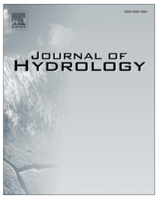
Journal of Hydrology 535 (2016) 301–317

Contents lists available at ScienceDirect

Journal of Hydrology

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



Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change

Ida B. Karlsson[a,*], Torben O. Sonnenborg[a], Jens Christian Refsgaard[a], Dennis Trolle[b,e], Christen Duus Børgesen[c,e], Jørgen E. Olesen[c,e], Erik Jeppesen[b,e], Karsten H. Jensen[d]

[a] *Geological Survey of Denmark and Greenland (GEUS), Denmark*
[b] *Aarhus University, Department of Bioscience – Lake Ecology, Denmark*
[c] *Aarhus University, Department of Agroecology – Climate and Water, Denmark*
[d] *Copenhagen University, Department of Geosciences and Natural Resource Management, Denmark*
[e] *Sino-Danish Centre for Education and Research (SDC), Denmark*

ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 13 January 2016
Accepted 23 January 2016
Available online 2 February 2016
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Alessio Domeneghetti, Associate Editor

Keywords:
Climate change impact
Hydrological model structure
Uncertainties
Land use changes

SUMMARY

Impact studies of the hydrological response of future climate change are important for the water authorities when risk assessment, management and adaptation to a changing climate are carried out. The objective of this study was to model the combined effect of land use and climate changes on hydrology for a 486 km^2 catchment in Denmark and to evaluate the sensitivity of the results to the choice of hydrological model. Three hydrological models, NAM, SWAT and MIKE SHE, were constructed and calibrated using similar methods. Each model was forced with results from four climate models and four land use scenarios. The results revealed that even though the hydrological models all showed similar performance during calibration, the mean discharge response to climate change varied up to 30%, and the variations were even higher for extreme events (1th and 99th percentile). Land use changes appeared to cause little change in mean hydrological responses and little variation between hydrological models. Differences in hydrological model responses to land use were, however, significant for extremes due to dissimilarities in hydrological model structure and process equations. The climate model choice remained the dominant factor for mean discharge, low and high flows as well as hydraulic head at the end of the century.

1. Introduction

The uncertainties of climate change impacts are numerous and originate from several sources described in the cascade of uncertainties (Schneider, 1983). The cascade describes the propagation of uncertainties from the top of the climate impact chain, in the form of emission scenarios, to the bottom, consisting of the impacts themselves. Several studies have investigated the uncertainties arising from the general circulation models (GCMs) and emission scenarios (Allen et al., 2000; Webster et al., 2002), and numerous studies have also investigated the GCM–RCM (regional climate model) coupling uncertainties using multi-model ensembles (Christensen and Christensen, 2007; Hewitt and Griggs, 2004; Kendon et al., 2010; Mearns et al., 2009). Some studies have analysed the consequence of the impact uncertainties on the hydrological regime, for example by using different emission scenarios or GCM–RCM combinations as basis for the hydrological model (Feyen and Dankers, 2009; Maurer, 2007; Teutschbein and Seibert, 2010; van Roosmalen et al., 2007) coupled with different downscaling methods (Chen et al., 2011; Rasmussen et al., 2012; Teutschbein and Seibert, 2012).

Most hydrological impact studies have, however, been limited to one hydrological model, and only a few studies have investigated the effect of hydrological model choice on the impact assessment result (e.g. Bastola et al., 2011; Boorman and Sefton, 1997; Jiang et al., 2007; Maurer et al., 2010; Najafi et al., 2011). A few have been undertaken with complex hydrological models (e.g. Ludwig et al., 2009; Poulin et al., 2011; Surfleet et al., 2012; Vansteenkiste et al., 2014; Dams et al., 2015). The studies have shown that the hydrological model choice had a large effect on river discharge, and they further indicated that the effect of hydrological model structure depends on catchment type (e.g. Bastola et al., 2011; Velázquez et al., 2013).

Land use changes and their impacts are also important for water management and sustainable resource exploitation. Several studies have assessed the impact of land use changes on hydrology for future climate change by using dynamic land use models

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* Corresponding author. Tel.: +45 9133 3613.
E-mail address: ika@geus.dk (I.B. Karlsson).

http://dx.doi.org/10.1016/j.jhydrol.2016.01.069
0022-1694/

(Wijesekara et al., 2012) or assumed future land use changes (Mango et al., 2011; Quilbe et al., 2007; van Roosmalen et al., 2009) combined with hydrological modelling.

In this study, the impact responses in two future periods from hydrological models of increasing complexity are used to investigate the dilemma and consequences of selecting climate model, hydrological model and land use scenario for a catchment in central Denmark. No previous studies have, to our knowledge, examined the combined effect of land use, climate model and hydrological model choice. The uncertainty contribution from four climate models, three hydrological models and four land use scenarios on stream discharge and groundwater head are separated, and we also investigate how the hydrological streamflow components (overland flow, interflow, base flow) react under changing climate and land use conditions for the different hydrological models.

2. Study area and data

The Odense River Basin is situated in the central part of Denmark on the island of Funen (Fig. 1). The observed climate data include precipitation, temperature and reference evapotranspiration from the Danish Meteorological Institute (DMI) climate grid (Fig. 1A; Scharling (1999)). Precipitation has subsequently been corrected using a dynamic gauge catch correction by Stisen et al. (2012). The area has an annual average precipitation of 808 mm and an annual average temperature of 8.8 °C (1991–2010).

In this study, focus is on the upstream part of the Odense River basin with an area of 486 km^2. This sub-catchment is bound to the southeast and northwest by moraine hills and to the southwest by end moraines, while the northeast slopes towards the Odense Fjord. The area is drained by the Odense River that runs from southern to north-eastern Funen and into Odense Fjord (Fig. 1B). The river segments in the catchment are 200 km long and consist of 31 branches connected to the Odense River, all gaining reaches. To some extent the hydraulic head in the area follows the topography, sloping downward to the river valley.

Fig. 2 depicts the locations of measurement stations, as well as the distribution of farms, crops and soils. The layout of the catchment can be seen in Fig. 2A. The subcatchment has four discharge stations, 455 wells with hydraulic head measurements and 105 abstraction wells, but none of these are used for irrigation.

The soil is divided into 10 different soil profile types (Fig. 2B): two types of moraine sand, three types of diluvial sand, four types of moraine clay and one type of freshwater sand. The soil types are based on a national database and values for soil properties are estimated by pedotransfer functions (Børgesen et al., 2013; Greve et al., 2007). Moraine clay soil no. 67 is the overall dominant soil type.

Land use is dominated by agricultural lands (Fig. 2C) with three dairy farm types (18%), two plant production types (16%) and two pig farms types (48%). A smaller area of 10% is equally occupied by grassland and forest (deciduous and coniferous). Urbanised areas constitute 8%; while water bodies (1%) are only sparsely present (Nielsen, 2000). The three most dominant crops are winter wheat, spring barley and grass (Fig. 2D; Thodsen et al. (2015)).

The shallow geology in the basin is primarily a result of the latest ice advances in the Weichselian. The ice advanced three times during this period; the first two advances covered the entire Funen area (Old Baltic Ice stream and the Main Advance). The last advance (Young Baltic Ice stream) did not fully cover Funen as old dead-ice from the Main Advance blocked the new ice sheet. However, the Young Baltic Ice sheet had several re-advances during deglaciation of which one of the larger (the Baelthav Advance) covered south and south-eastern Funen (Kjær et al., 2003). The

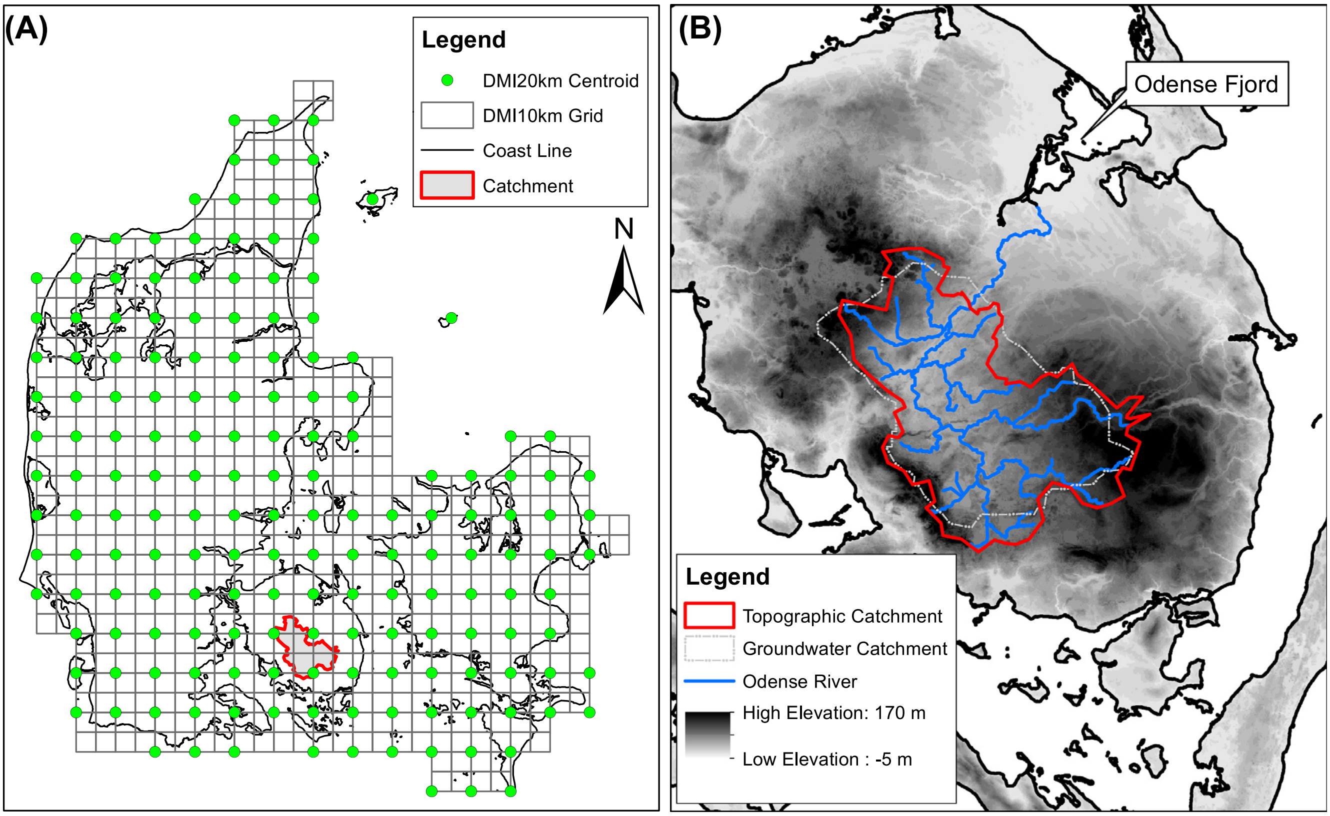

Fig. 1. Location of the study area and the distribution of the DMI climate grids (A); overview of the study area with elevation and groundwater catchment extent for the aquifer system's main water resources (B).