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LOCAL INFLOW CALCULATION FOR A CASCADE RESERVOIR

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Abstract: Local inflows from ungauged tributaries of a cascade reservoir are often calculated as the residual from the hydraulic balance for the reservoir due to discharges from the upstream and downstream facilities. Level pool reservoir routing is commonly used for its simplicity of application. However, the accuracy of level pool reservoir routing principle has been found questionable in many cases, especially during peak facility discharges. The slope of the water surface increases as the discharge through the reservoir increases. Therefore, the storage volume estimated based on the measured reservoir elevation at the downstream end is no longer accurate. The change of reservoir volume in each time-step is under-estimated during the spill ramp-up period. This generates significant negative local inflows as output of the hydraulic balance equation. The additional storage volume under the sloping reservoir surface does not change if the spill discharges from the upstream and downstream facilities remain steady. As a result, the hydraulic balance equation provides reasonable output for local inflows during steady spill periods. Again, as the spill discharges ramp-down the slope of the reservoir surface diminishes releasing the additional volume of water. This unaccounted change of storage volume generates significant positive local inflows as output of the hydraulic balance equation. Hydrodynamic modeling was carried out for a cascade hydropower reservoir to demonstrate the inaccuracies of level pool reservoir routing calculations. The model results showed that the inaccuracies in storage volume estimates appear to be insignificant (<<1%), but the calculated local inflows could be significantly erroneous. Some simple solutions were proposed to eliminate significant errors in local inflow calculations using hydraulic balance equation.

1 INTRODUCTION

Two or more reservoirs are often impounded by dams along the same course of a river to form a cascade facility. Flows from an upstream reservoir are released to a downstream reservoir by various discharge facilities; e.g. spillways and hydropower plants. Generally, the upstream reservoir receives water from a large drainage basin and it serves as the storage reservoir. The downstream reservoirs are generally smaller than the upstream reservoir. They do not provide any long-term storage. The downstream hydropower plants are considered run of river plants, typically operating in daily hydraulic balance with upstream facilities. The average daily discharges from the cascade facilities are approximately equal. The drainage basins for the downstream reservoirs are generally small and often ungauged. However, it is essential to estimate the local inflow for the downstream reservoirs for optimum operation of the hydropower plants and above all for the safety of the downstream facilities.

The objective of this study was to identify the sources of error in local inflow calculation for a cascade facility. BC Hydro's Peace River Hydropower Project was considered as a test case for the purpose of investigation.

2 BACKGROUND

2.1 Peace River Project

The Peace River Project is located in the northeastern side of British Columbia. It includes Williston Reservoir, W.A.C. Bennett Dam, G.M. Shrum Generating Station (GMS), Dinosaur Reservoir and Peace Canyon Dam and Generating Station (PCN). Williston Reservoir is impounded by W.A.C. Bennett Dam and has a drainage area of about 70,000 km^2. Peace Canyon Dam impounds Dinosaur Reservoir, about 20.5 km downstream of Bennett Dam. The drainage area between Bennett Dam and Peace Canyon Dam is very small (860 km^2). Flow regulation is provided by Williston Reservoir storage and GMS releases with limited short-term storage provided by Dinosaur Reservoir for load factoring purposes only. PCN is considered a run of river plant, typically operating in daily hydraulic balance with GMS. Therefore, average daily discharges from GMS and PCN are approximately equal.

2.2 Dinosaur Reservoir Local Inflow

BC Hydro uses an internal tool called CRO/Flocal to record plant operations and compute inflows and outflows from all its plants. Some operational data comes directly from measurements (e.g. reservoir forebay level, tailwater level, gate position etc.); some are estimated based on measured data and standard relationships (e.g. turbine discharge, spillway discharge etc.); and some data are back-calculated based on other measurements and estimations (e.g. natural inflows to the reservoirs).

Dinosaur Reservoir local inflows are calculated as the residual from the hydraulic balance for the reservoir due to discharges from the GMS and PCN facilities. An analysis of the operational records showed that Dinosaur Reservoir daily average local inflow values are frequently (~25% of the time) negative. These negative values are generally small (0 to -40 m^3/s for 75% of the occurrences) during normal operating conditions (i.e. without spill) at GMS and PCN. Even larger negative values (as low as -160 m^3/s) can appear during spill events. Negative inflows are more common and significant when calculated at an hourly interval. While small negative values were considered to arise from the imprecision of the measurement of reservoir elevations, large negative inflows were suspected to occur due to error in spillway discharges from Bennett Dam as high correlations were observed during GMS spilling. Similar negative local inflows were observed at other BC Hydro reservoirs (e.g. Revelstoke, Seven Mile) when calculated in hourly and daily intervals. This paper describes the detailed engineering study undertaken to identify the precise source of error, and proposes potential solutions.

3 REVIEW OF THE AVAILABLE INFORMATION

3.1 Method of Calculation

The forward calculation of the propagation of a flood wave in an open channel, known as flood routing, is a problem of applied hydrology that has been studied extensively. The relevant methods of solution, all within the framework of one-dimensional free-surface flow, span the spectrum from numerical solutions of the hydrodynamic equations of Saint-Venant to storage routing models of the diffusion-wave. Local inflows from ungauged tributaries of a cascade reservoir are often calculated as the residual from the hydraulic balance for the reservoir due to discharges from the upstream and downstream facilities; i.e. reverse flood routing. Computation of diffusive wave propagation in reverse time is ill-posed; i.e. the solution exists but it is unstable and may not be unique (Koussis et al. 2012). In such cases, small data perturbations cause large spurious solution. Therefore, the reverse solution must be smoothness-constrained towards stability and uniqueness (regularized).

Level pool reservoir routing is commonly used for its simplicity of application. It is based on the continuity equation which simply states that; the inflow minus the outflow equals the rate of change in storage.

[1] $I(t)-Q(t)=dS/dt$

where $I(t)$ is the inflow, $Q(t)$ is the outflow and $S(t)$ the storage at time t.

The first order Euler's scheme produces the following simple expression for level pool routing:

[2] $I(t)-Q(t)= [S(t+\Delta t)-S(t)]/\Delta t$

This explicit scheme is conditionally stable. However, the solution is unstable when there is a rapid change of storage. Therefore, level pool reservoir routing has been found questionable for local inflow calculation for cascade reservoirs, especially during peak facility discharges (e.g. during spill periods).

CRO/Flocal uses a hydraulic balance equation, similar to Eqn. [2], to calculate Dinosaur Reservoir local inflow:

[3] NI_DNR_CRO = Delta_Str_ DNR*(10^6/3600) – Rel_ WSR + Rel_DNR

where NI_DNR_CRO = Natural inflow to Dinosaur Reservoir in the CRO/Flocal records in m^3/s;

Delta_Str_ DNR = Change in storage volume over the measurement interval in Dinosaur Reservoir in million m^3 units calculated from the forebay elevation change. [(10^6/3600) is to convert the hourly million m^3 values to the m^3/s units];

Rel_ WSR = sum of all releases from Williston including releases from all the 10 turbines and the spills from all of the 3 radial gates if any, 9 sliding gates if any and 4 low level outlets if in service, in m^3/s; and

Rel_DNR = sum of all releases from Dinosaur Reservoir including releases from all the 4 turbines and the spills from all of the 6 radial gates if any, m^3/s.

The principal assumption of this reservoir routing approach is that the reservoir level remains horizontal from the upstream to the downstream boundary for each time step of the flow routing period. The accuracy of this calculation depends on the validity of this principle (i.e. diffusive wave propagation) and the accuracy of each pertinent input data and assumptions. Dinosaur Reservoir local inflow (i.e. *NI_DNR_CRO*) can be negative if either or a combination of the following inaccuracy occurs:

a) change (increase) in storage volume (i.e. *Delta_Str_ DNR*) is underestimated,

b) sum of releases from Williston Reservoir (i.e. *Rel_ WSR*) are overestimated; and

c) sum of releases from Dinosaur Reservoir (i.e. *Rel_ DNR*) are underestimated

3.2 Input Data for Hydraulic Balance Equation

- **Water Levels**

Forebay and tailwater levels are measured continuously. For CRO/Flocal calculations data is taken at the top of each hour as instantaneous values. Use of instantaneous values could introduce randomness in the Flocal results.

- **Turbine Discharge Calculations**

A powerhouse with multiple units can have highly variable turbine operations within an hour. Flow through a turbine is a function of generator output (MWh for the hour), generator state information (e.g. generating or offline), forebay and tailwater elevations, and unit characteristics (i.e. flow as a function of head and power). The hourly average flow for a single unit is calculated on the basis of hourly average gross head (forebay minus tailwater) on the unit, the number of minutes in the hour that the unit is in a generating state and the average MW generated in that period. If a unit operates for a short period within an hour, the estimated hourly average head obtained from the instantaneous values of forebay and tailwater levels at the top of the hour may not be representative due to the variation of discharges from the adjacent units. Therefore, turbine discharge calculations may produce some random errors in Flocal calculated reservoir inflow.

- **Non-Power Release Calculations**

Non-power release facilities at GMS and PCN consist of spillways with radial gates. Calculation of spillway discharges in CRO/Flocal is based on forebay elevation, spillway gate position (recorded to a minute time resolution) and the spillway gate rating curves. Average forebay elevations are determined for each gate position-time interval within an hour. This is done via linear interpolation of the elevations between the beginning and end of the hour. Using the elevation-position-flow relationship, the flow through the gate for each interval within the hour is determined. Then an hourly average spillway discharge is calculated as, average flow = ∑ (interval duration in minutes) * (calculated interval flow) / 60, where the sum is over all position-intervals in the hour.

Due to its large storage volume Williston Reservoir level at the forebay does not change noticeably within an hour even during spillway operation. Moreover, the spillway approach channel is about 1.5 km away from the power intake tower where the forebay gauge is located. Therefore, no cross-flows are expected in front of the spillway.

PCN powerhouse is located adjacent to the spillway gates. There is a 280 m long anti-vortex dyke across the reservoir at ~400 m upstream of the dam. The purpose of this dyke is to create cross-flows near the dam to sweep away air-entraining vortices from the power intakes. Therefore, the flow travels across the forebay from the right side to the powerhouse located on the left side of the concrete dam. This cross-flow may affect the calculation of PCN spillway discharge.

- **Review of the Spillway Rating Curves**

The spillway rating curves at PCN and GMS were developed on the basis of physical hydraulic model studies undertaken during the design of the projects. Hydraulic models were built at small scales (1:84 for GMS and 1:60 for PCN) that did not include all the details of the spillways. In addition, design modifications are common during the construction period and this was the case for both GMS and PCN spillways.

A review of the prototype modifications for GMS spillways indicates that there are only minor unaccounted alterations in the spillway discharge rating curves. Due to these minor alterations GMS spillway discharge could be slightly underestimated. However, a similar review for PCN spillways shows that there are many unaccounted alterations (e.g. the anti-vortex dyke, gate radius and trunnion position, shape of the piers and side walls). The magnitude of the effects of all changes on the rating curves is difficult to estimate. The unaccounted issues appear to be insignificant when considered separately, but when taken together they act in the same direction and suggest that actual discharge may be higher than the rating curve. Because of these inaccuracies PCN spillway discharge may be underestimated.

- **Review of the Storage Volume Calculation**

Dinosaur Reservoir storage volume is calculated hourly in CRO/Flocal based on instantaneous measurement of forebay level at the top of each hour and the storage curve (volume vs. elevation relationship). The reservoir surface is assumed to be flat for each time step.

The Dinosaur Reservoir storage curve provides the relationship to estimate volume of water for reservoir elevations from El. 491.3 m to El. 504.5 m. The accuracy of storage curve is unknown. It was developed on the basis of pre-dam survey data. The accuracy of live storage volume near the operating level (El. 500 m to El. 503 m) would be critical for Dinosaur Reservoir local inflow calculation.

- **Review of the Backwater Effects**

An engineering study was carried out in 1970 to calculate the backwater effects of PCN Dam to GMS powerhouse. The standard step method was used to calculate steady water surface profiles from PCN forebay to the GMS manifold for various flow conditions and assumed forebay levels. The calculation showed that the water surface elevations just downstream of GMS tailrace could be 0.4 m, 1.8 m, 4.8 m above the PCN headpond level for 1274 m^3/s, 1982 m^3/s and 6230 m^3/s discharges, respectively (assuming PCN forebay level = 502.92 m). The slope of the water surface is relatively steep at the upstream reach of the reservoir. Therefore, for average powerhouse flows of 1200 m^3/s the water surface in the main body of the reservoir is essentially horizontal and normal reservoir routing would be adequate. But the difference in water level could be significant for higher powerhouse discharges and during spillway operation, and hence the assumption of a flat reservoir surface is not valid during these high flow events.

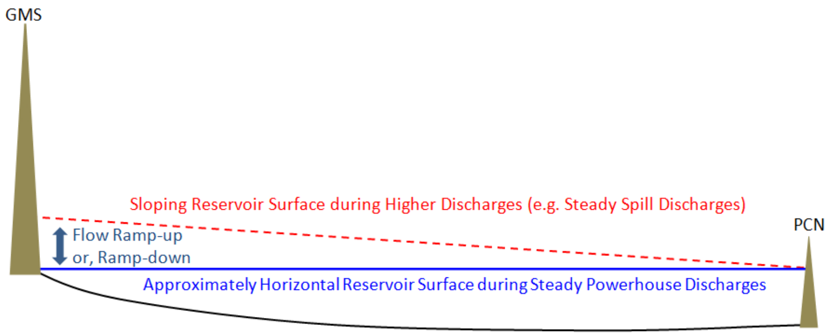

Figure 1: Schematic diagram of the water surface above PCN forebay

Figure 1 shows a schematic diagram of Dinosaur Reservoir surface for various flow conditions. During flow ramp-up periods (both inflows and outflows), upstream water levels in the reservoir will be elevated higher than the downstream water levels. This will provide additional storage in the reservoir. When inflows (i.e. GMS flow releases and local inflow) and outflows (i.e. PCN outflows) are in balance the difference between upstream and downstream water levels will remain constant. Therefore, storage volume will remain constant during steady flows. Again, when the flows ramp-down the reservoir level differences will be diminished. Thus the reservoir will flush out the additional storage developed during flow ramp-up. Therefore, the assumption of a flat reservoir level would impart errors in storage volume estimation, especially at the beginning and end of a balanced spill event.

An underestimation of the hourly change of Dinosaur Reservoir storage volume by 0.36 Mm^3 may lead to 100 m^3/s negative local inflow. A water level difference of about 0.1 m between upstream and downstream of the main body of Dinosaur Reservoir can hold 0.36 Mm^3 water (assuming an average width of reservoir = 350 m). This estimate shows the sensitivity of the input parameters on Dinosaur Reservoir local inflow calculation.

3.3 Review of the Historical Data

Hourly operational data for GMS and PCN facilities obtained from CRO/Flocal for three spill events in 1996, 2002 and 2012 were reviewed. Figure 2 shows the historical records during the spill period of 1996.

The following observations were made from the historical data review:

- Large negative local inflows to Dinosaur Reservoir were observed during balanced spill ramp-up conditions at GMS and PCN. GMS tailwater levels were similar to PCN forebay levels prior to spill initiation. During spill ramp-up the differences between GMS tailwater level and PCN forebay level increased. This indicates additional storage development during spill ramp-up period and it was coincident with the observation of large negative local inflow.

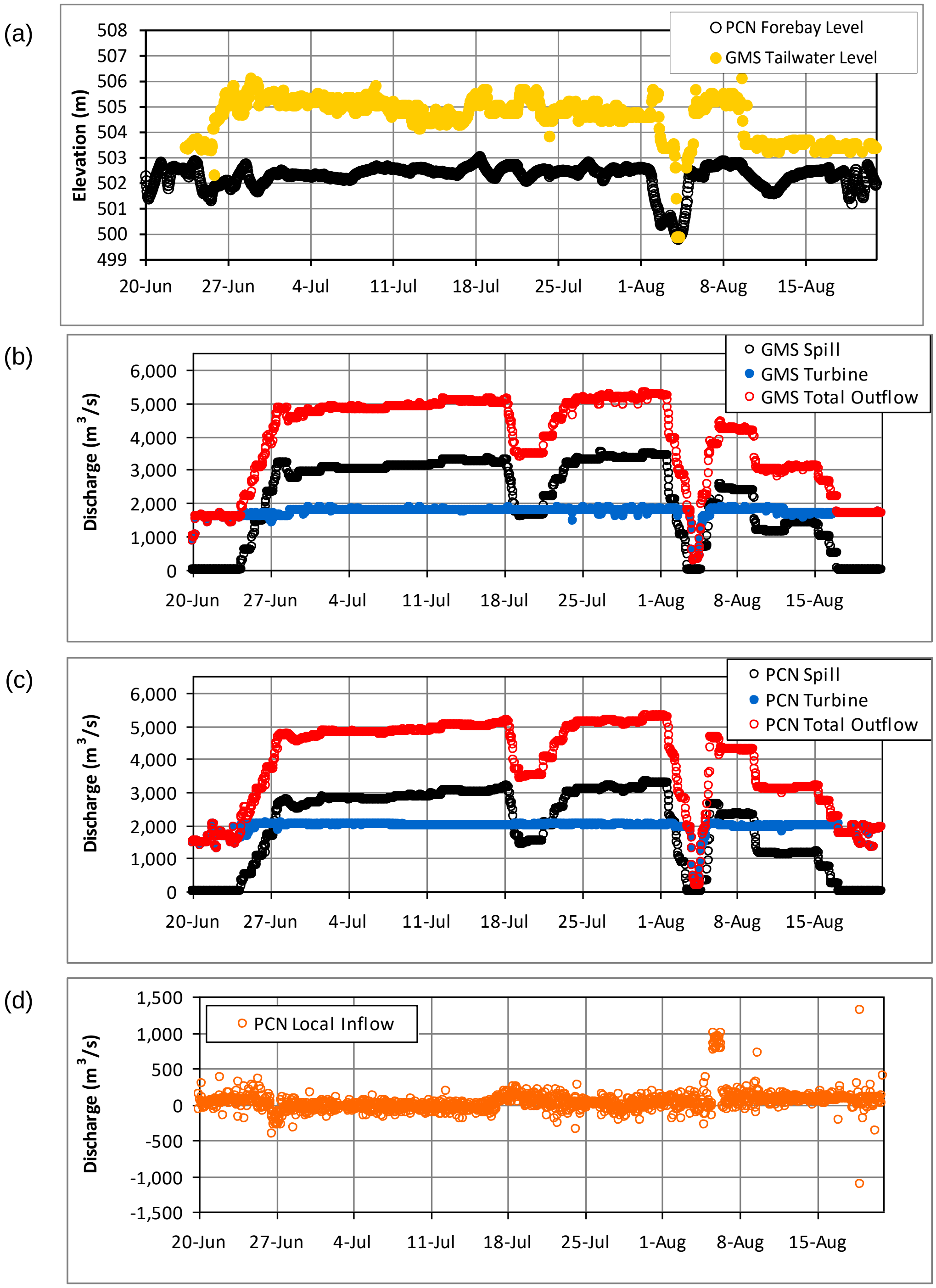

Figure 2: Review of historical data for 1996 spill event

- Large positive local inflows were calculated during spill ramp-down conditions when the difference between GMS tailwater level and PCN forebay level diminished. This indicates flushing of additional storage developed upstream of the reservoir.

- Considerably large negative and positive local inflows were also calculated for short durations during powerhouse flow ramp-up and ramp-down conditions, respectively.

- Consistently large negative inflows were observed during steady spill discharge conditions at GMS and PCN. Storage volume did not change much during steady spill conditions. Therefore, these negative inflows were caused by the inaccuracy of GMS and/or PCN discharges. Underestimation of PCN outflows and/or overestimation of GMS release could likely result in negative local inflows to Dinosaur Reservoir. Review of spillway rating curves in Section 3.2 shows that PCN spillway discharge could be underestimated, especially during partial gate opening.

4 HYDRODYNAMIC FLOW ROUTING FOR SPILL EVENETS

4.1 Hydrodynamic Model

The MIKE 11 model, a robust one-dimensional hydrodynamic model, was used in this study for hydrodynamic flow routing of Dinosaur Reservoir to confirm that this type of modelling can mitigate the negative inflows. GMS tailrace channel and Dinosaur Reservoir were represented in the MIKE 11 model with 34 cross-sections. Bathymetry for GMS tailrace channel (about 2 km reach) were obtained from BC Hydro survey data collected in October 2002. Bathymetry for the remaining 18.5 km reach of Dinosaur Reservoir was based 1984 B.C. Ministry of Environment maps. Topographic data were collected from B.C. Provincial TRIM (Terrain Resource Inventory Mapping) DEM (Digital Elevation Model).

The upstream boundary condition for the MIKE 11 model was the inflow to Dinosaur Reservoir (i.e. GMS releases from the powerhouse and spillway). The downstream boundary was set at PCN forebay with measured water levels during the period of simulation. No lateral inflows (i.e. local inflows) were assumed for model simulations.

Manning’s coefficients for channel roughness was set in the model as 0.035 to represent deep channel through natural rocks with limited vegetation and obstructions (Chow 1959).

4.2 Model Accuracy

The MIKE 11 model representation of the Dinosaur Reservoir storage was checked by comparing the modelled volume with the CRO/Flocal storage curve between Maximum Normal Reservoir Level (El. 502.92 m) and El. 500 m. The modelled volumes were within 0.1% of the CRO storage curve volume, and therefore acceptable.

4.3 Modelling Spill Events

Hydrodynamic routing of Dinosaur Reservoir was performed for three spill events in 1996, 2002 and 2012. These results are compared with CRO/Flocal recorded quantities. Figure 3 show the time series plots of various parameters for the spill event in 1996.

Observations are provided below:

- Estimations of storage volume in Dinosaur Reservoir for normal operating conditions (i.e. before and after the spill period) are found to be generally similar for both reservoir routing (Flocal approach) and hydrodynamic routing (MIKE 11 model) methods. However, during spill discharges the hydrodynamic model estimated storage volumes are higher than the reservoir routing method.

- The difference in estimated storage volume between reservoir routing and hydrodynamic routing remains essentially unchanged for steady spill discharge conditions. The difference is found to grow during spill ramp-up and diminish during spill ramp-down.

- Modelled hourly outflows at PCN appear to be very similar to CRO/Flocal records of PCN outflow for the entire simulation period (i.e. with and without spill) for three events. But these apparently small differences between model outflow and CRO/Flocal records of PCN outflow are in very good agreement with CRO/Flocal estimated Dinosaur Reservoir local inflow. Local inflows to Dinosaur Reservoir were assumed to be zero for model simulations. Since local inflows are practically very small (in the order of 10 m³/s), these differences are actually the errors in CRO/Flocal calculation.

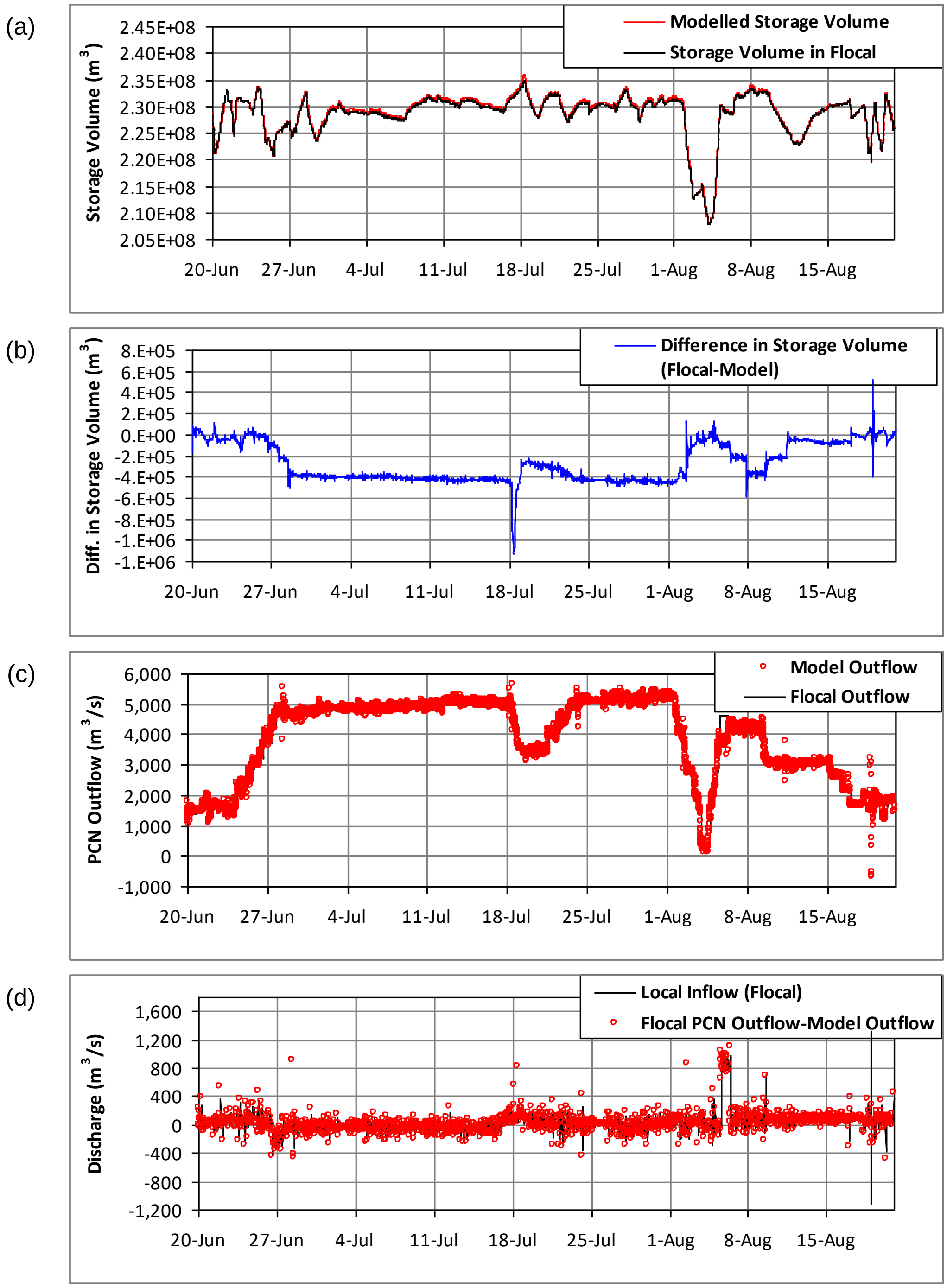

Figure 3: Comparison of Flocal calculations and model results for 1996 spill event

5 METHODS TO REDUCE ERRORS IN LOCAL INFLOW CALCULATION

Reverse routing can be performed using the shallow water wave equations (Chow 1959) in an iterative technique. At each time step the inflow is approximated and routed downstream. The simulated and measured downstream discharges are compared and the inflow is adjusted until the desired accuracy is obtained. It is recognized that the solution of the shallow water wave equations should provide the most accurate results, but this method is computationally inefficient and not suitable for operational record keeping. Therefore, a literature review was conducted to prescribe a suitable reverse routing method to reduce errors in local inflow calculation for a cascade reservoir.

The main features of flood wave motion are translation and attenuation, the latter due to (hydraulic) wave diffusion; both are nonlinear features resulting in nonlinear deformation. The main flood body travels as a kinematic wave. A channel routing method (e.g. the Muskingum scheme) approximates the propagation of the diffusion wave efficiently when the kinematic wave mode dominates (Koussis et al. 2012). Therefore, it can reduce large errors associated with rapid change of storage in a reservoir. The principle of this method is similar to reservoir routing, but it considers both prism storage (for horizontal water surface) and wedge storage (storage above a horizontal water surface) (Chaudhry 2008). In this method, the storage in a reach is expressed as a linear function of the weighted mean of inflow and outflow:

[4] $S=K[xI+(1-x)Q]$

where K and x are two numerical parameters.

An essential requirement to ensure accuracy in such finite difference calculations is that the finite time interval (Δt) must be small relative to K. An exact method of solution under the storage assumption was developed by Nash (1959). He derived modified equations for the Muskingum parameters. These equations are true even when Δt is not small relative to K.

Koussis et al. (2012) showed that the accuracy of a reverse Muskingum routing method could be as good as the reverse solution of the St. Venant equations of flood wave motion at a fraction of the computing effort compared to a hydrodynamic solution. However, they recommended low-pass filtering (symmetric, second order, five-point Savitzky-Golay filter) of the imperfect outflow hydrographs to control noise amplification and assemble true data from spurious information. For superior solution the results can be optimized by using objective function, e.g. absolute error.

The literature also shows that a non-linear implicit scheme was traditionally used by hydrologists for its unconditional stability, but its solution was derived by an iterative procedure (Zoppou 1999). This approach is computationally inefficient and the solution of I(t) is dependent on I(t-Δt), estimated at the previous time step and its associated errors.

There are some simplified approaches of reverse reservoir routing that can reduce errors in local inflow calculation for reservoirs between two dams. For example, the reverse level pool routing equation can be expressed in central difference scheme as,

[5] $I(t)=Q(t)+[S(t+\Delta t)-S(t-\Delta t)]/(2\Delta t)$

The advantage of this scheme over the implicit scheme is that the inflow I(t) is not dependant on the inflow I(t-Δt). Zoppou (1999) showed that this simple explicit scheme can eliminate random errors caused by small inaccuracies in the input data, and it is not necessary to employ computational effort in filtering the imperfect flow records obtained from the field.

Therefore, reverse reservoir routing using the Muskingum method can be adopted for local inflow calculation for a cascade reservoir. This will provide a practical balance between simplicity and accuracy for operational calculations. In addition, a central difference scheme can be used to eliminate random errors caused by small inaccuracies in the input data.

6 CONCLUSIONS

- This study has shown that there are multiple sources of errors that caused negative local inflows into Dinosaur Reservoir. The large errors are correlated to flow ramping conditions due to inaccuracies in storage volume estimation on the basis of flat reservoir level assumption. In addition, there is an indication that the PCN spillway rating curves are underestimating discharge. Some random errors in local inflow calculation are also caused by inaccuracy of hourly turbine discharge.

- The principle of level-pool reservoir routing is acceptable to calculate local inflows for reservoirs between two dams if the hydrodynamic effects are negligible (i.e. for relatively small flows through the reservoir). For higher flows between the dams, the reservoir water surface develops a gradient like a river. In such cases, reservoir routing will generate errors and hydrodynamic flow routing would be most appropriate.

- There are some simplified approaches for reverse flood routing that can reduce errors in local inflow calculation for reservoirs between two dams. A central difference scheme can eliminate random errors caused by small inaccuracies in the input data. Channel routing using Muskingum method can reduce large errors associated with the wedge storage for reservoir inflow calculation.

7 RECOMMENDATIONS

- This study recommends a simple channel routing approach (Muskingum method) to eliminate large errors (both positive and negative) in the estimated local inflows for a cascade reservoir between two dams. The use of an explicit central difference scheme can be considered to avoid the need for low pass filtering of the imperfect input data.

- Time-averaged values of forebay and tailwater levels should be used as input for operating discharge calculations.

- Turbine discharge calculations can be improved by using average forebay and tailwater levels measured for each generating state. When there are multiple units and the generating conditions change frequently, turbine discharges should be calculated at shorter intervals.

- A Computational Fluid Dynamics (CFD) model study is recommended to investigate the effects of the unaccounted issues on PCN spillway discharge. The spillway rating curves can be revised based on the CFD model results for future applications.

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