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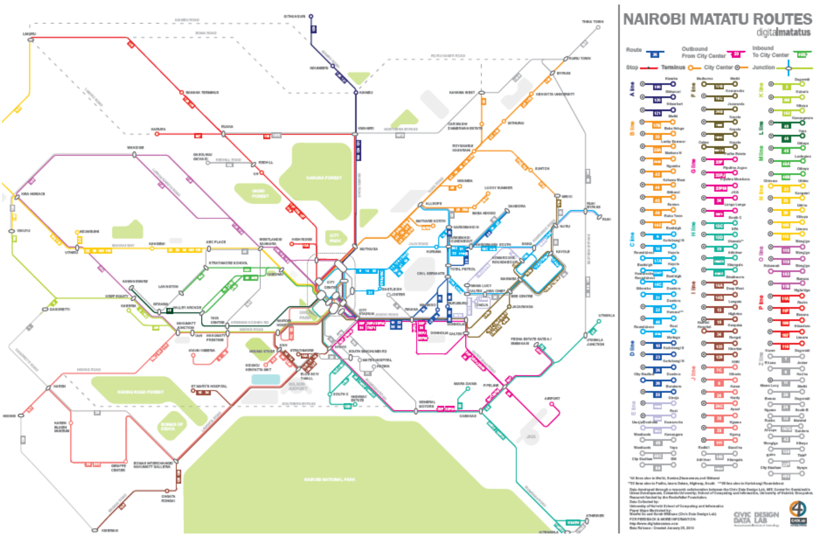
Opportunities for geological modelling and integrated modelling within the ODA Resilience of Asian Cities project

Engineering Geology Directorate

Internal Report OR/17/018



BRITISH GEOLOGICAL SURVEY

ENGINEERING Geology DIRECTORATE

INTERNAL REPORT OR/17/018

Opportunities for geological modelling and integrated modelling within the ODA Resilience of Asian Cities project

A G Hughes, H Kessler, B Wood

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London tube style map of Nairobi's Matatu mini-bus taxi system

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Summary

This report describes the scoping of potential work associated with the BGS ODA Asian Cities and improving their resilience programme. It is aimed at understanding how geological and integrated modelling can address problems identified to improve the resilience of Asian Cities, particularly in India, Malaysia and Vietnam. A series of activities are proposed over a three-year period. These include developing the BGS Groundhog to be applicable to Asian Cities, creating an Asian City Environmental Observatory and applying tools and techniques which can quantify resource flows around cities. Use of integrated modelling to understand the interactions and feedbacks between natural events and the built environment are also proposed. These activities all have to be undertaken with the appropriate stakeholders and seek their approval.

1 Introduction

Over the next three years BGS is aligning more of its funding to Official Development Assistance (ODA) related projects. BGS plans to undertake three strands of ODA work: Global Risk, Resource Management in East Africa and Resilience of Asian Cities. This report concerns itself with the latter: Resilience of Asian Cities and specifically how both geological modelling and integrated modelling can be used to solve problems in Asian Megacities. Whilst both are relatively sophisticated approaches, many problems can solved with simpler approaches. There is a scalability in approach from simple calculations through to "all-singing all-dancing" integrated modelling. The most important consideration is that of quantification using appropriate techniques matching the resources available (data, staff, understanding) so that problems can be tackled successfully.

Cities survive and prosper by being resilient and being able to withstand threats that are either acute, e.g. Floods or Earthquakes or chronic, e.g. growing populations or reducing availability of water resources due to climate change. The threats should be able to be translated into questions that need to be addressed and suitable approaches identified to provide a quantifiable answer to these threats to enable the city to improve its resilience.

The aim of the report will be to examine the opportunities, their relevance to BGS and the gaps. Note that the gaps will be assessed to see if they are tractable, i.e. within the ODA programmes (~1 year) or require much more effort and external funding, e.g. GCRF bid (3-5 year project). The proposed activities will sit within the three year BGS ODA programme; the first year is predominantly about scoping / stakeholder elicitation but with some science activities. Further linkages with external organisations, e.g. Open Geospatial Consortium (OGC) need to be considered.

The report is split into four further sections: geological and integrated modelling and its use in cities; stakeholder needs; gaps identified and finally proposed activities and timing.

2 Geological and integrated modelling and its use in cities

2.1 GEOLOGICAL MODELLING AND INTERPRETATION

Geological framework models are 3D representations of the distribution and orientation of the subsurface geological formations. Such models are now established as the basic foundation for any urban geoscience project. They often act as the central hub or framework for the integration of other urban datasets or models, such as buildings, infrastructure, geotechnical data or groundwater models. 3D geological models are also commonly used as inputs to numerical models, such as groundwater models and heat flow models, as they provide the necessary stratigraphic boundary constraints for geologically realistic simulations. A range of 3D geological modelling approaches are available and these fall into two broad categories (1) explicit and (2) implicit.

(1) Explicit techniques generally allow the geologist to manually control the shape the 3D model by inputting available data, digitizing, gridding and re-iterating. A widespread methodology is to interpret the terrain (DTM), the geology exposed at surface (geological map) and any subsurface data (such as boreholes, trial pits and geophysical data) using a network of cross-sections. Explicit techniques are relatively labour intensive, but permit greater control by the geologist. They allow conceptual models to be built with very sparse data and generally have a lower technical and financial entry barrier.

(2) Implicit techniques apply mathematical functions to all available input data to generate a 3D output. Different routines may be applied depending on the availability and quality of the input data. Examples include stochastic simulation of geological deposits, and fitting of shapes to input data and structural measurements (geological trends) using mathematical techniques such as radial basis functions. Implicit models are quicker to produce and more statistically robust as uncertainty metadata is often a by-product of the modelling routine. However, they require complex and often expensive proprietary software, expert operatives and a reasonable coverage and quality of input data to produce meaningful results.

Most geological modelling projects, especially where data is highly variable, involve significant data collation and interpretation work prior to the final 3D computation stage. This can take various forms. As urban areas are subject to continuous re-development and expansion (both laterally and increasingly vertically) new data and information about the composition of the subsurface are becoming available frequently. This might be in the form of new borehole or excavation records, which may be paper based or digital, or increasingly remotely sensed measurements of properties such as water levels. Therefore, besides specialist 3D modelling software, general-purpose software combined with simple geo-data handling software can yield significant benefits at relatively little cost. Such solutions allow the geologist or engineer to visualize, filter, interpret and digitize the baseline data. A suite of low and no-cost tools are available for this type of work and include spreadsheet and database applications (e.g. Libre Office), GIS applications (e.g. QGIS) and more specialized geological interpretation applications (e.g. Groundhog Desktop).

BGS Groundhog Desktop (desktop geoscientific information system) is an example of a free-to-use graphical software tool that is tailored to geological data, and which can serve as a simple data and model integration platform. Groundhog Desktop was developed by the BGS for the display and creation of geological and geospatial information such as interpreted (correlated) geological cross sections, maps and boreholes – it therefore performs the important first integration step in the creation of an integrated subsurface model – data can be exported for 3D calculation and visualisation in other free software such as QGIS or commercial packages such as ESRI, GeoVisionary and CAD, or by using proprietary 3D geo-modelling packages.

2.2 WHAT IS INTEGRATED MODELLING?

The basic vision for integrated modelling is to "develop hardware and software so that deceptively simple questions can be answered using models which can be linked and the results displayed in the appropriate form with an assessment of uncertainty"

Integrated modelling is a relatively recent discipline and aims to facilitate the solution of complex problems by joining models from a range of different sources together (Laniak et al., 2013). At its purest it is taking a model code making it linkable and then allowing the scientist or other end-user to answer their question by joining together models in a bespoke combination (Barkwith, Pachocka, Watson, & Hughes, 2014). The aim is to develop methods so that questions can be answered that are more complex than can currently be addressed using single instance models.

At its heart, integrated modelling is about converting a question into a workflow and providing a quantified solution. This involves combining data and models such that the solution can be obtained. The model can be thought of a unit operation (Figure 1) and be seen as having two facets: model codes which solve the governing equations and model instances which is the application of the model code to a particular area or problem. By considering a model as a unit operation and defining the input and output data such that the output form one model code can be passed to another then a linked series of models can be created, a workflow and the question be addressed.

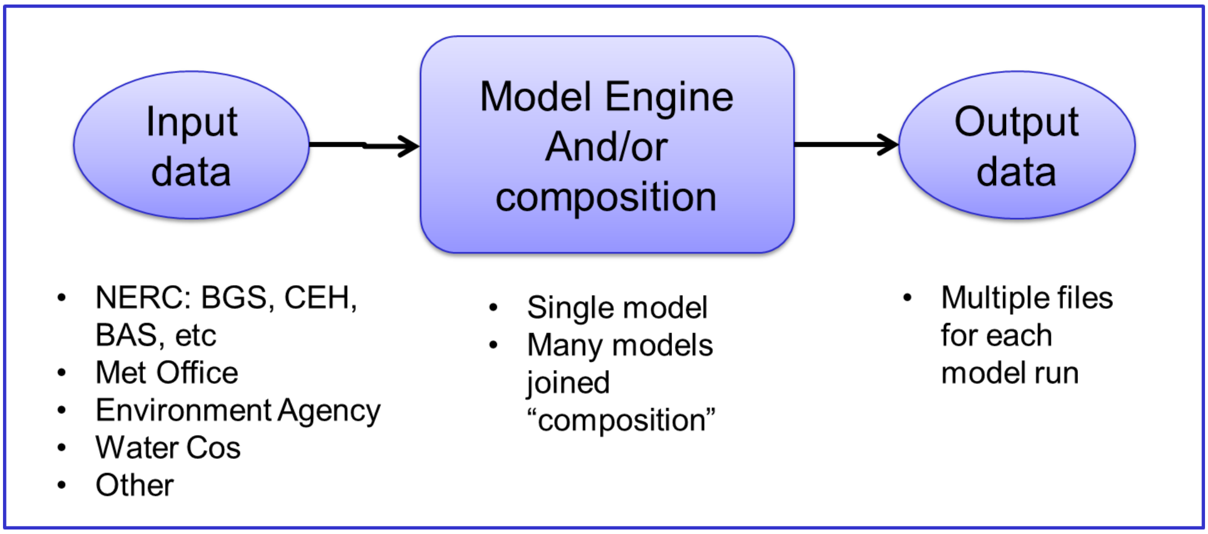

Figure 1. Model as a "unit operation"

To achieve model integration various elements have to be in place, particularly the models themselves need to be:

- Described and made available – metadata catalogues have to exist with access to a way of running the model; this includes documenting the model code development process and the underlying physics / maths and the assumptions made (Harpham & Danovaro, 2015)
- Made linkable – either by using well described file formats or runtime coupling, e.g. OpenMI (Harpham, Cleverley, & Kelly, 2014) or CSDMS (Peckham, Hutton, & Norris, 2013)
- Linkages between models described properly – e.g. semantics / ontologies, so that different disciplines can recognise the same variable even if its described differently (Nativi, Mazzetti, & Geller, 2013)
- Computational resources made available – does it need to run in the cloud and be made available via Web Services (Castronova, Goodall, & Elag, 2013)
- Uncertainty properly evaluated for the model chain – e.g. UncertWeb (Bastin et al., 2013)

- Results visualised appropriately, e.g. summaries for decision-makers or full datasets for scientists / higher level users.

2.3 SMART CITIES AND MODELLING DATA

Given the recent efforts put into smart cities and the infrastructure associated with their development it was felt that this was a subject area that could be explored to determine what efforts have been made in integrated modelling in urban environments. Asia does have a very strong smart cities movement. There are many and various smart cities: South Korea (Songdo), Singapore, Masdar City UAE to name but a few. Songdo is an example of a bespoke smart city built from the ground up on reclaimed land 65 km west of Seoul and Singapore is classed as a smart nation given its status of an island state.

These examples are mainly ICT driven and do not necessarily include modelling of any description. However there is a growing movement for "predictive analytics" which build on data availability, i.e. Open Data movement and availability of code and tools to produce useful predictions. Examples have been found for Chicago where predictive analytics have been used to determine where health inspectors should focus their visits for restaurant hygiene inspections.

A couple of interesting views on smart cities in Asia, firstly regarding sensors:

"Sensors with sophisticated control systems can work in cities such as Melbourne or London or Sydney, but 90 percent of people in cities don't live in cool, temperate climates -- they live near the equator and there, most of this smart tech does not apply," says Gerhard Schmitt of ETH Zurich. "These cities can be smart, but the innovations need to be affordable and useable." http://www.wired.co.uk/article/smart-city-planning-permission

Examples of data use and data analytics using Chicago and Nairobi are provided in more detail below.

2.3.1 Chicago city

Chicago City Mayor Emanuel, elected in 2011, made it one of his priorities to make Chicago City's data open and provide it via an open data portal. This proved successful and a number of initiatives have been undertaken to utilise this infrastructure. One example was the development of a script to understand what factors could determine failures in restaurant inspections using predictive analytics– i.e. prediction: ttps://chicago.github.io/food-inspections-evaluation/. The aim was to prioritise visits by health inspectors by ranking fast food outlets in order of likelihood of non-compliance with food hygiene regulations.

The decision was made to use an open approach for both the data and the tools developed to undertake the predictions. The choice of the code was R and the finished project (code, data and documents) has been published on GitHub. The end result was a R script which produced graphical and tabular output, but no interface was produced. The aim was to make the process as open and transparent as possible as well as encouraging users not originally involved in the project to build on the approach.

2.3.2 Nairobi city

One of the common methods of transport in Nairobi is a Matatu or minibus taxi which follow fixed routes. The tracking of these vehicles using student volunteers by GPS enabled a route map to be generated. Open source tools was used to serve out the data and a range of apps have been built on the data – including the open source traffic data platform: www.ma3route.com. Whilst modelling as such hasn't been undertaken on the data it has been used for further analysis. Traffic calming measures using oil drums to close off certain junctions have been assessed using data gleaned by this open approach. The Nairobi example shows how limited resources can be used to build useful outputs.

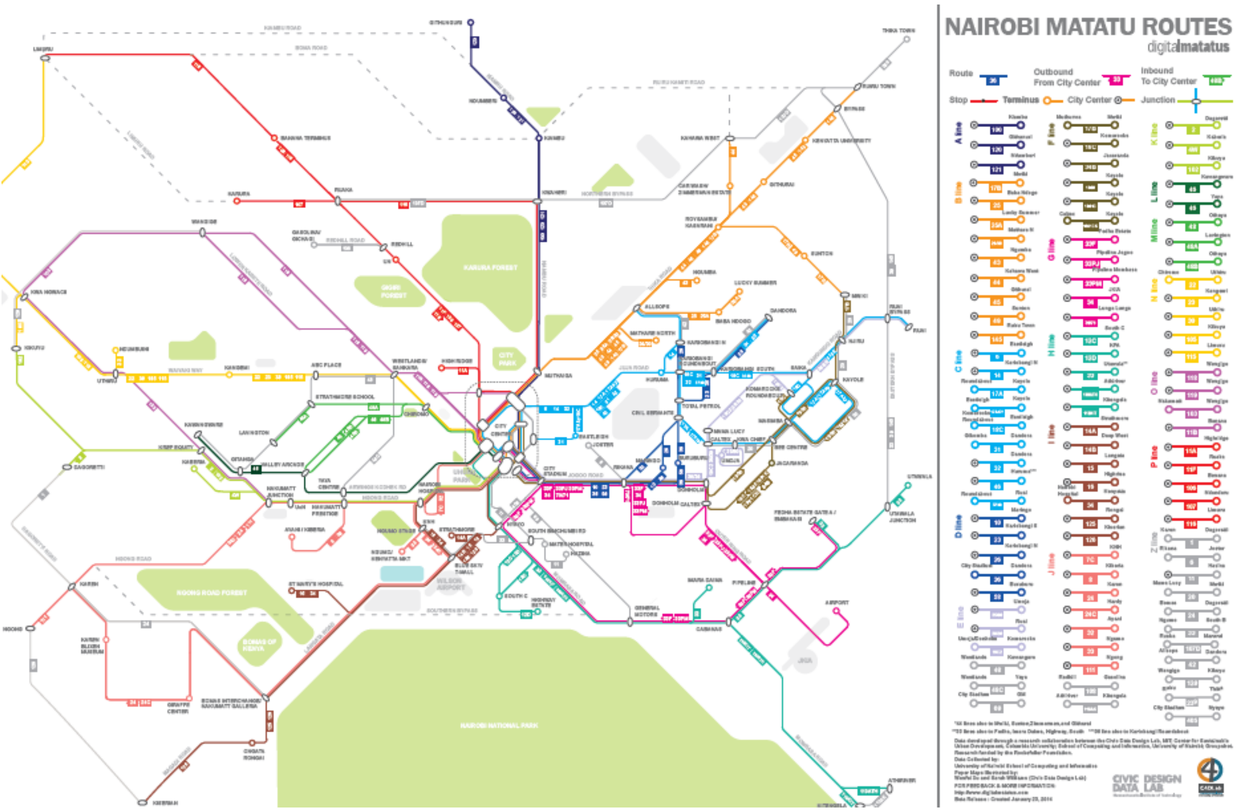

Figure 2. London tube map style Matatu routes, Nairobi (source: digital matatus www.digitalmatatus.com/map.html).

3 Stakeholder needs and identification of issues

3.1 INTRODUCTION

The identification of stakeholder needs has been undertaken using a number of different sources:

- Meeting notes from BGS "fact-finding" mission to Kuala Lumpur in autumn 2016 and India and Vietnam in January 2017.
- Literature searches using the keywords: integrated, model and city / urban along with each country / city (India, Malaysia or Vietnam) name
- Background knowledge of the smart city / Integrated modelling subject
- Using the results of other ODA Asian Cities initiatives undertaken in FY 16/17

The findings have been summarised both generically and on a country basis below.

Whilst the three Asian countries and key cities within have been chosen, Singapore is considered as a Smart nation and is part of BGS' overseas initiatives. The lessons learnt working in such an environment with excellent sensors, along with involved and well-informed stakeholders and tractable sub-surface problems, particularly in the novel use of underground space could be usefully transferred to the ODA Asian Cities project.

3.2 GENERIC ASIAN CITY ISSUES

Rapid industrialisation has resulted in a number of issues which are not necessarily unique to Asian cities (Taniguchi, Burnett, & Ness, 2008). The drive to accommodate people and business and the ready availability of technology to build upwards, i.e. steel frame buildings has resulted in cities based around skyscrapers. This has also put pressure on the sub-surface both in terms of weight of buildings but in terms of focussing on its use once land for building them has been exhausted, i.e Singapore. This rapid urbanisation has led to uncontrolled abstraction of groundwater leading to drop in piezometric surface and subsidence. Modern cities tend to be coastal and so this has resulted in the degradation of habitats, e.g. Mangrove swamps (Malaysia and Vietnam) and over-abstraction resulting in saline intrusion into aquifers.

The rise in population has put pressure on water supply and sanitation systems which can result in disease outbreaks, particularly in poorer areas and those without effective sanitation. However modern chemicals have also been finding their way into drinking water in terms of both industrial chemicals and lifestyle compounds, i.e. caffeine. A younger, growing population has resulted in poorer gender balance which can lead to social problems in some parts of Asia. In other parts then the population is aging which provides its own challenges, such as need for suitable housing.

Heat and heat island effects with the subsurface storing heat and the lack of natural circulation during high temperature episodes, can lead to increased mortality. Traffic and mobility problems result in the increase in air pollution and in particular combined with canyon effects, i.e. tall buildings limiting air flow, to reduce air quality resulting in health impacts.

All these problems can also interact which makes their quantification challenging.

3.2.1 City Resilience

It is acknowledged that understanding the stocks and flows of the resources that helps a city survive / prosper / increase resilience need to be understood and quantified. This is recognised by100 Resilient Cities in their City Resilience Index (CRI) (The Rockefeller Foundation & Arup, 2014). This espouses that a discussion of resilience is required within a framework and the realisation that this needs to be addressed. This could offer a generic framework for working in cities. Examples of features relevant to this work includes:

- Actively engaged citizens

- Comprehensive hazard and exposure mapping
- Effective stewardship of ecosystems
- Retained spare capacity
- Comprehensive hazard monitoring and risk assessment
- Widespread community awareness and preparedness
- Comprehensive city monitoring and data management.

By addressing these issues using integrated modelling then the city resilience can be improved.

3.3 MALAYSIA

The fact finding mission (autumn 2016) which included visits to FCO, meetings as part of Newton-IUK Kuala Lumpur hazards project, Geological Survey, University of Nottingham Malaysia campus and consultants. The main findings are as follows:

- Groundwater is an untapped resource; karst aquifers and their management
- Development of shallow underground space is being considered
- Flood mitigation and water storage during droughts
- Water balance problem is not well resolved
- Pollution of groundwater waters: Disused mines and source apportionment
- Crops for the Future (CFF) programme
- Changing rainfall patterns, e.g. Monsoon
- Managed Aquifer Recharge (MAR) / Aquifer Storage and Recovery (ASR) is being considered
- Re-use of abandoned mines for aquaculture
- Transport – air quality and health
- Urban heat island effect

The results of searches undertaken in the peer-reviewed literature suggest that whilst there are limited integrated modelling projects undertaken in Malaysia, (Pradhan & Youssef, 2011) however flooding and groundwater resources are significant issues.

3.4 INDIA

The BGS fact finding mission, during which BGS staff attended the Future Cities workshop in Kolkata and various other meetings including Indian Institute Technology, High Commission and the GSI.

- Smart city movement – how to properly engage?
- Modelling of a future city with sparse data
- Solid waste disposal and the sub-surface: options, pollution, etc
- Himalayan Climate Change and sea level rise in the Bay of Bengal on city resilience

In general, India has a highly developed scientific infrastructure with world-leading researchers and a burgeoning smart city movement providing a high technical base on which to build.

Searching the peer-reviewed literature as well as using the experience of colleagues working in India suggests that there is a strong cross-disciplinary approach. One example is that of socio-hydrology, a concept developed by (Gober & Wheater, 2014) which aims to quantify flows and stocks in the human modified water cycle at different temporal and spatial scales. This approach is gaining currency in India via the work of (Srinivasan, Seto, Emerson, & Gorelick, 2013) who have applied it to the urbanised water cycle in Chennai. This offers a promising way of quantifying the impact of human activities on the water cycle and requires an integrated approach.

3.5 VIETNAM

The BGS fact-finding mission visited Hanoi and met with the GS (VIGMR) and the issues were summarised as follows:

- Lots of data – how to deal with?
- Karst aquifers – already being investigated: German and USGS
- Underground transport infrastructure and its development
- Sustainable drainage
- Other issues include: geothermal, water supply, subsidence due to groundwater abstraction, tectonics and energy supply

The work on Climate Resilient Cities The Rockefeller Foundation & Arup (2014) has identified a number of issues for Vietnam and Hanoi: Sea level rise, flooding, solid waste disposal, urbanisation and loss of natural flood management. Seawater intrusion into aquifers is another sub-surface issue which could be a problem in the future.

Integrated studies have been undertaken in Vietnam a typical example has investigated flood and urban growth and its interaction, (Huong & Pathirana, 2013). This study simulated urban growth, weather model and urban drainage by separate models and then using the outputs of one to drive the other. It showed that urban growth could affect micro-climates which in turn impacts on flood response.

4 Gaps identified and opportunities

4.1 GENERIC

There are a number of issues which beset Asian Cities and are echoed within Malaysia, India and Vietnam urban areas. Common themes include:

- Resources: too much, e.g. flooding, too little, e.g. droughts / water scarcity
- Mobility and pollution, particularly with respect to increased car ownership
- City growth and land use / cover change and how this is managed
- Use of underground space: groundwater, heat, voids
- Environmental pollution either by polluting activities or by secondary effects, i.e. groundwater abstraction leading to saline intrusion
- Climate change and its impact on rainfall amounts, duration and intensity and temperature as well as accelerating sea level rise

4.2 MALAYSIA

The main question derived from the stakeholder meetings are:

- Groundwater and catchment functioning including pollution movement
- Use of groundwater to mitigate lack of supply, e.g. MAR / ASR; how do changing rainfall patterns affect the supply system
- Flood mitigation by use of underground space, the "Dutch" example
- Health living in cities: Transport, heat and health

However, others identified in the literature include: Flooding (Pradhan & Youssef, 2011), land use change (Huong & Pathirana, 2013) and air pollution (Azid et al., 2014). There does seems to be a low base from which to start with and underpinning basic quantification of groundwater processes: recharge / water balance / regional modelling might be a good place to start. However flooding is of significant concern and trying to balance storage for water supply with flood mitigation might be a useful start.

4.3 INDIA

Like most countries who have experienced rapid growth then India suffers from the food – energy – water nexus. How does it feed its people whilst providing supply for drinking, irrigation and industrial purposes and ensure energy is provide for all its population and that it has a secure supply? These are problematic to solve using single instance modelling and require an integrated solution.

Alongside this, problems are centred round the treatment of solid waste. This could be developed into a use case along the lines of "How can solid waste be managed successfully and the sub-surface protected from pollution?"

It is suggested that the situation in India is ripe for more advanced approach of a City Environmental Observatory that combines data and models to answer key questions. This could build on experience of the York City Environmental Observatory / Chicago Open Data Platform approach. However, this relies on open data movement which is limited to the UK / Europe /North America. The issue may be whether data is available and can it be shared?

4.4 VIETNAM

The country appears to the subject of a large number of studies and geological data, at least, appears to be available. The issues identified show the following as being important in Vietnamese cities (World Bank, 2009):

- Climate: rainfall and temperature
- Sea level rise
- Runoff
- River hydraulics
- Solid waste
- Subsidence
- Urban development and growth and rural / urban land use
- Urban Heat Island effect and rainfall

All these issues are subject to interactions and feedbacks which makes for a useful applications of integrated modelling.

Following on from the example of Nairobi, basic provision of data in a suitable form, possibly using Smart phones if there use is widespread could be useful. The major cities in Vietnam, e.g. Hanoi or Ho Chi Min City could be ripe for leapfrogging / transfer of approach. An App for mobility / traffic could be highly useful.

5 Summary and conclusions

This report has summarised the likely stakeholder needs for the ODA Asian Cities "platform". It has summarised the current stakeholder needs, the gaps identified in the research landscape and proposed a number of projects that could fill these gaps.

Whilst these stakeholder needs are those currently identified, it will be necessary to undertake further workshops to clarify their requirements. This should be undertaken as soon as feasibly possible.

There are significant gaps in integrated modelling within a city environment as well as opportunities to understand these complex systems. It is proposed that a study to fully understand what models exist and, importantly, are available be undertaken. Multi-stressor analysis in Malaysia as well as fully understanding interactions of the natural and built environment in controlling the water environment are necessary.

Other project which are beyond the likely level of funding by the BGS ODA budget are developing systems to allow model integration building on smart cities initiatives. These should be pursued by identifying suitable funding calls.

BGS geological modelling expertise as well as system currently available to deliver them can be built upon to provide suitable products for provision of geological information to support the resilience of Asian cities.

There is no doubt that this area is set to grow as more people move to cities and resources are required to meet city dwellers' needs.

References

Azid, A., Juahir, H., Toriman, M. E., Kamarudin, M. K. A., Saudi, A. S. M., Hasnam, C. N. C., . . . Yamin, M. (2014). Prediction of the Level of Air Pollution Using Principal Component Analysis and Artificial Neural Network Techniques: a Case Study in Malaysia. *Water, Air, & Soil Pollution, 225*(8). doi:10.1007/s11270-014-2063-1

Barkwith, A. K. A. P., Pachocka, M., Watson, C., & Hughes, A. G. (2014). Couplers for linking environmental models: scoping study and potential next steps.

Bastin, L., Cornford, D., Jones, R., Heuvelink, G. B. M., Pebesma, E., Stasch, C., . . . Williams, M. (2013). Managing uncertainty in integrated environmental modelling: The UncertWeb framework. *Environmental Modelling & Software, 39*, 116-134. doi:https://doi.org/10.1016/j.envsoft.2012.02.008

Castronova, A. M., Goodall, J. L., & Elag, M. M. (2013). Models as web services using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard. *Environmental Modelling & Software, 41*, 72-83. doi:https://doi.org/10.1016/j.envsoft.2012.11.010

Gober, P., & Wheater, H. S. (2014). Socio-hydrology and the science–policy interface: a case study of the Saskatchewan River basin. *Hydrology and Earth System Sciences, 18*(4), 1413-1422. doi:10.5194/hess-18-1413-2014

Harpham, Q., Cleverley, P., & Kelly, D. (2014). The FluidEarth 2 implementation of OpenMI 2.0. *Journal of Hydroinformatics, 16*(4), 890-906. doi:10.2166/hydro.2013.190

Harpham, Q., & Danovaro, E. (2015). Towards standard metadata to support models and interfaces in a hydro-meteorological model chain. *Journal of Hydroinformatics, 17*(2), 260-274. doi:10.2166/hydro.2014.061

Huong, H. T. L., & Pathirana, A. (2013). Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences, 17*(1), 379-394. doi:10.5194/hess-17-379-2013

Laniak, G. F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., . . . Hughes, A. (2013). Integrated environmental modeling: A vision and roadmap for the future. *Environmental Modelling & Software, 39*, 3-23. doi:10.1016/j.envsoft.2012.09.006

Nativi, S., Mazzetti, P., & Geller, G. N. (2013). Environmental model access and interoperability: The GEO Model Web initiative. *Environmental Modelling & Software, 39*, 214-228. doi:https://doi.org/10.1016/j.envsoft.2012.03.007

Peckham, S. D., Hutton, E. W. H., & Norris, B. (2013). A component-based approach to integrated modeling in the geosciences: The design of CSDMS. *Computers & Geosciences, 53*, 3-12. doi:https://doi.org/10.1016/j.cageo.2012.04.002

Pradhan, B., & Youssef, A. M. (2011). A 100-year maximum flood susceptibility mapping using integrated hydrological and hydrodynamic models: Kelantan River Corridor, Malaysia. *Journal of Flood Risk Management, 4*(3), 189-202. doi:10.1111/j.1753-318X.2011.01103.x

Srinivasan, V., Seto, K. C., Emerson, R., & Gorelick, S. M. (2013). The impact of urbanization on water vulnerability: A coupled human–environment system approach for Chennai, India. *Global Environmental Change, 23*(1), 229-239. doi:10.1016/j.gloenvcha.2012.10.002

Taniguchi, M., Burnett, W. C., & Ness, G. D. (2008). Integrated research on subsurface environments in Asian urban areas. *Science of the Total Environment, 404*(2-3), 377-392. doi:10.1016/j.scitotenv.2008.04.033

The Rockefeller Foundation & Arup. (2014). City Resilience Index: Understanding and measuring city resilience.

World Bank. (2009). Climate resileint Cities - A primer on reducing vulnerability (Hanoi, Vietnam).