Journal of Hydrology 404 (2011) 117–129

Contents lists available at ScienceDirect

Journal of Hydrology

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

Modelling the historical water cycle of the Copenhagen area 1850–2003

Jan Jeppesen [a,b,*], Steen Christensen [b], Ulla Lyngs Ladekarl [a]

[a] ALECTIA A/S, Skanderborgvej 190, DK-8260 Viby J, Denmark
[b] Department of Earth Sciences, Aarhus University, Høegh Guldbergsgade 2, Bldg. 1672, DK-8000 Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 2 February 2010
Received in revised form 25 November 2010
Accepted 20 December 2010
Available online 25 December 2010
This manuscript was handled by P. Baveye, Editor-in-Chief

Keywords:
Urban hydrology
Historical climate change
Water cycle
Integrated modelling
Modflow
Dry cells

SUMMARY

The paper describes a set of modelling utilities (a root-zone model, a grid-distribution tool, and a modified Modflow-2000 model) that can be used to simulate the water cycle of a city in terms of root-zone water balance, water supply, wastewater, storm runoff, groundwater flow, streamflow, and the interactions between these subsystems. The utilities are used to simulate the water cycle in the Copenhagen area (976 km^2) during the period 1850–2003. Long-term time series of hydraulic head, streamflow, and inflow to sewage works have been used to manually calibrate the model parameters. We used a step-wise calibration strategy, using different parts of the data in the various steps, to calibrate hydrogeological parameters, storm runoff parameters, and parameters governing the interactions between groundwater and leaky pipe systems, respectively. Simulations indicate that present rates of groundwater leakage into streams, lakes, and wetlands constitute 60% of pre-urbanization levels due to massive groundwater extraction. However, the current problems of groundwater shortages and streamflow depletion would have been far worse, if precipitation had not increased by 20% since 1850. Model simulations indicate that urbanization has lowered current groundwater recharge due to the establishment of impervious areas and due to negligible contributions from leaky pipe systems. This is opposite to the reported general tendency of enhanced recharge due to urbanization. However, current recharge rates within Copenhagen are simulated to be 20% higher than prior to urbanization, which is attributed to the increase in precipitation during the study period.

1. Introduction

Urbanization has a significant impact on the hydrological cycle, both in terms of water quantity and water quality. For example, urbanization and population growth increase water demand which affects surface water and groundwater resources; the provision of water supply, drainage, and sanitation leads to the development of sub-surface pipe networks such as water mains for water supply and sewers for wastewater and storm runoff; the pipe systems can be leaky and interact with groundwater; and vegetation removal and growth of impervious areas produce storm runoff at the expense of infiltration and evapotranspiration.

Integrated sustainable urban water management, including groundwater, is becoming increasingly important because of its significance to economic, social, political, and environmental issues. For example, in Denmark decentralized storm water infiltration to the groundwater system is considered as a strategy to overcome the present and future problems with sewer overflows in urban areas. However, in order to evaluate alternative water management scenarios, quantification of the urban water cycle is an essential task, which is complicated by the numerous possible flow interactions between the urban subsystems (Lerner, 1986, 1990a,b; Foster, 1990). Lerner (2002) recommended the application of integrated model approaches, including a groundwater model, to minimize, or at least to better understand, the uncertainty associated with urban water cycle quantification, and Vázquez-Suñé et al. (2005) recommended the inclusion of historical changes in the urban water cycle analysis in order to reduce uncertainty of the integrated model. These changes include land use, evolution of indirect recharge sources from leaking pipe systems, groundwater extraction by industries and water works, and possible interactions with urban underground structures.

Only a few published studies have used groundwater flow models to analyze the long-term effects of large-scale urbanization on the hydrological cycle. Yang et al. (1999) used a groundwater flow and solute transport model to quantify historical recharge in Nottingham, UK. Vázquez-Suñé and Sánchez-Vila (1999) used a groundwater flow model in a water balance study for Barcelona. The model was calibrated using hydraulic head data for the period 1900–1999 and explicitly included seepage into underground railway tunnels.

To our knowledge no study has yet included all major components of the water cycle into one model framework in the context

* Corresponding author at: ALECTIA A/S, Skanderborgvej 190, DK-8260 Viby J, Denmark. Tel.: +45 27138033.
E-mail address: jaje@alectia.com (J. Jeppesen).

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.12.022

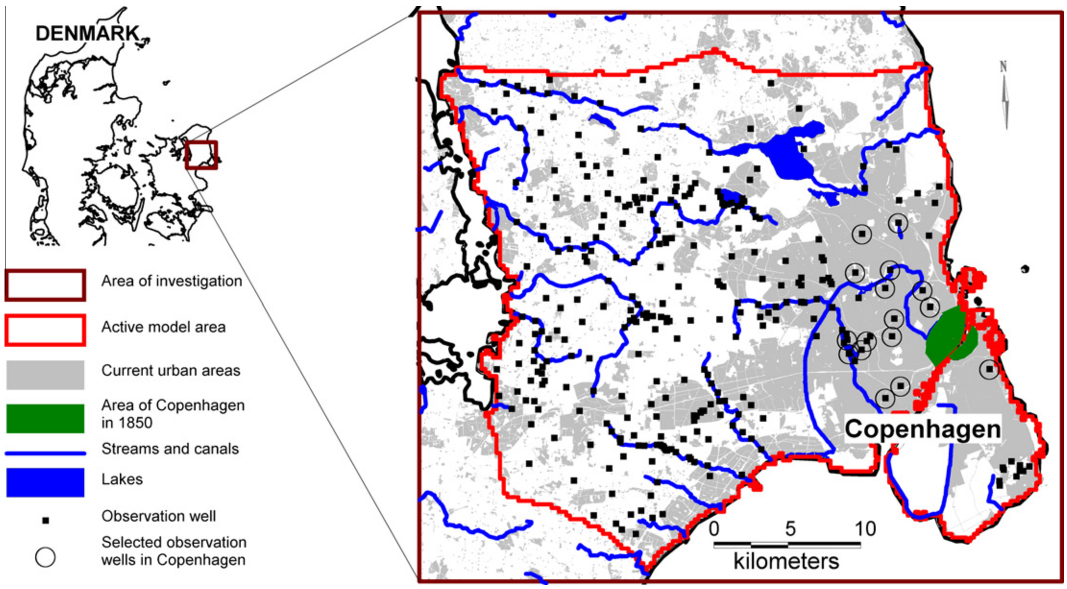

Fig. 1. Map of Copenhagen, Denmark, showing the area of investigation, streams and lakes, current urban areas, area of Copenhagen in 1850, and observation wells.

of analyzing historical impacts from both urbanization and climate variations at the city-scale water cycle. Nor has any study yet used sewer discharge data together with observations of stream discharge and hydraulic head to calibrate and validate an integrated model for an entire city area. We do both in this study, where an integrated groundwater/surface water model is developed for the Copenhagen area (976 km^2, Fig. 1) for the period 1850–2003. The urban water cycle is quantified in terms of root-zone water balance, water supply, wastewater, storm runoff, groundwater flow, and interactions between these systems. By simulating the period 1850–2003 the complete history of groundwater extraction and major city development in the region is covered.

The main objective of this paper is to present and discuss the modelled water balance for the period 1850–2003. We begin by presenting the modelling principles and the actual model setup for the Copenhagen area. Then follows a description of the model parameterization and the procedure used for calibration and validation. Finally the results are presented in terms of model performance and simulated historical water cycle.

2. Urban hydrology model

The urban hydrology model developed in this study consists of three tools used in sequence: (1) a root-zone model; (2) a grid-distribution tool; and (3) a groundwater flow model. The major water flows simulated by the model are illustrated in Fig. 2 and explained in the following.

2.1. Root-zone model

The root-zone model Daisy (Hansen et al., 1991) is used to simulate daily water balance at the surface and in the soil for relevant combinations of soil type, land use, and climate zone. The surface part of the model includes snow accumulation and melting, interception, through-fall, transpiration from the crop canopy, infiltration, and surface runoff. The soil part of the model includes vertical flow in the soil matrix as well as flow in macro pores, water uptake by plants, pipe drainage, plant growth, development of leaf area index, and root depth. The rural parts of the Copenhagen area are drained via tile drains, and the urban parts are drained as well. (Otherwise large parts of today's Copenhagen would be swamps.) Groundwater rising above the drainage depth will therefore runoff via drains and only cause minor change in water content in the soil above. Consequently we judge that varying groundwater levels will only have minor feedback effect on evapotranspiration. Such feedback mechanism is therefore neglected in our modelling.

2.2. Grid-distribution tool

The grid-distribution tool distributes relevant information about water balance components and the physical systems to the finite difference grid of the groundwater flow model.

For non-urban areas, recharge from the root zone is distributed to the grid in accordance with soil types, climate, and land uses within each grid cell. Similarly is done for the pervious parts of urban areas.

The impervious (covered) part of an urban area is specified by a fraction; the value of this cover fraction depends on the urban area

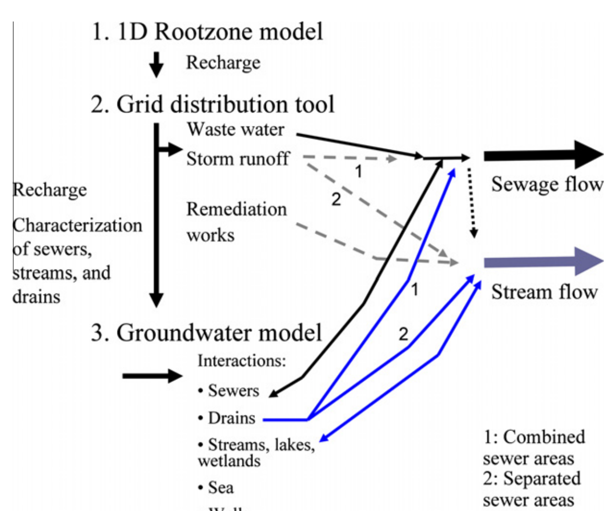

Fig. 2. The three modelling tools: a root-zone model, a grid-distribution tool, and a groundwater flow model. The arrows indicate either exchange of output from one model tool to another, or (sometimes two-way possible) exchange of flow between a model tool and a recipient (sewer or stream).