Assessing urban groundwater table response to climate change and increased stormwater infiltration

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The global climate is expected to show continued warming throughout the coming century. As a direct consequence of higher temperatures, the hydrological cycle will undergo significant changes in the spatial and temporal distribution of precipitation and evapotranspiration. In addition to more frequent and severe droughts and floods, climate change can affect groundwater recharge rates and groundwater table elevation (Bates *et al.* 2008).

Some previous studies of climate change impact on groundwater have suggested alarming reductions in groundwater recharge and lowering of water tables. Other studies, especially those focusing on regions of higher latitudes, have indicated a potential rise in water tables due to increased precipitation and recharge (Scibek & Allen 2006; Woldeamlak *et al.* 2007).

In addition to changes in precipitation patterns, a shift in stormwater infrastructure design may also alter the hydrologic cycle of urban areas. In recent years, there has been a growing trend towards adoption of low-impact development practices managing stormwater runoff. These practices aim to mitigate the impacts of urbanisation such as increased runoff volume, higher peak runoff flows, lowered water tables and reduced water quality (Prince George's County 1999). In contrast to conventional stormwater infrastructure, which is designed to rapidly collect and convey runoff, low-impact development practices are designed to slow runoff, remove pollutants and evapotranspirate and infiltrate runoff locally.

In recent years, numerous modelling studies have investigated the potential impact of stormwater infiltration on groundwater levels. Gobel *et al.* (2004) used a combination of models (GwNeu, HYDRUS-2D, SPRING) to demonstrate that the installation of infiltration practices across an urban catchment area in Germany could raise the groundwater surface by up to 2.3 m in some locations. In another catchment scale study, Maimone *et al.* (2011) used the modelling code DYNFLOW to show that the future groundwater table may eventually stabilise up to 1.5 m higher than its current level in parts of Philadelphia, if the city's plan to alter 40% of its impervious areas into so-called 'green' stormwater recharge areas is completed. Thompson (2010) used HYDRUS-2D to demonstrate that a stormwater infiltration basin could cause up to 1.3 m of localised groundwater mounding. In yet another study, Endreny & Collins (2009) used MODFLOW to show that rain gardens installed throughout a residential catchment area could raise the steady-state groundwater table by up to 1.1 m.

The studies mentioned above have investigated groundwater level response to either changes in climate or stormwater management infrastructure. However, to the authors' knowledge no studies have investigated the concurrent effects of both alterations on the urban hydrologic cycle. In urban areas, it is necessary to determine the potential magnitude of the combined impact, as a steep rise in groundwater level can damage building foundations and subsurface infrastructure due to flooding and buoyancy forces (Gobel *et al.* 2004; Vázquez-Suñé *et al.* 2005). This study aims to assess the potential changes in groundwater response caused by both increased precipitation and widespread instalment of stormwater infiltration infrastructure in the city of Silkeborg, Denmark, using the MIKE SHE model. Change of groundwater level at the planned location of a new motorway in Silkeborg is the focus of this study as portions of the con-

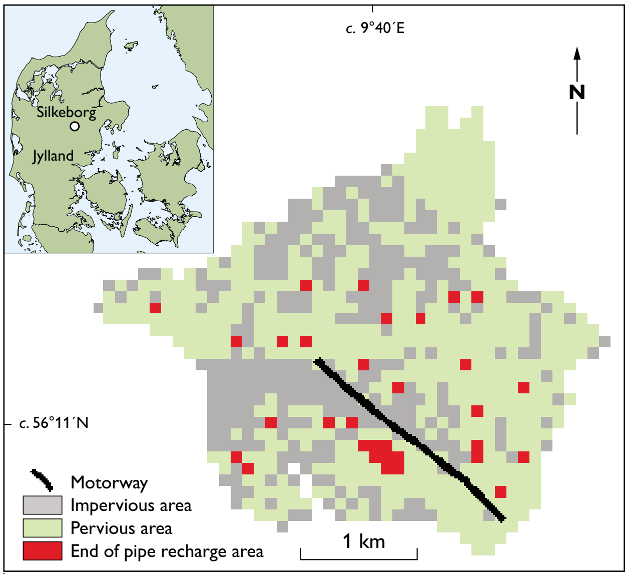

Fig. 1. The Silkeborg study area and the proposed course of the motorway. Inset: the location of Silkeborg in Jylland.

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Table 1. Summary of model scenarios

Scenario name	Climate data input	Stormwater infrastructure
CD-2010	Recorded 1991–2010	Conventional drainage to river system
EPR-2010	Recorded 1991–2010	End of pipe infiltration ponds
LAR-2010	Recorded 1991–2010	Local area recharge
CD-2100	Projected 2081–2100	Conventional drainage to river system
EPR-2100	Projected 2081–2100	End of pipe infiltration ponds
LAR-2100	Projected 2081–2100	Local area recharge

struction are expected to come critically close to the present high groundwater table in that area. Knowledge of the magnitude of potential groundwater changes is essential because improved drainage measures and increased use of concrete will significantly raise the costs of the new motorway.

Study area

The city of Silkeborg has a population of *c.* 43 000 inhabitants and is located in the central part of Jylland, Denmark (Fig. 1). The focus of this study is just north of the river Gudenåen, where a portion of the new motorway will be constructed *c.* 6 m below the present terrain surface. The surficial geology is dominated by coarse-grained, postglacial, sandy sediments that form an upper unconfined aquifer with a vertical extent of 10–15 m. The average precipitation in Silkeborg during the period 1961–1990 was 903 mm per year, and the average potential evapotranspiration was 546 mm per year. The average monthly temperature during that period was 15.2°C in July/August and −0.3°C in January/February (Kidmose *et al.* 2013).

Methods

Hydrological models – MIKE SHE is a deterministic, fully-distributed and physically based model software capable of simulating surface and subsurface hydrological processes. The Danish National Water Resources Model (DK-model) is based on MIKE SHE and incorporates national data on geology, soil type, land use, topography, river network geometry, water abstraction and climate. The Silkeborg model is a 100 m grid local model using hydraulic head boundary conditions from the 500 m grid DK-model. A 9.2 km^2 area within the 103 km^2 Silkeborg model, which encompasses the new motorway construction and the greater part of the urbanised surroundings, was chosen for the current study (Fig. 1). Details on the development, calibration and validation of the DK-model and the Silkeborg model are found in Højberg *et al.* (2013) and Kidmose *et al.* (2013), respectively. Six different model scenarios have been evaluated (Table 1).

Stormwater infiltration modelling – The Silkeborg study area consists of 65.5% pervious and 34.5% impervious cover. In the scenarios with conventional drainage stormwater infrastructure (i.e. the 'CD' scenarios), 100% of the precipitation on impervious cells was routed directly to the river system (Fig. 2A). Precipitation on impervious cells had one time step (i.e. one day) to infiltrate or evapotranspirate. At the end of the time step, any water in excess of a detention storage of 4.7 mm (based on calibration results) was routed overland to adjacent cells based on topography. It is assumed that the CD-2010 scenario is representative of Silkeborg's current climate and stormwater conditions.

In the end of pipe recharge (EPR) scenarios (Fig. 2B), it was assumed that 10.7% (34 ha) of the city's pervious area has been turned into end of pipe stormwater infiltration ponds (Figs 1, 2). Model cells which were assumed to contain in-

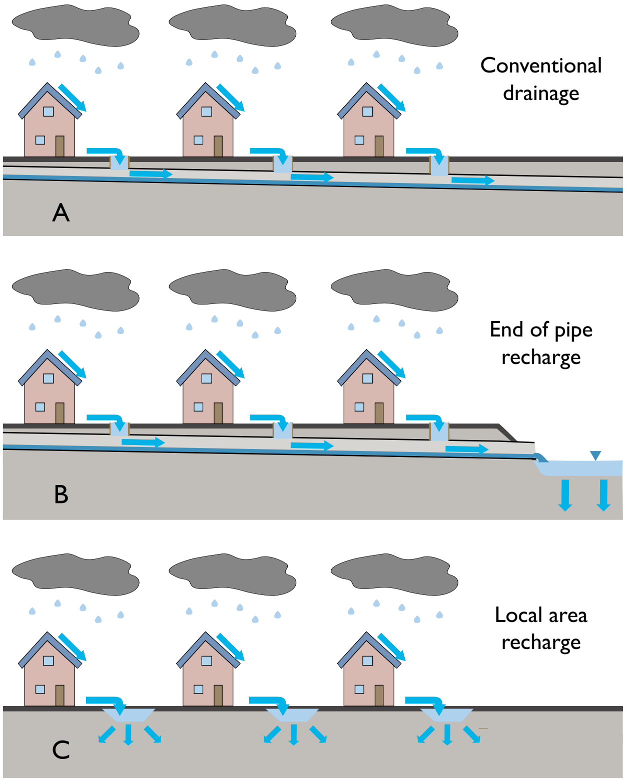

Fig. 2. Three model scenarios for stormwater drainage infrastructure.

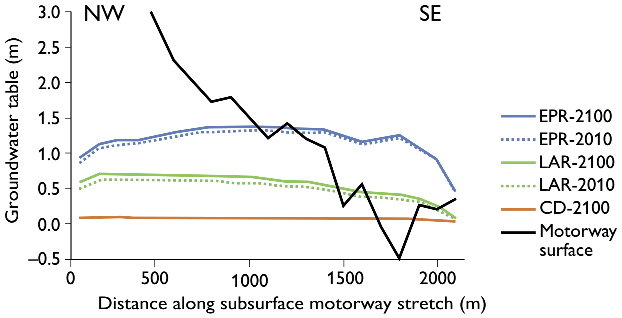

Fig. 3. Average modelled groundwater table elevations along the 2000 m of projected motorway at Silkeborg. The results are relative to CD-2010.

filtration ponds were assigned detention storage of 500 mm to represent the storage depth of the pond. In the EPR scenarios, precipitation which would normally be applied to impervious cells was reduced to zero, and the equivalent volume of precipitation was instead evenly distributed over the infiltration pond cells via an increase in precipitation applied to those cells. In the EPR scenarios there were 9.3 times as much impervious drainage area as infiltration pond area, so the infiltration pond model cells had 1030% (i.e. 100% + 9.3 × 100%) of the actual rainfall applied to them. This method of manipulating precipitation to simulate the collection of stormwater in specialised infiltration areas on a city-wide scale is similar to the modelling strategy used by Holman-Dodds *et al.* (2003).

The local area recharge (LAR) scenarios represent a system where stormwater is managed at the level of individual plots through any combination of infiltration practices, each no more than tens of metres across. It was assumed that infiltration possibilities are numerous and located in close proximity so that at the scale of the model, each cell effectively behaves as a pervious cell. Therefore, all paved areas were given properties identical to the pervious areas with infiltration rates controlled by the underlying soils.

Climate input – Precipitation, temperature and evapotranspiration data from the Danish Meteorological Institute from 1991 to 2010 were used as input to the '2010' model scenarios. The input climate data for the '2100' scenarios were generated by applying correction factors based on nine climate model projections from the ENSEMBLES project (Christensen *et al.* 2009) to present-day climate data. Further information on the Delta Change downscaling method used can be found in Seaby *et al.* (2013). To generate the results for each of the three '2100' infrastructure scenarios, the model was run nine times (once for each of the nine climate model projections), and the results averaged.

Results

Water table elevation – Average groundwater elevations along the area planned for the motorway construction were extracted from the MIKE SHE model results (Fig. 3). Areas where the solid black line (i.e. the motorway surface) drops below the water table indicate portions of the motorway which could be flooded by groundwater.

In the CD-2010 scenario, a stretch of 160 m of motorway is below the average water table. In the CD-2100 scenario, the average groundwater table elevation is raised by 0.08 m, and the length of motorway surface at risk is extended to 180 m. Hundreds of metres of the proposed motorway are potentially flooded in the LAR-2010 and the LAR-2100 scenarios where the average water table rose 0.48 and 0.55 m above CD-2010 levels, respectively. The highest average water tables of 1.15 and 1.19 m above CD-2010 occur in the EPR-2010 and EPR-2100 scenarios, which would both put a stretch of nearly 1 km of the proposed motorway at risk.

The results indicate that the impact of climate change (i.e. the difference between the '2010' and the '2100' scenarios) is small compared to the impact of extensive implementation of either local area or end of pipe stormwater infiltration practices. Only average water tables are presented here to compare the relative impacts of different model scenarios. However, maximum water tables could put much longer sections of the motorway at risk and will therefore be considered in the final design of the motorway.

Water balance – Average yearly volumes of precipitation, evapotranspiration, recharge and overland flow were calculated for the 1991–2010 time period for each stormwater in-

Table 2. Catchment water balances for different stormwater infrastructure scenarios

Model scenario	Mean (mm/year, 1991–2010)				
	Precipitation	Evapotranspiration	Recharge	Overland flow	Baseflow
CD	911	319	304	292	8
LAR	911	441	463	11	15
EPR	911	311	588	19	29

frastructure scenario using MIKE SHE's water balance tool (see Table 2). Evapotranspiration was greater in the LAR scenario, due to the much larger evaporation surface available. Recharge was much higher in both infiltration scenarios than in the CD scenario. Overland flow, or the volume of water which flows directly into the river system, was very small in both the infiltration scenarios in comparison to the CD scenario which routed all water from impervious areas into the nearest stream. Baseflow was highest in the EPR scenario, followed by the LAR scenario and finally the CD scenario, as would be expected based on the relative recharge volumes in these scenarios.

Summary and conclusions

Previous studies have reported groundwater level rise due to either climate change (Scibek & Allen 2006; Woldeamlak *et al.* 2007) or stormwater infiltration practices (Gobel *et al.* 2004; Maimone *et al.* 2011). However, these two changes to the urban hydrologic cycle are typically not assessed in an integrated way as in this study. The modelling results presented in this paper are within the ranges of the above studies, i.e. tens of centimetres due to climate change and potentially more than 1 m due to the widespread adoption of stormwater infiltration practices. However, these results are specific to the Silkeborg motorway and it is expected that the relative magnitude of the impact due to climate change and stormwater infiltration could vary greatly under different climatic and geological regimes.

Stormwater infiltration practices are often regarded as a form of climate change adaptation in the field of stormwater management as they can help to accommodate the higher intensity and larger volume precipitation events expected in the future. However, as the results of this study indicate, these same practices amplify other problems associated with climate change (i.e. groundwater table rise). The study clearly shows the need for integrated research of urban hydrology, and communication between hydrogeologists, stormwater engineers, planners and policy makers.

Acknowledgement

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