ADAPTABLE ANALYSIS – DIFFERENT APPROACHES THAT LEAD TO THE SAME RESULTS

Mark Pennington, Tonkin+Taylor

ABSTRACT

Analysis of historic records has been, and will continue to be, a reliable means of gaining an understanding of surface water system behavior. If the design condition under consideration falls within the envelope of historic records, then it is possible to have a high degree of confidence in the analysis results used for design.

However, it is often the case that the set of historic records at a specific site is either non-existent or does not envelope the range of events for which the design is required. In such cases a designer will still seek to have a high degree of confidence in the analyses, and alternative approaches are required.

Such alternative approaches include extrapolation (of observations), detailed analysis using established hydraulic principles with detailed input data (modelling) and sensitivity assessment using statistical and other means. All of these approaches are intended for the same end point, this being a high degree in confidence in results that are to be used in design.

In this paper these approaches are benchmarked against each other using a case study. The results show that in some cases there are alternative approaches to the detailed hydrological and hydraulic modelling approach that result in the same end point conclusions being able to be reached (confidence in results). These alternative approaches will be demonstrated, and in this paper the relative time inputs to them are discussed using the case study examples.

KEYWORDS

Modelling, stormwater

PRESENTER PROFILE

Mark Pennington is a Senior Water Engineer at Tonkin and Taylor, based in Tauranga.

1 INTRODUCTION

The challenge of establishment of a design flood level for a particular site is one that frequently arises for designers. This challenge is further complicated by climatic variability, with the design brief often being to predict a flood level for a specific probability of event at some future point in time allowing for currently understood climatic changes. For example, the design brief may be to:

"Establish the design 100-year ARI flood level for the year 2116 at XYZ site."

There are several approaches to this that are frequently adopted. The starting point, being the posing of the above question, and the ending point, being the answer to the question, remain the same regardless of approach adopted. This can be illustrated in Figure 1.1.

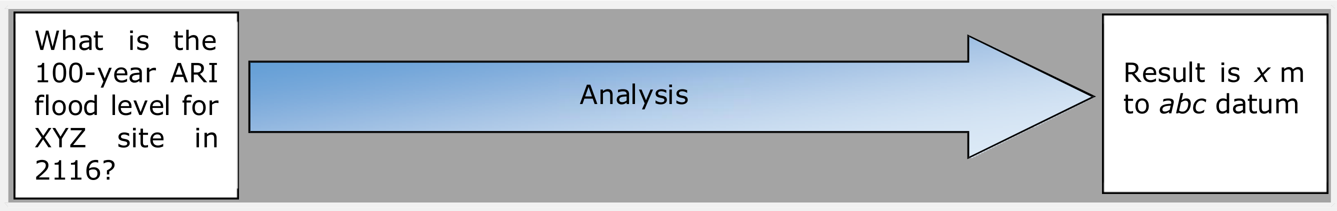

Figure 1.1: Start and end points

Numerous techniques exist to go about making the assessment required to deliver the design flood level with an acceptable degree of confidence. The current diversity of approaches can result in predicted levels varying significantly at the interfaces between areas where different approaches have been applied.

In this paper some of the major approaches to the "analysis" part shown in Figure 1.1 are further examined. These are covered in Section 2 of this paper. A particular emphasis is given to comparison between two variants of the same approach described in Section 2, with a results comparison between these given in Section 3. Some conclusions are given in Section 4. Most notably, the reader is directed to the descriptions in approaches given in Sections 2.4 and 2.5, these being the major focus of this paper.

2 ANALYSIS

2.1 HISTORIC OBSERVATION PATHWAY

By far the simplest approach to the question is to base the predicted flood level on observations that have historically been recorded at the site. The only trouble with this approach is that it is exactly that, which is "based on *historic* observations". Where historic performance is not likely to be representative of future performance, an allowance for the difference between historic and future performance needs to be made.

If a historic discharge record exists for the subject site, then it is possible to undertake frequency analysis of the gauged record and prepare discharge frequency estimates, as shown in Figure 2.1. Shown in this figure is the recorded data together with two different statistical estimations relating discharge to anticipated frequency of occurrence. The statistical analysis applied, which has influence on the results, is not covered in this paper. Rather, the approach whereby a long term record can be sued to estimate discharge at different frequencies is shown.

Evident from Figure 2.1 is that, for this particular site, the highest gauged discharge on record is about 27 m^3/s, with an estimated Average Recurrence Interval (ARI) of 15-20 years. Any discharge or ARI in excess of this requires extrapolation and, as shown in the figure, the statistical approaches frequently diverge when extrapolated beyond the source data.

Also shown in Figure 2.1 is that a discharge of 28 m^3/s has an estimated frequency of occurrence of 30-35 years (red chain-dashed line).

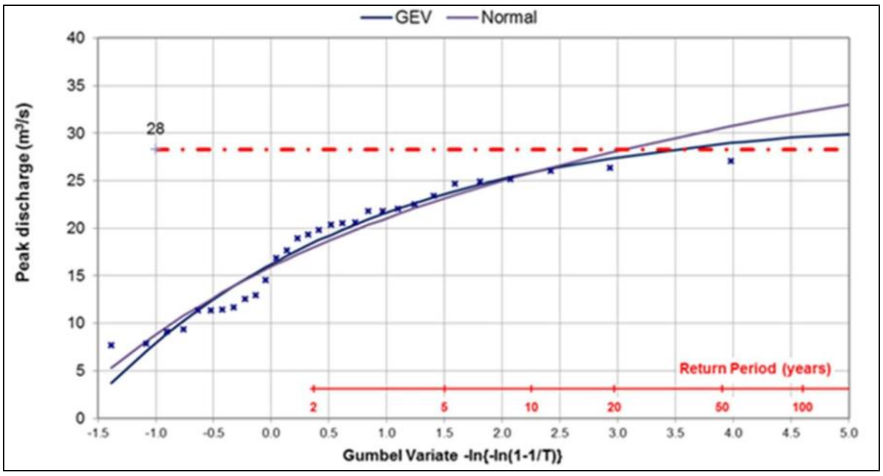

Figure 2.1: Example of discharge frequency plot

Thus for the sample question posed in this paper, a 100-year ARI discharge for the subject site would be some 30-33 m^3/s.

This represents the historic performance of the waterway in question (i.e. over the period of record). Some correction to this would be required to estimate the 2116 discharge estimate for the given frequency. This could be done by reference to climate data, and a percentage increase applied. However, some uncertainty exists in undertaking this.

A site rating curve could then be considered which links discharge to water level. An example is shown in Figure 2.2. From this the design water level for the given event frequency for the required time horizon can be estimated. For the discharge estimate of 30-33 m^3/s, a design level of around 14.2 m would result.

The uncertainty that exists in this estimate can be covered in a *freeboard* allowance.

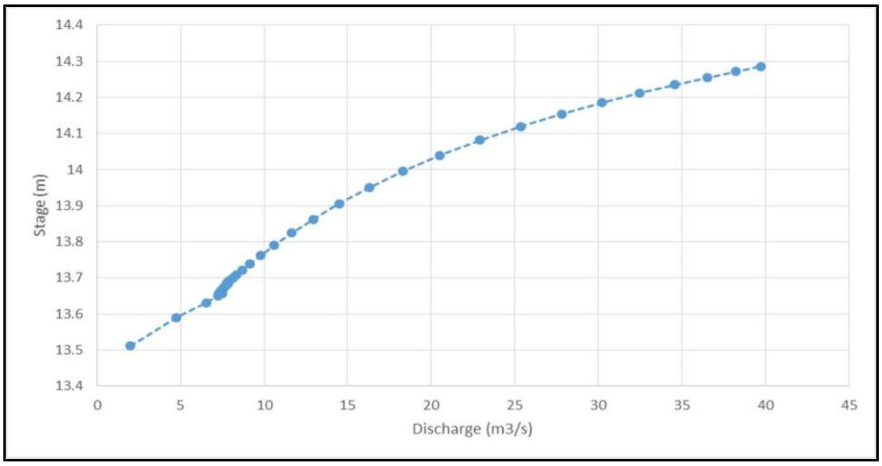

Figure 2.2: Example of rating curve

Thus it can be seen that, following the historic observation pathway and provided that adequate observations exist at the point of interest, an estimate of the design flood level at the current point in time can be made on robust statistical grounds. Extrapolation of this estimate to a future horizon is less certain, as no "historic" records exist for future situations.

2.2 REGIONAL FLOOD ESTIMATION PATHWAY

As was shown for the historic observation pathway, it is possible to apply analysis techniques that are based on recorded data, but these analyses can be limited by what events have occurred during the historic period of record. Because recordings do not exist at all locations where flood levels may be required, empirical approaches that are regionally adjusted, based on historic observations, have been developed. Such methods are often referred to as Regional Flood Estimation methods, and often involve estimation of a peak flood discharge at a specific location.

As with the method outlined in Section 2.1, some conversion of flood discharge to flood level is required in order to answer the question as posed in the Introduction and as shown in Figure 1.1.

A limitation of the regional method approach is that it generally applies only to major waterways, and would therefore not be easily applicable to any urban drainage type setting. A positive for the method is that it has been shown to produce results that are defendable via a reasonably simplistic analysis.

Like the Historic Observation approach, the Regional Flood Estimation approach may require some extrapolation beyond observed data for some of the event frequencies for which results are often required.

Confidence in the results of this type of analysis is generally given by proven robustness in predictions of actual flood events.

2.3 STATISTICAL APPROACH

Many of the variables that have influence on flood level estimation have a degree of probabilistic nature. Typical rainfall based design flood estimation generally treats these variables as constants, with the only real variable being rainfall depth.

A Monte Carlo simulation approach is a holistic approach to design flood estimation that considers probability-distributed inputs and model parameters and their correlations, to determine probability-distributed flood outputs.

There are methods that have been developed, not covered in this paper, that treat hydrological and hydraulic parameters as random variables, each with its own probability distribution function, in a model simulation of catchment response to rainfall.

While statistically robust, such methods if applied to floodplain models may be prohibitively time-consuming. However this approach can be adapted to account for extreme events and different time horizons, although the probability distributions used for each random variable will generally have been derived from historic observations.

Confidence in the results is derived from the robust statistical analyses carried out.

2.4 DETAILED MODELLING PATHWAY

A long-term discharge record at the site of relevance to the question posed is a luxury that is seldom able to be relied upon – simply because waterways are not gauged at multiple locations, and in many cases the subject site is not adjacent to any notable waterway. In such cases, a different type of hydrological and hydraulic analysis is a potential solution. One such pathway that is frequently adopted is to simulate catchment behavior using application of proven analysis techniques to physically measurable parameters. The event frequency used in such analysis is driven by rainfall frequency. Such models are usually calibrated to observations made during historic events, but it is very common that the “calibration events” used are nowhere near the severity of the “design event” required to be simulated, the results of which get used in some design setting.

In this way, hydrological and hydraulic equations are solved at a fine spatial resolution to simulate hydraulic performance in response to a rainfall event (sometimes combined with the frequency of a tailwater condition, such as tide level) of the required frequency of occurrence. Confidence in model results is derived from the knowledge that sufficient details exists in the model to accurately represent the physical factors that influence the hydrological and hydraulic processes, and that these processes are adequately described by theory applied in the solutions.

This can be termed a “model-what-you-can-see” approach. Where, for example, a modeller can “see” a 600mm diameter pipe that is 23.2m long, then the model will contain a pipe that is 600mm in diameter and is 23.2m in length. Every element in the drainage system is faithfully represented in the detailed model, and in this way the designer gains confidence that the model is capable of delivering results of a high degree of confidence, even when operated outside its range of calibration.

2.5 DETAILED MODELLING SHORTCUT

A common feature of inundation models as described in Section 2.4 is that they contain a large number of parameters, each of which may vary within reasonable bounds (e.g. distribution of inflow, floodplain roughness, topographical details, friction losses). For example, a frequently used roughness parameter, Manning’s *n*, is shown to be able to be varied within fairly wide bounds, for any particular surface as shown in Figure 2.3.

Manning's n for Channels (Chow, 1959).

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160

Manning's n for Closed Conduits Flowing Partly Full (Chow, 1959).

Type of Conduit and Description	Minimum	Normal	Maximum
1. Brass, smooth:	0.009	0.010	0.013
2. Steel:			
Lockbar and welded	0.010	0.012	0.014
Riveted and spiral	0.013	0.016	0.017
3. Cast Iron:			
Coated	0.010	0.013	0.014
Uncoated	0.011	0.014	0.016
4. Wrought Iron:			
Black	0.012	0.014	0.015
Galvanized	0.013	0.016	0.017
5. Corrugated Metal:			
Subdrain	0.017	0.019	0.021
Stormdrain	0.021	0.024	0.030
6. Cement:			
Neat Surface	0.010	0.011	0.013
Mortar	0.011	0.013	0.015
7. Concrete:			
Culvert, straight and free of debris	0.010	0.011	0.013
Culvert with bends, connections, and some debris	0.011	0.013	0.014
Finished	0.011	0.012	0.014
Sewer with manholes, inlet, etc., straight	0.013	0.015	0.017

Figure 2.3: Sample Manning n values (Chow, 1949)

Immediately visible from Figure 2.3 is that the values for the roughness parameter, Manning's *n*, varies by more than 20 percent between the "minimum" and "maximum" values for each category. This is typical of many of the parameters used in this kind of analysis, from hydrological parameters (percentage of impervious cover, surface soil infiltration rate or other hydrological loss parameter, sub-catchment lag time, etc).

The exact value of any of the many parameters in an inundation model can seldom be known to a high precision, such that the combination of exact parameter values will lead to a unique calibration to observed data. This is highlighted in Pappenberger and Beven (2006), where the implications of such issues not being taken into account is discussed.

It is likely that there will be no single "optimum" set of parameter values in such models that will lead to the best representation of actual system performance, and there could be many such parameter sets that are capable of meeting an acceptable calibration test. This concept is defined as the principle of equifinality in environmental modelling by Beven (2006). It presents a potential difficulty when models are used to produce results in response to events that are way outside their range of calibration, as frequently such inundation models are used to obtain a single-value result at any location. A major limitation in this regard is model run-time, which in many cases, inhibits the ability to investigate the result sensitivity to variation of the component parameters within the given reasonable ranges.

However, if the detailed modelling approach is adapted to take advantage of computational enhancements that are now readily available, and also adapted away from a "model-what-you-can-see" approach to a "model-the-behaviour" approach, then a more acceptable set of results becomes possible. Using the "model-the-behaviour" approach, minute detail is omitted from any detailed description in the model. While it is the inclusion of sufficient detail and appropriate theory that gives confidence in model results that are outside of the range of calibration in the Detailed Modelling approach, in the short cut approach confidence in results is attained through sensitivity analysis.

Sensitivity analysis in inundation modelling can be tedious and time-consuming, but if the model is specifically built for the purpose, then it can happen quickly and efficiently and can overcome the limitations that are potentially linked to the principle of equifinality. One way of achieving this is to build a "model-the-behaviour" type of model using a fast GPU processor. Knowing that in urban drainage situations, buried pipe infrastructure can carry a significant portion of the stormwater flows (with the balance occurring overland), these elements require representation within the model. To replicate the effect of these pipes (rather than explicitly represent the pipes), a modeller will need to accurately simulate both the conveyance capacity and the storage that the pipes in reality do deliver. Together with this is the representation of connectivity between the ground surface and the buried pipe.

One way to achieve this is as follows. The horizontal location of buried pipes is often available via a GIS database. It is possible to use this to locate buried pipes within an urban setting, and overlay this onto a LiDAR derived digital terrain model (DTM). To replicate the effect of the pipes a modeller can modify a 2D DTM to include representation of buried infrastructure in the location of such infrastructure. That is, a representation can be "burned into" a LiDAR DTM in the exact location of each pipe. The dimensions of the "burned in" representation can be calculated to be being faithful to storage and conveyance of the actual pipe in question. If a 2D terrain has a rectangular channel burned into it of the same depth is the pipe diameter, the channel width can be scaled to give the same cross sectional area as the pipe which it represents. Combining this with the pipe length gives the correct representation of the storage. Understanding that a 2D solution is frequently driven by the 2D shallow water equations, in which hydraulic radius is approximated by flow depth, a scaling of the Manning *n* roughness can be undertaken such that the "burned in" channel has the same conveyance capacity as the actual pipe. A full derivation of these relationships is available in Fisher, et al (2014). A model that is able to be used for sub-grid scale hydraulic calculation is required for this.

Following the above approach, a 2D model can be built that contains representation of the effect of the buried pipe infrastructure together with the overland flow characteristics – a "model-the-behaviour" approach. Such a model can be run using a GPU solver and avoid the tedious run-times of traditional detailed inundation models.

Given the relatively short run-times, a modeller can address the principle of equifinality by conducting multiple sensitivity runs. Doing this, each parameter's effect on the final model results can be isolated. Where model results display the greatest sensitivity, a greater effort on firming up on the parameter values can be placed. Alternatively, model results can be aggregated over all sensitivity runs into a "*fuzzy map*", which essentially shows which parts of the model results are subject to change when parameter values reach extremes of their defined ranges. The results obtained by this process are compared to those from the detailed modelling approach in Section 3.

3 RESULTS COMPARISON

In Figure 3.1 three panels are shown, in which different sets of model results are presented. In the left-most panel, a set of results derived via the Detailed Modelling approach described in Section 2.4 is shown. Modelled depths are shown overlying an aerial photograph, with greater depth being indicated by greater colour intensity. Buildings which have had floor levels surveyed (for the purpose of a flood risk assessment) are indicated in black. The model used in generation of this result took a number of months to fully develop.

In the middle panel in Figure 3.1 is the set of results obtained via the Detailed Modelling Shortcut, described in Section 2.5. The effects of the "burned in" pipe can be seen (running more or less north-south in the figure). The extents and depths of this set of results closely mimic those obtained via the detailed modelling approach (left hand panel). Significantly, both sets of results indicate the same buildings to be floodable. Using automated modelling processes, followed by some manual checking of critical areas, the modelling result for this was obtained within two days. Model run-time can be as little as a twentieth of the Detailed Modelling approach.

In the right-hand panel in Figure 3.1 a *fuzzy map* is shown, obtained by sensitivity analysis of multiple parameters for the same event as represented in the middle panel. In this the area of low sensitivity (ie the flooded area remains the same regardless of parameter value adopted) is shown in blue, with increasing sensitivity being displayed by progressively lighter colours. In the right-hand panel the areas where sensitivity is greatest are shown in yellow.

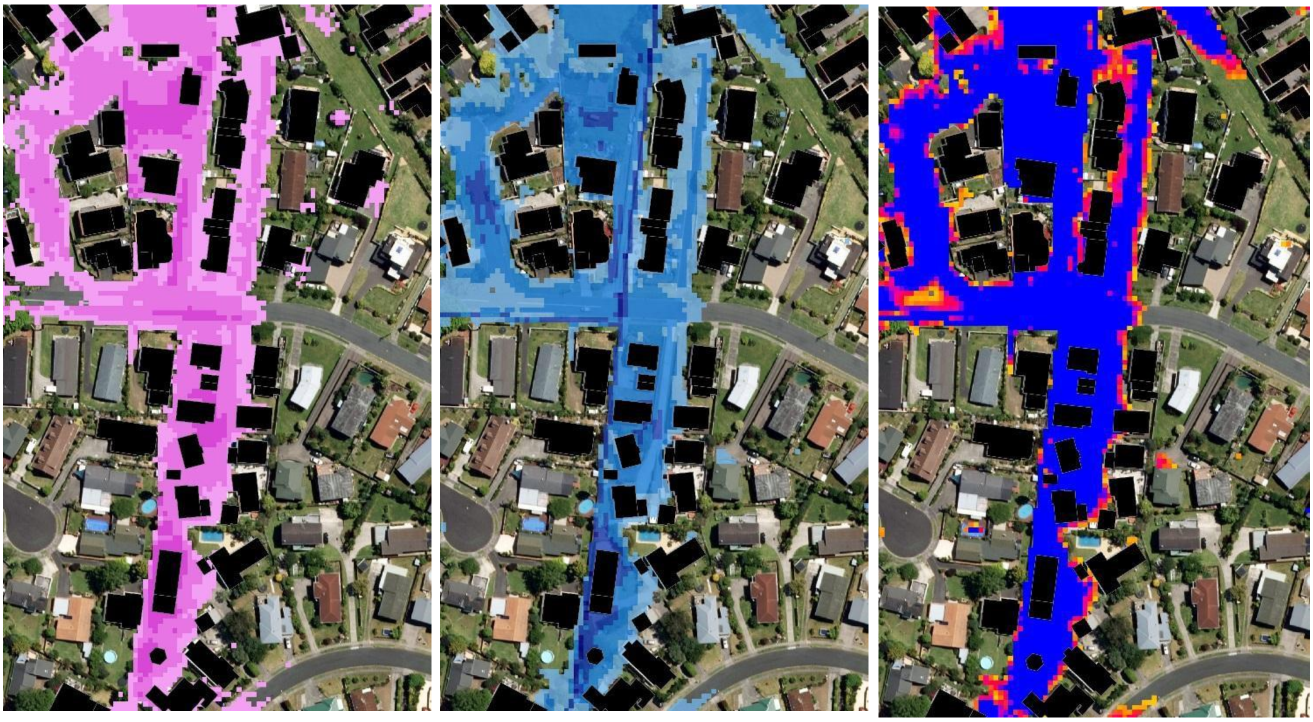

Figure 3.1: Results comparison

What can be seen from Figure 3.1 is that comparable results can be obtained by the Detailed and the Shortcut modelling approaches. Where these results diverge, results confidence can be indicated by making use of the fuzzy map and the cross-over appears to be very good.

4 CONCLUSIONS

There are many "pathways" by which the "journey" from an initial question of a design flood level to obtaining the final answer to a suitably high degree of confidence may be traversed (Figure 4.1). The challenge for a designer is to employ the *best* approach applicable to the specific situation encountered. Some of the potential approaches are open to uncertainty, particularly when extrapolated beyond the observed data that validate the approach. Some are also open to uncertainty driven by the principle of equifinality.

Recent comparative work between the Detailed Modelling and Detailed Modelling Shortcut approaches as described in this paper has revealed that the shortcut approach is not only faster, cheaper and more usable but arguably can provide a greater understanding of model confidence, giving a designer a very useful tool for further use.

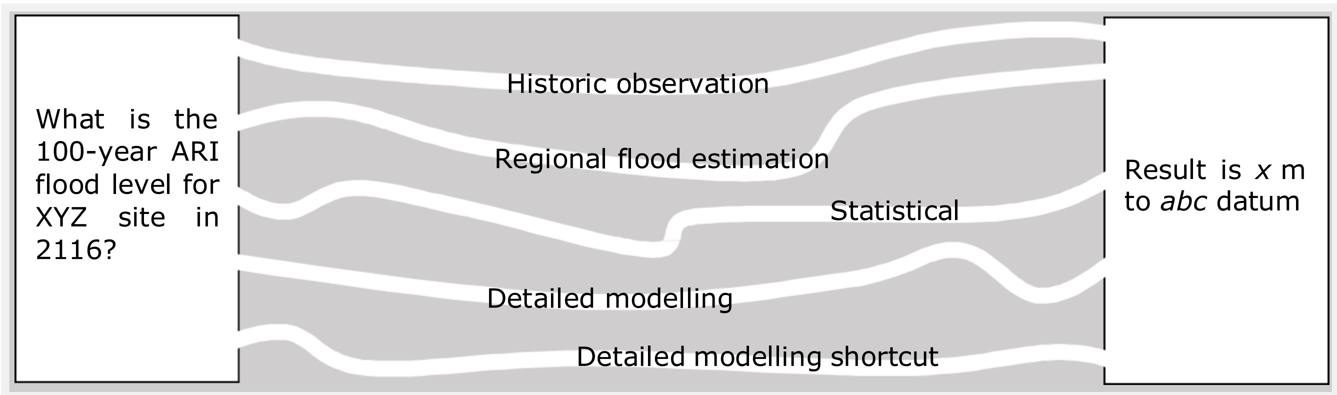

Figure 4.1: Start and end points

5 REFERENCES

Beven, K. J. (2006): A manifesto for the equifinality thesis, J. Hydrol., 320(1–2), 18–36, 2006.

Fisher, T, Taylor, M, Ng, K and Pennington, M (2014), Assessment of increased flood vulnerability due to the Canterbury earthquake sequence, WaterNZ Stormwater Conference, Christchurch, 2014.

Pappenberger, F., Matgen, P., Beven, K. J., Henry, J.-B., Pfister, L.,and de Fraipont, P. (2006): Influence of uncertain boundary conditionsand model structure on flood inundation predictions, Adv. WaterResour., 29(10), 1430–1449, 2006.

Pappenberger, F., Beven, K. J., Frodsham, K., Romanowicz, R., and Matgen, P. (2007): Grasping the unavoidable subjectivity in calibration of flood inundation models: A vulnerability weighted approach, J. Hydrol., 333(2–4), 275–287, 2007.