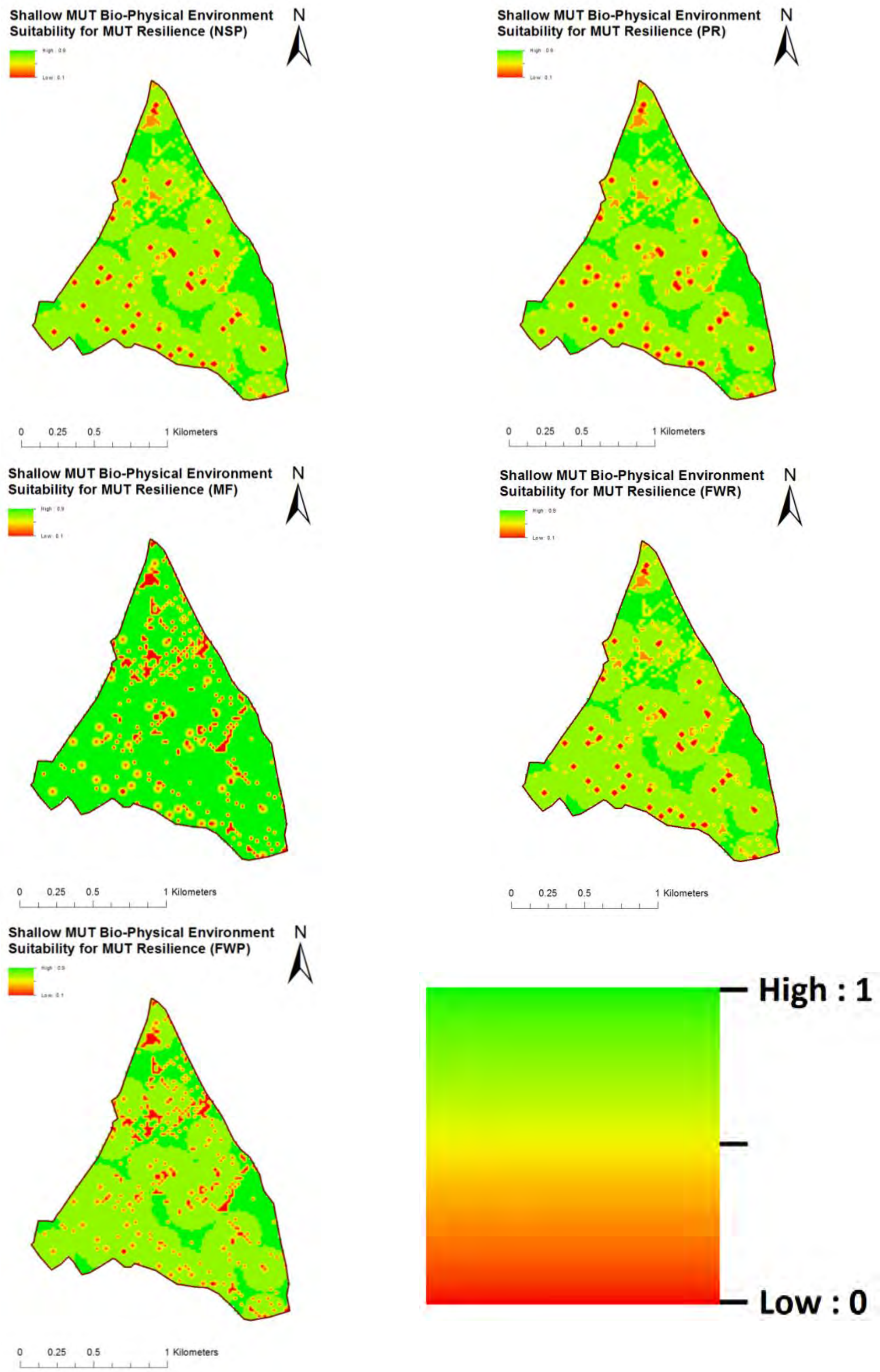


Figure: Derived scenario resilience maps of bio-physical environment for shallow MUT under different future scenarios

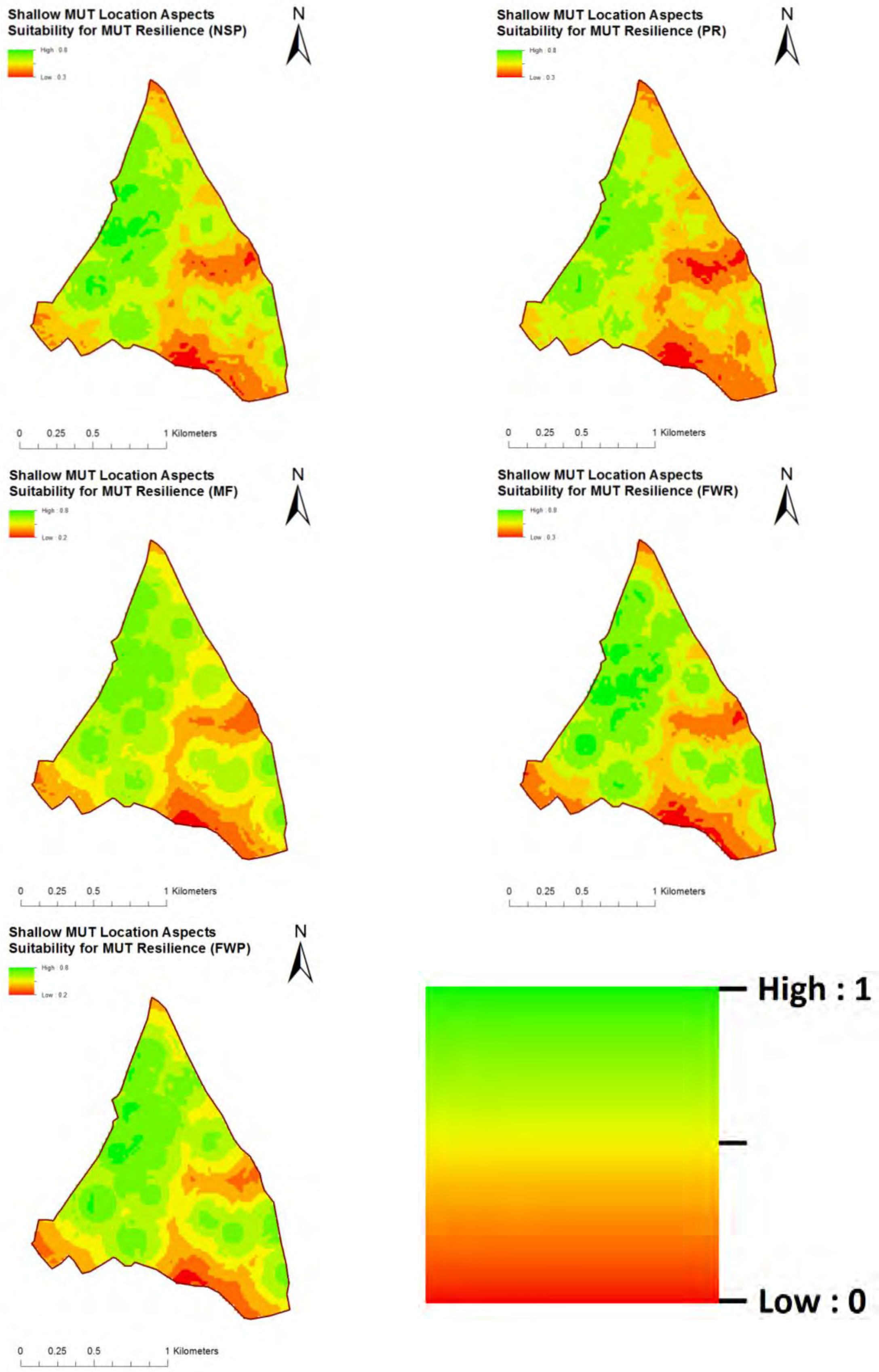


Figure: Derived scenario resilience maps of location aspects for shallow MUT under different future scenarios

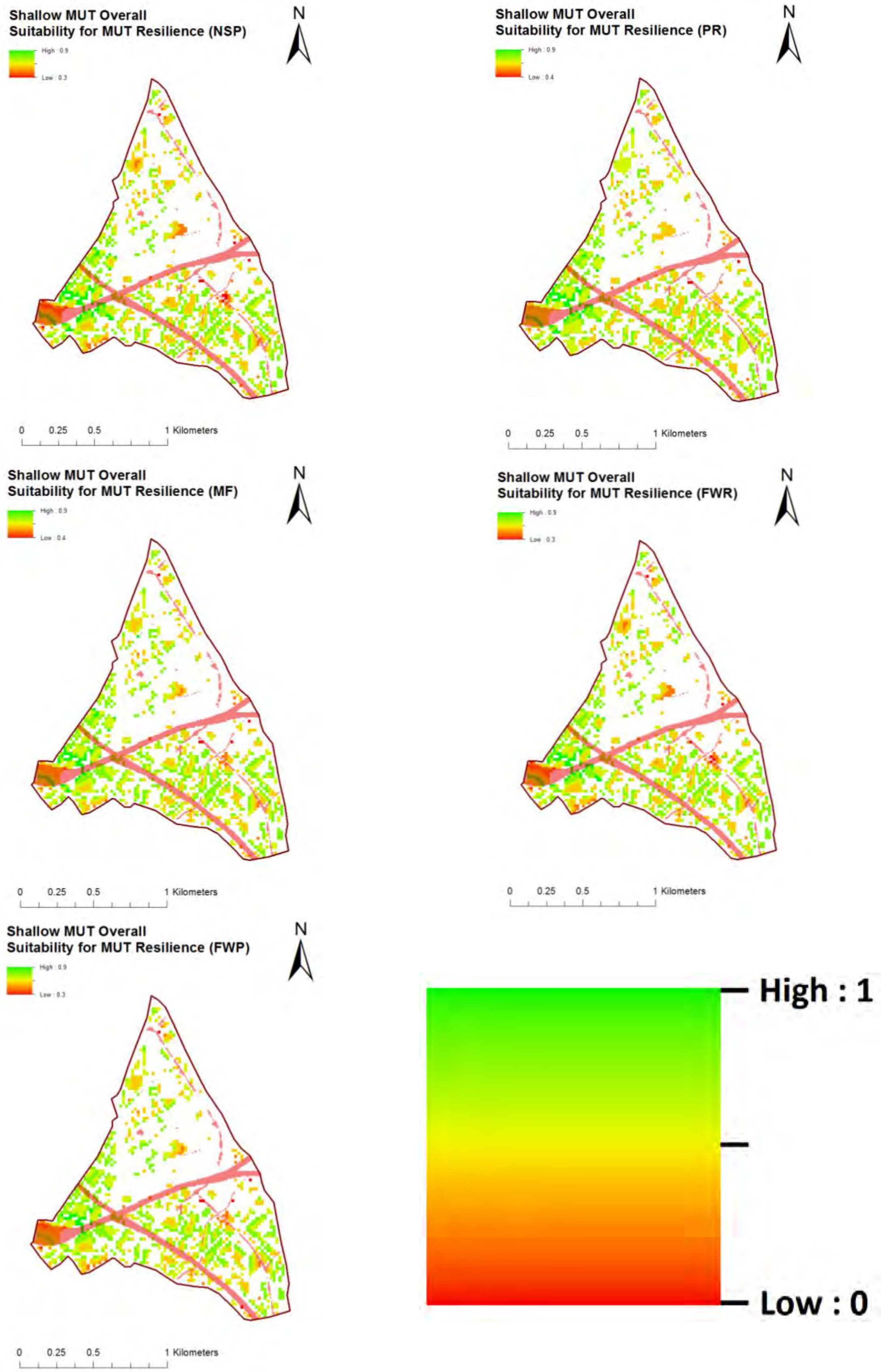


Figure: Derived scenario resilience maps of overall resilience suitability for shallow MUT under different future scenarios

APPENDIX K DEEP MUT SCENARIO ANALYSES RESULTS

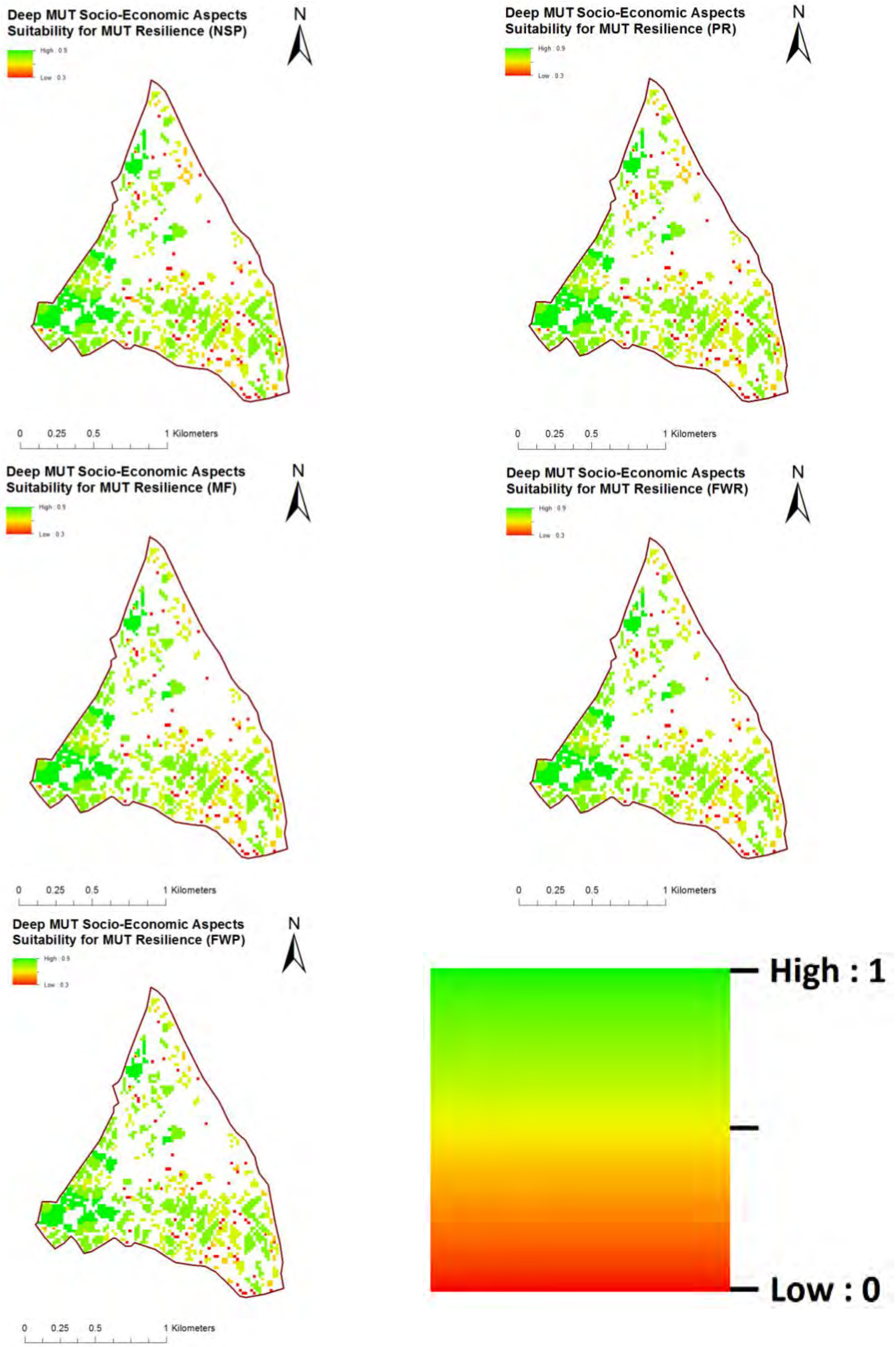


Figure: Derived scenario resilience maps of socio-economic aspects for deep MUT under different future scenarios

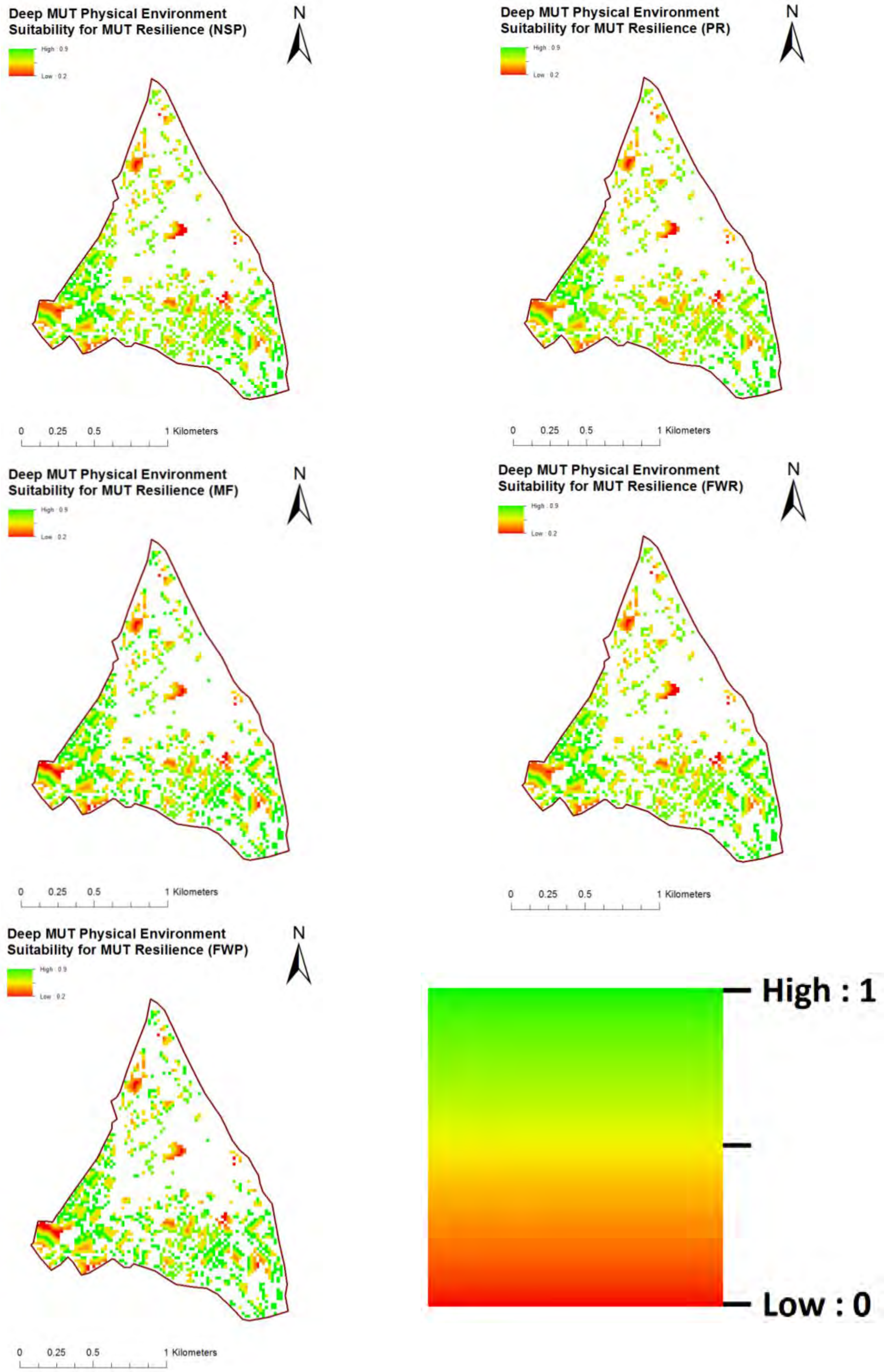


Figure: Derived scenario resilience maps of physical environment for deep MUT under different future scenarios

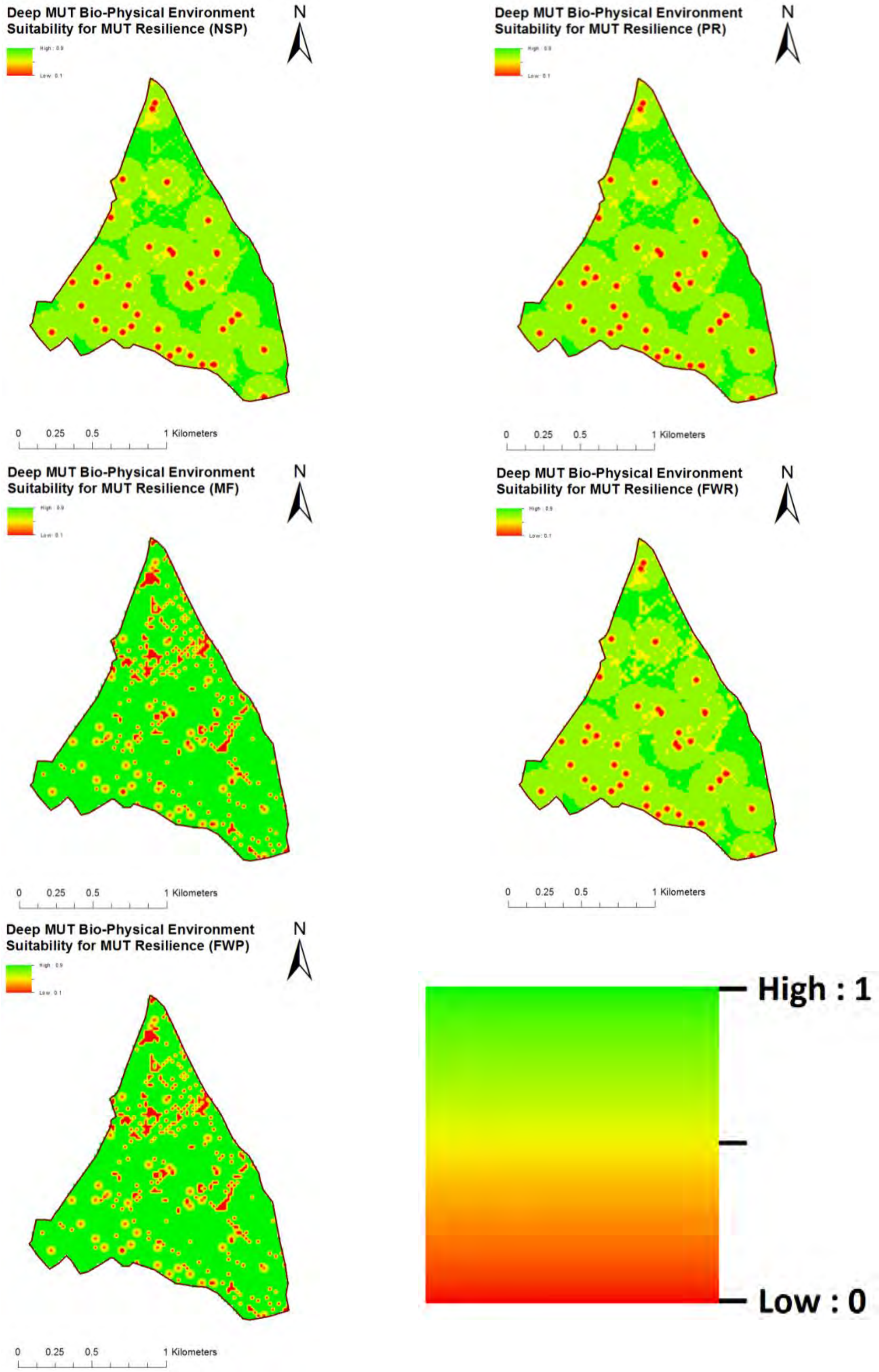


Figure: Derived scenario resilience maps of bio-physical environment for deep MUT under different future scenarios

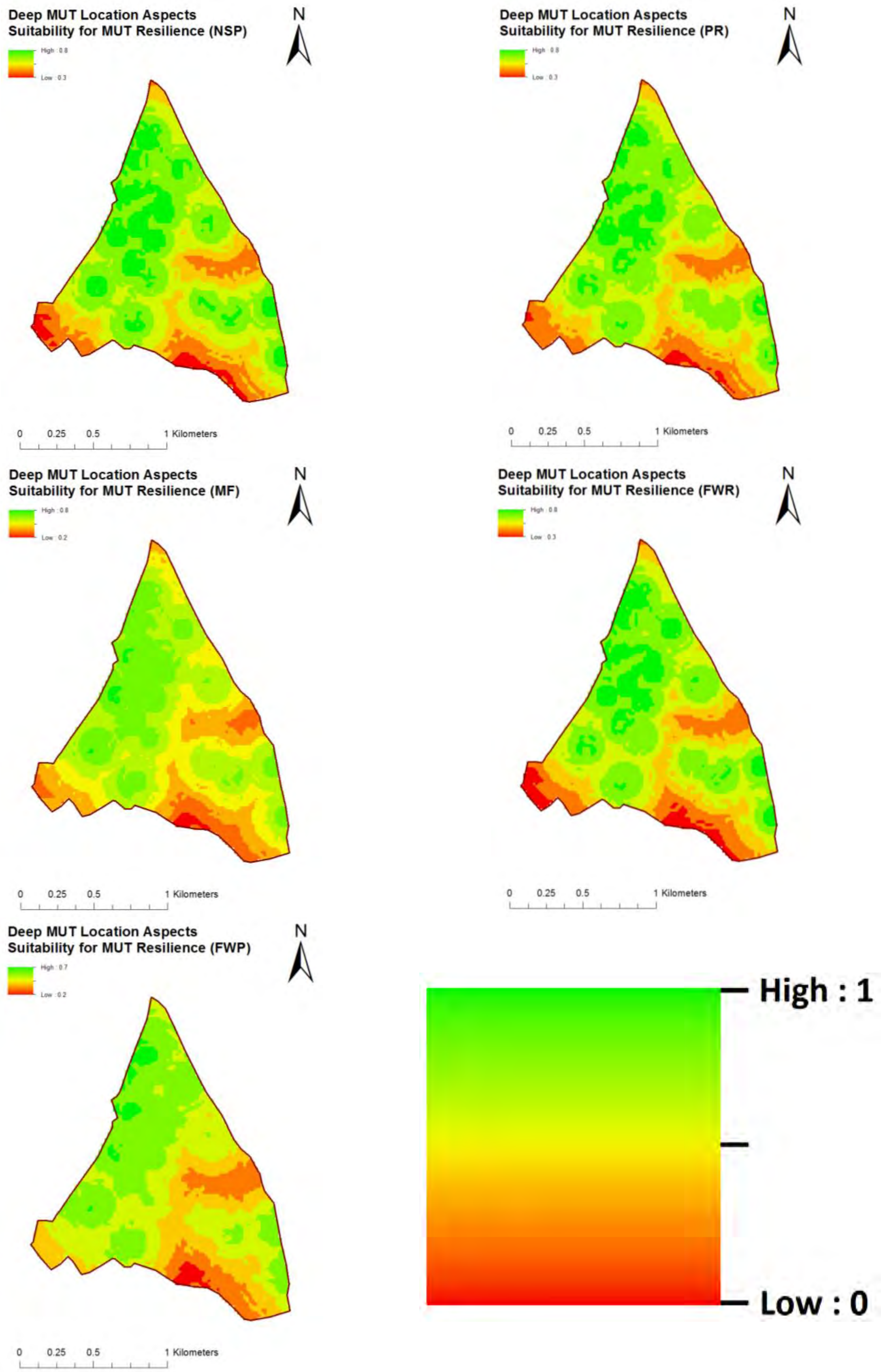


Figure: Derived scenario resilience maps of location aspects for deep MUT under different future scenarios

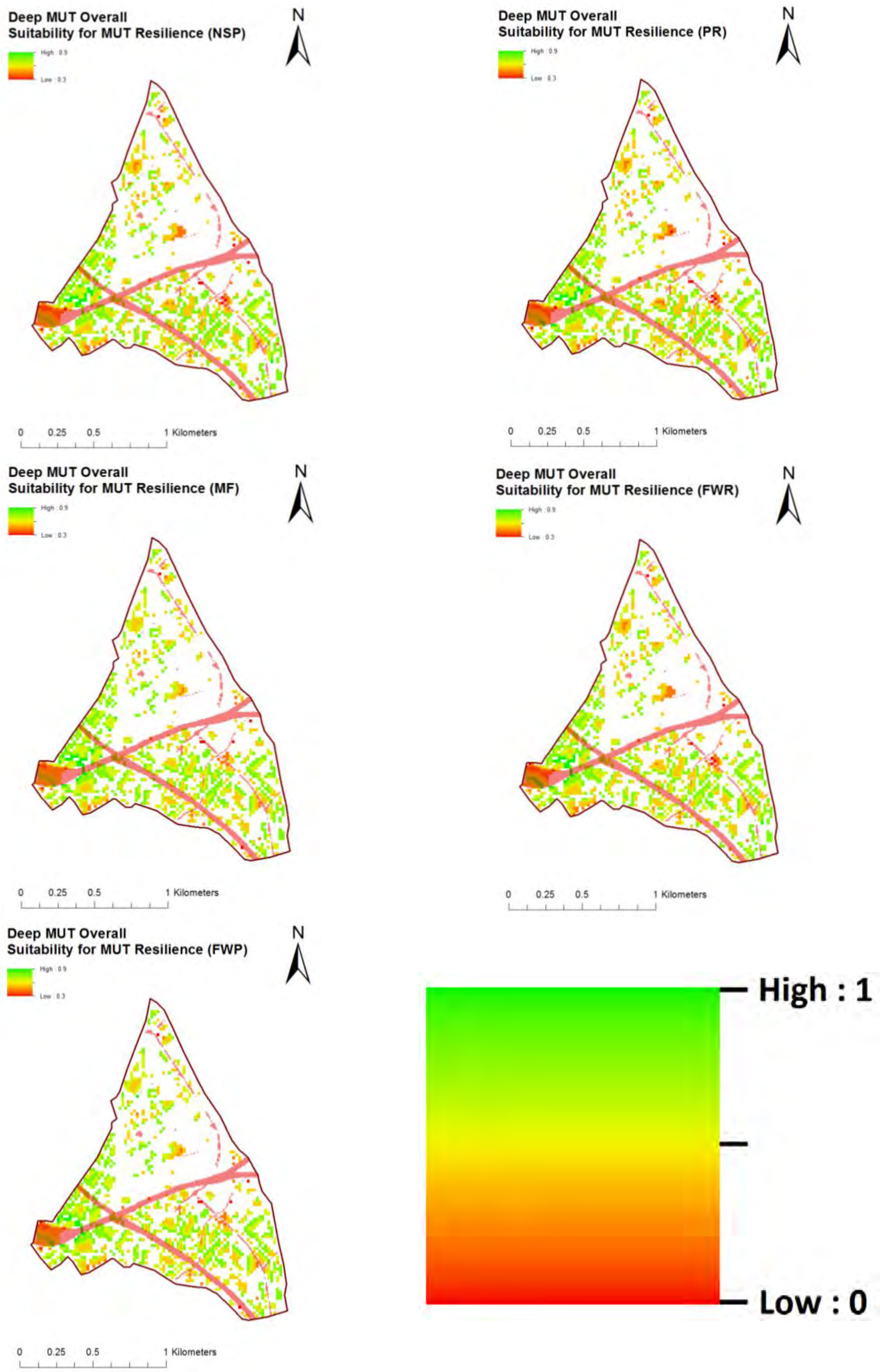


Figure: Derived scenario resilience maps of overall resilience suitability for deep MUT under different future scenarios