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Sustainable Water Management in the City of the Future

Integrated Project

Global Change and Ecosystems

Deliverable D2.3.2b Combined surface and ground water modelling studies

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1 Introduction

Future groundwater responses to changes to the pattern of urban water management across a city are not related solely to stormwater management but to all aspects of urban water management from alterations to water supply and waste water management through to adaptations to the natural water systems including precipitation. As a consequence, the relationship between a groundwater body and surface water should not be investigated piece meal but as part of integrated water resources planning. For this reason the decision was made to expand the evaluation of stormwater management on groundwater conditions to include the whole urban water management system.

To carry out the modelling studies, the current research integrates the work undertaken under WP1.2 on the development of the City Water Balance model for scoping urban water management options with the evaluation of groundwater surface water interactions. City Water balance was created to evaluate the response of the natural water as well as the piped water systems in a city to changes in urban water management. An objective of the research is to examine whether City Water Balance can be effective for evaluation of the groundwater response to changes in surface water management practices.

For the current studies, the application of City water Balance to establish potential impacts of surface water management on groundwater conditions in Birmingham was extended to consider the range of groundwater adjustments that would arise from the scenario planning derived by the Birmingham Learning Alliance. In addition, three Master's projects were undertaken in different cities using City Water balance to explore the applicability of City Water Balance for urban groundwater – surface water interactions. The three projects addressed three rather different cities: Alexandria, Egypt, Dunedin (Florida), USA and Accra, Ghana. The studies provided valuable applications of the City Water Balance modelling system and the underpinning concepts employed for its development.

This report summarises in greater detail the results from the primary study in Birmingham and provides a brief overview of the key findings from the application of City Water Balance to the other three Cities. The complete results for all four studies are given in the following theses:

Last, E. M. (2010) CITY WATER BALANCE A New Scoping Tool For Integrated Urban Water Management Options, Unpublished PhD Thesis, University of Birmingham

Spencer, E. (2010) City Water Balance (CWB): an analysis of a new Integrated Urban Water Management scoping tool, using the city of Dunedin, Florida,

Unpublished MSc Thesis, School of Geography Earth and Environmental Sciences, University of Birmingham

Jaweesh, M (2010) Application of City Water Balance to explore options for change in Alexandria, Egypt. Unpublished MSc Thesis, School of Geography Earth and Environmental Sciences, University of Birmingham

Simister, R. (2010) Urban water management: Using The city water balance model to model urban water systems in Accra, Ghana, Unpublished MSc Thesis, School of Geography Earth and Environmental Sciences, University of Birmingham.

2 City Water Balance

City Water Balance forms part of the City Water KBS/DSS and is a scoping model for simulating the dynamic balances of water, energy and pollutants at the city scale. It works on a daily time step over decadal periods and can explore water and wastewater stresses in response to climate change and changing urban populations under a range of strategic technical options for improved IUWM. Five indicators, characterizing neighbourhood or city-scale conditions, are currently derived for output: water demand/supply ratios; wastewater production; water quality; life cycle energy and life cycle cost.

2.1 City Water Balance – model concepts

A primary design goal for City Water Balance (*CWB)* was that it should be applicable to cities where mapping and monitoring are underdeveloped as well as to cities possessing detailed knowledge of their water and wastewater systems. The key idea for City Water Balance is that it is an urban hydrological modelling system that works at the lowest spatial and temporal resolution commensurate with the provision of meaningful indicator outputs for the comparison of different water management options.

2.1.1 Spatial and Temporal Resolution

To model land use within the cityscape, the unit block concept adopted for the water balance model, *Aquacycle* (Mitchell *et al.*, 2001) is employed within *CWB*. The unit block describes the storage, use and transmission of water of easily recognized land uses (e.g houses with gardens, apartment blocks, hospitals or golf courses). Fundamental attributes of the unit block are pervious/impervious areas, water demand profiles and pollutant loads (Mitchell *et al.*, 2001; Mitchell and Diaper, 2005). A library of forty-nine unit block types has been created based on data from the United Kingdom. This will expand as new types are identified during the application of the model to other SWITCH demonstration cities.

The city waterscape is characterised for input to CWB by mapping the mosaic of neighbourhoods containing similar unit block types. Neighbourhoods can be identified using a combination of available aerial photography and road maps, with some additional ground truthing: a city can be mapped quickly through this approach. *CWB* departs from the modelling of water transfers between neighbourhoods adopted by *Aquacycle* and models lateral flows using a network of subcatchments formed by the wastewater and natural drainage networks. Subcatchments may contain any number of whole neighbourhoods. The use of subcatchments to aggregate lateral flows from neighbourhoods means that the neighbourhood areas can be based solely on the pattern of land use. This enables more rapid mapping of the water demands across a city as well as improving the representation of the wastewater and stormwater networks at the city scale.

A daily timestep was selected as appropriate for modeling the transient behavior of the city water system under changing land use, water management strategies and climate scenarios. Although this level of aggregation results in the loss of flow variations needed for flood analysis, it provides sufficient information (*Makropoulos et al.*, 2008) for the comparison of different water management options, especially for the long-term simulations necessary for sustainability assessments.

2.1.2 Mains Water

Mains water is modelled as an external supply. The mains water demand is calculated as the sum of the neighbourhood demands that are not met by local or decentralised supply schemes. A proportion of the supply is lost as leakage within the modelled region. Mains water is supplied at fixed contaminant concentration and with a fixed energy and economic cost attached to it. This simplified approach to the modelling of the mains supply has been adopted as cost, energy and contaminant data for water supply are typically more easily gathered as aggregate values and mains source modelling is avoided. Water demand input to *CWB* is based on land use in terms of per capita demand or per unit area demand for different water use requirements (*Hunt and Lombardi*, 2006). *CWB* can simulate the impact of seasonal occupancy to account for population influx through tourism at certain times of the year or migration outwards at times of high temperatures (*Manoli*, 2009). The application of *Aquacycle* in the early stages of the SWITCH project to Athens proved to be problematic as it was unable to simulate demand during the summer for this reason (*Karka et al.*, 2006). For residential blocks an alternative model for the estimation of indoor demand is available. This has been based on ideas adopted in *UWOT* (*Makropoulos et al.*, 2008) where the demand profile is built from a selection of water using appliances (bath, W.C., kitchen tap etc.). A library of default options is available with *CWB*, to which the user can add their own appliances, if required.

2.1.3 Runoff

There are five types of surface that can generate runoff in *CWB*: roof, pavement, garden, road and Public Open Space. In each neighbourhood, the degree to which these surfaces are connected to the piped stormwater system varies. To address the issue of overland flow outside the sewer network *CWB* uses the idea of effective areas, originally introduced in *Aquacycle* (*Mitchell et al*., 2001). The effective area is defined as the proportion of the total area of an impermeable surface (roof, paved, road) generating runoff that goes directly to the stormwater system. Runoff from non-effective areas flows onto nearby pervious space or sustainable urban drainage systems (SUDS), if available.

2.1.4 Natural Systems

A single layer two dimensional areal groundwater system can be modelled beneath a city. The groundwater is fully coupled to the neighbourhoods and surface water features. Rivers, lakes and ponds can all be represented as discrete water bodies. Rivers are split into reaches. Backwater or reverse flows in a river cannot be simulated. External water supplies to surface water bodies are simulated as simple source terms. Stormwater or wastewater subcatchments may discharge to the surface water network.

The groundwater model uses a fully implicit finite difference numerical approximation. Connections between the surface and the groundwater system are coupled whereby interflows are based on groundwater conditions at the start of a timestep and the groundwater heads at the end of a timestep based on the calculated interflow. The adoption of a daily timestep permits this approximation in the coupling to be used with little loss of accuracy.

2.1.5 Water Management Options

CWB allows exploration of the sustainability of a variety of water management options at different spatial scales. These are green roofs, rainwater harvesting, wastewater recycling, septic tanks, borehole abstraction, porous paving, porous asphalt, swales, filter strips, soakaways, retention ponds and detention basins. Inflows to SUDS are direct precipitation and runoff. Outflows are evaporation, infiltration, throughflow, and overflow. Flow along conveyance swales is modelled by a normal depth approximation using the swale cross-section and a manning's resistance coefficient.

3 Birmingham

3.1 Birmingham

Birmingham is located in central England (Fig. 3.1) and is the second most populated British city after London. It has an elevation of 75 to 350 m above sea level and a population of approximately one million people (*Office for National Statistics*, 2001a). The City of

Birmingham, the focus of this case study (Fig. 3.2), is part of the larger West Midlands conurbation which includes several neighbouring towns and cities; such as Solihull, Wolverhampton and the towns of the Black Country.

Although Birmingham's industrial importance has declined since the post-war economic boom during the period 1950-1970 (*Lerner,* 2004), it has developed into a national commercial centre, being named as the second best place in the UK to locate a business, the 14th best in Europe (*Birmingham Post*, 2009) and the fourth most visited city by foreign visitors in the UK (*Khatri & Vairavamoorthy*, 2009). In 2003 the service sector accounted for 78% of the city's economic output and 97% of its economic growth (*National Office for Statistics*, 2003). The Birmingham area accounts for 42% of the UK's conference and exhibition revenue (*NEC Group*, n.d.). It has three universities and two university colleges which have over 65,000 students and employ approximately 15,000 staff. It also has the country's busiest shopping centre (*icBirmingham*, 2004), the Bullring, and the largest department store outside of London, House of Fraser (*PropertyMall*, 1998).

Figure 3.1 Location of Birmingham within the UK.

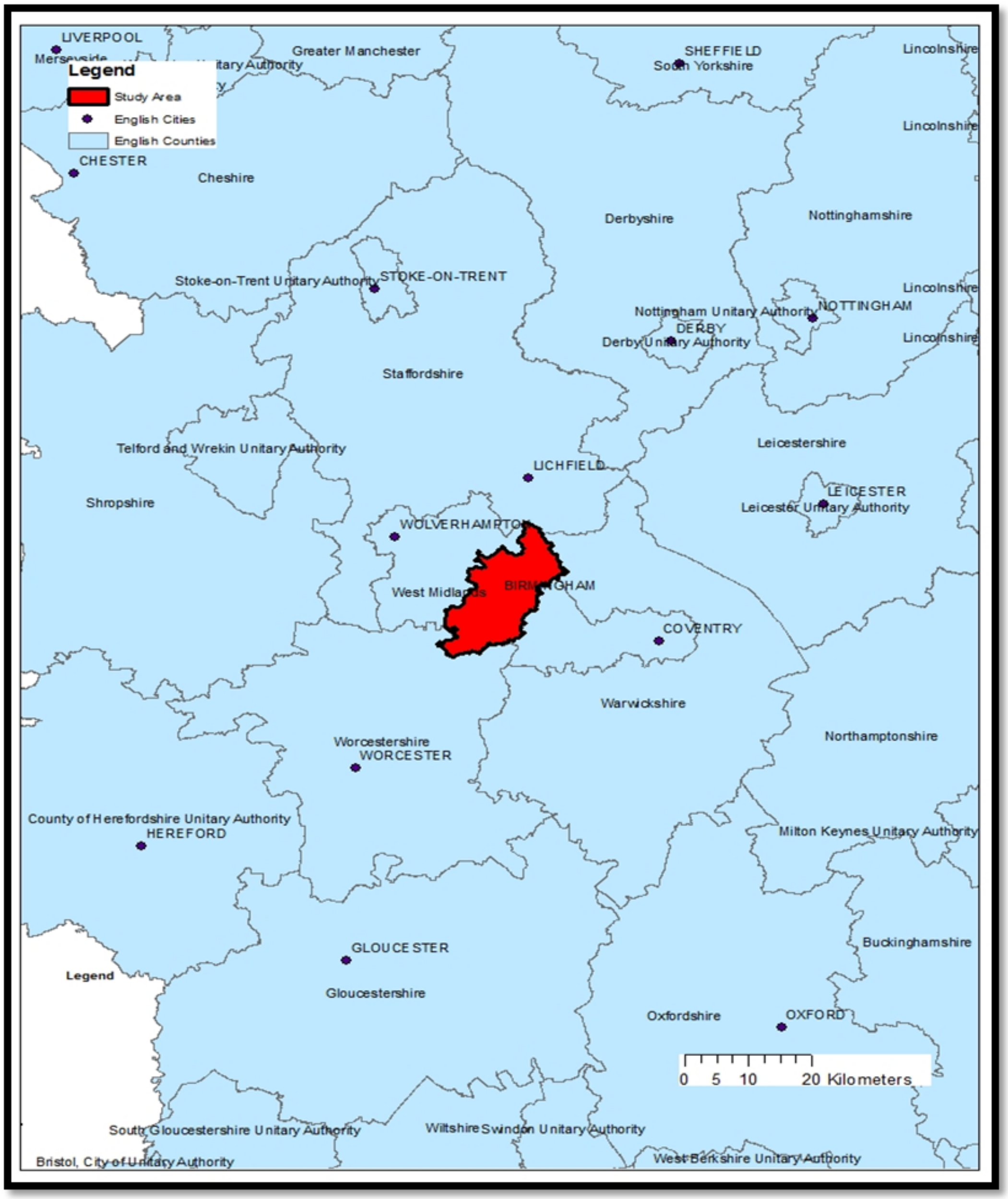

Figure 3.2 The Birmingham Study Area and surrounding area.

Birmingham has a temperate maritime climate with average maximum temperatures in summer (July) of 20°C and in winter 4.5°C (*Wikipedia*, 2010). Annual average precipitation from 2000-2009 was 877 mm and annual average potential evaporation was 616 mm (*University of Birmingham Climate and Atmospheric Research Group*, 2007).

The City of Birmingham is underlain by quaternary glacial deposits (0 – 40m) beneath which two rock formations dominate: Mercia Mudstones and Sherwood Sandstones (*Ellis & Rivett*, 2007). The Sherwood Sandstones form an unconfined aquifer bounded in the southeast by the Birmingham Fault which downthrows the sandstone layer to the east confining the aquifer beneath the Mercia Mudstone Formations. At the west and south-west boundaries the Sherwood Sandstones thin out over older Carboniferous formations (Warwickshire mudstones and sandstones).

The Triassic sandstone aquifer was used extensively for public supply until approximately 1900 at which time reservoirs were established in Wales and since then the majority of groundwater abstraction has been for industrial use (*Hughes et al.*, 1999). Groundwater levels have risen significantly since 1960 as a result of industrial decline and consequent reduced abstraction (*Lerner*, 2004).

The dominant river in Birmingham is the Tame whose tributaries include the Rea and the Cole as well as numerous brook and streams. It is the main river in the West Midlands and the most important tributary of the River Trent (*EA*, 2004). The Tame flows in an easterly direction and stretches about 40 km from its source in Oldbury to its confluence with the Trent. The catchment of the Tame up to its confluence with the river Blythe, just to the East of the study area, is ~54,500 ha (*EA*, 2010).

The canal network in Birmingham is one of the densest in the country (*Greswell*, 1992). Within the study area there are four main canals: the Tame Valley, the Worcester & Birmingham, the Grand Union and the Birmingham & Fazeley (*Turner*, 2009).

The privatised water company Severn Trent Water Limited (STW) is responsible for most of the water supply and all of the drainage and sewage treatment within the Birmingham area. STW supplies 1,900 Ml/day to 7.4 million people, and sewerage services, treating 2,500 Ml/day, to 8.5 million people in an area covering 21,000 square kilometres in the Midlands and mid-Wales. Severn Trent's assets include 46,000 km of water mains, 54,000 km of sewers, 181 groundwater treatment works and 1,017 sewage treatment works. Water is sourced from river abstraction (40%), groundwater (30%) and reservoirs (30%) (*Severn Trent Water*, 2007). The Birmingham Water Resource Zone (WRZ), one of 6 that STW supplies, includes most of the City of Birmingham. The Elan Valley reservoir in Wales is the principle source of water for this WRZ, supplying in excess of 300,000 Ml/day (*Khatri & Vairavamoorthy*, 2009). Minworth Wastewater Treatment Works is STW's largest plant, treating sewage from a population equivalent of 1.75 million (*BiWater*, n.d.). The catchment for Minworth includes the entire city of Birmingham.

Water issues and challenges that the city faces are population increase, climate change, allocation of responsibility for water management, affordability and source control of pollution. The Regional Spatial Strategy is looking at development options to meet the government's national housing targets. There are currently 400,000 dwellings (2001 Census) in Birmingham and the three options being considered for Birmingham are the addition of a further 70,000, 90,000, or 105,000 new houses by 2026 (*SWITCH*, 2007). This would increase the population to 1.3 million in the next 15 years and place more pressure on the existing, aging Victorian centralised supply systems. Demand management and the consideration of stormwater harvesting and wastewater re-use are strategies that are likely to

be increasingly employed in response to the rising demand. Climate change, resulting in greater intensity rainfall events, is likely to increase the frequency of river flooding and sewer overflows. A further significant challenge that faces UK cities, including Birmingham, is the difficulty in adopting strong policies and Best Practice when there are multiple authorities involved in urban water management: primarily the Environment Agency, the City Corporation and the Water Company.

3.2 Introduction to the Scenarios

Three scenarios were proposed by the Birmingham Learning Alliance to investigate alternative water management strategies. These are summarised here.

3.2.1 Scenario 1

The urban heat island effect has caused the maximum annual temperature to rise by 10 °C, resulting in air conditioning in nearly every building. The energy crisis has hit and there is limited availability of fossil fuels. Increasing temperatures across the UK has caused a rapid increase in the population of Birmingham, which has doubled to approx. 2 million by 2050, due to migration from the South-East. As a result of the large population rise, there is increasing densification/urbanisation of the city. Building controls have been lax, and legislation surrounding water and environmental management is not cohesive. Many of the developments are inefficient in terms of water and energy use, but approximately 30% have brown roofs. The water requirements of an increased population have not been met by improved capacity of the existing Victorian infrastructure, which is now close to collapse. Water and wastewater is pumped large distances but, due to energy rationing, there is often interrupted supply (no water supply for four hours per day on a rota system between districts).

Modelling implications:

- Increased occupancy factor in city centre from 300 to 600. Double residential occupancy factors from 2.1 to 4.2. Since much of central Birmingham has recently been regenerated (*Birmingham City Council*, 2008) it may reasonably be assumed that there will not be significant further work undertaken in this area before 2050. If it is also assumed that it is unlikely that large areas of existing housing stock will be regenerated then the most probable consequence of increased population is greater household occupancy, forced by rising house prices.
- 30% of study area has brown roofs. The total roof area in the study area is 3,680 hectares and 30% of this is 1104 ha. Application of green roofs is more economical the larger the roof (*Groundwork*, 2004) and so is more likely to be applied to industrial and commercial landuses than residential. In addition it is required that roofs have a slope of less than 15 degrees (*Daywater*, n.d.b) which renders many residential properties unsuitable. The sum of all non-residential roof areas is 1,390 ha. It is assumed that brown roofs have been applied to this sector.
- Increase leakage to 35% from 25%.
- Increase energy cost of centralised supply by 50% from 2.1 (*Water UK*, 2009) to 3.25 kWh. Increase cost by 50% from £1.3/m^3 to £1.95/m^3 at net present value.

- Reduce mains supply to 90% of demand, representing interrupted supply. Many commercial and industrial developments have some degree of water storage capacity and so are unlikely to be affected by supply interruption. In addition, many of the regeneration developments have on-site water storage capacity because the current network is unable to meet projected peak demand (*Birmingham City Council*, 2008). However, new build residential stock outside the city centre have been built without water tanks and so are reliant on mains pressure. These will be affected by the interruptions and it is assumed that a conservative 10% of total demand will not be met.

3.2.2 Scenario 2

The population has doubled to nearly 2 million inhabitants resulting in high density housing and increased urbanisation. The supply of fossil fuels is running low. After the recession of 2008/2009 the economy boomed, but there was no planning or investment in water management or energy supplies. Much of the water network is still based around the Victorian infrastructure and the city relies on conventional energy supplies. Water has become increasingly scarce, potable water is imported from Scotland and Wales allowing 80 l/p/d, but there are rumours of the supply being restricted to 50 l/p/d. Therefore the city is now looking at recycled water to provide 50 l/p/d of additional non-potable supplies. Flash flooding has caused storm tanks to fill up too quickly and overflows are allowed to discharge freely to receiving watercourses adversely affecting aquatic systems.

Modelling implications:

- Increased occupancy factor in city centre from 300 to 600. Double residential occupancy factors from 2.1 to 4.2.
- Increase leakage to 35% from 25%.
- Increase energy cost of centralised supply by 50% from 2.1 (*Water UK*, 2009) to 3.25 kWh. Increase cost by 50% from £1.3/m^3 to £1.95/m^3 at net present value.
- Reduce mains supply to equivalent of 80l/c/day and 50l/c/day (reduce available mains supply to 80/150 of total demand, where 150 is the present day per capita daily demand. Reduce residential demand to 130 l/c/day in accordance with DEFRA's Future Water strategy (*Water UK*, 2009).
- Supply deficit with combination of rainwater harvesting, greywater re-use and borehole abstraction.

3.2.3 Scenario 3

After the 2008/2009 recession, the economy never fully recovered and Britain is still paying off the debt incurred. There was an energy and water crisis in 2015, but the radical shake up over the course of the following 5 years resulted in the UK becoming more self sufficient. The population of Birmingham has not significantly increased above the 2010 level of approximately 1 million. This is in agreement with the report produced by *Entec* (2003) on "The Potential Impacts of Climate Change in the West Midlands" which estimates the

population of Birmingham will not increase by more than 100,000 by 2025. In 2020 Birmingham went through a green revolution and became a water sensitive city. Potable water was removed from the supply chain and is now delivered to offices and private dwellings in a similar way to "water at work". The piped supply is provided to a "good" standard and is suitable for washing, clothes washing etc but not drinking. As a result of a widespread education programme to increase awareness of individual responsibility with regard to sustainability, communities have become more proactive in their approach to environmental management. There is a single agency responsible for water management in the city and it is adequately funded. Privatised water companies have been dissolved and there is now a government agency responsible for water/wastewater management in the UK. The UK now produces 80% of its own food, and Birmingham meets its targets through a mixture of rooftop gardens, allotments and common green space planted with fruits and vegetables which residents maintain and use.

Modelling implications:

- Occupancy factors stay constant
- Leakage stays constant
- If 60% of the energy cost of centralised water supply is due to pumping (*Tarantini and Ferri*, 2001; *Friedrich et al.*, 2006) then the remaining 40% will be reduced as a consequence of lowered treatment standards for centralised supply. If this is assumed to be halved, a reduction in the energy cost of centralised supply from 2.15 kWh/m^3 (*Water UK*, 2009c) to 1.72 kWh/m^3 is achieved. Similarly the economic cost is reduced from £1.3/m^3 to £1.04/m^3 NPV. Cost of wastewater treatment remains the same at 2.15 kWh (*Water UK*, 2009).
- All commercial and industrial areas have brown roofs. 30% of residential areas have green roofs.
- Increase irrigation of POS to 70% but not supplied with mains water. Irrigation demand satisfied with MC-scale greywater re-use.

3.3 Base Cases

To undertake an analysis of the impacts of the different scenarios and the range of alternative water management strategies that could be deployed to mitigate the impacts of the scenarios two cases were used for comparative purposes.

3.3.1 2009 Base Case

For comparative purposes business-as-usual (centralised supply and wastewater treatment) was simulated for the year 2009 (Fig. 3.3). Note that decentralised alternative water management (WM) energy use and cost is non-zero because borehole abstraction is currently (2010) used to supply a number of commercial establishments in the study area.

3.3.2 2055 Base Case

Climate data for 2055 were calculated using percentage changes of temperature and precipitation, from current climate, predicted by the UKCP09 model (*Met Office*, 2010). Data from 2009 were used as the base year for extrapolation to 2055 since this is the most recent full year of climate data. This year was slightly wetter (914 mm precipitation) than the average for the period 2000-2008 (877 mm) (*University of Birmingham Climate and Atmospheric Research Group*, 2007). If a drier year had been used as a basis for calculation of the 2055 climate then less runoff and recharge would be expected and the effectiveness of rainwater harvesting strategies would be reduced for example. In addition irrigation demand would increase. Apart from the change in climate no other data were altered from the 2009 simulation.

The 2055 climate change scenario affected the groundwater conditions substantially. Annual recharge depths from the pervious stores were 216 mm (2009) and 182 mm (2055), which is a 16 % reduction. Steady-state aquifer-averaged groundwater levels are predicted to fall by 0.5 m between 2009 and 2055 as a result of the reduction in recharge. Figure 3.3 shows the distribution of the change in groundwater level (GWL) across the aquifer. The groundwater level drops more in areas away from the river systems. The reason for this is that the reduced recharge lowers the flows to the rivers and reduces the hydraulic gradients. However, the reduction in gradient to the rivers has only a minor impact on water levels near the rivers because the river water levels are largely unchanged. The effect of reduced hydraulic gradients on groundwater levels is larger at distance from the discharge point; the river acts as the pivot point.

Surface runoff decreased by 8.3% (325mm to 298mm) as a result of decreased average precipitation, increased evapotranspiration (7.4%) and a decrease in groundwater overflow as a result of slightly lowered groundwater levels. Irrigation demand doubled from 4 mm/yr to 8 mm/yr as a result of increased evaporation from the soil stores. In reality garden irrigation is usually not applied based solely on soil moisture deficit, as modelled in *CWB*, but depends on the behaviour of the gardener, which is less easily quantifiable. Their decision to irrigate is affected by perceived plant water requirements, desired garden condition and affluence (*Mitchell et al.*, 2001). The increased temperatures predicted for 2055 may result in irrigation in excess of that predicted by the soil moisture deficit, as gardeners may perceive a greater need for irrigation based on increased temperatures.

The base case climate change scenario shows changes in urban water flows of the order of 10-20% from current climate, with reduction in runoff, recharge and precipitation and increased evaporation and irrigation demand.

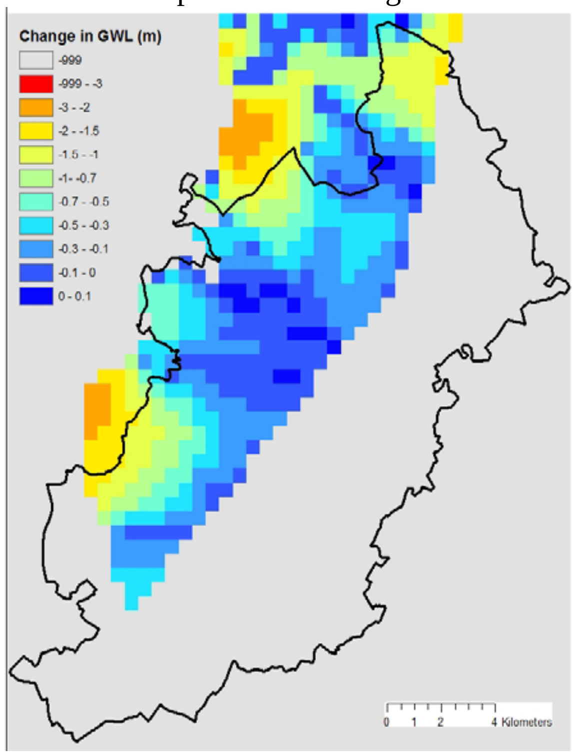

Figure 3.3 Change in GWL from 2009 base case to 2055 base case

3.4 Summary of Groundwater responses to alternative water management strategies

For the different Scenarios the following strategies were examined

Scenario 1

- Business as usual (ie no changes to current water management practices adopted in the city
- Non-residential Brown Roofs and Local Rainwater Harvesting (Brown roofs were applied to all non-residential buildings and rainwater harvesting (RH) ($40m^3$ concrete tanks with lifetime of 50 years; 5 toilets / unitblock) was installed for all industrial and commercial buildings)

Scenario 2

- Business as usual (ie no changes to current water management practices adopted in the city
- Rainwater Harvesting (Using neighbourhood rainwater harvesting to supply non potable indoor use, garden and public open space irrigation demands
- Minicluster Wastewater Recycling (Using fixed or variable tank capacity for neighbbourhood WW recycling for non potable indoor use and irrigation)
- Minicluster Rainwater Harvesting and Wastewater Recycling (Using a combination of rainwater harvesting and WW recycling at neighbourhood scale to supply non potable indoor use and irrigation demands to eliminate the mains deficit
- Borehole abstraction and Minicluster Wastewater Recycling (Using Large boreholes situated in each subcatchment that overlies the unconfined aquifer and away from the western boundary, where the Sandstone thins out over the Carboniferous formations, and reasonable separation distance.)

Scenario 3

- Business-as-Usual
- Brown Roofs and neighbourhood Wastewater Recycling (Brown roofs were applied to all non-residential buildings, high-rise residential, apartments, old people's homes and detached residential buildings. Irrigation was supplied to public open spaces using 800 m^3 capacity subcatchment-scale wastewater reuse plants and mains back-up)

Illustrative Figures (3.4, 3.5 and 3.6) below show groundwater responses areally to different scenarios and strategies

Aquifer averaged groundwater levels are shown in Table 3.1. Groundwater levels are slightly lowered as a result of climate change between the 2009 and 2055 base cases. The water table stays at about the 2009 average level for Scenario 1 and 2 as a result of the increased leakage volumes from a deteriorating, centralised supply system struggling to cope with the greater demand of an increased population. The borehole abstraction strategy caused significant local drawdown (from 4 to 9 metres – Fig.3.5) and resulted in a lowering of the average water table by 1.3 m. Scenario 3 has the same population and leakage as the 2055 base case but has increased evapotranspiration as a result of widespread urban agriculture. This leads to a lowering of the average water table by 2.3 m across the aquifer as a result of reduced recharge.

Table 9.8 Water table heights averaged over the aquifer.

Scenario and strategy	Average groundwater height (m above datum)
2009 base case	125.6
2055 base case	125.1
Scenario 1 base	125.8
Scenario 2 base	125.2

Scenario 2 boreholes	123.9
Scenario 3	122.8

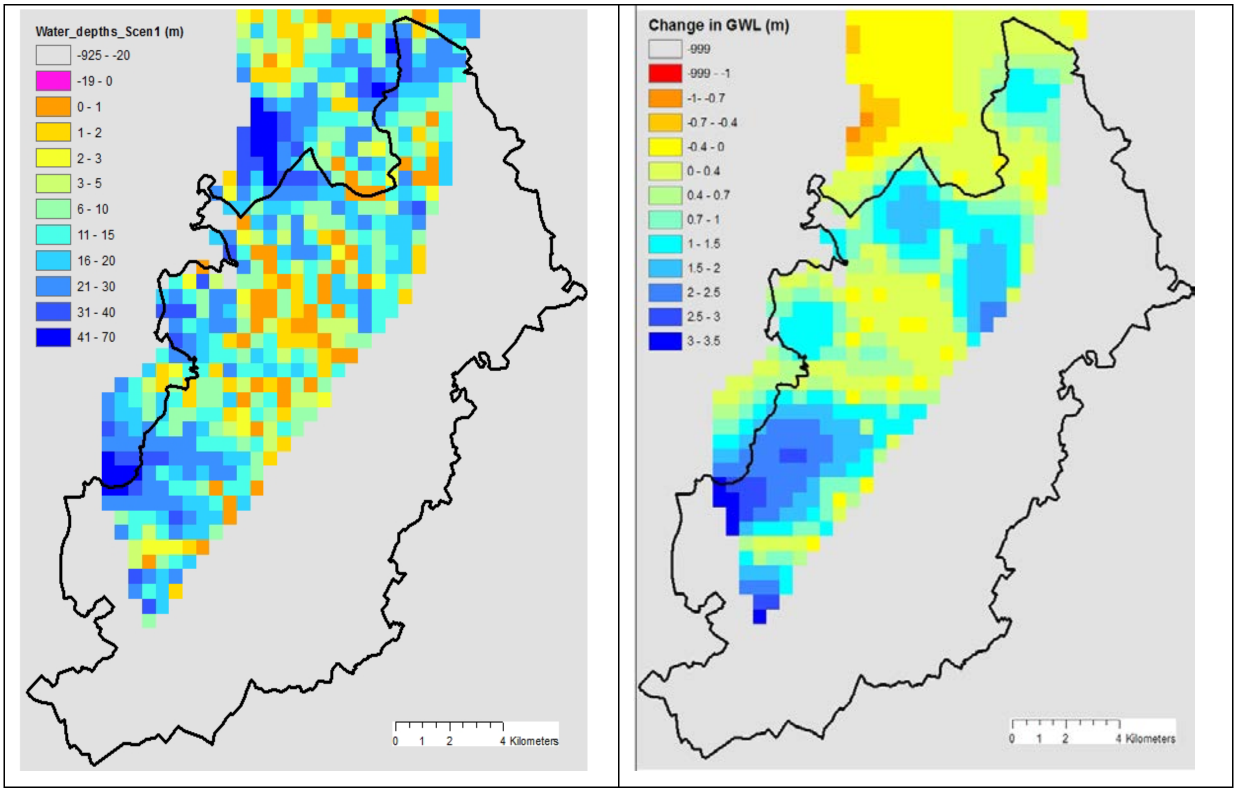

Figure 3.4 Steady state groundwater depths for the 2055 Scenario 1 business as usual (left). Change in GWL from 2055 base case to Scenario 1 business as usual (right).

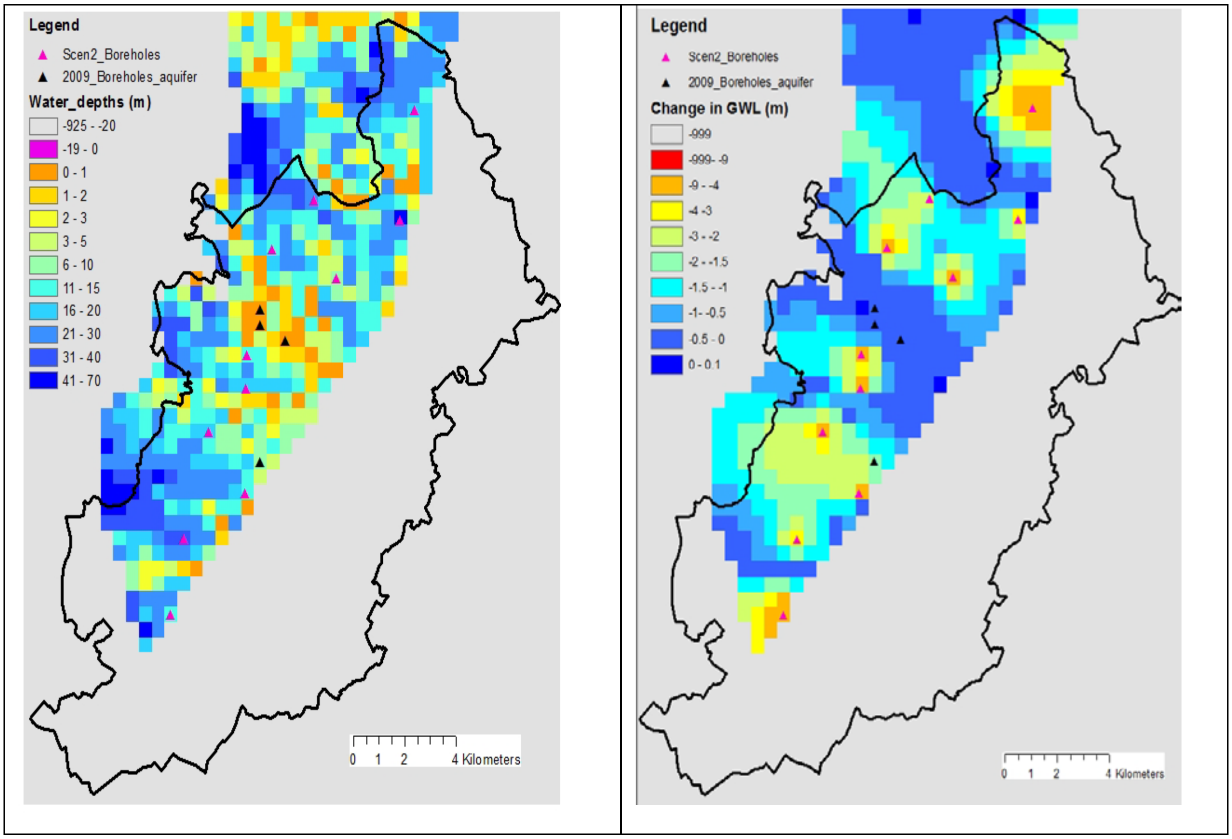

Figure 3.5 Steady state groundwater depths for the 2055 Scenario 2 borehole abstraction with WW strategy (left). Change in GWL from 2055 base case to Scenario 2 borehole abstraction with WW strategy (right).

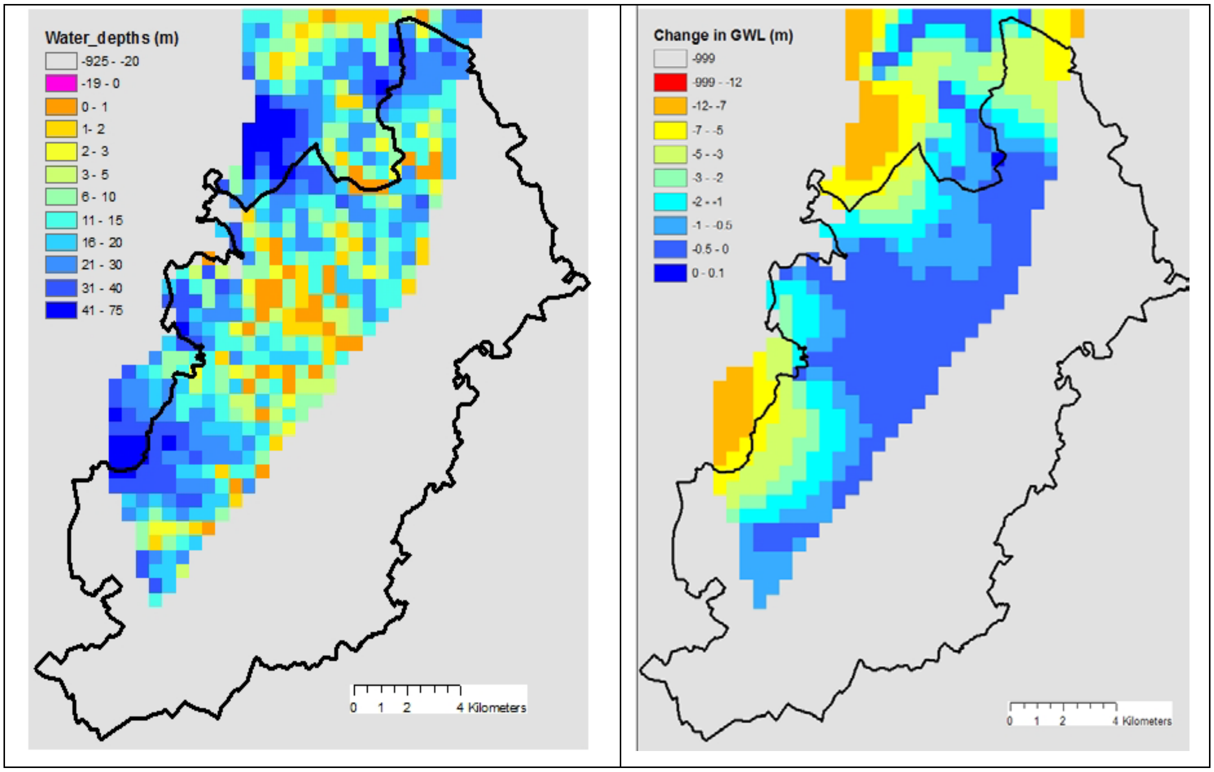

Figure 3.6 Water depths to groundwater for base case Scenario 3. Change in GWL from 2055 base case to Scenario 3 business as usual (right).

The key observations from the application of the alternative scenarios and strategies in terms of groundwater impacts have less to do with the magnitude of change in groundwater level and its relationship to the patterns of recharge and discharge across the city but more to do with the interdependence of the groundwater response to all factors influencing its response. This includes climate change, demographic change, economic change, stormwater management, water supply control and waste water management. Given this interdependence and given that in areas of shallow groundwater the potential negative effects of rising groundwater levels on drainage infrastructure could be influential, the value of City Water Balance as a tool for scoping potential groundwater surface water responses is made evident.

However, the modelling also shows that some simplifications in the modelling approach adopted within City Water Balance may not be appropriate for evaluating groundwater responses at the level of detail required and refinement of the model could be usefully undertaken in future. Moreover, in order to fully appreciate the significance of possible future groundwater conditions it is essential to examine the spatial patterns of change and not just the aggregate or average change, which might be preferable from the standpoint of indicator presentation. Significant volumes of groundwater discharge to overland flow were evident in areas where the groundwater is near the surface, generally around the rivers, in all scenarios. This is partly a result of the terrain smoothing that *CWB* uses and the coarse finite difference grid size (500m by 500m) used for the simulations. The current configuration of *CWB* is designed to give general indications, and not detailed groundwater dynamics. In addition, there are known areas of very shallow groundwater in Birmingham (e.g. springs on

the University of Birmingham campus), particularly near the Birmingham Fault and the River Tame and these cannot be adequately characterised using the simplified modelling approach .

4 Accra, Alexandria and Dunedin

Summaries of the modelling undertaken for these 3 cities and the key findings are presented below. Greatest interest lay in the application to Dunedin, where groundwater is a key resource for the city and where reclamation of waste water and management of the stormwater flows across the city are most important. While groundwater beneath Alexandria is important, the options for adapting the city's water scape so as to affect the groundwater flows are restricted. In Accra, the aquifer has little capacity for exploitation and draining the aquifer has little prospect for improving the surface drainage across much of the city.

4.1 Accra

Currently, only 55% of Accra has access to mains water, with water shortages and intermittent water connection to households becoming more common (AVRL 2010). In 2006 Accra became part of the SWITCH project as a demonstration city, which means that it promotes and undertakes research into sustainable urban water systems. A City Water Balance (CWB) model was successfully developed and calibrated, within the available limits of data availability, for the Accra Metropolitan Area that quantifies the inputs, processes and outputs of water within the urban water cycle. Three different population scenarios for Accra in 2030 were tested along with five different water management options for present day city. The population scenarios showed that the imported water might reach up to three times the imported water volume at present, prompting the need for implementing more sustainable water practices in the future. The results from using different water management options show, at the household scale, that the imported water volume for the study area was reduced by 15% by implementing either rain tanks or wastewater recycling options. The effect of implementing swales to prevent flooding reduced the stormwater run-off by up to 30%. Implementing larger scale stormwater tanks and wastewater tanks showed a decrease of imported water by 29%. The mains water supply system and sewer networks in Accra will need to be improved as a result of projected population increase and demand. The use of water management options and sustainable urban drainage schemes have been shown to reduce the demand of water at the household and at the larger scale and provides a way forward for implementing re-use and recycling of water in the city. Groundwater interactions with the surface water management could not be adequately tested as the groundwater conditions beneath the city could not be adequately identified. Groundwater quality beneath the city is known to be poor and drainage of the aquifer to promote infiltration and improved surface water conditions across the city would appear to be difficult to implement.

4.2 Alexandria

Water demand in Alexandria, like all other cities in Egypt, is increasing as the population expands. The water supply to Alexandria is derived almost exclusively from the Nile river and this is a finite resource and the allocation to Alexandria is fixed. A mismatch is beginning to arise between the available resource and the demand. In addition to resource limits, the disposal of wastewater from the effluent treatment plants is also of concern. Nearly all the waste water passes through Lake Mariout, after which it is discharged to the sea. This has rendered the water quality of the lakes to be poor and there is a considerable water resource that is being potentially wasted. Leakage rates from the water supply infrastructure are large. The leakage is to the low yielding aquifers beneath the city. Groundwater beneath the city is of low quality generally with salinities that are too high for potable water use. Precipitation is low over the city and can be regarded as negligible in water supply terms. There is a need, therefore, to examine the approaches that can be made to maximise the value of the water derived from the Nile by considering aspects of water demand management, wastewater treatment and recycling. Integrated Urban Water Management (IUWM) concepts are being examined within the city through a strategic planning exercise. Scenarios of change for the city have been identified and strategies for meeting the challenges posed by these scenarios are being explored. As part of this effort City Water Balance (CWB) was deployed to examine options for change and the consequences in terms of water sustainability for the city. The Alexandria model was developed with CWB to simulate all water components in the city. It was calibrated and validated based on the available data. The calibrated model has been used afterwards to simulate several initial scenarios to assess its performance and the impact of a 'business as usual' approach to the management of the city's water. The results highlight the anticipated problems for the city and the value of waste water recovery as an option for mitigating the lake pollution and the water shortages. The resulting model is sufficiently developed to be used by the City's learning alliance to explore in a more systematic framework the broad range of alternative strategies and scenarios that have been identified during the strategic planning process. Groundwater responses were found to be insignificant under the range of scenarios and strategies tested.

4.3 Dunedin

The city of Dunedin is located in Pinellas County, near the Gulf of Mexico in west-central Florida. The city land area is approximately 27km^2 and has an estimated permanent population of approximately 37,000 and a functional population including tourists and seasonal occupants of around 44,000. The City uses the groundwater in the underlying aquifer as its primary source for mains and irrigation water. It relies on its own well field for potable water. The 26 wells in use are all located within the city limits as is the water treatment plant.

There are two major aquifer systems in Pinellas County; the surficial (unconfined) unit and the Floridian Aquifer. The two aquifers are separated by an intermediate confining layer. The

combined depth reaches from the surface to nearly 400m below ground level. The City's well field exploits the upper section of the Floridian aquifer.

In the past the city has had problems with water quality, resulting from aggressive iron laden waters being pumped, along with reduced quantity available and the threat of salt-water intrusion. Since the early 1990s the city has placed emphasis on groundwater resource management, to maintain groundwater that is as low in chloride content as possible. This includes well protection and monitoring of the storm water quality, to limit groundwater contamination via recharge processes. To ensure a high quality product, the city also built a Reverse Osmosis (R.O) Water Treatment Facility.

The city also operates an extensive storm water collection and treatment network, which consists of man-made and natural drainage channels, drainage pipes and over ground storage areas such as ponds and swales. The wastewater treatment plant uses advance biological removal and most of the highly treated water is reclaimed and reused within the city. The reclaimed network within Dunedin is now extensive and one in four drinking water customers are also reclaimed water users, making Dunedin the city with one of the best reclaimed water systems in Florida. The reclaimed water is only permitted for irrigation use and hence usage varies seasonally.

The city therefore provides an interesting case study for the application of City Water Balance (CWB), CWB version 1 is designed based primarily on a traditional water supply and wastewater system but with the intention to be applicable more generally. Application of CWB to Dunedin has demonstrated that adaptations to the tool would be essential to simulate adequately the extensively integrated supply and reclaimed water systems adopted in Dunedin and to model a city that solely used water from within its own boundaries. The required adaptations have been initiated to CWB based on the experience gained in Dunedin. The limitations of CWB to model the heavily integrated water management strategy in Dunedin prevented the project from producing new findings in relation to the integrated control of surface and groundwater resources for optimal urban water management.

5 Concluding Remarks

The application of CWB to the investigation of alternative future scenarios and strategies for the City of Birmingham has shown the importance of taking a holistic approach to integrated urban water management planning and evaluating the consequences for the groundwater system below a city, in particular. It has shown that relevant information can be derived from a scoping model that addresses natural systems within the urban water cycle, but that the typical resolution of the model used for scoping can only provide indicative responses. While the results are relatively coarse for the applications carried out to date, the simulations do identify the key problem areas where groundwater conditions may exert a long term control on the implementation of surface water management strategies. Useful indicative knowledge can be extracted from the simulation results. Detailed design calculations are required to explore the risks to surface water control options that are groundwater dependent. Implementation of CWB to three further cities identified shortcomings in the design of the model where integration was extensive at the city scale. The result has been that a set of

adaptations of the current model have been identified for extension of CWB to simulate the conditions in cities such as Dunedin Florida. Primarily these relate to the feedbacks between different components of the water supply system. The cascade methodology employed to route flows through a city in the initial version of CWB is not effective for all cities and especially for cities where urban water supply is sourced locally and recycled at the city scale.

Full accounts of the different modelling studies undertaken with City Water Balance are provided in the four theses developed using the software. The PhD thesis provides full details of the conceptual design and implementation of the modelling tool.

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