Impacts of Climate Change
on Urban Infrastructure
& the Built Environment

A Toolbox

Tool 2.4.1: Climate change and urban drainage modelling – data, issues and assumptions

Author

A. Semadeni-Davies[1]

Affiliation

[1] NIWA, Private Bag 99940, Auckland

Contents

---

1. Introduction

The Ministry for the Environment Climate Change Guidance Manual (MfE, 2008) provides climate change risk assessment guidelines for council core services and functions, including urban water management, to determine the need for adaptation and also to test alternative adaptation strategies. This tool reviews the issues and assumptions involved in urban drainage modelling to determine the possible impacts of climate change and their associated risk. Typical model applications include flood hazard mapping and evaluating waste- and stormwater network capacity. The objectives of this tool are to provide local government guidance regarding:

- The choice of urban drainage models with respect to purpose;
- The choice and use of climate change scenarios; and
- Representation of urban development and change in water management practices.

Examples of urban drainage models which have been applied to Auckland, including a discussion of how the issues addressed in Section 1.1 were handled, are provided in Tools 2.4.2 (Current Practices), 2.4.3 (Guidelines) and 2.4.4 (North Shore City waste water simulation).

1.1 Urban drainage modelling and climate change impact assessment

Most urban climate change risk and impact assessments for stormwater management to date have concentrated on the need for quantity control to limit the risks of flooding or combined sewer overflows due to increased rainfall intensity, and, in some cases, land use change (e.g., Arnbjerg-Nielsen and Mikkelsen, 2009; Arnbjerg-Nielsen and Fleischer, 2009; Kleidorfer *et al.*, 2009; Semadeni-Davies *et al.* 2008 a and b; Denault *et al.*, 2006; Ashley *et al.*, 2005). Examples from Auckland relevant to this case study include:

- Wastewater flows in North Shore (Lockie and Brown, 2010)
  - overviewed in Tool 2.4.4;
- Capacity of the stormwater system in the Wairau Valley (Shaw *et al.* 2005) - overviewed in Tool 2.4.3;
- Metrowater / Auckland City Integrated Catchment Study (ICS) investigation of climate change impacts on stormwater flows and

flood risk (Kinley *et al.*, 2007, Dayananada *et al.*, 2005) - overviewed in Tool 2.4.2;

- ARC flood hazard mapping for Papakura (not yet published at the time of writing); and
- Regional flood hazard mapping in the Auckland Region (e.g., van Kalken *et al.*, 2009; Roberts and van Kalken, 2010) - overviewed in Tool 2.4.2.

In addition, Davis *et al.* (2010) have recently reviewed the studies of flood risk under climate change for the Auckland Region to illustrate how the methodologies used have changed over the past decade as the information on climate change and assessment tools available has improved.

2. Urban Drainage Model Choice

Huber and Dickinson (1988) state that urban drainage models can be generalised according to their primary purpose as follows:

- **Screening models**, which provide immediate insight into the magnitude of problems expected from a certain site or catchment, that is, problem identification.
- **Planning models**, which are comprehensive enough to give an overall assessment of system performance and trade-offs for a range of alternative stormwater solutions, but are simple to use and have low data requirements. Planning implies a forward-looking process to analyse “what-if” scenarios.
- **Design models** focus of specific details of different drainage components (e.g., size and configuration) within the network as a whole. Design models should not be confused with tools for the design of individual components which follow set criteria.
- **Operational models** are intended for everyday running of the drainage system (e.g., real time control).

The boundaries between these model types are not fast and some models can be used for several purposes. With respect to climate change impact assessment, the model chosen should be robust over the range of projected climatic and hydrological conditions. Model choice should reflect the purpose of the assessment as well as data availability; that is, the routines included, time-step and spatial representation should all be compatible with the scale of the processes under investigation. The study purpose will also dictate whether the model is run long-term (i.e., continuously) or over a discrete event such as a historical rainfall or design-storm.

To illustrate, compare the modelling needs for assessing the number and volume of sewer overflows against flood hazard mapping. Both tasks require hydrologic and hydraulic modelling, however, the processes simulated and the level of detail required differ. The former modelling task will require a hydraulic model of the sewer system, but may only need a simple surface runoff generation model (see Lockie and Brown, 2010, overviewed in Tool 2.4.4). The latter task would require complex surface flow routines and detailed topological data but may have a simplified representation of the pipe network or simulate only surface flows with a constant abstraction rate to account for losses to the pipe network (see Davis et al, 2010, overviewed in Tool 2.4.2). Moreover, while the models would have a similar time-step, simulation with a long-term rainfall time-series would be favoured for the first application and extreme rainfall events for the second.

Urban drainage models available in New Zealand include the US EPA models SWMM and SUSTAIN, the Australian MUSIC model (CRCCH, 2005), INFOWORKS (Wallingford Software) and MOUSE / MIKE URBAN (Danish Hydrological Institute, DHI). SWMM, INFOWORKS and MIKE URBAN have primarily been designed for hydraulic simulation of flows in sewers, although they do have surface water hydrological routines for routing water to the pipe network as well as detention and pollution transport modules. While these models have been used for planning and design applications, they are generally operational models. MIKE URBAN and SWMM have been applied in a number of the climate change impact assessments cited above. SUSTAIN and MUSIC also simulate the pipe network, but have been developed largely as planning tools with a focus on surface drainage infrastructure for low impact urban design and water treatment. All the models have GIS functionality.

Models which have been used for climate change impact assessment in urban catchments in relation to flood risk assessment include the DHI MIKE-SHE (surface hydrology, ground water), MIKE 11 (channel flow) and MIKE 21 (2D dynamic flow) as well as AUDACIOUS (Adaptable Urban Drainage - Addressing Change In Intensity, Occurrence And Uncertainty of Stormwater; Ashley *et al.*, 2008). The DHI models can be coupled together; MIKE 11, MIKE 21 and MIKE Urban are collectively known as MIKE FLOOD (see the description of the Auckland Rapid Flood Hazard Mapping programme in Tool 2.4.2 for an example). AUDACIOUS was purpose-developed in the UK for planning and evaluating adaptation strategies to mitigate urban flood risk at different spatial scales (building, neighbourhood and catchment) due to climate change. The AUDACIOUS package includes tools (i.e., rainfall estimates and model modules), guidance and procedures for flood risk assessment.

It is noted that urban drainage models are complex, have intensive data needs, long set-up and run times, and require users to have advanced modelling expertise. Consequently, they are expensive to set-up and run, and this can limit the number of scenarios that can be simulated for climate change impact assessment.

3. Scenario development

3.1 Climate change scenarios

The main drivers associated with climate change in urban areas are rainfall, especially rainfall extremes, and sea level rise in coastal areas. While evapotranspiration is also a consideration, it is a relatively minor part of the urban water balance which is dominated by flows from impervious surfaces. This section outlines the rainfall requirements for urban water modelling. Guidance on the adjustment of rainfall data for urban drainage modelling in the Auckland area can be found in

3.1.1 Extreme rainfalls (design-storms)

MfE guidance (2008, 2010) recommends event-based modelling sing adjusted rainfall extremes as part of risk assessment preliminary screening. The method (overviewed in Tool 2.4.3) adjusts rainfall extremes according to the average annual temperature increase. Screening should be carried out for a range of climate projections. If the screening indicates high sensitivity, continuous modelling may be warranted.

The concept of hypothetical design-storms to represent extreme rainfalls is very familiar to urban drainage engineers and is used for design (e.g. ARC, 2003 for the Auckland Region) as well as assessment of drainage infrastructure and evaluation of flood depth and extent. Design-storms are characterised by their Intensity-Duration-Frequency (IDF) relationship whereby for a given event duration, rainfalls with the greatest intensity occur least often. Design-storms are referred to either by their average recurrence interval (ARI) or annual exceedence probability (AEP) which is the probability that an event of a given duration and depth will be exceeded in a given year. The AEP is related to the ARI as:

$$AEP = 1 - \exp\left(\frac{1}{ARI}\right)$$

The 1% AEP event is equivalent to the 100-year rainfall. The terms ARI and AEP are also applied to the frequency of floods events. While it is often assumed that a rainfall with a particular ARI will result in a flood event with the same ARI, the depth and extent of runoff generated by a rainfall event is highly dependant on antecedent catchment conditions.

For Auckland, regional design rainfall maps for the 2, 5, 10, 20, 50 and 100-year ARIs are provided in TP 108 (ARC, 1999). TP108 also gives guidance on how to distribute the rainfall depth temporally over the duration period and provides methods for determining surface runoff generation. The hyetograph chosen is a modification of the Chicago hyetograph which accounts for changes in rainfall intensity over the event. Post Auckland Council amalgamation, TP108 is currently under review and it is anticipated that there will be a recommendation to apply the MfE (2008) adjustments with a projected annual temperature increase of 2.1°C in the new document (personal communication: Bodo Hellberg, Auckland Council). It should also be pointed out that other council water management guidelines currently under preparation, such as the Auckland Council Stormwater Flood Modelling Specifications (2011; personal communication: Nick Brown), are likely to contain the same recommendation.

Design rainfalls are also available from the High Intensity Rainfall Design System (HIRDS; Thompson, 2002) developed by the National Institute of Water and Atmospheric Research (NIWA). The tool is now available online (http://hirds.niwa.co.nz) and returns design storms for any location in New Zealand. HIRDS automatically applies the MfE (2008) adjustments for climate change given user specified changes in mean annual temperature.

Several examples from Auckland which demonstrate the use of adjusted design storms for climate change impact assessments are overviewed in Tools 2.4.2 and 2.4.3. International examples include Arnbjerg-Nielsen and Fleischer (2009); He et al, (2006); Denault et al (2006) and Watt *et al.* (2003).

One of the failings of adjusted design storms is the implication that there is no change in the frequency of extreme events, rather, only the intensity of those events increases. However, increases in rainfall could also result from no change in rainfall intensity, but an increase in the total number of events; or a skew in the rainfall distribution with more frequent high intensity events and fewer low intensity events. Moreover, the hyetograph chosen may not be representative of the actual rainfall distribution over observed extreme rainfalls which can have a profound impact on runoff calculations. This possibility led Metrowater to run their risk assessment for both historical events and also TP108 design storms (see Tool 2.4.2 for details). Even without the added complication of climate change, problems with the use of designs-storm in urban water management are well recognised (e.g., USEPA: Clar *et al.*, 2004), and there have been calls for continuous simulation models be used to aid design (e.g., Newman *et al.*, 2000; Palmstrom and Walker, 1990).

3.1.2 Long-term continuous rainfall

Simulating a continuous rainfall record corresponding to future climate change scenarios with a suitable spatial resolution and time-step remains a major challenge for urban drainage modelling. Urban drainage processes occur at scales of metres and minutes (e.g., Schilling, 1991); however, climate change projections are typically regional and seasonal requiring spatial downscaling and temporal disaggregation. The discordant scales mean that urban process must be scaled-up whereas climate projections must be scaled-down. Either way, scaling is likely to increase model uncertainty.

There are four alternatives for obtaining long-ter, continuous rainfall records under climate change:

1. Adjusting historical records according to projected percentage changes in rainfall (the delta-change method);
2. Creating an artificial rainfall record with the same statistical characteristics as the historical rainfall record adjusted for climate change;
3. Directly using the outputs of a regional climate model; or
4. Using rainfall data from a region with a similar climate to that projected as an analogue

The first three methods are discussed in more detail below; the final method is not common in hydrological modelling as it can be difficult to find suitable analogues.

The Delta-Change Method

The delta-change method empirically adjusts historic rainfall on the basis of projected changes in rainfall, either absolute (observations vs. future projections) or comparative (climate model simulated present vs. future projections). The percentage change or anomaly between current and future projected rainfall is applied to the historic record. The method can be refined by applying delta-change coefficients monthly, seasonally or according to some ranking of rainfall (e.g., percentile groupings). The advantage of the delta-change method is its simplicity, that is, no manipulation of climate model output data is required. Since an existing data set forms the basis of the transformation, the impact of climate change on individual rain events and the response of the hydrological system to those events can be compared. In the strictest sense, the method should only be applied to observations with similar spatial and temporal resolutions to avoid over-generalising trends seen in the climate model. For example, a change in monthly rainfall projected by a climate model could equally imply changes to either the frequency or intensity of events in that month, or a combination of both. However, in practice, delta-change has been used to adjust higher resolution observations for climate change in order to carry out hydrological impact assessments.

A delta-change approach is suggested in MfE (2010) which adjusts daily rainfall records for use in flood risk assessments according to seasonal climate projections. The challenge for urban drainage modelling is to apply the delta change method at time-steps in the order of minutes. Semadeni-Davies *et al.* (2008a and b) used the delta-change technique to alter a high resolution (5-minute) rainfall series for future climate signals from a regional climate model. The output of the climate model had a temporal resolution of six hours. The high-resolution historical data was aggregated into 6-hourly time-steps to identify high and low intensity events using a threshold of 10mm/6 hours. Each event was tagged accordingly in the record. Separate delta-change coefficients were determined for each month and event type by comparing modelled rainfall for present and end-of-century climates; these were applied to the 5-minute record according to the tagged event type. Delta-change transformations were also applied to monthly potential evapotranspiration. Two issues were noted: (1) the method assumed that the relationship between local and regional climate will not alter; and (2) increased monthly rainfall volumes predicted by the regional model were assumed to be due to changed rainfall intensity. There was an obvious mismatch between the signal from the regional model (which suggested that extreme rainfalls would become more common) and the delta-change method which assumed no change in event frequency or duration.

Disaggregation and artificial rainfall series

A comparison of rainfall disaggregation methods for urban applications can be found in Hingray and Ben Haha (2005). They show that deterministic and simple stochastic methods perform poorly, and scale-based methods (fractals) are only marginally better. Cowpertwait *et al.* (2004) had more success with a stochastic weather generator to extend historical rainfall records. However, both studies started with hourly observed rainfall records and neither intended that the methods be used to disaggregate future rainfall scenarios for impact assessments. The latter work is of particular interest here as the model was developed for the Auckland City Council to disaggregate historical one-hour rainfall blocks into 5-minute blocks suitable for urban drainage applications. The method is further described in Cowpertwait *et al.* (2006; 2009) and was tested by comparing simulated (MOUSE) flows in Auckland's wastewater and combined sewer system. Historical 5-minute rainfall data from six sites across the city were aggregated into one-hour blocks which were then disaggregated into artificial 5-minutes rainfall series. The flows simulated with the historical and artificial series were comparable. The method was also used to derive an artificial rainfall series (Cowpertwait, 2003) for the Wairau Valley climate change study (Shaw *et al.*, 2005) summarised in Tool 2.4.3.

Regional Climate Model (RCM)

NIWA are currently developing a regional climate model based on the UK Met Office unified model framework (Drost *et al.*, 2007; Baskaran *et al.*, 2002) which can provide rainfall with a temporal resolution of down to 3 minutes. The use of rainfall records from this model for flood risk assessment is discussed in MfE (2010). Rainfall records are currently available for two time periods: current base-line (1970-2000) and end of century (2070-2100). The RCM downscales projections from the Hadley Centre HadCM3 global circulation model which has been forced by two gas emission scenarios for future climate. These emission scenarios are the B2 and A2 (low and moderately high) SRES scenarios which span the range of projections possible. Future runs of the RCM will be based on an extended range of emission scenarios.

Rainfall from the RCM was provided to North Shore City Council for simulation of flows in the waste water system (Lockie and Brown, 2010; summarised in Tool 2.4.4). Significant research effort is being directed by NIWA towards improving and enhancing the RCM. High temporal resolution output, such as short-duration rainfall, also requires statistical bias correction, which is an ongoing research field.

3.1.3 Simulation length

Continuous simulations should be run for a period long enough to capture the range of natural variability – at least 10 years. MfE (2008, 2010) report that the main drivers of variability which affect hydrological processes in New Zealand are El Niño - Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). ENSO has three to seven year cycles while the IPO has phases lasting between 15 and 30 years. MfE (2010) notes that the magnitude of climate change projections for 2040 are in the same order as variability due to the IPO.

3.2 Urbanisation scenarios

MfE (2008) recognizes the importance of socio-economic scenarios to risk assessment. The key socio-economic drivers associated with urban water management are urbanisation (i.e., land use change) and urban drainage practices. With the latter, new networks and replacement of old pipes can be expected. There is also a current transition in stormwater management from reticulated networks to stormwater management devices as part of low impact design (LID) which favours compact urban forms around transport nodes. These changes can be simulated in drainage models by adjusting the boundary conditions and parameters. The exact nature of how socio-economic scenarios should be represented depends on the study purpose, the model to be used, and the area to be simulated.

3.2.1 Urban water management story-lines

The notion of development storylines is comparable to gas emission scenarios. In the context of urban drainage, the storylines set up how urban water is likely to be managed in the future in relation to current trends and foreseeable changes in drivers including technology and social, cultural, environmental and economic values.

One of the most comprehensive studies to determine socio-economic storylines for climate change impact assessment has been undertaken as part of the UK Climate Impacts Programme (UKCIP, 2001; Berkhout *et al.*, 2002; Shackley and Deanwood, 2003). A variety of stakeholders ranging from researchers and policy makers to industry and NGOs were consulted to create four storylines based on differing world views. Each storyline has interlinked impacts on, among other factors, education, trade, industry, agriculture, water and biodiversity. The storylines were developed in parallel to the IPCC SRES (2001) storylines and are *national enterprise*, *world markets*, *global sustainability* and *local stewardship*. These are roughly equivalent to the IPCC SRES A2, A1, B1 and B2 gas emission scenarios respectively and can be arranged in quadrants according to their emphasis on the spectra of values and governance (Figure 3.1).

To illustrate, the *global sustainability* storyline sees the world as an interconnected whole while retaining community values. In this storyline, sustainable development takes precedence over regional development and resource management transcends national boundaries. UKCIP (2001) speculates that increased water demand due to an improved standard of living would be met with demand management and adoption of clean technologies. The latter, along with decreased pesticide use in agriculture, would also result in improved water quality. In contrast, the *national enterpris*e storyline organises society according to short-term consumerist values on a national or regional level. The environment is seen as a commodity to be traded, and only where there is there is a direct economic gain will a resource be protected. This storyline will also see increased water demands along with low investment in infrastructure and high levels of leakage, these would be mitigated by pricing and metering rather than innovation. Both storylines suggest slow population growth and a move towards smaller households leading to new housing developments.

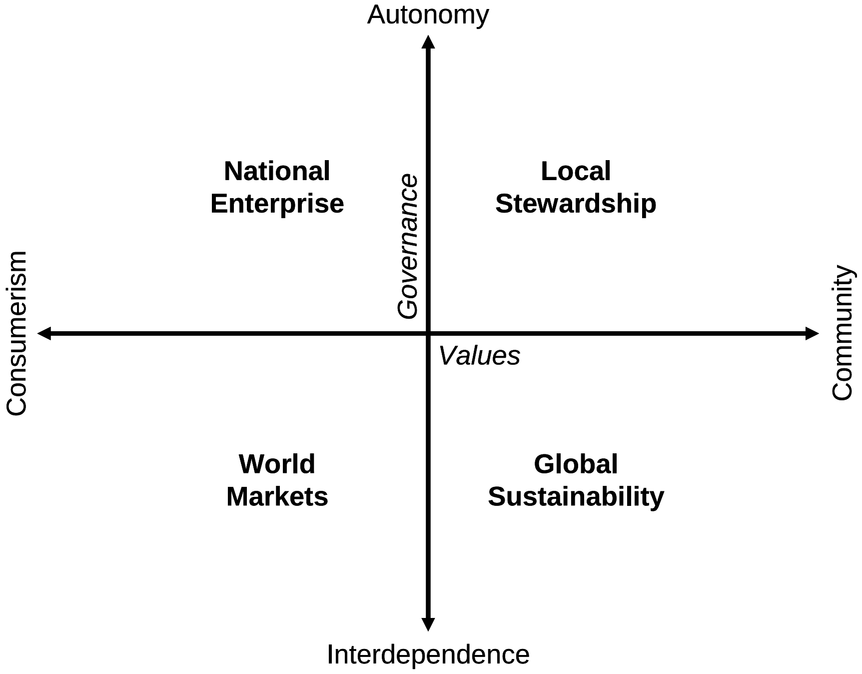

Figure 3.1: UKCIP socio-economic storylines arranged in quadrants according to the axes of *values* (i.e., goals of consumers and policy makers) and *governance* (i.e., political and economic power structures) (after UKCIP, 2001)

The way in which urbanisation scenarios are developed is dependent on the storyline chosen. Take the example of flood risk which has been a major driver of change for stormwater management in some parts of Auckland and is expected to increase as a consequence of climate change (see Tool 2.4.2). There are a range of alternative strategies currently available for adapting to increased flood risk including;

- Business as usual (i.e., living with the consequences);
- Increasing network capacity by replacing pipes or constructing storage infrastructure such as tunnels or tanks;
- Separating combined sewers and rehabilitating aging networks to reduce surface water inflows and sewer infiltration to sanitary sewers;
- Re-zoning flood plains for less sensitive land uses and relocating at-risk businesses and residents;
- Diverting flood waters to temporary storage facilities such as sports fields and play grounds;

- Artificial recharge – this option is being explored for parts of Auckland currently drained by soakage to basalt aquifers ((Harding *et al.*, 2008; Parkinson *et al.*, 2008);
- Requiring LID for brown and greenfields developments and disconnecting stormwater from existing networks in favour of retrofitted stormwater management devices for local disposal; or
- Combinations of the above measures.

Each approach will have a different impact on both water quantity and quality reaching receiving environments. Moreover, each will be represented in urban drainage models in a different way.

3.2.2 Land use and surface hydrology parameters

Parameters commonly found in urban drainage models which can be altered to simulate land use change and possible impacts of surface hydrology include:

- Stormwater catchment or management unit area to simulate new sources as drainage networks are extended with urban development;
- Ratio of permeable to impervious surfaces;
- Hydrological properties
    - vegetation (parameters for evapotranspiration) – trees, scrub, grass/lawn, bare soil
    - depression storage
    - soil compaction and top-soil removal - infiltration capacity, storage capacity, porosity and hydraulic conductivity
    - surface roughness (e.g., Manning's n for grass vs. concrete or asphalt)
    - time-of-concentration - shorter pathways to drainage inlets with land use intensification
- Contaminant sources and build-up and wash-off rates.
- Population growth (critical for modelling waste water flows)
    - spatial distribution of population (e.g., spatially even increases across region vs. local increases at growth nodes)
    - water demand per capita (demand could rise due to both population growth and increased summer soil moisture deficits in city gardens– these could be met by restrictions and metering/water rates as well as

    - water saving technologies such as dual flush toilets and front-load washing machines, harvesting of roof runoff and grey-water reuse)
    - wastewater per capita - volumes (disconnection of grey-water from sewers) and nutrient loads (urine separation toilets, changing diet).
- Traffic fleet composition and associated vehicle emission factors (i.e., emissions of exhaust contaminants, tyre and brake wear-and-tear).

3.2.3 Drainage network parameters

The drainage network has traditionally consisted of a both primary and secondary flow system. The primary system refers to reticulated pipe networks and surface conveyance to pipe inlets via gutters. Secondary flow paths are surface or overland flow paths which convey stormwater when the primary system is at capacity such as gullies and stream channels. Over recent years, stormwater management devices which variously convey, store and treat stormwater at the surface have been installed as part of LID. While at the surface, they are designed as part of the primary system. Changes in urban water drainage systems such as new drainage conduits and system deterioration, and replacement or rehabilitation of existing networks can be expressed by changing model parameters which describe:

The reticulated network (primary network):

- Separated versus combined sewers;
- System capacity, expressed as pipe dimensions – length and diameter / cross sectional area;
- Pipe hydraulic characteristics
    - shape (e.g., round or keyhole)
    - roughness (e.g., Manning's n of concrete vs. plastic);
- Network geometry including the number, location and hydraulic characteristics of drainage infrastructure such as inlets (e.g., catch pits), lateral connections from buildings (i.e., roof downpipes and wastewater), manholes, network joints, culverts, flood protection and storage facilities (e.g., tanks, tunnels), pumping stations, proprietary treatment devices, overflows, and outfalls;
- Sewer infiltration coefficients, i.e., pipe leakiness; and
- Network depth and slope (energy line).

Secondary system:

- Surface flow-paths with respect to the reticulated network and receiving environments; and
- Presence of emergency diverts to storage facilities such as sports fields.

There may also be changes in natural flow paths such as streams, including channelisation, diversions, channel morphology and restoration (e.g., riparian planting).

Stormwater management devices for LID:

- Type (detention/retention facilities, conveyance, infiltration);
- Dimensions/capacity (device and detention volumes, depth, width and length, shape);
- Inlet and outlet configurations (size, relative position, offline or online);
- Other design features such as presence of baffles, underdrains and geo-textile linings which can affect flow; and
- Point of connection to other devices (i.e., treatment trains), the reticulated network or receiving environment.

3.2.4 Boundary conditions

The choice of hydrological catchment boundary conditions is particularly important for event-based simulations. This is because drainage model response to rainfall is highly dependant on the antecedent storage available with regard to soil moisture and the volume stored in pipes and storage facilities (such as tanks, tunnels and detention basins). The conservative approach is to assume the soil is saturated and the system storage capacity is full. For continuous modelling, models can be run with the first one or two years of data repeated until the storage reaches a steady-state.

In areas with coastal outfalls, mean sea level, tidal ranges and storm surge could also have an impact on the drainage system including back flow in pipes and changed energy lines. These can be changed in many urban drainage models – coastal advice can be found in Toolbox Bin 2.2.

4. Spatial representation

The representation of future drainage networks should be considered when designing an impact assessment which includes urbanisation and land use change. That is, what changes are likely, and where and when will they occur? Most drainage models now operate within GIS platforms and it is relatively easy to adjust the drainage network by adding new nodes (e.g., confluences, pumping stations, inlets, outfalls) and links (e.g., pipes, streams, channels). However, given the need to generate and model a range of urban scenarios, spatially aggregating flow network elements can provide some model simplification especially where land is zoned for change over coming decades but detailed plans are not yet available.

There has been precedence for aggregating drainage units in urban stormwater modelling, particularly with respect to water treatment. The USEPA SUSTAIN model (Shoemaker *et al.*, 2009), for instance, allows simulation at the neighbourhood scale with each drainage element defined explicitly or at the catchment scale with aggregated representative flow-paths. In New Zealand, Elliott *et al.* (2006, 2009) aggregated treatment devices and flow pathways within the MUSIC model for a catchment with an area of 0.83 km^2. An initial total of 810 drainage nodes were aggregated to 55, 7 and, finally, a single node. The parameters governing the performance of modelled treatment devices (i.e., dimensions of the devices) were scaled-up proportionally to the greater contributing area upon spatial aggregation. They found that there was some loss of model skill with respect to peak flow, but aggregation had little effect on the predictions of water quality, mean discharge and base flow when there were uniform soil properties and sizing of devices relative to the source area.

The use of spatially distributed and aggregated representations of drainage networks for climate change impact assessment was demonstrated for combined sewer flows in Helsingborg, Sweden, by Semadeni-Davies *et al.* (2008a). Inner city flows to the system were represented explicitly as the pipe network geometry is already in place and is not expected to change. The system was modelled using a fully calibrated MOUSE model for the central city that was developed for operational purposes. Surface flows in the inner city were simulated using the RDII module for MOUSE. However, wastewater flows from the surrounding suburbs, which are not yet included in the model set-up were aggregated. The suburban waste water is conveyed from a separate system to the wastewater treatment plant via connections at several points to the combined system. The land use intensity and population in these suburbs is expected to increase over the coming decades, and this was simulated by increasing the volume of wastewater flowing into the connection points on a per capita basis. Direct inflow and sewer infiltration to the separated systems were assumed to be negligible.

5. Stormwater quality

The quality of urban stormwater has a major impact on the ecosystem health of urban receiving environments. Changes to the frequency of rainfall events (i.e., build-up and wash-off cycles) rainfall intensity will have an effect on base-flow and peak flow volumes and the contaminant loads and concentrations transported during flow events. Moreover, increased water temperature and reduction in dissolved oxygen could put further stress on aquatic environments. Despite the conceptual impacts of climate change on water quality, these impacts have not been addressed in the literature beyond contamination due to wastewater sewer overflows. There has been some discussion of using stormwater management devices as an adaptation to the possible impacts of climate change on water quantity (e.g., Semadeni-Davies *et al.*, 2008 a and b; Ashley *et al.*, 2008; Shaw *et al.*, 2007) which could also have an impact on water quality, but this aspect of device function has not been discussed in relation to climate change.

Part of the reason that the impact of climate change on contaminant loads from diffuse sources has largely been excluded from impact assessments is that the processes involved are complex and highly site specific making simulation problematic (for an overview of modelling issues see Sutherland and Jelan, 2003). Important parameters are the accumulation rate, the accumulation period between events (i.e., rainfall frequency) and wash-off rates. Accumulation refers to the build-up of contaminants such as chemical weathering of building materials, deposition of abraded road and tyre particles, vehicle exhaust and industrial emissions and wind borne soil sediments. The accumulation rate is not constant and can plateau between events. Wash-off varies depending on the type of contaminant and the processes in operation (e.g., wash-off of accumulated contaminants or mechanical weathering / erosion); generally, wash-off rates increase with rainfall intensity. Theoretically, the projections for Auckland of lowered annual rainfall but increased intensity of storm events could lead to increased accumulation periods and a greater potential for first flushes and surface erosion increasing event loads. However, increased flow volumes may also have the effect of reducing event concentrations.

Changing contaminant sources and yields must also be considered along with changes in imperviousness which affects flow rates. There is a trend towards the use of new low yield building materials (e.g., coated vs. unpainted galvanised steel roofing) and a shift in urban form and activities which will affect contaminant loads. The transport sector in particular has a great impact on stormwater quality, with contaminants from road and tyre wear-and-tear, brake pads and exhaust emissions. These yields are set to change over the coming decades. The ratio of public to private transport, fleet composition, use of alternative fuels, materials used in vehicle manufacture, journey frequency and length will all have an impact on water quality. For instance, Los Angeles encourages the use of electric cars to improve air quality and as a climate change mitigation strategy (Dubin *et al.*, 2011) and several American states have introduced or are considering bills requiring low metal yield brake-pads (Washington - SB6557; California - SB 346) to improve water quality.

Finally, stormwater management should also be considered, particularly given the emphasis in the Auckland metropolitan area for LID (ARC, 2001). Timperley and Reed (2008) demonstrated the potential impacts of land use change and water treatment on annual sediment, zinc and copper loads from urban catchments to the central Waitemata Harbour using the ARC Contaminant Loads Model. This model does not include a climate component; assuming that over the course of a year, the total wash-off from a surface is independent of rainfall dynamics. While Timperley and Reed (2008) did not consider climate change, their work does offer an insight into urban scenario creation for water quality modelling.

6. Conclusion

This purpose of this tool is to overview the issues and assumptions surrounding urban drainage modelling with respect to climate change risk assessment. It is noted that modelling is at the heart of the risk assessment process, as set out in the MfE *Climate Change Effects Manual* (2008), for both preliminary screening and detailed analysis.

The too; has discussed model choice and development of both climate change (i.e., input data) and urbanisation scenarios (model set-up and parameters). The detail to which urban drainage pathways are modelled and the data required depends on the purpose of the assessment. It is noted that changes in climate are simulated by adjusting or replacing input data whereas changes due to urbanisation are simulated by changing model parameters. The report points to other tools for examples of how models have been applied in the Auckland Region, notably Tools 2.4.2, 2.4.3 and 2.4.4.

References

Auckland Council (2011) Stormwater Flood Modelling Specifications. Draft Manuscript – unpublished.

ARC, Auckland Regional Council, ARC (1999). Guidelines for stormwater runoff modelling in the Auckland Region. Auckland Regional Council Technical Publication No. 108. (ARC TP108). Auckland Regional Council.

Auckland Regional Council, ARC (2001) Low Impact Design Manual for the Auckland Region. Primary Author, Earl Shaver. TP 124.

ARC, Auckland Regional Council, ARC (2003) Stormwater management devices: design guidelines manual. Second Edition, TP 10.

Arnbjerg-Nielsen, K. and Fleischer, H.S. (2009) Feasible adaptation strategies for increased risk of flooding in cities due to climate change. Wat. Sci. Tech. 60(2); 273–281.

Arnbjerg-Nielsen, K. and Mikkelsen, P.S. (2009) Design of urban drainage structures incorporating climate change impacts in a risk framework. Ozwater, 2009, Australian Water Association, Leonards, NSW, Australia

Ashley, R.; Blanksby, J.; Cashman, A.; Fewtrell, L.; Jack, L;. Wright, G.;, Packman, J.; Maksimovic, C. and Kellagher, R. (2008) Building Knowledge for a Changing Climate (BKCC): Adaptable Urban Drainage - Addressing Change In Intensity, Occurrence And Uncertainty of Stormwater (AUDACIOUS). Main summary report. EPSRC/UKCIP.

Ashley, R.M.; Balmforth, D.J.; Saul, A.J. and Blanskby, J.D. (2005) Flooding in the future - predicting climate change, risks and responses in urban areas. Wat. Sci. Tech. 52(5):265–273.

Baskaran, B.; Renwick, J. and Mullen, A. B. (2002) On the application of the Unified Model to produce finer scale climate information for New Zealand. Weather and Climate 22, 19-27.

Berkhout, F.; Hertin, J. and Jordan, A. (2002) Socio-economic futures in a climate change impact assessment: using scenarios as ‘learning machines’. Global Environ. Chang. Part A. 12(2):83-95.

CRCCH (2005) Music User Manual. Version 2.1. Cooperative Research Centre for Catchment Hydrology, Urban Stormwater Quality Program, Australia

Clar, M.L.; Barfield, B.J. and O’Connor, T.P. (2004) Stormwater Best Management Practice Design Guide Volume 2: Vegetative Bio-filters. US Environmental Protection Agency, EPA/600/R-04/121A.

Cowpertwait, P.; Salinger, J. and Mullan, B. (2009) A spatial-temporal stochastic rainfall model for Auckland City: Scenarios for current and future climates. Journal of Hydrology (NZ) 48 (2): 95-109 2009.

Cowpertwait, P.S.P (2003). A Stochastic Rainfall Model for North Shore City. Client Report for North Shore City Council, May 2003.

Cowpertwait, P.S.P.; Lockie, T. and Davies, M.D. (2006) A stochastic spatial-temporal disaggregation model for rainfall, Journal of Hydrology New Zealand, 45(1), 1-12.

Davis, M.D.; Kinley, P.; van Kalken, T.; Johnson, C.; Brown, N.; Islam, J.; Dayananda, K.G. and Pathirana, J. (2010) a decade of flood inundation assessment under climate change in the Auckland Region. Water NZ Stormwater Conference, 2010.

Dayananda, K.G.; Pathirana, J.; Davis, M.D.; Salinger, M.J.; Mullan, A.B.; Kinley P. and Paterson, G. (2005) Flood risk under existing and future climate scenarios in Auckland City (New Zealand). World Water and Environmental Resources Congress 2005, American Society of Civil Engineers, Reston, Virginia, doi:10.1061/40792(173)477.

Denault, C., Millar, R.G, and Lence, B.J. (2006) Assessment of Possible Impacts of Climate Change in an Urban Catchment. Journal of the American Water Resources Association (JAWRA) 42(3):685-697.

Drost, F.; Renwick, J.; Bhaskaran, B.; Oliver, H. and McGregor, J. (2007) Simulation of New Zealand’s climate using a high-resolution nested regional climate model. Int. J. Climatol. 27: 1153–1169.

Dubin, J.; Barney, R.; Csontos, A.; Um, J. and Wu, N. (2011) Realizing the potential of the Los Angeles electric vehicle market. Luskin Center Electric Vehicle Research Program. UCLA Anderson, Los Angeles, USA.

Elliott, A.H.; Trowsdale, S. and Wadhwa, S. (2006) Upscaling a model of on-site stormwater control devices. 7th International Conference on Urban Drainage Modelling and the 4th International Conference on Water Sensitive Urban Design, Melbourne, Australia, Volume 1. 271-278.

Elliott, A.H.; Trowsdale, S.A. and Wadhwa, S. (2009) Effect of aggregation of on-site storm-water control devices in an urban catchment model. J. Hydrologic Eng. Volume 14, Issue 9, pp. 975-983 (September 2009).

Harding, B.; Strayton, G.; Pattle, A.; Captain, X. and Ockleston G. (2008) Auckland's stormwater – increased disposal issues. NZWWA Stormwater 08 Conference.

He, J.; Valeo, C. and Bouchart, F.J-C. (2006) Enhancing infrastructure investment planning practices for a changing climate. Water Science and Technology, 53(10):13-20.

Hingray, B. and Ben Haha, M. (2005) Statistical performances of various deterministic and stochastic models for rainfall series disaggregation. Atm. Res., 77(1-4):152-175.

Huber, W. and Dickinson, R. (1988) Stormwater Management Model, V4. USEPA, Athens, GA.

IPCC SRES (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K., 599 pp.

Kinley, P.; Sharman, B. and Davis, M. (2007) A pragmatic assessment of climate change impacts on drainage infrastructure and resulting management practices in Auckland City. 5th South Pacific Stormwater Conference.

Kleidorfer, M., Möderl, M., Sitzenfrei, R., Urich, C. and Rauch, W. (2009) A case independent approach on the impact of climate change effects on combined sewer system performance. Wat. Sci. Tech. 60(6):1555-1564.

Lockie, T. and Brown, N (2010) Potential impact of climate change on NSCC's wastewater capital works programme. North Shore City Council Report.

MfE Ministry for the Environment (2008) Preparing for climate change: A guide for local government in New Zealand. Publication number: ME 891.

MfE Ministry for the Environment (2010) Preparing for future flooding: A guide for local government in New Zealand. Publication number: ME 1012.

Newman, T.L.; Omer, T.A. and Driscoll E.D. (2000) "SWMM Storage-Treatment for Analysis/Design of Extended-Detention Ponds." In: Applied Modeling of Urban Water Systems, Monograph 8 in the Series. William James (Ed.), Proceedings of the Conference on Stormwater and Urban Water Systems, Modeling, Toronto, Ontario, February, 1999.

Palmstrom, N. and Walker, W.W. (1990) P8 urban catchment model: User's guide. Program documentation, and evaluation of existing models, design concepts, and Hunt-Potowomut data inventory. The Narragansett Bay Project Report No.NBP-90-50.

Parkinson, N.J., Hewitt, J., Summerhays, M., Ockleston, G. and Captain, X (2008) Optimisation of basalt aquifer stormwater disposal for flood hazard mitigation in Auckland City. NZWWA Stormwater Conference, Rotorua, New Zealand.

Roberts, C. and van Kalken, T. (2010) Regional and local flood hazard mapping. Presentation to the Auckland Regional Council Stormwater Seminar, 21 July, 2010.

Schilling, W. (1991) Rainfall data for urban hydrology: what do we need? Atmos. Res. 27:5-21.

Semadeni-Davies, A.; Hernebring, C.; Svensson, G. and Gustafsson, L.-G. (2008a) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: combined sewer system. J. of Hydrology, 350:114-125.

Semadeni-Davies, A.; Hernebring, C.; Svensson, G. and Gustafsson, L.-G. (2008b) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: suburban stormwater. J. of Hydrology, 350:100-113.

Shackley, S. and Deanwood, R. (2002) Stakeholder Perceptions of Climate Change Impacts at the Regional Scale: Implications for the Effectiveness of Regional and Local Responses. J. Environ. Plan. Managem., 45(3):381-402.

Shaw, H.; Reisinger, A.; Larsen, H. and Stumbles C. (2005) Incorporating climate change into stormwater design – why and how? 4th South Pacific Stormwater Conference, Auckland, 2005.

Shaw, R.; Colley, M. and Connell, R. (2007) Climate change adaptation by design: a guide for sustainable communities. TCPA, London.

Shoemaker, L.; Riverson. J.; Alvi, K.; Zhen, J.X.; Paul, S. and Rafi, T. (2009) SUSTAIN – a framework for placement of best management practices in urban watersheds to protect water quality. EPA/600/R-09/095, US EPA.

Sutherland, R.C. and Jelen, S.L. (2003) Stormwater Quality Modeling Improvements Needed for SWMM., Practical Modeling of Urban Water Systems Monograph 11, edited by William James, CHI Publications, pp. 253-289.

Thompson, C.S. (2002) The High Intensity Rainfall Design System: HIRDS. Proceedings, International Conference on Flood Estimation, March 2002, Berne, Switzerland. International Commission for the Hydrology of the Rhine Basin, CHR Report II-17, pp 273 – 282.

Timperley, M. and Reed, J. (2008) Modelling the fate of Auckland’s stormwater chemicals over the next 100 years. NZWWA Stormwater 08 Conference.

UKCIP (2001) Socio-economic scenarios for climate change impact assessment: a guide to their use in the UK Climate Impacts Programme. UKCIP, Oxford.

URS (2004) Climate Change and infrastructure design case study: Wairau Catchment, North Shore City. 48232/046/R090. Summary report prepared for North Shore City Council and NZ Climate Change Office.

van Kalken, T.; Taylor, A.; Davis, M. and Hellberg, B. (2009) Rapid two dimensional flood hazard mapping in the Auckland Region. Water NZ South Pacific Stormwater Conference, 2009.

Watt, W.E., Waters, D. and McLean, R. (2003) Climate Variability and Urban Stormwater Infrastructure in Canada: Context and Case Studies. Toronto-Niagara Region Study Report and Working Paper Series, Report 2003-1. Meteorological Service of Canada, Waterloo, Ontario.