Response surfaces for climate change impact assessments in urban areas

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Abstract Assessment of the impacts of climate change in real-world water systems, such as urban drainage networks, is a research priority for IPCC (Intergovernmental Panel of Climate Change). The usual approach is to force a hydrological transformation model with a changed climate scenario. To tackle uncertainty, the model should be run with at least high, middle and low change scenarios. This paper shows the value of response surfaces for displaying multiple simulated responses to incremental changes in air temperature and precipitation. The example given is inflow, related to sewer infiltration, at the Lycksele waste water treatment plant. The range of plausible changes in inflow is displayed for a series of runs for eight GCMs (Global Circulation Model; ACACIA; Carter, 2002, pers. comm.). These runs are summarised by climate envelopes, one for each prediction time-slice (2020, 2050, 2080). Together, the climate envelopes and response surfaces allow uncertainty to be easily seen. Winter inflows are currently sensitive to temperature, but if average temperature rises to above zero, inflow will be most sensitive to precipitation. Spring inflows are sensitive to changes in winter snow accumulation and melt. Inflow responses are highly dependent on the greenhouse gas emission scenario and GCM chosen.

Keywords Adaptation; climate scenarios; impacts; mitigation; sensitivity analysis; socio-economic scenarios; uncertainty

Introduction
Urban areas represent some of the most modified hydrological environments. They are also where increasing numbers of people live and work. Drainage infrastructure has been designed to meet public demands — usually in terms of a design storm, which sets a limit for damage considered acceptable. Climate change leaves us with a number of problems: how will infrastructure already in place weather future, possibly more frequent/higher intensity storms? And how can we design new systems to cope with a largely unknown future with unknown variability? What will happen in cold regions where snowmelt is currently the dominant hydrological event of the year? The objective of this paper is to show how sensitive an existing drainage system is to a range of possible climate change scenarios using a response surface. A response surface is a graphical tool to display responses of a variable given a range of changes in two determinants, in this study, temperature and precipitation. While the method does not resolve uncertainty and does not address changes in variability, it provides a visual measure of sensitivity that can be used as an education tool to increase public awareness of the problems faced by urban water managers. A secondary objective is to show that response to climate change in cold regions is discontinuous, that is, snowmelt represents a threshold so that a change in temperature to above freezing will cause changes in runoff unrelated to change in precipitation.

Climate change is a contentious issue; climate has changed in the past and will continue to do so. The Intergovernmental Panel on Climate Change, IPCC, states there is strong evidence that the global climate will warm over the next decades due to the release of greenhouse gases through human activities (IPCC, 1996, 2001a). Climate change has the potential to affect not only the natural water environment but also the human or built
The hydrological impacts of climate change are usually evaluated from estimates of stream flow using rainfall-runoff models calibrated with historical data and forced by some form of climate scenario. Leavesley (1994) provides a review of modelling techniques that is still current. In many respects, water management acts as a buffer between climate and hydrological impacts; however, little attention has been paid to infrastructure design and operation. Thus, IPCC (2001b) has called for real-world studies into water systems. Recent examples have tended to focus on water resources for hydropower or irrigation (e.g., Lettenmaier et al., 1999). Impact assessments for urban areas are scarce; those available tend to focus on water supply and demand (e.g., Boland, 1997) or catastrophic flooding (e.g., Schreider et al., 2000).

Another priority area for IPCC (Parry, 2001) is to identify climate change thresholds that lead to discontinuous biophysical responses. Snowmelt induced runoff is such a response. Large scale (0.5 × 0.5° grid) river simulations forced by a climate scenario derived from the Hadley Centre GCM, HadCM2, showed that northern Norway and eastern Sweden could have increased winter runoff by the 2050s at the expense of spring peak flow while south Sweden could have spring flow peaks occurring a month earlier (Arnell, 1999). IPCC (2001a) provides a literature review suggesting European winters currently classified as cold will be rare by the 2020s and disappear almost entirely by 2080. Changes in snow accumulation and melt have great implications for urban drainage in cold regions where towns currently experience problems ranging from poor water quality and flooding to combined sewer overflows (CSO) and high hydraulic loads in sanitary sewers (Marsalek, 1991; Oberts, 2000). Clearly, the need for urban impact assessments for water management is great.

Impact assessment in urban settings is hampered by discordant scales between atmospheric and land surface processes. GCMs used for climate scenario development have scales of 100–1,000 km and weeks whereas simulation of runoff from large catchments requires a resolution of around 1–10 km and 1 day (e.g., Hostetler, 1994). Urban catchments require even finer resolutions (<1 km, minutes; e.g., Schilling, 1991). Urbanisation causes a shift from large to small scale hydrological processes. The ground surface becomes highly heterogeneous with high imperviousness, and the storage and flow functions of the soil are replaced by a network of gutters and pipes leading to a shortening of response times and high peak flows. Regional climate models such as the Swedish RCA model developed at the Rossby Center (Rummukainen et al., 2001) represent the state-of-the-art when it comes to downscaling GCM climate data. Even with an impressive resolution of six hours and 20 km (Phil Graham, SMHI personal comment, 2002), the model is too coarse for many urban applications. Herein lies the rub; the extreme complexity of an urban drainage network makes development of meaningful climate scenarios for impact assessment extremely complex.

Scale issues notwithstanding, uncertainty within climate change scenarios is problematic and can be described as a cascade where every step in scenario development introduces new uncertainties. Moreover, predictions will differ depending on the GCM, the starting point chosen and the gas emission scenario. Many authorities advocate use of high, middle and low climate change scenarios in impact assessments (see Jones, 2000). The need to acknowledge a range of plausible predictions is at loggerheads with the needs of managers and policy makers for simple, concrete values of response to pin their plans on. The lack of detail concerning variability and storm intensity is a particularly sore point as they are the basis for the design-storm concept. A method of displaying uncertainty that is understandable is needed, if only as an education tool. To that end, this paper demonstrates the value of response surfaces for impact assessments in urban areas. The case study is wastewater inflows (initial time-slice 1984–1993) to the Lycksele WWTP (waste water
treatment plant) in north-central Sweden. The choice was motivated by the scale issues discussed above, that is, the inflows largely reflect sewer infiltration from groundwater which is a slow process less vulnerable to surface heterogeneity than stormwater generation. At present the highest hydraulic loads occur in spring due to melt water fed groundwater recharge. Climate scenario envelopes derived from the results of the ACACIA project (A Concerted Action Towards A Comprehensive Climate Impacts and Adaptations Assessment for the European Union, Carter, 2002) are overlaid onto the response surfaces to indicate possibility space; that is, the range of plausible changes to waste water inflows. These envelopes represent decadal time-slices for the 2020s, 2050s and 2080s respectively.

This paper highlights the method shown in Semadeni-Davies (2003), which examines the effect of socio-economic change on urban drainage systems. She found that changes in urban infrastructure design and operation have a greater potential to impact hydraulic loads at the WWTP than climate change.

**Defining possibility space**

In light of the uncertainties involved in downscaling GCM outputs to a resolution compatible with urban applications, an incremental or synthetic scenario, where climate variables are altered systematically step-by-step, was thought to be just as reliable as a more sophisticated scenario. This is the easiest type of scenario to apply, however, there is a potential to create unrealistic scenarios and scenarios are not linked to greenhouse gas emissions. Moreover, there is an underlying assumption that the base data represent a period of stable climate. An across-the-board incremental scenario also fails to acknowledge seasonal differences in climate change. Indeed the ACACIA GCM predictions discussed below are quite different for summer and winter (pers. comm., Carter, 2002). The method also allows the event magnitude to increase without adjusting the frequency; this could lead to an under-representation of low magnitude events. In contrast, the reality could be for increased magnitudes of medium frequency events with unchanged extremes; alternatively, there could be a skew towards either extreme. A related assumption is that the number of days with precipitation will remain the same. How event variability will change presents special problems for urban water managers concerned with dimensioning tomorrow’s infrastructure, which are largely unresolved. Indeed, complaints about the treatment of variability also hold for stochastic weather generators (IPCC, 2001b), which are often used where small temporal scales are required (e.g. Schreider et al., 2000).

Use of an incremental climate scenario approach lends itself to construction of response surfaces (Figure 1). Multiple runs of a transformation model forced by the altered climate data sets are used to generate a matrix of response points that is summarised by contours or isolines. Each point represents a measure of shift from the base no-climate-change response. The direction of the isolines shows which determinant the system is most sensitive to, and the closer the isolines, the greater that sensitivity. Figure 1 shows a discontinuity where the relative sensitivity of the response variable to determinants X and Y changes depending on their combination. To illustrate in the unshaded section, a change in X and Y of (40,0) will lead to a change in response of around 45%; in contrast, a change of (0,40) will lead to a change in response of only 28%. Moreover, GCM derived scenarios can be overlaid on the response surface to indicate the possible direction of change and the differences in their outcomes are easily visible in the context of system sensitivity to climate (Fowler, 1999). The area between climate scenarios is termed possibility space in this paper and represents the range of plausible responses to changed climate.

Here winter (DJF) and spring (MAM) response surfaces are created for simulated wastewater inflows to the Lycksele WWTP. The forcing data, daily average air temperature and daily precipitation totals, were collected between 1984 and 1993. Precipitation is
varied by changes between –10 and +40% and temperature between –5 to +15°C. Thus the response matrices have a total of 1,000 points, each point represents the percentage change from seasonal inflow totals simulated with the observed, no-change, climate data.

The range of predicted changes in seasonal air temperature and precipitation is superimposed in the form of envelopes to indicate the boundaries of possibility space. These envelopes (Figure 2) are derived from winter GCM climate scenarios developed for Sweden as part of the ACACIA project (Parry, 2000; Hulme and Carter, 2000). They relate to four possible socio-economic futures represented by four emission scenarios. There are three decadal time-slices: 2020s, 2050s, and 2080s. All the time-slices were simulated by the GCMs: HadCM2a-GG 1-4; CGMI-GG; CSIRO-GG; and ECHAM4-GG, GDFL model outputs were also available for the 2020s.

Study site: Lycksele

Lycksele (Figure 3a) is a small town situated in central northern Sweden. Snow starts to accumulate in November; snowmelt is usually in the last weeks of April and is finished by early May (Figures 3b, c). High hydraulic loads at the WWTP due largely to sewer infiltration for several weeks following snowmelt are common in May and June. The stormwater is

![Figure 1](https://iwaponline.com/wst/article-pdf/48/9/165/423778/165.pdf)

**Figure 1** Response surface showing response to incremental changes in determinants X and Y. The patterns and density of the isolines are a measure of sensitivity (after de Freitas and Fowler, 1989)

![Figure 2](https://iwaponline.com/wst/article-pdf/48/9/165/423778/165.pdf)

**Figure 2** Winter (DJF) climate scenario envelopes for Sweden for three time-slices. Derived from the eight (2020s) or seven (2050s, 2080s) GCM simulations forced with four emission scenarios (derived from Carter, 2002, pers. comm.)
mostly separated from wastewater, but there is a very minor combined sewer (Hernebring, 1996). Daily data available for the study period 1984–1993 include inflow to the treatment plant and estimates of monthly wastewater as well as snow depth, average temperature and precipitation observations from a local weather station. Figure 3b shows that temperature was fairly stable, however precipitation (Figure 3c) showed high intra-annual variability with a spread of over 150 mm in July. It is thus important that the transformation model is robust for a wide range of climate conditions. Comparison with 30-year climate normals (Swedish Meteorological and Hydrological Institute, 1961–1991) suggests that the period was somewhat wetter, with the period average being up to twice the normal rainfall some months; however, there was no discernable trend.

**Transformation model**

The combined part of the sanitary sewer is minimal, and most “surface” water that enters the network is via sewer infiltration. Sewer infiltration from groundwater occurs when the water table rises above the level of the pipes. Water leaks in via cracks and joints. The volume is related to the length and depth of the pipes as well as the hydrologic characteristics of the soil and trench backfill; it is difficult to say what the exact conditions are at the point of entry without detailed observation. However, since it is a slow persistent process, conceptual rainfall/runoff models can be used to estimate sewer infiltration (e.g. Gustafsson et al., 1991; Mein and Apostolidis, 1992; Hernebring, 1996). Gustafsson et al. (1991) and Hernebring (1996) used the Danish Hydrological Institute MOUSENAM model to relate sewer infiltration empirically to groundwater recharge. The latter to determine the effect of snowmelt on wastewater flows throughout Sweden. Semadeni-Davies (1998) based sewer infiltration calculations on simulated soil moisture for Luleå with much the same goodness-of-fit as Hernebring (1996). This model is used here with the exception that snowmelt is simulated by the degree-day or temperature-index method rather than the
original physically-based routine. The degree-day method is well known and has been used for a wide range of catchment scale applications, however it is generally unsuited to urban applications (Semadeni-Davies, 2000). Despite the shortfalls, modest data and processing needs make it the standard in urban drainage packages. As the method represents a spatial and temporal average value of snowmelt, it is incompatible with the modelling of short-term drainage problems in urban areas such as CSO (e.g. Matheussen and Thorolfsson, 1999), but is probably justified for sewer infiltration. With respect to climate change, excessive data requirements for physically-based snowmelt modelling make the degree-day method attractive.

IPCC (2001a) notes that the costs of infrastructure for urban water management require long-term planning for an unknown future. In this paper the status quo is assumed; that the drainage system and water use do not change. In reality over 80 years we can expect maintenance and rehabilitation that involves some innovation independent of climate change. Neither population nor economics nor policy will remain static. Semadeni-Davies (2003) looked at the effect of possible changes to the sanitary sewer in Lycksele and found them to be potentially more influential than climate change. Socio-economic changes and their interaction with climate change are discussed in detail as part of the UK Climate Impacts Programme (Berkhout et al., 2002; UKCIP, 2001).

The hydrological transformation model was calibrated for the period 1989–1991. Sewer infiltration was well modelled; the $R^2$ value is 0.65 for the calibration period and 0.57 for the entire period. The results are very similar graphically to those obtained by Hernebring (1996) using the same data set, however as no statistical summary was provided, a true comparison is not possible. A paired student-t test showed no significant difference between the measured and simulated data sets with 90% confidence. There is a slight tendency to overestimate winter and underestimate early spring inflows evident in Figure 4 – possibly due to frozen soil changing winter and spring flow paths. This would cause stormwater to flow overland rather than percolate and enter the pipes via groundwater. The ability of the model to perform well for all seasons suggests that it is transferable to a warmed climate.

**Displaying possibility space**

The overall result of climate change is to “even out” the seasonal distribution of wastewater inflows by changing the timing of snow accumulation and melt (Figure 5). Summer inflows
show low sensitivity to climate change. The changed climate inflows in Figure 5 were simulated mean change in temperature (+3°C) and precipitation (15%) from the 2050s climate change envelope. While useful, Figure 5, which represents a single case, illustrates the difficulty in displaying simulations forced by multiple plausible climate change scenarios. That is, it is hard to visualise more than say three or four cases. This means that comparison between different gas emission scenarios, GCMs or even time-slices becomes extremely complicated.

The response surfaces have the advantage that multiple climate scenarios can be compared. The winter response surface shows two distinct patterns of sensitivity (Figure 6). At low temperatures, inflow is highly sensitive to temperature change, but as temperature...
rises, inflow becomes most sensitive to precipitation. Decreased temperature is met with rapid reduction of inflow as greater volumes of water are held in the snowpack. Although Lycksele currently has winter long snow cover, there is some scope for minor melt events which will diminish if air temperatures drop. In contrast, a 1°C increase in daily temperature could cause a 20–40% increase in inflow irrespective of changes in precipitation. Winter long snow covers would become increasingly rare with a 2°C temperature rise. In the absence of a snowpack to store water, winter wastewater inflows will become more influenced by precipitation. The distance between the isolines shows that sensitivity to precipitation is fairly linear once the influence of the snowpack is removed. Each time-slice climate envelope encapsulates inflow possibility space while preserving the context of response direction. For instance, the 2080 envelope shows that inflows can increase by between 40 and 180% due to the combined impact of reduced snow storage and increased precipitation.

The inflow response is more complicated in spring and is highly related to winter snowmelt (Figure 7). Drops in temperature of more than 3°C lead to water being held in the snowpack until summer and a corresponding decrease in inflow irrespective of precipitation changes. The greatest increase in inflow will occur when there is a slight drop in temperature but increased precipitation. This would allow a deep snowpack to build up during winter and early spring that will melt, perhaps with rain-on-snow, in late spring. However, the climate envelopes indicate that increased temperature, and therefore reductions in inflow, is more likely in both seasons. Warmer winters will cause substantial drops in spring inflows – even with a precipitation increase of up to 30% – by reducing snow storage for spring melt. The time series for the mean of the 2050s envelope (+3°C, 15%, see Figure 5) suggests that high spring peaks lasting several weeks could still occur, but melt induced peaks would become largely a winter phenomenon. Spring melt events will cease altogether with a rise of 4°C so that all spring sewer infiltration is a consequence of rainfall. This finding is consistent with predictions of European snow covers given by Arnell (1999) and IPCC (2001a). For the most part, the climate envelopes point to drops in spring inflow,

![Climate scenarios](https://iwaponline.com/wst/article-pdf/48/9/165/423778/165.pdf)

**Figure 7** Response surface showing the sensitivity of spring (MAM) wastewater inflow (%) to incremental changes in air temperature and precipitation. Climate change envelopes for the 2020s, 2050s and 2080s derived from ACACIA winter predictions are overlaid to provide an indication of possibility space (from Semadeni-Davies, 2003).
though modest increases are plausible for parts of the 2080s envelope, albeit due to increased rainfall rather than snowmelt.

The obvious lesson from the response surfaces and climate envelopes is just how uncertain the future is. Response surfaces cannot provide information about discrete events but rather show the direction of sensitivity over longer time periods. Simulated spring inflows in the 2080s could decrease by 10% or increase by 5% depending on the socio-economic worldview and GCM chosen. Winter variations in predicted wastewater inflows are more dramatic. While snowmelt will largely be a winter phenomenon by the 2080’s, the 2020s and 2050s are transition periods where some years may experience high melt induced runoff in spring and others in winter.

Ramifications and suggestions for further study
This paper has been restricted to sewer inflows in a town with a mostly separated sewer system in recognition of the uncertainty involved in downscaling large scale climate model outputs to the small scale processes in urban areas. Sewer infiltration has arguably the slowest response to precipitation within an urban drainage system, which allows conceptual modelling. The data set and method presented here were used by Semadeni-Davies (2003) to show how urban drainage systems are also sensitive to socio-economic change. In that study, sewer infiltration was limited under the assumption that changing technology in tandem with social values forced complete renovation of the sewer network.

Dimensioning stormwater devices according to design-storm characteristics is problematic especially as predictions of event variability are largely unresolved. Yet this sort of detail is precisely that which is lacking from current state-of-the-art climate scenarios. Thus, running transformation models forced by a single climate scenario for impact assessments is a dangerous, but tempting, exercise. Confronted with such a wide range of responses, stakeholders can be forgiven for failing to see the value of a study such as the one presented here given the high level of inter- and intra-annual variability they already deal with. In view of the needs of planners and policy makers, accounting for uncertainty is problematic. Even so, response surfaces could prove useful, at least on a monthly or seasonal level. Their use could be largely educational by pointing out the level of uncertainty and sensitivity.

Analyses offer a qualitative method of resolving variability. Trondheim, Norway, could be used as a spatial analogy of flood risk for a shift towards mild winters in north Sweden. Despite its high latitude, Trondheim has a maritime climate and there are several accumulation and melt cycles per year driven by warm air advection and rainfall. A combination of snowmelt, frozen soil, rain on snow can lead to high flood risks in winter and early spring. Recent floods in March 1997 and February 1999 are good examples (see Milina, 2000). Besides surface inundation, raw sewage surging into basements was a major cause of property damage during both events. While the first had a rainfall return period of 15 years, runoff represented the 50-year flood. A move from low intensity, radiation driven, melt-generated flow peaks to rapid response, rain-on-snow events such as in Trondheim could introduce new flood hazards to Swedish communities, particularly those with combined systems.

Response surfaces with changed temperature and precipitation could be used to examine impacts on seasonal stormwater drainage, allowing inferences to small-scale processes involved in storage and treatment. For instance, flood risk and combined sewer overflows now encountered during spring melt could be extended to winter. Other response surface axes are possible, say runoff vs. traffic for assessing pollutant loads. Traffic is, of course, responsible for many of the pollutants found in stormwater. Winter lowers engine efficiency so that vehicles produce more exhaust, and there is also greater wear and tear on
roads, tyres and break-linings, thus warmer winters could reduce these pollutant sources. Snow handling could also be considered. Furthermore, alternative fuels or the introduction of fossil-fuel taxes as part of international agreements such as the Kyoto Protocol could lead to improved water quality by limiting traffic.

**Conclusions**

This paper has presented response surfaces to display sensitivity analyses for climate change impact assessments. The case study was wastewater inflows to the Lycksele WWTP. The range of plausible outcomes, or possibility space, is bounded by climate change envelopes derived from a number of GCM runs with different gas emission scenarios. Despite the shortfalls in the incremental scenario method, response surfaces along with GCM derived climate envelopes can allow stakeholders to get a feeling for the direction and significance of climate change. It can also allow quick assessment of where there are discontinuities; the dip in Figure 7 caused by changed timing of the melt season is a prime example. The relative sensitivity of a response variable to either determinant is also plainly visible. New climate scenarios can be plotted easily and can be viewed within the context of sensitivity captured by the response surface. Criticism of incremental scenarios, and the simplistic variability assumption in particular, does remain a cause for concern. Yet until such time that climate change can be reliably predicted at scales compatible with urban drainage, an incremental scenario offers an effective and easily understandable educational tool for urban drainage applications.

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**References**


