Bay of Plenty hydraulic modelling guidelines

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Bay of Plenty Regional Council Hydraulic Modelling Guidelines

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Contents

Part 1: **Introduction**

1.1 Objective of guidelines

This document contains guidelines that provides direction by way of principles, approaches to model schematisation, modelling methodologies, and technical specifications. The guidelines are developed to support the building of hydraulic computer models. The objective of these guidelines is to introduce a consistent standard of modelling and reporting based on practical knowledge and experience within the Bay of Plenty.

These guidelines are primarily developed for commonly used 1D and 2D flood model approaches applied in New Zealand. Simpler methods (e.g. static backwater calculations) or more advanced approaches (e.g. Computational Fluid Dynamics models) may be used in flood studies but these guidelines might not be as relevant for those applications.

Catchment-based applications where these modelling guidelines are expected to be used include:

- river capacity and systems performance analysis,
- flood plain mapping,
- flood levels for setting of building floor levels,
- climate change scenario analysis,
- breach scenario analysis,
- growth planning,
- optioneering assessments related to activities such as stopbank management, pump station management, canal and culvert design,
- risk analysis of natural hazards, and
- hydraulic studies that support scour, erosion and sediment transport investigations.

The scope of the guideline is for hydraulic models created on behalf of Bay of Plenty Regional Council (Council) and models created as part of regulatory processes and applications lodged with the Council. For clarity, District and City councils are referred to as Territorial Local Authorities (TLAs). The guidelines do not cover all aspects of modelling and is not exhaustive but guides the reader on modelling practice to help manage risks and issues observed to date with models in the Bay of Plenty. The intended audience is consultants building models for Council, Council staff building or using models, consent applicants and model peer reviewers.

A range of other related topics such as hydrology, sediment transport, water quality, cultural assessments, land development, resource management, consenting and engineering design are not covered in detail but references to other material and guidance is provided where appropriate. Scientific applications such as investigations into minimum river flows to maintain ecological values are not covered in these guidelines and the focus is on flood risk assessment, asset management and engineering. Overlap with coastal modelling is limited to the river mouth and estuary shape and generation of downstream river mouth coastal boundary conditions.

For clarity, hydrology is referred to as the transformation of rainfall into runoff (i.e. discharges) while hydraulic modelling is prediction of the fluid transport processes over land, in waterways and through structures such as culverts where discharge, depth, surface elevation and velocity estimates are required.

1.2 Drivers for the guidelines

Hydraulic modelling is a specialist field that incorporates environmental science, engineering, physics, mathematics and information technology. It represents real-world water phenomena numerically and enables predictions of scenarios that might occur in the future. This complex specialist field is data rich with many different technology platforms, approaches to represent real world phenomena, assumptions, and limitations on when to use model results. The reality of hydraulic modelling is that modern, high-resolution models can be complex computer systems that require significant rigour in how they are built, operated and maintained over time.

Authorities in New Zealand broadly face the following common challenges with hydraulic modelling:

- producing accurate and defensible outputs that support policy and planning, operational decisions, and consent applications,
- generating stable outputs that do not change in unpredictable ways due to data updates or software versions upgrades,
- creating simple-to-use scenario testing that can be undertaken by trained modellers,
- enabling fast turn-around from initial request for modelling work to delivery of results,
- ensuring value for money and ease of maintenance of model currency,
- facilitation of third-party use and streamlined model reviews,
- having a single source of truth through controlling different versions of models for a particular location, and
- simple tracking and comparison of model versions, with the ability to easily retrieve previous versions.

Council manages five major river and drainage systems[4] which include assets that require on-going maintenance and upgrades. As a key authority with responsibilities for natural hazard management, Bay of Plenty Regional Council need to manage risk of these significant waterways on life and property.

Council is regularly provided analysis that comes from models, often during regulatory processes. The approaches used, software, climate and boundary condition assumptions and many other model parameters can vary widely. For example, there are options for the treatment of sea level rise, or the version of the High Intensity Rainfall Design System (HIRDS) used for design events. It is also common for legislative timeframe requirements to make detailed review of model set ups and results difficult, especially if inconsistent modelling practices are used. Efficiencies are required to deal with this situation for the benefit of all stakeholders in models. A common approach nationally for this problem is the publication of modelling guidelines to support standardised approaches to modelling needs specific to a district or region. Model guidelines can provide assurance to the

[4] Major river and drainage systems are the Kaituna Catchment Control Scheme, Rangitāiki-Tarawera Rivers Scheme, Rangitāiki Drainage Scheme, Whakatāne-Tauranga Rivers Scheme and the Waioeka-Otara Rivers Scheme.

model-build process and set model reporting standards in order to highlight any issues and provide improved confidence in a model's predictions.

For these reasons, these guidelines outline standards for hydraulic modelling to align hydraulic models with Council's associated hazard and asset management needs. It seeks to improve the consistency of hydraulic models and reduce interpretation errors due to diverse and undocumented methodologies.

1.3 About this document

The document structure is as follows:

Part 2 describes a number of hydraulic modelling principles to consider when planning, building and using a model.

Part 3 overviews a recommended series of modelling phases to follow, based around a process framework of **plan, build, use**. The framework recommends modellers to **plan** a model solution, **build** the model, then **use** the model for its intended purpose. Guidance on points of engagement with Council through this process are highlighted. Recommended approaches to reporting and where independent peer review may be required are provided.

Part 4 contains a range of technical standards and recommended practices. These include treatment of structures and physical phenomena, climate change considerations, boundary condition development, information collection and datums. This section is intended to be used as a reference guide for topic specific guidance.

1.4 Review and updates

These guidelines will be subject to review from time to time and the latest version will be published on the Bay of Plenty Regional Council website. Additional national guidance, such as relating to climate change predictions, will supersede this document when released. The Council's Engineering Manager will provide guidance directly when situations such as this occur.

1.5 Role of the Bay of Plenty Regional Council

Council has specific functions relating to the management and use of land, air, water and coastal resources. These functions are legislated through the Resource Management Act 1991 (RMA) and give effect to the broader purpose of the Act within the Bay of Plenty in order to promote sustainable management of natural and physical resources. Additionally, Council has other funding and community outcome responsibilities under the Local Government Act 2002. Numerous additional statutory responsibilities are held by the Council such as to manage the quantity of water through land drainage schemes. Hydraulic models contribute to a range of Bay of Plenty Regional Council's planning and operational functions, and they are also used by Territorial Local Authorities and private landowners for a broad range of purposes.

Council has a role to implement clear and consistent regulatory processes. Hydraulic modelling plays a role in some of these processes including but not limited to:

- Territorial Local Authorities catchment, growth planning and infrastructure planning,
- river engineering,
- water diversion and drainage works including agricultural drains and culverts,
- stormwater network discharge consents,

- asset management,
- assessments of environmental effects,
- freshwater vessel navigation, and
- catchment planning.

Council does provide a limited advisory service to consent applicants. However, there is an expectation that applications for consent be supported by robust and technically sound analyses and assessments undertaken by suitably qualified technical specialists. Under such scenarios, the Council's role will be that of a regulator, and is involved in reviewing information presented in support of such applications. The requirement to use a hydraulic model in these scenarios will be dependent on the usefulness of the model to help understand environmental effects.

1.6 Relationship with other plans

These guidelines fit within a complex legislative national framework and range of policy, regulatory and funding tools developed for the Bay of Plenty region. Water by its nature integrates widely into many Mana Whenua, community, industry and landowner activities and areas of interests.

A brief outline of the key policies and plans of broader interest to modelling studies is given below. Where there is a conflict between this document and other TLA guidance or policy, this will need to be discussed and resolved on a case-by-case basis with the Council Engineering Manager.

- Te Ara Whanui o Rangitāiki - Pathways of the Rangitaiki
- Other Iwi plans (e.g. Iwi Management Plans)
- Regional Policy Statement
- The Regional Natural Resources Plan
- Building Act
- Bay of Plenty Regional Council Hydrological and Hydraulic Guidelines
- Climate Change Action Plan -
- Bay of Plenty Regional Council's Long Term Plan (LTP)
- Council's Asset Management Plans
- Third Party Infrastructure Funding Policy
- Triennial Agreement
- Council Protocol for Bay of Plenty RMA Policy and Plans
- Dangerous Dams Policy
- Bay of Plenty Regional Council Floodway and Drainage Bylaw
- Floodplain Management Plans (e.g. Wallace, 2007 and 2013)

Part 2:
Hydraulic Modelling Principles

These guidelines establish key principles to help guide the modelling process and should be considered when building and using hydraulic models. This is important since a model cannot be used without understanding limitations when interpreting results.

All models are simplifications of complex processes

No models can be perfect or represent all of the important processes accurately. There will be reliability, accuracy and uncertainty of input data, assumptions in modelling engines and trade-off for model speed against resolution.

Use the model for the purpose that it was built for

A model developed for a specific purpose may not be suitable for another application without modification, adjustment and possible re-calibration.

Resolve the relevant phenomena

Models needs to be scaled at the level of detail and quality suitable to the model purpose and representation of the real world.

Maintain a base model

Maintaining an up to date base model can be prudent to achieving maximum value from investments in hydraulic modelling.

Models are best built iteratively

Focus on creating a running a model that is refined through iterative design and build phases as more is learnt about the data, environment and the model.

The real-world risk should drive the complexity and accuracy of the model

The risk to lives, infrastructure and the environment of the modelling application should be evaluated when understanding how accurately a model needs to represent reality.

An inadequately built model might still be able to be calibrated to the observed data

Modifying parameters, geometry and spatial layers to align measured and modelled data may be achievable, but may only be relevant to such specific events.

No model is "correct" therefore the results require interpretation

Modelling experience and understanding of the physical processes is required to interpret results, reporting of limitations and assumptions.

New software should be validated before being used.

New software version releases or new modelling tools should be validated against fundamental hydraulic principles or previous model results.

Modelling is a data rich exercise

The management of different model versions, sources of data and tracking of changes throughout the process is a critical discipline of hydraulic modelling.

Part 3:
Steps to build a hydraulic model

This section of the guidelines is designed to provide a framework of steps to follow when building a hydraulic model. No specific technology platform is specified because a diverse range of phenomena may need to be represented and due to the rapid development of new modelling platforms. Instead, a broad process based around the three modelling phases below is defined.

The **plan**, **build**, **use** framework in Figure 1 provides a checklist of steps to work through to support the creation of a model that is robust, easy to review and capable of supporting Council planning and consenting processes. The technical details outlined in this section draw on the Australian Rainfall and Runoff documentation on building a catchment modelling system, and readers are referred to Ball *et. al* (2019a) for more information.

It is suggested that the principle of *models are best built iteratively* be followed where a modelling team might go backwards a few steps as new understanding is gained or problems arise. A focus should be put on releasing of potentially useable models and refining accuracy and representation of detail over time to the level required to achieve the purpose of the study. The alternative of perfecting every element of a model build without knowing if the model will run or data is missing may focus efforts on unimportant areas. Since models are complex computer systems, lessons from "agile software development" techniques are worth considering. These include adaptive planning, iterative delivery of versions of a working model and continual improvement, to encourage rapid and flexible responses to events in the model build process as they arise. This sentiment is also echoed in Ball *et. al* (2019b) where it is proposed that the model conceptualisation is re-assessed after calibration and validated based on model performance. They also recommend that after the model is applied to a design problem, any previous step can be revisited depending on the plausibility of the results. Figure 1's **plan-build-use** process framework shows the key steps and range of iterative loops and back steps that might occur when completing a modelling study.

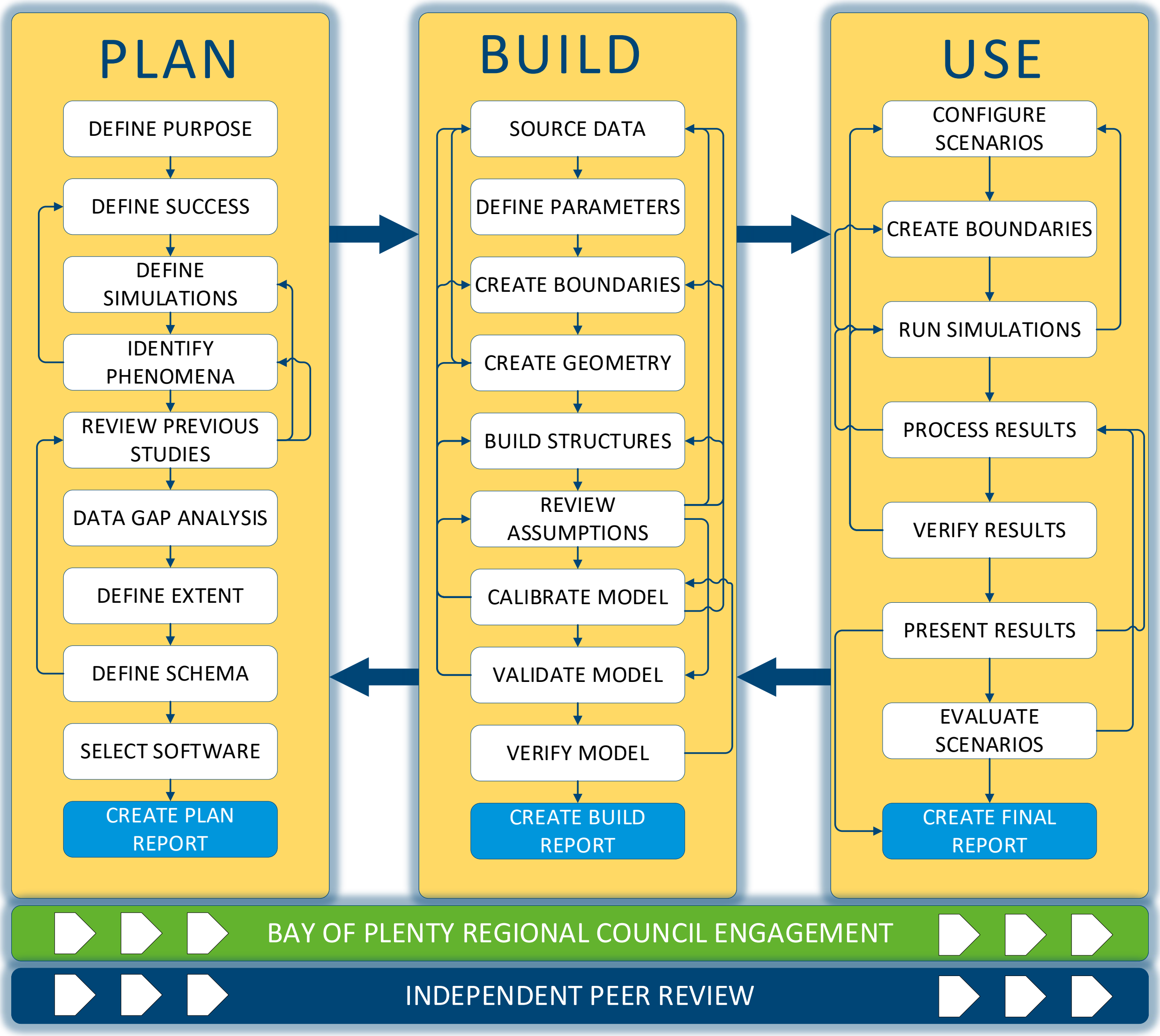


Figure 1 ***Plan-build-use*** *process framework.*

3.1 Council engagement and independent peer review

Hydraulic modelling studies support a broad range of planning, consenting, scientific and engineering processes. Due to the many types of situations where models are used, there are different levels of obligation for engagements with Council and different levels of rigour required for independent peer review. Some common scenarios and recommendations to ensure support for results predicted by hydraulic models are included in Table 1. It is best to think of Council engagement and peer review as themes that could occur at multiple stages of the model **plan**, **build** and **use** processes, and the information below provides some indication of what obligations might exist.

Reference documents will at times become superseded or additional reference documentation created. Engagement with experts and Council will be needed when this new information impacts modelling studies.

Table 1 Example scenarios for Council engagement and need for peer review.

Scenario	Description	Recommendations	
		For Council engagement	**For peer review**
Scenario 1	A consent pre-application meeting occurs and there are no pre-existing plans to build a hydraulic model. Bay of Plenty Regional Council formally requests a model.	The pre-application meeting is occurring at the very start of the model **plan** process. Because the initial application did not include a model, additional reporting and peer review during the remaining plan-build-use process will be required to provide Council with confidence in model results presented. Agree broadly on the model purpose and success criteria at the pre-application meeting. Provide Council with reporting on the findings of the **plan** and **build** phases to avoid requests for additional information or changes in methodology. If Council agreement confirms reporting is only required at the end of the **use** phase, ensure **plan** and **build** steps are completed to a level that will support scrutiny. Agree simulations to be run in **use** phase at the **plan** phase.	**Seek Council agreement** about whether independent review is required or if the professional expertise and quality assurance of the modelling project team will suffice. Ensure the level of peer review reflects any feedback from any pre-application meeting about the scale, risk and complexity of the proposed project to avoid rework and project delays.
Scenario 2	A consent pre-application meeting occurs with a pre-existing plan for hydraulic modelling, with an approach to modify an existing model.	Provide any legacy reporting on the historical model that will be used. Describe any potential issues with the base model and differences between the purpose of the base model and how it will be used in the new study. Describe proposed changes to the base model. Define any risks, issues and limitations expected through the proposed modelling approach. Agree simulations to be run in the **use** phase. If the base model was created by Council or on behalf of Council, determine how Council's existing knowledge will be leveraged during **plan**, **build**, and **use** phases.	**Seek Council agreement** about whether independent review is required or if the professional expertise and quality assurance of the modelling project team will suffice. Consider any role that the builders of the base model will have in the review. Ensure changes in the model are clearly reported to the reviewer. Ensure the level of peer review reflects any feedback from any pre-application meeting about the scale, risk and complexity of the proposed project to avoid rework and project delays.

Scenario	Description	Recommendations	
		For Council engagement	For peer review
		Agree on quality of base model and how much rework is required in **plan** and **build** phases.	
Scenario 3	A comprehensive catchment consent has been granted and more detailed modelling is planned to support additional development at a finer scale.	Align to the stakeholder engagement requirements of the comprehensive catchment consent. Agree simulations to be run in **use** phases. Set model purpose in relation to: • contribution to total discharge allowed by the comprehensive catchment consent; and • flood risk and mitigation of development. Seek access to existing Council knowledge on the catchment through the **plan**, **build** and **use** phases.	Due to the number of stakeholders involved in catchment management plans, an independent peer review of any detailed modelling may be required to provide confidence to all stakeholders.
Scenario 4	A consent application is submitted with modelling results; no details of model build, calibration or validation; no independent peer review of model build process and no history of consultation with Council.	This situation creates difficulty for Council to understand supplied model results within statutory timeframes and will likely result in Section 92 requests for more information related to the application. Seek direction on hydraulic modelling methods and peer-review standards. Seek guidance on previous studies, consents, policies, plans and proposed future developments and engineering in the area of interest. Expect some rework to be requested.	Expect additional requirements for peer review due to lack of understanding of Council requirements to date.
Scenario 5	A rapid flood hazard assessment is proposed to as part of compliance for comprehensive catchment consent and mitigation options for a green fields area.	Discuss with Council levels of accuracy required to satisfy consent condition, agreed on model methodology and accuracy. Seek guidance on previous studies, consents, policies, plans and proposed future developments and engineering in your area of interest.	An independent peer review may be required.

3.2 Plan phase

PLAN

This section details activities to be undertaken in the *Plan* phase of a hydraulic modelling study.

3.2.1 Define the purpose of the modelling study

A hydraulic model is not an end in itself and is typically a study within a larger initiative where flooding and hydraulic responses need to be understood. The purpose of the model needs to be defined to ensure the model fits within these broader objectives. This can usefully be done as a series of discrete purpose statements that show clear scope and objectives. Examples of the types of purpose statements expected for a modelling study are:

- to predict maximum water depths and levels to enable the setting of building floor levels for new development,
- to determine stopbank design levels for construction,
- to determine and assess mitigation options to resolve dangerous depth times velocity areas in a flood plain,
- to determine the hydraulic impacts of land use changes,
- to predict impacts of climate change on flood depths, velocities and levels,
- to assess changes in flood risk from a proposed development,
- to assess hydraulic impacts of services crossing a watercourse,
- to assess impacts of increasing impervious surface areas (e.g. road, carparks),
- to generate mapping and water level prediction as a contribution to flood hazard assessment around strategic infrastructure,
- to evaluate options for stream realignment and channelling,
- to evaluate options for flood detention,
- to create scenario predictions that inform evacuation plans and emergency planning,
- to define the lateral extents of flooding from design rainfall events,
- to estimate the capacity of existing network infrastructure's ability to meet design levels of service,
- to provide flood extents for catchment management planning,
- to provide hydraulic impact analysis that informs an assessment of environmental effects,
- to enable understanding of the dynamic hydraulic behaviour of a system under flow design flow conditions,
- to understand the impacts of a stopbank breach on flooding of urban settlements and productive rural land, and
- to determine river capacity for probable future scenarios and enable prioritisation of engineering interventions.

A small number of these types of purpose statements should be reported within a broad narrative on objectives of the wider initiative. The communication of the model purpose needs to be a clear brief to allow the modeller/s and other stakeholders to understand why the model is being used and the model's scope. Chapter three of Ball *et al.* (2019b) also contains a number of factors for consideration when defining the purpose of a model.

3.2.2 Define the criteria for success

Now that the purpose of the model is understood, the measures of success for different stakeholders (Council, Territorial Local Authorities, developers, project managers, engineers, landowners etc) should be set. These criteria should be listed and can be technical but must be able to be understood by those without modelling expertise. At the end of the modelling process, the success criteria can be evaluated as met, not met, exceeded or in some other appropriate ways for the purpose of the model. Examples of success criteria include:

- predicted maximum water depths, duration and propagation of flooding match observed data in calibration and validation events,
- impacts on flood depth and velocity of a new growth area is understood,
- the initial range of engineering options has been narrowed down to a preferred option that can progress to detailed design,
- the highest risk (combined impact and probability) stopbank breach scenario has been identified and maps are available of flooding parameters that can be used to progress risk management investigations,
- it is clear if the existing river capacity inside stopbanks can support expected river flows and levels for the climate change planning horizon,
- sections of the rivers scheme that are below the required Level of Service are known,
- hydraulic model construction, calibration and validation has been documented in a form that provides confidence in the use of the model for its stated purpose,
- flood maps for key design events are available,
- a survey database of the model geometry is available, and
- a calibration database is organised for use in future models.

At this stage it will be useful to identify the specific model outputs and deliverables that will contribute to achieving the success criteria. These include outputs such as:

- model results files,
- time series datasets of flow or water levels,
- tabular summary data,
- summary graphs,
- spatial data of modelled attributes such as max depth, peak velocity and depth times velocity, and
- maps.

3.2.3 Define simulation schedule

It is common that a broader initiative will provide direction on the different simulations that a modelling study needs to complete. For example:

- a District Plan mapping exercise has statutory requirements for flood plan mapping,
- a project that requires assessment following the Bay of Plenty Regional Policy Statement Appendix L (Bay of Plenty Regional Council, 2018a) needs to determine simulations for a broad range of risk and consequence scenarios, or
- a design project needs to comply with relevant codes of practices, standards and plans that set design life and level of service expectations.

The modelling study should create a schedule of model runs as part of the planning process. This may highlight gaps in requirements that are best addressed early on. For example, coincident rain and river flow return events might be specified but tidal boundaries might have been missed, antecedent moisture condition not assessed or the joint probability of flooding in neighbouring rivers may not have been considered. At this time in the model planning, it is good to get approval from all stakeholders of a simulation schedule at the level required to execute the model runs. This will inform model schema design, required data, project timeframes and resource requirements for subsequent steps of the study.

Ball *et al.* (2019b) usefully defines a number of types of scenarios which can be considered when defining a simulation schedule:

- existing hydraulic conditions,
- historical hydraulic conditions,
- changes in land use,
- infrastructure changes,
- structural flood mitigation measures (such as dams and stopbanks),
- future development scenarios,
- change in dam operations,
- changed catchment conditions assessment,
- climate change,
- parameter sensitivity tests, and
- ocean interaction.

As well as any options analysis or design events that need to be run, **it is recommended that one calibration and two validation events are used for most applications**, with exceptions where data isn't available, or flood risk is low. Calibration and validation events should, where possible, reflect the annual exceedance probability (AEP) of the design events to be simulated.

3.2.4 Identify the relevant phenomena to be included in the model

Different hydraulic modelling platforms are capable of representing a range of physical hydraulic phenomena. At this stage, the relevant phenomena most important to the purpose of the model and success criteria need to be identified. This will be important when confirming the software platform that will be used for the study. This initial list of key phenomena may be updated as more is learnt about the site, more data is received, and previous studies are reviewed. The phenomena that need to be included will have an impact on model schema design.

An example of identifying phenomena is that a river model planned to assess capacity questions will need a tidal boundary at the river mouth. However, understanding the tidal wedge where salt water and freshwater are separated at the mouth but mixed further upstream is not required. Another example is a large agricultural farm drain being represented for its ability to drain land after flooding won't necessarily need to resolve velocities perfectly. Phenomena are commonly coupled and interact in complex ways often requiring models that are coupled and exchange information at each time-step.

Examples of common phenomena to consider in hydraulic modelling are:

- Water depth
- Water velocity
- Super elevation
- Tidal patterns
- Groundwater levels
- Wave set up
- Wave run up
- Rainfall
- Seiching
- Storm surge
- Secondary circulations
- Eddies
- Antecedent moisture conditions
- Vortices
- Wind
- Waves
- Wave-driven currents
- Sediment transport
- Resistance
- Morphology (erosion, scour, accretion, aggradation).

Sourcing data such as aerial photography, existing flood map, historic flood information and terrain data may be useful to determine phenomena. Figure 2 shows an example flood plain landscape that is to be simulated by a hydraulic model. A number of important characteristics are highlighted, some of which are phenomena (e.g. super elevation, tidal influence) while others are real-world structures or natural features that influence flow patterns causing phenomena of interest. For example, the rain falling on hill sub-catchments is routed as runoff through valleys and discharges onto the periphery of the flood plain. This phenomenon of runoff can be spatially variable due to factors such as rain patterns, geology, land cover and catchment shape and there are many approaches for representing it.

Another characteristic in the Figure 2 example is the high groundwater table. Why this occurs, what it means during flood and non-flood conditions, and how this will impact the model schema will depend on the purpose of the study. For example, a high groundwater table can affect runoff volume depending how *Antecedent Moisture Conditions* are set at the start of model simulation. Groundwater can also interact directly with surface water, so it is necessary to determine the significance of this phenomenon for each modelling study. Similarly, storage of flood water in wetlands must be accounted for in model schematisation, but a range of approaches for representing this storage may be applied depending on the focus of the study. Modelling wetlands for ecological studies may also require a completely different approach to flood modelling.

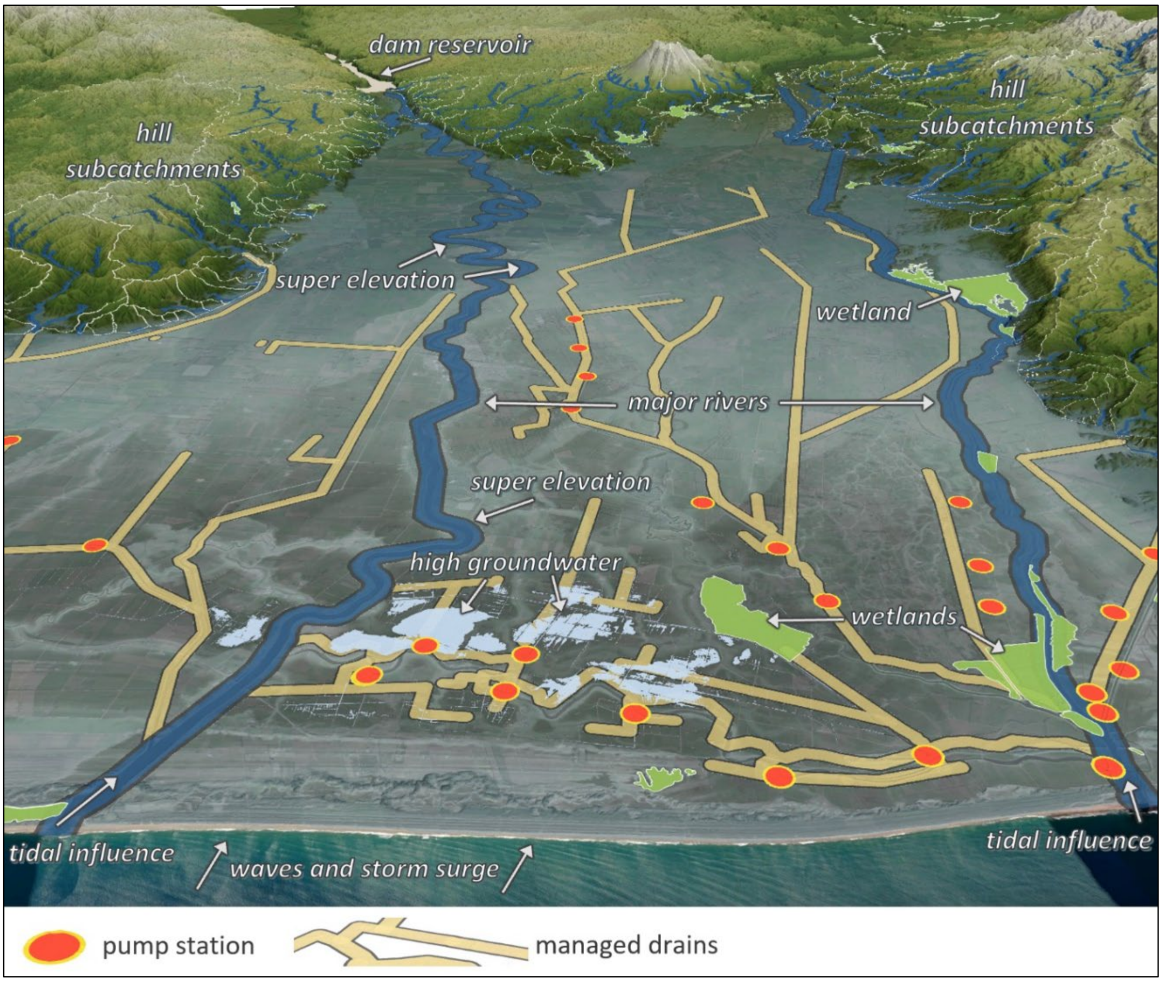


Figure 2 Examples of catchment characteristics, the importance of which must be reflected by model schematisation. For example, significant numbers of pump stations may indicate that there are important phenomena, such as elevated groundwater, that are managed by pumping.

The phenomena of rainfall generation and hydrological routing and loss, while important for creating boundary conditions for hydraulic models, is a hydrological endeavour and not prescribed in this hydraulic guidance. There is a long history of hydrological study in the Bay of Plenty in a range of locations and environment types. It is beyond the scope of the guidance to address hydrological methodologies, but the importance of the hydrological analysis used create boundary conditions in the final quality of hydraulic modelling results needs to be highlighted.

3.2.5 Review previous studies and guidelines

In order to build on existing knowledge relevant to the purpose of the model, previous studies should be reviewed. Table 2 below provides an overview of types of studies and information that may be important to review.

Table 2 Types of studies of relevance for reviewing during the planning and design of a modelling study.

Study type	Important information
Previous modelling studies	• key phenomena identified in the study • model extent • key features of model schema • model parameters used (e.g. Manning's "n") • factors that had largest influence on calibration • boundary condition information such as flows, velocities and timings of events • flooding extents during previous calibration and validations events • study conclusions and recommendations • design results
Catchment management plans	• catchment pressures and issues (such as growth, land use and flooding) • community objectives • summary of physical aspects of a catchment • key projects being planned
Asset management plans	• key assets • key projects being planned • recent projects that may have changed geometry or other elements important to the model • evaluate the impact of asset management plans on the purpose and success criteria of the model
Environmental studies	• summary of physical aspects of a catchment
Engineering options assessments	• key phenomena identified in the study
Guidelines, codes and standards	• Ministry for the Environment climate guidance • Scientific guidance on rainfall and hydrology • Council guidelines, policy, codes of practice and standards

3.2.6 Analyse available data and gaps

Since collating all required data for a modelling study is a significant task, it is recommended that this occurs in the **Build** phase. However, completing a gap analysis of missing data during the **Plan** phase can be useful, or requesting key information. It is important as missing data will limit the types of approaches used or delay model studies while awaiting data to be collected. Note that some of this information (e.g. river cross sections, LiDAR, gauge data) may need to be resupplied during the **Build** phase if updated so considerations on what and how much data to request at this time needs to be made.

3.2.7 Define the model extent

A working draft of the model's spatial extent should be created based on:

- key topographic features such as ridge lines,
- consideration of impact of key hydraulic phenomena and engineering structures, and
- understanding of other natural boundaries between environmental systems that can be used to define what is considered in and out of scope of the modelling study.

Ball *et al.* (2019b) refer to a *model study area* and a *model applicability area* as separate concepts in defining a model extent. The *model study area* will be larger and is required so that boundary conditions are sufficiently far away from the area of interest to ensure the *model applicability area* can produce reliable results.

During the model planning and building phases, the model extent will adjust as more information and knowledge is gained about the location. However, developing a working draft will greatly assist in defining the model schema and planning the model build.

It is common to use a readily available surface model of the catchment terrain shape and undertake a catchment delineation exercise to create a first prediction of the model extent. During this delineation, key assets and hydraulic features should be considered to provide the best estimate of model extent with the information available. This draft extent should be ratified by relevant stakeholders at this stage to ensure general support and all concerns addressed. As discussed in the “Identify the relevant phenomena to be included in the model” section, some pragmatism on what data is required and this stage is needed.

3.2.8 Define model schema

It is suggested that a model schema is created as a blueprint of what the model will be comprised of. This is a conceptualisation task to design the model at an architectural level, before model building begins. The schema is intended to be a centralised record that holds the "features" of the model being built.

Documenting a model schema at this stage can also form the basis for model reporting. This reporting can be updated regularly through the modelling process. This is recommended over the alternative of not starting reporting until late in the project when memory of details is fading and project timeframes are often under pressure. A well presented model schema can also support clear communication as part of any Council engagement, but also any internal project or independent reviews. An example of a model schema is published in Scarfe and Johnson (*in press*).

Since the model build is still only being planned, this schema will be based on the best knowledge at the time and would be expected to evolve during the remainder of the **plan** and **build** phases. It may be that the review of previous studies highlights a number of design elements for the model schema. For example, sources of data for land cover or types of structures and assets to include.

At this stage it is important that a strong understanding of key catchment features and critical infrastructure is established. Site visits and discussions with experts in the area will support knowledge gained from the review of previous literature as the schema is defined. Ball *et al.* (2019b) provides a list of key catchment features and acknowledges that these features can be represented in different ways within a model and recommends that the method of representation needs to fit the purpose of the model. Catchment features identified by Ball *et al.* (2019b) include:

- landforms, vegetation and land use catchment areas influencing runoff response,
- streams, stream network, floodplains and overflow paths,
- natural and man-made flow constraints,
- natural and man-made storages,
- roads and railway lines,
- weirs,
- flow structures including bridges and culverts,
- stopbanks,
- flow diversions, and
- pits and pipe network.

A high-level view of recommended key elements of a model schema is given in Table 3.

Table 3 Recommended components of a model schema.

Model schema components	Definition	Details to describe in schema
Model overview	A summary of the model, events and miscellaneous details.	• Model purpose (from previous steps) • Equations (eg steady/unsteady, St Venant etc) • 1D, 2D, 3D or combination/coupled... • Software platform • Coordinate system • Vertical datum • Calibration scenarios • Validation scenarios • Design events
Data sources	Data that is being used, version and where it was sourced.	• Spatial information • Non-spatial information
Description of the model domain	All real-world spatial features and geometries represented by the model.	• Overland flows • 2D river flows • Pipe network • River mouth • 1D open channels • Sub catchments • Lakes, ponds and wetlands
Key structures and assets	The different infrastructure that is being	• Pipe network • Surface drainage

Model schema components	Definition	Details to describe in schema
	included in the model and how it will be represented.	• Transport infrastructure • Flood protection • Building foot prints • Spillways • Dams
Computational approaches	The computational approach for the various components and hydraulic and hydrological parameters that are being used.	• Internal model coupling • Overland flow to pipe network • Open channels to overland flow • Open channels to pipe network • Boundary condition application • Full model domain • 1D domain • 2D domain • Hydrodynamic parameters • Resistance • Flood and dry parameters • Eddy viscosity • Initial conditions • Pipe energy losses • Energy diffusion • Open channel radius type • Losses • Hydrology model
Boundary condition derivation	Description of different boundary conditions for the model, and their source.	• Rainfall • Tide/storm surge • Downstream river level • Initial conditions
Known limitations	List of issues that should be considered when using the model or interpreting any outputs.	• Data quality • Data transformations • Model type • Model accuracy • Model resolution • Model runtime • Presentation of results
Assumptions	List of any draft assumptions known before the building of the model.	• Hydraulic assumptions • Hydrological assumptions • Other assumptions

3.2.9 Selecting a modelling software platform

It is ideal to select the modelling platform once the purpose of the modelling study is defined and important phenomena have been identified. However, at times the selection of the modelling platform is already determined based on the selection of the modeller/s for the study. There is benefit for the modellers to be involved through the initial process so some pragmatism will be required on how linearly to apply the process in this **Plan** phase.

Modellers typically select modelling platforms they are experienced with, which has direct impacts on delivery costs, timeframes and ultimately reliability of the results. Familiarity with the platform enables selection of suitable parameters, steps to work through and known workarounds for issues.

Other considerations for selection of model platform include:

- client preference,
- standardisation to platforms used for existing models,
- relationship to past modelling studies,
- model runtime performance,
- requirement of resolution and model outputs,
- known reliability for data gaps,
- whether multiple platforms are required to be coupled,
- access to actual modelling software, and
- hardware compatibility.

If the broad modelling platform has already been selected due to the reasons above, it will be common that this stage of the planning process will focus on which features and tools within the platform should be used to achieve the model purpose and represent relevant phenomena. Depending on the study specific context, the level of external review may be increased where the modelling software is different to approaches used previously in the area, new for the modelling team or extremely complex.

These guidelines are primarily developed for commonly used 1D and 2D flood model approaches applied in New Zealand. Simpler methods (e.g. static backwater calculations) or more advanced approaches (e.g. Computational Fluid Dynamics models) may be used in flood studies but these guidelines might not be as relevant for those applications.

3.2.10 Create model plan report

This stage is a combination between a draft model summary report and an updated project plan for the remaining work. It's not intended to be a single publication, or a final publication, but way of taking stock of progress made to date. The actual approach and formality should be tailored to the specific model situation and will be driven by the size and complexity of the broader initiative the model sits within and stakeholder requirements. Ownership of the model, intellectual property, data agreements and other matters can also be usefully included in this report.

The model summary will largely be comprised of the analysis completed when developing the model schema, but other additional information may also be useful to document based on project specific information. The benefits of taking time at this stage to prepare documentation include:

- reducing the work required for final reporting,
- provide details for quality assurance, either within the modelling team or through independent means, and
- provide details for other stakeholder engagement, including with Council if required.

The project planning aspect of this reporting will be broadly to take model design decisions made in the model schema, and refocus project tasks, timeframes and risks based on new information. The implementation approach to project planning will vary widely from model to model.

3.3 Build phase

This section details activities to be undertaken in the *Build* phase of a hydraulic modelling study.

3.3.1 Source relevant data

Considering modelling is a data rich exercise, this step requires an organised approach to requesting data, tracking of requests and file management for information received. A schedule of required data is recommended (Kapiti Coast District Council, 2020) to communicate clear information requirements. To avoid delays it is important not only to confirm that data is received but also that it covers the required area, timeframe and is in a usable format.

Collating as much of the relevant information as possible at the start of the build process will avoid delays later in the **build** process. It will be common during the plan phase for a range of data to be also sourced, highlighting the iterative nature of modelling. This is particularly true if new data is required (such as site surveys). A range of common data types to consider sourcing are outlined in section 4. However, it will be typical for new information to be found or identified as required throughout the model **build** process in an ongoing manner. At this stage it is recommended that some degree of quality review and gap analysis is completed to avoid delays later if it is found that some information is not fit for purpose.

3.3.2 Define modelling parameters

Some model parameters and other configurations, such as mesh size or model extent, will be defined in the model schema during the planning phase. Other parameters, such as eddy viscosity, will have initial values defined in the model schema then may be modified during model calibration. The list below provides a starting point for a number of key areas to set parameters in the model. Note not all will be relevant depending on the type of model being used.

- Preliminary time step size
- Preliminary hydraulic parameters
  - Bed resistance
  - Eddy viscosity
  - Pipe network major and minor losses
  - Overland flow roughness zones
  - Open channel roughness
- Flood and dry parameters.

3.3.3 Create boundary conditions

When creating boundary conditions, what happens at the boundaries needs be considered first. Once the physical process occurring is understood, options for what an appropriate boundary condition is can be evaluated. Section 4 outlines categories of boundary which can have boundary conditions applied and sources of data for their generation.

Common types of boundary conditions detailed in Section 4 are:

- discharge,
- precipitation,
- water level,
- point source inflow,
- point sink (draining) outflow, and
- discharge-Stage (Q-H) relationship.

3.3.4 Create model geometry

Model geometry is a mathematical model comprised of coordinates and elevations representing the surfaces of a catchment, waterbodies and flow paths. Model geometry references a coordinate system and a vertical datum. The geometry includes the shape of the land, obstacles to flow, rivers and storage volumes for ponds, lakes and wetlands. There are a range of levels of detail that can be represented and this is further expanded on in Part 4 (Model domain). Considering many of the hydraulic formulas within models have depth as a parameter, establishing model geometry is a very important step and the quality and treatment of geometry data (e.g. transformations, editing) and decisions made can have substantial impacts on the model results. Key elements of model geometry include:

- terrain model including key features like road crests, bunds and historical flow paths,
- river and drainage channel cross sections,
- stopbank shape and crest centrelines,
- river mouth and estuary shape, and
- river alignment, network of channels, connections.

The first step in creating the model geometry is to review all of the information that was sourced in previous steps. It will be important to check coordinate systems, datums, age of data, formats and undertake a range of activities using GIS or modelling software to consolidate the information into useful formats. At this stage, a gap analysis might be useful and additional data may need to be sourced from survey, as built drawings, site visits or from other organisations.

LiDAR and channel cross section data typically will be the base datasets used to create the model geometry. These data will be augmented with more specific information as required. For example, where LiDAR is a few years old, as built survey data of a recent engineering project may replace parts of the LiDAR data to better represent the current geometry.

Depending on decisions in the **plan** phase, different waterways can be represented in a number of ways, with balancing required between run times, effort to build the model and quality of results. For example, a one-dimensional model of a river will run faster than a two-dimensional model but more phenomena will be represented by the two-dimensional model (such as super elevation at bends and transverse distribution of velocity).

As the geometry is refined in specific areas of a model, especially if variable grid cell sizing is used, the model time step and eddy viscosity parameters may need to be updated. This will be required to satisfy numerical stability criteria and ensure the model can complete a simulation.

3.3.5 Build structures into the model

Structures in the waterway and on the floodplain may have a significant influence on flood predictions. Building structures into the model will be a significant part of the model building process and approaches to representing each different type of structures may vary depending on the modelling application. A range of common structures are listed below and the level of detail they are required to be represented in the model depends on their contribution to the flow of water and impact on the model's ability to be calibrate, validate and verify.

- Pipes
- Inlets
- Bridges
- Buildings
- Manholes
- Culverts
- Soakholes
- Pump stations
- Weirs
- Gates
- Fish passage
- Stopbank
- Barrages
- Dams
- Soakage trenches

3.3.6 Review known limitations and assumptions

A number of principles in Part 2 all point to the need to understand limitations and assumptions of a model when interpreting the output and using a model someone else has built. These are the principles that highlight the need for caution:

- all models are simplifications of complex processes,
- there is always a limitation to the accuracy and reliability of a model, and
- no model is "correct" therefore the results require interpretation.

Based on knowledge gained so far through the **plan** and **build** phases, a list of limitations and assumptions should be made with each one being written as a clear, easy to interpret statement. These statements will also need to be updated during the model build reporting based on experiences gained through the calibration, validation and verification steps. If the findings of this review are not acceptable in context of the model purpose, previous steps such as source data, create boundaries, build structures etc may need to be revisited.

Table 4 Definitions of model limitations and assumptions.

Term	Definition	Example
Limitations	Acknowledgement of the inability for a model to meet all objectives by way of stating situations that should be avoided when using the model.	The modelling platform does not support groundwater interactions and significant water is lost to ground. The largest calibration or validation event was smaller than the 100-year Average Recurrence Interval (ARI) event run in the study.
Assumptions	What was taken to be true, often due to lack of information, in order to proceed with the modelling process.	In order to achieve objectives of the study, it is assumed that farm drains narrower than 1 m can be resolved through the supplied digital elevation model and that they do not require additional survey or representation in one dimensional channel models. It is assumed that the timing during a flood event for water to travel from the upstream boundary to the long-term water level gauge is six hours.

3.3.7 Calibrate the model to known events

Once a model is built it will need to undergo the process of calibration. This is the process of modifying model schematisation and parameterisation in order to align simulation results with field measurements from a historical event. It is part of the tuning of the model to the study environment and measured data and is critical to quality control. The calibration of a model seeks to see how close the model results compare to a predetermined set of data or data from a known event (calibration data), and this is discussed at length in Ball *et al.* (2019b). During calibration, parameters need to be set within realistic values derived from previous studies and modelling application, and not stretched unrealistically to match the model to measurements.

The model should be calibrated against at least one flood event where suitable flow, level or other data is available. Calibration data is typically comprised from a number of sources, these may include (adapted from Ball *et al.,* 2019b):

- background data and inputs:
  - historical topography,
  - changes to land use, structures and infrastructure,
  - records of bed, banks, floodplain and other natural features to assist with interpretation of roughness,
  - rainfall records.
- data that the model is being calibrated to:
  - gauged water level, hydrograph,
  - streamflow gauging,
  - long term and short-term groundwater levels,
  - tidal level,
  - flood locations, debris survey and markings,
  - observed water level at a given time,
  - anecdotal information, flood reports, rate of rise of flood,
  - photographs or videos,
  - photograph or visual evidence of extent of inundation,
  - records or observation of water speed or flow patterns,

- records of blockages on infrastructure, and
- road or railway closure.

Table 5 The four primary categories reflecting the amount of calibration data and its quality (adapted from Ball et al., 2019b). The importance of sensitivity tests increases going up the table.

Level of available calibration data	Description	Implications
No Data	There is little to no data available of the catchment. Very little local knowledge of the area. Anecdotal records are the best available data.	Regional, large scale or higher level information may be sought. Parameters can be determined from experience with the modelling platform or similar projects in other areas where physical characteristics may be similar. Note any limitations and assumptions that have been made and consider if re-planning of model is required to achieve purpose and success criteria of modelling study.
Very Limited Data	The data that is available may be based on anecdotal records, (for example, the frequency of road closure due to flooding). Information may be obtained through marked local observations. Limited amount of measured data and the quality of the data is inaccurate or inconsistent.	Make every effort to incorporate any available information while assessing the information for accuracy and reliability. Note any limitations and assumptions that have been made and consider if re-planning of model is required to achieve purpose and success criteria of modelling study.
Some Data	Data is available, based on gauges and measurement, but the data that is recorded is for very short period of time. There may be records on a single flood event or multiple records for higher frequency flood events. Rainfall gauge information is available. There is a greater degree of confidence in the data.	Most of the available data is accurate and reliable but there is still uncertainty when the model is used for events outside the range of the calibration data or applied to different scenarios. Note any limitations and assumptions that have been made and consider if re-planning of model is required to achieve purpose and success criteria of modelling study.
Extensive Data	There is extensive data for the catchment. Data is available for a wide range of flood events in terms of magnitude and conditions. The flood data is accurate, reliable and consistent of a high quality.	Criteria for which data to use will need to be set up to overcome issues with too much information, and difficulties selecting the most important data. The completeness and accuracy of the data means that if the calibration is considered reliable, there is a high level of confidence in the use of the model and its results once the model is validated and optionally verified.

Depending on the available data as outlined in Table 5 a range of scenarios may occur that mean that the approach to calibration, validation and verification might change. In an ideal case (some data or extensive data) all three steps (i.e. calibrate, validate, verify) may be included. However, where data is missing or limited, some steps may be skipped which will increase the limitations of the model and reduce the range of purposes the model can be used for. Some example scenarios are included below and depending on the situation, the level of independent review or requirements for Council engagement may vary:

1. there is no calibration data or validation data,
2. there is no calibration data but information available for verification,
3. there is calibration data but no verification data, or
4. there is calibration and validation data but no verification data.

Determining if calibration is achieved is subjective. Further details on criteria for assessing if model calibration is achieved are included in Section 4. This quote from Ball *et al.* (2019b) well describes the balancing act between achieving calibration and project timeframes, and considerations of model resolution and type of model used.

"During calibration the full impact of the trade-off between model resolution and run time is felt. Calibration runs and the calibration process can be very time-consuming and costly. The "benefits" of a finer resolution model may be negated by the fact that the excessive run times limit the number of calibration runs able to be undertaken, resulting in a model that is not as well-calibrated as it could be.

The longer run times of two dimensional hydraulic models means that model calibration can take significantly longer to complete than for one dimensional models. However, correctly schematised two dimensional hydraulic models have less uncertainty and require less engineering judgment than one dimensional models, so fewer calibration runs are usually required."

3.3.8 Validate calibrated base model against different information

The validation process confirms that the adjustments made to create a calibrated base model are suitable for applying a broader range of design events. The process assists in qualitatively or quantitatively assessing the capacity of the model to accurately reproduce different events. Effectively it is a semi-independent validation of model parameters and geometry and typically involves simulating one or more historical flood events of different scales and characteristics to the calibration event. This is required as it is assumed that the model will be used over a range of scales for design and predictive purposes. For example, a smaller event, a larger event or an event with different rain patterns (such as a double peaked storm). After this validation process, this version of the model is considered the *base* model, unless an additional verification process is completed.

The validation events may also highlight model stability issues that need to be resolved that weren't apparent in previous investigations. Depending on the results of the validation, any previous step in the model **build** process may need to be repeated.

The methodology detail for calibration outlined above (e.g. the types of data used, assessment of level of data available) are also applicable for performing a validation, however no hydraulic parameters should be adjusted. If validation events cannot be reproduced, then course of action can be:

1. explain plausible discrepancies between simulated and measured data,
2. revisit the calibration,

3 adopt the validation event as a calibration event, update calibration and find additional validation events.

If no validation data is available this could still be a valid model, but this will impact on the range of applications that the model can be used for. Kapiti Coast District Council (2020) notes that consideration should be given to changed conditions on the floodplain between the calibration and validation events (such as changes to drainage, topographic features or structures), and these changes in assets and geometry may need to be updated to the model.

3.3.9 Complete additional verification

Additional verification may be required depending on the model purpose, stated success criteria and risks associated with use of the model outputs. It seeks to review the model's performance against an independent method (e.g. results compared to existing flood frequency analysis or outputs from another model) and/or review the suitability of the model to achieve its stated purpose. It could also include a sensitivity analysis to testing the response to changes in particular parameters. Verification will be increasingly important if data isn't available to calibrate and validate. Common types of verification that might be undertaken include:

1 independent peer review,

2 comparing results against another model for the same location,

3 an analysis (e.g. testing the sensitivity of the model's response to changes in particular parameters (e.g. roughness), boundary conditions (e.g. storm surge) or geometry (e.g. river mouth shape)), and/or

4 comparison to existing analysis (e.g. flood frequency analysis).

Ball *et al.* (2019b) provides some useful qualitative questions to consider in the verification stage:

- Is the model suitable for the problem being investigated?
- Does the model include sufficient detail in the spatial coverage of flooding?
- Does the model represent the flooding with sufficient accuracy to answer the required questions?
- Can the model be extrapolated accurately to rarer (or sometimes smaller) floods from the flood magnitudes used to establish it?
- Can the model be used to represent the range of design conditions (such as developed conditions or flood mitigation options) that are required in the design applications?

3.3.10 Create the model build report

The model build report will be a final artefact that can provide a complete overview of the model's purpose, design, source data and success of calibration and validation efforts. This will be a report that should be able to withstand independent review if required and may be revised after review by a peer reviewer, key stakeholders and/or Council. Where the model does not align to these guidelines, this should be noted. Also, an independent per-review is recommended. Key sections to include in the build report are listed over the page.

Model Build Report Required Sections
Executive summary
Purpose of the modelling study
Criteria for success
Intended simulation schedule
Relevant phenomena identified
Review previous studies
Model extent
Model schema
Modelling software platform summary
Data sources
Modelling parameters
Boundary conditions used
Summary of model geometry
Summary of structures used
Summary of known limitations and assumptions
Calibration results
Validation results
Model verification
Discussion
Conclusions and recommendations
References
Appendices

3.4 Use phase

This section details activities to be undertaken in the **Use** phase of a hydraulic modelling study.

USE

3.4.1 Configure the model for required scenarios

During the **plan** phase a schedule of model runs for different scenario was created. Some time may have passed since this schedule was made, and new information and requirements may have surfaced during the rest of the **plan** and **build** steps. It will be useful to reconfirm or update this schedule as the first step of setting the models up for running scenarios. Once the schedule is confirmed, configuration of boundary, asset and geometry changes for each scenario can begin.

3.4.2 Create boundary conditions for scenarios

During the **build** phase boundary conditions will have been made for the calibration and validation events. However, typically in the **use** phase, design events for Annual Exceedance Probability (AEP) or Average Recurrence Interval (ARI) scenarios are required and therefore boundary conditions for these scenarios will need to be generated.

Where upstream river inflows are a primary discharge boundary condition, flood frequency analysis or other methods will be used to generate flows and additional work may be required to format the data as a suitable input into the software platform being used. Depending on the software, hydrology may be generated in the same software as the hydraulic model during the model simulation. Where precipitation methods such as rain-on-grid are being used, a rainfall hyetograph will need to be generated and this might drop rain spatially uniformly across the model extent or in a spatially variable form where interpolation between gauges is possible or raster data is available (e.g. HIRDS or rain radar). Broadly speaking, the generation method for these discharge and hydrological inputs further described in Section 4 are out of scope of this guidance.

3.4.3 Run simulations

The running of simulations can be a stage in a modelling study that can either make up time, or cause delays, especially when the number of simulations is large. Care should be taken to ensure model runs are set up correctly, monitored, and finished as expected. Significant time will be lost when rerunning failed simulations or ones where the configuration was not set up as expected. This is especially true if multiple simulations are run from multiple machines where it can be easy to lose track of what has been completed or where issues are. A log of model simulations can help with this situation.

3.4.4 Process results

This will involve the conversion of raw model outputs to usable data. Some of this work may be facilitated by modelling software, GIS tools, custom automation scripts or some reasonably repetitive manual processing. Where a lot of repetition is needed, care should be taken to quality assure the work and remove human errors. An example of processing of results is taking the raw results files and extracting the velocity at the maximum water depth, or all cells with flood depths greater than 10 cm during the simulation.

The simulations stage will produce a lot of files and some of these files will have been superseded and need to be discarded to avoid confusion in the future. As outlined in Section 4, only the final versions of model files need to be kept.

3.4.5 Verify results

The large amount of data produced should have a clear verification step to make sure the individual simulation results are acceptable, so that analysis of the full series of scenarios can be completed with confidence. This will involve checking for internal consistency between model runs as well as checking against other known data sources, model outputs and studies. Any verification steps should be noted for reporting in the final report.

During the processing stage, it is possible that review of processed data shows issues related to simulation set up. For example, two sets of results are identical indicating that the same simulation was run twice. If this is the case, the missing simulations need to be rerun.

3.4.6 Present results

A number of deliverables will have been agreed with stakeholders in the **plan** phase and some of these can be produced at this stage. These will commonly be maps, graphs and tables relating to core results of interest. At this stage some initial interpretation, discussion and analysis may also be created but full analysis across all results will occur in the next, evaluation stage. Where required to achieve the purpose of a modelling study, freeboard (*see* page 63) may be applied at this stage to account for uncertainty and unknown phenomena. Freeboard is not applied when processing results as the model results may be used for a range of purposes that do not require freeboard.

3.4.7 Evaluation of scenarios

This step is where results are assessed in relation to the model purpose and success criteria. All results are assumed valid within stated limitations and assumptions, and now analysis across all results can be undertaken. The actual method of evaluation will vary broadly. It is also possible that the modelling study itself does not complete this evaluation and simply provides the data to another process to assess implications on planning, land use, flood risk or a number of other possible areas. If this is the case, this should have been made clear in the model purpose and success criteria developed in the **plan** phase.

If an engineering options analysis is completed during this evaluation, additional tasks may be required to review, tabulate and report data. Interactions with engineering design tasks may occur. Evaluation of results in this stage can create summary information that will be drawn on for options analysis, business case development or detailed engineering design.

3.4.8 Create final model report

The final model report can be presented in two forms:

1. an updated model build report with additional steps and findings from the **use** phase; or
2. a separate report that complements the model build report and has additional steps and findings from the **use** phase.

Whichever format is used, in addition to the sections outlined in *Create the model build report*, the following sections need to be included.

Final Model Report Required Sections	
Scenarios run	
Summary of changes to geometry	
Summary of changes to boundary conditions	
Findings and challenges from running simulations, processing and verifying simulations results	
Summary of results provided as appendices or addendum (e.g. maps, tables)	
Evaluation of scenarios	
Discussion	
Conclusions and recommendations	

During this reporting findings should be recorded and documented in a manner that meets the purpose of the model and model success criteria. Results need to be discussed and analysed in the context of reported limitations and assumptions and understanding of existing information outside of the model results (e.g. morphology, flood analysis, flood records). Keep these principals in mind when presenting results:

- all models are simplifications of complex processes,
- there is always a limitation to the accuracy and reliability of a model, and
- no model is "correct" therefore the results require interpretation.

Acknowledging the target stakeholders will help communication at a level of detail that can be understood. There will be a balance between providing sufficient technical detail so that the results stand up to peer review and communicating less technical key findings to non-modelling stakeholders. Care must be taken to manage risks of misinterpretation or misuse of the results. Different versions of result documentation and maps may be required to satisfy the varied audiences and their respective objectives, and this will be broadly outside of the scope of the final model report.

3.5 Update an existing base model with new information

Updating a base model is another phase of a model's life and what is required can vary. The principle that *the base model is the most important model to manage* is very relevant here and if models are considered as assets that depreciate, it may be more cost effective to keep a model up to date than rebuilding it from scratch once its useful life is over.

It is recommended that a clear distinction between the base model and models altered for scenarios and optioneering is made or there is a risk that models adapted for particular situations (e.g. engineering options analysis) are updated with new information and subsequently used as base models.

Updating models should focus on these two areas:

- geometry (e.g. engineering changes, new survey, new asset data, changes in river alignment, new cross sections, land use change), and
- changes in behaviour (e.g. operation procedures for pump stations, breach mechanisms).

The process to update a model with new information should follow the **plan** and **build** processes previously described. The **use** phase isn't considered relevant as updating a base model is concerned with providing a robust model to be used in future **use** scenarios. The update process can follow the **plan** and **build** phases in a very light fashion, or effectively require a complete rebuild. Table 6 below provides some scenarios as a guide for specifics of updating a model in different situations.

Table 6 Example scenarios where updating models will be required.

Scenario	Assessment	Recommendations
A 10 yearly asset management plan review is needed and an existing base model from the previous review needs updating	The base model may require a completely new model to be created. Modelling software, available data and methodologies for modelling may have evolved to the point where it is useful to understand what was done in the past, but the model for all intents and purposes needs to be built from scratch.	The base model will likely be simpler than the new model that will be created, but key phenomena, structures, one dimensional channels and locations of boundaries identified in the legacy model may still represent important considerations to be included in the model schema. Identify key changes (e.g. land use, land cover and engineering structures) that have occurred since the last base model was created.
A robust base model exists but has not been used in the last couple of years, and a review shows there are changes that need to be incorporated	It is possible that the existing model can be enhanced to be fit for purpose.	Review the purpose of the original base model and ensure it is suitable for the new application. Run the existing model in the latest version of software and look for issues and instabilities. Review changes in the catchment environment and engineering structures and incorporate them into the model. Update any core datasets (such as LiDAR, river cross sections) with the latest information. Review any advancements in modelling methodologies and incorporate them into the model. Seek independent review on what level of re-calibration, validation and/or sensitivity analysis will be required.

Scenario	Assessment	Recommendations
A base model is regularly used for a range of analysis and consistently is trusted for its predictive ability, and a new river alignment has now been constructed	This is an ideal situation where a base model is managed as a trusted software asset and now an enhancement to the model is required to match the model geometry to the real world situation.	Complete a sensitivity analysis to understand impacts of the geometry change to confirm if re-calibration and/or validation will be required.

Part 4:
Standards and recommended practices

4.1 Antecedent Moisture Conditions

Antecedent Moisture Conditions (AMC) describe the degree of saturation of hydrologic or hydraulic models at the start of a simulation. Specifically, this determines the filling of initial abstraction volumes and other storages and initialises the model state with regard to any number of process descriptions, such as in the storage-to-runoff process description of the Soil Conservation Service (SCS) Curve Number graph.

Table 7 below summarises phenomena connected with antecedent moisture conditions and requirements for representing them. While AMC is often considered a hydrological concern, components of hydraulic models can be set to represent different AMC conditions such as infiltration rates and channel base flows.

Table 7 Considerations important to antecedent moisture conditions.

Consideration	Recommendations
Increased soil moisture contributes to elevated groundwater and the resulting base flows.	Observed base flows preceding historic events are to be assessed and incorporated in some way in design event inflow boundary conditions. Wetter AMC is reflected with elevated base flows. For very large catchments, extended hydrological simulation may be required to estimate suitable base flows. Base flows may be represented as: • inflows from hydrological analysis via boundary conditions; or • fixed base flows for minor streams that are not modelled explicitly as they are peripheral to the area of interest.
The importance of AMC varies with the capacity for the catchment to store water. Runoff from an impervious catchment with no depression or other storage is insensitive to AMC while runoff from large rural catchments with porous soil are highly sensitive to AMC. Where a catchment is sensitive to AMC, AMC will have a significant impact on the Annual Exceedance Probability (AEP) of the simulated flood event and invalidate the often implicit assumption that precipitation AEP matches that of the resulting flood.	AMC is accounted for in joint-probability sets of boundary conditions. A relationship between AMC and AEP must be established from historic measurements if AMC is to be effectively included in joint-probability event design. Where it is not feasible to create such a relationship, *average* AMC should be used for base case events and *wetter than average* for future-climate, post-development and mitigation-option scenarios in order to overpredict the impacts to allow in some way for uncertainty. For level of service analysis, wetter than average AMC should be applied to base models.

Consideration	Recommendations
AMC affects the following aspects of hydraulic models: • initial and continuing losses; and • infiltration rates and subsurface storage volume (above groundwater table), where distributed hydrology is employed in the hydraulic model (so called *rain-on-grid* approach).	Hydrological model elements included in the hydraulic model must reflect AMC. Initial abstraction and continuing losses should be reduced to account for wetter AMC for design. Historic events should be used to estimate the degree to which losses are modified. Where a *rain-on-grid* hydrology approach is employed, initial subsurface storage capacity, determined from calibration and validation, must be reduced to reflect both *Wetter than average* AMC and elevated sea levels for design purposes, particularly in future climate scenarios.
Soil moisture increases with rainfall and gradually decreases over extended periods of dry weather. The coincidence of a flood-producing storm event with elevated moisture conditions greatly increases the magnitude of flooding. Therefore, AMC has significant influence on the return period of the flood event. Soil type and land cover will strongly influence moisture levels.	AMC must be considered in historic-events and joint-probability design event simulations to produce flooding of the required Annual Exceedance Probability (AEP). For historic events, rainfall records prior to the event of interest must be analysed to determine the state of the catchment at the beginning of the simulated period. The Antecedent Precipitation Index (API) method may be used to qualitatively assess soil moisture (Ball *et al.,* 2019c), however it may only be possible to classify the AMC for a particular event as *Average*, *Wetter than average*, or *Drier than average.*
The Interdecadal Pacific Oscillation (IPO) increases and decreases precipitation in the Bay of Plenty on a decadal time scale.	Analysis of precipitation in aid of determining appropriate design event AMC must account for influence of IPO.

4.2 Boundaries

A hydraulic model has two kinds of boundaries, domain and internal. Boundary conditions can be applied at these boundary locations to represent a real-world scenario of interest. For both domain and internal boundary, it is crucial that the boundary is sufficiently distant from the focal point of the model to attenuate errors introduced by boundary conditions (Ball *et al.*, 2019b). A failure to make appropriate allowances commonly results in water ponding against a boundary without an appropriate boundary condition, which is sometimes termed a "glass wall" and should be avoided. Domain and internal boundary are described in Table 8 below.

Table 8 Descriptions of the two types of hydaulic model boundary conditions.

	Description	Examples
Domain	These are described by Ball *et al.* (2019b) as "external boundaries" and are outside of the model domain. Domain boundaries are located where: • flow is controlled (e.g., dam spillways), • flow transitions through critical depth (weirs, waterfalls, etc.), • flow is either transmitted into or out of the boundary at any specific point in time and varies slowly in time and gradually in space, • the computational grid does not dry out during the simulation (Ball *et al.*, 2019), and • flow is well described by a single property such as discharge or water level. Note that the conditions above are for hydraulic catchment models and cannot generally be satisfied for coastal and oceanic models.	Dams Ridge lines Pipe reticulation outlets Locations of reticulated inflows Chainage position of open channel representing upper extent of domain Constrictions in flow paths Stopbanks Lakes Open coast River mouths where coastal processes influence flow conditions. It is assumed that the effect of high frequency features, such as waves, are sufficiently represented by time-averaged quantities and that river mouth discharge does not alter coastal processes.
Internal	Boundaries inside the model domain. Often defined for practicality at the limits of analysis methods or software. Assumes that upstream stages of the described process are not affected by downstream stages.	Runoff discharges generated by hydrologic models. It is assumed that runoff generated by a hydrologic model is not affected by elevated water levels simulated in a downstream hydraulic model.

4.3 Boundary conditions

Boundary conditions (or model forcings) are applied at domain or internal boundaries and define the context or influence of the environment that the model is set in. The model simulates the response to this setting. A set of boundary conditions defines the characteristics of a scenario, but a number of sub scenarios (e.g. two or three) may need to be investigated. For example, to understand the 1% AEP scenario a series of rainfall dominated and tide dominated simulations may be required to determine the envelope of flood levels.

In cases where the exact configuration of boundary conditions is unknown for a scenario, a suite of configurations with their own sub-scenarios is required and a joint probability approach must be used.

Figure 3 shows an example of different boundary conditions for a flood plain model that has a dam defining the upstream extent. The *dam discharge* boundary is a *domain* boundary at the upper extent of a river and can be a constant or time-varying discharge quantity. The discharge may be informed by measurements during a real event or design discharge estimates from flood frequency or other analysis techniques. The *runoff discharge* is loaded onto the flood plain and is typically calculated using hydrological methods.

Whether this *runoff discharge* is a *domain* or *internal* discharge depends on where the loading point is located, either on the boundary or within the domain. Some simulation engines integrate hydrological and hydraulic simulations, while others require the hydrological timeseries to be generated prior to the hydraulic simulation. For models that allow for *precipitation boundary* conditions to be applied directly to the modelled surface (e.g. rain-on-grid methods), a constant or time-varying quantity of water can be specified.

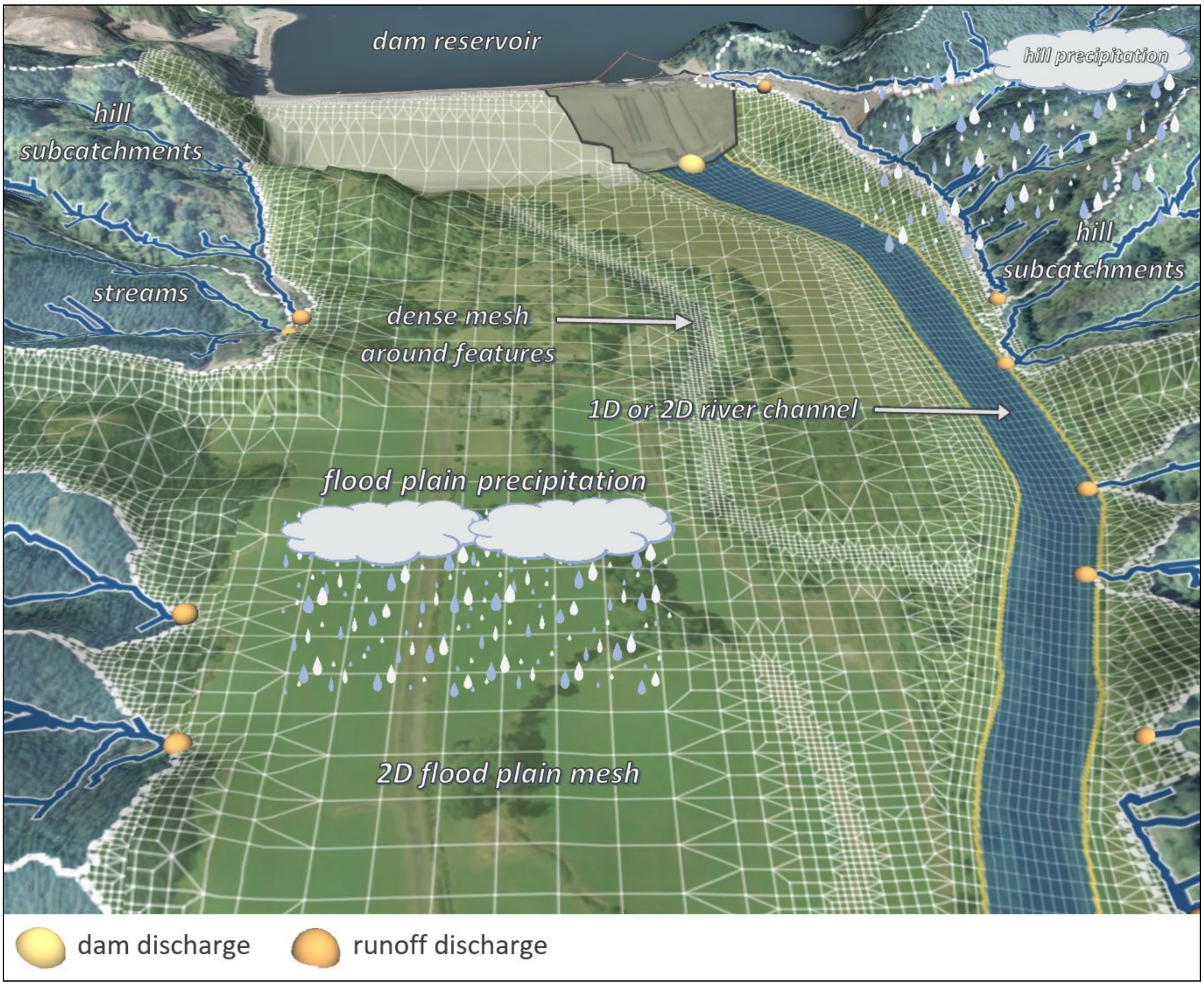


Figure 3 Example model concept showing some of the different boundary conditions explained in Table 9.

Boundary condition types and source data

There are different types of boundary conditions used in hydraulic models and these are outlined in Table 9. Boundary conditions may be generated from field measurements, extracted from the results of other simulations or based on an idealised design situation. River models often provide water level timeseries at chainages adjacent to pipe reticulation outlets to serve as downstream boundary conditions for models of urban areas. Table 10 summaries data source types.

For all design events, joint probability must be considered and the relevance of the effects of the Interdecadal Pacific Oscillation (IPO; Salinger *et al.*, 2001) should also be considered when generating boundaries for design events. Council's Engineering Manager will advise latest available guidance.

Table 9 Types of boundary conditions used in hydraulic models.

Type	Description	Applicability and limitations
Discharge	A constant or time-varying quantity of water per unit of time entering the model domain at a specific boundary. Timeseries values are instantaneous.	To be used at upstream boundaries to introduce flows generated prior to simulation. Open channels or other flow paths, whether the model is 1D or 2D. Does not allow for flow out of the model domain. Defined a priori so does not adapt to model response.
Precipitation	A constant or time-varying quantity of water per unit plan area of model domain per unit of time. Rainfall can be represented as rainfall intensity or rainfall depth. Rainfall depth timeseries for calibration are typically provided by tipping bucket rain gauges which record fixed-depth tips at irregular intervals. Rainfall intensity is applied as a constant for each interval in the timeseries; rainfall depth is distributed evenly across the preceding time interval (step accumulated). Rainfall can be distributed unevenly across a model domain according to measurements made during historic events. Rain radar provides such spatial grids of rainfall intensity that vary with time. For design events a series of synthetic precipitation events for required return periods are created, often based on timing, distribution and depth of rainfall during historical events.	Rainfall is traditionally applied to hydrological models and the resulting runoff is then applied as a discharge or point source inflow boundary condition to a hydraulic model. Where catchments are flat and lack distinctive ridgelines, delineation of sub-catchments may be difficult: in these situations, it is appropriate to use a *rain-on-grid* approach, wherein rainfall volume is applied directly to 2D domain cells/elements. Areal reduction factors, which are designed for use with lumped catchments, may be applied in the rain-on-grid approach. It should be noted however that, in general, when factors are applied, flooding will be under-predicted in upstream areas of the catchment, and when they are not, flooding will be over-predicted in downstream areas.
Point source or distributed inflow	A constant or time-varying quantity of water per unit of time entering the model domain at a specific location or locations. Timeseries values are instantaneous.	Applied within spatial domain. May be paired with a sink outflow to simulate timed pumping or complex structure behaviour.

Type	Description	Applicability and limitations
		Defined a priori so cannot adapt to model response.
Water level	A constant or time-varying water level at a specific boundary. Timeseries values are instantaneous reduced levels. Values may vary spatially along a boundary as well as temporally.	To be used where the model response has a negligible influence on water levels at the boundary. Inflow from or outflow into a large body of water, such as the ocean or a reservoir. Commonly used to simulate ebb and flood flow caused by tides where a model lies adjacent to the coast. Depending on implementation can cause instabilities at boundar*y, particularly when waves are reflected.* This may be mitigated by applying a Flather type approach. Water levels set below normal depth or critical depth at the boundary will cause unphysical draw down of the water surface unless sufficient distance for a gradually varying flow profile is provided within the model domain. Take care with datums for tidal records. A number of measured long-term tide records are in a low-tide datum (e.g. chart datum, lowest astronomical tide) for safe boat navigation reasons. In contrast, LiDAR elevations are more commonly based on a mean sea level-based datum and more commonly New Zealand Vertical Datum 2016 (NZVD2016). Note that the zero value of a mean sea level datum is not always the current mean sea level due sea level rise (e.g. Moturiki Vertical Datum 1953) and an offset will often need to be applied.
Point sink outflow	A constant or time-varying quantity of water per unit of time removed from the model domain at a specific location. Timeseries values are instantaneous.	Applied within spatial domain. May be paired with a source inflow to simulate timed pumping or complex structure behaviour. Defined a priori so cannot adapt to model response.
Discharge-Stage (Q-H) relationship	Discharge values are described as a monotonically-increasing function of stage or water level. Provides a downstream outflow boundary condition where a large water body is not present. Water levels at the boundary will vary with discharge to maintain the relationship and so an a priori description of water level variation is not necessary.	Provides a dynamic boundary condition appropriate for downstream boundaries in channels where flow is realistically described as gradually varying or uniform. Does not allow for flow into the model domain. Cannot account for hysteresis in relationship, which is caused by flood wave surface slope.

Type	Description	Applicability and limitations
Combination	A complex boundary type that may control any combination of water level, flow, velocity and water level slope.	May be applied at locations of complex flow patterns such as in coastal environments where swirling currents or Coriolis effects preclude uniform values. Typically these boundary conditions are extracted from models of broader extent and would otherwise be very difficult to develop analytically. Generally applied in coastal models and are very rare in flood models. The *Flather* boundary type is useful for downstream water level boundaries as it can smother reflections and dampen fluctuating flows and water levels. Results in the vicinity must be treated with caution as they may not be realistic.

Table 10 Data sources used in the generation of boundary conditions.

Type	Historic events	Design events
Precipitation	Consultation with Council regarding appropriate data sources is advised. Rainfall gauges maintained by Council and TLAs provide timeseries and generally are available online. Rain-radar (spatially and temporally varying datasets) may be available from the New Zealand Met Service. Correction of this data using local rain gauges will be necessary before use.	Nested storm hyetographs are used by Council. Consultation with Council will be necessary to create a conforming timeseries for modelling purposes. HIRDS (Carey et al, 2018) may provide depth-duration-frequency data for developing an appropriate nested hyetograph.
Tide	Consultation with Council regarding appropriate data sources is advised. Tide gauges maintained by Council provide coastal water level timeseries for estuaries and generally are available online. NIWA and Port of Tauranga have additional tidal data.	Coastal models may be used to source design tides. Where boundary conditions are not available from a relevant study or model, storm surge and wind setup sea level increases are to be added to a representative tidal signal. Use Coastal Calculator (Stephens et al, 2018) results provided by Council for storm tide estimation.
Lake	Lake levels Council recorders.	Contact Council's Engineering Manager for specific guidance.

Type	Historic events	Design events
Water level	Consultation with Council regarding appropriate data sources is advised. Water levels will not generally be required as boundary conditions. In rare occasions where there is low confidence in a rating, a timeseries of water levels may replace a discharge at an upstream domain boundary. Gauged water levels will be used in calibration, validation and verification. Stage gauges maintained by Council provide timeseries for open channels and generally are available online	Water level boundary conditions are not generally required in design events, except where timeseries from a neighbouring model or a regional model are used. In this case, these boundary conditions should be sourced from appropriate scenarios of the other model, which may not correspond directly with the scenarios of the model being developed.
Dam outflows	Spillway discharge or downstream flow gauging will be available.	Council has developed methodology for determining appropriate dam discharges for design events that take storage scenarios into account. Consultation with Council will be necessary to obtain a conforming timeseries for modelling purposes.
Runoff	Discharges generated by calibrated/validated hydrological models upstream of hydraulic model domain and used as domain or internal boundary conditions, or both.	Discharges generated by calibrated/validated hydrological models upstream of hydraulic model domain and used as domain or internal boundary conditions, or both. Runoff AEP may not match precipitation AEP due to AMC.

Design-event (precipitation)

When a rain-on-grid simulation is carried out, a design hyetograph must be developed (Figure 4). An appropriate hyetograph should be constructed as follows.

1. Determine marginal probability Annual Exceedance Percentage (AEP) from the joint-probability scenario of interest.
2. Use the planning horizon to determine the future climate change scenario.
3. Determine temperature increase for the applicable representative pathway and future climate change scenario (see **Climate Change**, page 71).
4. Extract depth-duration-frequency rainfall tables from local rain gauge analysis, based on guidance from the Territorial Local Authority or from NIWA's HIRDS website (Carey-Smith *et al*, 2018).
5. Determine rainfall depth augmentation factors provided by Carey-Smith et al (2018) and modify rainfall depths if necessary.
6. Use Areal Reduction Factors (ARF) provided by Carey-Smith et al (2018) to scale down rainfall depths based on the total area of the catchment being simulated. Note that applying these factors may cause rainfall volumes to be underestimated in peripheral areas of the catchment.
7. Apply depths to the nested storm profile provided in Table 11 by reducing the depth for each storm duration by the depth of the embedded storm duration. Be sure to confirm the depths for various durations are correct.

8 Shift the timeseries in time to align peak runoff with any inflows to the model domain (including tide), from upstream or otherwise.

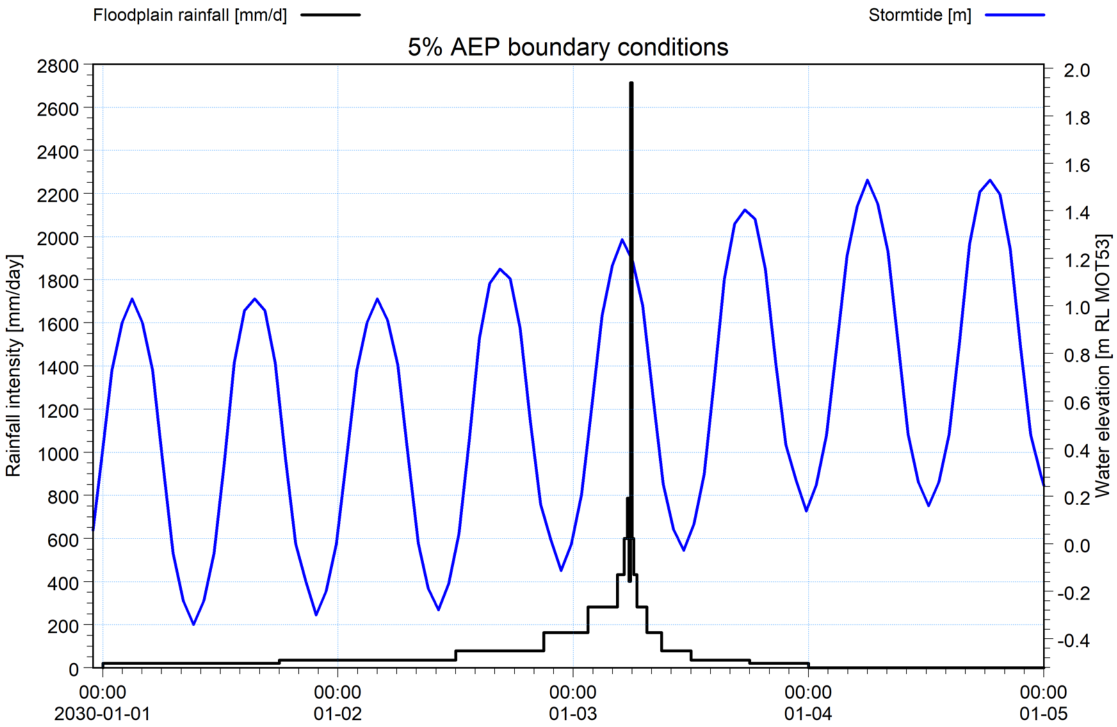


Figure 4 Example nested design storm profile (hyetograph) showing precipitation against a design tidal boundary that includes storm surge.

The nested storm profile, summarised in Table 11, has a total duration of 72 hours and the peak rainfall intensity (10 min storm) is timed to occur at 75% of the 72-hour storm. This "heavy-ended" weighting of storm intensity is designed to reflect rainfall experienced during Cyclone Cook at the beginning of April 2017, which caused significant flooding (Bay of Plenty Regional Council, 2017). Table 11 can be used to develop the specific time-based hyetograph for use as a model boundary condition.

Table 11 Bay of Plenty Region Council's nested rainfall profile.

Start of Interval Offset	End of Interval Offset	Interval Length (min)	Rainfall Depth Duration Applied to Interval
0 hr 0 min	18 hr 0 min	1080	72 hr
18 hr 0 min	36 hr 0 min	1080	48 hr
36 hr 0 min	45 hr 0 min	540	24 hr
45 hr 0 min	25 hr 30 min	270	12 hr
25 hr 30 min	52 hr 30 min	180	6 hr
52 hr 30 min	53 hr 10 min	40	2 hr
53 hr 10 min	53 hr 30 min	20	1 hr
53 hr 30 min	53 hr 40 min	10	30 min
53 hr 40 min	53 hr 50 min	10	20 min
53 hr 50 min	54 hr 0 min	10	10 min
54 hr 0 min	54 hr 10 min	10	1 hr
54 hr 10 min	54 hr 30 min	20	2 hr

Start of Interval Offset	End of Interval Offset	Interval Length (min)	Rainfall Depth Duration Applied to Interval
54 hr 30 min	55 hr 30 min	60	6 hr
55 hr 30 min	57 hr 0 min	90	12 hr
57 hr 0 min	60 hr 0 min	180	24 hr
60 hr 0 min	66 hr 0 min	360	48 hr
66 hr 0 min	72 hr 0 min	360	72 hr

Design-event (tide)

Bay of Plenty Regional Council's Coastal Calculator (Stephens *et al*., 2018) provides storm tide levels, wave run up and wave set up estimates for a range of design events. Design tide boundary conditions must be based on the storm tide level only, and in most cases shall not account for wave run-up and wave set up. An exception to this guidance will be where wave setup can mobilised and have a measurable impact, such for stormwater pipes and smaller streams discharging onto a steep beach.

Coastal boundaries require a tidal boundary condition, which should be constructed as follows.

1 Determine the probability Annual Exceedance Percentage (AEP) storm surge scenario from the joint-probability scenario of interest.

2 Use the planning horizon to determine the future climate change scenario.

3 Determine the applicable category from Coastal Hazards and Climate Change Guidance Report to find the representative pathway (and combine with the future climate change scenario to decide the appropriate sea level rise to apply (see Climate Change, page 1).

4 Use the tables in the Supporting documents on BOPRC website to look up appropriate coastal (Stephens *et al*., 2018) and Tauranga Harbour (Reeve *et al.,* 2019) storm tide levels.

5 Use the representative tidal signal (Table 12), as defined by Wallace (2011), as the basis of the boundary condition timeseries and repeat it as many times as required (note that it covers 25-hour period).

6 Multiply the surge scale factor timeseries (Table 13) by the storm tide (found in Supporting Documents on BOPRC website) less the peak representative tidal signal level (0.67 m RL). Linearly interpolate intervening time steps before adding this profile to the modified representative tidal signal.

7 Shift the timeseries vertically by the sea level rise determined in the previous steps.

8 Shift the timeseries in time so that the peak level coincides with peak discharge from the model domain to the coast (Figure 4).

Table 12 shows that the representative design event tidal signal that can be combined with the storm surge profile from Table 13 to create a coastal tidal boundary condition.

Table 12 Representative design event tidal signal with mean tide set to Moturiki Vertical Datum 1953 0.00 m RL.

Time offset	Typical tide elevation [m RL Moturiki 1953]
0 hr 0 min	0.67
1 hr 2.5 min	0.57
2 hr 5 min	0.37
3 hr 7.5 min	-0.02
4 hr 10 min	-0.40
5 hr 12.5 min	-0.60
6 hr 15 min	-0.70
7 hr 17.5 min	-0.60
8 hr 20 min	-0.40
9 hr 22.5 min	-0.02
10 hr 25 min	0.40
11 hr 27.5 min	0.62
12 hr 30 min	0.67
13 hr 32.5 min	0.62
14 hr 35 min	0.40
15 hr 37.5 min	0.00
16 hr 40 min	-0.36
17 hr 42.5 min	-0.52
18 hr 45 min	-0.66
19 hr 47.5 min	-0.56
20 hr 50 min	-0.36
21 hr 52.5 min	0.00
22 hr 55 min	0.37
23 hr 57.5 min	0.57
25 hr 0 min	0.67

Table 13 Representative storm surge scale factor profile.

Time offset	Surge scale factor
0 hr 0 min	0
25 hr 0 min	0.5
50 hr 0 min	1
62 hr 30 min	1
87 hr 30 min	0.5
112 hr 30 min	0

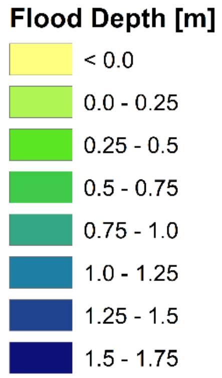
4.4 Cartography standards

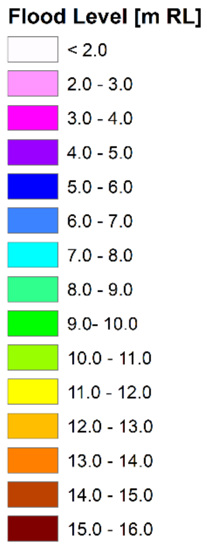
Cartography plays an important role in the presentation of model simulation results. Standards applied to cartography improve familiarity for the user and reduce time spent in reading maps and misinterpretations. Maps prepared for use by Council staff should adhere to Table 14 following recommendations. If maps are produced directly from modelling software, this may limit the flexibility in symbolising information compared with GIS software approaches.

Table 14 Recommended cartographic considerations for mapping modelling results.

Subject	Recommendation
Map extent	Include all features of interest and add approximately 5% to the map extent width and height to provide context.
Catchment outline	Include catchment outline in a context map to indicate location in Bay of Plenty region.
Point features	Use different shapes for different feature types, and then use different colours to distinguish subtypes of those features. The following symbol shapes should be used. Pump station - black outline with single-colour, orange-fill square shape.
Linear features	Use different colours for different feature types with varying thickness to distinguish subtypes of those features. The following symbol shapes should be used. Culvert - single-colour, grey unadorned line. Stormwater main - single-colour, blue unadorned line. Stopbank crest line - single-colour, yellow unadorned line. Bridges (scale dependent) – match road and rail symbology. Note for larger scale maps some linear features will need to be represented as points.
Topographic relief	Vary topographic relief colours and contour lines to ensure communication of key messages and features of the map.
Rasterised model results	A range of distinctive colours so that subtleties are highlighted rather than shades of the same colour which may not reproduce well in printed form. This may require using a classified palette.
Legend	Provide a legend for all items except in small map figures which can be explained by the figure caption in the report. A legend on a small figure can clutter the map.
Scale	Provide a scale bar, which can be simple for small maps.
North arrow	Provide a north arrow for all sized maps, especially for rotated maps.
Page size	The size of the page needs to reflect scale and symbology of the map detail, and enable printing at intended size.
Orientation	This is flexible depending on application.

<table>
<tr><th>Subject</th><th>Recommendation</th></tr>
<tr><td>Flood depth mapping</td><td>This is the mapping of water level depth above the ground level and it should be done using a yellow to green to blue pallet as shown this the example presented here. The actual depth classes may require changing depending on results and the application). This pallet is using the standard ArcGIS palate called “Yellow to Green to Dark Blue”. ArcGIS is not required for mapping and any suitable software can be used. A semi-transparent layer may be used if the flood depths are still clearly being communicated.


</td></tr>
<tr><td>Water level mapping</td><td>This is the mapping of water level relative to a datum and it should be done using the pallet shown this the example presented here. Since the reduced levels of water vary greatly a number of different colours are required to ensure patterns in levels are clear. The actual depth classes may require changing depending on results and the application. This pallet is using the standard ArcGIS palate called “Temperature”. ArcGIS is not required for mapping and any suitable software can be used.


</td></tr>
</table>

4.5 Data

This section outlines types of data that are commonly used in hydraulic modelling studies. It describes pre-existing data that can be sourced and considerations for collection of new information.

Quality

Consideration of the quality of data being used in a model needs to be made to ensure behaviour of the model works as expected. Also, the interpretation of results needs to consider the source data quality.

When assessing and reporting on data quality the following four aspects should be commented on. This will aid in determining the limitations of the data and the effects on model results. The assessment of data quality covers (from Srivastava, 2008):

- completeness (the extent to which data covers the domain and time period of interest),
- precision (the resolution of the data),
- accuracy (how well the data reflects reality), and
- consistency (the degree of conflicts within the dataset).

Data types

Table 15 Data commonly used in hydraulic models and where they are used.

Type	Description	Usage
Aerial photography	Aerial photography are photographs corrected to their position on the earth surface. They are typically from large format photographs or LiDAR and are transformed using photogrammetric and other survey methods.	Used to confirm location of model features. Digitisation of surface resistance, such as floodplain vegetation, fences or riverbank vegetation. Used to digitise building footprints or other obstacles such as fence lines or walls. Used to capture historical data sets for historical calibration events
Hydrologic and hydrometric information	Rainfall and dynamic river flow and level information. Typically, there are long-term gauge sites managed by Council across the region. At times shorter term records may be collected for specific purposes. Council provides access to this data via its *Live Monitoring* web portal but other data sources may be available. For example, NIWA, TLAs, power companies, MetService and some private individuals will have data sources. Reliability of data needs to be considered. Rain radar collected nationally and supplied by Metservice.	Long term sites provide calibration and validation time series for significant historical events. Long term sites provide data for return period analysis which informs design boundary conditions. Short term sites provide information specific for a location and can be put in place for a modelling study. However, they are unlikely to record the more extreme events that cause flooding, leading to uncertainty over extrapolating the model's results in a design context (Titterington *et al.*, 2017). The utility of short-term monitoring is for low flow events unless larger events happen to be captured in the monitoring period. Care in their use for flood hazard analysis should be *taken*. For developing estimates of flow or stage frequency. However, if large events are under-represented as they do not occur in the data record, the resulting analysis will be biased towards smaller, more frequent events and extreme events will be under predicted. Additional discussion the use of rainfall information in hydraulic modelling is covered in Bailey *et al.* (2016) such as for model verification and generating design storms. Rain radar depth measurements must be calibrated to local gauge information before use.

Type	Description	Usage
Topography	Topographic survey, including LiDAR (aerial and ground-based), and more conventional survey techniques. Other remote sensor such as from drones, photogrammetry	Used to produce a digital elevation model, which in turn may be used to determine overland flow model surface. Should not be relied on for detailed channel definition unless specific ground survey of channel has been completed. Used to identify flow paths and obstacles. Important driver of overland flow and ponding in models. To confirm accuracy of other data.
Stormwater asset data	Includes stormwater mains, open channel alignments, inlet and outlet structures and other structures such as pump stations, weir/gates, flap gates and culverts. This is generally stored in a GIS database format.	Heavily used for urban modelling but its usage will be on a case by case basis where required for river modelling applications.
Transport Network	Road centrelines, kerb lines, railway lines, bridges, footpaths etc.	Analysis of the environment, where infrastructure may exist (e.g. culverts) and features that may modify overland flows (e.g. bunds from road embankments) Used to locate bridges.
As built plans	A record showing how an engineering project was constructed, with details of measurements of important devices, locations, elevations and other important information.	Providing details of types of structures to be built in a model and measurements of attributes of the structure. Often used when GIS data is missing information.
Design drawings	Engineering plans used for concept, preliminary or detailed design phases of a project. They could be in CAD files or drawings.	Where as-builts or survey data not available.
Flood maps	Maps indicating areas of flooding for historic or design events. May be hand drawn or informed by simulation.	Comparison with model results as verification.
River, lakes, ponds and wetlands	Point or polygon information describing the water body.	River data can be used as a starting point for building river models. Lake, pond and wetland data can be included as storage devices in a model.
Calibration data	Surveyed water levels from direct recordings or debris, Council flood incident reports, fire service reports, photographs, anecdotal records.	Data relating to a particular historic event is compared to results of a simulation of the same event to guide the iterative tuning of model parameters so that the model reproduces reality to a sufficient degree.

Type	Description	Usage
Validation data	Surveyed water levels from direct recordings or debris, Council flood incident reports, fire service reports, photographs, anecdotal records.	Data relating to a particular historic event is compared to results of a simulation of the same event to quantify the model's ability to reliably reproduce reality.
Verification data	Information from other sources than those events that are simulated. This information could include flood levels from similar events, flood frequency analysis or design event simulations.	A verification process may be required to prove the robustness of a model, especially if calibration and validation data is unavailable. The range of verification techniques is broad and covered in the "Complete additional verification" section.
Historic flood information	Photos of breaches, call out reports including surveyed water levels and surveyed debris levels.	To be used in model calibration, validation and verification processes.
Open channel survey	Typically cross sections along an open channel, but may include a thalweg survey or bridge survey.	For one dimensional channel modelling. For generation of grids or meshes as part of a two-dimensional model.
Land use/land cover	Spatial database (GIS) of land use or land cover classifications. Land use relates to activities (e.g. forestry) and land cover relates to what is on the land (e.g. grass, native vegetation)	Used to distribute overland flow resistance parameters. Used to distribute hydrological model parameters sets such as initial and continuing losses.
Building footprints	Plan view outline of building.	Locates model cells or elements to raise or apply increased flow resistance in order to simulate flow obstruction as a treatment for impacts of buildings on two dimensional flow.
Geology and soil maps	Spatial database (GIS) of soil types, formation, and drainage classifications.	Used to distribute hydrological model parameters sets such as initial and continuing losses. Used in AMC analysis.
Flood protection assets	Stopbanks, flood walls, stop locks, spillways location, crest elevation and alignment.	Used to augment surface model to improve the model's ability to reflect the behaviour of the flood protection assets. Can be represented in model as weirs or dike/wall/stopbank structures (e.g. for coarse resolution models) or through modification of the model topography (e.g. in fine resolution models). As examples, narrow features, such as walls, may be represented as sharp-crested weirs, whereas broader features, such as roads, are better represented by model cell/element elevations raised to the road crest level (approximating broad-crested weirs).

4.6 Datum and reference system

Vertical datums and horizontal reference systems are two related but somewhat independent considerations in hydraulic modelling. Land Information New Zealand's (LINZ) latest vertical datum is New Zealand Vertical Datum 2016 (NZVD2016) and since 2018, Council data has been procured in NZVD2016. Historical data before 2018 is commonly stored in Moturiki Vertical Datum 1953. Council uses New Zealand Transverse Mercator (NZTM) for storing all core corporate datasets, but at times datasets in Bay of Plenty Circuit 2000 may also be available. New Zealand Maps Grid (NZMG) precedes NZTM and can be readily converted if required.

For new hydraulic models, the recommended standards for datum and horizontal reference systems are NZVD2016 and NZTM. However, for certain locations there will be valid reasons to use Moturiki Vertical Datum 1953, such as when substantial related work is using these approaches. It is acknowledged that Bay of Plenty is in a transitional period for vertical datums and introducing mandatory NZVD2016 to modelling studies may lead to errors and project delays without any benefit.

Conversion between horizontal coordinate systems (e.g. NZMG to NZTM) is a relatively straight forward task and accuracy in centimetres can be achieved in desktop studies. This is completely acceptable for modelling purposes. However, vertical datum transformations (e.g. Moturiki Vertical Datum 1953 to NZVD2016) vary widely over short scales (kilometres) due to gravitational impacts of the earth's geoid, particularly in areas with undulating landforms. The starting point for vertical transformations will be the LINZ Coordinate Converter but care must be taken and independent verification of any transformations may also be required. For example, it cannot be assumed that a single vertical correction can be applied to transformation across a model extent that may cover kilometres or even less. In this situation a varying surface may need to be applied to represent variation between datums over two-dimensional space. The key principle for transformation of both horizontal and vertical datums is to have checks and evidence to support any changes made.

4.7 File management

Sound file management is crucial to reduce errors and rework, assisting with efficiencies in model build and use, and protecting investment in models by ensuring they can be used again in the future. File organisation facilitates a range of functions in hydraulic modelling as outlined in Table 16.

Table 16 Core functions of good file management in hydraulic modelling studies.

Function	Requirements
Retrieval	All data relating to a model must be accessible and stored together so that a future third-party can quickly and easily run a simulation or modify a model for other purposes.
Understanding	A consistent and well-named folder structure adds meaning to file names and will vary between different modelling platforms. Metadata information on how scenarios are defined and used should be stored alongside model files including reports, spreadsheets and other model build tools. Naming conventions must be consistent and descriptive enough to allow clear identification, yet no longer than it is required. Long file names may cause issues with some software and with ease of understanding.

Convenience	Only files of direct relevance should be stored: only log files or results for the latest simulation of the stored model should be retained. If intermediate results from a process are required, then copies of the model that generated them should be retained as well. Very large result files may be discarded where they can be easily regenerated with minimal effort or where all relevant results have been extracted. Extracted results, perhaps generated for reporting, are to be stored alongside results files.
Version control	The top-level folder contains the project title, a date and a key (unique identifier). Where a version number is required, a software versioning convention is recommended such as *Major.Minor.Patch/Build* (e.g. 1.1.10) or a left-filled ordinal (e.g. 0000, 0001, 0002)

This document establishes a naming convention for models created by, for, and supplied to Council. Where a consistent naming convention has not been applied, significant effort is required to arrange, rename files and restore internal connections. It is expected that all submitted models and associated results conform to the Council folder layout and naming conventions described below.

Folder layout

It is recommended that simulations for a particular scenario are grouped together and separated from other high-level scenarios. The purpose is that a model simulation is fully contained in a single folder and can be archived, tracked and shared as a discrete set of data. Each sub-scenario should be separated into its own folder with all files required for a simulation. Common files however, such as timeseries, may be moved to a common folder higher in the hierarchy.

An example layout that incorporates a number of model iterations as well as scenarios is provided below (Figure 5) using the naming convention from the next section. In this example, the base model is the April 2004 storm calibration event and all other modelling work is based on this base model. Note that the final version of the model files that require archiving have been highlighted, and all older versions would be discarded to avoid confusion with regard to which version to use in the future. It may be useful to use file compare utilities to interrogate the different model versions and provide consistency between models.

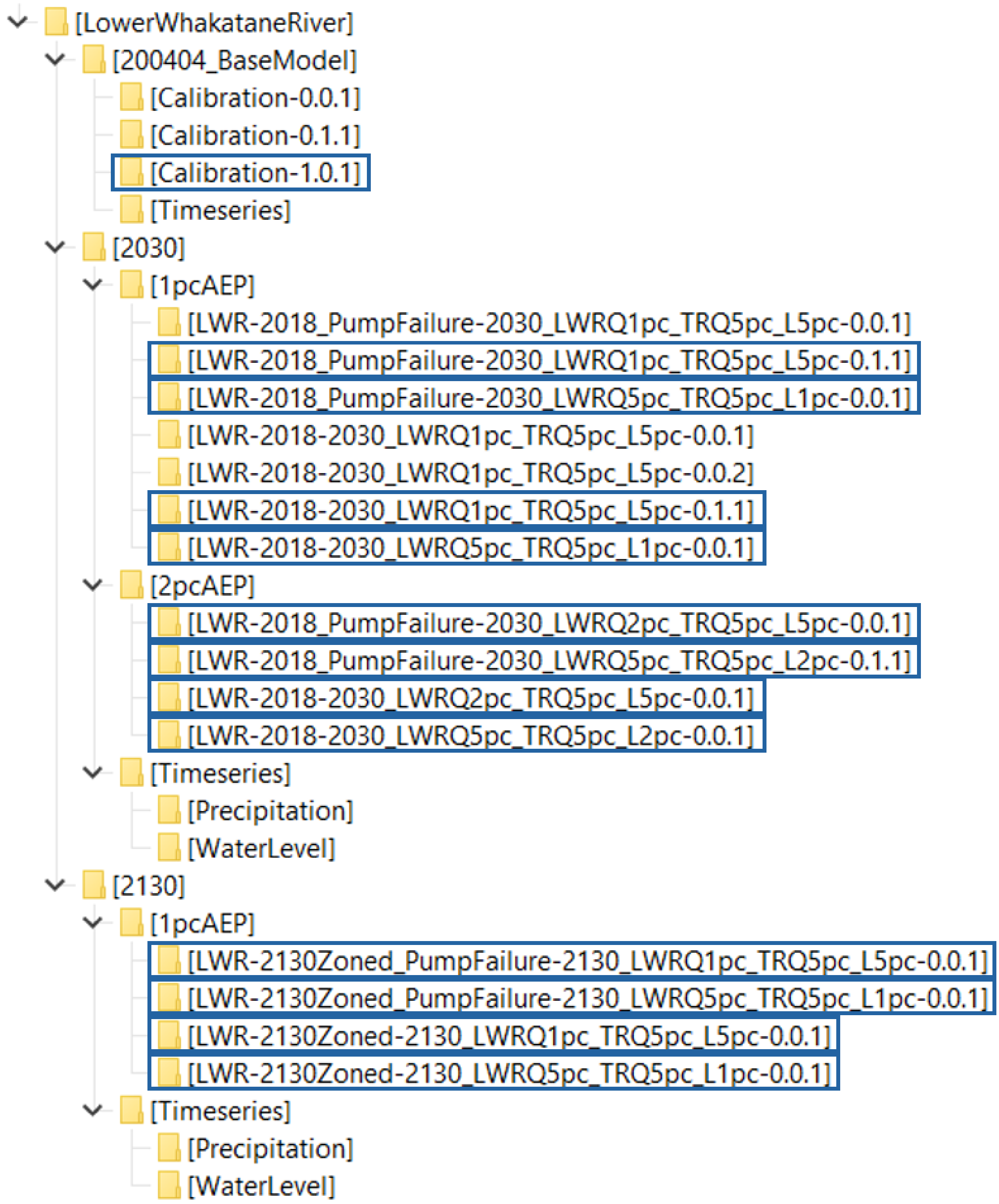


Figure 5 *Example folder structure showing the calibrated base model (**build** phase) and scenarios for 2030 and 2130. Note the final folders to keep are outlined in blue and others are draft versions not to be included in deliverables unless requested.*

File and folder naming convention

Files should be named to clearly identify what distinguishes the specific file from others. In general file names should be short and generic, reserving specificity for folder names. Folder names are to be made up of segments that describe the file contained within (provide metadata). These segments are to be separated by dashes. The following segments are considered a minimum.

1 River/catchment identifier.

2. Geometry and behaviour scenario. Specific sub-scenarios may be separated by underscores.
3. Environment scenario. The context designation may contain multiple boundary conditions and antecedent moisture conditions identifiers all separated by underscores.
4. Version - a consistent numbering scheme.

This approach results in a template such as below:

<river/catchment identifier>-<geometry and behaviour scenario>-<environment scenario>-<version>

This is an example of how this file naming convention is to be used. The model metadata is:

- the Lower Whakatane River,
- existing development scenario (based on 2018 data such as land use and imperviousness, etc.),
- with all pump stations failing,
- 2130 climate conditions,
- 1% AEP river inflows,
- 5% AEP Te Rahu inflows, and
- 5% storm tide.

Applying this to the template results in:

LWR-2018_PumpFailure-2130_LWRQ1pc_TRQ5pc_L5pc-0.0.0

Consider the following:

- Special characters such as ~ ! @ # $ % ^ & * ( ) ` ; < > ? , [ ] { } ' " and | may cause problems at times for some software. If allowed by the software special character % can be used.
- Do not use spaces. Some (older) software will misinterpret filenames containing spaces. Spaces are to be enclosed in quotes when working from a command line. Instead use:
    - underscores: e.g. *file_name.xxx*;
    - dashes: e.g. *file-name.xxx*;
    - no separation, e.g. *filename.xxx*; or
    - use camel case where the first letter of each section of text is capitalized: e.g. *FileName.xxx*.

4.8 Debris and blockage

In developing a blockage scenario, the following points should be considered. Blockage is typically accounted for as a type of sensitivity analysis in order to assess robustness of the model results. The theory and practice for assessing blockage is not yet mature. Ball *et al.* (2019d) provides a probability-neutral approach for cross-drainage structure blockage (for bridges and culverts) estimation: this should be referred when undertaking an assessment of a blockage-prone structure. Aspects of this approach are summarised below.

Points to consider are as follows.

- The type and dimensions of likely debris:
  - floating vegetation such as leaves and sticks to branches and even entire trees where banks have collapsed,
  - non-floating debris such as sediment and sand (suspended and bed load) through to boulders larger than 200 mm (bed load), and
  - urban debris such as signage and rubbish bins up to cars and shipping containers.
- Source area of debris is the flood extent upstream of the structure along with other significant flow paths or channels feeding the floodplain. This area will vary with event size.
- Estimating the availability of different types of debris includes determining what exists in the directly upstream catchment and whether soil types, channel shapes, land usage/clearing and preceding conditions (such as saturated soil increasing the chances of slips) increase the chances of debris becoming available.
- Mobility determines whether debris reaches an open channel.
- Transportability determines the capability of a particular open channel to transport debris to the blockage location.
- How debris affects the structure depends on whether bridging debris initiates a blockage so that smaller material can also collect. Fish passages and fixtures increase the chances of a blockage developing. Blockage is generally classified as:
  - top-down,
  - bottom-up,
  - porous plug, or
  - on piers
- Random chance dictates that the degree of blockage should be considered as a distribution of probabilities.

Ball *et al.* (2019d) provides tables to use in categorising blockage risk into *High*, *Medium* and *Low* and then quantifying blockage based on these categories and structure opening width. In addition, quantification of blockage based on sedimentation is provided.

As analysis of blockage requires considerable effort, a risk-based approach should be used to identify structures of interest:

- these structures should have a history of blockages or have a high availability of upstream debris, and
- a high cost of consequent damages to upstream property, the structure itself or to alternate flow paths.

As blockage can have a significant impact on upstream flood levels, consideration of blockage for historic events is necessary.

4.9 Model domain

Model extent

GIS analysis to delineate catchments is completed for the development of a model domain by defining the extent. Generally, this process involves the following steps.

1. Sourcing of surface model and generation of a DEM.
2. Iterative steps of GIS-based drainage analysis using the DEM. The area of interest and sufficient distance to the boundary should be included in the analysis. In general it will be necessary to generate many smaller sub-catchments and merge the ones of interest to form the overall catchment extent. Asset information (e.g. culverts, open channels, pump stations, stormwater reticulation) and local experience may be required to create an accurate delineation that accounts for linear and point drainage features. It will be necessary to delineate sub-catchments that fringe the eventual model extent in order to define clear ridgelines.
3. Modification of the delineated boundary to accommodate boundary conditions. At this point it may be necessary to return to the previous step.
4. When backwater effects impinge on the area of interest, the model boundary should extend to the cause, which may be the coast or a man-made structure such as a dam.
5. Pipe networks connecting surface areas that are not connected by overland flow paths to the area of interest should be included in the model domain as these may define large influential storage areas and may attenuate flow through the area of interest or they may contribute flow to the area of interest.

When modifying a model extent, care should be taken to ensure that the new area drains realistically and does not pond against the boundary of the model, causing unrealistically elevated flooding.

Surface model

There are four different types of surface models to be considered when developing geometry for a hydraulic model (GIS Geography, 2020).

Table 17 Different types of surface model.

Name	Description	Uses
Digital Elevation Model (DEM)	A rectilinear grid of bare-earth surface reduced-level elevation. This model excludes, as much as practically possible, buildings, fences, vegetation and other above-ground obstacles.	Defining the first estimate of the surface of the overland flow model.
Digital Surface Model (DSM)	A rectilinear grid of the highest reduced-level elevation within each cell. This model accounts for the bare-earth, vegetation and man-made structures, such as buildings and telegraph poles.	Identification of obstructions to flow. May be used to estimate flow resistance parameters.

Name	Description	Uses
Digital Terrain Model (DTM)	A vector representation of a DEM where point spot heights at cell centres are augmented with contour lines. This may be synonymous with DEM in many settings.	Generation of a DEM using interpolation techniques.
Triangulated Irregular Network (TIN)	A Delaunay triangulation, or more generally a constrained Delaunay triangulation, in the horizontal plane of spot height locations. Contour lines and other linear features may be incorporated to better define the surface shape.	A continuous surface representation of discrete spot heights. Used in generation of other surface models.

Hydraulic overland flow models require a 2D planar computational domain that is tessellated into discrete, non-overlapping structured cells of either uniform shape, and in some cases uniform size, or unstructured elements, which may vary in size and shape depending on the simulation engine. The surface model, be it a DEM or TIN, is used to inform the computational domain, but is generally not identical to it for the following reasons:

- simulation engines may constrain the cell or element shape,
- computer memory requirements constrain cell or element counts,
- timeline constraints may preclude lengthy simulation run times that are due to high cell or element counts,
- in unstructured grids elements should ideally be as close to regular shapes as possible to improve computational solution speed and stability, and
- computational constraints such as the Courant–Friedrichs–Lewy (CFL) condition discourage very small (in terms of plan area) cells or elements, particularly in areas of deep water.

Smooth gradients across cells or elements across a computational domain improves computational stability, however the need for stability must be balanced with the requirements of reproducing real-world flow obstacles, which often require significant steps in elevation. In assigning elevations to the computational domain the following steps are recommended:

- create a smooth first estimate of computational domain surface elevations by using an area-weighted or natural neighbour interpolation approach,
- use crest levels from linear features such as roads or stopbanks to set cell or element elevations to accurately define spill levels, and
- use building footprints to raise elevations within buildings to simulate flow obstruction. (refer to the later section on structures/buildings)

Very fine resolution obstructions, such as fences or shelter belts are best represented through heightened overland flow model hydraulic resistance/roughness. It is generally not advised to use building footprints directly in unstructured mesh generation without significant simplification of polygon geometries.

Internal linkages

Hydraulic modelling software has traditionally clearly distinguished between one-dimensional (1D) and two-dimensional (2D) solution techniques, often being developed independently of one-another. Separate pieces of software, each specialising in either 1D or 2D solution schemes, were then modified to minor extents in order to allow for flow exchange across software, solution-scheme and subdomain boundaries to facilitate coupled 1D and 2D simulations. Internal linkages are distinct to internal boundaries.

Ball *et al.* (2019) refers to the linkages between subdomains of a model. Implementation of these linkages is software specific, however, in general, there are a number of advantages and disadvantages of this approach to be considered during schematisation. Advantages include the following.

- The individual strengths of 1D and 2D modelling approaches can be combined.
- 1D model components can be used to simulate narrow or small hydraulic features such as pipes, manholes and incised drains without significant approximation.
- Computational grid spacing can be increased in 1D in deep channels to avoid Courant-Friedrichs-Lewy (CFL) condition constraints on timestep size.
- Linkages allow for a large variation in computational grid sizing across the subdomain boundary.
- There is greater precedence for the use of 1D models to simulate open channel flow than there is for 2D models. It is possible to draw on the large range of literature values for parameters such as flow resistance for 1D models while flow resistance parameters for 2D models of rivers are not well established.
- The 1D component generally runs much faster than the 2D component and so schematising parts of a domain in 1D can reduce run times.

Disadvantages include the following.

- The individual weaknesses of 1D and 2D modelling approaches are combined.
- The linkage between 1D and 2D components are often the source of numerical instabilities which do not conform to numerical modelling norms and can be difficult to resolve.
- Developing linkages requires considerable effort and skill. Ensuring that linkages are correctly aligned and do not straddle structures, and so bypassing the hydraulic constriction, is crucial.
- There are a number of linkage types and most are built on structure discharge equations, such as those for a weir. In cases where this reflects the real-world entity being represented, such as a stopbank, this works well, however in other situations this may introduce unrealistic afflux.
- 1D models cannot account for transverse momentum effects and so where there are significant high bank flows included in the 1D model component in highly meandering sections of river, the flow pattern will be inaccurate, particularly when combined with issues stemming from the previous point.

4.10 Eddy viscosity

Energy loss due to turbulence in water flows is simulated by flow resistance and Reynolds stresses, which may be approximated by eddy viscosity and shear rate. While flow resistance acts as a momentum sink, conceptualised as friction drag, in the governing equations eddy viscosity does not; instead, energy is dissipated by a process that, on average on the large scale, operates like diffusion. Approximation of the turbulent distribution of momentum should account for lateral transmission of momentum without gross overestimation. The following table of eddy viscosity approaches is ordered from least to most preferred.

Table 18 Approach to Eddy viscosity.

Approach	Recommendations
Constant, flux-based	Available in some simulation engines as a legacy approach that has little physical justification. Should only be used where there is little variation in flow depth. Typical eddy viscosity (DHI 2019a): 0.02 * $\Delta x^2 / \Delta t$, where Δx is a characteristic cell length and Δt is the timestep size.
Constant, velocity-based	Typical eddy viscosity for inland flooding applications (DHI, 2019b): 0.02 * $l^2 / \Delta t$, where l is a characteristic element length and Δt is the timestep size. When a simulation engine employs a variable time step or allows for non-uniform cells and elements, the choice of a uniform constant eddy viscosity becomes arbitrary. Applicable when the cell size is much greater than the water depth or in the presence of high flow resistance. Eddy viscosity should be set to 1.0 m^2/s (BMT, 2018).
Smagorinsky	Simulated eddy viscosity values should be checked to ensure that values are within a reasonable range. Smagorinsky coefficient between 0.25 and 1.0 (DHI, 2019b). Minimum resultant eddy viscosity of 0.05 m^2/s (BMT, 2018).
Wu 3D	Consider findings of Collecutt and Symes (2019) and Symes (2020) on comparison of different approaches and finding that Wu 3D provided best outcomes for a range of test model geometries. This approach should be used when possible.

The following points may also be considered.

- High estimates of eddy viscosity act to smooth velocity profiles in an unrealistic manner which makes the simulation of channel and high-flow bank interaction inaccurate (Ball *et al*., 2019d).
- Hunt and Brunner (1995) state that standard practice within the US Army Corps of Engineers is to specify the minimum eddy viscosity that admits stable simulations.
- It may be possible to spatially distribute eddy viscosity, or related parameters, and so increase expected losses in the vicinity of turbulence-inducing obstacles to flow. This technique may be used to improve numerical stability in exceptional circumstances.

4.11 Flooding, wetting and drying

Flooding and drying or *wetting and drying* is a technique commonly used by overland flow simulation engines that allow for a dynamic internal boundary between wet and dry elements. The user inputs fixed flooding/wetting and drying depths, which are applied uniformly across all cells or elements. When determining these parameters, the following points should be considered.

- Drying depth can depend on software being used and grid cell size. DHI (2019b) recommends a value between 0.1 mm and 5 mm whiele BMT (2018)) recommends a value between 0.2 mm and 50 mm and can depend on software being used and grid cell size. Below the drying depth the cell or element is effectively excluded from the hydrodynamic simulation.
- Flooding and wetting depth must be greater than the drying depth and can range between 20 mm and 100 mm (DHI, 2019b) but it is common for values as low as 3 mm to be used. Between the draying and flooding depths, simplifications to the solution of the governing equations are applied. The greater the difference between flooding and drying depth, the smaller the possibility of numerical instability, generation of spurious velocities or the artificial generation of water.
- Increasing the drying depth may improve stability and reduce water generation, but it can delay the start of shallow runoff (effectively acting as additional initial abstraction), particularly when used in a rain-on-grid simulation. Unfortunately, in practical applications the final parameters values reflect a balance between simulation performance and realism.
- Small values are appropriate for rain-on-grid.

As these parameters are implementation specific, the software user guide for the specific version of software used should be consulted for changes in recommendations.

4.12 Freeboard

Freeboard is a standard engineering provision for estimating imprecision and uncertainty of inputs. Even the most sophisticated design techniques are unlikely to exactly predict complex hydraulic scenarios plus some phenomena are not explicitly included in the hydraulic calculations (e.g. waves, aggradation, bend effects and debris blockage and passage). Where debris is explicitly modelled, this component of freeboard may be removed. In some circumstances freeboard also includes a provision for construction tolerances and the Building Act refers to a provision for waves.

Freeboard should be applied to simulation results where model uncertainty is to be included in flood mapping. Bay of Plenty Regional Council (2018b) notes freeboard of between 500 and 800 mm in urban areas and zero and 450 mm in rural areas and Table 11 in that document has specific freeboard levels for various waterways. It is recommended to leave freeboard considerations to the time in the modelling study when maps are being produced or asset design levels are being calculated rather than in model boundary conditions. Processed model results without freeboard should be retained and used as the basis for any analyses; different levels of freeboard can then be applied as required by the analysis. The model purpose and success criteria will stipulate freeboard levels, which must be clearly stated in any deliverables.

With regard to hydraulic models, freeboard may be accounted for by:

- adding a vertical offset to maximum water levels when analysing or presenting flood maps, or
- creating an additional hydraulic simulation scenario initialised by maximum flood level results, as described by Wallace (2011), when addressing uncertainty of peak water levels in large channels.

Different levels of freeboard are applied in different locations and in different settings throughout the Bay of Plenty (*see* Bay of Plenty Regional Council, 2018b). In deciding an appropriate freeboard, the following factors are considered.

- The largest freeboard allowances should be used in simpler analyses and as the sophistication and scope of the analysis and quality of input data increases, freeboard allowances can be reduced.
- Freeboard approaches including spatial location to be considered.
- Existing requirements (Bay of Plenty Regional Council, 2018b).
- Urban versus rural land uses.
- Traditionally, a fixed freeboard was (e.g. 1' or 300 mm, 2' or 600 mm etc) used. Now days 300 mm or 500 mm is commonly applied. More sophisticated approaches can consider the amount of uncertainty in model parameters and sensitivity of results to those parameters.

Minimum Floor Levels are set by TLAs with consideration to the New Zealand Building Code, the Resource Management Act, the applicable District Plan and the latest flood hazard information available.

4.13 Groundwater interactions

Commonly hydraulic models are only concerned with surface water or reticulated flows. Situations where groundwater has a significant impact on surface water include:

- where surface elevations are close to mean sea level,
- where the groundwater table has exceeded the ground level during historic events,
- where previous studies have highlighted the role of groundwater in flooding, and
- in the vicinity of wetlands, springs and lakes.

In hydraulic models, the interaction of surface water with groundwater, if accounted for, has traditionally been accounted for through boundary conditions such as:

- reduction in hydrological losses (elevated antecedent moisture conditions), either initial or continuing losses,
- including an upper limit on soil storage capacity,
- constant baseflows into the head of water courses,
- distributed inflows along open channels,
- point inflows simulating leakage into low-lying chambers (e.g. pump stations, manholes), or
- a water surface level.

A key difficulty in including groundwater in a surface water model is the disparity in time scales of the two systems: surface flood waters respond in minutes or hours, whereas groundwater responds over tens of hours up to days or weeks.

Correctly treating the interactions between groundwater and surface water is complex and requires additional levels of attention and review around methods and assumptions. Assumptions and constraints should be clearly reported and accounted for in any analysis. In general, groundwater effects can be effectively considered to be constant for the period of most simulations (a day or so), however, when the simulated period extends to more than 24 hours then variation in groundwater may become important. Consider the scale of groundwater effects relative to river flow, and also groundwater treatment in generation of any hydrological boundary conditions (base flow).

4.14 Natural features

Table 19 lists many key types of natural features and recommendations for how they be represented in hydraulic models.

Table 19 Approach of natural features.

Type	Description	Recommendations
Confluence	The location where two or more open channels merge and flow is combined.	1D branch connections are sufficient when the main channel is much larger than the connecting side branch. 1D models do not conserve momentum at confluences and so cannot be relied upon to predict water levels in the vicinity: a 2D model, as a minimum, is required where water level estimation is critical at confluences.
River mouth	The location where an open channel or river joins to a large water body.	River mouths often coincide with downstream boundaries. Flow behaviour at the river mouth should be accounted for in order to correctly reproduce back water effects. Consider model sensitivity to river mouth shape, any mouth scour during flood events, and pre and post flood geometry.
Pond	Ponds may be natural but also the results of artificial or modified environments. The key aspects to ensure they are modelled correctly will be storage volume, discharge curves and any representation of outflow such as from channels, culverts, orifices or weirs.	When storage is of primary concern, representing the flood prism (volume above usual water level) is sufficient. When representing conveyance, the pond bathymetry should be accounted for.

Type	Description	Recommendations
Wetland	An area of land that is saturated with water.	Unless extremely dry conditions are simulated, hydrological loss should be set to zero. Due to thick vegetation and uneven topography, high flow resistance values should be used: Manning's n > 0.1 (estimated from Arcement and Schneider, 1989). The groundwater table reaches or surcharges the ground surface in this area and so can indicate the groundwater table elevation in the vicinity.

4.15 Flow resistance

Flow resistance, often referred to as *roughness*, accounts for a significant portion of energy loss in flowing water. For this reason, resistance parameter sets (composed of Manning's n values) are important aspects of a model. The table below summarises the appropriate sources for developing initial estimates of resistance parameter sets for a range of applications. This should then be refined during model calibration but should still be within typical ranges.

Table 20 Sources for flow resistance parameter sets.

Application	Source
Pipes and closed conduits	Manning's Roughness Coefficients (from "Urban Drainage Design", Sutherland Shire Council, Sydney 1992) shown in Figure 6.
Open channels and streams	Figure 6 and Cowan's (1956) procedure for estimating roughness coefficients, as presented by Arcement and Schneider (1989) and by Ven Te Chow (1959). Resistance estimates produced by Cowan's procedure should be compared with values in Figure 6.
Rivers and canals	Mason and Hicks (1998) provides hydraulic parameters for a range of New Zealand rivers. A depth-varying resistance must be considered. Barnes (1967) provides further guidance and additional resources for selecting appropriate resistance estimates.
Steep gravel beds	Gary Williams gravel bed formula (Manning's n) is as follows: $\mathrm{n} = 0.104 \times \mathrm{S}^{0.178}$ where: S is slope in m/m.
Flood plain	Figure 6 and Cowan's procedure for estimating roughness coefficients, as adapted by Arcement and Schneider (1989). Resistance estimates produced by the modified Cowan's procedure should be compared with values in Figure 6.
Buildings	A Manning's n of 5.0 should be applied to the footprint of any building that has not been removed from the model domain. This represents the obstacle to flow without removing flood volume from the floodplain (Syme, 2008).
Dunes	Arcement and Schneider (1989) provide some guidance on when dunes may form and their impact on bed resistance.

I Closed Conduits:

A Concrete pipe 0.011-0.013
B Corrugated metal pipe or pipe arch:
  1 68 mm by 13 mm corrugation 0.24
  2 150 mm by 50mm corrugation (field bolted) 0.030
C Vitrified clay pipe 0.012-0.014
D Cast iron pipe, uncoated 0.013
E Steel pipe 0.009-0.011
F Brick 0.014-0.017
G Monolithic concrete
  1 Wood forms, rough 0.015-0.017
  2 Wood forms, smooth 0.012-0.014
  3 Steel forms 0.012-0.013

II Open Channels, lined (straight alignment):

A Concrete, with surfaces as indicated:
  1 Formed, no finish 0.013-0.017
  2 Float finish 0.013-0.015
  3 Float finish, some gravel on bottom 0.015-0.017
  4 Gunite, good section 0.016-0.019
  5 Gunite, wavy section 0.018-0.022
B Concrete, bottom flat finished, sides as indicated:
  1 Random stone in mortar 0.017-0.020
  2 Dry rubble (rip rap) 0.020-0.030
C Gravel bottom, sides as indicated:
  1 Formed concrete 0.017-0.020
  2 Random stone in mortar 0.020-0.023
  3 Dry rubble (rip rap) 0.023-0.033
D Brick 0.014-0.017

  1 Random stone in mortar 0.017-0.020
  2 Dry rubble (rip rap) 0.020-0.030
C Gravel bottom, sides as indicated:
  1 Formed concrete 0.017-0.020
  2 Random stone in mortar 0.020-0.023
  3 Dry rubble (rip rap) 0.023-0.033
D Brick 0.014-0.017

III Open channels, excavated (straight alignment, natural lining):

A Earth, uniform section:
  1 Clean, after weathering 0.018-0.020
  2 With short grass, few weeds 0.022-0.027
  3 In gravelly soil, uniform section, clean 0.022-0.025
B Earth, fairly uniform section:
  1 No vegetation 0.022-0.025
  2 Grass, some weeds 0.025-0.030
  3 Dense weeds or aquatic plants in deep channels 0.030.0.035
  4 Sides clean, gravel bottom 0.025-0.030
  5 Sides clean, cobble bottom 0.030-0.040
C Dragline excavated or dredged:
  1 No vegetation 0.028-0.033
  2 Light brush on banks 0.035-0.050
D Rock:
  1 Smooth and uniform 0.035-0.040
  2 Jagged and irregular 0.040-0.045
E Channels not maintained
  1 Dense weeds, high as flow depth 0.08-0.12
  2 Clean bottom, brush on sides 0.05-0.08
  3 Clean bottom, brush on sides, highest stage of flow 0.07-0.11
  4 Dense brush, high stage 0.10-0.14

IV Highway channels and swales with maintained vegetation: (values shown are for velocities of 0.6 m/s and 1.8 m/s)

A Depth of flow up to 210 mm
  1 Good stand, any grass:
    (a) Mowed to 50mm 0.045-0.07
    (b) Length 100 mm to 150 mm 0.05-0.09
  2 Fair stand, any grass:
    (a) Length about 300 mm 0.08-0.14
    (b) Length about 600 mm 0.12-0.25
B Depth of flow 210 mm to 460 mm:
  1 Good stand, any grass:
    (a) Mowed 50 mm 0.07-0.12
    (b) Length 100 mm to 150 mm 0.10-0.20
  2 Fair stand, any grass:
    (a) Length about 300 mm 0.06-0.10
    (b) Length about 600 mm 0.09-0.17

V Street and Expressway Gutters:

A Concrete gutter, trowelled finish 0.012
B Asphalt pavement
  1 Smooth texture 0.013
  2 Rough texture 0.016
C Concrete gutter with asphalt pavement:
  1 Smooth 0.012
  2 Rough 0.013
D Concrete pavement:
  1 Float finish 0.014
  2 Broom finish 0.016
E For gutters with small slope, where sediment May accumulate increase above values of n by 0.002

VI Natural stream channels

A Streams
  1 Fairly regular section
    (a) Some grass and weeds, little or no brush 0.030-0.035

May accumulate increase above values of n by 0.002

VI Natural stream channels

A Streams
  1 Fairly regular section
    (a) Some grass and weeds, little or no brush 0.030-0.035

    (b) Dense growth of weeds, depth of flow greater that weed height 0.035-0.05
    (c) Some weeds, light brush on banks 0.035-0.06
    (d) Some weeds, heavy brush on banks 0.05-0.07
    (e) Some weeds, dense willows on banks 0.06-0.08
    (f) For frees within channel, with branches submerged at high stage increase all above values by 0.01-0.02
B Flood plains, adjacent to natural streams
  1 Pasture, no brush
    (a) Short grass 0.030-0.035
    (b) High grass 0.035-0.05
  2 Cultivated areas:
    (a) No crop 0.03-0.04
    (b) Mature row crops 0.035-0.045
  3 Heavy weeds, scattered brush 0.05-0.07
  4 Light brush and trees:
    (a) Winter 0.05-0.06
    (b) Summer 0.06-0.08
  5 Medium to dense brush
    (a) Winter 0.07-0.11
    (b) Summer 0.10-0.16
  6 Dense willows 0.15-0.20

Note: The value of n for natural channels must be increased to allow for the additional energy loss caused by bends. The increase may be in the range of perhaps 3 to 15 percent.

Figure 6 Manning's Roughness Coefficients (from "Urban Drainage Design", Sutherland Shire Council, Sydney 1992).

4.16 Scenarios

Models are used to simulate particular scenarios, typically for existing environmental settings and to forecast flooding in future planning horizons. A scenario can be broken down (Table 21) into a context for the scenario (e.g. environmental conditions) and the model's response configurations (geometry and behaviour).

The “base” model, or baseline scenario, is usually the existing environment and state of the catchment. All other scenarios can be considered “project” studies for a particular purpose and are defined in terms of deviations from this baseline in context, geometry or behaviour.

Table 21 The components of a modelling scenario that can be altered to convert a base model to a future development scenario, future climate scenario, options assessment of other hypothetical situations that a hydraulic model seeks to investigate.

Scenario component	Description	Example
Environment	A consistent set of boundary conditions (model forcings) and initial conditions that represent the influence of the environment that the model is embedded in. A particular environmental context may be composed of multiple sub-scenarios, each in turn composed of a specific arrangement of boundary conditions.	Historic storm event (e.g. Cyclone Debbie in April 2017): • rain gauge rainfall measurements; and • tide gauge measurements. Existing climate design scenario boundary conditions: • rainfall timeseries informed by 1% AEP/100 year-ARI depths distributed across a nested storm temporal pattern, • tidal timeseries informed by a representative tidal pattern offset raised to align with 5% AEP/20 year-ARI storm tide and wave setup peak water levels, and • antecedent moisture conditions
Geometry	The spatial description of the model.	Overland flow model surface. Open channel cross sections and alignments. Pipes and other structures.
Behaviour	Model parameters and related relationships.	Pump curves or control strategies. Timed breach development during historic storm events Level-triggered breach development during design events.

4.17 Joint probability

A joint probability approach is applied when developing a suite of sets of correlated boundary conditions and other parameter sets for a particular context: Ball *et al.* (2019d) discuss the theory and application and Ball *et al.* (2019b) covers increased detail on this topic. The goal of the approach is to produce an unbiased estimate of flooding. It should be noted that flooding in only some areas of a model domain will be influenced by interaction of different boundary conditions.

For practicality purposes, a reduced set of all possible boundary condition types are considered for design storm events in the Bay of Plenty. An approach that resembles a simplified *Ensemble Event*, as described by Ball *et al.* (2019b) should be applied. A Monte Carlo approach may be warranted in high value or risk situations but will most likely be limited to hydrological analysis for practical reasons (large number of simulations required). A list of boundary condition types is provided in Table 22.

Currently for Bay of Plenty, only rainfall, sub-catchment runoff, river inflow and tidal (including storm surge) conditions are considered in the design of joint-probability scenarios (Bay of Plenty Regional Council, 2012). Correlation between precipitation and storm surge is expected to increase with more extreme events as the storm system increases in size. Climate change will have some impact on each of the phenomena in Table 22 and it is assumed that in future climate scenarios the correlation between phenomena does not change.

Table 22 Considerations for joint probability.

	Phenomenon	Interaction with other phenomena
1	Precipitation, sub-catchment runoff and river/stream inflows	Rainfall is the principal predictor of flooding and is treated as the preliminary boundary condition. Runoff from nearby sub-catchments may be produced by same storm event. River base flows may be elevated due to recent precipitation and so are correlated with AMC.
2	Storm surge and wind setup	Is generally caused by same storm as precipitation and so a significant correlation is expected.
3	AMC	Wetter AMC results in greater local runoff and flood volume than would be expected for a particular storm event.
4	Discharge peak timing	The worst-case scenario of peak tide coinciding with peak discharge from rivers or floodplains. Currently variability of coincidence with tidal cycles is not accounted for other than the worst case where peaks align. Approximation is best suited to situations in which discharge peaks over many hours.
5	Stopbank breach	Stopbank failure is a function of ground state, soil strength, and adjacent flood levels. Currently stopbank failure probability is not factored into joint probability scenario design and is treated separately.
6	Groundwater	Groundwater levels may be considered as highly correlated with AMC.

7	Flow resistance	Seasonal variation in land use is relevant for rural land when a distinction between summer and winter storms is made. River channels and drains are also affected by vegetation growth and maintenance.

Bay of Plenty Regional Council (2012) stipulates the pairings of precipitation and storm surge boundary conditions as represented in Table 23. All other phenomena are considered to occur in their most-likely states.

Table 23 Joint probability between precipitation and storm surge for different AEP scenarios (adapted from Bay of Plenty Regional Council, 2012).

Scenario	Sub-scenario	Precipitation or flow	Storm surge	Other phenomena
0.2% AEP	Rainfall/flow-dominant	0.2% AEP	1% AEP	~1% (>=0.2%) AEP
0.2% AEP	Tide-dominant	1% AEP	0.2% AEP	~0.2% (>=0.2%) AEP
1% AEP	Rainfall-dominant	1% AEP	5% AEP	~5% (>=1%) AEP
1% AEP	Tide-dominant	5% AEP	1% AEP	~1% (>=1%) AEP
2% AEP	Rainfall-dominant	2% AEP	5% AEP	~5% (>=2%) AEP
2% AEP	Tide-dominant	5% AEP	2% AEP	~2% (>=2%) AEP
5% AEP	Rainfall-dominant	5% AEP	50% AEP	~50% (>=5%) AEP
5% AEP	Tide-dominant	50% AEP	5% AEP	~5% (>=5%) AEP
10% AEP	Rainfall-dominant	10% AEP	50% AEP	~50% (>=5%) AEP
10% AEP	Tide-dominant	50% AEP	10% AEP	~10% (>=10%) AEP

Deciding on the AEP of additional inflows from tributaries or other sources peripheral to the area of interest (right-most column in Table 23) relies on the following considerations:

- proximity of catchments increases correlation,
- areal reduction factors and hydrological characteristics will alter correlation,
- storm size and location,
- that the combinations of boundary conditions provide upper and lower bounds of the expected behaviour for the AEP,
- relation of storm to catchment system size,
- AEP flows from neighbouring small catchments of similar size, alignment and land cover should be strongly correlated as storms are likely to affect both equally, and
- a large disparity in catchment sizes should reduce the strength of correlation.

Climate Change

The Bay of Plenty Regional Policy Statement (Bay of Plenty Regional, 2018a) sets out the broad regional policy for climate change, including the Council position on future temperature and sea level rise projections. Policy NH 11B of this policy includes the statement "*Authoritative up-to-date projections of changes in sea level … will be used as updated scientific data become available*." Maltai *et al.* (2019) has subsequently applied new national guidance to the Bay of Plenty and new projections are adopted by BOPRC as a requirement for future temperature and sea level rise values in the BOP for Councils regulatory, engineering and scientific technical processes.

As climate change guidelines get updated regularly to provide the most up to date information, the latest climate change requirements are listed in the Supporting documentation of this guideline document on BOPRC's website.

4.18 Structures and assets

Different structures and assets will be modelled in a range of ways depending on software and their role in the specific model. Examples include artificial wetlands, storage ponds, dams, canals, drains, ripraps and stopbanks. Depending on the modelling purpose and scale, more or less detail will need to be included, influencing which structures and assets are modelled.

Urban drainage infrastructure

The model-build methodology for urban areas should consider both BOPRC guidance and local Territorial Local Authority guidance. Where this is not available, guidance from elsewhere in the region should be applied. Where flood levels will inform minimum floor levels for construction, it is crucial that guidance is sought from BOPRC and the local Territorial Authorities with consideration to the New Zealand Building Code, the Resource Management Act, the applicable District Plan and latest information available.

Bridges

The representation of bridges should include appropriate losses to account for the hydraulic profile across the structure. There are two scenarios for bridges:

- where there is limited constriction of flow, and
- where there is significant restriction of flow under the bridge.

Where there is limited restriction, this is generally modelled as an open channel with pier and bridge losses which may be conceptualised as depth varying form loss or increased roughness. Where there is significant flow restriction, an appropriate bridge structure should be used: Hunt and Brunner (1995) discuss suitable approaches. The use of a large culvert structure may be appropriate as this simplifies the description of losses. Features of different software will influence options available. In absence of calibration data, check afflux results for critical bridges against hand calculations or other methods.

Buildings

Including buildings in a model results in using building footprint information to mimic likely water flow effects (Table 24). Levels of available information will vary and the need to include buildings will depend on the scale and purpose of the model. See Syme (2008) for additional information.

Table 24 Approaches for building structures in models.

Building type	Recommendations
Large buildings that displace significant water and unlikely to flood	Treat as voids, land or other method to remove from flood plain. If runoff from this site will impact overall purpose of the model, this will need to be accounted for. This can include modelling the building as a sub-catchment.
All other buildings that may flood	Two options are suggested and depend on how much building information is available: 1. If you have information on slab construction, raise the building footprint with a flattened surface to known building floor level, this will cause some buildings to flood and some not. Also increase roughness over building surface (Manning's n = 5). 2. If you have limited information, or a building has pile foundations, then raise the building surface 100 mm above surrounding ground and increase roughness over building surface (Manning's n = 5).

Pump stations

Depending on the location of pump stations, they can be represented within the one- or two-dimensional model components. The level of detail that pump stations are represented in depends on the available feature of the modelling software and importance of the pump station within the broader model purpose. Kapiti Coast District Council (2020) recommends where possible that pump capacity should be based on manufacturer's capacity curves and that the pumps performance should, where possible, be confirmed on site by drawdown tests. However, in large rural areas dozens of public and private pump stations may exist and this might not be practical, cost effective or even possible.

Any limitations, constraints or assumptions with information about pump stations or ability to model them accurately need to be reported and considered when interpreting results. For example, pumps are important to drain land after flooding and if they are not included, the model will predict flooding for longer than expected in reality. This can be addressed when interpreting results if the limitation is reported clearly.

Culverts

Critical culverts should be identified and cross check calculations produced for a range of water levels using methods such as culvert hydraulic analysis (e.g. HY8 software by the U.S. Federal Highway Administration). Realistic upstream and downstream cross sections will be required to simulate inlet and outlet losses.

For smaller and less critical culverts, GIS, survey or as built data can be used and cross sections upstream and downstream of the culvert can be estimated from the surface model. Head loss parameters may be adjusted where there is justification to do so.

Where the barrel losses exceed the entry and exist losses the culvert is considered a "long" culvert and the culvert should be represented as a pipe network or a reach of closed cross sections with suitable entry and exit losses. This will improve the flow description along the pipe and allow for more accurate estimates of flood wave propagation.

Overtopping of culverts can occur and treatments such as including a weir over the culvert may be required. This will be dependent on the software platform in use, the environment around the culvert, whether a one- or two-dimensional model is used and whether the culvert is long or short.

Breaches

Breaches are represented by dynamic structures in the model that allow for varied flow throughout the simulation. There are two main types:

- timed breach used for historic simulation, and
- trigger level breach where simulated variables such as depth and velocity may trigger initiation of a breach.

Breaches are defined by time series of geometric parameters such as width and crest level and can be represented as specific “dam-break” type structures in one dimensional models or as dynamic topography (or weir/dike structures) in two dimensional model domains. Geotechnical sources should be consulted to determine breach type (overtopping or piping failure), and evolution (in both time and shape).

Breaches are not included in joint-probability-event design.

4.19 Complex hydraulic phenomena

Bend losses

Hydraulic energy losses at bends in open channels are a localised phenomenon that have diminishing effects on flow with increasing distance from the bend in both subcritical and supercritical flow regimes. Bend loss effects may be difficult to distinguish from those of other model features such as cross section variation or flow resistance (roughness) estimates. As such, the decision to include bend losses, and the associated additional model complexity, must be weighed against verifiable improvements in model accuracy.

Where open channel bend losses are significant, the following approach for calculating energy loss, taken from Henderson (1966), is recommended. This approach is expected to overestimate losses by up to four times in some situations, particularly where secondary currents are suppressed but as bend losses are generally minor effects this error is not significant.

$$h_f = C_L \frac{V^2}{2g}$$

$$C_L = 2\frac{b}{r_c}$$

Where:

h_f is energy loss (in terms of hydraulic head) around bend,
C_L is head loss coefficient,
V is average velocity in channel,
g is acceleration due to gravity (9.81 m/s^2),
b is the channel flow width, and
r_c is the radius of curvature of the bend measured from the channel centreline.

The approach detailed in Chow (1959) and shown below is more complicated and should be used in spot checks.

Cross-flow from river berms to main channel

The cross-flow from the main channel to adjacent berm channels inside stopbanks can influence water levels results and needs consideration in the model set up. A hybrid 1D-2D approach to modelling flows is common and three primary use cases are described below.

The first scenario (Figure 7) is for large channels confined by stopbanks where flow is slow and roughly parallel to the internal boundary between the 1D and 2D model domains. The location of the internal boundary is recommended to be at the transition between the high and low flow banks. In this instance it is desirable that flow patterns on the high flow bank are resolved in the 2D model. If water becomes too deep at the location of exchange, instabilities in the coupling may arise.

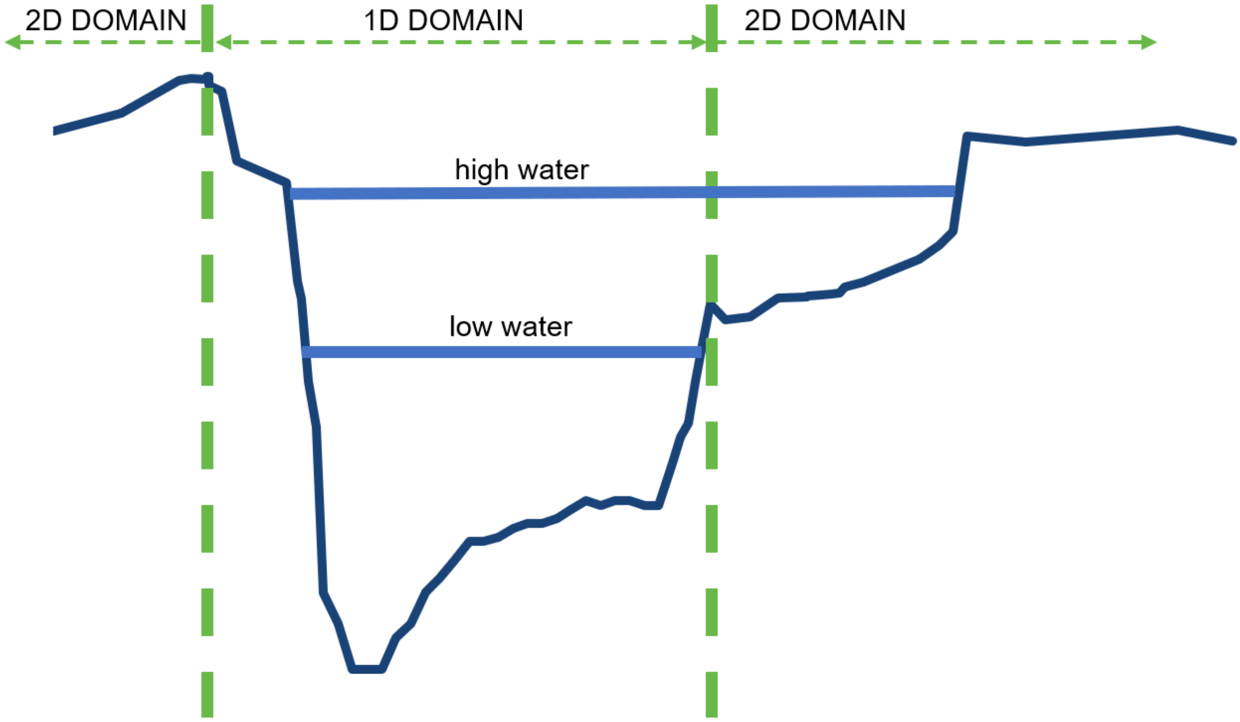


Figure 7 Cross flow scenario where complex 2D patterns need to be represented on high flow banks.

The second scenario (Figure 8) needs to be considered where 2D flows are generally directed towards the internal boundary between 1D and 2D (overland flow is directed perpendicular to the channel alignment). This is common in field drains that cut across the natural fall of the land surface. Where possible, the head loss across the drains should be reviewed and effects minimised or explained.

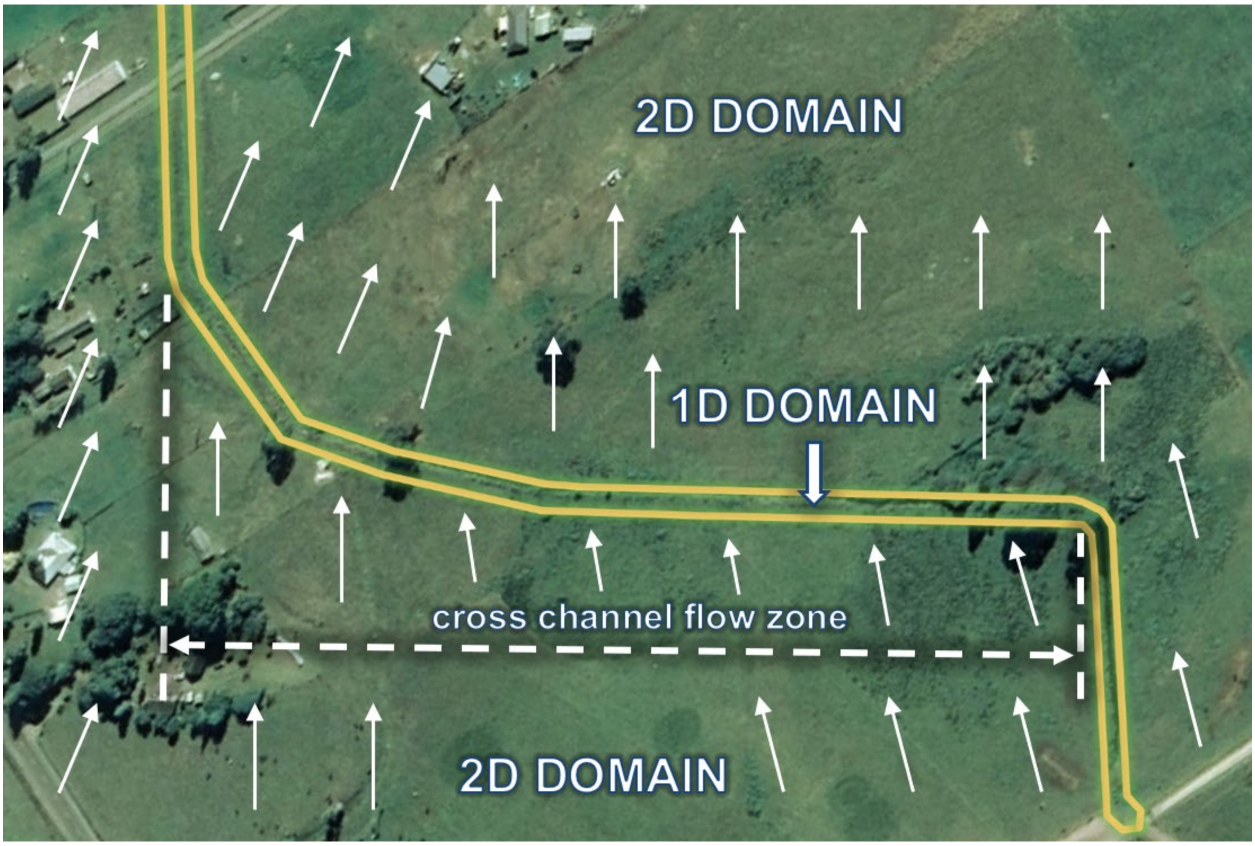


Figure 8 *Cross flow scenario where 2D flows are perpendicular to the channel.*

The third scenario (Figure 9) is where there are large channels confined by stopbanks and the internal boundary between 1D and 2D model domains is aligned with stopbank crests. Weir flow across the stopbank crest at the point exchange is appropriate in this situation, particularly as the flow may be very shallow.

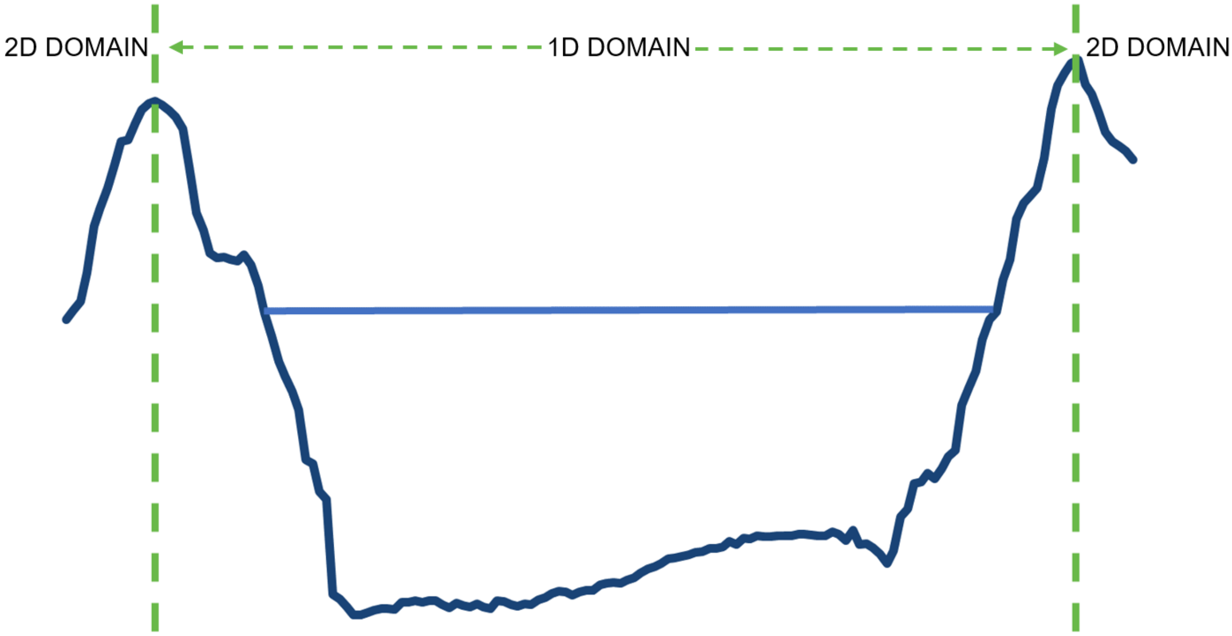


Figure 9 *Cross flow scenario where the 1D domain is confined to the stopbanks.*

A solely-2D approach is appropriate to use where there is significant exchange of flow between the main channel and high-flow banks, a phenomenon common in meandering channels. In this situation, the conservation of momentum is crucial in distributing flow between the channel and banks, particular as flow resistance on banks due to uneven ground, vegetation or other obstacles will be considerably higher than that in the main channel. An incorrect distribution of flow can lead to artificially elevated flow resistance in the main channel during the calibration process. It is recommended that channels are resolved by at least five 2D elements across the width.

Note that techniques are available for controlling grid cell size locally as well as incorporating high resolution topographic information into coarser grid cells. This is particularly useful around complex topographic features such as river channels. These techniques are well suited to representing flow in rapidly varying geometries, while avoiding the need for 1D components.

Dunes

Dunes on the channel bed form where bed material is mobile and the flow is subcritical; anti-dunes form where bed material is mobile, the channel is steep and the flow is super-critical. They are dynamic bed forms that may only exist for a portion of a flood's duration. Dunes may form in channels near the coast and have been speculated to be present in rivers in the Bay of Plenty during flood events. They increase flow resistance and hence raise upstream water levels.

Arcement and Schneider (1989) provide guidance on assessing dune bed forms in sandy channels using stream power and bed material grain size criteria. This approach should be used to determine whether it is reasonable to increase flow resistance (in order to calibrate or validate a model) where it is suspected that dunes are forming in a channel. The magnitude of the resistance increase may be cross checked against the formula for Manning's n provided in Arcement and Schneider (1989).

Superelevation

Superelevation is the phenomenon of a transverse grade in water surface at bends in open channels where flow is subcritical. Water becomes elevated above the average channel level on the outside of the bend and becomes depressed on the inside of the bend. Depending on the criticality or complexity of flow at a particular bend in a river or open channel the following approaches are recommended in order of decreasing preference.

1. The bend and channel reaches upstream and downstream are simulated using a 2D model, solving the full shallow water wave equations, where the channel is resolved with at least five elements across the breadth.
2. The variation in water surface elevation across the breadth is approximated using the following calculation, which is taken from Chow (1959).

$$\Delta h = \frac{C^2}{2g{r_o}^2{r_i}^2}({r_o}^2 - {r_i}^2)$$

$$Q = C\left(E - \frac{C^2}{2g{r_o}^2{r_i}^2}\right) ln\frac{r_o}{r_i}$$

Where:

Δh is the water surface variation across the open channel,
C is the circulation constant from the law of free-vortex motion (to be calculated implicitly from the second equation,
g is the constant of gravitational acceleration (9.81 m/s^2),
r_o is the radius of curvature of the outside edge of flow in the channel,

r_i is the radius of curvature of the inside edge of flow in the channel,
Q is the flow/discharge, and
E is the specific energy at the radial section passing through the point of maximum surface depression on the inside of the curve (Chow (1959) provides further guidance on how to locate this section).

For angles of the bend less than 90°, the circulation constant (C) should be scaled by the following factor:

$$\frac{\theta}{90°} + \left(1 - \frac{\theta}{90°}\right)\left(\frac{r_c V_m}{C}\right)$$

Where:

V_m is the mean streamwise velocity in the channel; and
r_c is the radius of curvature of the centreline of the channel.

The variation in water surface elevation across the breadth is approximated using the following equation. Note that this approximation does not taken the extent of the bend into account, and assumes the variation in both the radius of curvature and streamwise velocity is negligible across the channel breadth. This equation from Chow 1959 should be cross checked with the calculation provided above.

$$\Delta h = \frac{{V_m}^2 b}{g r_c}$$

Where:

Δh is the water surface variation across the open channel,
V_m is the mean streamwise velocity in the channel,
b is the breadth of the water surface through the bend,
g is the constant of gravitational acceleration (9.81 m/s^2), and
r_c is the radius of curvature of the centreline of the channel.

In a recent studies such as the Waipaoa River, Webby (2002) and the Hydraulic modelling of lower Whakatāne River Floodplain, Wallace (2004) a modified version of the above formula was used based on recommendations by the USACE (1994).

$$\Delta h = \frac{0.5\ {V_m}^2 b}{g r_c}$$

In cases of supercritical flow, the modified Chow formula is recommended. In general, it is expected that cross waves create an interference pattern that causes undulations in the water surface around the bend with peaks twice that expected if the flow were subcritical.

4.20 Calibration criteria

Ball *et al.* (2019b) defines some key calibration criteria to be considered when determining if a calibration will be accepted or not. These criteria are reproduced in Table 25 but are subjective and require expert consideration in relation to the broader purpose of the model study.

Table 25 Considerations for evaluation of model calibration quality (adapted from Ball et al., 2019b).

Criteria	Discussion
Accuracy of calibration data	The quality of calibration will depend on the assessed accuracy of the calibration data. For example, if the calibration of a hydraulic river model is based on flood levels from observed debris marks, these levels may not be more accurate than ± 300 mm, so working towards matching a number of levels to a higher level of accuracy cannot be justified. Even where there is a streamflow gauge located on the catchment, the quality of the measured discharge will depend on the quality of the rating curve, which could cause quite significant inaccuracy in this measured data. In some cases, a quantitative assessment of calibration fit can be helpful to understand accuracy, such average difference from peak debris levels. For a floodplain model a higher level of accuracy may be required. Photogrammetry, drone or other photography, video imagery also recommended to be collected during or after the flood event which can be used for the calibration.
Representativeness of calibration data	Calibration data may not be representative of the floods required for application of the model. For example, it is often the case that calibration floods are relatively frequent while design applications require much rarer floods. In this case, the value of refining the model calibration extensively to the frequent floods cannot be justified. Sometimes the parameters are different for the design floods. This needs to be appropriately considered in the modelling or the imprecision component has to be adjusted.
Number of calibration events	The quality of calibration depends on the representativeness of the data and an important factor in this area is the number and range of events with suitable calibration data. In some cases, there may be only a single frequent flood event available for calibration and in this case, the quality of calibration will be poor especially where the model must be extrapolated to rare design events. When a model can be calibrated to several different flood events of a range of sizes and covering a range of different conditions (such as rainfall distribution or season), the resulting model can be applied with much more confidence than is possible where the data is limited. Ideally a range of three flood events is desirable.
Model response and catchment consistency	The calibration of models relies on the available data and the estimated parameters are based on the data used to estimate the parameters. However, the catchment conditions that are applied during model calibration, especially if rare historic floods have occurred, may not be completely representative of conditions required for design applications. Because of this the model parameters required for design should be "generic" parameters based on the calibration but applicable for the design application. The exact catchment conditions for design applications may not be consistent with the particular conditions that applied for the calibration process. For example, vegetation coverage on a floodplain or the channel conditions in water courses will vary from time to time, so the conditions that applied for a single calibration flood

Criteria	Discussion
	event may not be representative of long term average conditions. Parameter values therefore must be modified to account for the expected future design conditions, rather than an unrepresentative calibration event.
Consistency of data	Review of data may indicate that the recorded data is inconsistent. For example, recorded flood levels for two different floods may be impossible to model with the same parameter set. There are several possible reasons for this case. For example, the recordings may be inaccurate, the catchment or floodplain may have changed between flood events or the model may be being used for an application inappropriate for the purpose of the model. The effort should then be concentrated on resolving the source of the inconsistency rather than pursuing further calibration.
Requirements for model	The calibration acceptance may vary depending on the application required. For example, if the model is required for a bridge design, the calibration is only really critical for the bridge site, but model performance over a wider extent of the catchment is needed for floodplain planning. Also if the model is required for assessment of frequent floods, the performance for major overbank flooding is not as relevant so poor performance for these events is not a serious concern.
Overfitting	This is the process where the model calibration process is taken to an extreme, and the model parameters are extended to possibly unrealistic values and can vary unrealistically throughout a catchment or floodplain to ensure that the model fit is close for all data points and all events. This situation may result when there are unrealistic calibration acceptance criteria adopted for the project and the only way of meeting the criteria is by an extreme and unrealistic parameter set. While the resulting model calibration may appear to be high quality and does meet calibration performance criteria, the resulting model parameters will not improve the performance of the model for extrapolation to the design situation.

4.21 Model stakeholders and communication considerations

Table 26 Considerations for presenting modelling results to different stakeholders (adapted from Ball et al., 2019b).

Stakeholder	Communication and reporting considerations
Client or consent applicant	Provide full reporting that outlines the whole scope of work and full technical details in case in-depth analysis is required by a specialist in the future. Emphasise main issues and findings clearly. Provide full commentary on limitations, assumptions, accuracy and reliability. Focus report on requirements of the broader planning, engineering design or flood risk initiative the model is supporting. Provide full detail from the model plan report**, and** model build report. Provide model, results, GIS information and maps for archiving.
Council or other regulatory authority	Provide full reporting that outlines the whole scope of work and full technical details in case in-depth analysis is required by a specialist in the future. Emphasis on establishing as base model for baseline purposes Full commentary on limitations, accuracy and reliability Report is focused on main requirements: Base model Optioneering Scenario Full detail on methodology and demonstration of fitness to requirements Council archives full report, model and results for future use and reference
Land owners and community	Emphasis on issues with direct impact on individuals Report is focus on the main requirements: • impacts to local community • mitigation of flooding • Easy to understand language providing basis of technical credibility and sources for further details
Other Stakeholders	Emphasis on issues with direct impact to a particular area or catchment Report is focus on the main requirements: • impacts to local community • mitigation of flooding • Easy to understand language but with higher substantial technical standards

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Glossary of Terms

This glossary of definitions was evolved from a list initially published in Kapiti Coast District Council (2020).

Term	Definition
1D	One dimensional means only one spatial dimension is considered, i.e. the longitudinal direction of flow
2D	Two dimensional means two spatial dimensions are considered i.e. the horizontal and lateral (x and y) directions of flow.
2D surface	The surface which is used in the model for 2D flow computations
Annual Exceedance Probability (AEP)	The probability that a given event will be exceeded in a single year.
Antecedent Moisture Conditions (AMC)	The degree of saturation of hydrologic or hydraulic models at initialisation of the simulated period of interest.
Average Recurrence Interval (ARI)	Average period of time between rainfall events or flow rates which exceed a certain magnitude.
Base model	A fully built, calibrated and validated model that is ready to be used for a range applications. Boundary conditions may be included with the model files so that model may run, however these are not considered part of the base model.
Behaviour scenario	How the model is configured to behave. It related to the range of states, and the transitions between states, that a (hydrological/hydraulic) system exhibits in response to inputs (boundary conditions). For example, representing a pump station failure.
Calibration	Process of modifying model schematisation and parameterisation in order to align simulation results with field measurements from a historical event.
Catchment	An area of land draining by force of gravity to a given location.
Climate change	Climate change resulting from global warming due to greenhouse gas emissions.
Dynamic Adaptive Pathway Planning (DAPP)	An assessment tool for developing climate change adaptation options to help decision makers during policy development. Ministry for the Environment (2017) is related to **Error! Reference source not found.** and states that the DAPP approach is built on the notion that decisions are made over time in dynamic interaction with the system itself and cannot be considered independently or predetermined.
DEM	Digital Elevation Model representing the surface elevation of the catchment.

Term	Definition
Design storm	The rainfall event calculated from historical record that can be expected for a specific AEP or ARI.
Design flows	The flow estimated from various design storms, selected as a basis for the design of works in watercourses and catchments
Existing development [ED]	The land development within the catchment at the time of model development
Energy grade line [EGL]	The total energy of flow at a given location. It is the sum of the elevation head, the pressure head, and the velocity head. This is also referred to as the total energy line (TEL).
Energy loss	Energy or head loss occurs due to frictional resistance, contraction and expansion at entrance and exit, change in flow direction, change in elevation and change in cross-section.
Environment scenario	A consistent set of boundary conditions (model forcings) and initial conditions that represent the influence of the environment that the model is embedded in.
Floodplain	The plan extent of flooding in a given AEP or ARI storm.
Freeboard	Freeboard is an additional vertical offset added to maximum water levels when analysing or presenting simulation results. Freeboard clearance is a standard engineering provision for estimating data imprecision and uncertainty of results plus phenomenon that are not explicitly included in the hydraulic calculations (e.g. waves, aggradation, bend effects and debris blockage and passage). Even the most sophisticated design techniques are unlikely to exactly predict complex hydraulic scenarios.
Geometry	A mathematical model comprised of coordinates and elevations representing the surfaces of a catchment, waterbodies and flow paths. This includes the shape of the land, obstacles to flow, rivers and storage volumes for ponds, lakes and wetlands.
GIS	Geographical Information System.
HEC-1 / HEC HMS software	Suite of software that provides a wide range of hydrological and routing models for simulating hydrological catchment response.
HIRDS	NIWA's High Intensity Rainfall Design System for assessing rainfall depths at any point in New Zealand. It can be used for assessing storm rarity and for hydrological design purposes. See https://www.niwa.co.nz/software/hirds.
Horton's decay exponent (k)	Determines the dynamics of the infiltration rate reduction over time during a rainfall event.
Hydraulic Grade Line (HGL)	A line coinciding with the level of flowing water in an open channel. In a closed conduit flowing under pressure, the HGL is the level to which water would rise in a vertical tube at any point along the pipe. It is equal to the energy grade line (EGL) elevation minus the velocity head.

Term	Definition
Hydraulic phenomena	physical processes such as tides, currents, storm surges, circulations patterns, eddies, vortices, wave driven currents.
Hydrograph	A graph illustrating the variation of flow or water level with time.
Initial loss	A one-off loss which accounts for wetting of the catchment surface and defines the precipitation depth required for filling the depressions on the catchment surface before runoff can occur.
Interdecadal Pacific Oscillation (IPO)	A Pacific-wide climate weather pattern that straddles the equator and is associated with variation in precipitation across New Zealand acting on a decadal time scale.
Link	Link represents stormwater drainage pipes, culverts, bridges, stream channel reaches or overland flow paths. Some software may have specific definitions of this term also in the software solution domain.
Manning's "n"	Manning's coefficient is a lumped energy loss parameter representing losses in the flow between the sections used to define the water level slope. The Manning's number (M) is the inverse of Manning's "n" (i.e. $M = 1/n$).
Marginal probability ARR (e.g. Bell et al.)	The probability of occurrence of one component of a joint probability. For example, in a 1% AEP joint probability event the marginal probability of storm surge may be 1% or 5% depending on the particular sub scenario.
Master model	The same as a base model.
Mesh	The mesh defines the 2D surface. Mesh elements can be triangular, square or quadrangular.
Model extent	The outer most spatial extent of a model domain. The extent is often defined by landscape features, key phenomena and engineering structures.
Model domain	All real world spatial features and geometries represented by the model.
Moturiki Vertical Datum 1953 (MVD53)	Long term, regional, mean sea level-based datum in the Bay of Plenty, referenced to Moturiki Island, Mount Maunganui.
New Zealand Vertical Datum 2016 (NZVD16)	The official vertical datum for New Zealand and its offshore islands.
Node	Generally node represents drainage system attributes such as manholes, inlets, outlets, junction between open channels, ponds. Nodes can also be defined by different software, such as H points in MIKE11 where stage is calculated at different cross sections locations.
Overland flow	Stormwater runoff travelling downhill over the surface of the ground along the path of least resistance towards streams and watercourses or the sea.
Phenomenon	Physical environment process that needs to be simulated in the model to ensure robust hydraulic predictions.

Term	Definition
Planning horizon	A period of time into the future used in analysis of proposed construction. This period is stipulated by legislation, plans or is based on the expected design life of that being constructed.
Primary drainage system	The pipes, stream networks and open watercourses that carry the main, frequent stormwater within a catchment.
Representative Concentration Pathway (RCP)	Time-dependent projections of the impacts of climate change for four main scenarios (RCP8.5, RCP6, RCP4.5 and RCP2.6) that represent different rates and magnitudes of climate change as a basis for assessing the risk of crossing identifiable thresholds in both physical change and impacts on biological and human systems.
Runoff	The fraction of the rainfall which runs off the land surface to the drainage system.
Sea-level rise (SLR)	The projected increase in sea-level due to climate change for a planning horizon.
Secondary drainage system	The overland flow paths that carry excess stormwater when the capacity of the primary drainage system is exceeded.
Sensitivity analysis	Testing the sensitivity of the model's response to changes in particular parameters (e.g. roughness), boundary conditions (e.g. storm surge) or geometry (e.g. river mouth shape).
Section 92	Section 92 (s92) of the Resource Management Act 1991 grants Councils the authority to request that a consent applicant provide furthers information relating to the application.
Sub catchment	A smaller sub-area within a catchment that drains to a single location.
Statutory timeframes	Timeframes required by law to be met, such as related to resource consent applications under the Resource Management Act 1991.
Storage loss	A one-off loss which defines the precipitation depth required for filling the depressions on the catchment surface before runoff can occur.
Validation	Process of simulating historical events and comparing results to field measurements in order to qualitatively or quantitatively assess the capacity of the model to accurately reproduce those events.
Verification	A review of the models performance against an independent method (e.g. results compared to existing flood frequency analysis or outputs from another model) and / or a review of suitability of the model to achieve its stated purpose by an independent peer reviewer. It could also include a sensitivity analysis to testing the response to changes in particular parameters.
Wetting loss	A one-off loss that accounts for wetting of the catchment surface.