Land Use Policy 69 (2017) 618–630

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Accounting for groundwater in future city visions

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ARTICLE INFO

Keywords:
Groundwater
Future cities
Visions
Urban
Scenarios

ABSTRACT

City planners, urban innovators and researchers are increasingly working on 'future city' initiatives to investigate the physical, social and political aspects of harmonized urban living. Despite this, sustainability principles and the importance of urban groundwater are lacking in future city visions. Using London as a case study, the importance of groundwater for cities is highlighted and a range of future city interventions may impact on groundwater are reviewed. Using data from water resource plans and city planning strategies, changes in the groundwater balance which may occur as a result of city interventions are calculated for two future city scenarios: a 'strategic' future informed by organisational policy and an 'aspirational' future guided by sustainability principles. For London, under a strategic future, preferential investment in industry-scale technologies such as wastewater treatment and groundwater storage would occur. Acknowledgement that behaviour change offers the potential for a faster rate of transformation than innovation technologies is ignored. The capacity of community-led action and smart-home technologies to deliver sustainable water use under an aspirational future is evident, with a measurable impact on urban groundwater. These methods may be used to inform city interventions that consider the social context in addition to environmental constraints and business drivers.

1. Introduction

As urban populations continue to dominate globally, city planners, urban innovators and researchers are increasingly working on joint initiatives to investigate the physical, technological, social and political aspects of harmonized urban living. The aim is to create cities which perform well, that are, prosperous, sustainable, resilient, and liveable. Whilst significant attention is given to smart city information technologies, data and innovation products, the broader city initiatives tend towards 'future city' concepts where knowledge dissemination, cooperation, policy reform and urban design run in parallel with big data and smart technologies (Rogers et al., 2012; Angelidou, 2015). Despite this broader approach to future city thinking John et al. (2015), in their review of 92 urban visions across 13 countries, found that sustainability principles were poorly covered and that no city fully integrated all of the defined sustainability principles (i.e. relating to built form; ecosystems services; resource consumption and production; social and cultural practice; governance, and; city-catchment systems) within their vision. In the context of a sustainable urban future, the vision may be defined as a desirable society, which provides permanent prosperity within biophysical constraints and in a manner that is fair and equitable now and in the future (Costanza, 2000). A city foresight exercise, undertaken by the UK Government Office for Science, aims to gather science evidence in support of policy decisions to inform the analysis, design and transformative actions needed to shape the UK's urban future (GO-Science, 2016). Adopting a trans-disciplinary approach, the foresight exercise considers urban economies, metabolism, form, infrastructure, governance, and city living. At a time when sustainability principles need promoting in city visions, inclusion of urban metabolism is critical. Originally proposed by Wolman (1965) urban metabolism may be defined as the inflow and outflow transactions required to sustain city functions, or the production, consumption and disposal of resources (Huang and Hsu, 2003). In this way the biophysical demand to sustain urban society is evaluated. Linking urban metabolism concepts with future city programmes brings another dimension to urban performance metrics by making the connection between the city and its resource support area, commonly referred to as its hinterland (Lee et al., 2016). Here, there is an acknowledgment that, in terms of resource demand, the city cannot sustain itself using only materials within the city limits and additional resources must be imported; and it follows that the by-products, or waste, arising from city metabolism are also disposed of beyond the city boundary. Strongly aligned with urban metabolism principles is the ecosystem services approach adopted by UK National Ecosystem Assessment (2014) through the Natural Capital Asset Check. Here the ecosystem services (stocks and flows) provided by the natural environment within the city and its hinterland are

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http://dx.doi.org/10.1016/j.landusepol.2017.09.018
Received 29 March 2017; Received in revised form 4 July 2017; Accepted 12 September 2017
Available online 20 September 2017

Table 1
Anthropogenic interventions in the urban water cycle (recharge, through flow and discharge).

	Human intervention	Potential impact
Recharge		
Evaporation	Climatic warming allows more moisture to be held in the atmosphere.	Increased rainfall and increased intensity of individual rainfall events.
	Hard surfacing (anthropogenic aquitards) and reduced vegetative cover.	Potential reduction and redistribution of effective porosity. Reductions in the potential for evapo-transpiration.
	Funnelling of wind through high storey developments.	Increased evaporation.
Run-off	Hard surfacing (anthropogenic aquitards).	Increased run-off and reduced baseflow to surface water courses; potential to mobilize more sediment; water arrives more quickly increasing the potential for contaminant mobilisation. The reduced run-off times and base flow result in greater flashiness of surface water courses. Layers of hard surfacing, e.g. palimpsests of development may result in multiple levels of perched water.
Recharge	Hard surfacing	Reduction in natural groundwater recharge: exacerbated by silt and sediment clogging; local increases in recharge associated with pipe leakage, and anthropogenic aquifers (e.g. gravel packs to services).
	Made Ground	Increase in near surface storage, particularly in areas underlain by low permeability lithologies.
	Quarrying	Local increases in the extent of bare ground available for recharge.
	Urban development	Leakage from pipes; irrigation water (parks and recreation areas); potential for groundwater level rise beneath urban environments. Granular bedding materials form anthropogenic aquifers.
Freshwater/saline interface	Dewatering	In coastal environments dewatering and lowering of the groundwater table may lead to saline intrusion.
Through-flow and storage		
	Water as a resource.	Lowering of groundwater table and changes to geochemistry, increased depth of unsaturated zone. Increased hydraulic gradients, potential to mobilize contaminants to greater depth. Potable supply can result in cross-catchment transfer of water. The introduction of artificial storage (e.g. reservoir storage to maintain water supply) removes groundwater from aquifers. Overuse may result in derogation of supply.
	Dewatering	In coastal environments dewatering and lowering of the groundwater table may lead to saline intrusion.
	Culverting of watercourses in unconfined aquifers.	Water culverted to allow access across watercourses; may affect recharge processes; potential impact on quality (reduced oxygenation).
	Geothermal energy.	Changes to ground temperature with potential impacts on evapo-transpiration
	Deep construction, e.g. underground tunnels, reservoir construction, landfill.	Compartmentalisation of water; a more irregular water table, and time of vadose zone recharge lengthened by obstacles to flow.
	Discharges, e.g. soakaways.	Ponding of water may alter flow paths.
	Moving water through the unsaturated zone more quickly as a result of underground development and physical disturbance to the ground.	May result in a change to groundwater chemistry, e.g. negative saturation indices move to greater depth in the aquifer, resulting in changes to baseline water chemistry; dry fallout moved deeper into the aquifer.
Discharge		
	Industrial discharge to surface watercourses, e.g. process and mine water, contaminated drainage from industrial units.	Changes to water quality and temperature impacts on ecology.
	Use of abstraction wells.	Alters flow to natural discharge points.

evaluated. However in their review of sustainability in city visions, John et al. (2015) conclude that the visions which are led by city representatives emphasize the functioning of the built environment within the city limits only, and the relationship with the hinterland is weak. Furthermore, they argue that this leads to a reduction in city resilience as experts on the hinterland are not represented and therefore not involved in the design of solutions.

Water supply and disposal form two critical components of the city's metabolism that become more acute as cities grow (Wolman,1965; Jones, 1966), particularly as ecosystem service demand and consumption of resource per capita are outpacing population growth (John et al., 2015). In recent decades the rate of demand for water has been twice the rate of population growth and, under a business-as-usual climate scenario, a 40% global water deficit is predicted by 2030 (UN-WWAP, 2015). As traditional water sources become depleted there is an expectation that cities will need to exploit their hinterlands to broaden their water supply catchment area, utilize marginal water resources and invest in innovation solutions and more advanced technologies to manipulate the natural water systems. The internal city processes that facilitate the supply, consumption and disposal of resources disturb natural systems and alter the urban environment and morphology (Huang and Hsu, 2003). Disturbance of the natural water environment in urban areas and pressure on the ecosystem services it provides is likely to become more pronounced where the physical expansion of cities is occurring at a faster rate than population growth (Sterling et al., 2012; Hunt et al., 2016). As a result inclusion of water within urban metabolism and future cities assessment is common (Rojas-Torres et al., 2014), but explicit consideration of urban groundwater systems is not, which is symptomatic of the fact that ecosystem services provided by urban underground space are not yet appreciated by most city representatives (Hunt et al., 2016).

It is estimated that half of the world's megacities are groundwater-dependent and over 40% of water supply across much of Europe comes from aquifers lying beneath urbanized areas (Wolf et al., 2006). Additionally, groundwater resources in urban areas do not just extend to water for domestic and industrial supply but also to ground source heating. For example, in London it is estimated that 19% of the city's total heat demand (2010) could be derived from ground heat sources (GLA, 2013). The interaction of groundwater with other urban systems, such as infrastructure and surface water networks is well-recognized by expert practitioners and is increasingly on the city agenda, for example in consideration of baseflow provision to urban and peri-urban rivers (blue networks), flood risk, management of blue-green infrastructure (e.g. sustainable drainage systems), adverse effects on underground infrastructure, control of underground construction, and impacts of industrial legacy on water quality. These different examples highlight the range of urban groundwater processes that operate at different temporal and spatial scales and across the rural-urban transition. Here we consider the factors that affect the groundwater cycle in urban environments where the interaction between the anthropogenic and natural environment causes not only physical alteration to the ground but also a change in natural capital stocks, disturbance to natural flows and shifts in natural boundary conditions.

Using London, the UK's megacity as a case study, the complexity of groundwater systems in urban and peri-urban environments is illustrated. A semi-quantitative water balance method is used to highlight a number of physical, social and political interactions between the natural environment and anthropogenic activity and to account for changes to the groundwater system that may arise as a result of future city interventions. Insights into urban water management to underpin plausible and scientifically-informed city visions and interventions are provided.

2. Urban-groundwater systems

Conceptually, urban groundwater accounting should follow the path of the water cycle, which essentially comprises a system of recharge or replenishment by rainwater through the unsaturated zone; storage and through-flow within underground voids (fractures and pores in the subsurface geology), and; discharge or abstraction via springs, rivers or boreholes. Using this approach, consideration can be given to the constituent elements of urban development that intervene in the natural water cycle, thereby impacting the quality and quantity of the resource (Table 1). Rates of water movement are also fundamental to water accounting in terms of both water quantity and water quality. Therefore one also needs to establish: [1] resource catchment boundary conditions in terms of recharge and base-level (the level to which groundwater flows, e.g. the main river of outlet at the sea) and [2] physical material properties such as porosity and permeability (the underground voids and their degree of connectivity).

The key components of urbanisation that impact on boundary conditions (points of recharge, discharge or barriers to flow) are: alteration of groundwater tables as a consequence of resource exploitation, dewatering for construction, quarrying and industry and leakage from urban water transport systems or tunnel drainage. Where these effects are measurable at a regional scale they are monitored through groundwater level monitoring, e.g. by environmental regulators and by resource suppliers such as Thames Water Utilities Ltd (TWUL) in London. Mathematical modelling in conjunction with geospatial analysis can be used to evaluate these impacts and their sensitivity, e.g. the conceptual model presented for Bucharest, Romania, by Boukhemacha et al. (2015) or Jones et al. (2012).

The physical properties of urban groundwater systems are altered by a range of anthropogenic interventions (Table 1). The greatest impact results from the construction of near surface and buried low permeability layers that impede water flow. Anthropogenic construction of hard surfacing in urban environments takes a range of forms from foundations, tunnels and reservoirs to the provision of buildings with their associated services, such as parking, storage and leisure facilities, e.g. sports areas, including swimming pools and the range of buried services that convey people and resources (water, energy and waste) beneath ground. The construction of "impermeable hard surfacing" not only limits water infiltration to the ground by virtue of the low permeability of the construction materials, but it is also commonly associated with ground loading and compression, which closes near surface voids, further limiting infiltration. The presence of surface hard standing both increases overland flow (rather than infiltrating the ground to replenish aquifers) and focuses accelerated surface flow to surface drainage systems. The consequential surface water flooding is increasingly occupying the minds of planners (e.g. Pitt Review, 2008; Slingo et al., 2014) and modellers since the early 1990s (e.g. Macdonald et al., 2012; Jankowfsky et al., 2014), leading to the realization that urban systems have to be viewed in an integrated manner and in terms of the host river catchment (i.e. the entirety of their recharge area), e.g. River Basin Catchment Management plans (Jaspers, 2003).

Though not explicitly considered here in the groundwater accounting exercise, changes to groundwater quality in the urban environment may result from a number of impacts, including: contaminating land uses, leaking infrastructure industrial cooling and processing water, leachate from landfills and other industrial discharges. Many of these impacts occur at discrete points (point-source pollution) or occur along linear routes such as transport networks or drainage channels. Furthermore, many major urban developments are close to the downstream end of catchments, because their development is closely associated with water transport and trading and where natural groundwater is supplemented by anthropogenic sources that are situated farther upstream, e.g. mine drainage impacts on the River Humber (Neal and Robson, 2000). This reinforces the fact that urban groundwater systems cannot be considered in isolation, but as part of connected catchment or hinterland. As well as exposure to a large range of contaminants, there are changes in groundwater quality that are brought about as a consequence of physical changes to the groundwater environment, e.g. saline intrusion in coastal cities where influx of seawater occurs as a result of groundwater lowering–often as a result of groundwater abstraction, or changes in Oxidation/Reduction Potential (Eh) or pH conditions that result from a change in groundwater level, including for example culverting of surface water. There is an extensive literature that describes these impacts, e.g. (Barker et al., 1998; Everard and Moggridge, 2012). However, to date cost accounting has not been fully embraced in this conceptual understanding, e.g. Banks et al. (2014). Some of the impacts are well understood, e.g. the macro-pollutants determined from monitoring the impacts of landfill (Peel, 2014) septic tanks and sewage networks (Navarro and Carbonell, 2007) and legacy industries (Hatheway and Doyle, 2006). This contrasts with low levels of understanding with respect to the impacts of emerging groundwater contaminants (Stuart et al., 2012), such as micro-pollutants (Musolff et al., 2009) and nanoparticles (Baun et al., 2009). Specific determinands commonly detected in UK groundwater include pesticides, metabolites, pharmaceuticals including carbamazepine and triclosan, nicotine, food additives and alkyl phosphates (Stuart et al., 2012).

There are a number of other impacts which to date have been less well constrained, but nevertheless are identified in Table 1. Many of these impacts broadly align with the direction of climate change (Taylor et al., 2013), consequently mitigation of urban impacts aligns well with developing broader climate change resilience.

As well as exacerbating the potential for surface run-off to contribute to the issue of surface flooding (Perry and Nawaz, 2008), the construction of paved areas leads to the reduction of moisture in the soil zone and reduces the potential for evapotranspiration in these areas, in turn leading to changes in the engineering properties of near-surface soils. A level of mitigation can be achieved through green roofs, which provide additional benefits of lowering absorption and release of solar radiation. The penetration of foundations into the unsaturated zone has the potential to block groundwater flow paths, resulting in localized focusing of flow, and provides the potential for compartmentalisation of groundwater, which can potentially impact on water quality and resource availability. There is potential to mitigate against these impacts through the use of sustainable drainage systems (SuDs), which comprise alternatives to channelling surface water through networks of pipes and sewers, either through storage or managed infiltration to the ground. However, increased intensity of rainfall events, as a potential consequence of climate change, may demand greater capacity for temporary storage and release of surface water, particularly in flood susceptible areas.

2.1. London's groundwater system

London, a megacity with significant historical legacy having undergone multiple phases of development, makes an excellent case study for evaluating urban groundwater systems and accounting for future change. It is located in the estuary of the River Thames catchment with the Chalk aquifer, the most important aquifer within the UK (MacDonald and Allen, 2001), lying at depth beneath the city. The aquifer is covered and confined by clays with interbedded sand and gravel deposits. These overlying deposits afford a degree of protection to the Chalk aquifer as well as providing a small component of additional resource from the more permeable granular deposits. The Chalk aquifer in London has been significantly exploited for public and industrial supply since the 1850s and is one of the most monitored and managed aquifer-systems in the UK (Royse et al., 2012). The ready supply of groundwater in London has been an integral part of its industrial development (e.g. Wilkinson, 1985); similarly changes in industry are reflected in fluctuations in water demand and water resilience (groundwater resource, energy, hazard and ecosystem services).

Here we systematically try to capture the current baseline for London (water supply and utility, built environment, energy, ecosystem services and hazard), whilst recognizing the significance of the historical industrial development to this baseline. So whilst London does make a good case study for cities that have experienced multiple phases of development, it represents one of the most historic urban developments in the world. Therefore, a unique set of circumstances prevail that make urban planning particularly difficult in terms of changes in land use and transition through secondary and tertiary industries, which results in competition for subsurface space, legacy contaminants and heavily exploited natural resources in an area of heterogeneous ground conditions.

2.1.1. Water supply and utility

Privatisation of water supply in the UK has resulted in the formation of twenty four water companies. TWUL is responsible for the provision of water to the London area and five other water resource zones to the west of London. TWUL serves over 13.5 million customers in London and the Thames Valley (TWUL, 2015). Within the broader River Thames catchment within which London lies, 80% of public water supply comes from groundwater and 20% from surface water sources, while the reverse is true in London where 20% of public water supply comes from groundwater. Whilst direct groundwater abstraction for public water supply in London is low, the baseflow index (BFI) for the River Thames at Kingston (Thames tidal limit) is 0.63 (NFRA; gauging station 39001—period of record 1883–2014), indicating that 63% of the river flow is derived from groundwater. This demonstrates the indirect contribution of groundwater from the wider river catchment to support London's surface water abstraction.

With a rising population that uses an increasing volume of water per head, in conjunction with climate change projections, London is facing an increasing water supply deficit, projected to rise from 59.4 Ml/d in 2015–415.9 Ml/d in 2040 (TWUL, 2015). As well as emphasising the requirements for leakage detection and repair, this increasing deficit requires the sourcing of additional resources, which includes artificial recharge schemes, e.g. the North London (Enfield-Haringey) and South London (Merton, Streatham) artificial recharge schemes (Jones et al., 2012; O'Shea and Sage 1999; TWUL, 2015). Abstraction and recharge for these schemes is typically not balanced. For example, at the North London facility abstraction reaches up to 10981 Ml/yr but typically has been less than 5000 Ml/yr in recent years. In contrast artificial aquifer recharge at the sites reaches quantities of up to ~4000 Ml/yr but has been negligible in recent years.

Water supply and demand reduction in the short to medium-term is being driven through a combination of leakage reduction, progressive metering and water efficiency measures (TWUL, 2015). However whilst leakage from the pipe network is 665 Ml/d, equivalent to 25% of the total water demand (2014/15; TWUL, 2015) the Economic Level of Leakage has been reached i.e. the level at which the cost of further reducing leakage exceeds the cost of producing water from an alternative source (DEFRA, 2008; TWUL, 2015). The water deficit is also increasingly being met through increasing the hinterland for groundwater supply, i.e. through trading with other water companies such as Essex and Suffolk Water and RWE N-Power and identifying new resource options. The first water desalination plant in the United Kingdom, the TWUL Desalination Plant, or Beckton Desalination Plant was built in Beckton, in the London Borough of Newham in east London for TWUL at a cost of £250 million (Water Technology, 2016). It was opened on 2 June 2010 and provides up to 150 Ml/d. This is enough for nearly one million people in north-east London. Consideration is also being given to new wastewater re-use schemes, e.g. two wastewater reverse osmosis re-use plants are planned: Deephams recycling 60 Ml/d in 2027 and Beckton recycling 100 Ml/d in 2032 (TWUL, 2015). However the problems of emerging contaminants e.g. pharmaceuticals (Stuart et al., 2012) have to be considered in the evaluation of these schemes.

Water for public supply is the primary consumptive use of abstracted groundwater under licence in London (80%), with non-consumptive groundwater abstraction licences for ground source heating and cooling systems also increasing across the city (Environment Agency 2015). Proportionally about half of TWUL's supply is for household use, a quarter is lost through leakage and just 20% is used for non-household purposes (TWUL, 2015).

2.1.2. Built environment

London's subsurface is host to an increasing density of infrastructure such as transport tunnels, requiring dewatering schemes to control groundwater during their construction (Royse et al., 2012). Conflicting demands and restrictions on underground space render it necessary to take such infrastructure to increasing depths, e.g. at the time of construction (2010) the Lee Sewerage Tunnel was the deepest tunnel in London, exceeding the depth of the deepest underground station Hampstead (58.5 m) by 20 m. Whilst this depth may not seem significant when compared with the Gotthard Tunnel (Simoni, 2013), which is 2.3 km under the Alps at its deepest point, construction beneath London is difficult because of the weak nature of the ground and the requirement to manage the groundwater conditions. Engineering in London is made even more difficult by rising groundwater levels, which result from reductions in water demand by industry (Fry, 2009; Lucas and Robinson, 1995; Wilkinson, 1985).

The demands for urban space, accompanied by a relaxation in planning constraints, have resulted in a proliferation of basements, which impact on natural recharge and impede shallow groundwater, thereby lowering resilience to flooding e.g. the London Borough of Kensington and Chelsea received 450 applications for basements in 2013. To help address this local planning policy in parts of London restrict basement size to 50% of the garden to protect "the character and function of gardens, allow flexibility in planting and natural surface water drainage" (RBKC, 2014). The urban flooding issue is complex and has been compounded by rising groundwater levels in the Chalk aquifer in central London following reductions in groundwater abstraction after industrial decline (Fry 2009; Lucas and Robinson, 1995) and the historic culverting of the surface water system (Barton, 1992). Rising groundwater levels have been addressed and are now stabilized through a collaborative groundwater abstraction operation led by the environmental regulator, TWUL and London Underground. Meanwhile broader flooding issues are being addressed through the Greater London Authority Drain London programme, a partnership of 33 London boroughs, the Environment Agency, TWUL and Transport for London, which is aimed at better prediction and management of surface water flood risk in London.

The consequences for groundwater of construction in the subsurface are multi-facetted and include: (i) partitioning of groundwater, thereby altering natural flow paths, which adds complexity to groundwater modelling; (ii) increasing vulnerability due penetration of the confining layer which affords protection to the groundwater quality; (iii) the networks of transport, energy and fluids all have the potential to leak contaminants; (iv) the networks of transport, energy and fluids have the potential to take up groundwater through any ruptures; (v) as construction moves deeper into the subsurface dewatering imposes a greater potential for groundwater mixing with the potential for reductions in groundwater quality. Such consequences demand increasingly technical and more robust solutions to meet the resilience requirements of the city's growing population. New technologies are emerging to achieve this, e.g. the use of robots to repair underground pipes (Hollingum, 1998) and geophysics for pipe leak detection (Kuras et al., 2016). The extent of groundwater abstraction can be monitored from the induced ground level change, seen in remotely sensed radar interferometry (e.g. Cigna et al., 2015; Boni et al., 2016; Pratesi et al., 2016).

2.1.3. Ecosystem services

The multiple functions that ecosystem services provide with respect to the ground beneath urban areas are increasingly being recognized by city practitioners. For example groundwater provides multiple services, primarily for potable water supply but also by diluting and attenuating contaminants and by acting as a medium for exploiting ground heat. However, appropriate assessment and management of ecosystem services provided by the ground are less clearly understood. There are more than 40 active ground source heating and cooling systems utilising groundwater in central London, including those used by London Underground where groundwater pumped from Victoria Station as part of the station's dewatering system is used to cool the platform. It is estimated that up to 19% of London's total heat demand (2010) could be derived from ground heat sources (GLA, 2013). Despite the opportunity, rising groundwater temperatures are already a concern with a 2 °C rise in temperature between 2005 and 2014 recorded in parts of London (Environment Agency, 2015).

Groundwater is also influenced by other ecosystem services provided in urban areas. For example, to facilitate natural recharge, sustainable drainage systems have been promoted and incorporated as local planning policy for London. A drainage hierarchy is adopted, whereby storage of rainwater for subsequent use, natural infiltration systems and attenuation of water are to be considered in preference to direct discharge of water to water courses and combined sewers. Whilst sustainable drainage systems have the benefit of increasing natural groundwater recharge, enhancing urban ecology and attenuating contaminants in surface water, if not installed in appropriate locations they may increase local groundwater flood risk, cause dissolution of soluble rocks and mobilize contaminants present in soils and the shallow subsurface unsaturated zone (Dearden and Price, 2012). Additionally, they may disrupt natural filtration and geochemical processes operating in the subsurface.

3. Future city interventions

Commonly, environmental challenges in cities are a construct of multiple social and political dynamics. For example, low environmental standards are not merely problems of human behaviour, caused by collective human and political actions, but of their underlying interests, beliefs, and values as well (Koger and Winter, 2010). Conversely, collective creative management of the urban environment across industry domains, can deliver improved human well-being, leisure, recreational and biodiversity benefits (Rachwal et al., 2014). As we transition to a desirable, but sustainable future state, and tackle these environmental challenges, a range of different interventions or measures will be implemented by various city actors, for different purposes that will have complimentary and competing objectives. Urban planners, working collaboratively with experts across environmental, social, economic and political domains have a critical role in shaping the necessary conditions that deliver positive outcomes for both urban environments and communities. In consideration of the relationship between water and cities, Rachwal et al. (2014) construct five nonexclusive visions of how communities might potentially tackle the issue of integrated water management. The visions embrace the role of sensitive urban design, green landscapes and nature-based solutions, sensors and system efficiencies, in addition to citizen participation and sustainable habits, each of which has a bearing on the urban groundwater system. However, their vision of 'Cities and the Underworld' deals directly with groundwater systems and highlights a future where infrastructure is increasingly built underground in cities and the subsurface is more effectively managed to deliver effective drainage, water storage, heating and cooling. These concepts are in keeping with recent research which highlights the benefits of modern urban innovation and policy, for example, growing investment in smart utilities and digital technologies (Angelidou 2015), conjunctive use of alternative water storage and water re-use options (Dillon et al., 2006; Hunt et al., 2013; Rojas-Torres et al., 2014), decentralized water supply systems (Chen et al., 2010) and green infrastructure and sustainable urban drainage (Chow et al., 2014; Dearden and Price, 2012).

In addition to the anthropogenic influences described in Table 1, the following urban interventions have a potential influence on urban groundwater systems: use of marginal groundwater, aquifer storage and recovery, sustainable drainage systems, urban greening, rainwater harvesting, wastewater recycling, household water efficiencies, smart metering and sensor technologies, pipe leakage reduction and ground source heating systems. These interventions are described further in Table 2 and represent measures for which a simple semi-quantitative assessment of their impact can be undertaken using existing research outcomes and openly available data. Though not an exhaustive list, these interventions cover a mix of measures provided by different city organisations which significantly affect water supply and demand, behavioural change and new technologies.

4. Future visions for London

London covers 1595 km^2, is home to over 8.5 million people and is one of the largest metropolitan economies in the world. By 2036 London's job market is expected to grow to 5.8 million jobs from 4.9 million in 2011 and an additional ~1 million households will be accommodated over the same period (GLA, 2015). In parallel significant investment in infrastructure, of the order of £1.3 trillion, is anticipated by 2050 (Mayor of London, 2014). Whilst much of this investment is allocated for transport and housing, investment in water infrastructure (4%) and green infrastructure (2%) is accounted for and ambitions for a 10% increase in urban green space have been outlined (Mayor of London, 2014).

London is located in a water-stressed region in the southeast of England and already experiences water-deficits during dry years (TWUL, 2015). By 2036 London's population is projected to exceed 10 million (GLA, 2015), increasing water demand by approximately 16%. Pressures on water availability within the river Thames catchment will be compounded by climate change with storm events and climatic extremes expected to dominate. At present 15% of London, 1.5 million people and 480,000 properties lie within the floodplain of the Thames and its tributaries (GLA, 2015). By 2050 winter rainfall is predicted to increase by 14% with an associated increase in river flows of approximately 13%, meanwhile summer rainfall is predicted to fall by 19% leading to a reduction in summer river flows of 15% (Prudhomme et al., 2012; Haxton et al., 2012). These effects are potentially very significant for London given its high reliance on surface water and groundwater baseflow. TWUL currently expect the effects of climate change to reduce water availability by approximately 72 Ml/d (TWUL, 2015)–equivalent to the daily water demand of over 400,000 Londoners.

London's future water resource situation is dictated not only by changes in climate and the natural systems but also by the anthropogenic activities, described earlier, that act on or intervene with it. As we tend towards a more desirable sustainable future, a series of measures or interventions will be put in place, by various stakeholders in

Table 2
Interventions used for the groundwater accounting exercise discussed in this paper.

	Intervention	2036 Future Vision: Strategic London	2036 Future Vision: Aspirational London	Responsible organisations (UK)
Supply	Rainwater harvesting	All new homes in London are fitted with rainwater harvesting systems.	All suitable roof space in London is used for rainwater harvesting systems.	Home builders Citizens
	Aquifer storage and recovery	All currently planned artificial recharge (AR) and aquifer storage and recovery (ASR) schemes are implemented utilising storage in the chalk aquifer.	All currently viable artificial recharge (AR) and aquifer storage and recovery (ASR) schemes are implemented. Additional sites for ASR and AR are sought.	Water company Environmental regulator
	Wastewater recycling (effluent re-use)	Currently planned wastewater recycling scheme is implemented.	A second wastewater plant is developed, in preference to a new reservoir and water transfers in keeping with public opinion and net present value (TWUL, 2015).	Water company
	Leakage reduction	Pipe leakage is reduced by 16% in line with targets planned by the water company.	Pipe leakage targets are doubled, as a result of pressure from the public, despite the economic leakage level. Hydraulic engineering to reduce leakage is considered.	Water company
	New groundwater borehole supplies	Currently planned new groundwater borehole supplies are constructed.	No further groundwater sources are developed, as water recycling is preferred. Research into 'marginal' groundwater sources is on-going.	Water company Environmental regulator
	Water transfers	Planned water transfers into London remain in place.	Water transfers into and out of London's water supply area are stopped.	Water company
	Greywater recycling	Grey-water recycling is installed as standard in all new homes in London.	All homes in London are retrofitted with grey-water recycling systems.	Home builders
	Infiltration sustainable drainage systems (SuDS)	SuDS are installed to reduce the volume of surface water flowing into the combined sewer network in London.	Infiltration SuDS are installed across 10% of London land area where run-off rates are high and infiltration SuDS are suitable.	Local authority Home builders Landscape architects
Demand	Smart Home – water efficiency	All new homes in London are fitted with water saving devices.	All of London's homes are retrofitted with water saving devices.	Home builders Designers and architects Citizens Water company
	Smart water meters	735,000 homes in London have water meters installed in line with water company targets.	All of London's homes have a water meter installed.	Water company
	New water tariffs and behaviour change	Planned activities to encourage behaviour change are effective and new tariffs are introduced.	Behaviour change brings London's per capita water consumption in line with the national average (150 l/person/day).	Water company Water company Citizens
Neutral	Groundwater sourced heating systems	Groundwater source heating systems utilising London's aquifers continue to be installed in line with current trends.	Groundwater source heating is actively promoted as a low carbon energy source and the installation rate of new systems doubles.	Environmental regulator Home builders Designers and architects

Table 3
Groundwater accounting results.

	Interventions	Effect on urban water cycle	Future Vision for 2036	Total change in water balance (Ml/d)	% of London's water demand in 2036	% of London's groundwater recharge in 2036	Source data and assumptions
Supply	Rainwater harvesting	Rainwater that would otherwise go to surface water drains (or into the ground) is intercepted and held in storage for onward use in the home. The volume of treated water distributed to the home is reduced, increasing water availability.	Strategic	39.9	1.8	13.0	Future Water (2008). TWUL Final WRMP 2015–2040 Appendix E. GLA (2008).
			Aspirational	80	3.7	26.0	Assumptions: 28.29 Ml/d of rainwater can be obtained per person per home. Rainwater tanks provide sufficient storage to ensure daily water needs during dry periods.
	Wastewater recycling (effluent re-use)	Domestic wastewater is treated centrally by the water utility and recycled for domestic use. The volume of wastewater being discharged to rivers and seas is reduced.	Strategic	150	6.9	48.7	TWUL Final WRMP 2015–2040 Exec summary.
			Aspirational	300	13.8	97.4	Assumption: Under an aspirational future invested is diverted towards wastewater recycling and away from the development of a new reservoir which is in keeping with public perception (London 2036) and cost-benefit analysis (TWUL Final WRMP Exec summary).
	Greywater recycling (internal household water recycling)	Demand for treated water in the home is reduced, increasing water availability.	Strategic	67.3	3.1	21.9	Hunt et al. (2013). TWUL Final WRMP 2015–2040.
			Aspirational	419.6	19.3	136.2	Assumption: Greywater recycling within domestic homes delivers a 25% water saving. Its assumed that either rainwater harvesting or greywater recycling technology would be installed not both.
	AR (Artificial recharge) ASR (Aquifer storage and recovery)	Spare storage in London's aquifers, where groundwater levels are low, is used to store surplus water for later use increasing water availability in times of shortages.	Strategic	23	1.1	7.5	TWUL Final WRMP 2015–2040 Executive Summary and Appendix R.
			Aspirational	26	1.2	8.4	Assumptions: TWUL explored all aspirational ASR and AR sites in their options appraisal.
	Sustainable drainage implementation	The volume of surface water going to piped drainage is reduced, reducing the risk of storm 'overflows' and pollution. Natural urban groundwater recharge is increased. The volume of water held in surface water storage increases.	Strategic	87	3.9	28.3	BGS Infiltration SuDS Suitability Map (Dearden et al., 2013). BGS Thames Run-off − Recharge Model (Mansour and Hughes, 2004). HR Wallingford SuDS tool (HR Wallingford 2016).
			Aspirational	282	13	91.6	Assumptions: 1 in 1 year estimated discharge for a 1 ha site in London suitable for infiltration SuDS is 2.5 L per second. Sites have 25% open area, i.e. 75% of land needs to be drainage at greenfield run-off rate. London's development rate is 0.5% of land per year, meaning 10% of land is developed by 2036.
	New groundwater sources	More water is available for public supply as new abstraction wells are drilled. Groundwater available to support groundwater dependent ecosystems is reduced. Groundwater levels are lowered near to the well.	Strategic	17	0.8	5.5	TWUL Final WRMP 2015–2040.
			Aspirational	0	0	0	Assumption: Under an aspirational future additional groundwater abstraction is to be minimized.
	Leakage reduction	The amount of treated water and wastewater that leaks from the pipe network is reduced. Contamination of groundwater by wastewater is therefore reduced but so is urban groundwater recharge.	Strategic	109	5.0	35.4	TWUL Final WRMP 2015–2040 Exec summary.
			Aspirational	218	10.0	70.8	Assumptions: Under an aspirational future leakage reduction doubles despite the fact that the economic leakage level has already been reached.
Demand	Smart Home – water efficiency	Demand for treated water in the home is reduced and therefore less waste water needs to be treated. Capacity in the sewer network is increased and the risk of 'overflows' and pollution events is reduced.	Strategic	238	10.9	77.3	Future Water (2008). TWUL Final WRMP Appendix E.
			Aspirational	590	27.1	191.6	Assumptions: Installation of water saving devices receives public acceptance and volumes of water saved are in line with predictions.
	SMART meter installation	Demand for treated water in the home is reduced and therefore less waste water needs to be treated. Capacity in the sewer network is increased and the risk of 'overflows' and pollution events is reduced.	Strategic	38	1.8	12.3	TWUL Final WRMP 2015–2040.
			Aspirational	208.8	9.6	67.8	Assumptions: The water saving delivered by water meters is linearly scalable with the number of meters installed. In reality greater water saving will be delivered by those who opt for water meters compared to compulsory metering (ref).
	New water tariffs and behaviour change	Demand for treated water in the home is reduced and therefore less waste water needs to be treated. Capacity	Strategic	62	2.9	20.1	TWUL Final WRMP 2015–2040.
			Aspirational	170.9	7.9	55.5	Future Water (2008). Mayor of London (2011).

(continued on next page)

Table 3 *(continued)*

	Interventions	Effect on urban water cycle	Future Vision for 2036	Total change in water balance (Ml/d)	% of London's water demand in 2036	% of London's groundwater recharge in 2036	Source data and assumptions
		in the sewer network is increased and the risk of 'overflows' and pollution events is reduced.					Assumption: Proposed activities receive public acceptance and deliver predicted water savings.
Neutral	Groundwater sourced heating	There is no net change to the urban water balance as water is recirculated between the ground and the homes heating system but groundwater temperatures increase locally and regional groundwater temperature increase by over 2 °C.	Strategic Aspirational	118 new sites. 338 new sites.	No net change No net change	No net change No net change	Environment Agency (2015) Assumptions: The chalk aquifer can deliver the heating and cooling demand required from the projected increase in ground source heating systems under both the strategic and aspirational visions.

London to deliver on agreed social, environmental and economic goals. There is a need to consider the ways in which the proposed interventions may interact with other city systems and the extent to which undesirable outcomes or complimentary benefits may occur (e.g. Price et al., 2016). This point is illustrated by considering how groundwater systems might be affected by the implementation of a range of city interventions in London. To assess the extent to of these effects two contrasting visions for London have been selected and simple groundwater accounting undertaken for a range of future city interventions (Table 2). The aim of the accounting exercise is to calculate, across the London water supply area, the effect that different city interventions have on the urban water balance and to identify which elements of the urban groundwater system are disturbed as a result. Hydrometric data, geospatial data and water supply information embedded within water resource management plans and urban strategic plans are used in combination to perform the semi-quantitative analysis. For example, TWUL uses industry standard methodologies to forecast future demand taking into account population (an increase of 2.0–2.9 million people by 2040 with 75% forecast in London); property projections; water use data and trends to forecast how the components of demand for water are likely to vary over the next 25 years (TWUL, 2015). Further information about the data sources and assumptions are provided in Table 3. The impact of the interventions is expressed in megalitres per day (Ml/d) and as a proportion of i) London's predicted water demand in 2036, and ii) London's predicted groundwater recharge in 2036.

The first vision, referred to as 'Strategic 2036' sets out a future for London guided by strategic plans and policy information provided by the organisations with responsibility for planning London's future, e.g. the local authority, water provider and environmental regulator. In essence, this scenario provides a projection of a likely future state should the organisational objectives for London in 2036 be implemented as planned. Current operational and business needs dominate in this vision.

The second, referred to as 'Aspirational 2036', provides a future vision for London which goes beyond the city strategic plans and adopts a desirable but plausible sustainable future. Under this vision, in line with the Urban Futures new sustainability paradigm (Rogers et al., 2012), resources are used sustainably, social responsibility dominates and citizens are engaged. This vision also embodies a more idealistic, innovative and open approach in keeping with the notion of visioning exercises (Wiek and Iwaniec, 2014).

These two visions were chosen to highlight the potential disparity between i) strategic plans developed by individual organisations that are guided by operational needs and short-term business models, and ii) a future which is still plausible but unconstrained in the way that city interventions are implemented to transition to a sustainable urban future. That is, the visions contrast a projected future and a desirable future. A description of the various interventions included within the groundwater accounting exercise, under a strategic and aspirational future vision for 2036 is provided in Table 2.

5. Results: groundwater in London 2036

The results of the groundwater accounting exercise for the future city interventions are summarized in Table 3. The interventions are categorized into those which affect the availability of supply, those which affect demand for water and those which have a neutral impact on water supply. The water balance is also presented graphically, for both future visions, in Figs. 1 and 2 to highlight the extent to which the individual components of the urban water cycle are affected by the selected future city interventions.

5.1. Strategic future 2036

Under a strategic future for 2036 the greatest water-saving gains, as a percentage of London's water demand, would be made through the

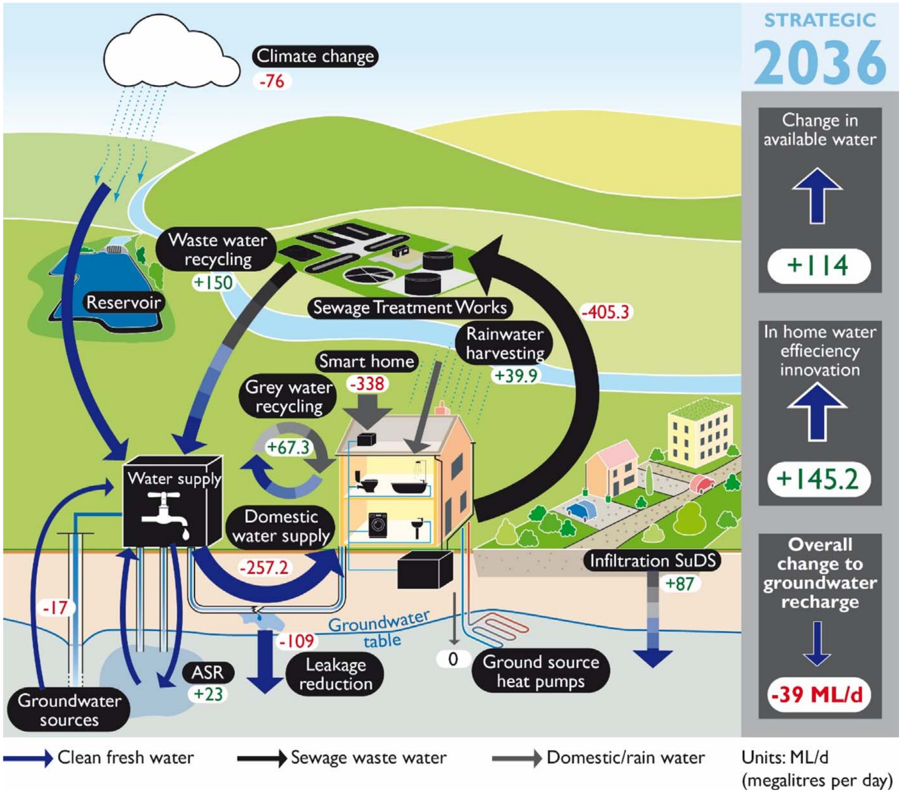

Fig. 1. An annotated urban water cycle showing the results of the accounting exercise for a strategic future.

construction of smart homes (10.9%) and the development of wastewater recycling technologies (6.9%). These are also positive interventions with respect to groundwater as smart homes and wastewater recycling both reduce demand for water, reducing pressure on groundwater supplies. Furthermore, water discharged to foul sewers is also reduced under this scenario reducing the risk of sewer water overflows into natural water systems. Groundwater recharge is not reduced.

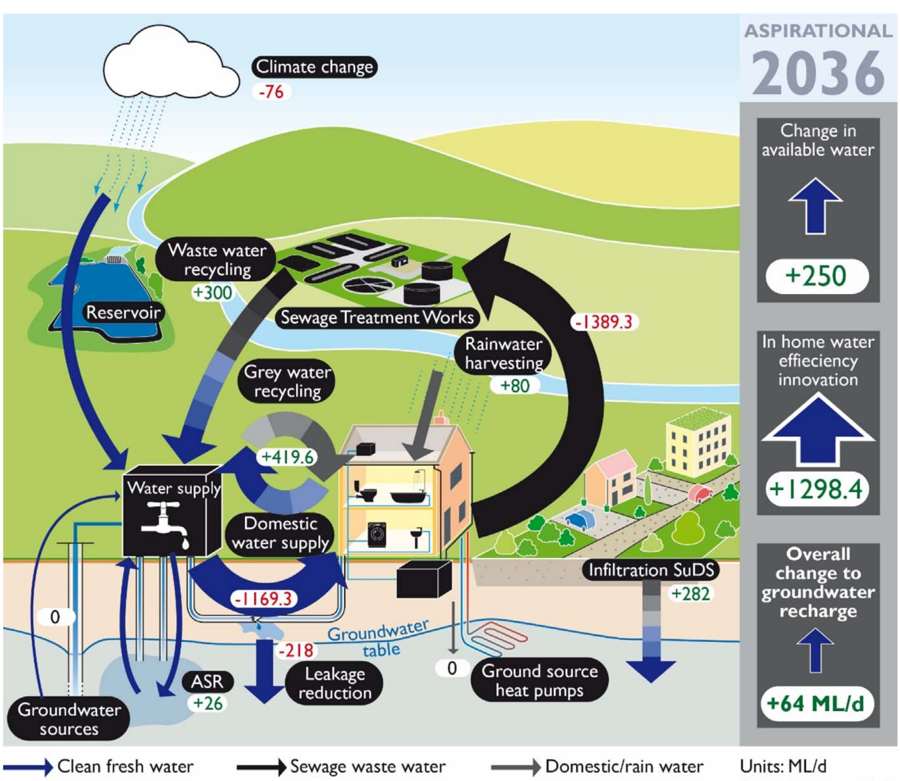

Fig. 2. An annotated urban water cycle showing the results of the accounting exercise for an aspirational future.

5.2. Aspirational future for 2036

Under an aspirational future for 2036 the greatest water-saving gains, as a percentage of London's water demand, would be delivered through the construction of smart homes (27.1%) and installation of greywater recycling (19.3%). Wastewater recycling is also capable of delivering significant gains. As with the strategic future vision, both of these interventions deliver positive benefits for groundwater systems through, demand reduction and water recycling, with pressure on groundwater supplies reduced and groundwater recharge unaffected.

5.3. Disparity between strategic and aspirational

The level of disparity between a strategic vision and aspirational vision for 2036 is evaluated, that is, where organisational policies are out of line with what is achievable under a more aspirational sustainable future. The greatest disparity is observed for both smart homes and greywater recycling, where organisational policy for these interventions falls short and a further 16% of London's water demand could be found through each of these interventions if more aspirational targets were set. Organisational ambitions for the implementation of sustainable drainage systems and water meters also fall short of what is plausible, where an additional 9% and 8% of London's water demand respectively could potentially be if more proactive initiatives were implemented.

5.4. Implications for urban groundwater systems

A number of future city interventions included in the accounting exercise have a direct bearing on groundwater systems. For example the direct withdrawal of groundwater through the development of new extraction wells and the utilisation of aquifer storage through artificial recharge schemes (ASR). Traditionally we might expect these schemes to have the greatest impact on the urban groundwater balance. Under both the strategic and aspirational visions for London 2036, the development of new groundwater sources and ASR schemes has a minimal impact on groundwater systems compared with other interventions (i.e. ~2% of London's water demand). Other interventions have a more indirect, but potentially significant effect on groundwater systems. For example, rainwater harvesting and pipe leakage reduction both serve to reduce urban recharge to aquifers while infiltration SuDS are designed to enhance groundwater recharge to urban aquifers. Under a strategic vision for 2036, rainwater harvesting would potentially reduce recharge to urban aquifers by up to 13%, though arguably a significant proportion of rainfall is currently lost to surface water drains and does not contribute to aquifer recharge, and leakage reduction could reduce urban recharge up to ~35%; meanwhile infiltration SuDS may increase urban recharge by 28.3%, the net effect being a reduction in recharge of ~20%. Under an aspirational future there is a less significant net effect on urban recharge (< 5%) as increased groundwater infiltration is delivered through greater implementation of sustainable drainage systems.

6. Discussion

Applying a groundwater accounting exercise to plausible cities interventions provides semi-quantitative scenario analysis of aspirational urban futures. Primarily an insight is gained as to the expected extent of disturbance to groundwater stocks and flows that might occur as a result of fulfilling the city's ambitions. It has the distinct advantage over traditional groundwater balancing, in that it considers not only the direct groundwater processes (e.g. recharge, interflow, discharge) but also the ways in which these processes are coupled to other anthropogenic activities (e.g. surface sealing, construction) and behaviours (e.g. water saving, policy development). As a result, a more holistic evaluation of urban groundwater management can be defined. For example, based on disturbance to groundwater systems should future investment in water infrastructure be focused on increasing supply or reducing demand? Equally, it is possible to evaluate whether the most positive interventions from a groundwater perspective will be delivered through new technologies or by a change in people behaviour and whether there is an over-reliance on organisational policy and practice and an under investment in private enterprize and innovation.

Considering urban groundwater systems in isolation, there is significant merit in adopting wastewater recycling and greywater recycling technologies in combination with smart home water efficiency and water meters, as measures to meet London's projected water resource demand. These interventions have the potential to deliver significant benefits under both strategic and aspirational futures. They also reflect a balance between the development of new water recycling technologies to increase supply in parallel with modification of people behaviour to reduce water demand and consumption. These options are also economically favourable in terms of the net present value calculated by the water supplier (TWUL, 2015).

Controversially, from a groundwater perspective, leakage reduction might be discouraged as it is likely to lead to a significant reduction in urban recharge, though there are inevitable water quality concerns associated with leakage from sewage pipe networks. Groundwater recharge modelling under future climate scenarios (Haxton et al., 2012) suggests that the volume of water lost from pipe network through leaks is equivalent to ~35% of London's total groundwater recharge in 2036. Even under an aspirational future, the level of groundwater recharge delivered through infiltration SuDS is unlikely to be sufficient to deliver an equivalent volume of recharge to urban aquifers that is lost if pipe leakage is reduced to zero.

However, we must not consider groundwater in isolation but in combination with economic assessments and public acceptance. Kirkpatrick and Smith (2011) show, for aging cities in the US, that public water infrastructure works are funded independently of city budgets such that key infrastructure decisions are often far removed from community sentiment. Under both a strategic and aspirational futures, the greatest water gains can be delivered through the introduction of water-saving technologies in smart homes–noting that this also has a positive effect on groundwater systems. This sentiment is echoed by Newton and Meyer (2013) in their discussion of water use, that "individual and household behaviour changes offer the potential for a much faster rate of sustainability transformation than supply-side technological innovation of key infrastructures and services". Significantly though, there is the greatest disparity between the strategic future and aspirational future for smart home water-saving, suggesting that current and projected organisational practice falls someway short of the potential for change. Here then we can start to consider the organisational and behavioural constraints that are limiting in-home water saving. For example, there is currently no policy driver for installing water-saving technologies in new homes and a heavy reliance on home-builders to drive uptake in new builds. Moreover, London's water provider has rejected retrofitting domestic properties with modified toilet cisterns and showerheads and enforced use of water efficiency measures in new buildings on the grounds that the costs and benefits cannot be modelled by comparison with alternative water management options (TWUL, 2015). This is largely a result of high uncertainty that, given the heavy reliance on modified people behaviours, these technologies will deliver the predicted water-savings once installed.

The influence of people's behaviour in the uptake and use of water-saving technologies is an important consideration in water utility (Hunt et al., 2013). While there are many environmentally minded citizens, the environment is not a major motivator for water conservation. Appeals to environmental values when asking people to change their water-use habits are unlikely to succeed on their own as they are often outweighed by barriers such as lifestyle factors (Ministry for the Environment, 2009). Selby (2011) argues that in many cultures water usage is not just a product of climate but reflects the social and political ideals, for example maintaining private lawns and gardens, and perceived levels of hygiene and cleanliness (Kooy and Bakker, 2008). Additionally, water provision is seen by some as a fundamental human right and plans to curtail water use may be viewed as a challenge to social justice and equity (Ministry for the Environment, 2009). These ideas driven by political distinctiveness and social standing are difficult to challenge and overcome (Selby, 2011).

Wiek and Iwaniec (2014) draw attention to more sophisticated visualization techniques and gaming approaches such as 3D visuals and immersive experiences to encourage people to participate in visioning exercises. These gaming-models (e.g. SimCity) allow a more systemic vision to be created by participants where interconnected systems and dynamic feedbacks can be presented (Wiek and Iwaniec, 2014). In this way people can understand how their actions and goals relate to and affect each other. Though not a controlled visioning exercise, such an approach was adopted by the Future Cities Catapult, the UK's Government-funded enabler of urban innovation. Using an interactive gaming-model, questions on water resources, housing and transport were posed to members of the public to provide integrated systematic insights into the public's aspirations for London's future in the year 2036. Each participant was provided with a forecasted future for London unique to their answers which evaluated water availability, carbon emissions, housing levels and transport capacity, thus allowing participants to reflect on the implications of their responses. As well as providing participants with individual feedback on future scenarios, results from the gaming-models provide an informal insight to assess public acceptance of new initiatives and policy decisions for London. It also provides an opportunity to review people's perceptions on London's future against the strategic and aspirational futures mapped out for London in 2036.

Over a four-month period more than 15,000 people played the London 2036 gaming-model, of these participants a third failed to implement measures to meet London's forecasted water demand. Additionally and equally concerning for groundwater practitioners are respondents' views on urban infrastructure, a clear preference for both increased subterranean rail networks and high rise buildings would result in greater disturbance to, and greater need for protection of shallow groundwater systems in London. Despite these outcomes, prospects for water management and water-saving options are generally positive with respect to the urban groundwater system. 80% of participants indicated a preference for waste water recycling (also favourable under both the strategic and aspirational futures presented here) over importing water from the hinterland. Meanwhile there was clear inclination for rainwater harvesting (48.5%) over leakage reduction (36.5%), new reservoirs (10%) and reduction of water exports from the catchment (5%) as a means to increase water availability, and equally there was support for water metering and in-home water saving devices to reduce water demand. These results suggest that people are generally open to the idea of innovative approaches to urban water management and perhaps it is organisational policy and practice that is more of a barrier to implementation. However, implementation of novel water efficiencies, re-use and decentralisation of water systems, e.g. as proposed by Rachwal et al. (2014) in their water and cities vision, requires people in the UK to be active water managers, rather than passive consumers. Given that a plentiful and uninterrupted water service is already established and remains an operational requirement there exists a challenge to motivate people to be active managers of water when a passive attitude delivers what is needed.

Semi-quantitative scenario forecasting and more qualitative insight assessments provide useful mechanisms to evaluate city visions, but there exist a number of natural and anthropogenic interventions and influences that remain difficult to account for, e.g. changes in climate and localized weather patterns, rates of development and ground disturbance and population changes. Understanding the uncertainty of these pressures and the potential impacts requires not just future scenarios forecasting but predictive modelling. Implementation of integrated and linked modelling approaches such that multiple processes can be considered in tandem is increasingly being employed for integrated water management (Heinz et al., 2007) and presents the opportunity for linked physical and socio-economic modelling of city visions.

7. Conclusion

Visioning exercises are increasingly being used in cities to define desirable future states, to create a shared vision that cuts across technical and social spectrums, and which acknowledges the physical city constraints whilst still being ambitious. As cities attempt to trend towards a more sustainable urban future, visioning exercises may be used as a tool to evaluate environmental challenges and innovative solutions against urban futures. At present however, sustainability principles and the natural environment tend to be lacking in city visions with a focus on the built environment instead.

For environmental considerations to be better captured in city visions we need to consider the city in the context of its connected resource catchment or 'hinterland', furthermore an integration of, urban metabolism approaches completed by city-practitioners, and ecosystem service assessments–completed by environmental experts, is needed. For this to be implemented successfully a more-fluid approach to natural catchment and political boundaries is warranted where boundary conditions are instead guided by the dynamics of the system stocks and flows operating across the rural-urban fabric.

Significant effort is being invested to map the pathways needed to transition towards a desirable sustainable future and to enable the implementation of urban innovations and city interventions to meet these aspirations. Frequently, and particularly for water resource supply, the interventions and future management plans are guided by individual organisational needs and business demands. These planning exercises, which are completed separately to visioning exercises, are robust but they are constrained by operational practice, siloed, and not systemic.

There is a growing body of evidence highlighting the importance of groundwater to support urban living and the impact of urbanism on natural groundwater systems however it is rarely considered in city systems thinking. The groundwater accounting exercise employed here is successful in highlighting the interconnections between groundwater processes and other city systems; in doing so the potential benefits and undesirable consequences of various city interventions on urban groundwater systems are defined and can be evaluated against other social and political considerations. For London, if a strategic future guided by existing operational practice and organisational need were to unfold, we would see preferential investment in industry-scale technologies such as wastewater treatment and aquifer storage and recovery. While these interventions deliver positives benefits under both futures, acknowledgement that behaviour change offers the potential for a faster rate of sustainability transformation than innovation technologies is ignored.

We need to be guided by unconstrained ideas and innovation and encourage more joint business and community enterprize and invite city practitioners to inform the pathways to implementation that consider the social context in addition to the environmental constraints and business drivers. For London, adopting such an aspirational vision there is greater opportunity to deliver benefits via community-led action such as sustainable drainage and green infrastructure and in-home water efficiency measures.

For more aspirational urban groundwater interventions to be implemented in cities we need to encourage more integrated, systemic and quantitative evaluation of the likely pathways, interventions and interactions. This is increasingly possible with the use of linked and integrated modelling where groundwater process models, physical models and water industry models can be coupled and inform socio-economic assessment, where the value of water, in all its guises, is increasingly being recognized (e.g. Barthel et al., 2005).

Throughout the visioning exercises we need to be mindful that the plausible and the possible are only achievable if there is public acceptance. In tandem with more traditional predictive, quantitative groundwater modelling which allows for probabilistic forecasting, more-qualitative future scenario assessments is being advocated (GO-Science, 2016). Such scenario development encourages greater participatory engagement and unconstrained ideas, to support judgement-based, context-driven future states. Such approaches are starting to be utilized by the water resource sector and should be further-encouraged to develop more active behaviours in water resource management by communities.

Acknowledgments

This study was carried out as part of a NERC knowledge exchange fellowship (NE/M020673/1) held by S. Bricker undertaken in partnership with Innovate UK's Future Cities Catapult. The investigations were co-funded by the British Geological Survey's Urban Geoscience research programme. Support from the Future Cities Catapult data lab team through the London 2036 data exhibit is gratefully acknowledged. The authors thank Henry Holbrook for provision of the illustrations and artwork for the paper. Bricker, Banks and Tapete published with the permission of the Executive Director of BGS-NERC.

References

Angelidou, M., 2015. Smart cities: a conjuncture of four forces. Cities 47, 95–106.

Banks, V.J., Patton, A.M., Hulbert, A., 2014. Quick scoping review: impact of contaminated land on controlled waters. British Geological Survey Commercial Report CR/14/127. 92 pp.

Barker, A.P., Newton, R.J., Bottrell, S.H., Tellam, J.H., 1998. Processes affecting groundwater chemistry in a zone of saline intrusion into an urban sandstone aquifer. Appl. Geochem. 13 (6), 735–749.

Barthel, R., Nickel, D., Meleg, A., Trifkovic, A., Braun, J., 2005. Linking the physical and the socio-economic compartments of an integrated water and land use management model on a river basin scale using an object oriented water supply model. Phys. Chem. Earth Parts A/B/C 30 (6-7), 389–397.

Barton, N., 1992. The Lost Rivers of London. Phillimore, Chichester.

Baun, A., Hartmann, N.B., Grieger, K., Hansen, S.F., 2009. Setting the limits for engineered nanoparticles in European surface waters—are current approaches appropriate? J. Environ. Monit. 11, 1774–1781.

Boni, R., Cigna, F., Bricker, S., Meisina, C., McCormack, H., 2016. Characterisation of hydraulic head changes and aquifer properties in the London basin using persistent scatterer interferometry ground motion data. J. Hydrol. 540, 835–849. http://dx.doi.org/10.1016/j.jhydrol.2016.06.068.

Boukhemacha, M.A., Gogu, C.R., Serpescu, I., Gaitanaru, D., Bica, I., 2015. A hydrogeological conceptual approach to study urban groundwater flow in Bucharest city, Romania. Hydrogeol. J. 23, 437–450. http://dx.doi.org/10.1007/s10040-014-1220-3.

Chen, C.-L., Hung, S.-W., Lee, J.-Y., 2010. Design of inter-plant water network with central and decentralized water mains. Comput. Chem. Eng. 34 (September (9)), 1522–1531. http://dx.doi.org/10.1016/j.compchemeng.2010.02.024. ISSN 0098-1354.

Chow, J.-F., Savic, D., Fortune, D., Kapelan, Z., Mebrate, N., 2014. Using a systematic, multi-criteria decision support framework to evaluate sustainable drainage designs. Procedia Eng. 70, 343–352. http://dx.doi.org/10.1016/j.proeng.2014.02.039.

Cigna, F., Jordan, H., Bateson, L., McCormack, H., Roberts, C., 2015. Natural and anthropogenic geohazards in greater London observed from geological and ERS- 1/2 and ENVISAT persistent scatterers ground motion data: results from the ECFP7-SPACE PanGeo Project. Pure Appl. Geophys. 172 (11), 2965–2995.

Costanza, R., 2000. Visions of alternative (unpredictable) futures and their use in policy analysis. Conserv. Ecol. 4 (1), 5. http://www.consecol.org/vol4/iss1/art5/.

Department for Environment, Food and Rural Affairs (DEFRA), 2008. Future Water: the Government's Water Strategy for England: Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs by Command of Her Majesty. February 2008.

Dearden, R.A., Price, S.J., 2012. A proposed decision-making framework for a national infiltration SuDS map. Manage. Environ. Qual.: Int. J. 23 (5), 478–485.

Dearden, R.A., Marchant, A., Royse, K., 2013. Development of a suitability map for infiltration sustainable drainage systems (SuDS). Environ. Earth Sci. 70 (6), 2587–2602. http://dx.doi.org/10.1007/s12665-013-2301-7.

Dillon, P., Pavelic, P., Toze, S., Rinck-Pfeiffer, S., Martin, R., Knapton, A., Pidsley, D., 2006. Role of aquifer storage in water reuse. Desalination 188 (February (1–3)), 123–134. http://dx.doi.org/10.1016/j.desal.2005.04.109. ISSN 0011-9164.

Environment Agency, 2015. Management of the London Basin Chalk Aquifer, Status Report 2015. . https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/429468/2015_London_GWL_Report_online.pdf.

Everard, M., Moggridge, H.L., 2012. Rediscovering the value of urban rivers. Urban Ecosyst. 15 (2), 293–314.

Fry, V.A., 2009. Lessons from London: regulation of open-loop ground source heat pumps in central London. Q. J. Eng. Geol. Hydrogeol. 42, 325–334. http://dx.doi.org/10.1144/1470-9236/08-087.

Future Water, 2008. The Government Strategy for England. February 2008 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69346/pb13562-future-water-080204.pdf.

Greater London Authority (GLA), 2008. Living Roofs and Walls, Technical Report: Supporting London Plan Policy. Greater London Authority ISBN 978 1 84781 132 5.

Greater London Authority (GLA), 2013. London's Zero Carbon Energy Resource: Secondary Heat, Report Phase 1. January 2013.

Greater London Authority (GLA), 2015. The London Plan, The Spatial Development Strategy for London Consolidated with Alternations since 2011. March 2015. City Hall, London. Available online 19 April 2016. https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/London%20Plan%20March%202015%20(FALP).pdf.

GO-Science, 2016. Government Office for Science, Future of Cities: Foresight for Cities. A resource for policy-makers GS/16/5 www.gov.uk/go-science.

Hatheway, A.W., Doyle, B.C., 2006. Technical history of the town gas plants of the British Isles. In: International Association of Engineering Geologists Conference Paper 564. Nottingham, September 2014.

Haxton, T., Crooks, S., Jackson, C.R., Barkwith, A.K., Kelvin, J., Williamson, J., Mackay, J.D., Wang, L., Davies, H., Young, A., Prudhomme, C., 2012. Future Flows Hydrology. http://dx.doi.org/10.5285/f3723162-4fed-4d9d-92c6-dd17412fa37b.

Heinz, I., Pulido-Velazquez, M., et al., 2007. Hydro-economic modeling in river basin management: implications and applications for the european water framework directive. Water Resour. Manage. 21 (7), 1103–1125.

Hollingum, J., 1998. Robots explore underground pipes. Ind. Rob.: Int. J. 25 (5), 321–325. http://www.emeraldinsight.com/doi/abs/10.1108/01439919810232468.

Huang, S.L., Hsu, W.L., 2003. Material flow analysis and emergy evaluation of Taipei's urban construction. Landsc. Urban Plann. 63, 61–74.

Hunt, D.V.L., Braithwaite, P., Rogers, C.D.F., 2013. A band rating system for domestic water use: influences of supply and demand options. In: The 3rd World Sustainability Forum. November 2013.

Hunt, D.V.L., Makana, L.O., Jefferson, I., Rogers, C.D.F., 2016. Liveable cities and urban underground space. Tunnelling Underground Space Technol. 55 (May), 8–20. http://dx.doi.org/10.1016/j.tust.2015.11.015. ISSN 0886-7798.

Jankowfsky, S., Branger, F., Braud, I., Rodriguez, F., Debionne, S., Viallet, P., 2014. Assessing anthropogenic influence on the hydrology of small peri-urban catchments: development of the object-oriented PUMMA model by integrating urban and rural hydrological models. J. Hydrol. 517 (September (19)), 1056–1071. http://dx.doi.org/10.1016/j.jhydrol.2014.06.034. ISSN 0022-1694.

Jaspers, F.G.W., 2003. Institutional arrangements for integrated river basin management. Water Policy 5, 77–90.

John, B., Withycombe Keeler, L., Wiek, A., Lang, D.J., 2015. How much sustainability substance is in urban visions?—An analysis of visioning projects in urban planning. Cities 48 (November), 86–98. http://dx.doi.org/10.1016/j.cities.2015.06.001. ISSN 0264-2751.

Jones, M.A., Hughes, A.G., Jackson, C.R., van Wonderen, J.J., 2012. Groundwater resource modelling for public water supply management in London. In: Shepley, M.G., Whiteman, M.I., Hulme, P.J., Grout, M.W. (Eds.), Groundwater Resources Modelling: a Case Study from the UK. Geological Society of London, pp. 99–111 Geological Society Special Publications, 364.

Jones, E., 1966. Towns and Cities. Oxford University Press 152 pp.

Kirkpatrick, L.O., Smith, M.P., 2011. The infrastructural limits to growth: rethinking the urban growth machine in times of fiscal crisis. Int. J. Urban Reg. Res. 35, 477–503. http://dx.doi.org/10.1111/j.1468-2427.2011.01058.x.

Koger, S.M., Winter, D.D., 2010. The Psychology of Environmental Problems: Psychology for Sustainability. Psychology Press, New York, NY, USA.

Kooy, M., Bakker, K., 2008. Technologies of government: constituting subjectivities, spaces, and infrastructures in colonial and contemporary jakarta. Int. J. Urban Reg. Res. 32, 375–391. http://dx.doi.org/10.1111/j.1468-2427.2008.00791.x.

Kuras, O., Wilkinson, P.B., Meldrum, P.I., Oxby, L.S., Uhlemann, S., Chambers, J.E., Binley, A., Graham, J., Smith, N.T., Atherton, N., 2016. Geoelectrical monitoring of simulated subsurface leakage to support high-hazard nuclear decommissioning at the Sellafield Site, UK. Sci. Total Environ. 566 (-567), 350–359.

Lee, S., Quinn, A., Rogers, C., 2016. Advancing city sustainability via its systems of flows: the urban metabolism of Birmingham and its hinterland. Sustainability 8 (3), 220. http://dx.doi.org/10.3390/su8030220.

Lucas, H.C., Robinson, V.K., 1995. Modelling of rising groundwater levels in the Chalk aquifer of the London Basin. Q. J. Eng. Geol. Hydrogeol. 28, S51–S62. http://dx.doi.org/10.1144/gsl.qjegh.1995.028.s1.05.

MacDonald, A.M., Allen, D.J., 2001. Aquifer properties of the Chalk of England. Q. J. Eng. Geol. Hydrogeol. 34, 371–384.

Macdonald, D., Dixon, A., Newell, A., Hallaways, A., 2012. Groundwater flooding within an urbanised flood plain. J. Flood Risk Manage. 5 (1), 68–80. http://dx.doi.org/10.1111/j.1753-318X.2011.01127.x.

Mansour, M.M., Hughes, A.G., 2004. User's Manual for the Distributed Recharge Model ZOODRM. British Geological Survey, pp. 61 IR/04/150 Unpublished.

Mayor of London, 2011. Securing London's Water Future, The Mayor's Water Strategy October 2011. https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/water-strategy-oct11.pdf.

Mayor of London, 2014. London Infrastructure Plan A Consultation 2050.

Ministry for the Environment, 2009. On Tap? Attitudes, Behaviours, and Perceptions of Household Water Use—informing Demand Management. Ministry for the Environment, Wellington.

Musolff, A., Leschik, S., Möder, M., Strauch, G., Reinstorf, F., Schirmer, M., 2009. Temporal and spatial patterns of micropollutants in urban receiving waters. Environ. Pollut. 11, 3069–3077.

NFRA, 2015. National River Flow Archive, Gauging Station 39001 Thames at Kingston 1883–2015. http://nrfa.ceh.ac.uk/data/station/info/39001. Accessed December 2015.

Navarro, A., Carbonell, M., 2007. Evaluation of groundwater contamination beneath an urban environment. J. Environ. Manage. 85 (2), 259–269. http://dx.doi.org/10.1016/j.jenvman.2006.08.021.

Neal, C., Robson, A.J., 2000. A summary of river water quality data collected within the Land-Ocean Interaction Study: core data for eastern UK rivers draining to the North Sea. Sci. Total Environ. 251-252, 585–665. http://dx.doi.org/10.1016/S0048-9697(00)00397-1.

Newton, P., Meyer, D., 2013. Exploring the attitudes-action gap in household resource consumption: does 'environmental lifestyle' segmentation align with consumer behaviour? Sustainability 5 (3), 1211–1233.

O'Shea, M.J., Sage, R., 1999. Aquifer recharge: an operational drought-management strategy in North London. Water Environ. J. 13 (6), 400–405.

Peel, A., 2014. Abandoned Landfill Sites Throughout the UK Routinely Leach Polluting Chemicals into Rivers, Say Scientists. Planet Earth Online. 28 August 2014. http://planetearth.nerc.ac.uk/news/story.aspx?id=1754.

Perry, T., Nawaz, R., 2008. An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom. Landscape Urban Plann. http://dx.doi.org/10.1016/j.landurbplan.2007.12.004.

Pitt Review, 2008. Learning the Lessons from the 2007 Floods. pp. 505. http://webarchive.nationalarchives.gov.uk/20100807034701/http:/archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html. (Accessed online 1 October 2016).

Pratesi, F., Tapete, D., Del Ventisette, C., Moretti, S., 2016. Mapping interactions between geology, subsurface resource exploitation and urban development in transforming cities using InSAR persistent scatterers: two decades of change in Florence, Italy. Appl. Geogr. 77, 20–37.

Price, S.J., Ford, J.R., Campbell, S.D.G., Jefferson, I., 2016. Urban Futures: the sustainable management of the ground beneath cities. In: In: Eggers, M.J., Griffiths, J.S., Parry, S., Culshaw, M.G. (Eds.), Developments in Engineering Geology. Geological Society Engineering Geology Special Publication 27. Geological Society of London, London, UK, pp. 19–33.

Prudhomme, C., Dadson, S., Morris, D., Williamson, J., Goodsell, G., Crooks, S., Boelee, L., Davies, H., Buys, G., Lafon, T., 2012. Future Flows Climate. http://dx.doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797.

RBKC, 2014. Basements Policy Formulation Report, Partial Review of the Core Strategy. Regulation 19, Town and Country Planning (Local Planning)(England) Regulations 2012. The Royal Borough of Kensington and Chelsea February 2014.

Rachwal, T., Culshaw, F., Leeks, G., 2014. Future Visions for Water and Cities: A Thought Piece. London:UK Water Partnership. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/439301/gs-15-27-future-visions-for-water-and-cities-thought-piece.pdf. (Accessed online 20 November 2016).

Rogers, C.D.F., Lombardi, D.R., Leach, J.M., Cooper, R.F., 2012. The urban futures methodology applied to urban regeneration. Proc. ICE Eng. Sustainability 165 (1), 5–20 ISSN 1478-4629.

Rojas-Torres, G., Nápoles-Rivera, F., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M., 2014. Optimal design of sustainable water systems for cities involving future projections. Comput. Chem. Eng. 69 (October), 1–15. http://dx.doi.org/10.1016/j.compchemeng.2014.05.026. ISSN 0098-1354.

Royse, K.R., de Freitas, M., Burgess, W.G., Cosgrove, J., Ghail, R.C., Gibbard, P., King, C., Lawrence, U., Mortimore, R.N., Owen, H.G., Skipper, J., 2012. Geology of London, UK. Proc. Geol. Assoc. 123, 22–45.

Selby, J., 2011. 'Behaviour Change and Water Demand Management', Presentation to Institution of Civil Engineers and Royal Academy of Engineering, 22 November 2011. Department of International, Relations University of Sussex.

Simoni, R., 2013. Gotthard Base Tunnel The World's Longest Railway Tunnel AlpTransit Gotthard AG. http://akce.fd.cvut.cz/sites/default/files/dokumenty/NEAT2013_1_Simoni.pdf. (Accessed online 9 January 2017).

Slingo, J., Belcher, S., Scaife, A., McCarthy, M., Saulter, A., McBeath, K., Jenkins, A., Huntingford, C., Marsh, T., Hannaford, J., Parry, S., 2014. The Recent Storms and Floods in the UK. Met Office CEH Report. 29 pp.

Sterling, R., Admiraal, H., Bobylev, N., Parker, H., Godard, J.P., Vähäaho, I., Rogers, C.D., Shi, X., Hanamura, T., 2012. Sustainability issues for underground space in urban areas. Proc. ICE-Urban Des. Plan. 165, 241–254.

Stuart, M., Lapworth, D., Crane, E., Hart, A., 2012. Review of risk from potential emerging contaminants in UK groundwater. Sci. Total Environ. 416, 1–21. http://www.sciencedirect.com/science/article/pii/S0048969711013908.

TWUL, 2015. Thames Water Utility Ltd. Final Water Resource Management Plan 2015–2040. Appendix E Exec Summary https://www.thameswater.co.uk/tw/common/downloads/wrmp/WRMP14_Section_0.pdf.

Taylor, R.G., Scanlon, B., Döll, P., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M., MacDonald, F.P., Fan, A., Reed, Y., Yechieli, M.M., Gurdak, Y., Allen, J.J., Shamsudduha, D.M., Hiscock, M., Yeh, K., Holman, P.J.-F., Treidel, H., 2013. Ground water and climate change. Nat. Clim. Change 3, 322–329.

UK National Ecosystem Assessment, 2014. The UK National Ecosystem Assessment: Synthesis of the Key Findings. UNEP-WCMC, LWEC, UK.

UN-WWAP (United Nations World Water Assessment Programme), 2015. The United Nations World Water Development Report 2015: Water for a Sustainable World. UNESCO, Paris Available at: https://www.unesco-ihe.org/sites/default/files/wwdr_2015.pdf.

Water Technology. http://www.water-technology.net/projects/water-desalination/.

Wiek, A., Iwaniec, D., 2014. Quality criteria for visions and visioning in sustainability science. Sustainability Sci. 9, 497–512. http://dx.doi.org/10.1007/s11625-013-008-6.

Wilkinson, B., 1985. Rising groundwater levels in London and possible effects on engineering structures Hydrogeology in the Service of Man. In: Memoires of the 18th Congress of the International Association of Hydrogeologist. Cambridge.

Wolf, L., Morris, B., Burn, S., 2006. AISUWRS: Urban Water Resources Toolbox, 2006. IWA Publishing, London, UK ISBN 1843391384.

Wolman, A., 1965. The metabolism of cities. Sci. Am. 213, 179–190.