Long Term Continuous Simulation: Lessons Learned from Real-Life Applications

Jacobs M[1]
[1]pitt&sherry, Brisbane, QLD

Introduction

The author has developed an understanding of the uses and limitations of Long Term Continuous Simulation (LTCS) through its application in a variety of consultancy projects.

The reasons for using LTCS, rather than an event-based approach in these projects, include the following:

- tackling the conundrum of joint probabilities and combinations of different flooding mechanisms in complex drainage systems
- providing a more comprehensive set of metrics to assess impacts[1], especially flow duration curves or flood level duration curves
- setting up models for use in forecasting and operating systems
- improving the understanding of catchment behaviour

The opportunities to use LTCS in these projects have arisen through:

- advances in computing power, especially faster processing, the management of larger data sets and suitable programs
- improvements to the accessibility of real and synthetic long-term records through public web portals (especially SILO Climate Data[2])
- innovations in rainfall disaggregation[3]
- improvements to the accessibility of high quality terrain data through public web portals (especially the ELVIS Elevation and Depth Foundation Spatial Data Portal[4])

Preamble: Model Theory

Before any modeller gets to work, he or she should first consider what a model is, and what it is for. Every model is imperfect, and no model can completely represent the reality it represents, so careful consideration must be given to what the model includes or excludes. Models are designed to answer specific questions, and much of the modeller's time and energy should be spent in determining what these questions are, and how they might be answered, before he or she gets to work.

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[1] Impacts include the potential effects of proposed urban development, proposed transport infrastructure and climate change.
[2] https://legacy.longpaddock.qld.gov.au/silo/
[3] Rainfall disaggregation translates rainfall records from larger timesteps to smaller timesteps, for example from 24 hours to 1 hour to 5 minutes. It is required for the modelling of small catchments. The author has developed a methodology and program, which is the subject of a separate paper to be presented in a future conference.
[4] http://elevation.fsdf.org.au/

If the primary questions relate to catchment behaviour, uncertainty and risk, LTCS is well suited to answering them through the generation of behavioural profiles. However, because of its use of proleptic data and fixed rainfall loss or soil storage parameters, which are further described below, LTCS might not yield precise reproductions of specific historic events.

Preamble: Fundamental concepts

Behavioural profiles

Common behavioural profiles include

- Flood frequency analyses (FFA) of peak annual floods, which may be estimated using Log Pearson III plots
- Flow duration curves or flood duration curves, which show the proportion of time a flow or flood level is exceeded

Potential impacts may be assessed by considering how these behavioural profiles respond to changes. These changes could include future development, the construction of infrastructure such as road embankments and detention basins, and climate change.

Proleptic data

In the real world, catchments change with time through urban development, the natural evolution of the creek and river system, and variations in climate. When long term time scales are used, not just the water in the river system, but also the landform and catchment, are fluid. The uncertainties introduced by this fluidity can be reduced by asserting a proleptic quality to some of the data, especially in relation to the state of urban development, land-form and climate.

The term "proleptic" describes something that is extrapolated to an earlier date than at which it first existed[5]. In the context of this paper, proleptic data means that the states of urban development, the landform and the climate are assumed to be fixed for the entire duration of the analysis, which may be 130 years. Obviously, modern urban development and landform features, such as road embankments and airports, would not have existed 130 years ago, but the proleptic approach asserts that they did.

Strictly, changes to development, landform and climate will change catchment behaviour. However, a preliminary assessment of the projects described below indicate that the impacts of these changes may be of a lesser magnitude than the modelling uncertainty, such that they can be practically ignored for the purposes of model calibration.

[5] The term is used to describe the application of Gregorian dates to the Julian calendar prior to the adoption of the Gregorian calendar in 1582.

Irreducible uncertainty

The concept of irreducible uncertainty relates to the inability of every model to precisely reproduce the reality it represents.

Because of the scarcity of rain and river gauges, the modeller never has enough data. Likewise, with urban development and landforms, there were no few sources of data prior to the first early maps. The quality and quantity of data improved with the introduction of aerial photography and has improved again with developments in modern LiDAR and ALS.

Even when these data are available, they may not be sufficient. For example, rain gauges might only record daily totals, and LiDAR or ALS may not include true creek or river bed levels[6]. Further instrumentation and measurement can provide more data from future measurements, but they cannot be applied retrospectively to historic data, which affects calibration.

The concept of irreducible uncertainty implies that all models, and hence their results, are imperfect. The only remaining questions of practical concern relate to the acceptability, or otherwise, of the uncertainty in the model results.

In the author's experience, an intangible consequence of LTCS is that it forces the issue of uncertainty into view.

Scalability

Scalability refers to the ability of the model to scale up or down in time and space. For example, there may be a large catchment with a long response-time that reports to a river gauge, but the area of interest lies in a smaller upstream sub-catchment with a short response-time. In this case the model must be scaled from the large catchment to the smaller sub-catchment in both the spatial and temporal dimensions. Likewise, models may be required to be scaled from single, discrete events to long term series, or vice versa.

Practical application of Long Term Continuous Simulation: Lockyer Valley

This investigation comprised the modelling of creeks and catchments at Gatton, Queensland with the objective of estimating the effects of combined flows from the several creeks that converge at Gatton. Follow-on investigations considered the potential impacts of revegetation in the Lockyer River channel.

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[6] LiDAR or ALS, being based on the reflection of light from a surface, has difficulty in penetrating the leaves of dense vegetation to actual ground level. Of course, the availability of moisture in creek beds fosters the growth of dense vegetation, leading to the recurring problem of interpreting actual bed levels from the surveyed data. Further, LiDAR or ALS does not typically penetrate below water level. The more expensive forms of LiDAR and ALS include the use of waveforms that can penetrate below the water surface, but they are limited by turbidity and aquatic vegetation. The net result is that the LiDAR or ALS almost always shows creek, river and lake bed levels at higher elevations than the reality.

The hydrology was modelled using HEC-HMS[7], with Clark Unit Hydrograph, soil-moisture accounting, Muskingham routing and disaggregated rainfall using the author's rainfall disaggregator[8]. The hydrological model was run for 130 years, which covers the full extent of the rainfall record available from the SILO website. The distribution of peak annual flows was estimated from the model results by Flood Frequency Analysis (FFA) using a Log Pearson III (LPIII) distribution and was compared with flow distributions estimated FFAs from most existing stream gauges. The catchments are illustrated in Figure 1.

The hydraulic model was constructed in HEC-RAS 2D[9], using publicly available terrain data acquired from the ELVIS website (1m DEM, 2010) and Council's recent LiDAR survey (1m DEM, 2018). A roughness map was interpreted from the roughness used in previous TUFLOW[10] hydraulic modelling and current aerial photography. The aerial photography was used to refine the extents of vegetation within the Lockyer Creek channel, and the extents of urban development. The floodplain roughness values of the HEC-RAS model were adjusted to yield flood levels that aligned with the previous TUFLOW model[11]. The HEC-RAS model was then used to generate rating curves at points of interest, such as the gauges, within the model so that calculated flows could be related to calculated flood levels at virtual gauging stations. The modelled flood depths for the January 2011 event are shown in Figure 2.

The calibration of the model to the flows and gauge data proved to be problematic for flows more than about 20%AEP. Above about 20%AEP, the creeks around Gatton tended to break out into the adjacent flood plains. For example, Gauge 143204A - Lockyer Creek at Wilsons Weir, which is located at the downstream boundary of the model, registers about one third of 1%AEP flows, the remaining two thirds being conveyed overland to the north and south of the creek channel, as illustrated in broad-scale 2D modelling (see Figure 2). This yielded a poorly conditioned rating curve, in which large changes in flows corresponded to small changes in elevation, as illustrated in Figure 3. Poorly conditioned rating curves, such as this, are sensitive to changes to the creek channel, such as scouring or deposition, or changes to creek roughness from changes to the vegetation.

Example of plots of model results are shown as the computed rating curve at the Gatton Rail Bridge in Figure 4, and the corresponding flow duration curve in Figure 5.

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[7] https://www.hec.usace.army.mil/software/hec-hms/

[8] The author's rainfall disaggregator combines daily rainfall records from SILO, BoM IFD curves and ARR2016 temporal patterns to generate 5 minute series up to 130 years'. The daily rainfall totals are preserved, and the sub-daily distribution is synthetic. Rainfall disaggregation is a topic of itself, and is used here to generate a rainfall record for the purposes of LTCS

[9] https://www.hec.usace.army.mil/software/hec-ras/

[10] https://www.tuflow.com/

[11] The scope of the consultancy did not extend to re-calibration to all available flood level data

Incidentally, the type of plot shown in Figure 3 and Figure 4, which combines rating curves, AEPs and durations, is easily generated from LTCS model results, and provides a useful summary of the characteristics or behavioural profiles of the river at the gauge. Because the model has been created as a scalable model, plots of rating curves, AEPs and durations may be generated at any point within the model domain as virtual gauges.

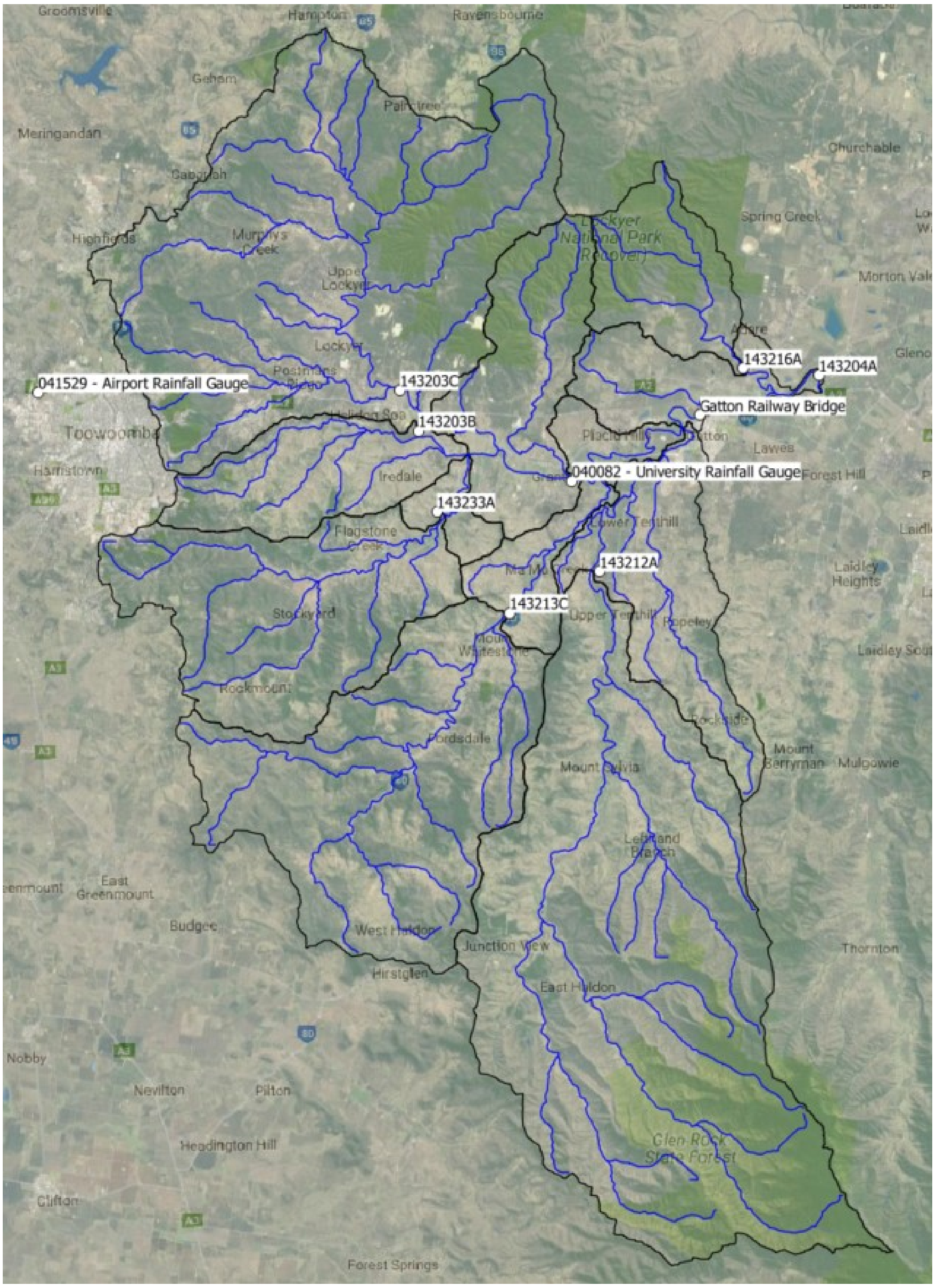

Figure 1: Lockyer catchments and gauges

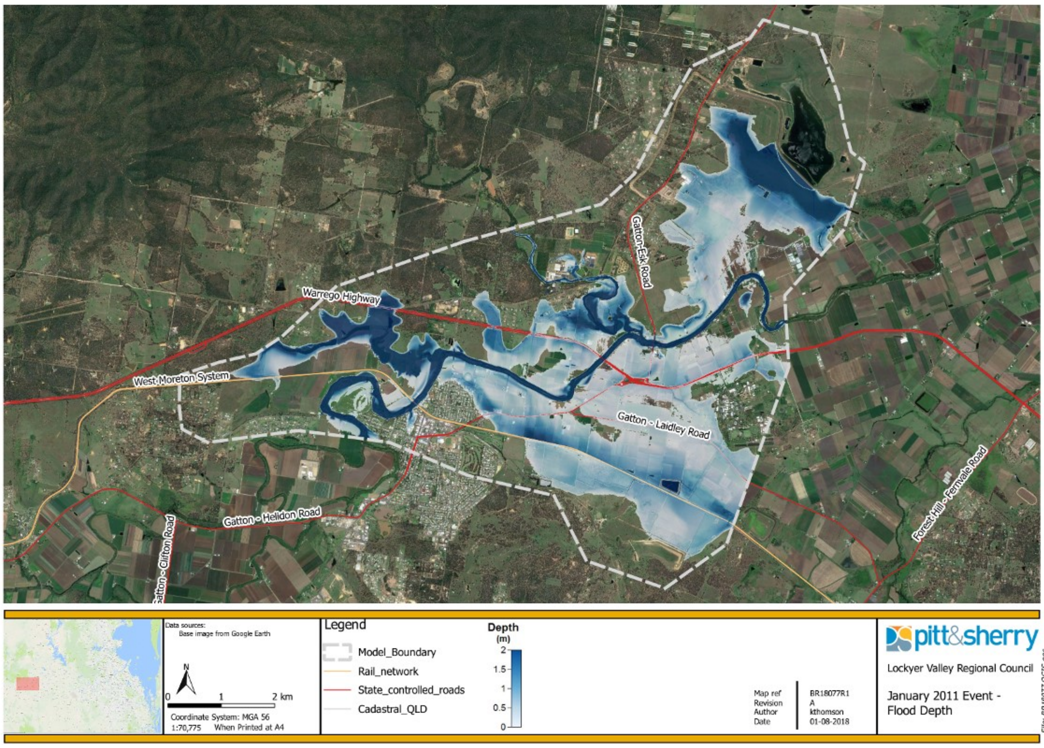

Figure 2: Modelled flood depth for January 2011 flood event

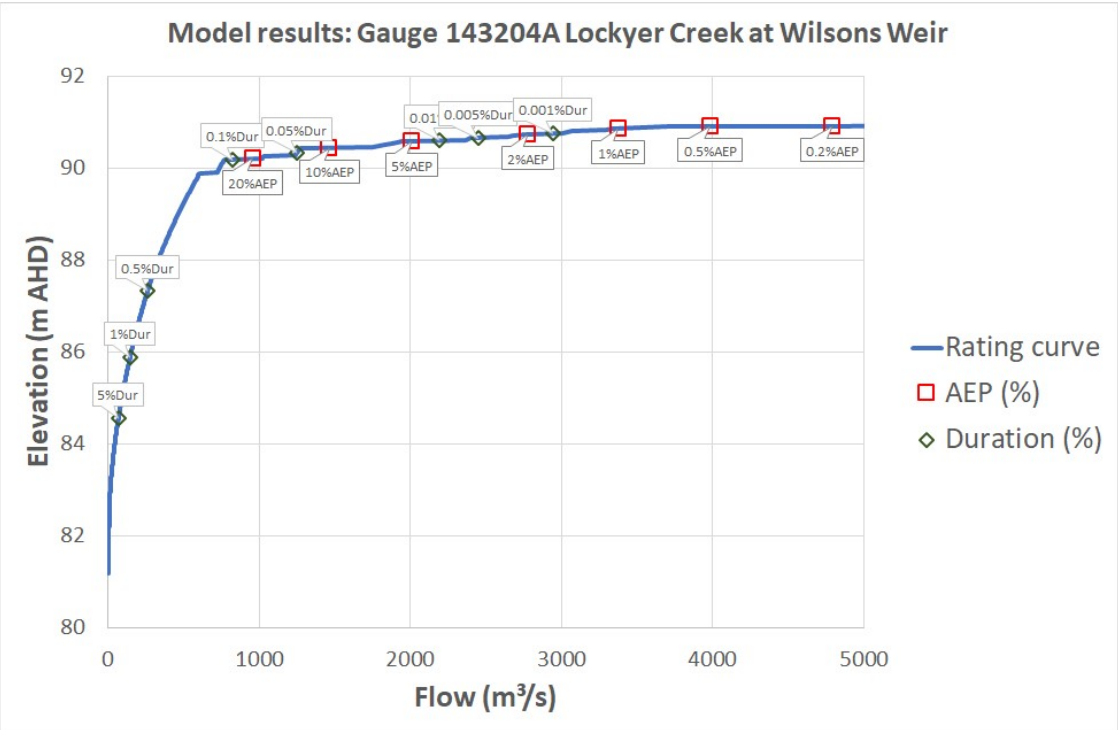

Figure 3: Rating curve at Gauge 143204A generated from model results

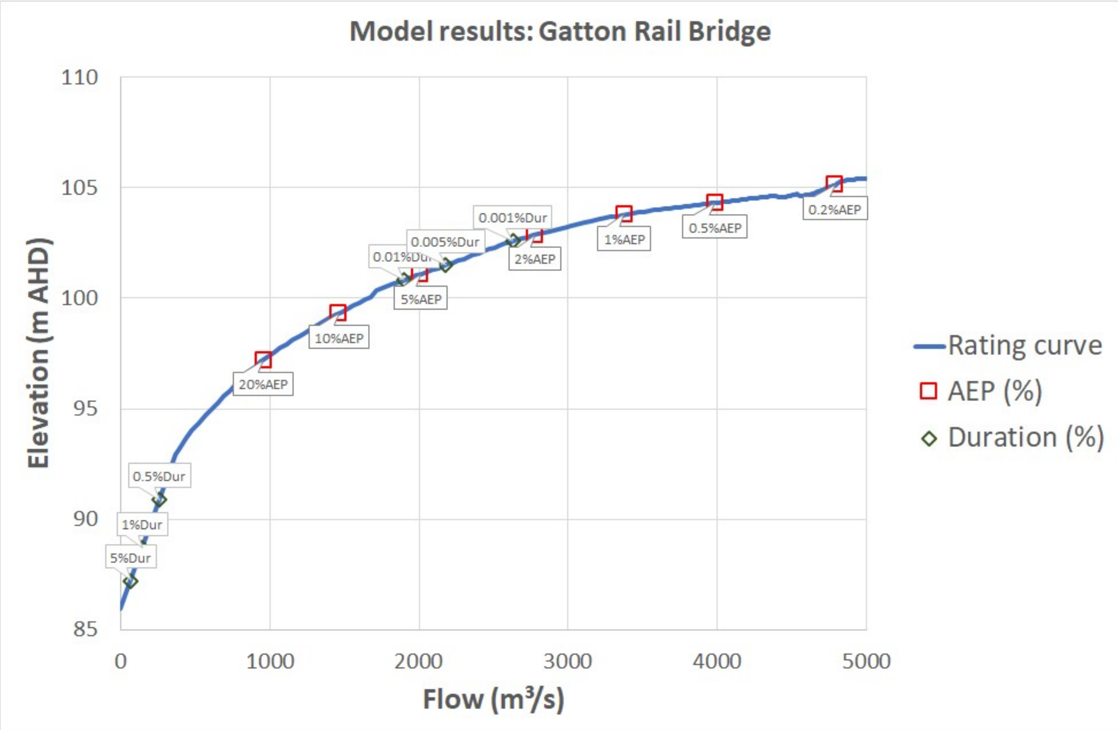

Figure 4: Model results at Gatton Rail Bridge, showing rating curve, AEP and duration

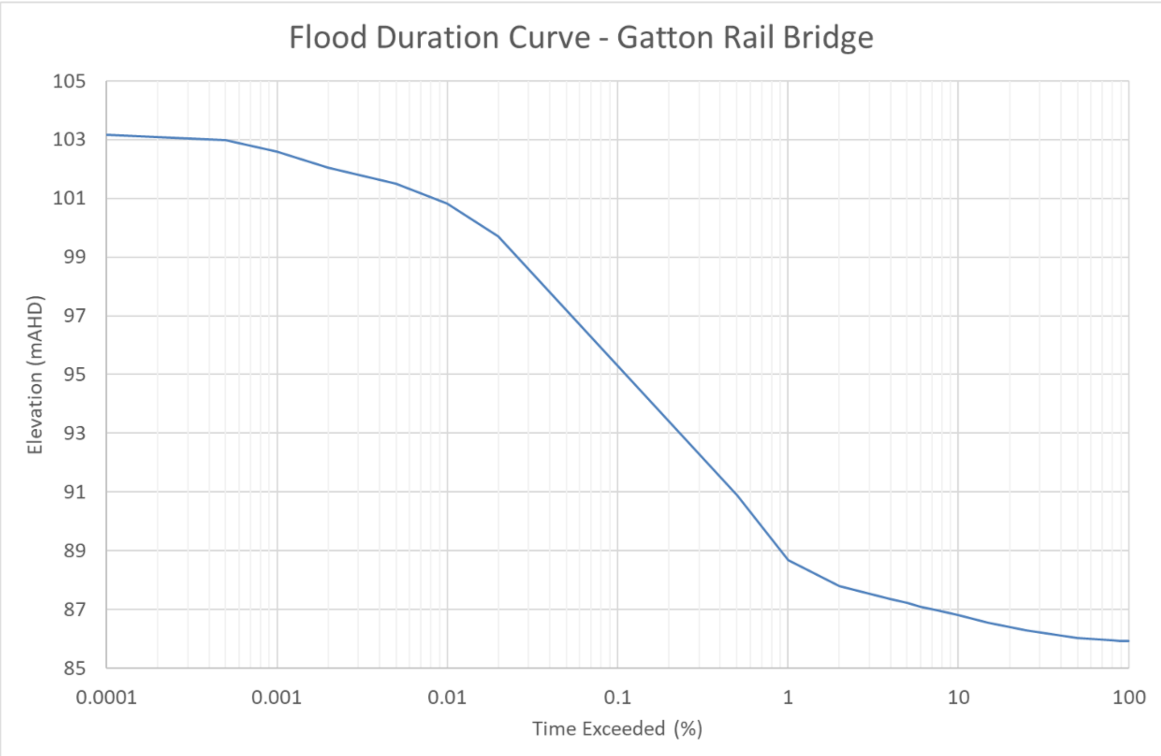

Figure 5: Flood level duration curve at Gatton Rail Bridge generated from model results

Practical application of Long Term Continuous Simulation: Cane Drains at Sunshine Coast Council

This investigation comprised the modelling of cane drains, which were situated downstream of an urban development, to estimate what works could be implemented to mitigate the impacts of the development on the drainage of the cane fields. Because this is a current project and is subject to ongoing negotiations between Council and the developer, the precise nature of the proposed mitigation works cannot be described in detail. However, the methodology and the general findings are described below.

The factors that prompted the use of LTCS included the following considerations.

- Water levels in the cane drains are controlled by stormwater runoff from the development and tide levels in the Maroochy River
- The cane fields drain into the cane drains through levees and flap valves. The efficiency of the drainage of the cane fields depends on the duration of high water levels in the cane drains, as much as peak water levels. Further, the drainage of the cane fields can extend over many tidal cycles.
- The duration of high water levels in the cane drains is affected by runoff from upstream development, which is routed through detention basins. Though the detention basins reduce peak flows by prolonging discharges into the cane drains, they do not reduce runoff volume. The prolongation of the discharges could impact the efficiency of the drainage of the cane fields.

A schematic of the catchment is shown in Figure 6 and a schematic of the hydrological model is shown in Figure 7.

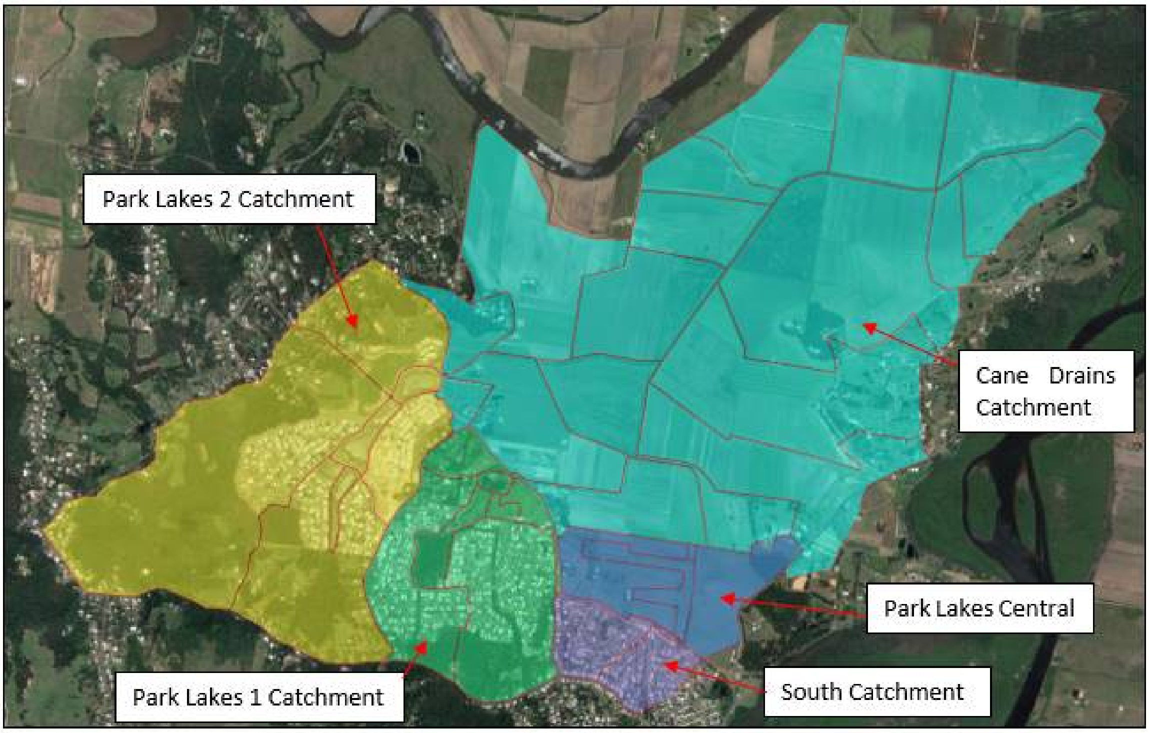

Figure 6: Schematic of catchment

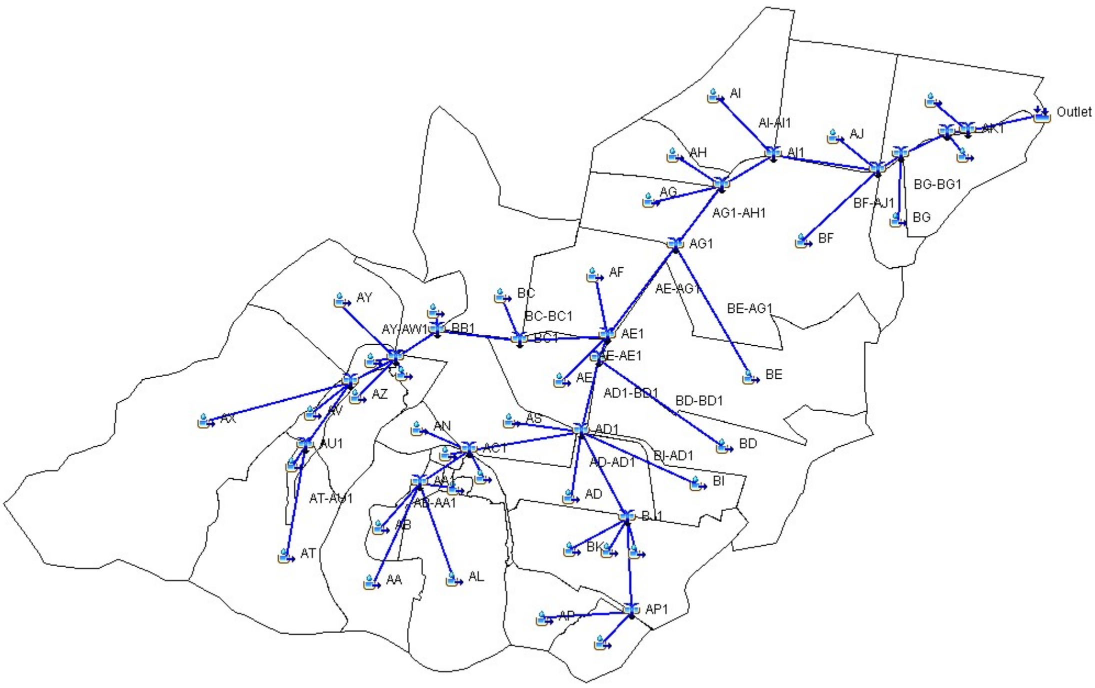

Figure 7: Schematic of hydrological model

The methodology adopted was to simulate 130 years with a linked hydrological and hydraulic model. The hydrology was carried out in HEC-HMS and the hydraulics in HEC-RAS. The hydrological modelling was verified by comparing the peak flow distribution with peak flow estimates derived from Council's draft flood flow estimation tool. The results were assessed using flood level duration curves. The post-processing of the results was carried out in HEC-SSP[12].

The rainfall was acquired from the SILO website as daily rainfall. This was disaggregated into 5-minute increments using the author's Rainfall Disaggregator.

Sensitivity testing on timesteps indicated that a reduction from 1-hour to 30-minutes increased computed peak flows by about 10 m³/s, and a reduction from 30-minutes to 5-minutes increased computed peak flows by about 2 m³/s. Given the logistics of running the model, the 30-minute timestep was adopted as a practical approach. The outcomes of the sensitivity testing are illustrated in the hydrographs in Figure 8.

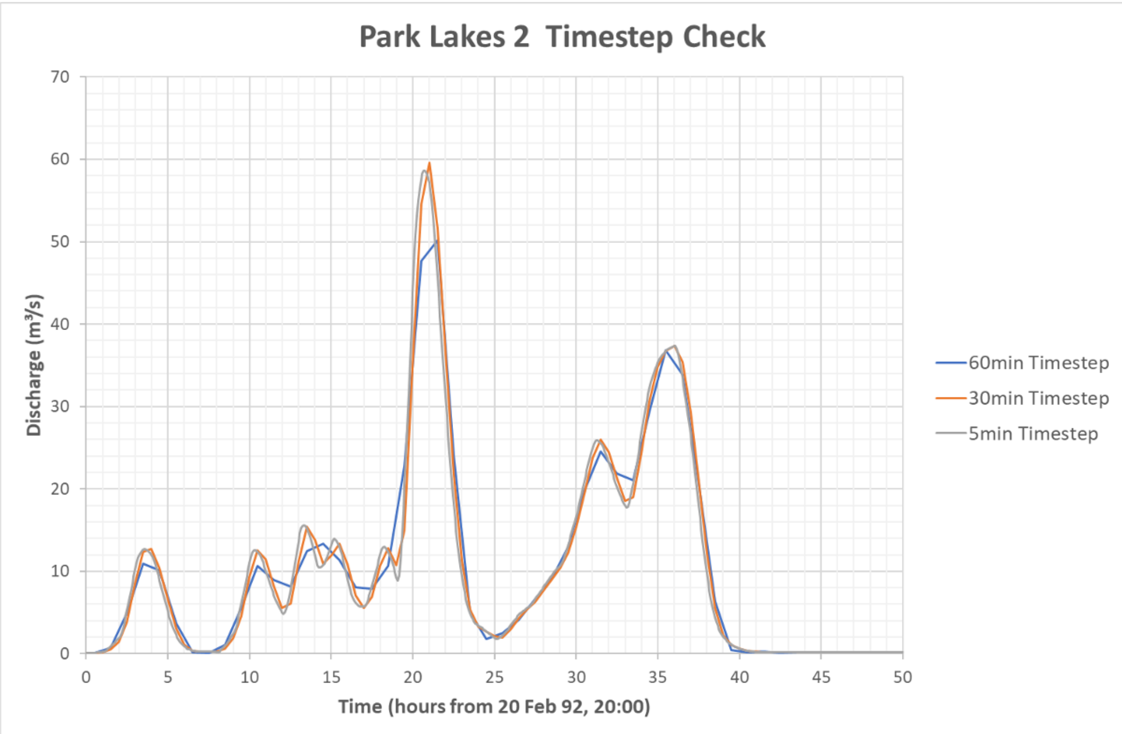

Figure 8: Hydrographs from sensitivity tests using different timesteps

Verification included the examination of model behaviour. Figure 9 shows the draining of a cane field following a major rainfall event. Because the cane field

[12] https://www.hec.usace.army.mil/software/hec-ssp/

drains through a flap valve, discharges from the cane field only occur after the peak stormwater flow has passed down the cane drain, and at low tide, as shown in the model results.

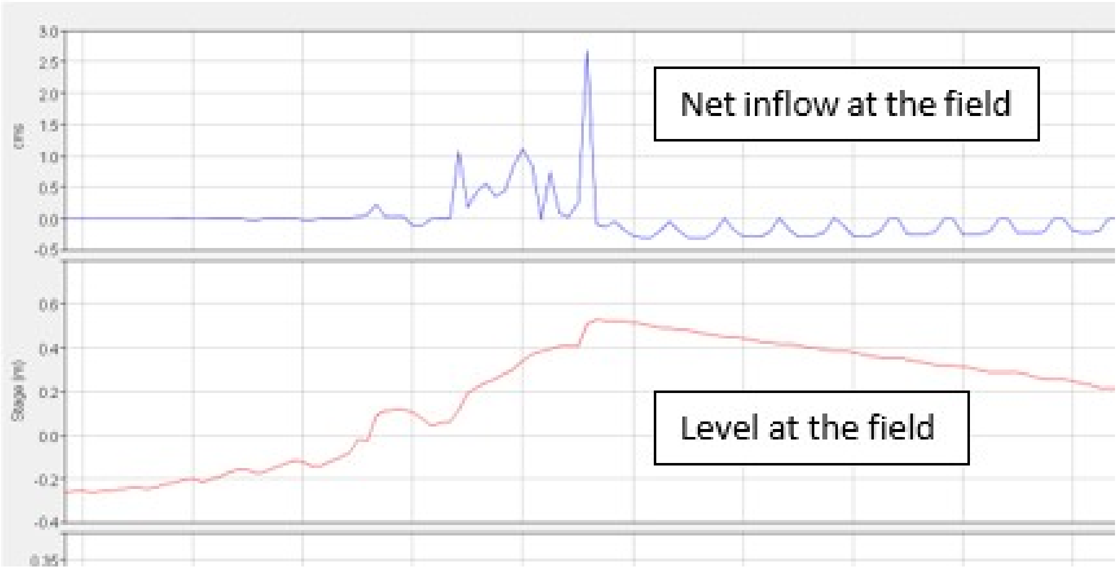

Figure 9: Model behaviour at cane field, showing discharge to the cane drains during low tides following a major rainfall event

The logistics of running 130 years at 30-minute timesteps required the modelling to be split into 70 simulations of 2 years' each. The main limitations were the use of RAM by the hydrological model (HEC-HMS), and the number of entries for flow in the hydraulic model (HEC-RAS). If this exercise were repeated, HEC-WAT[13] might be used to manage the various model runs and scenarios. The results of the individual runs were combined into flood frequency analyses and flood level duration curves, as illustrated in Figure 10 and Figure 11.

[13] https://www.hec.usace.army.mil/software/hec-wat/

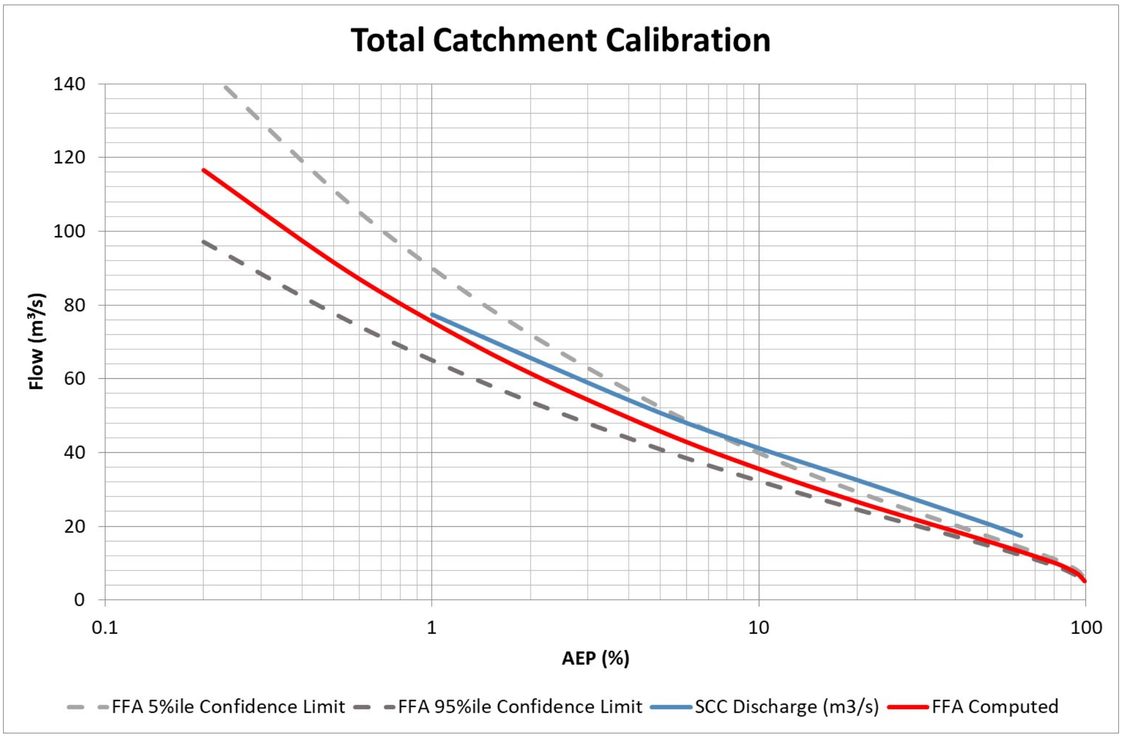

Figure 10: Example of flood frequency analysis of model results and comparison with SCC Discharge Estimation Tool

The flood level duration curve in Figure 11 shows the proportion of time that flood levels are exceeded for three different scenarios. The predevelopment case is taken as the base case. The green dashed line indicates the changes due to development with no mitigation, and the orange dashed line indicates the changes due to development with mitigation. In this case, the mitigation works reduce the flood level duration curve below the base case. This reduction in the profile of flood levels in the cane drain demonstrates that the mitigation works adequately reduce impacts in the cane fields at this location.

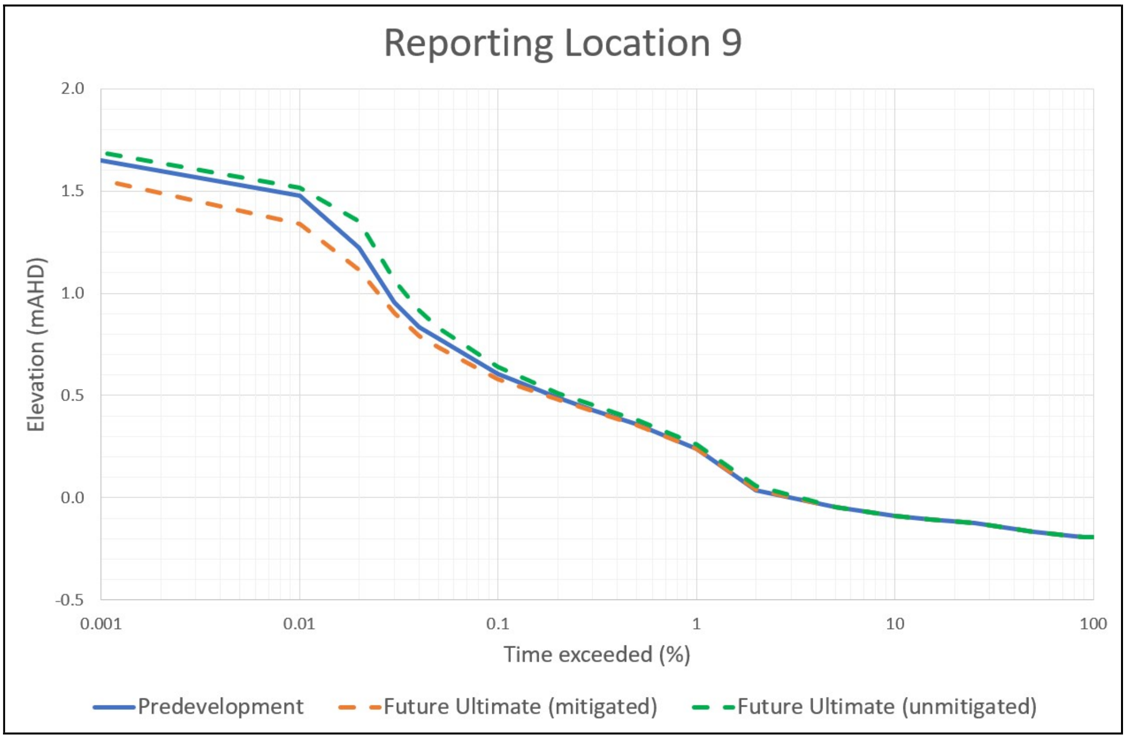

Figure 11: Example of flood level duration curve

Practical application of Long Term Continuous Simulation: Hydrological and Hydraulic Study, Papua New Guinea

This investigation comprised the review of design flows for the design of new bridge crossings at two major Rivers in Papua New Guinea. For reasons of commercial-in-confidence, the Client and the project cannot be named.

Gauge data were compiled in the HEC-DSS data storage system, accessed through HEC-DSSVue[14]. Hydrological modelling was carried out using HEC-HMS and hydraulic modelling was carried out using HEC-RAS.

Long term rainfall series, such as the gridded series of Australia from SILO, were not available, but several short-term rainfall series were available from rain gauges at several mine sites in one of the catchments. The rainfall series were compiled and run in a long term continuous model, and the results calibrated to available river gauge data. Calibration comprised the adjustment of soil store parameters and link routing parameters.

The rivers are characterised by distinct highland zones and lowland zones, with little transition in between. The highland zones are characterised by steep terrain and narrow, steep channels. The lowland zones are characterised by extensive

[14] https://www.hec.usace.army.mil/software/hec-dssvue/

swampland and floodplain, oxbow lakes, and braided, meandering rivers. Flood storage in the swampland and floodplain yields significant attenuation of floodplain flows, which is difficult to represent in the Muskingham link-routing parameters in the hydrological model. The outcomes of calibration are shown in Figure 12 and Figure 13.

Figure 12 shows a reasonably successful calibration of a highland catchment to a single event. The channels are narrow and constrained, so the Muskingham link-routing is appropriate because it represents linear storage within the link.

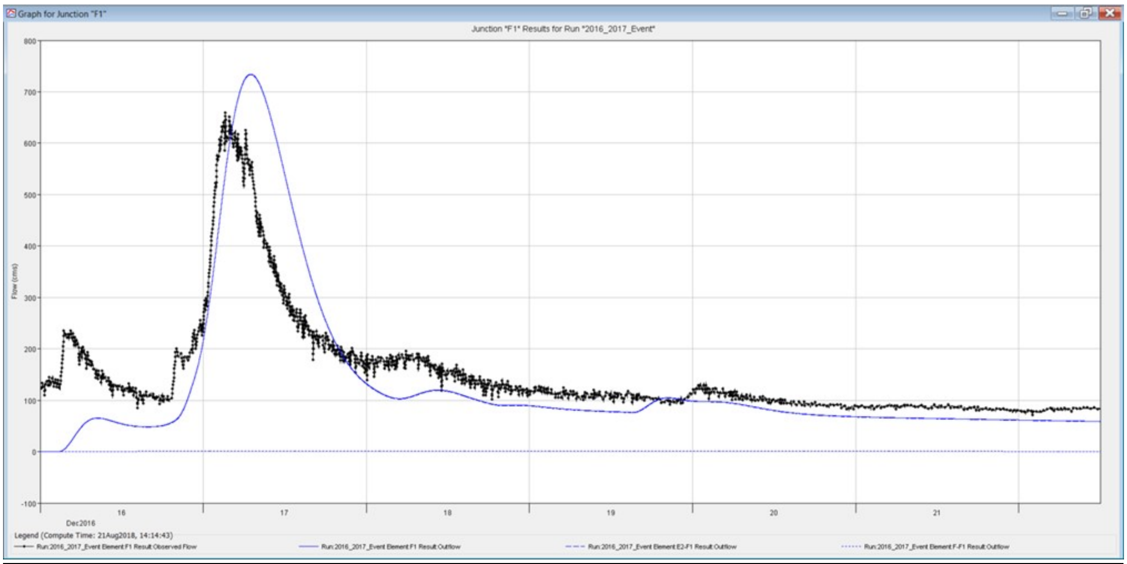

Figure 12: PNG Study, Calibration at highland catchment (observed data in black, modelled data in blue)

Figure 13 indicates problematic calibration in the lowland catchment. The model over-estimates high flows and under-estimates low flows. The reason is that there is a considerable step-change in link storage between in-bank flow and out-of-bank flow, which requires more complex link-routing than the linear Muskingham method. A better fit might be attained if non-linear storage parameters were included in the lowland links, but the exigencies of the project did not warrant further improvements to the model. It was sufficient, at this stage of the project, to estimate peak flows for the purposes of designing the bridges.

These data were later applied to two and three dimensional hydraulic models to inform the structural design of four bridges and their scour protection measures.

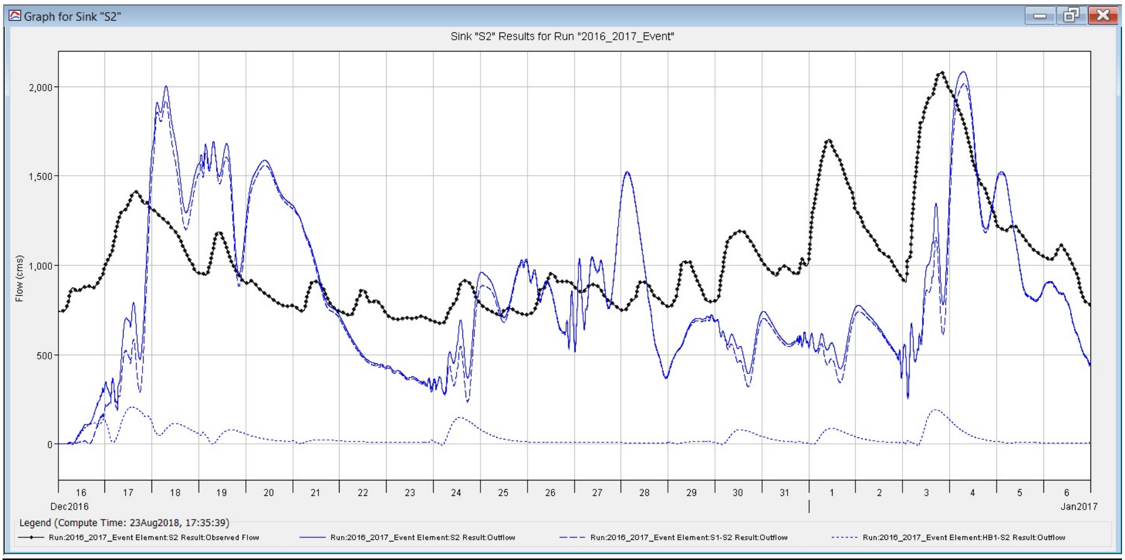

Figure 13: PNG Study, Calibration at lowland catchment (observed data in black, modelled data in blue)

Practical application of Long Term Continuous Simulation: Concept design of Forecasting and Operating System for a mine water release system

This project included the hydrological modelling of an ephemeral river system in Australia with a catchment of about 1300 km². For reasons of commercial-in-confidence, the Client and the project cannot be named.

A hydrological model was developed through Long Term Continuous Simulation (LTCS) for use in a Forecasting and Operating System (FOS)[15], which manages the release of mine-affected water into the river system. The river system extends to several mines that are spread widely over a river basin, and the release of mine water is subject to environmental constraints on flows, salinity (electrical conductivity) and pH, which are measured at specific monitoring points. An important factor is that the environmental conditions relate to minimum flows. Rather than estimating peak flows in major events, which would be the case for a flood forecasting system, this FOS is concerned with the estimation of frequent, low flows, and the hydrological model has been configured accordingly.

Because of the lag time between the most upstream release point and the most downstream monitoring point, the FOS needs to forecast flows, EC and pH up to

[15] The Forecasting and Operating System for this project is in the early stages of development. It includes a pre-processing stage that collects and cleans data from instrumentation within the catchment; a processing stage that runs many release scenarios; and a post-processing stage that approximates the transport and dilution of salinity and pH. The objective is to identify and forecast the most beneficial combination of mine-water releases, whilst maintaining compliance with the environmental conditions as weather events unfold in real time. There is a classic trade-off between speed and accuracy, and in the interests of improving the responsiveness of the system to changing conditions in the catchment, speed is given the higher priority.

four days in advance. Inputs into the forecasting system included rainfall data, river gauge data and various scenarios relating to possible combinations of releases of mine water. A snapshot of the output is illustrated in Figure 14, which shows the concentrations of salinity (EC) following a fictitious combination of mine water releases during a river flow event.

Gauge data were compiled in the HEC-DSS data storage system. The hydrological model was developed in HEC-HMS using long term continuous simulation (LTCS) for validation and calibration.

An example of the calibration is shown in Figure 15, which illustrates the variance between observed flows and modelled flows at one of the river gauges in the catchment in 2000. This illustrates that the model over-estimates an early flow event in October, does not represent several events in November, and under-estimates a major event in December.

The variance in Figure 15 between observed and model results illustrates the difficulties in calibrating models of large catchments with sparse data. In this case, the nearest rain gauges are situation to the north and south of the catchment. The SILO data, which interpolates and grids the data from the gauges, were used to generate data for individual sub-catchments. It is apparent that, where the rain gauges are widely spaced, the interpolated, gridded rainfall records on intermediate catchments are unlikely to accurately represent real, local storms, and this is thought to be a major factor in the variances seen in Figure 15.

In the context of the FOS, the hydrological model developed through LTCS is appropriate. By using fixed soil stores, the data inputs required from the instruments are reduced to rainfall, creek flow and water quality parameters. It is acknowledged that more accurate models can be built with varying soil stores, the solution of the full suite of hydrodynamic equations, and the diffusion of salinity and pH throughout the water column. However, the computational cycle is greatly reduced by applying simplified approaches, such that many thousands of scenarios can be run quickly in a responsive system. The responsiveness of the FOS is the pre-eminent factor in operating the mine water release valves so that the best use can be made of the limited release opportunities, whilst maintaining compliance with the environmental conditions throughout the release event as it unfolds in real time.

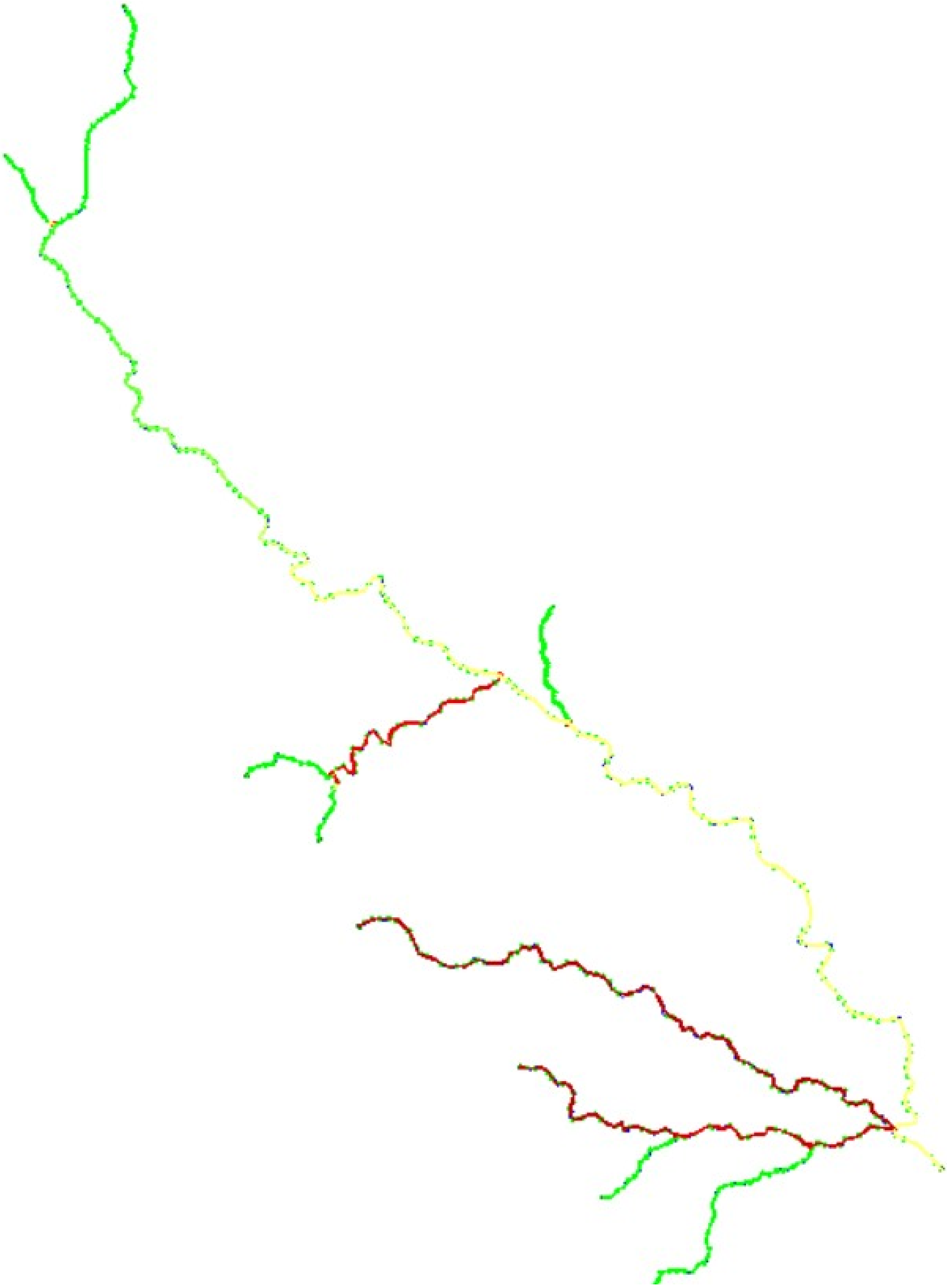

Figure 14: Snapshot of salinity concentration in creek system following a possible combination of release of mine water

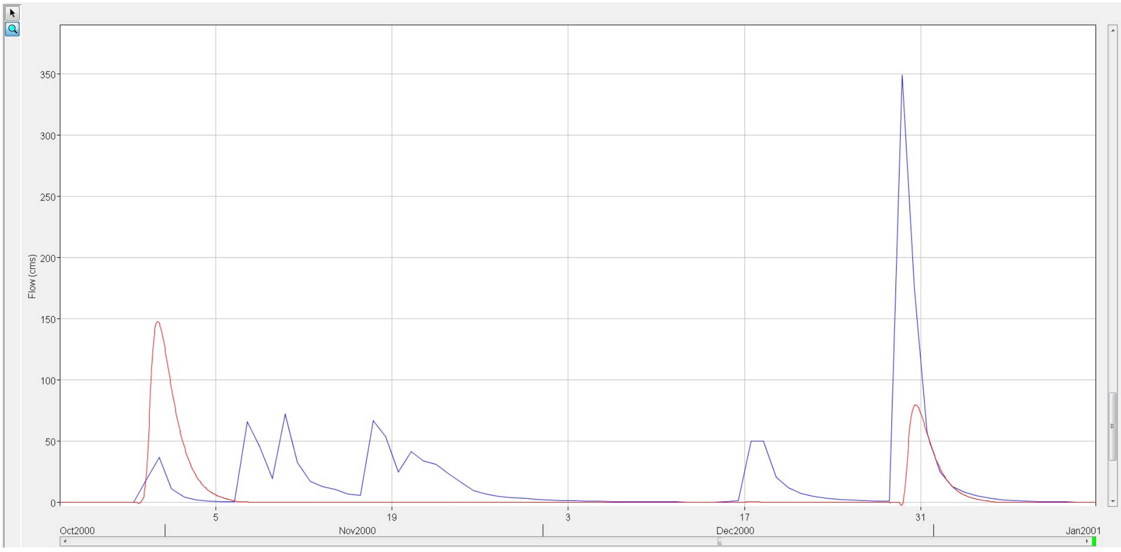

Figure 15: Comparison of observed (blue) flows and modelled (red) flows at a river gauge

Discussion and lessons learned

It is the author's experience that the outcomes of Long Term Continuous Simulation (LTCS) may be considered in terms of tangible and intangible classifications.

The tangible, or measurable outcomes or lessons learned, include the following

- LTCS is possible for simulation periods of up to 130 years in Australia, due advances in computing technology, gridded rainfall data such as SILO, and Rainfall Disaggregation. Further improvements to computing technology will reduce the logistical burden of generating and handling the large amounts of data involved.
- LTCS focusses on behavioural profiles, and how they respond to changes, rather than individual events.
- LTCS naturally combines the factors related to flooding to solve the conundrums posed by joint probabilities.
- LTCS relies on good data, particularly rainfall and terrain.
- Hydrological models developed through LTCS are suitable for use in Forecasting and Operating Systems
- The longer the duration of the LTCS, the more reliable the extrapolation from frequent to extreme events

The comparison with event-based modelling is worthy of further consideration. As event-based modelling generally allows for variations to soil storage, or loss parameters according to the magnitude of the rainfall event, it may yield better reproductions of historic events. LTCS typically yields greater variance between real and modelled flows because of its use of fixed soil store or rainfall loss parameters. The pros and cons of either approach are subject to philosophical, rather than mathematical, reflection. It is the author's opinion that LTCS forces the issue of modelling uncertainty into the open such that any interpretation of the model and its results must reckon with the limitations related to the sparsity of data and modelling assumptions and idealisations.

It is these kinds of considerations that lead to the greatest benefits of LTCS, which are intangible, by nature. In summary, LTCS forces the modeller to learn the fundaments of hydrology and hydraulics. In LTCS, there can be no avoidance of questions relating to what the model is for, or of the difficulties posed by sparsity of data, the physical limitations of real gauge readings, or trade-offs between speed and accuracy. These issues must be tackled head-on as the modeller attempts to align the model to the data.

Ultimately, the most important model is not the assembly of numbers and equations held in the computer's circuitry, but the modeller's own mental understanding of how these data relate to one another in a unifying concept of how the real river or drainage system behaves. Only then can the modeller apply this understanding to whatever purpose the model is intended to serve, be it the design of flood mitigation works, planning schemes, road and rail bridges, or forecasting and operating systems.

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