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A review of hydrological modelling of basin-scale climate change and urban development impacts

Sarah Praskievicz and Heejun Chang*

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Abstract: Hydrological modelling is a valuable tool for researchers in geography and other disciplines for studying the processes governing impacts of climate change and urban development on water resources and for projecting potential ranges of impacts from scenarios of future change. Modelling is an inherently probabilistic exercise, with uncertainty amplified at each stage of the process, from scenario generation to issues of scale, to simulation of hydrological processes, to management impacts. At the basin scale, significant factors affecting hydrological impacts of climate change include latitude, topography, geology, and land use. Under scenarios of future climate change, many basins are likely to experience changes not only in their mean hydrology, but also in the frequency and magnitude of extreme hydrological events. Impacts of climate change on water quality are largely determined by hydrological changes and by the nature of pollutants as flushing- or dilution-controlled. The most significant impact of urban development on water resources is an increase in overall surface runoff and the flashiness of the storm hydrograph. The increase in impervious surface area associated with urban development also contributes to degradation of water quality as a result of non-point source pollution. Modelling studies on the combined impacts of climate change and urban development have found that either change may be more significant, depending on scenario assumptions and basin characteristics, and that each type of change may amplify or ameliorate the effects of the other. Hydrological impacts of climate change and urban development are likely to significantly affect future water resource management.

Key words: basin hydrology, climate change, hydrological modelling, urban development, water quality.

I Introduction

In a world in which the consensus view predicts substantial impacts of anthropogenic climate change on global water resources in the near term and distant future (Kundzewicz et al., 2007), hydrological impact analysis has become a thriving area of research. Understanding potential climate-related im-
II Impacts of climate change on hydrology

1 Uncertainty in climate change impact modelling

There are four different aspects of uncertainty in climate change impact assessment in hydrology and water resources. The first source of uncertainty is the choice of general circulation models (GCMs). The second is associated with transferring large-scale climatology to regional-scale climatology appropriate for hydrological and water resource impact assessment, namely downscaling processes. The third is related to the parameters and structures of hydrological models used for impact assessment. The fourth source of uncertainty stems from water resource impact models employed for study.

There are two general classes of climate change impact studies, differing in the way in which the assumptions about the direction and magnitude of climate change that may occur in the study area are generated. One approach is to use synthetic climate change scenarios, in which the historical average temperature and precipitation are changed by fixed amounts at annual, seasonal, or monthly scales. This approach avoids the uncertainty associated with GCMs and allows for sensitivity analysis, an estimate of the amount of change in a hydrological variable resulting from a series of incremental changes in a climatic variable, which is a highly useful type of impact analysis for the purpose of determining how much the climate must change in order for significant impacts to occur.

One disadvantage of synthetic scenario generation is that the chosen amounts of change in climatic variables are not necessarily realistic consequences of increased atmospheric greenhouse gas concentrations. This problem can be avoided by not selecting amounts of change arbitrarily, but instead by basing these on some other data, such as anomalies in the historical record or the range of changes predicted by climate models for the region. Another disadvantage of the
synthetic approach is that, when the changes are applied to raw historical climate data, the range of variability in the scenario remains unchanged, which is problematic because climate change is likely to alter variability, particularly in precipitation. To address this problem, Chiew et al. (2003) developed a refined method known as daily scaling, in which change factors are applied to ranked historical precipitation data. In this method, change factors are not constant across all years, seasons, or months, but are dependent on the relative magnitude of the event.

The alternative approach to climate change scenario generation begins with one or more greenhouse gas (GHG) emissions scenarios, usually from the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Emissions Scenarios (SRES). These scenarios are used to drive GCMs, which rely on large-scale simulations of the coupled ocean-atmosphere system to predict the response of the climate to the projected increase in GHG concentrations. Because the outputs from these models are at too large a scale to be useful for most hydrological applications, they must be downscaled using either a regional climate model (RCM), which simulates local topographic and other influences on climate, or a statistical downscaling technique, which alters historic climate records according to the projected future change.

Studies indicate that the greatest source of uncertainty in the climate impact modeling chain is the GCM (Wilby et al., 2006; Graham et al., 2007). Because they all model atmospheric conditions and feedbacks differently, GCMs vary widely in their projections, particularly for precipitation. The choice of emission scenario is less important for the near term, because most scenarios show very similar levels of emissions through the 2050s and it takes time for the atmosphere to respond (Wilby and Harris, 2006). In basins where summer is the low flow period, the uncertainty in GCM-derived river flows is greatest in summer (Wilby et al., 2006), suggesting that changing precipitation and temperature patterns will alter seasonal water balance components in different ways.

Another source of uncertainty is downscaling methods. Wood et al. (2004) compared three statistical downscaling methods, using the Variable Infiltration Capacity (VIC) macroscale hydrological model. The most accurate method was bias correction and spatial disaggregation. Dibike and Coulibaly (2005) used output from a GCM to compare two downscaling methods, regression analysis and a stochastic weather generator. The weather generator performed better when estimating the length of wet spells in the historical period. Salathé et al. (2007) found significant differences in regional climate response in the Pacific Northwest using statistical downscaling versus an RCM, with the RCM more accurately reproducing the historical climate. In comparing downscaling methods, RCMs and other dynamic techniques are generally more successful because they replicate regional climate systems, but also require more data and time to implement than the simpler statistical techniques.

An additional source of uncertainty stems from the choice of a hydrological model in climate impact assessment. Different hydrological models vary in their parameters and assumptions and are suited to simulate runoff at certain spatial and temporal scales. In comparing the temperature-based potential evaporation (PE) with the physically based Penman-Monteith PE, Kay and Davies (2008) found that the temperature-based PE matched the observed PE better than did Penman-Monteith PE, for all the climate models studied for three catchments spread across Britain. The uncertainty introduced by the PE formulation was less than that due to the climate model, but could still be important for some applications. Similarly, other studies have shown that results of climate impact studies are less sensitive to the hydrological model than the climate change scenario (Graham et al., 2007; Kay et al., 2009). In other words, different hydrological models tend to produce similar outcomes,
given the same climatic inputs, but the same hydrological model run under different GCM simulations may give widely differing results. Jiang et al. (2007) compared six conceptual water balance models and found that their simulations of observed conditions were similar, but there were greater differences when run under future climate simulations, particularly among those models that represented soil moisture differently.

The outputs from hydrological models can be further used in water resource management models to take the socio-economic aspects of the hydrological system into account (Christensen et al., 2004), where additional uncertainty might occur. These may include models representing water demand (Groves et al., 2008), dam and reservoir storage (Payne et al., 2004), or conservation and efficiency policies (O’Hara and Georgakakos, 2008). At each stage of this modelling chain, assumptions must be made and error is inevitable, leading to amplified uncertainty throughout the modelling process (Wilby and Harris, 2006; Kay et al., 2009). No climate change impact studies, however, have quantified all sources of uncertainty yet.

2 Factors influencing basin hydrological response to climate change

Drainage basins are natural hydrological units, each with its own water balance. Accordingly, basins are ideal spatial units for hydrological modelling, and many climate change impact studies are at this scale (Table 1). An added benefit of basin-scale modelling is that many water resource management plans are made at this scale, which facilitates the application of modelling results to real-world decision-making.

The projected impacts of climate change on basin hydrology obviously depend on the geography of the study area. A rise in air temperature will lead to increases in evaporation and thus precipitation, accelerating the global hydrological cycle (Huntington, 2006; Oki and Kanae, 2006). The implications of this acceleration for water resources vary by region. Some areas, particularly in tropical regions and the higher latitudes, may have increased access to water resources as a result of more precipitation. This may have negative implications for flood risk in these regions. In other areas, especially those that are already experiencing water stress, such as Mediterranean and semi-arid climates, increased hydrological variability may decrease water availability. Modelling studies by Arnell (2003a), Manabe et al. (2004), Milly et al. (2005), and Nohara et al. (2006) predicted increases in the runoff of Arctic and many tropical and mid-latitude rivers, with decreases in semi-arid regions, particularly during the dry season. Accordingly, one of the fundamental characteristics determining a basin’s hydrological response to climate change is latitude.

Humid mid-latitude basins may generally experience increased runoff. Jha (2005) used downscaled GCM output to drive the Soil and Water Assessment Tool (SWAT) in order to project impacts of climate change through the 2040s on the hydrology of the Upper Mississippi River Basin. The results included a 51% increase in annual streamflow, a 43% increase in groundwater recharge, and a 50% increase in total water yield. Thodsen (2007) used the lumped conceptual hydrological model NAM, driven by an RCM, to simulate impacts of climate change on runoff in five Danish basins, and found that mean annual runoff will increase by 12% by the end of the twenty-first century.

Even within a nation in a humid temperate climate, differences in latitude may determine basin-scale hydrological response. Andréasson et al. (2004) investigated potential impacts of climate change on water resources in six Swedish basins. Results differed according to the latitude of the basin, with southern Sweden mostly experiencing decreases in annual runoff and northern Sweden experiencing increases, particularly in autumn. Similarly, Graham (2004), using four climate change scenarios in the Baltic
### Table 1  Basin-scale modelling studies of impacts of climate change on hydrology

(PCM = Parallel Climate Model; UBC = University of British Columbia; HBV = Hydrologiska Byråns Vatten-balansavdelning; SWAT = Soil and Water Assessment Tool; VIC = Variable Infiltration Capacity; NAM = Nedbor-Afstromings Model; PRMS = Precipitation-Runoff Modeling System; Hydro-BEAM = Hydrological River Basin Environmental Assessment Tool)

<table>
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<td>Loukas et al (2002b)</td>
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<td>Eckhardt and Ulbrich (2003)</td>
<td>Central Europe (693 km²)</td>
<td>Ensemble of 5</td>
<td>2090s</td>
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<td>Increased winter runoff; earlier spring peak; decreased summer runoff and groundwater recharge</td>
</tr>
<tr>
<td>Christensen et al. (2004)</td>
<td>Colorado River Basin</td>
<td>PCM</td>
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<tr>
<td>Jha (2005)</td>
<td>Upper Mississippi River Basin (490,000 km²)</td>
<td>HadCM2; CGCMa1</td>
<td>2040s</td>
<td>SWAT</td>
<td>51% increase in annual streamflow; 43% increase in groundwater recharge; 50% increase in total water yield</td>
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<tr>
<td>Andréasson et al. (2004)</td>
<td>Sweden (1100–6000 km²)</td>
<td>HadCM2; ECHAM4/OPYC3; HadAM3H</td>
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<td>HBV</td>
<td>Southern Sweden: decreased annual runoff; Northern Sweden: increased annual runoff</td>
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<tr>
<td>Graham (2004)</td>
<td>Baltic Sea Basin (1,600,000 km²)</td>
<td>ECHAM4/OPYC3; HadAM3H</td>
<td>2071–2100</td>
<td>HBV</td>
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<td>Thodsen (2007)</td>
<td>Denmark (23–814 km²)</td>
<td>HIRHAM RCM</td>
<td>2071–2100</td>
<td>NAM</td>
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</tr>
<tr>
<td>Bae et al. (2008)</td>
<td>South Korea (43–2293 km²)</td>
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</tr>
<tr>
<td>Fujihara et al. (2008)</td>
<td>Turkey (21,700 km²)</td>
<td>MRI-CGCM2</td>
<td>2070s</td>
<td>Hydro-BEAM</td>
<td>Decrease in annual runoff of 52–61%</td>
</tr>
</tbody>
</table>
Sea region, found annual changes in runoff ranging from a decrease of 30% to an increase of 40%, generally with decreases in the south and increases in the north. Bae et al. (2008) assessed potential impacts of climate change on runoff amount and timing in South Korea’s 139 drainage basins. They used scenarios from two GCMs, downscaled through a stochastic weather generator, to drive the hydrological model Precipitation Runoff Modelling System (PRMS). The results suggest that the changes in runoff will vary seasonally and regionally within the nation, with increases in the north and decreases in the south.

Arid and semi-arid basins are more likely to experience a decrease in annual runoff. For example, Fujihara et al. (2008) modelled the hydrological impacts of climate change in Turkey’s Seyhan River Basin, using the Hydrological River Basin Environmental Assessment Model (Hydro-BEAM) driven by two GCMs. The results include a decrease in annual runoff of 52–61%.

In addition to whether the basin is located in a relatively humid or arid region, basins located near one another may also differ in their hydrological response. One important factor is elevation and, accordingly, whether the basin is dominated by rainfall or snowmelt. Loukas et al. (2002b) used GCM scenarios to drive the University of British Columbia’s conceptual Watershed Model, in order to determine climate-driven changes in runoff in two British Columbia basins. In the rainfall-dominated basin, the results indicate that total runoff will increase in fall and winter and decrease in spring and summer, while the snowmelt-dominated basin is projected to experience an earlier spring peak and a nearly 18% increase in winter runoff. Generally, the hydrology of rainfall-dominated basins is more controlled by changes in precipitation than temperature, while snowmelt-dominated basins are highly sensitive to temperature changes.

Because of the loss of snowpack, higher-elevation basins in the mid-latitudes may experience increasing water shortages. Christensen et al. (2004) examined future hydrological impacts of climate change in the Colorado River Basin using statistically downscaled GCM scenarios to drive the Variable Infiltration Capacity (VIC) hydrological model. Under a business-as-usual emissions scenario, the model projects a 17% decrease in annual basin runoff by 2098, because of higher temperatures and decreased precipitation. Severe declines in runoff as a result of glacial retreat have also been projected for other world regions, such as a decrease of up to 94% by 2100 in the Himalayan area (Akhtar et al., 2008).

Particularly in higher-elevation basins, where the spring snowmelt provides a major peak in the annual hydrograph, not only the total amount of flow, but also its timing, is important. Barnett et al. (2005) determined that, in snowmelt-dominated basins, climate change is likely to cause a shift in the timing of peak runoff to earlier in the spring, consequently lowering flows during the summer, when demand for water is highest. In a follow-up study, Barnett et al. (2008) analysed trends in and causes of observed changes in snowpack, timing of peak runoff, and average January through March daily minimum temperatures for the western United States from 1950 to 1999. The results indicate that anthropogenic greenhouse gas emissions are responsible for up to 60% of the observed hydroclimatic changes, a finding similar to that of Hamlet and Lettenmaier (2007). Morrison et al. (2002), modelling British Columbia’s Fraser River Basin, projected a shift in peak flow to 24 days earlier in the year and an 18% decrease in average peak flow, despite an average annual flow increase of 5% by 2099, relative to the 1961 to 1990 baseline. Eckhardt and Ulbrich (2003) used SWAT to project impacts of two climate change scenarios on streamflow and groundwater recharge in a central European basin where snowmelt is an important part of the water cycle. The results include little change in annual runoff, but increased winter
runoff, earlier peak spring flow, and decreased summer runoff and groundwater recharge, findings similar to those in other snowmelt-dominated basins, like those in the western United States (Barnett et al., 2005).

Several studies have attempted to identify elevation thresholds at which the characteristic temperature-related impacts of climate change on the snowpack are significant. Regonda et al. (2005) and Graves and Chang (2007) found that, between 1950 and 1999, there has been an advance in the timing of the peak spring flow, a decrease in snow water equivalent, and an increase in winter rainfall in snowmelt-dominated basins in the western United States, particularly in lower-elevation basins in the Pacific Northwest, with a possible threshold elevation of approximately 2500 m. Dettinger et al. (2004) also found earlier peak runoff in three Sierra Nevada basins averaging in elevation from approximately 1250 to 2800 m, a trend that hydrological modelling suggests will continue throughout the twenty-first century. Stewart et al. (2004), using regression modelling, found similar results for the mountainous regions of the western United States. Knowles and Cayan (2004), in investigating the impacts of climate change on hydrology in the San Francisco Bay basin, found that snowmelt-driven changes in timing of peak runoff are dependent on elevation, with the most significant effects in the range of 1300 to 2700 m.

Another important determining factor for hydrological response to climate change is the geology of the basin. Basins with significant groundwater exchange may be less sensitive to changes in climate in the near term. Tague et al. (2008) compared a basin in Oregon’s Western Cascades, with a shallow active groundwater system, to one in the High Cascades, with deep aquifer reserves. Surface flows in the High Cascades basin were predicted to be reduced more by temperature increases resulting from climate change than in the Western Cascades basin. Climate change modelling studies often do not produce consistent outcomes among scenarios. Different emissions scenarios and climate models may result in different projections of hydrological change. Frei et al. (2002) investigated the impacts of climate change on water resources in two basins in New York’s Catskill Mountains, which contribute to the municipal water supply of New York City. The results included potential changes in water supply in both basins ranging from an increase of 10% to a decrease of 30% by 2080, because of differences in precipitation projections among the climate models and emission scenarios. Similar ranges in potential future water availability, dependent on scenario choice, have been found in global-scale studies (Arnell, 2004). The runoff responses to climate change in these basin-scale modelling studies depend on both the modelling approach used and the characteristics of the basin.

3 Hydrologic variability

In addition to the previously discussed changes in mean hydrology, climate change is also likely to affect hydrological variability. Even in areas where annual runoff changes only slightly, flow levels that are currently considered extremely low or high may become more common. For example, Arnell (2003b) examined the impacts of climate change on hydrological variability in six basins in the United Kingdom during the twenty-first century, with results including a slight increase in mean monthly flow and a decrease in low flow amount of up to 40% by the 2080s, with a corresponding increase in interannual hydrological variability.

In many world regions, particularly lower-elevation tropical and humid mid-latitude areas, increased flooding is a significant risk of climate change. Milly et al. (2002) found an increase in the observed frequency of large floods in major world river basins during the twentieth century. Kleinpen and Petschel-Held (2007) estimated, using statistically
downscaled climate change-driven alterations of a water balance equation, that up to 20% of the global population lives in river basins that may experience greater flooding as a result of climate change by 2100. Palmer and Räisänen (2002) predicted that heavy winter rainfall events in the United Kingdom and summer monsoons in Asia may increase by a factor of five during the twenty-first century.

In a continental-scale modelling study, Lehner et al. (2006) predicted increases in flood frequencies for northern Europe and drought frequencies for southern Europe. Kundzewicz et al. (2005) found that past and projected future large floods in central Europe may be related to anthropogenic climate change. Kay et al. (2006), using a conceptual model driven by high-resolution RCM outputs through the 2080s, found increases in flood frequency and magnitude for most of their 15 study basins in the United Kingdom. In six Australian basins, Evans and Schreider (2002), using a conceptual hydrological model driven by stochastic weather generator outputs, found an increase in the magnitude of floods, despite a decrease in mean annual runoff. Mote et al. (2003) also predicted increases in winter flooding in smaller rainfall-dominated and transient basins in the Pacific Northwest, because of increases in temperature and precipitation.

In snowmelt-dominated basins, however, flood risk may decline under climate change. In an Ontario basin, for example, Cunderlik and Simonovic (2005), using the Hydrological Engineering Center Hydrological Modelling System (HEC-HMS) driven by a stochastic weather generator under two GCM scenarios, found a decrease in the severity of high and low flow events as a result of climate change. In British Columbia, Loukas et al. (2002a) predicted an increase in flood frequency and magnitude in a rainfall-dominated basin and a decrease in a snowmelt-dominated basin. Similarly, the Columbia River Basin and other large rivers in the Pacific Northwest may not experience an increase in flood risk resulting from climate change, but are more likely to have problems with low flows (Mote et al., 2003). These contrasts in results indicate that different regions may respond to climate change with varying impacts on the frequency and severity of hydrological extremes, because of differences among the basins in runoff generation processes.

### III Impacts of climate change on water quality

Although water quality will probably be affected by climate change, fewer studies (Table 2) have modelled these impacts than have modelled runoff and other hydrological variables, perhaps because it is more difficult to obtain comprehensive water quality data in many regions and because modelling complexity increases with the inclusion of water quality parameters (Whitehead et al., 2009). In particular, water quality is significantly affected by non-climatic factors such as channel morphology, which controls erosion and sediment transport, and vegetation growth, which is closely connected with the uptake and export of nutrients. Few existing hydrological models are able to adequately simulate these processes. Because of the modelling uncertainty, the dynamics of water quality response to climate change are not well known. For water quality studies, the spatial scale of the basin is especially important, because pollutant loadings are governed by local land-surface characteristics as well as by the more regional climatic processes (Chang, 2008). Accordingly, the study basins referred to in Table 2 are all meso-scale basins, with areas ranging from approximately 1000 to 3000 km², in order to facilitate comparison.

Except for stream water temperature (Ducharne, 2008), which is highly influenced by air temperature, the impacts of climate change on water quality are indirect and primarily occur through hydrological changes. An increase in surface runoff can have two possible effects on a pollutant:
flushing or dilution (Walling and Webb, 1992). Different pollutants vary in how they respond to increased flow. The loadings of some constituents, such as sediment and adsorbed phosphate, are controlled largely by erosion, so an increase in surface flow results in increased loading. The concentration of these flushing-controlled constituents will continue to increase until additional flow no longer has the energy to transport additional load, at which point dilution effects take over and concentrations begin to decrease. With dilution-controlled pollutants, the direction of this hysteresis is reversed. Nitrate, for example, is typically found in higher concentrations in groundwater than surface water. An increase in surface flow, then, dilutes the nitrate-enriched groundwater and lowers concentrations. Nitrate concentrations only begin to increase with increasing surface flow when the amount of nitrate transported by surface water is higher than the background level.

Basin hydrology therefore affects both the loading and the concentration of pollutants differently. Higher surface runoff may increase the loading of flushing-controlled pollutants while decreasing the concentration of dilution-controlled pollutants, while lower surface runoff may produce the opposite effects. These changes in water quality are also seasonally variable. Water quality and aquatic ecology can be severely harmed, for example, when high nutrient concentrations occur during the growing season, because these can lead to noxious algal blooms.

Some modelling studies have focused on how climate change may affect concentrations of certain pollutants. Mimikou et al. (2000) used the physical hydrological model Water Budget (WBUDG) and the point source water quality model R-Qual to simulate impacts of climate change on runoff, biological oxygen demand (BOD), dissolved oxygen (DO), and ammonium in a Greek basin. Because the climate scenarios included increased temperatures and decreased precipitation, the results were decreased mean monthly runoff, particularly in summer, and impaired water quality. Varanou et al. (2002) used SWAT to model the impacts of climate change, derived from six GCMs, on runoff and water quality in a Greek basin. Because of reduced flows, concentrations of some pollutants
pollutants may increase as a result of climate change, particularly in the summer months, a finding similar to that of Mimikou et al. (2000).

Other studies have modelled changes in pollutant loading resulting from climate change. In a retrospective study, Bouraoui et al. (2004) modelled runoff, suspended solids, total nitrogen, and total phosphorus in a Finnish basin with SWAT, using 34 years of historic climate data. They then removed the trends in temperature and precipitation, finding that observed climate change has resulted in increased winter runoff and increased annual and winter nutrient transport of up to 85%, as a result of higher precipitation and associated flushing of the soil matrix. Arheimer et al. (2005) modelled the impacts of climate change on nitrogen and phosphorus levels in a Swedish basin. Climate scenarios with increased precipitation projected higher average river flows while others with decreased precipitation projected decreased flows, but the average overall nitrogen loading in the basin for all scenarios increased by 10–33% by 2100. In a forecasting study, Imhoff et al. (2007) used the Climate Assessment Tool (CAT), driven by regional climate scenarios, to project changes in nutrient loadings as a result of climate change for the period 2010–2039 in a Maryland, USA, basin. There were significant differences among land-use types in their sensitivity to climate change, with agricultural land experiencing larger climate-driven increases in nutrient export than forest land, findings that are similar to those of Chang et al. (2001). Overall, the water quality results are closely tied to basin hydrology in terms of flushing and dilution responses, and cannot be examined independently.

IV Impacts of urban development on hydrology

It is well known that an increase in impervious surface area accompanied by urban development significantly alters hydrological response, in particular by increasing the ‘flashiness’ or quickness to and magnitude of peak flow from rainfall events (Dunne and Leopold, 1978). As impervious surface area increases, the entire water balance of the basin is altered, with increased surface runoff and decreased groundwater recharge and evapotranspiration. Several studies have modelled the hydrological response of basins to historical or potential future urban development (Table 3).

One major research question that has been explored is whether there exist thresholds of impervious surface area above which the hydrological response is characteristically urban. Wang (2006) conducted a retrospective analysis of the impacts of urban development on flood risk in an approximately 400 km² Texas basin, using both 30 m digital elevation models and high-resolution Light Detection and Ranging (LiDAR) data. He found that, from 1974 to 2002, the basin impervious surface area increased from approximately 10% to over 38%, with an accompanying increase in the 100-year flood peak of 20%. In another retrospective analysis, Nirupama and Simonovic (2007) used data on land use, meteorology, and hydrology to estimate the increase in flood risk caused by urban development in London, Ontario. This study demonstrates that approximately 15% impervious surface area may be a threshold above which basin hydrology exhibits the typical urban flashiness. Also, basin size influences hydrological sensitivity to urban development, with smaller basins experiencing relatively greater impacts than larger ones. Runoff does not increase linearly with rainfall, and the amount and location of basin impervious surfaces affects the relation between these variables (Dunne and Leopold, 1978).

V Impacts of urban development on water quality

1 Empirical studies

Much of the existing research of the impacts of urban development on water quality is
either empirical or statistical. Significant effort has gone into developing techniques for quantifying the impact of urban development on water quality, in terms of how both urban development and water quality are defined. One simple approach is to compare water quality parameters from different sub-basins that are similar to one another except in their levels of urban development. For example, Almeida et al. (2007) found that values of total fecal coliform bacteria, Escherichia coli, total heterotrophic bacteria, chemical oxygen demand (COD), BOD, and phosphate were significantly higher in urban areas than at undeveloped sites in an Argentinian basin, particularly during the wet season, illustrating the negative impact of urban development on water quality.

Similarly, Rose (2007) found that solute concentrations in the baseflow of a Georgia, USA, basin increased along a rural-to-urban gradient, indicating increasing levels of non-point source pollution in urban areas. Tu et al. (2005) also found that, in their Massachusetts study area, per capita developed land use was a strong predictor of specific conductance, dissolved ions, and dissolved solids.

A more sophisticated approach to quantifying water quality impacts of urban development is sensitivity analysis, in which an attempt is made to determine the amount of basin impervious surface area at which water quality begins to degrade. In three New Jersey basins with a combined area of approximately 1200 km², Conway (2007) determined that a threshold of impervious surface area of 2.4–5.1% results in negative water quality impacts, as measured by pH and specific conductance. Identifying impact thresholds can be beneficial for management of water resources, because they can be used to set ecologically relevant and achievable goals.

Additional considerations in studying impacts of urban development on water quality include the location of the development and the scale of analysis. For example, in a study of 42 sub-basins in Washington’s Puget Sound lowland, ranging in area from 4 to 69 km², Alberti et al. (2007) found that

### Table 3  Basin-scale modelling studies of impacts of urban development on hydrology and water quality (GIS = Geographic Information System; SWAT = Soil and Water Assessment Tool; BASINS = Better Assessment Science Integrating Point and Nonpoint Sources; L-THIA = Long-Term Hydrologic Impact Assessment; HSPF = Hydrologic Simulation Program – Fortran)

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<th>Author(s)</th>
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<th>Study period</th>
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<td>Tong and Chen (2002)</td>
<td>Ohio</td>
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<td>1988–1994</td>
<td>BASINS</td>
<td>Higher levels of nitrogen, phosphorus, and fecal coliform bacteria on urban/agricultural lands</td>
</tr>
<tr>
<td>Im et al. (2003)</td>
<td>Virginia</td>
<td>Small</td>
<td>1994–2000</td>
<td>SWAT; HSPF</td>
<td>Both models accurately simulated runoff; sediment, and nutrient transport</td>
</tr>
</tbody>
</table>

*A small basin is defined as <1000 km²; a medium basin is 1000–10,000 km².
both greater amount and connectivity of impervious surface area degrade water quality and biotic integrity, as measured by indices of benthic macroinvertebrate diversity. Four land surface characteristics were significant in determining water quality impacts: land-use intensity, land-cover composition, landscape configuration, and impervious area connectivity. Boeder and Chang (2008) conducted a multiscale empirical analysis of trends in DO, COD, and nitrogen levels in Oregon’s Rock Creek basin from the mid-1990s to 2003 and found that forest cover is negatively correlated with COD at the basin scale and positively correlated with nitrogen at the local scale. These results suggest that the scale of analysis significantly affects the determination of land-cover impacts on water quality parameters.

2 Modelling studies

In addition to establishing empirical relations between level of urban development and water quality, researchers have also modelled the response of water quality parameters to land-use change (Table 3). Modelling water quality is particularly difficult, because loading of water quality constituents depends not only on basin hydrology, but also on other characteristics such as channel morphology and vegetation dynamics that are complex enough to require models of their own. Nevertheless, several hydrological models incorporate water quality modules that can be used for studying urban development impacts. Im et al. (2003) compared the ability of two hydrological models, SWAT and the Hydrological Simulation Program – Fortran (HSPF), to simulate historical impacts of urban development on hydrology, sediment, and nutrient transport in a Virginia basin, finding that observed water quality can be reasonably reproduced using these models, and that nutrient and sediment loading was associated with higher levels of urban development.

As with empirical studies, modelling studies of urban development impacts are highly scale-dependent. Tang et al. (2005) used the Land Transformation Model (LTM), a land-use change model, in combination with the Long-Term Hydrological Impact Assessment (L-THIA), a physically based hydrological model, to project land-use change impacts on runoff and non-point source water pollution in the Muskegon River watershed in Michigan, and found that increases in pollutant loading were more significant in some urbanizing sub-basins than at the scale of the entire basin. This scale issue is related to the concept of urbanization thresholds, because basins where the relative change in impervious surface area is greater may exhibit more sensitivity to additional urban development. The location of development may also be significant; increased impervious surface area in headwater regions tends to have more impact than development further downstream (Tang et al., 2005).

While many studies have focused on the impacts of urban development on water quality, other types of land-use change are associated with water quality degradation. Tong and Chen (2002) used Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) to model the relation between land use and water quality in an Ohio basin and found that agricultural and urban lands were associated with high levels of nitrogen, phosphorus, and fecal coliform bacteria. The highest loadings were associated with agricultural lands where, compared to urban land, nitrogen levels were seven times greater, phosphorus levels were six times greater, and fecal coliform bacteria levels were five times greater. Accordingly, both agriculture and urban development tend to lead to degradation of water quality.

VI Combined impacts of climate change and urban development on water resources

As climate change and land-cover change, two major drivers of global change, are expected to continue throughout the twenty-first century (Olson et al., 2008), there is a
growing concern that the sustainability of freshwater resources are threatened in many parts of the world. In some parts of the world, future water stress will be influenced more by non-climatic factors such as increasing water demand fuelled by population growth and economic development than by climate change (Vörösmarty et al., 2000; Alcamo et al., 2007). To assess potential regional impacts of global change and to improve understanding of the interactions of climate change and land-cover change in hydrology and water resources, an increasing number of basin-scale hydrological modelling studies take both changes into account (Table 4). This line of research is important for water resource management, because the two types of changes may either ameliorate or amplify one another’s effects at different spatial and temporal scales. Identifying the sensitivity of changes in runoff and water resources to climate change and urban development is the first step to guide climate adaptation strategies at the regional scale (Metzger et al., 2005).

Some studies have found that land-cover change is likely to affect water resources more significantly than climate change. For example, Herron et al. (2002) used the Integrated Quantity-Quality Model (IQQM), driven by outputs from a regional climate scenario generator, to simulate impacts of climate change and proposed increase in forest cover for 2030 on runoff in an Australian basin and found that a 10% increase in forest cover results in a 17% decrease in runoff, while the climate change scenario only reduces runoff by 5%. Davis Todd et al. (2007) used the VIC model to attribute observed changes in baseflow, streamflow, and peak runoff to climatic change and urban development in Indiana, using 50 years of historic data, finding an increase in monthly baseflow and streamflow, but not in precipitation, indicating that non-climatic factors may be more significant. Similarly, Cuo et al. (2009) investigated twentieth-century land-cover change and climate change on Puget Sound Basin hydrology using the Distributed Hydrology-Soil-Vegetation Model (DHSVM), identifying that both land cover and temperature change are important in upland areas, while land-cover change is the primary driving force of hydrology in lowlands.

Other studies, however, have found that scenarios of potential future climate change are more significant than land-use change scenarios in determining hydrological response. Barlage et al. (2002) found that hydrology in a Michigan basin is more sensitive to climate change than land-use change. Chang (2003) modelled impacts of climate change and urban development on runoff in a Pennsylvania basin, using the hydrochemical model ArcView Generalized Watershed Loading Function (AVGWLF), and found that mean annual runoff increases by up to 11% under scenarios of climate change, but by less than 2% under an urban development scenario. Chen et al. (2005) used SWAT and the lumped Climate and Human Activities-sensitive Runoff Model (CHARM) to simulate the effects of climate variation and land-cover change over the past four decades in China’s Suomo River Basin and found that climate variation explains 60–80%, and land-cover change explains 20%, of the changes in runoff. Choi (2008) modelled impacts on runoff in an Illinois basin of downscaled GCM climate change scenarios and urban development scenarios generated from a dynamic growth model and found that the climate change scenarios result in significantly decreased total runoff, while land-use change affects only surface runoff. Franczyk and Chang (2009) modelled changes in runoff depth in a small Oregon basin using SWAT, finding maximum increases in winter runoff of over 12% for a scenario of climate change and less than 2% for a scenario of urban development.

Whether climate change or urban development scenarios produce more significant change in a particular basin, combining the two changes may result in larger impacts
Table 4  Basin-scale modelling studies of combined impacts of climate change and urban development on water resources (IQQM = Integrated Quality and Quantity Model; AVGWLF = ArcView Generalized Watershed Loading Function; BASINS = Better Assessment Science Integrating Point and Nonpoint Sources; CHARM = Climate and Human Activities-sensitive Runoff Model; VIC = Variable Infiltration Capacity; HEC-HMS = Hydrologic Engineering Center – Hydrological Modeling System)

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Study area</th>
<th>GCM(s)</th>
<th>Study period</th>
<th>Hydrological model</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herron et al. (2002)</td>
<td>Australia</td>
<td>ECHAM4/OPYC3; CSIRO DARLAM; HadCM3</td>
<td>1860–2100</td>
<td>IQQM</td>
<td>17% decrease in runoff from increased forest cover; 5% decrease in runoff from climate change</td>
</tr>
<tr>
<td>Chang (2003)</td>
<td>Pennsylvania</td>
<td>HadCM2; CGM1</td>
<td>1990–2100</td>
<td>AVGWLF</td>
<td>11% increase in mean annual runoff from climate change; 2% increase in mean annual runoff from urban development</td>
</tr>
<tr>
<td>Maximov (2003)</td>
<td>Ohio</td>
<td>HadCM2</td>
<td>2100s</td>
<td>BASINS</td>
<td>Up to 70% increase in annual runoff; 40–50% increase in phosphate concentrations</td>
</tr>
<tr>
<td>Chen et al. (2005)</td>
<td>China</td>
<td>None (retrospective)</td>
<td>1970–1999</td>
<td>CHARM; SWAT</td>
<td>Climate variation explains 60–80% of changes in runoff; land-cover change explains 20% of changes in runoff</td>
</tr>
<tr>
<td>Samaniego and Bárdossy (2006)</td>
<td>Germany</td>
<td>CGCM1; HadCM2</td>
<td>2100s</td>
<td>Non-linear equations</td>
<td>Increase of 17–44% in winter runoff</td>
</tr>
<tr>
<td>Davis Todd et al. (2007)</td>
<td>Indiana</td>
<td>None (retrospective)</td>
<td>1940–2005</td>
<td>VIC</td>
<td>Increase in streamflow and baseflow; no trend in precipitation; greater influence of land cover than climate</td>
</tr>
<tr>
<td>Ducharme et al. (2007)</td>
<td>France</td>
<td>ARPEGE-IFS</td>
<td>2070–2099</td>
<td>RIVERSTRAHLER</td>
<td>Climate change increases nutrient concentrations; land management practices potentially mitigate climate impacts</td>
</tr>
<tr>
<td>Beighley et al. (2008)</td>
<td>California</td>
<td>None (climate variability)</td>
<td>1929–2050</td>
<td>HEC-HMS</td>
<td>El Niño years 5 times more likely to produce large runoff events than non-El Niño years and to increase nitrate and phosphate concentrations to 5–10 times greater than baseline levels</td>
</tr>
</tbody>
</table>
than from either scenario alone. For example, Samaniego and Bárdossy (2006) developed a set of non-linear mathematical models, linked to a stochastic land-use/land-cover change model, to simulate impacts of climate and land use on runoff in a German basin and found, using their worst-case climate change and land-use scenarios, an increase in winter runoff of 17–44% by 2025. Harrison et al. (2008) assessed the impacts of climate change and urban development on wetland ecosystems in the United Kingdom, finding that climate change affects the distribution of both high and low flows, and that urbanization increases the flow sensitivity of wetland ecosystems, particularly by increasing the severity of low flows.

Several studies have examined the combined impacts of climate change and urban development on both water quantity and quality. Maximov (2003) used HSPF to model impacts of climate change and land-use change on hydrology and nutrient transport in Ohio’s Great Miami River. The results included an increase in phosphate concentrations of 40–50% as a result of projected climatic and land-use changes. Similarly, Chang (2004) found an increase of up to 50% in phosphorus loads under urban development and climate change scenarios in a Pennsylvania watershed. Ducharne et al. (2007) examined the separate and combined impacts of climate change, land-cover change, and agricultural practices on the water quality of France’s Seine River, finding that climate change increases or slightly decreases mean annual runoff, depending on the climate model used, and increases nutrient concentrations by up to 20%, but that this increase can be mitigated by improved agricultural practices, illustrating the importance of potential adaptation measures in resource management. Beighley et al. (2008) simulated runoff and nutrient transport for historic and future climate variability and land use in a coastal basin in southern California and found that, with an increase in basin urban area from 39% to 50%, the mean event runoff will increase by 200% by 2050.

VII Implications for water management

1 Adaptation in the water sector

Nelson et al. (2007) defined adaptation to environmental change as ‘an adjustment in ecological, social, or economic systems in..."
response to observed or expected changes in environmental stimuli and their effects and impacts in order to alleviate adverse impacts of change’. The related concept of resilience refers to the ability of a system to withstand change. Different regions and different sectors vary in their resilience, and therefore in their capacity for adaptation (Arnell, 2000).

Milly et al. (2008) argued that climate change has undermined the principle of stationarity, a central concept in water resource management which holds that future hydrological events will be within the range of past variability. Currently, water managers make decisions based on probability density functions, which are generated with observed data on the inverse relation between the frequency of an occurrence and its magnitude. Because climate change is likely to change both the mean conditions and the variability of hydrological regimes, basing long-term management decisions on these functions is highly problematic, a reality increasingly acknowledged by water resource managers.

2 Modelling water management

Some studies have gone beyond asking merely what the potential hydrological impacts of future changes are likely to be, to attempting to model potential adaptation responses of water resource managers to these impacts (Table 5). For urban areas, some of the most significant potential impacts of climate change and further urban development are those related to stormwater management (Semadeni-Davies et al., 2008). High-intensity precipitation associated with climate change, combined with higher impervious surface area accompanying urban development, increases surface runoff and creates flashy storm discharge, which has negative hydrological and water quality impacts. Waters et al. (2003) used the water resource model Personal Computer – Storm Water Management Model (PCSWMM), driven by a synthetic climate change scenario, to simulate the management actions needed to maintain peak discharge at current levels under a 15% increase in rainfall intensity in an urban basin in Ontario. The most effective methods were downspout disconnection, increased depression storage, and increased street detention storage. Such sustainable stormwater management techniques may become increasingly necessary to avoid the worst impacts of climate change and urban development.

A further consequence of the increased flashiness of urban runoff resulting from higher-intensity precipitation and higher impervious surface area is that dry periods may be more severe (Meehl et al., 2007). The increased surface runoff and reduced groundwater recharge associated with some scenarios of climate change and urban development not only mean higher floods, but also more frequent and severe droughts, because of the reduction in water storage. Fowler et al. (2007) used the Mospa water management model, driven by a regional climate change scenario based on the HadCM3 GCM, to determine twenty-first-century impacts of climate change on the water supply system of northwestern England. They found that overall available yield will decrease by 18%, but that existing water infrastructure and management practices should be sufficient to meet future demand. Problems with increased hydrological variability associated with climate change and urban development are likely to be more severe in regions with pronounced seasonal variability in flows. O’Hara and Georgakakos (2008) assessed the water supply system in San Diego, California, as a case study to develop a methodology for evaluating the need for changes in water storage capacity as a result of climate change, finding an increase in future storage costs under climate change, exacerbated by population growth. These combined pressures may force some urban water utilities to limit demand through
conservation measures or to seek alternative sources of supply, such as groundwater reserves or interbasin transfers.

Finally, in addition to the direct impacts on urban water supplies, climate change is also likely to exacerbate conflicts over competing uses for water resources, such as extraction for municipal and agricultural use, hydropower, and environmental flows. This problem is likely to be especially severe in regions like the mountains of the western United States, where increased temperatures will diminish the snowpack and shift the timing of peak runoff to earlier in the spring, leaving lower flows available during the high-demand summer. Payne et al. (2004) used a macroscale hydrological model, driven by outputs from a macroscale hydrological model perturbed by statistically downscaled GCM scenarios, to examine the impacts of climate change on water management in California’s Sacramento and San Joaquin basins. They found that the modelled adaptation measures could meet only up to 96% of environmental flow requirements in the Sacramento River Basin and less than 80% in the San Joaquin basin by 2099. These findings illustrate the potential exacerbation of water resource conflicts under future climate change and urban development and the impossibility of meeting all demand for water in some regions.

### VIII Conclusions

Geographers and researchers in other disciplines are increasingly using hydrological models to study the potential impacts of future climate change and urban development on basin water quantity and quality. Although modelling is an uncertain and probabilistic process, it is a useful methodology for experimenting with the dynamics that govern complex environmental and social systems and for projecting possible ranges of impacts.

### Table 5  Basin-scale modelling studies of impacts of climate change on water resource management (PCM = Parallel Climate Model; SWMM = Storm Water Management Model; VIC = Variable Infiltration Capacity; CVmod = Central Valley model)

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Study area</th>
<th>GCM(s)</th>
<th>Study period</th>
<th>Hydrological model</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waters et al.</td>
<td>Ontario</td>
<td>CGCM2</td>
<td>2090s</td>
<td>SWMM</td>
<td>Flooding can be mitigated with disconnected drains, bioswales, and green streets</td>
</tr>
<tr>
<td>Payne et al.</td>
<td>Columbia River Basin</td>
<td>PCM</td>
<td>2070–2098</td>
<td>VIC</td>
<td>Decrease in hydropower production of 9–35%</td>
</tr>
<tr>
<td>VanRheenen et al.</td>
<td>California</td>
<td>PCM</td>
<td>1995–2099</td>
<td>CVmod</td>
<td>96% of instream flow targets met in the Sacramento basin and &lt;80% in the San Joaquin basin</td>
</tr>
<tr>
<td>Fowler et al.</td>
<td>England</td>
<td>HadCM3</td>
<td>2070–2100</td>
<td>Mospa</td>
<td>Decrease of 18% in overall water yield</td>
</tr>
</tbody>
</table>
that may be faced by water resource managers over the next several decades. In particular, there is a need for more studies that examine the combined effects of climate change and urban development, because both types of changes are likely to occur in many basins, but their interactive effects are still not well understood.

There are several knowledge gaps in hydrological impact modelling that need particular attention if this methodology is to continue to improve in epistemological sophistication and to offer increased practical benefits for management purposes. These include improved methods for downscaling from GCMs to the regional and basin scales, adding water quality impacts in modelling studies, improving model simulation of channel morphology and vegetation dynamics, further integrating the effects of climate change and urban development scenarios, and quantifying uncertainty in modelling outcomes. Advances on all these fronts will improve the reliability of modelling projections and scientific understanding of the underlying processes.

As the trends of climate change and urban development continue throughout the twenty-first century, there will be increasing demands by governments and other institutions for reliable projections of how water resources may be affected. Although uncertainty will never be eradicated from what is necessarily a probabilistic exercise, ongoing developments in the science and technology of hydrological impact analysis may improve researchers’ ability to generate realistic scenarios that will be of use to the water resource sector as it adapts to these changes. These issues will be a rich source of questions for researchers in a variety of disciplines in the years to come.

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