Opanuku Stream Accuracy Benchmark

1. Introduction

1.1 Fundamental Approach

The proposed approach to flood model accuracy assessment uses data directly measured during an actual physical flood event.

In principle this is the same idea as using laboratory models for testing, which has the advantage that intensive instrumentation can be deployed under controlled conditions. However laboratory models cannot completely reproduce the complexities of channel flows in the natural world, in particular because of scale effects. The alternative here proposed is to deploy field scale observational instruments on actual flood channels, using an intensity of measurement sufficient to support forensic reconstruction of key full scale flow parameters, both in space and in time.

1.2 Key Parameters

The key flood parameters at a surveyed cross-section are generally accepted to be discharge Q and mean water level h, because when these are both known, the distribution of other variables such as velocity can be deduced by high resolution 3D modelling if required. This is based on a hypothesis by St Venant that the effects of boundary resistance and turbulence are the same in unsteady flood flows as in steady flows in the same channel.

The same idea supports the expectation by laboratory modellers that all measurements of the model flow properties will be repeatable if the laboratory supply pump is set to deliver the same flow and the control gates are set to produce the same water levels.

"The same channel" must be taken to imply water at the same temperature and resistance elements of the same scale (for example vegetation at the same stage of growth), and to exclude erosion or accretion, as otherwise observations can readily be found to contradict the St Venant hypothesis. Also "steady flow" must mean flow with constant discharge and level at any point, excluding cases where cyclic or unstable flows may develop within a reach, even when served by steady boundary conditions.

1.3 Steady Flow Analysis

If Q and h are known at a section, then the energy flowing through that cross-section can be computed. The energy flowing through the next downstream section will be lower, and this loss of energy is attributed to flow resistance or friction. Various resistance models (for example, the Manning formula) have been proposed which link Q and h with a "friction slope" S_f at the section.

By definition the integral of S_f through the reach between the upstream and downstream sections must equal the energy difference across the reach (excluding any "shock losses" which do not originate from channel friction). This means that in general non-uniform steady flows, the accuracy of resistance models can be benchmarked *only* if flow data is available for computation of the energy at both ends of a reach.

1.4 Resistance Model Benchmarks

To be usable for predictive purposes, a resistance model must *not* depend on flow parameters in some unspecified way. For example, the Manning n must take a fixed value for a given wall surface material and fixed configuration (such as those values specified in hydraulic design codes for pipes or street paving). Similarly, flexible vegetative cover must have given constant stiffness characteristics. For this reason it is important that accuracy benchmarks exercise the model through a range of flow conditions during each test.

1.5 Unsteady Flow Analysis

According to the St Venant hypothesis, the resistance model will be as for steady flow, except the benchmark energy differences must now be adjusted to take local flow accelerations into account.

Similarly, computations of differences in discharge must now take account of local changes in channel storage during floods (in addition to provision for possible tributary inflows).

2. The Opanuku Stream Dataset

This dataset derives from one of the most intensively monitored river reaches in the urban territory of the Auckland Council, New Zealand. At the upstream section, the Border Road bridge, the water level is monitored continuously by a recorder. At the downstream section, the Vintage Reserve footbridge, the water level is also monitored continuously. In addition, the discharge has been gauged there repeatedly over almost 20 years under a range of conditions, including steady flow and rising and falling flood flows.

2.1 Analysis of Flow Gaugings

Flow gaugings establish a history of the relationship between discharge Q and stage (surface water level) h at the Vintage Reserve gauging cross-section on the channel, as shown in Figure 1.

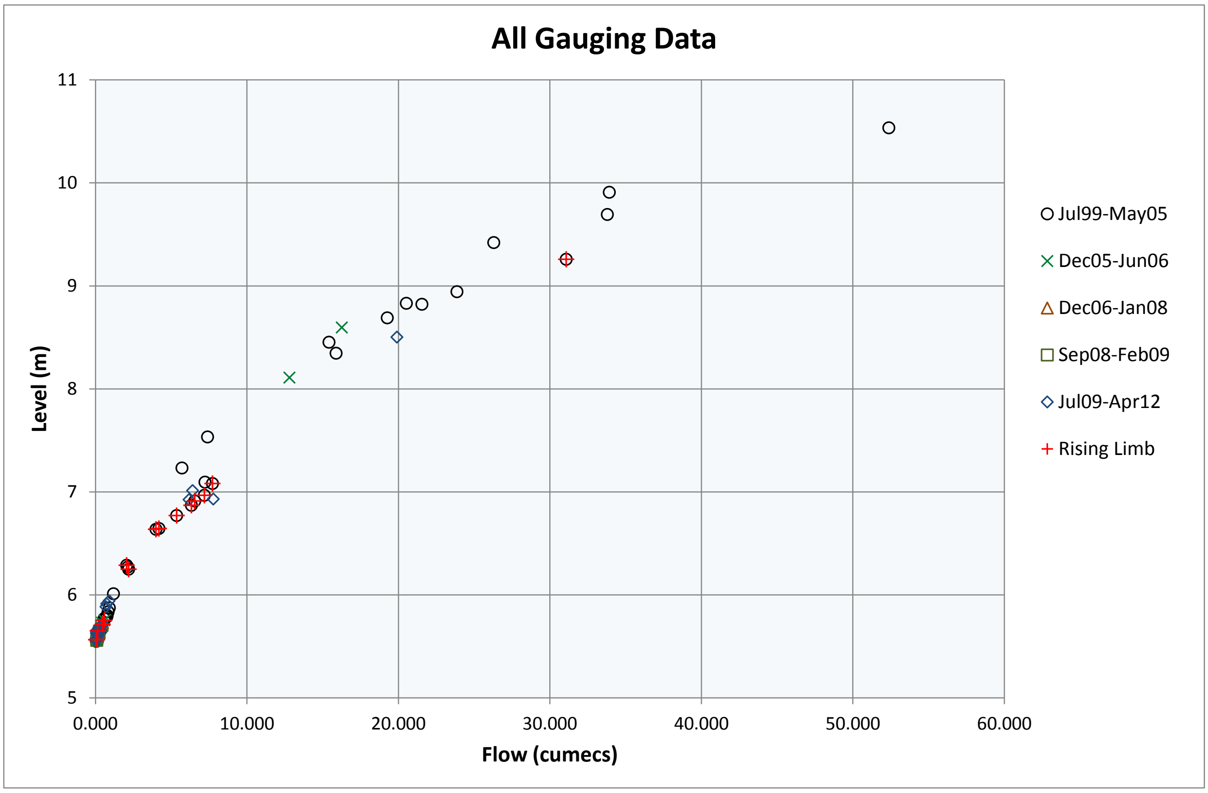

Figure 1. Opanuku Stream: Recorded Gauging Data

This scatter of gauging points indicates a balance between the hydraulic gradient driving the discharge and the channel boundary roughness resisting flow, with resistance decreasing as the stage increases and the cross-section enlarges.

Textbook analysis (e.g. F.M. Henderson "Open Channel Flow" MacMillan, 1966) suggests that any attempt to formulate this balance should be based on the generic Chézy formula

$$Q/A = C\sqrt{RS}$$

where A is the total area of the cross-section at the gauging point, R is the "hydraulic radius", a length scaling a representative distance of flow from the fixed channel boundary, and S represents an applied local hydraulic gradient.

C is the "Chézy C" which varies with the boundary roughness. C has also been found to be weakly dependent on R, with many tests having established variation to a small power of R, typically about a 1/6th power. Therefore, the Chézy formula is usually rewritten

$$Q/A = \frac{M}{n} R^m S^{1/2}$$

where m is about 2/3. For historical reasons the convention has long been adopted that the boundary roughness is represented through a dimensionless scalar n, the "Manning n", and that the required dimensional adjustment is supplied by the constant M, taking the value 1.00 $m^{1/3}s^{-1}$ in the metric system.

However, such use of a single value of n assumes that the boundary roughness is uniform. Figure 2 shows this assumption does not apply to the Opanuku Stream at the gauging point, where the low flow channel conveyance is clearly less impeded by vegetation than overbank flow conveyance.

Figure 2. Opanuku Stream at the Vintage Reserve gauging site.

This suggests that the overbank roughness will become increasingly dominant in governing the total conveyance of flow through the channel as the level rises and flow spreads well outside the low flow channel. The same is likely to be true of many other natural rivers, requiring care in the application of the Chézy formula to the interpretation of gauging data for model calibration. Many adjustments have been proposed to correct any distortion, and it is a major objective of this Benchmark to assess the relative accuracy of alternative adjustment options in the context of an actual observed dataset.

2.1.1 *The "One-Dimensional" Model*

The Chézy formula is clearly three-dimensional, as a steady discharge Q can be assessed as the rate of change of volume in a reservoir, measured by length x width x depth. A popular simplification has been the so-called "one-dimensional" model, in which volume is measured as a linear function of depth alone. This implies a conceptual elementary reservoir is assumed in which the horizontal surface area does not vary with depth, that is, a reservoir channel with vertical walls. Also in this model, such virtual channel walls create no lateral velocity gradients. Therefore depth is the only scale of distance from the channel boundary, so the hydraulic radius $R = y$, the depth of the bed below the free surface.

Such simplified models have enjoyed practical success where the channel bed is nearly parallel with the free surface and lateral velocity gradients are weak, typically in the central part of flows most remote from the channel walls. However Figure 2 suggests that such conditions could apply to the Opanuku stream only (if at all) within flows wholly confined to the low flow channel.

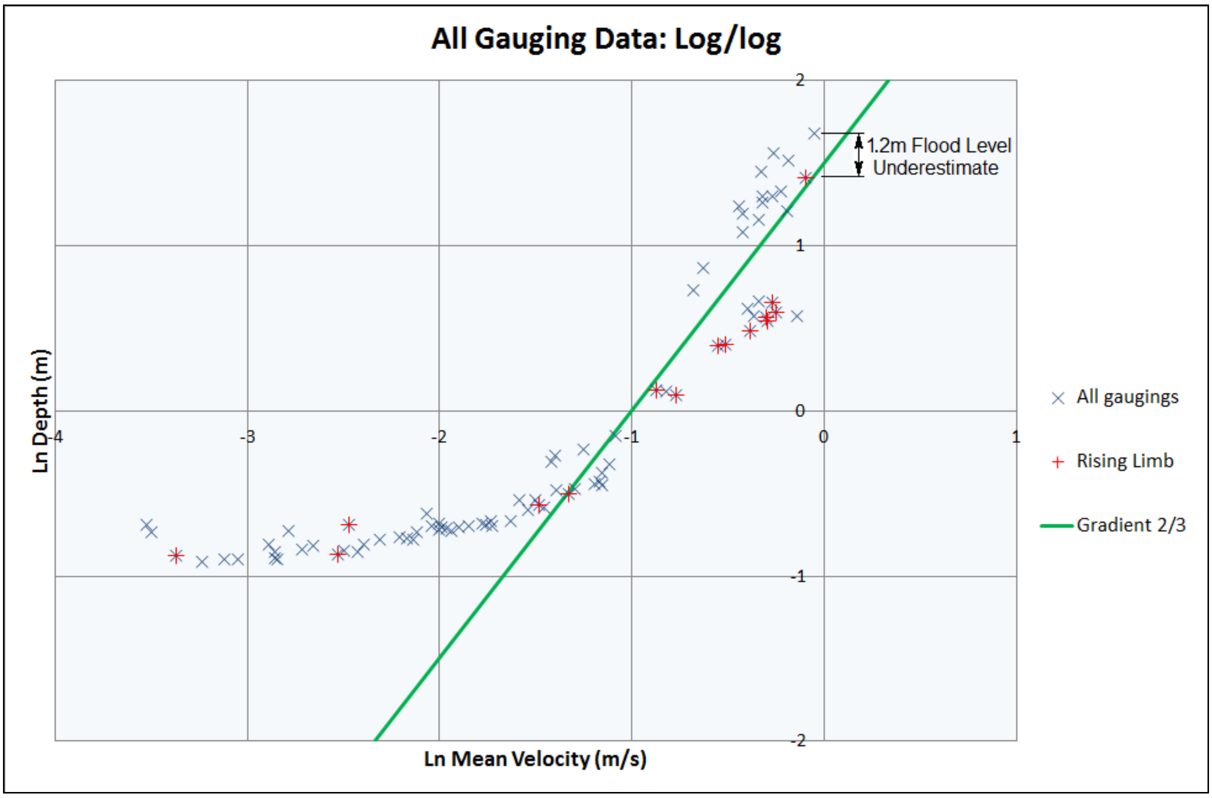

Figure 3. Log/log Plot of Mean Velocity vs Depth

Figure 3 tests the use of a one-dimensional model on Opanuku Stream gauging data, using a log/log plot to investigate the fitting of the usual value of 2/3 for the exponent m in the Chézy formula. This produces a gradient of 2:3 for a straight line representing the ratio of increments of ln (Q/A) to corresponding increments of ln y. A rough fit can be found as represented by the green line, but the errors are significant, for example the unacceptable 1.2m flood level underestimate compared with that recorded at the highest gauged flow.

Adjustment of the value of a single Manning n will shift this line laterally, but will not affect the gradient. Only if the exponent m is varied, or if Manning n is varied on higher parts of the cross-section, can a range of gradients be calibrated to fit the observed data.

2.1.2 *Three Dimensional Models*

In three dimensions a hydraulic radius can be constructed to better represent the typical distance of flow paths from the fixed channel boundary of a cross-section. For this reason, many standards (including New Zealand standards) define the hydraulic radius as $R = A/P$, where P is the wetted perimeter of the cross-section of area A.

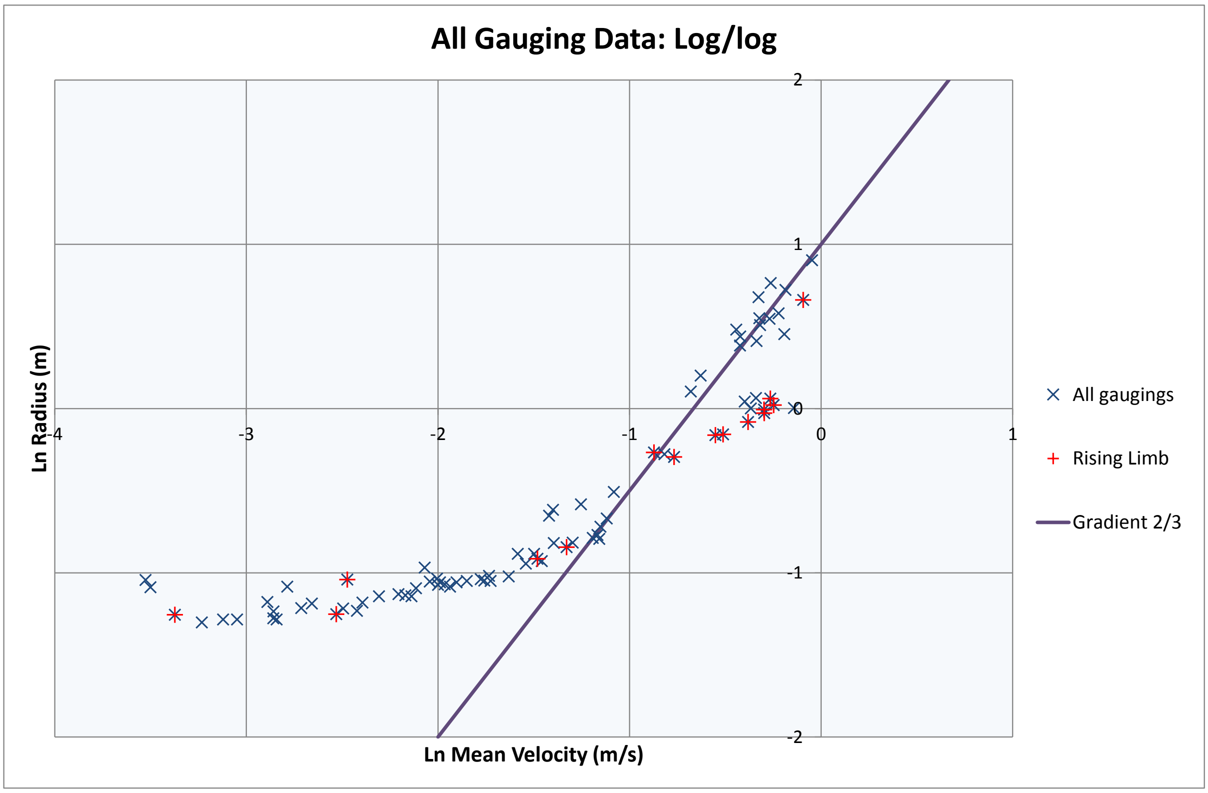

Figure 4. Log/log Plot of Mean Velocity vs Hydraulic Radius

In Figure 4, Figure 3 is replotted using as ordinate the logarithm of hydraulic radius in place of depth. Immediately, at least at higher depths the values fall much closer to a line with gradient 2:3, this time plotted in purple. Importantly, the highest gauged flow now falls close to that line with a roughly equal number of points on each side above a hydraulic radius of 0.5m (about ln(R) = -0.7).

In this higher depth range, all but one of the points marked in red as "Rising Limb" fall to the higher velocity side of the line. These points were selected on the basis of a rise in level being recorded during the corresponding gauging, and in such cases textbooks teach that an increase in friction slope can be expected, giving a loop rating if gaugings are recorded throughout an individual flood event. Therefore if the slope S is defined as the variable friction slope S_f rather than some fixed value, according to the Chézy formula the mean velocity will be larger during rising flows than that found during steady or falling flows at the same hydraulic radius.

Therefore there is no incompatibility between calibration of the Chézy formula to a fixed Manning n and significant departures of some gaugings to the right of a line fitting m=2/3, *provided* the outlying point values were observed during the rising limb of a flood. This means a very satisfactory calibration of the Chézy formula can be expected for the Opanuku stream at medium to high flows.

There remains the problem of the long tail at low flow gaugings to the left of the line, at hydraulic radius less than 0.5. This remains a challenge for each individual model submitted to accuracy testing against this benchmark. However a significantly lower roughness can be calibrated for low flows, and then combined with the overbank Manning n dominating high flows to provide a compound channel transition conforming to the observed behaviour. A solution along these lines has been published, but demonstrably equal accuracy achieved by alternative model approaches would also meet the Benchmark compliance standard.

2.2. *Calibration of Chézy Formula Upstream at Border Road*

Upstream of the Vintage Reserve gauging site, continuous records of the water level are also available at the Border Road bridge.

Figure 5. Opanuku Stream at the Border Road Level Recorder Site.

Comparing Figure 5 with Figure 2, the upstream end of the stream reach from Border Road to the Vintage Reserve has a similar combination of a relatively unobstructed low flow channel and thick vegetation on the channel berms. Although there are differences in the mixture of plant species, the similarity of apparent flow impedance is close enough to try the same low flow channel and berm Manning n values as a first approximation.

Under steady conditions the discharge at the Border Road level recorder can be assessed as a little less than the measured downstream discharge, because hydrological analysis can show that lateral inflow from the intervening subcatchment is an order of magnitude smaller than the flow passing through in the channel.

Under unsteady conditions, changes in the channel storage are continuously monitored by the level gauges each end, so corresponding unsteady corrections to the differences between upstream and downstream flows can also be estimated continuously with high accuracy.

3. Catchment Modelling

Under heavy local rainfall, hydrological modelling shows that lateral inflows may become significant for short periods. Fortunately the study area contains two local rain gauges, one directly within the reach subcatchment and one upstream of the reach.

Figure 6 shows the general layout of the study area, with shading in pink marking the subcatchment feeding the test reach between Border Road and Vintage Reserve. The Power NZ rain gauge lies near the northern edge of the subcatchment, while the Candia Road rain gauge lies on the main channel a short distance upstream.

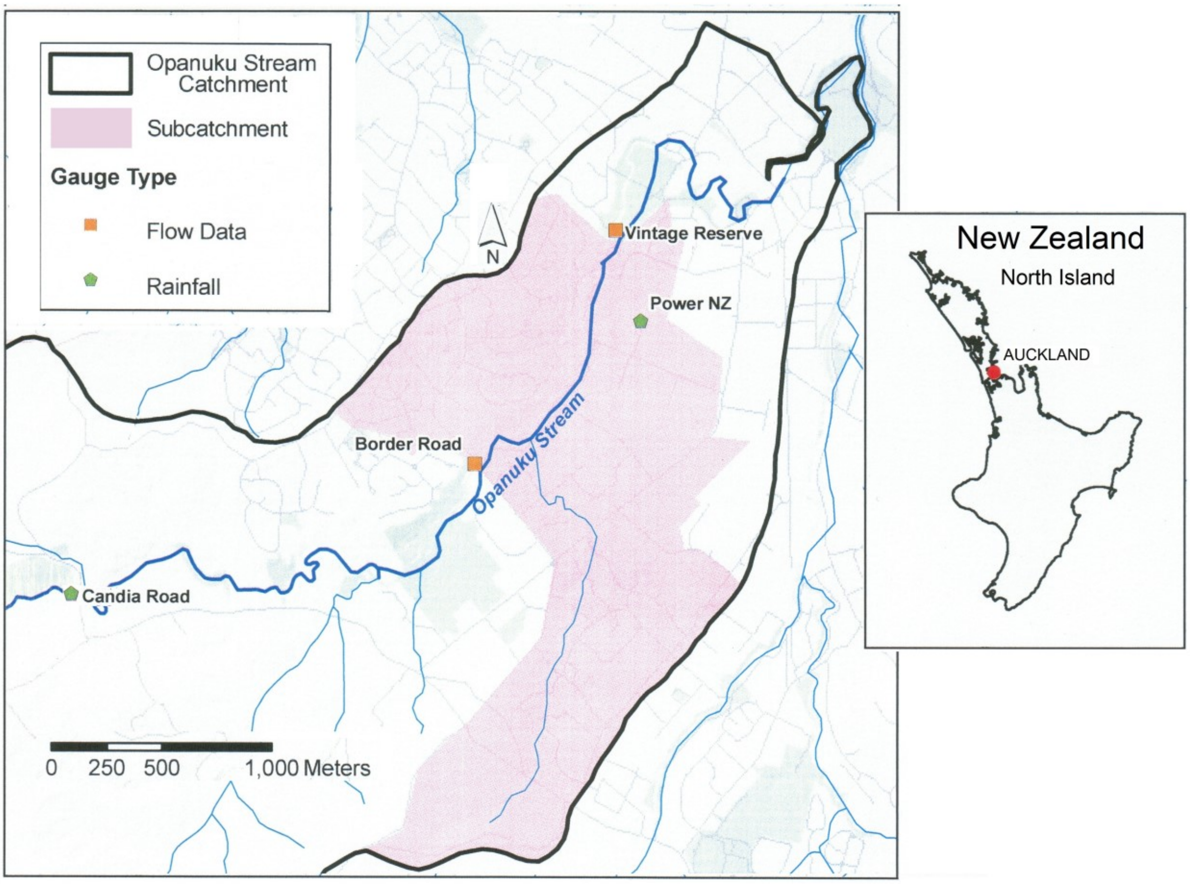

Figure 6. General Layout and Key Features of the Study Area.

In the supplied background dataset, more detailed maps are provided of the whole catchment and the location of other adjacent rain gauges, and of the Subcatchment boundary related to identified streets. The subcatchment area was estimated by Council staff as 271 ha.

4. Terrain Data

The dataset includes Lidar survey data of catchment terrain and an orthorectified aerial photograph of the study area, see Figure 7. This shows a typical suburban landscape of mixed commercial, light industrial and residential development interspersed with parkland.

Figure 7. Georeferenced Photograph of the Study Area

Opanuku Stream runs through the tree-lined corridor entering at the lower left corner and exiting near the top of the right side of the photo. The inscribed yellow rectangle has the coordinates 2654151.32E, 6477606.32N for the lower left corner and 2655847.33E, 6479554.30N for the upper right corner. The grid used, as for all map coordinates in the supplied dataset of Lidar readings, is the NZMG (New Zealand Map Grid) in metric units.

Coverage by this photo and the supplied Lidar dataset does not extend as far as the tail of the Subcatchment extending to the south, but this is also the most remote from the rain gauges and therefore likely to be the least accurate part of any hydrological models.

Each cross-section is also georeferenced to NZMG, but by only a single point. Council staff advised that their usual survey practice is to measure the curvilinear distance along the axis of the low flow channel to identify the cross-section location, then to measure the cross-section perpendicular to this axis at any point.

Cross-section survey often refers to a local datum, but the provided dataset has reduced all levels to a single metric datum (Mean Sea Level). This was also the level datum used for the Lidar survey.

5. Data Accuracy

There is enough redundancy in the information provided for experienced modellers to assess data uncertainties by inspection. First, records are available from two quite independent flood events.

The sensitivity of the level gauges is 1mm in a stilling well which damps out short period waves. Accordingly, level records at this resolution vary smoothly with little sign of short term oscillations.

The gauged discharges exhibit two low outliers around a heavily populated core, disruptions consistent with infrequent short term blockages from fallen trees. There is little sign of long term temporal drift in the gaugings. As would be expected from loop rating theory based on the Chézy formula, the discharges during rising floods consistently and significantly exceed the other measurements at comparable levels.

There are considerable differences between the rainfalls recorded at the two rain gauge sites during the same storm event, both in timing and intensity. Therefore this dataset well illustrates the uncertainties facing hydrological modellers. Fortunately the hydrological models are required only to estimate the differences between the upstream and downstream discharges, so as long as these corrections remain minor, estimations of the upstream discharge will remain acceptably accurate.

The channel berm levels are available from two independent survey techniques (cross-section survey and Lidar), providing data redundancy for error estimation in storage volume computations.

6. Summary

The Opanuku dataset provides an excellent basis for benchmarking flood model accuracy. The dataset has considerable redundancy at all levels, allowing modellers the option of performing sensitivity analysis on their results. Two independent storm events are included, with rainfall recorded at two independent gauges, while the channel cross-sections are available from two independent survey techniques.

Field measurements are available at both upstream and downstream ends of the test reach, allowing the energy difference to be computed for benchmarking of a proposed resistance model over a wide range of steady and unsteady flows. Therefore forcing an inaccurate Chézy resistance model to fit at one flow will simply produce consequent obvious errors at other flows.

Repeated flow gaugings at the downstream end of the reach are highly consistent with a loop rating model. At the upstream end, flows can initially be approximated to those at the downstream end, with small corrections then available through calibration of the resistance model upstream. This calibration can be refined by comparison of the lateral inflow residuals inferred by mass balancing and the runoff hydrographs predicted by hydrological modelling.

7. Accuracy Benchmark Compliance

To establish compliance with this accuracy benchmark, applicants should provide for at least one of the two floods the following plotted evidence of successful model results:

1. A match within measurement accuracy between modelled and observed level hydrographs at the upstream and downstream ends of the test reach.
2. A match within measurement accuracy between the model stage/discharge curve at the downstream cross-section and the observed gauging points there. Note the model discharge hydrograph must finally be derived by calibration of the resistance model.
3. A match within hydrological modelling accuracy between the model lateral channel inflow and the runoff hydrograph derived by rainfall/runoff modelling from observed rainfall records. (Note the "lateral channel inflow" is that deduced as the residual hydrograph obtained throughout the flood by adding downstream discharge to rate of change in reach volume, then subtracting the upstream inflow. This upstream inflow is the discharge through the upstream section, again derived from the calibrated resistance model).

Validation

Note this benchmark has been validated by a published demonstration of compliance using the Chézy formula as the base resistance model. Hydrological computations used a simple kinematic wave rainfall/runoff model.