Daily Time Step Refinement of Optimized Flood Control Rule Curves for a
Global Warming Scenario

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Abstract

Pacific Northwest temperatures have warmed by 0.8 °C since 1920 and are predicted to further
increase in the 21st century. Streamflow timing shifts associated with climate change would
degrade the water resources system performance for climate change scenarios using existing system
operation policies for the Columbia River Basin. To mitigate the hydrologic impacts of anticipated
climate change on this complex water resource system, optimized flood control operating rule
curves were developed at a monthly time step in a previous study, and were evaluated with a
monthly time step simulation model. Here a daily time step simulation model is used over a
somewhat smaller portion of the domain to evaluate and refine the optimized flood control curves
derived from monthly time step analysis. Daily time step simulations demonstrate that maximum
evacuation targets for flood control derived from the monthly analysis were remarkably robust.
However, the evacuation schedules for Libby and Duncan Dams from February to April conflicted
with Kootenay Lake level requirements specified in the 1938 International Joint Commission Order on Kootenay Lake. We refined the flood rule curves derived from monthly analysis by creating a gradual evacuation schedule, keeping the timing and magnitude of maximum evacuation the same as in the monthly analysis. After these refinements, the performance at monthly time scales reported in our previous study proved robust at daily time scales. Due to a decrease in July storage deficits, additional benefits such as more revenue from hydropower generation and more July and August outflow for fish augmentation were observed when the optimized flood control curves were used for a climate change scenario.

Key words: Climatic Change, Flood Control, Flood Rule Curve, Reservoir Operation, Columbia River, Optimization, Simulation, Hydrologic Modeling, Daily Time Step, Monthly Time Step

**Introduction**

Pacific Northwest temperatures have warmed by about 0.8 °C since 1920 (Mote et al. 2003) and are predicted to increase on average by approximately 0.3°C per decade over the 21st century (Elsner et al. 2009). The projected warming will cause seasonal flow volume shifts in the Western U.S. where snow is typically a major component of the hydrologic cycle (Serreze et al. 1999) due to reduced spring snow pack, earlier melt, earlier spring peak flow and lower summer flow. These hydrologic changes have been shown to degrade water resources system performance if existing system operation policies are used without any modification (Christensen et al. 2004; Payne et al. 2004; VanRheenen et al. 2004; Lee et al. 2009; Hamlet et al. 2009). In particular, providing sufficient water for hydropower, instream flow, and irrigation may become more challenging in summertime under warmer conditions (Elsner et al. 2009; Hamlet et al. 2009; Mantua et al. 2009). For example,
summer flow reduction associated with predicted climate change decreases hydropower generation at a time of year when cooling energy demands are expected to increase (Hamlet et al. 2009). Lower summer flow and increased summer temperature will likely exacerbate existing stress on productivity of Salmon in Washington State (Mantua et al. 2009). Adapting to such impacts may require increased use of reservoir storage for environmental purposes (Payne et al. 2004).

Flood control policies, which ultimately determine both flood mitigation performance and reservoir refill statistics, have impacts on many system objectives that depend on reservoir storage levels. To adapt to the hydrologic impacts of climate change, adaptation strategies must be devised to rebalance water resources systems in response to these changes, a process which requires the assessment of complex trade-offs among competing system objectives (Miles et al. 2000; Hamlet et al. 2009; Mantua et al. 2009; Whitely Binder et al. 2009).

Recently, we proposed (and applied in a case study of the Columbia River Basin) the use of optimization techniques for developing revised flood control curves to increase system efficiency for a climate change scenario (Lee et al. 2009). In that approach, optimized rule curves were developed for a climate change scenario using a hybrid optimization-simulation approach which rebalanced flood control and reservoir refill at a monthly time step. Use of existing flood control rule curves degraded system efficiency for a climate change scenario, but use of the optimized flood control curves restored reservoir refill capability without increasing flood risk. Lee et al. (2009) noted that these techniques for generating new flood rule curves needed to be tested and refined at shorter time scales (e.g. daily time step) to verify that the optimized flood control curves derived from a monthly analysis provide acceptable levels of flood risk at shorter time scales. These issues
are explored here using a daily time step reservoir simulation model (described below) to test and refine the optimized rule curves developed at monthly time scales by Lee et al. (2009).

Due to the increased complexity of daily time step optimization and simulation models and the many practical difficulties in applying them in climate change studies, we propose a two-step process for rebalancing flood control operations in response to climate change impacts. Monthly time step approaches are used to develop new reservoir operating rules (Lee et al. 2009) followed by additional testing and refining at daily time scales to resolve any specific problems that might be encountered. In exploring this framework for climate change adaptation the following questions are addressed:

1) Does the use of new flood control rule curves developed at monthly time scales for a climate change scenario produce acceptable performance at daily time scales?

2) If not, what aspects of daily time step simulation results differ from monthly time step simulation results?

3) If adjustments to monthly rule curves are required to achieve acceptable daily time step performance, can simple and objective methods be developed to “downscale” monthly flood control curves to daily flood control curves without explicit use of daily time step optimization?

4) What alternative approaches might be considered?

As a pilot study, the Kootenai (U.S. spelling) River Basin was chosen because reservoir operations in this sub-basin of the Columbia River Basin are particularly complex, requiring the coordinated operation of Libby, Duncan, and Corra Linn Dams for the management of Kootenay (Canadian spelling) Lake and downstream flows. Success in resolving any technical issues for this case study
would facilitate extension of these methods to a daily time scale study for the entire Columbia basin and other basins with similar hydrologic characteristics.

**Background**

**Description of Study Area**

The Kootenai River Basin is an international watershed located in the northeastern part of the Columbia River Basin. The Kootenay River originates in British Columbia, flows into northwestern Montana and northern Idaho, and then turns back to Canada and the southern arm of Kootenay Lake (Figure 1). Three large storage dams which are operated for multiple purposes including flood control are present in the basin: Libby Dam in the U.S., and Duncan and Corra Linn Dams in Canada.

Libby Dam, completed in 1973, is located on the Kootenai River in Montana and is operated for flood control, hydropower generation, fisheries, and other purposes by the U.S. Army Corps of Engineers [U.S. Army Corps of Engineers (COE) 2006]. Lake Koocanusa, impounded by Libby Dam, has a usable storage capacity of 6.10 x10^9 m^3 [U.S. Army Corps of Engineers (COE) 1989]. Bonners Ferry is located downstream of Libby Dam and is a control point for local flood regulation on the Kootenai River [U.S. Army Corps of Engineers (COE) 2006]. The upstream reservoirs are operated to meet local flood control objectives as well as system flood control objectives in the lower Columbia River basin (see Lee et al. 2009, for more details). Duncan Dam was the first dam built in the Canadian section of Columbia River Basin according to the terms of the Columbia River Treaty and is owned and operated by British Columbia Hydro [U.S. Army Corps of Engineers (COE) 1989]. Duncan Dam does not have hydropower turbines installed. It is primarily operated to
control the flow into Kootenay Lake in conjunction with releases from Libby Dam to maintain operational water levels in Kootenay Lake (impounded by Corra Linn Dam). Corra Linn Dam was constructed between 1930 and 1932 by West Kootenay Power and Light Company [U.S. Army Corps of Engineers (COE) 1999] and is operated to control water levels in Kootenay Lake (for flood control and recreation) and to produce hydropower.

**International Joint Commission (IJC) order on Kootenay Lake**

The Columbia River Treaty Flood Control Operating Plan states that Libby and Duncan Dams are required to operate in accordance with the 1938 International Joint Commission (IJC) Order on Kootenay Lake [U.S. Army Corps of Engineers (COE) 2003]. Similarly, Corra Linn Dam operations must meet the terms of the Order.

The 1938 IJC Order on Kootenay Lake requires that the lake elevation gage at Queens Bay (upstream from Corra Linn Dam, Figure 1) does not exceed 531.6 m on February 1, 531.1 m on March 1 and 530.1 m on or about April 1 except under extraordinary natural high inflow conditions (Stanley et al. 1938). This rule curve remains in force until the Kootenay Lake Board of Control declares the “commencement of the spring rise”, which indicates that spring snowmelt has begun. Historically, the date of declaration has usually been in the last half of April; however, it could be as early as late March or as late as early May. After the high flow season the lake is maintained at an elevation of 531.4 m until August 31 after which it may be raised to its maximum elevation of 532.0 m between September 1 and January 7 (Stanley et al. 1938). Under circumstances of high flow associated with spring melt, Kootenay Lake may rise above the established rule curve, and this is not technically a violation of the IJC Order provided the Board of Control has declared the commencement of the spring rise. Tight constraints on the operation of Libby and Duncan Dams are
required at certain times of year to preclude a Kootenay Lake level violation. For example, during the winter and spring Libby and Duncan Dams may be operated above their flood control rule curves (sometimes called “trapped storage”) [U.S. Army Corps of Engineers (COE) 1999] to maintain Kootenay Lake at an acceptable level. The lake levels specified in the IJC Order on Kootenay Lake were established to avoid local flooding and to meet the needs of the farming community.

**Methods**

An existing daily time step reservoir simulation model for the Columbia Basin was used to test and refine the optimized flood control curves that were developed at a monthly time step. As input data for the daily time step reservoir model, simulated daily time step inflows and daily time step flood control curves were prepared.

**Daily Time Step Reservoir Simulation Model**

The Autoreg reservoir routing model, developed by the Hydrologic Engineering Branch of the North Pacific Division of the U.S. Army Corps of Engineers, is a daily time step simulation model used for planning and flood control studies [U.S. Army Corps of Engineers (COE) 1999, 2002]. The model is described in detail by Davis (1997), but in essence the model is a refinement of the Streamflow Synthesis and Reservoir Regulation (SSARR) model [U.S. Army Corps of Engineers (COE) 1987], simulating each dam’s outflow and storage elevation while checking that specified operating rules (such as the 1938 IJC order, minimum outflows, flood control elevations, etc.) are not violated. Mean daily streamflow data and daily time step operating rule curves are utilized by Autoreg as input data. The model does not explicitly simulate hydropower operations or instream flow augmentation for fish.
Daily Time Step Inflows and Daily Flood Rule Curves

Inflow sequences for the historical period from 1916 to 2002 as well as a simple climate change scenario assuming an annual average 2°C warming were simulated using the Variable Infiltration Capacity hydrologic simulation model (Liang et al. 1994) implemented at 1/8th degree latitude/longitude resolution (Lee et al. 2009). A bias correction procedure was applied to remove systematic biases in the monthly time step streamflow simulation as described in Snover et al. (2003) and Vano et al. (2009). The bias-corrected monthly values were then used to rescale the simulated daily flow sequences produced by the hydrologic model to estimate daily flows for both historical conditions and a warmer climate. Although the time series behavior of these simulated flows was not always identical to the observed naturalized data, the daily flow duration curves for April, May, and June were faithfully reproduced overall as shown in Figure 2, where the 71-year (1929-1999) simulated daily flow streamflow record is compared with the measured daily flow data.

Daily time step HEC-PRM derived optimized flood control curves (HecFCs) were prepared by linearly interpolating monthly time step optimized flood control curves developed by Lee et al. (2009) for each day of the month.

Results and Discussion

We first examined the performance of the optimized flood control rule curves (Figure 3b) for the 20th century flow conditions in comparison to the current flood control rule curves (Figure 3a). At monthly time scales, using results from the Columbia simulation (ColSim) model, flood risks were generally lower for optimized rule curves (HecFCs) in comparison to the current flood control rule
curves (CurFCs) (Lee et al. 2009). At a daily time step, using the Autoreg simulation model, optimized flood control curves showed a higher flood risk at Bonners Ferry than the current flood control curves (CurFCs) for certain years in the 20th century climate record (Figure 4a).

Close examination of these years indicated that Libby and Duncan reservoir elevations were well above the optimized rule curves (HecFCs), preventing the desired reservoir evacuation from being achieved. This occurred because the evacuation schedule of Libby and Duncan Dams was too aggressive to allow compliance with the IJC order. Therefore, the Autoreg model reduced outflow from Libby and Duncan to preclude an IJC violation at Kootenay Lake. This resulted in higher flood risks using HecFCs than CurFCs. For instance, for water year 1933 the use of HecFCs caused a higher flood at Bonners Ferry in comparison to CurFCs. Figure 4a shows that beginning on March 1, outflow from Libby Dam was cut back to avoid an IJC violation at Kootenay Lake. Outflows from Libby Dam were increased up to the hydraulic capacity of the hydroelectric turbines after April 1st, when the IJC constraints (discussed above) were relaxed (Figure 4a). Even with a modest amount of storage evacuated in April, the Libby reservoir elevation remained well above the desired rule curve (Figure 4a). This condition was found to be an undesirable artifact of the relatively rapid evacuation requirements imposed by the optimized rule curves.

The ultimate source of this difficulty is related to key differences between the monthly time step ColSim simulation model used by Lee et al. (2009) in testing monthly rule curves, and the daily time step Autoreg simulation model used here. ColSim considered multiple system operations including hydropower generation, instream flow augmentation, and flood control. Thus in low to mid-flow years, storage levels simulated by ColSim were most strongly determined not by flood control requirements but by hydropower releases (see Lee et al. 2009). As a result, little or no
additional release was required in February, March, and April using the monthly time step model, and the difficulties discussed above were avoided. Autoreg, however, considers only flood control and IJC constraints (hydropower generation is not included). Thus, the heightened sensitivity to flood evacuation schedules was revealed in the Autoreg modeling.

Although these effects are partly related to the fundamental differences between the two reservoir simulation models used, the results showed that the timing of flood control evacuation at Libby and Duncan Dams needed refinement in the case of the optimized rule curves. When a gradual drafting of Libby and Duncan Dams was imposed, while keeping the magnitude and timing of maximum flood evacuation from the monthly analysis (as shown in Figure 3c), the issues discussed above were resolved. Figure 4b shows the results when modified optimized flood control curves (shown in Figure 3c) were used for water year 1933. Because optimized flood control curves were modified to release the water from Libby Dam more gradually, the modified curves successfully achieved the desired flood control evacuation at Libby Dam, resulting in lower flood risk using modified HecFCs in comparison with CurFCs (see Figure 4b). The maximum evacuation levels and timing were not affected by these adjustments.

Figures 5 and 6 show simulated daily and monthly average flood frequency curves at Bonners Ferry. As expected, the daily time scale peak flows (Figures 5a and 6a) are higher than the corresponding monthly-average values (Figures 5b and 6b). However, in comparison with monthly time scale simulations (Figures 5b and 6b), key relationships between the performance of current and optimized rule curves are maintained in daily time step simulations (Figures 5a and 6a). Thus once
the issues associated with flood evacuation timing were resolved to avoid having “trapped storage” at Libby and Duncan Dams, the monthly time step results were shown to be quite robust.

In comparison to the 20th century climate, storage deficits increased for the climate change scenario under the current flood control curves due to decreased summer flow associated with a warmer climate (see Figure 7). Modified HecFCs significantly decreased storage deficits for the climate change scenario. Daily time step simulations showed much greater reduction in storage deficits using HecFCs for climate change than monthly time step simulation obtained by Lee et al. (2009 a). As discussed in the work of Lee et al. (2009), optimized flood control curves are expected to produce greater improvements in storage deficits when hydropower is not included, which is confirmed here.

Using the revised flood evacuation schedules, monthly ColSim simulations were used to reconfirm the benefits using optimized flood control curves for climate change to achieve benefits in hydropower generation and fish flow augmentation. Using the current flood control curves, outflow volumes in July and August and hydropower production from May to July were significantly reduced for the climate change scenario in comparison with the 20th century climate (see Figures 8 and 9). Modified HecFCs increased July and August outflow volumes and power production from June to July and from November to January for the climate change scenario in comparison to the current flood control curves. When average energy prices shown in Table 1 (following Hamlet et al. 2002) were used, simulations using the optimized flood control curves yielded 36 million dollars annually more than when operating using current flood control curves for the climate change
scenario. This results from a shift in hydropower production, from spring (when the energy price is relatively low), to summer and winter (when the energy price is relatively high).

Assessment of Potential Impacts to Kootenay Lake Operations

For the climate change scenario, simulated storage at Kootenay Lake exceeded its nominal rule curve more frequently and more severely in comparison to the 20th century climate (see Figure 10). The Kootenay Lake level was above its rule curve more than 60% of the time (55 years out of 86) for the climate change scenario, whereas for the 20th century condition this occurred in 14 years. These simulations raise important questions about potential degradation of performance in the ability to draft Kootenay Lake for the climate change scenario.

When examining the cause of Kootenay Lake being above its rule curve in spring in the climate change simulations, the results showed that natural inflow to Libby and Duncan Dams associated with an earlier spring melt was passed downstream. This forced Kootenay Lake’s elevation above its rule curve. This is not technically a violation of the IJC order provided that the commencement of the spring rise is declared earlier in response to the earlier flow timing under climate change.

The objective of drawing down Kootenay Lake from January 7th through April 1st is to lessen the danger of damage by flooding during high water periods caused by snowmelt runoff. Therefore, an important question is whether the use of modified optimized rule curves at Libby and Duncan Dams might cause undesirable Kootenay Lake elevations in the summer. To investigate this, Kootenay Lake elevations for the 20th century climate were compared with those for the climate change scenario (Figures 10b and 11). Due to earlier snow melt, the simulated elevation at Kootenay Lake frequently exceeded its rule curve by late March for the climate change scenario as shown in Figure
11. However, the peak elevation was reduced for the climate change scenario relative to the 20th century climate due to reduced summer flow related to a warmer climate (see Figure 11). Annual maximum daily average flood elevation frequency curves at Kootenay Lake also showed that under CurFCs, lower flood risks were observed for the climate change scenario compared to the 20th century climate (Figure 10b).

A recent study by BC Hydro states that the zero-damage elevation at Kootenay Lake is 533.4 m (Estergaard, 2005). When modified HecFCs were used for the climate change scenario, there were fewer water years with peak elevations above 533.4 m in comparison with CurFCs. Thus although the timing of refill is different under climate change, the objective of avoiding local flooding is satisfied in more years under climate change, and is further improved in the majority of years by optimizing flood evacuation.

**Prospects for Refining Refill Timing at Daily Timescales**

We hypothesized that refill timing determined using monthly time scale optimization could be valid at a daily time scale. This hypothesis was supported by daily simulation modeling for the Kootenai Basin, because Libby and Duncan Dams achieved full storage for most of the simulated water years for the climate change scenario using modified HecFCs (see Figure 7). However, if the method reported here is expanded to the whole Columbia River Basin or applied to other watersheds, a refinement of refill timing on a daily scale may be required for a climate change scenario.

In the work of Lee et al. (2009), it was shown that refilling one month (30 days) earlier is required for Dworshak Dam when a monthly time step simulation is implemented. At the daily time step, the optimal refill time for Dworshak might be refined. “Refill parameters” have been used in many U.S.
Army Corps of Engineers flood control studies for the Columbia system to specify how to refill projects after the season's maximum flood control draft has been attained. The goal is to specify a schedule that will ensure reservoir refill without causing premature filling. Refill parameters are expressed as percentages of flood control space that can be filled during the refill months. For example, if a particular reservoir has refill parameters of 0%, 40%, 85%, and 100% for April, May, June, and July, respectively, that means refill timing is calculated to allow no refill during the month of April, 40% by the end of May, 85% by the end of June, and the remainder by the end of July. The U.S. Army Corps of Engineers has developed default refill parameters for many Columbia basin projects based on the typical runoff pattern that has historically been observed at a given location. One approach for refining daily refill schedules would involve the establishment of new “refill parameters” using daily time step optimization.

**Summary and Conclusions**

A daily time step simulation model was used to test and refine the proposed monthly flood control curves developed by Lee et al. (2009). When daily flood control curves were linearly interpolated from monthly time step flood control curves without any modification, optimized flood control curves (HecFCs) showed higher flood risk than current flood control curves (CurFCs) for the 20th century climate. These issues were traced to differences in flood evacuation timing in the optimized flood rule curves, and also to the operational elements incorporated in reservoir simulation models used for testing, one of which (monthly) included hydropower operations while the other (daily) did not. To resolve these issues a gradual daily evacuation schedule was devised for the optimized flood rule curves, keeping the timing and magnitude of maximum evacuation the same as in the monthly analysis. After these refinements, the conclusions at monthly time scales reported in Lee et al. (2009) proved robust at the daily time scale.
Although flood peak flow rates were about a factor of two larger at the daily time step than the monthly average values, key relationships between the performance of current and optimized flood rule curves were maintained in daily time step simulations. A larger reduction in storage deficits resulted at the daily time step than for the monthly time step using optimized rule curves because the daily reservoir model didn’t impose hydropower generation drafts, while the monthly simulation model did. These differences highlight the need for more consistent test procedures for daily and monthly time scales. If consistent test procedures had been used at daily and monthly time scales, the refinement of flood evacuation timing would probably have been minimal, and possibly not required at all.

Additional testing at monthly time scales over the entire Columbia basin showed that increased hydropower generation and flow augmentation for fish during summer resulted from the use of the modified optimized flood control curves for the climate change scenario, because of improved reservoir refill using modified HecFCs. Increases in revenue from hydropower generation were estimated to be about 36 million dollars per year on average.

Due to earlier snow melt, exceedance of flood rule curves at Kootenay Lake by late March occurred more often and with greater severity for the climate change scenario than for the 20\textsuperscript{th} century climate. However, the objective of the IJC order to avoid local flooding is met in more years under climate change, and is further improved in the majority of years by optimizing flood evacuation.

We have shown that a monthly time step approach provides robust results in terms of determining required maximum flood space. The optimized maximum flood space requirements were derived
based on known seasonal runoff volumes, so results reported here are more favorable than what would be possible when uncertainty in water supply forecasts is included explicitly. However, the approach could be modified to consider forecast error in both optimization and simulation.

Refinement of refill timing wasn’t required for the climate change scenario for the Kootenai River Basin when a daily time scale was used. However, in some other cases (e.g. Dworshak Dam, discussed by Lee et al. 2009) it would probably be desirable to refine refill timing at daily time scales for a warmer climate. In that case, a daily time step optimization approach could be explored to find optimal daily refill timing.

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References


U.S. Army Corps of Engineers (COE). (1999). “Work to date on the development of the VARQ flood control operation at Libby Dam and Hungry Horse Dam.” Northwest Division, North Pacific Region.


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