Stochastic Simulation of Inflow Hydrographs for Wivenhoe and Somerset Dams

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Wivenhoe and Somerset Dams are operated with the dual purpose of providing drinking water supply to South East Queensland and also to provide flood mitigation benefits for communities along the Brisbane River downstream of Wivenhoe Dam. Both dams have flood gates and the dams are operated during flood events in accordance with a Flood Operations Manual that provides strategies to reduce the impact on communities in Brisbane, Ipswich and smaller rural communities along the river. The flood operations rules for the dams consider flows in the catchments both upstream and downstream of the dams. The overall catchment area of the Brisbane River is 13,500 km², of which 7,039 km² is upstream of Wivenhoe Dam. For any individual flood in the Brisbane River catchment, the flooding outcome along the river downstream of Wivenhoe Dam depends upon the volume, peak flow and timing of the flood hydrographs generated from the individual catchments upstream of Somerset Dam, between Somerset and Wivenhoe Dam, and from the tributaries of the Brisbane River downstream of Wivenhoe Dam, including Lockyer Creek and the Bremer River.

This paper discusses the stochastic framework that was used to generate the 5449 sets of inflow hydrographs, to develop and stress test a dam operations model. The stochastic simulations were driven by 600 different space-time patterns of rainfall generated using a stochastic space-time multiplicative cascade model. Eight significant storms were identified in the radar archive to identify parameter sets for the stochastic generation algorithm and 600 replicates of space-time rainfall were generated. The statistical properties of spatial patterns of 48-hour rainfall bursts on eight major subcatchments of the Brisbane River catchment from the 600 stochastic replicates were verified against the same statistics derived from 38 major flood causing rainfall events observed in the catchment. The hydrographs were generated using an URBS rainfall runoff routing model of the Brisbane River catchment, which was calibrated to 38 historical flood events (between 1955 and 2013) and tested on a further 10 historical flood events (between 1987 and 1947).

The stochastically simulated sets of inflow hydrographs were then used to assess the impact of variations in flood operation rules for Wivenhoe and Somerset dams. The stochastically generated events exhibit substantial variability in runoff hydrographs but with variability that is statistically consistent with observed events. The stochastically generated hydrographs provide a considerably more realistic basis for testing the outcomes for different flood operations strategies than the single design event approaches that have previously been adopted.

Keywords: flood hydrology, flood operations, gated dams, stochastic rainfall generation.

Introduction

Wivenhoe and Somerset Dams are operated with the dual purpose of providing drinking water supply to South East Queensland and also to provide flood mitigation benefits for communities along the Brisbane River downstream of Wivenhoe Dam. Both dams have flood gates and the dams are operated during flood events in accordance with the Manual of Operational Procedures for Flood Mitigation at Wivenhoe Dam and Somerset Dam (Seqwater, 2012) that provides strategies to reduce the impact on communities in Brisbane, Ipswich and smaller rural communities along the River. The Flood Operations Manual requires Seqwater to consider inflows from the catchments entering the Brisbane River between Wivenhoe Dam and Moggill in setting flood releases from the dams, in addition to inflows to Wivenhoe and Somerset dams.

The overall catchment area of the Brisbane River is 13,500 km², of which 7,039 km² is upstream of Wivenhoe Dam (see Figure 1). For any individual flood in the Brisbane River catchment, the flooding outcome along the river downstream of Wivenhoe Dam depends upon the volume, peak flow and timing of the flood hydrographs generated from the individual subcatchments upstream of Somerset Dam, between Somerset and Wivenhoe Dam and from the tributaries of the Brisbane River downstream of Wivenhoe Dam, including Lockyer Creek and the Bremer River.

While design flood hydrology is important, a suite of ‘design floods’ alone (i.e. floods with a specified Annual Exceedance Probability (AEP)) are not sufficient to test the suitability and robustness of dam operating rules for the wide range of conditions that can occur in actual flood events. Flood hydrographs in actual flood events (as evidenced by historical events) can differ markedly from design flood hydrographs. Future flood events may well differ from both the historical floods that have been observed and design floods. The possibility of multiple rainfall bursts during an event and differing spatial extents of rainfall bursts upstream and downstream of dams are significant aspects that affect how dams are best managed for the passage of flood events.

The conventional flood hydrology approaches for large and extreme flood events assume a single temporal pattern of rainfall (for a given duration) that is consistent across the whole catchment. This results in flow hydrographs in each of the tributaries that are single-peaked and close to coincident for inflows to the dams and tributary flows on the catchments downstream. However, rainfall temporal patterns and flood
hydrographs for observed events in this catchment can have multiple peaks and variable timing between subcatchments. The characteristics of the January 2011 flood demonstrates this, with two large inflow peaks into Wivenhoe Dam within 36 hours unique in Brisbane River flood history.

Seqwater are currently undertaking a study to test the influence of different options for flood operations at Wivenhoe and Somerset Dams on flooding outcomes for locations that are downstream of Wivenhoe Dam. Seqwater have developed a model that simulates the influence of gate operations at Wivenhoe and Somerset Dams on flooding in the catchment in the simulation package GoldSim (GoldSim Technology Group, 2013), which implements the flood operations strategies that are included in the Flood Manual. Seqwater are also using the dam operations simulation model to test possible alternative flood operations strategies as part of the Wivenhoe and Somerset Dam Optimisation Study.

Flood operations were tested by developing a suite of 5000 different stochastically generated flood events. For each simulated flood event, the dam operations simulation model requires inflow hydrographs at ten locations: inflows into Somerset Dam, Wivenhoe Dam, Lockyer Creek at O’Reilly’s Weir, Bremer River at Ipswich, and six local area inflow hydrographs between Wivenhoe Dam and Moggill. The hydrographs at each of the ten inflow locations were simulated using the URBS semi-distributed rainfall runoff model with stochastically generated rainfall patterns applied to the catchment, as shown on the map in Figure 1.

This paper discusses the stochastic framework that was used to generate the 5000 sets of inflow hydrographs. The first section discusses the URBS rainfall runoff model developed for the catchments of the Brisbane River and briefly explains the calibration of those models to observed flood events in the catchment. This is followed by an explanation of the overall simulation approach that was adopted. Some results from the 5000 simulated flood events are then presented. Further details on the project can be found in Seqwater (2013) and Sinclair Knight Merz (2013).

Figure 1 URBS model catchments within the Brisbane River Catchment (from Seqwater, 2013)
**URBS Catchment Model**

The Unified River Basin Simulator (URBS) is a semi-distributed rainfall runoff routing modelling package (Carroll, 2012). This model was selected by Seqwater for all flood modelling in the Brisbane River catchment to be consistent with the Bureau of Meteorology’s flood forecasting system. URBS provides flexibility to run in both flood forecasting and design mode, customisation of flood routing behavior and the ability to incorporate flood-level dependent rating relationships.

The Brisbane River basin was divided into seven distinct catchment models based on review of topography and drainage patterns, major dam locations, key locations of interest for real time flood operations, and consideration of the best use of available data including water level gauges. A map of the seven models developed to represent the Brisbane River basin is shown in Figure 1.

For the Brisbane River catchment, losses were represented using an Initial Loss (IL) and Continuing Loss (CL) model. Different IL and CL parameters were adopted within each of the seven different URBS model catchments of the Brisbane River basin. The split routing approach within URBS was adopted for the Brisbane River catchment. Under this routing formulation, runoff generated within each subcatchment is routed using a non-linear conceptual store, with the routing properties of the conceptual store controlled using parameters $\beta$ and $m$. Runoff is then routed along the reach segments within the catchment using a non-linear Muskingum routing model, with the routing parameters of each reach controlled using parameters $\alpha$ and $n$.

Seqwater developed a suite of URBS models as a system for forecasting floods during real time operation of the dams in flood events. The models were calibrated by Seqwater to 38 large historical flood events that have been observed in the Brisbane River catchment between 1955 and March 2013 (inclusive) (Seqwater, 2013). Seqwater also used the calibrated URBS model to derive simulations for ten significant flood events between 1887 and 1947 (Seqwater, 2013). The models adopted for calibration were varied to represent the influence of dams as they have been constructed at different times during the development of the catchment. Nine conceptual storages were included in the URBS models to represent the additional routing influence of floodplains on higher flows.

**Simulation Method**

**Overall Simulation Framework**

The overall simulation framework adopted for the stochastic model runs is shown in Figure 2. The stochastic simulation process for each run involved selecting the AEP associated with the design rainfall burst or whole storm across the whole catchment to Moggill. Each available generated space-time rainfall pattern was used once for each selected AEP to disaggregate the catchment average rainfall total for the event in space and time across the catchment, generating one rainfall time series (“.r”) file for each of the 539 subcatchments in the URBS models. The patterns were scaled so that there is one “critical” burst of between 24 and 168 hour duration with rainfall for the entire catchment that has the specified AEP for the run. The same scaling factor is adopted for rescaling the within burst, pre-burst and post-burst rainfall in each simulation. Bursts for durations other than the critical duration will have a higher AEP than the nominated AEP for the critical burst in the event.

Each simulation run involved nine separate runs of URBS models, to represent each of the different URBS model catchments and also to simulate “no dams” scenario flood hydrographs at Wivenhoe Dam and Moggill. The process for undertaking the URBS model runs that are carried out within each stochastic simulation is shown in Figure 3.

![Figure 2 Overall approach adopted for simulation runs based on stochastic sampling of rainfall event and initial loss (IL) parameters, and deterministic application of continuing loss (CL) and URBS model parameters ($\alpha, \beta, m, n$)](image-url)
Figure 3 Approach adopted for URBS model simulations to generate hydrographs

Table 1 Sets of space-time patterns adopted for each rainfall burst duration and AEP

<table>
<thead>
<tr>
<th>AEP of 63% to 2%</th>
<th>AEP of 1% to 0.1%</th>
<th>AEP of 0.05% and greater</th>
</tr>
</thead>
<tbody>
<tr>
<td>480 space-time patterns generated with space-time model parameters derived directly from events observed by radar</td>
<td>480 space-time patterns generated with space-time model parameters derived directly from events observed by radar AND 120 space-time patterns generated with space-time model parameters adjusted to simulate large and extreme events</td>
<td>120 space-time patterns generated with space-time model parameters adjusted to simulate large and extreme events</td>
</tr>
</tbody>
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Stochastic Rainfall Generation Method

Seed et al. (2014) and Sinclair Knight Merz (2013) discuss the set of 600 stochastically generated space time patterns that were generated for the Brisbane River catchment. These stochastic space-time patterns were used as the basis for the stochastic flood simulations that were adopted in this study. Each of the available patterns in the set was used for one flood simulation for each URBS model subcatchments.

There is substantial theoretical and empirical evidence to support the notion that precipitation fields exhibit scaling (multi-fractal) and dynamic scaling behaviour e.g. Lovejoy et al. (1996) and Venugopal et al. (1996) This evidence has been used by numerous authors (e.g. Seed, 2003) to justify representing the spatial statistical properties of precipitation fields using a power law relationship of the spectral density:

\[ P(\omega) \propto \omega^{-k} \]  \hspace{1cm} (1)

where \( P(\omega) \) is the spectral density of the field at frequency \( \omega \) pixel\(^{-1} \) and the superscript \( k \) is known as the scaling exponent.

The stochastic simulation method exploits a cascade representation of precipitation fields to provide a suitable framework in which to model these spatial and dynamic scaling properties. This form of representation allows a field of instantaneous rain rate (estimated from radar), to be decomposed into a hierarchy of component fields representing variability on a discrete set of horizontal scales. The mathematics behind the simulation model are contained in Seed et al. (2014) and Sinclair Knight Merz (2013).

The stochastic flood simulations were produced using stochastically generated space-time rainfall patterns for the Brisbane River catchment. The approach used for stochastic generation of space-time patterns of rainfall was as follows:

1) Space-time rainfall fields were generated using the multiplicative random cascade method for a 256 x 256 km domain, at 1 km spatial resolution and 10 minute temporal resolution, assuming no orographic influences across the field;

2) The generated space-time rainfall fields were accumulated to 1 hour rainfall accumulation fields, for a 256 x 256 km domain at 1 km spatial resolution;

3) The boundaries of the 539 URBS model subcatchments were overlaid on the generated hourly accumulation fields – with the catchment positioned at one of six different spatial locations within the 256 x 256 km domain of the generated rainfall fields;

4) An orographic enhancement factor grid, with 1 km resolution, was positioned at one of the six possible spatial locations to be consistent with the position of the catchment within the generated data domain. The orographic enhancement factor value at each 1 km
grid cell was derived by dividing the 48 hour, 2% AEP design rainfall estimate from CRC-FORGE (Hargraves, 2005), at the grid cell location by the mean of the 48 hour, 2% AEP design rainfall estimate from CRC-FORGE;

5) Hourly rainfall time series were extracted from the generated data for each of the 539 URBS model subcatchments, for each of the six possible catchment positions (from step 3) by averaging the 1km grid square values from the product of the orographic enhancement matrix for the corresponding catchment position (from step 4) and the generated hourly space time rainfall for each of the replicates (from step 2).

Calibration and Verification of Stochastically Generated Rainfall Patterns

The stochastic model was calibrated for the eight significant storms that are in the radar record of Brisbane, which were observed between 1996 and 2012, including the January 2011 event. Discussion of the calibration of the parameters of the stochastic rainfall generation model is in Sinclair Knight Merz (2013) and Seed et al. (2014).

A semi-independent verification of the stochastically generated replicates was undertaken against observed data from 36 observed historical rainfall events (between 1954 and 2012 inclusive). The data sets that were used in the validation were:

- Hourly rainfall accumulation maps, at 1 km x 1km resolution, for 600 replicates generated by the multiplicative random cascade model (representing ten replicates each with parameters calibrated to eight large events observed by radar);
- Hourly rainfall accumulation maps for 36 observed events, which were derived by Kriging the hourly totals from all available pluviograph gauges around the Brisbane River catchment, whilst maintaining the spatial pattern determined by Kriging the totals for all of the available rainfall gauges. This data set includes the eight events that were used for calibration of the multiplicative random cascade and 28 other events that were not used for calibration.

![Figure 4 a) 24-hour accumulation of radar rainfall ending at 06:00 11 January 2011 and b-d) three stochastic simulations of the same day.](image)
Scatter plots were produced of the total rainfall for the 48 hour burst in each validation catchment and the rainfall for the concurrent 48 hours in each of the other catchments. Since there are eight major catchments, this produces a total of 56 scatter plots, which can be arranged on a square matrix with the diagonal missing. Full scatter plots for all 56 combinations are presented in Sinclair Knight Merz (2013) but scatter plots from only two combinations are presented in Figure 4 to illustrate the key features of the verification. Panels (a) and (b) of Figure 5 show all of the 600 simulated events, which illustrate the considerable variability in 48 hour spatial patterns that is achieved by the stochastic generation algorithm. Panels (c) and (d) of Figure 5 show only a random selection of 36 simulated patterns for each of the catchment pairs, providing a visually more realistic impression that a similar level of overall scatter is achieved by the simulated data when compared with data from the observed events. Panels (a) and (c) demonstrate that the orographic enhancement factor included in the simulation process has achieved a bias toward higher rainfall totals in the Stanley catchment (compared with the Gregors Creek catchment) in the simulated data, similar to the observed data. There is considerably more scatter between the Stanley and Lower Brisbane catchments (panels b and d) than the scatter between the Stanley and Gregors Creek catchments (panels a and c), which is consistent with the larger spatial separation between the Lower Brisbane and Stanley catchments than between the Gregors Creek and Stanley catchments.

**Results**

Figure 6 shows the simulated flood hydrographs at the major inflow locations for a sample of four out of the 5449 different flood events. All four of these events had a critical rainfall burst for the entire Brisbane River catchment with the same nominal AEP of 1%, although the duration of the critical rainfall burst differed between the simulated events due to variation in the space-time pattern. The four patterns selected for display in the figure include the events for this nominal AEP that produced the highest and lowest simulated peak flow at Moggill under catchment conditions with no Somerset Dam and no Wivenhoe Dam to emphasise the range of outcomes that can be produced depending upon the random variation in space-time pattern and random variation in initial loss.

Figure 7 shows the random variation in peak flow for the Upper Brisbane catchment with the simulated rainfall depth across the corresponding subcatchments. This figure again emphasises the strong influence of random variation in space-time pattern and initial loss on the peak flow produced from different parts of the catchment. Similar plots were produced for the other URBS model catchments (Sinclair Knight Merz, 2013).
Figure 6 Sample of simulated flood hydrographs for four stochastically generated events

Figure 7 Scatter plot illustrating the variation in generated peak flow as a function of total rainfall depth for the stochastically simulated flood events in the Upper Brisbane River catchment
Conclusions

This paper described the process for developing a set of more than 5,000 synthetic flood events, as sets of flood inflow hydrographs for ten separate inflow locations within the Brisbane River catchment required by Seqwater for dam operations simulation model. The synthetic flood events span a wide range of possible flood magnitudes. These synthetic flood events were produced using a world-leading technique for stochastic generation of space-time rainfall fields, which were generated from radar data observed during eight heavy rainfall events across the catchment (observed between 1996 and 2012 inclusive).

The techniques to derive flood events for this project demonstrates emerging potential to model the variability of potential flooding in catchments where the space-time pattern of rainfall is particularly influential on flooding outcomes. This can be important to realistically assess variability of flooding in catchments where there are one or more dams operating within a catchment where there is considerable variability timing of flood inflows to the dams and unregulated inflows from downstream catchments. Assessing the range of potential variability with numerous stochastically generated flood events can lead to better understanding of potential flooding outcomes in different flood events.

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