

Electronic Supplement S7 to Chapter 7: Projected Change – River Flow and Urban Drainage

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This Electronic Supplement aims to give the reader insight into the specifics of hydro-climate modelling, which will allow insightful interpretations to be provided on the projected hydrological impact results for the North Sea region, as presented in Chap. 7.

Need for Downscaling

The temporal and spatial resolutions at which hydrological models operate depend strongly on the scales of the major processes being modelled and the type of model/application.

Figure S7.1 shows the typical resolutions and scales (both are considered equivalent) of several hydrological applications. For applications such as water supply, irrigation, river hydrology and rainwater harvesting, time resolutions of current general circulation models (GCMs) and/or regional climate models (RCMs) are sufficient, but the spatial resolutions are too coarse. For applications of urban hydrology, both spatial and temporal resolutions are too coarse. The rainfall generating processes indeed occur over temporal scales ranging from multi-decadal to sub-minute with corresponding changes in spatial scale. For urban drainage it is necessary to go down to the minute resolution. The latest generation of high resolution RCMs go down to a spatial resolution of 1.5 km (Kendon et al. 2014) and time scales of minutes, but only a very limited number of such models and runs are available to date.

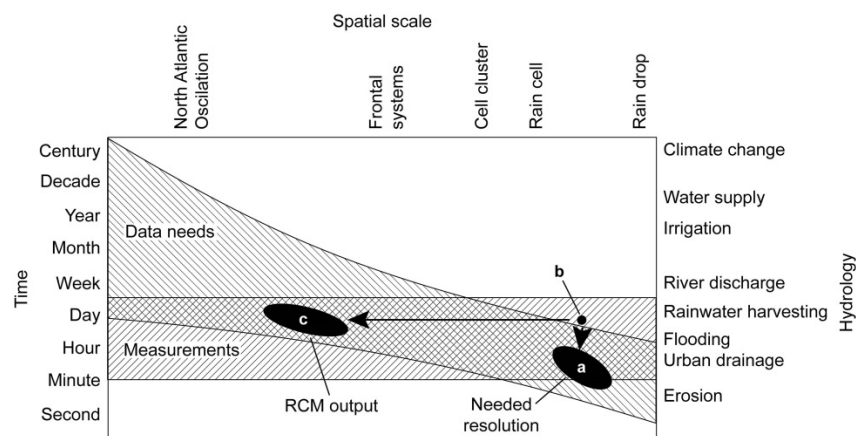


Fig. S7.1 Statistical downscaling of RCM output, down to the scale required for urban hydrological impact studies requires both temporal downscaling (a-b) and spatial downscaling (b-c) (after Willems et al. 2012a,b)

Downscaling has been one of the methods proposed for circumventing the resource burden. Downscaling entails the transformation of variables from a large scale to a smaller scale while maintaining the large- to small-scale physical relationships. It is categorised as dynamical and statistical, although a hybrid between the two is also possible (dynamical-statistical; see Fig. S7.2).

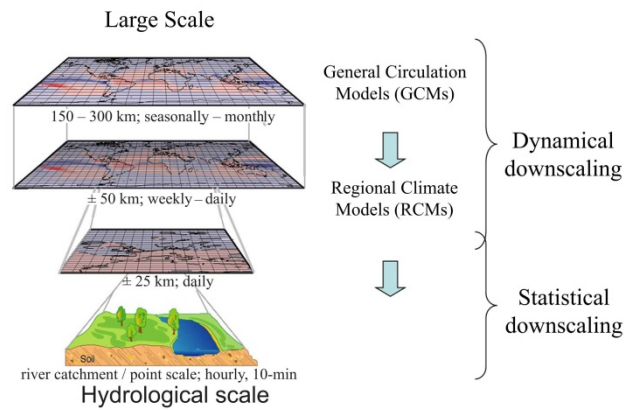


Fig. S7.2 Downscaling of GCM simulation results (note: although the graphic suggests that statistical downscaling is applied to RCM outputs, it can also be applied to GCM outputs)

Dynamical downscaling is the process whereby large-scale and lateral boundary conditions from GCMs are downscaled to generate higher resolution outputs (typically 5–50 km) with the use of RCMs. Since the RCM is embedded in the GCM, it is subject to the GCM uncertainties. RCMs aim to model regional scales while satisfying large-scale constraints. The GCM provides the initial conditions for variables such as soil moisture, sea surface temperature, sea ice, lateral conditions (temperature, pressure, humidity) and large-scale responses; and the RCM simulates the finer-scale processes (such as controlled by topography, soil type, vegetation, and lakes). However, it is worth noting that the increase in resolution does not necessarily mean an increase in output quality. Studies have shown that increased resolution may lead to more bias in some models. For example, the rainfall for 25-km RCMs was found to be higher than that of 50-km RCMs for the ENSEMBLES RCMs during winter and summer (Rauscher et al. 2009). This underlines the fact that increased resolution does not necessarily mean better skill; rather, other uncertainties may require more attention to avoid deterioration of the climatology. Some studies have found that precipitation is more sensitive to resolution effects through parameterisations than through high-resolution topography (Deque et al. 2005; Rauscher et al. 2009). Rainfall convection processes, for instance, can only be modelled explicitly at grid scales smaller than about 3 km (Willems et al. 2012a,b). Recent research by Kendon et al. (2012) has shown that some of the systematic RCM errors, such as the tendency to underestimate heavy rain events, to have the rainfall too persistent in time and widespread, to have too much persistent light rain and errors in the diurnal cycle, are considerably smaller when the spatial resolution of the RCM is reduced from 12 to 1.5 km. Nevertheless, RCMs remain the best tools for simulating regional climates. Collaboration between different research groups with the aim of inter-comparing models has led to a better understanding of the uncertainties which bodes well for the future quality of RCMs. This also involves collecting and processing high resolution observed gridded data, given that high resolution climate models demand such data for verification.

Statistical downscaling (also called empirical downscaling) involves the use of historical statistical relationships between predictors and predictands. Predictors are large-scale variables like pressure patterns and related atmospheric circulation, large-scale temperature and humidity while predictands are small-scale variables like local precipitation, temperature, etc. In other cases, large-scale variables may be used as predictors of the same variables but at local scale if the correlations are evident. The key requirement is that predictors should be able to explain, to a large extent, most of the observed variation in the predictand. Examples of statistical downscaling methods include weather typing, weather generators and regression relationships (Fig. S7.3). Weather generators aim to reproduce the statistical attributes of the local variable (e.g. mean and variance) by means of stochastic models. Regression relationships are established in the form of linear and non-linear relationships of the predictors and predictands. For a changing climate, it is likely that these relationships may not hold (Wilks 1992). In comparison, dynamical downscaling may be better suited for a changing climate because of its more physically-based nature. Indeed, the physically-based approach is more versatile than the statistical approach which is more tuned to given local data. However, statistical downscaling is less computationally intensive compared to dynamical downscaling. As a result, it is possible to assess the uncertainty of the variables through large ensembles. For hydrological extremes like floods, it is important that the downscaling method estimates

rainfall extremes reasonably well. The accuracy of the rainfall variable and particularly of its extreme states is, however, an order of magnitude lower than that of temperature (Fowler et al. 2005; Frei et al. 2006). Examples of the application of statistical downscaling of GCM and RCM outputs for the North Sea region are provided in Table S7.1.

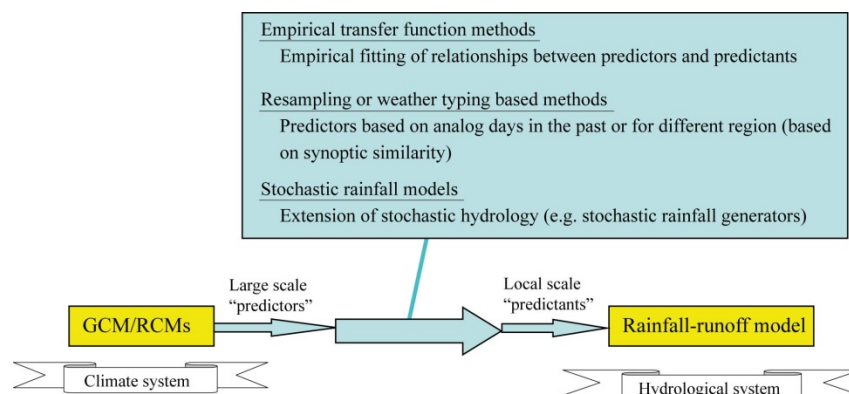


Fig. S7.3 Types of statistical downscaling methods

Table S7.1 Summary of impact results on river flows available for the North Sea region

Region	Source	Statistical downscaling method applied
Germany	Huang et al. 2013	Wettreg: weather typing based statistical downscaling tool
Belgium	Willems and Vrac 2011	Extended weather typing method, accounting for precipitation changes that depend not only on changes in weather type but also on temperature changes
Denmark	Sunyer et al. 2012	Different types of stochastic rainfall generators
Sweden (one catchment)	Teutschbein et al. 2011	Three statistical downscaling methods, covering all three classes (weather typing, weather generators and regression relationships)
UK (six catchments)	Chun et al. 2009	Generalised linear model to generate stochastic time series of rainfall based on GCM/RCM output

Bias correction is the name given to a simple subset of statistical post-processing methods for GCM or RCM data which attempt to scale climate model output to fit the observed day-to-day and seasonal distributional properties of the climate. The aim is to approximate, among others, observed climate properties such as the mean and variance (Shabalova et al. 2003; Horton et al. 2006; Lenderink et al. 2007; Lawrence and Hisdal 2011; Hempel et al. 2013), coefficient of variability (Leander and Buishand 2007; Leander et al. 2008), and/or selected quantiles or the full distribution (Cloke et al. 2010; Piani et al. 2010; Berg et al. 2012; Teutschbein and Seibert 2012; Seaby et al. 2013). After bias correction, the (dynamically downscaled) climate model outputs can be used as direct input in the hydrological impact models. Another approach is to derive change factors from a comparison of the climate model scenario versus control runs, and to apply these to available local historical series (Willems et al. 2012a,b). This method is commonly called the delta change method or perturbation method, and intrinsically involves bias correction as historical series are taken as reference for the current climatic conditions rather than the control runs. The change factors can again be based on the mean (Lenderink et al. 2007), variance (Arnell 2011), quantiles, or the full distribution (Andréasson et al. 2004; Yang et al. 2010; Olsson et al. 2011), per month or season. In their quantile perturbation approach for rainfall, as well as considering change factors on rainfall intensity, Willems (2013) and Ntegeka et al. (2014) also considered change factors on the number of rainstorms or wet/dry days. Changes in only the mean and/or variance have the limitation that changes in small-scale features or extremes are not well represented (Hempel et al. 2013). This was also shown by Sunyer et al. (2014), who compared several simple and more advanced bias correction and delta change methods for different catchments in Europe including Norway, Denmark, Belgium and Germany.

While attractive in theory, empirical methods are severely constrained by the statistical relationships which underpin them. For instance, when the impact model requires hourly inputs but the GCM/RCM outputs are daily, observed relationships between daily and hourly variables are used and it is again assumed that these do not change over time. It is highly likely that this assumption will be violated in the context of climate change.

Such caveats aside, downscaling and bias correction methods have increased data availability for hydrological assessments. Different approaches have been developed. Several have been applied in the North Sea region, depending, among others, on the area, type of hydrological impact, tradition and experience of the modeller and available resources. Typically, the approach for determining the hydrological climate change impact includes the following steps: evaluating the climate models; downscaling/bias correction of the hydrological variables from the climate scenarios; transferring of climate change signals/perturbations to hydrological parameters; and simulating the hydrological climate change effect.

Methods for Impact Analysis on Hydrology

Different types of hydrological models have been used for studying the impact of climate change, depending on the scale and the hydrological processes. Typically, hydrological models are classified as conceptual or physically-based. One crucial difference lies in the amount of input data required for each type of model. Detailed, spatially distributed physically-based models discretise a catchment into several units and parameters identified for each unit. They therefore have the potential to better represent the spatial variability of physical properties such as relief and soil type. Yet distributed physically-based models require extensive input data, which means that they have high demands for calculation time in comparison to conceptual models. There is no guarantee that all the variables will be readily available from the climate models; so assumptions must be made for the missing variables. Nonetheless, detailed physically-based models generate detailed results, which provide additional insights into the implications of climate change. On the other hand, conceptual models assume that the physical processes can be reduced to dominant processes and lumped over an area or basin, which implies expedient calculation times at reduced costs. Thus, several climate scenarios may be simulated for a broader consideration of hypothetical future greenhouse gas concentrations and related climate pathways. Conceptual model simplicity also means long transient periods may be investigated instead of time slices which enables a better assessment of near-term and long-term adaptability and vulnerability. However, the physical interpretation is less clear in conceptual models.

As is the case for climate models, any hydrological model needs careful implementation, calibration and validation, before it can be considered suitable and reliable for impact analysis. Given that calibration and validation are generally done for historical conditions (including climate), one major challenge is the proper evaluation of a model's skill at making reliable extrapolations of impacts under future climate conditions. Given that future climate conditions often involve more or higher extremes (e.g. higher rainfall intensities, longer dry periods), some researchers worked on methods for partly evaluating model skill under extreme or changing (climate) conditions; see Refsgaard et al. (2014) for an overview.

The type of model that is most appropriate strongly depends on the water system being modelled and the type of application. For instance, models for urban versus non-urban (or rural) systems, or for water quantity versus water quality related impact analysis, are highly different. The rest of this section reports examples from the North Sea region of what is typically used for impact analysis in hydrology.

Conceptual rainfall-runoff models have been widely applied to individual catchments because of their ease of use and calibration (limited number of model parameters) and because they provide overall runoff estimates at the scale of a catchment or sub-catchment (e.g. at the catchment outlet). The HBV model is one such model that has been used frequently in Europe to investigate the impact of climate change (Bergström et al. 2001; Graham et al. 2007b; Teutschbein and Seibert 2012; van Pelt et al. 2012), through different versions, such as the 'Nordic' version (Lawrence and Hisdal 2011). Other conceptual models applied in the North Sea region are NAM (Andersen et al. 2006; Thodsen 2007; Boukhris et al. 2008; Bastola et al. 2011), PDM (Kay et al. 2006, 2009; Arnell 2011; Christiersen et al. 2012), HyMOD (Bastola et al. 2011), TANK (Bastola et al. 2011), TOPMODEL (Cameron 2006; Bastola et al. 2011), ADM (Fowler and Kilsby 2007), and CATCHMOD (Cloke et al. 2010; Christiersen et al. 2012).

For larger river basins or regions, to capture the spatial variability of the hydrological responses, spatially distributed hydrological balance models have been applied. These can be of a conceptual nature or more detailed, depending on the types of impact studied. At the scale of the entire Rhine basin, Shabalova et al. (2003) and Lenderink et al. (2007) applied the RhineFlow hydrological model, a spatially distributed water balance model that simulates river flow, soil moisture, snow pack and groundwater storage with a 10-day time step. Huang et al. (2013) applied the distributed eco-hydrological model SWIM, for all river basins in Germany. The SWIM model was developed for climate and land-use change impact assessment on the basis of the models SWAT and MATSALU, and simulates the hydrological cycle, vegetation growth and nutrient cycling with a daily time step by disaggregating a river basin to sub-basins and spatial units with assumed homogeneous soil and land-use types. For the whole globe, Arnell and Gosling (2014) applied the Mac-PDM.09 conceptual water balance model to obtain impacts on daily flow extremes, flood hazards and flood risk. Also for the whole globe, Dankers et al. (2014) considered the nine global hydrology and land surface models from the Water Model Intercomparison Project (WaterMIP).

When investigating the impact of climate change on processes occurring at a smaller scale, detailed, higher resolution models are often applied, such as when studying local hydrological consequences like ground water recharge, water quality and flood waves. For example, Thompson et al. (2009) applied the MIKE SHE/MIKE 11 physically-based model to investigate hydrological wetland impacts. For a range of catchments across the Thames Basin, Bell et al. (2012) implemented the distributed hydrological Grid-to-Grid (G2G) model, to assess future changes in peak river flows.

Coarse-scale spatially distributed models also exist and have been applied by Prudhomme et al. (2012) (models JULES, WaterGAP and MPI-HM) and by Dankers and Feyen (2008) and Feyen and Dankers (2009) (model LISFLOOD) for the whole of Europe.

For the Scheldt estuary (EU FP7 Theseus project), Ntegeka et al. (2012) used a quasi 2-dimensional full hydrodynamic model and lumped conceptual hydrological models of the upstream sub-basins to investigate the impact of different inland and coastal hydroclimatic drivers on river level and flood risk. The quantification of flood risk was based on synthetic events developed for different return periods, and applied as boundary conditions to the model. This was done to save on computational time. It was found that when extreme changes for the three main drivers (mean sea level, storm surge level and upstream river flow) coincide, the impact would be disastrous (e.g. +2 m increase in water level at Antwerp).

These impact analyses on catchment runoff and river flow are based on RCM/GCM-based changes (after statistical downscaling) for daily or sub-daily (e.g. hourly) precipitation and potential evaporation. The time scale required for the precipitation input in the hydrological impact models depends on the response time of the river catchment. Peak flows and floods along the river caused by extreme rainfall are controlled by the mean rainfall intensity over that response time.

Influence of Downscaling Method

Several authors stressed that the impact analysis of climate change on hydrology does not only depend on the climate model, greenhouse gas scenario, climate scenario or hydrological model, but also on the method applied to transfer the climate change signal (climate model output or climate scenario) to changes in the hydrological model input.

Diaz-Nieto and Wilby (2005) compared hydrological impact results for the River Thames, after use of the delta change method versus a statistical downscaling method based on empirical transfer functions. The changes in flow associated with the transfer function-based scenarios were generally more conservative and complex than those arising from the use of delta changes. They explained these departures in terms of the different treatment of multi-decadal natural variability, temporal structuring of daily climate variables and large-scale forcing of local precipitation and potential evaporation by the two methods. Willems and Vrac (2011) compared percentile-based perturbation factors with a statistical downscaling based on weather type and also found strong differences if the basic weather typing method was applied. After advancing the method to account for the influence of rainfall changes due to temperature increase, the differences between the methods became less. Limited differences between downscaling methods were also found by Boé et al. (2009) after comparing a dynamical downscaling methodology based on a variable resolution atmospheric model, with a quantile-based bias

correction of the model variables, with a delta change approach. Some discrepancies were noted but they remained limited and to a large extent smaller than the climate model uncertainties. Larger differences were found by Graham et al. (2007a) when comparing the linear scaling approach for RCM bias correction with the delta change method. They concluded that the two approaches gave similar mean results, but considerably different seasonal dynamics. However, because there is insufficient evidence to justify the choice of one method over the other for hydrological climate change impact studies, Lawrence and Hisdal (2011) applied both bias correction and delta change methods and combined the impact results by both methods in their ensemble impact approach. For a single catchment in the UK, Smith et al. (2014) compared the impact results after applying the climate model outputs directly as inputs in the hydrological model, versus the use of quantile-based change factors and changes in the GEV extreme value distribution.

References

- Andersen HE, Kronvang B, Larsen SE, Hoffmann CC, Jensen TS, Rasmussen EK (2006) Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. *Sci Total Environ* 65:223–237
- Andréasson J, Bergström S, Carlsson B, Graham LP, Lindström G (2004) Hydrological change – Climate change impact simulations for Sweden. *Ambio* 33:228–234
- Arnell NW (2011) Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. *Hyd Earth Sys Sci* 15:897–912
- Arnell NW, Gosling SN (2014) The impacts of climate change on river flood risk at the global scale. *Climatic Change*, doi:10.1007/s10584-014-1084-5
- Bastola S, Murphy C, Sweeney J (2011) The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. *Sci Total Environ* 409:5403–5415.
- Bell VA, Kay AL, Cole SJ, Jones RG, Moore RJ, Reynard NS (2012) How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *J Hydrol* 442–443:89–104
- Berg P, Feldmann H, Panitz HJ (2012) Bias correction of high resolution regional climate model data. *J Hydrol* 448–449:80–92
- Bergström S, Carlsson B, Gardelin M, Lindström G, Pettersson A, Rummukainen M (2001) Climate change impacts on runoff in Sweden – assessments by global climate models, dynamical downscaling and hydrological modelling. *Clim Res* 16:101–112
- Boé J, Terray L, Martin E, Habets F (2009) Projected changes in components of the hydrological cycle in French river basins during the 21st century. *Water Resour Res* 45:W08426 doi:10.1029/2008WR007437
- Boukhris O, Willems P, Vanneuville W (2008) The impact of climate change on the hydrology in highly urbanized Belgian areas. Proceedings International Conference on ‘Water & Urban Development Paradigms: Towards an integration of engineering, design and management approaches’, Leuven, 15-17 September
- Cameron (2006) An application of the UKCIP02 climate change scenarios to flood estimation by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty). *J Hydrol* 328:212–226
- Christierson BV, Vidal JP, Wade SD (2012) Using UKCP09 probabilistic climate information for UK water resource planning. *J Hydrol* 424–425:48–67
- Chun KP, Wheeler HS, Onof CJ (2009) Streamflow estimation for six UK catchments under future climate scenarios. *Hydrol Res* 40:96–112
- Cloke HL, Jeffers C, Wetterhall F, Byrne T, Lowe J, Pappenberger F (2010) Climate impacts on river flow: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrol Process* 24:3476–3489
- Dankers R, Feyen L (2008) Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *J Geophys Res* 113:D19105. doi:10.1029/2007JD009719

- Dankers R, Arnell NW, Clark DB, Falloon PD, Fekete BM, Gosling SN, Heinke J, Kim H, Masaki Y, Satoh Y, Stacke T, Wada Y, Wisser D (2014) First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *PNAS* 111:3257–3261
- Deque M, Jones RG, Wild M, Giorgi F, Christensen JH, Hassell DC, Vidale PL, Rockel B, Jacob D, Kjellstrom E, de Castro M, Kucharski F, van den Hurk B (2005) Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results. *Clim Dynam* 25:653–670
- Diaz-Nieto J, Wilby RL (2005) A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in the River Thames, United Kingdom. *Climatic Change* 69:245–268
- Feyen L, Dankers R (2009) Impact of global warming on streamflow drought in Europe. *J Geophys Res* 114:D17116. doi:10.1029/2008JD011438
- Fowler HJ, Kilsby CG (2007) Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change* 80:337–367
- Fowler HJ, Ekstrøm M, Kilsby CG, Jones PD (2005) New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 1. Assessment of control climate. *J Hydrol* 300:212–233
- Frei C, Scholl R, Fukutome S, Schmidli J, Vidale PL (2006) Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models. *J Geophys Res* 111:D06105 doi:10.1029/2005JD005965
- Graham LP, Andreasson J, Carlsson B (2007a) Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods – a case study on the Lule River basin. *Climatic Change* 81:293–307
- Graham LP, Hagemann S, Jaun S, Beniston M (2007b) On interpreting hydrological change from regional climate models. *Climatic Change* 81:97–122
- Hempel S, Frieler K, Warszawski L, Schewe J, Piontek F (2013) A trend-preserving bias correction – the ISI-MIP approach. *Earth Sys Dyn* 4:219–236
- Horton P, Schaefli B, Mezghani A, Hingray B, Musy A (2006) Assessment of climate change impacts on alpine discharge regimes with climate model uncertainty. *Hydrol Proc* 20:2091–2109
- Huang S, Hattermann FF, Krysanova V, Bronstert A (2013) Projections of climate change impacts on river flood conditions in Germany by combining three different RCMs with a regional eco-hydrological model. *Climatic Change* 116:631–663
- Kay AL, Jones RG, Reynard NS (2006) RCM rainfall for UK flood frequency estimation. II. Climate change results. *J Hydrol* 318:163–172
- Kay AL, Davies HN, Bell VA, Jones RG (2009) Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change* 92:41–63
- Kendon EJ, Roberts NM, Senior CA, Roberts MJ (2012) Realism of rainfall in a very high-resolution regional climate model. *J Climate* 25:5791–5806
- Kendon EJ, Roberts NM, Fowler HJ, Roberts MJ, Chan SC, Senior CA (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Clim Change* 4:570–576
- Lawrence D, Hisdal H (2011) Hydrological projections for floods in Norway under a future climate. Report no. 5-2011, Norwegian Water Resources and Energy Directorate
- Leander R, Buishand TA (2007) Resampling of regional climate model output for the simulation of extreme river flows. *J Hydrol* 332:487–496
- Leander R, Buishand TA, van den Hurk BJJM, de Wit MJM (2008) Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output. *J Hydrol* 351:331–343

- Lenderink G, Buishand A, van Deursen W (2007) Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrol Earth Syst Sc* 11:1145–1159
- Ntegeka V, Decloedt LC, Willems P, Monbaliu J (2012) Quantifying the impact of climate change from inland, coastal and surface conditions. In: *Comprehensive Flood Risk Management – Research for Policy and Practise* (Klijn F, Schweckendiek T, eds), CRC Press
- Ntegeka V, Baguis P, Roulin E, Willems P (2014) Developing tailored climate change scenarios for hydrological impact assessments. *J Hydrol* 508:307–321
- Olsson J, Andréasson J, Graham LP, Rosberg J, Yang W (2011) Using an ensemble of climate projections for simulating recent and near-future hydrological change to Lake Vänern in Sweden. *Tellus A* 63:126–137
- Piani C, Haerter JO, Coppola E (2010) Statistical bias correction for daily precipitation in regional climate models over Europe. *Theo Appl Climatol* 99:187–192
- Prudhomme C, Williamson J, Parry S, Hannaford J (2012) Projections of flood risk in Europe. In: *Changes in Flood Risk in Europe*, CRC Press
- Rauscher SA, Coppola E, Piani C, Giorgi F (2009) Resolution effects on regional climate model simulations of seasonal precipitation over Europe. *Clim Dynam* 35:685–711
- Refsgaard JC, Madsen H, Andréassian V, Arnbjerg-Nielsen K, Davidson TA, Drews M, Hamilton D, Jeppesen E, Kjellström E, Olesen JE, Sonnenborg TO, Trolle D, Willems P, Christensen JH (2014) A framework for testing the ability of models to project climate change and its impacts. *Climatic Change* 122:271–282
- Seaby LP, Refsgaard JC, Sonnenborg TO, Stisen S, Christensen JH, Jensen KH (2013) Assessment of robustness and significance of climate change signals for an ensemble of distribution-based scaled climate projections. *J Hydrol* 486:479–493
- Shabalova MV, van Deursen WP, Buishand TA (2003) Assessing future discharge of the river Rhine using regional climate model integrations and a hydrological model. *Clim Res* 23:233–246
- Smith A, Freer J, Bates P, Sampson C (2014) Comparing ensemble projections of flooding against flood estimation by continuous simulation. *J Hydrol* 511:205–219
- Sunyer MA, Madsen H, Ang PH (2012) A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change. *Atmos Res* 103:119–128
- Sunyer MA, Hundecha Y, Lawrence D, Madsen H, Willems P, Martinkova M, Vermoor K, Bürger G, Hanel M, Kriaučiūnienė J, Loukas A, Osuch M, Yücel I (2014) Inter-comparison of statistical downscaling methods for projection of extreme precipitation in Europe. *Hyd Earth Sys Sci Disc* 11:6167–6214
- Teutschbein C, Seibert J (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *J Hydrol* 456-457:12–29
- Teutschbein C, Wetterhall F, Seibert J (2011) Evaluation of different downscaling techniques for hydrological climate-change impact studies at the catchment scale. *Clim Dynam* 37:2087–2105
- Thodsen H (2007) The influence of climate change on stream flow in Danish rivers. *J Hydrol* 333:226–238
- Thompson JR, Gavin H, Refsgaard A, Refstrup Sørensen H, Gowing DJ (2009) Modelling the hydrological impacts of climate change on UK lowland wet grassland. *Wetl Ecol Manag* 17:503–523
- Van Pelt SC, Beersma JJ, Buishand TA, van den Hurk, BJJM, Kabat P (2012) Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations. *Hydrol Earth Syst Sc* 16:4517–4530
- Wilks DS (1992) Adapting stochastic weather generation algorithms for climate change studies. *Climatic Change* 22:67–84
- Willems P (2013) Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium. *J Hydrol* 496:166–177

- Willems P, Vrac M (2011) Statistical precipitation downscaling for small-scale hydrological impact investigations of climate change. *J Hydrol* 402:193–205
- Willems P, Arnbjerg-Nielsen K, Olsson J, Nguyen VTV (2012a) Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings. *Atmos Res* 103:106–118
- Willems P, Olsson J, Arnbjerg-Nielsen K, Beecham S, Pathirana A, Bülow Gregersen I, Madsen H, Nguyen VTV (2012b) *Impacts of Climate Change on Rainfall Extremes and Urban Drainage*. IWA Publishing
- Yang W, Andréasson J, Graham LP, Olsson J, Rosberg J, Wetterhall F (2010) Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrol Res* 41:211–229