TRUCKEE RIVER HIGH-PRECISION OPERATIONS MODEL DESCRIPTION AND APPLICATIONS

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Abstract: The Truckee River basin is a small, but highly regulated basin that is under intense pressure from a wide array of interests competing for its relatively small water supply. A high-precision short-term forecast and routing model has been developed and implemented in the Truckee River Basin. The model supports the US District Court's Watermaster and other basin stakeholders in making precise operational decisions for the release and diversion of water from its seven upstream reservoirs and numerous diversions.

The model starts by bringing in the most current real-time streamflow, reservoir storage, and diversion data. It then facilitates the construction of a 96-hour forecast at three headwater nodes, and provides an easy interface to enter an hourly release and diversion schedule. The user then initiates an automated calibration of the routing of the flows through the stream network, and the model returns an hourly basin-wide forecast of flows based on the input release and diversion schedule. Once calibrated with the latest realtime data, the user can instantaneously test "what-if" scenarios for short-term release and diversion schedules over the next 96 hours. Schedules can then be set on an hourly scale to optimally meet flow targets and precisely deliver water to its proper destination. The model allows the Watermaster and stakeholders to utilize their water much more efficiently, and limits the water wasted due to a lack of precision.

The model and interface are described in detail as well as the unique methodology utilized for routing and forecasting on an hourly time scale. Finally, several examples of specific operations that are supported with this tool are given including a daily basin-wide travel time report that is posted to the web each day for basin stakeholders and the public to reference.

INTRODUCTION

Truckee River Basin: The Truckee River Basin lies in the states of California and Nevada. The upper reaches of the basin are in the northern Sierra Nevada mountains primarily in the state of California. The Truckee River begins at the outlet of Lake Tahoe, gains flows from several tributaries including Donner Creek, Martis Creek, Prosser Creek, and the Little Truckee River. It then crosses the California/Nevada state line flows through the metropolitan areas of Reno and Sparks, Nevada, over Derby Dam, where water is diverted through the Truckee Canal to Lahontan Reservoir in the Carson River basin, and then flows out to its terminus at Pyramid Lake on the Pyramid Lake Paiute Tribe's land near Nixon, Nevada. The river travels a total of 105 miles from Lake Tahoe to Pyramid Lake. Rieker et al, (2005).

While a relatively small river system, the demands on its supply, and the complexity of its operations are significant. There are seven storage reservoirs in the upper basin. These reservoirs control approximately 70% of the flow in the Truckee River. Two of the reservoirs are owned by private interests, Donner Lake and Independence Lake. These provide municipal

water to Reno and Sparks, and water to the irrigators within the Truckee Carson Irrigation District via the Truckee Canal. Martis Reservoir is owned by the Us Army Corps of Engineers and is strictly used for flood control. The remaining four reservoirs, Lake Tahoe, Stampede Reservoir, Boca Reservoir, and Prosser Reservoir, are Bureau of Reclamation facilities. They are used to provide storage for irrigation, municipal use, industrial use, and for recovery of threatened and endangered species in Pyramid Lake. A map of the Truckee River Basin is shown in Figure 1. Scott (2006).

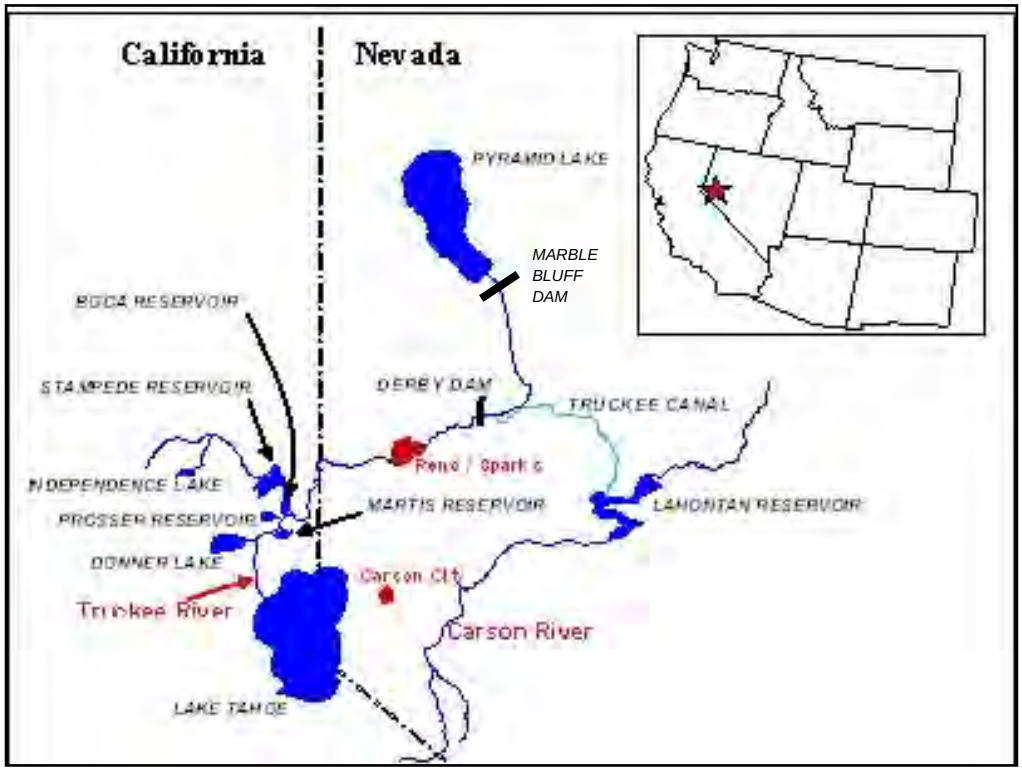

Figure 1 Map of Truckee-Carson Basin.

Operations of the Truckee River System are conducted by the US District Court's Watermaster, including operating the federal reservoirs and administering the water rights and diversions from the river. The policy governing the operations of the Truckee System is a combination of several significant decrees and agreements. Some of the most significant ones are the 1915 Truckee River General Electric Decree, the 1935 Truckee River Agreement, the 1944 Orr Ditch Decree, the 1959 Tahoe-Prosser Exchange Agreement, the 1989 Preliminary Settlement Agreement, and the 1997 Adjusted Operating Criteria and Procedures. Boyer (2006).

Because of the many demands on the system, the significant regulation in the system, and the relative scarcity of the supply in this basin, it is very important to operate the system as efficiently and precisely as possible. Reducing unnecessary or imprecise releases of stored water by delivering water in the exact amount and at precisely the right time per the agreements governing the Truckee River, is a great benefit to all parties in the basin and the basin itself. This is the charge of the Watermaster in Reno, Nevada.

High-Precision Realtime Modeling System Background: Throughout the western United States, one of the foremost challenges in operating water storage facilities is to minimize any adverse impacts they have to the ecosystems in which they operate. scientists and policy makers better identify ecological and political challenges and more precisely specify operational objectives to address these challenges, water managers' capabilities to meet these operational objectives must also advance. The operational criteria being placed upon managers, specifically the Watermaster of the Truckee River, due to political and environmental considerations are increasingly precise and demanding. Developing innovative and more precise modeling techniques that operate on a shorter time scale will allow them to meet these criteria fully and precisely while avoiding negative impacts to other water delivery responsibilities Coors (2006a).

A modeling system has been developed to support the daily operational responsibilities of the Federal Watermaster for the Truckee River system. This modeling system is short-term, looking forward only 96-144 hours. It models releases, diversions, and flows in the basin on an hourly timescale, pulling realtime streamflow and climate data from the internet and the Watermasters in-house database daily. The model is implemented in an Excel spreadsheet with a user interface shown in figure 2.

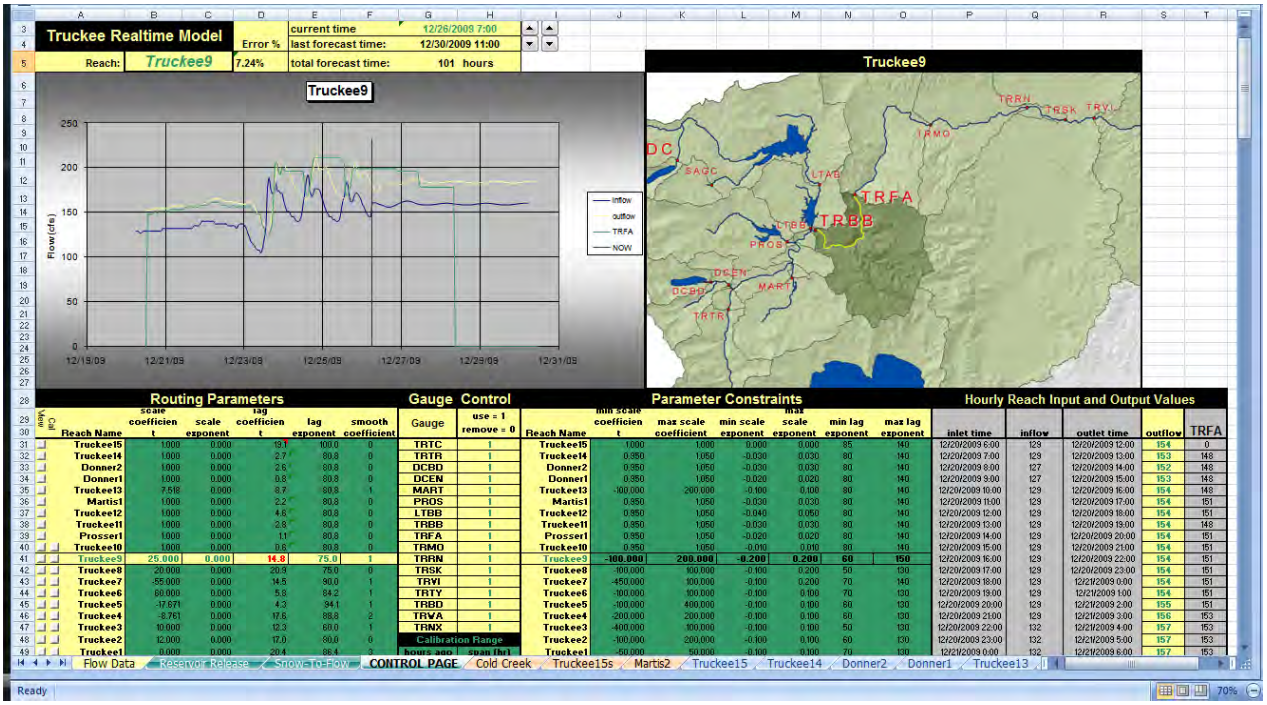

Figure 2 Screenshot of the Truckee Realtime Model User Interface.

The modeling system and its methodology come from similar modeling systems constructed for the operators of the Upper Colorado River Basin facilities, including Flaming Gorge Reservoir, the Aspinal Unit on the Gunnison River, and Navajo Reservoir on the San Juan River. These systems were constructed to assist the operators of these facilities during the spring runoff period to optimally meet objectives of an endangered species recovery program downstream from these facilities. These objectives are very precise, and to be met without wasting water that could be used for power generation or other important uses, required a very precise model to prescribe releases from the reservoirs on a hourly timescale. These modeling systems have been used,

particularly at Flaming Gorge Reservoir, successfully since its development in 2004. Coors (2006).

MODEL DESCRIPTION

Data: The model is driven by hourly streamflow and climate data that is pulled daily from the internet and from the Watermaster's in-house database. There is a separate spreadsheet that is used exclusively to query and store the data. This data spreadsheet has built-in queries that automatically initiate when the sheet is opened. These queries go to the watermaster's database to get the most current hourly flows at 17 USGS streamgages on the Truckee River, its tributaries, and the Truckee Canal. The sheet also queries the National Resource Conservation Service's (NRCS) website for the most current temperature and snow-water equivalent (SWE) data at its nine snotel sites within the Truckee Basin. Finally it queries the National Weather Service website for forecasted hourly temperatures at the precise locations of each of the nine Truckee basin snotel sites. These data are then archived within the spreadsheet and the model is linked to the data sheet. Each data sheet is used to query data and to store one year's worth of each of the data described above. At the end of a water year, the data sheet has its queries disabled, is archived, and a new one with live queries is started for the following water year. Coors (2004)

Forecasting Methodology: In order to make an hourly operational forecast and calibrate the model for use in testing potential release scheduling, a 96-hour forecast must be generated for three unregulated headwater subbasins in the upper reaches of the Truckee basin. These basins are shown in figure 3:

1. Cold Creek Basin - drains to Donner Creek between Donner Creek Near Donner Lake (USGS # 10338500) gage and the Donner Creek Near Highway 89 gage (USGS # 10338700).
2. Truckee Sidewater Basin - Truckee River between Tahoe City gage (USGS #10337500) and the Truckee nr Truckee gage (USGS # 10338000)
3. Martis Basin – Basin above Martis Creek nr Truckee gage (USGS # 10339400). Note the Martis basin does appear to be regulated by Martis reservoir, however the reservoir does not store any water unless flooding is imminent, otherwise it just passes natural inflows

During the majority of the year, the flows resulting from these three forecasts comprise a very small percentage of the total flows at the state line. For most of the year the flows in the river are determined primarily by releases from the seven upstream reservoirs. It is only during the spring months that these forecasts play a significant role in forecasting the flows downstream and the appropriate timing of operational changes.

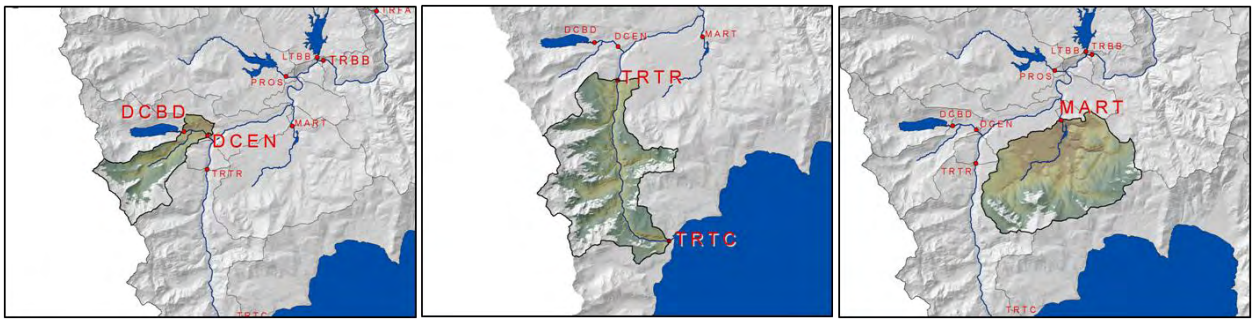

Figure 3 Three Headwater Forecast Basins.

The forecast hydrographs produced by the model are in the form of a line with a slope S superimposed on a sine wave of amplitude A and a period of 24 hours. To generate a forecast for these headwater basins, the user starts by viewing the realtime basin temperatures by elevation zone and estimated snow depth by elevation zone over the past five days, and the resulting flows over the same time period at the gaged outlet of the basin. Then given the forecasted temperature for the next 96 hours and the current state of the snowpack, the user constructs a 96-hour forecasted hydrograph for the basin. If the snowpack is significant, the response of the flows at the outlet to warm (or cold) temperatures over the past several days is a very good indicator for how the basin will respond to warm (or cold) temperatures over the next four days. This response for the past five days is quantified and displayed to the user in the form of two parameters per day, slope and amplitude.

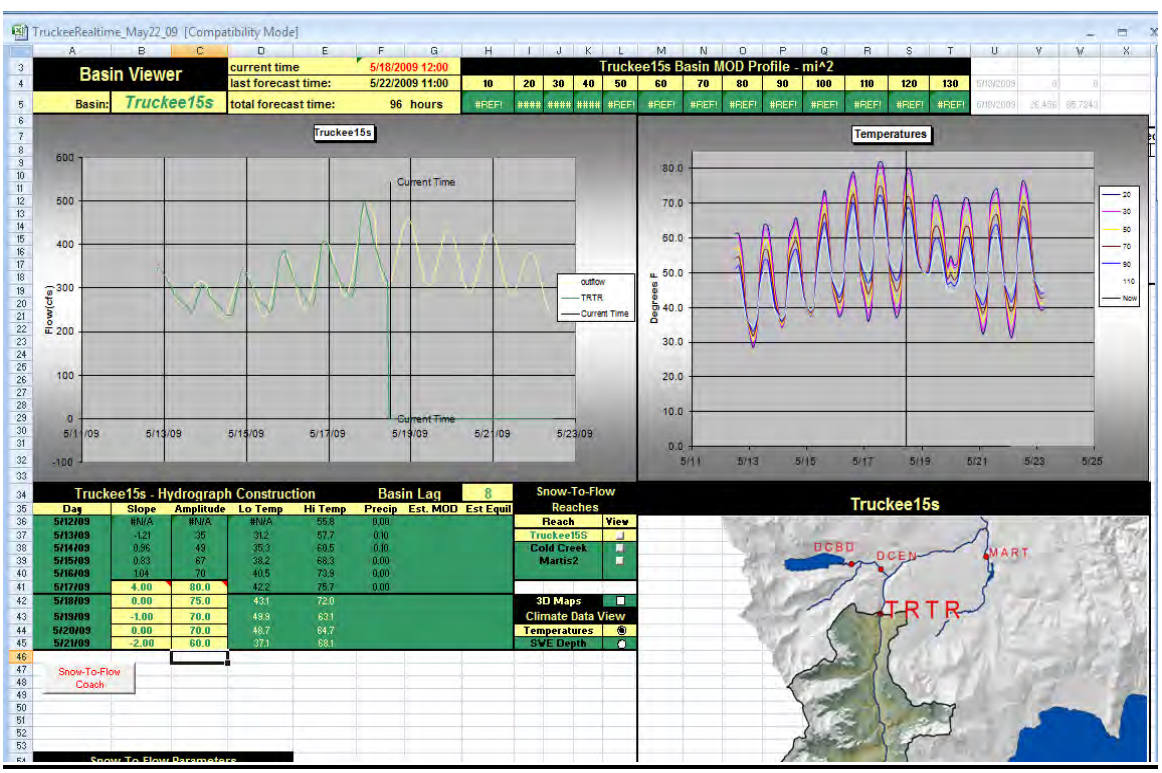

Figure 4 Forecast Generation Interface.

An interface is provided for the user to estimate slope and amplitude values for each of the next 4 days based on the forecasted temperatures in the basin and the state of the snowpack. Setting these eight parameters generates a 96-hour forecast for the unregulated basin. A sample view of the headwater forecast interface can be seen in figure 4.

Routing Methodology Background: Probably the most significant process within this modeling system is the process of routing the flows through the river once the inflows due to releases and ungaged inflows are set. The routing methodology utilized for routing flows through the network is specially designed for precisely routing hourly flows, and is unique to this modeling system. It is a semi-empirical method that does not conserve volume because significant sideflows, diversions, and losses are a defining characteristic of nearly all reaches in the basin.

Stream Network Delineation: The first step in constructing the model was to decompose the Truckee River basin into 20 separate subbasins within a GIS. An outlet point was placed on the river at the confluence of each major tributary and at each realtime USGS streamgage. Then the subbasin draining to each of those 20 break points was delineated. See figure 5 for a map of the Truckee Basin and the subbasins delineated for use in this model. Each USGS realtime gage is identified by a four letter identifier visible in the figure.

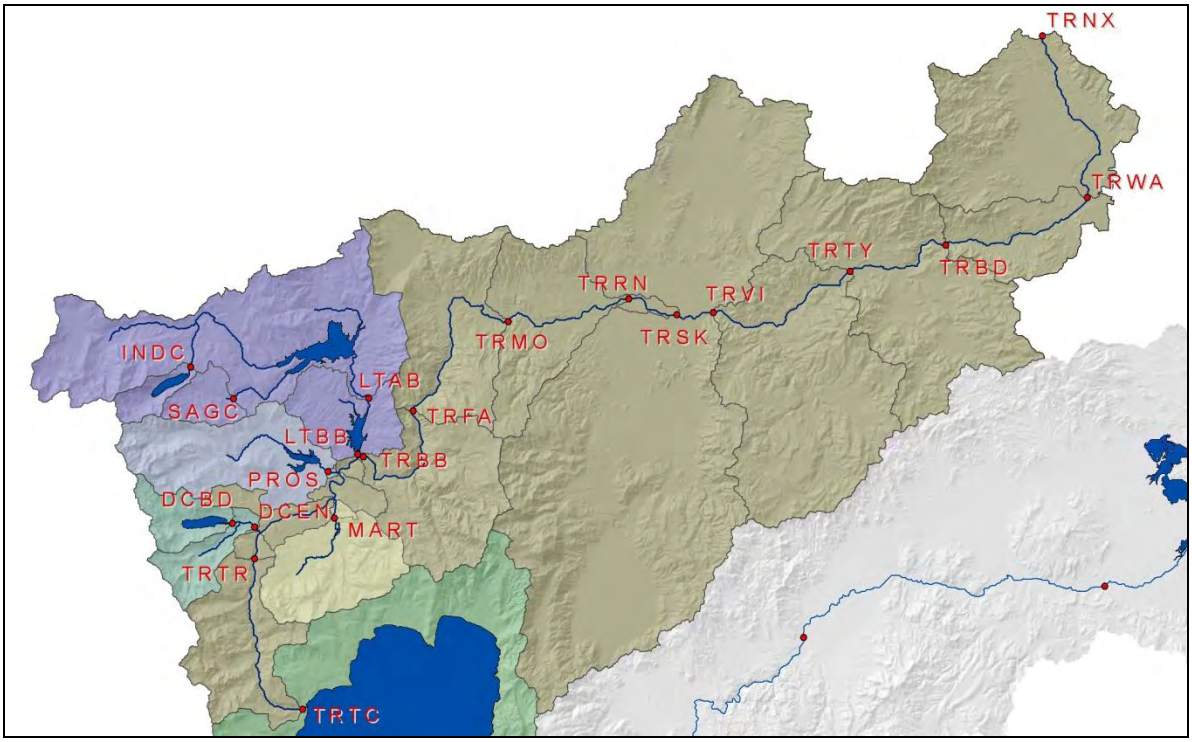

Figure 5 Breakdown of Truckee Basin for Use in the Model.

Several physical characteristics of each reach, including the reach length and average slope, were then extracted and used for the routing process.

Stream Network Modeling Structure: The stream network is modeled in the spreadsheet by modeling the flows through each reach in the network on a single worksheet within the spreadsheet. Each sheet has an inflow hydrograph and an outflow hydrograph and is linked to

upstream and downstream reaches to reflect the physical layout of the Truckee Basin. Each sheet takes the outflow hydrograph from the upstream reach (or combined outflow hydrographs from the upstream reaches for a confluence), performs the routing operation described below on the inflow hydrograph to lag and scale it to generate an outflow hydrograph. This outflow hydrograph is then passed to the next downstream reach's sheet which does its own routing process. If, at the outflow point of a reach, there is a streamgage, then the routed outflow is compared hour-by-hour with the actual outflow up to the current time. The routing parameters are then calibrated to match the calculated outflow hydrograph as closely as possible to the gaged outflow hydrograph. This is done using the "Solver" utility in Excel which performs a non-linear optimization of the parameters to determine the "best" fit between the routed outflow hydrograph with the gaged outflow hydrograph over a user-selected period of time. Coors (2004). The assumption is that if the parameters are optimized to define the best possible lag versus flow relationship for the last 24-72 (user specified) hours, then that relationship will also be a good estimate for the relationship for the next 96-140 hours. After utilizing this modeling system for many years on several basins under a wide variety of conditions, it has been well established that this assumption is remarkably accurate and useful. Coors (2006).

Routing Method Details: The routing methodology utilizes a point-by-point mapping technique that is based simply on the intuitive observation that in any given reach the lag time will decrease as the flow through the reach increases.

Generally, the inflow and outflow hydrographs for a reach have qualitatively the same shape. The outflow hydrograph is shifted forward in time and either up or down from the inflow hydrograph. The shift to the right is due to the travel time or time lag for the flow to travel from the inlet to the outlet. The shift up or down is due to gains or losses in the flows through the reach.

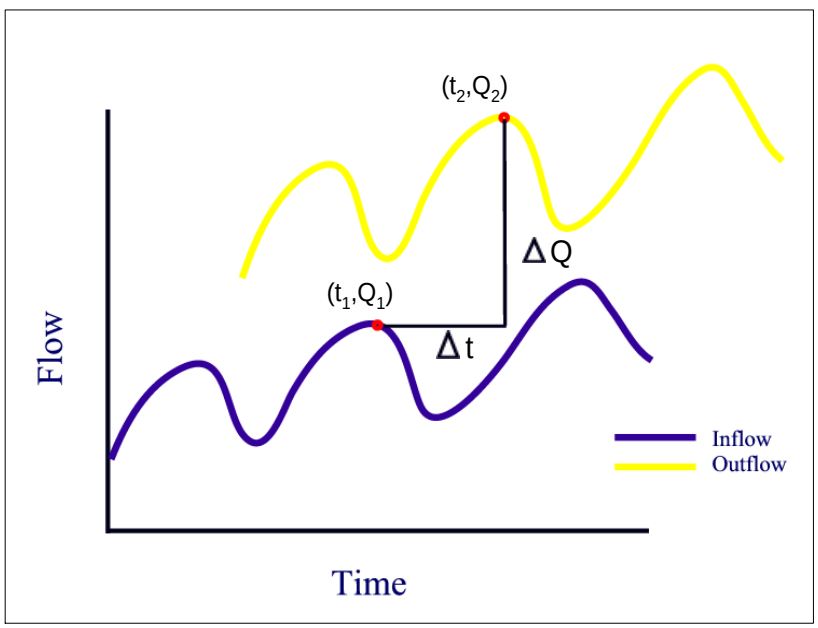

Figure 6 Routing Schematic.

The lag time (Δt) and scale factor (ΔQ) are defined as:

$$\Delta t = t_2 - t_1 \quad (1)$$

$$\Delta Q = Q_2 - Q_1 \quad (2)$$

The method takes each inflow data point consisting of a time and flow value (t_1 , Q_1) and maps it to an outflow data point (t_2 , Q_2). There are two mapping functions f_1 and f_2, one for the time lag and one for the scale factor. Note that both are functions of the inflow Q_1.

$$\Delta t = f_1 (Q_1) \quad (3)$$

$$\Delta Q = f_2 (Q_1) \quad (4)$$

The mapping functions define the relationship between lag and inflow (f_1) as well as the gain/loss and inflow (f_2). The actual relationship between inflow and lag time was analyzed for several gaged reaches in this and several other basins in the western United States, and then the resulting relationships for the different reaches were examined to see if any consistent correlations between relationship parameters to physical characteristics of the reach could be found. The details of this process are outside the scope of this paper. (reference manual), but it was found that there are consistent relationships between the parameters of the best fit mapping function f_1 and physical characteristics of the reach being analyzed. This finding can be leveraged to generalize the parameterization of the mapping function f_1 for any reach in any basin regardless of any gaging that exists on the reach.

First, it can be shown that the lag-flow relationship for a river reach is well characterized by a power function of the form

$$\Delta t = A * (Q_{in})^B \quad (5)$$

Here A and B are the two parameters of the mapping function f_1. Time t is measured in hours and the flow (Q_{in}) is measured in cubic feet per second (cfs). After analyzing a number of reaches and the lag-flow relationships they exhibited, it was observed that using the reach length in miles for parameter A renders an accurate lag mapping function. This makes intuitive sense in that as a hypothetical reach of a particular slope gets longer, one would expect the lag time to increase proportionally. Second, it was also noted that the best fit value for parameter B was always very nearly proportional to the inverse of the slope of the reach. This says that for hypothetical reaches all of the same length with differing average slope, the more steeply sloped the reach is, the shorter the lag time through that reach will get, which again makes intuitive sense, and was demonstrated to be true in analyzing many reaches in many different basins.

As for the mapping function f_2, describing the gain/loss through a reach, it was concluded that for high-elevation basins in the high-flow times of the year during which significant lateral inflow was coming to the reach due to melt, the best form of the function f_2 is also a power function of the form

$$\Delta Q = C * (Q_{in})^D \quad (6)$$

However no consistent relationship between physical characteristics of the reach and the best values for the parameters C and D could be ascertained. This is not unexpected however, as the magnitude of the gain/loss in a reach is dependent on seasonal and hydrologic factors that are different at different times. However, these values do remain consistent over time periods on the order of five to ten days which is all the further the model goes into the future. Consequently the model tunes these two parameters each time it is run, whereas it never tunes the parameter A and just slightly tunes the parameter B from mapping function f_1, because of their established relationship to static physical characteristics of the reach. Figure 7 below shows a screenshot of a reach worksheet and the results of mapping two different inflow points to two different outflow points, and illustrates the results of the method. Note that for a lower inflow (point 2) the lag time increases and the gain increases. Coors (2004).

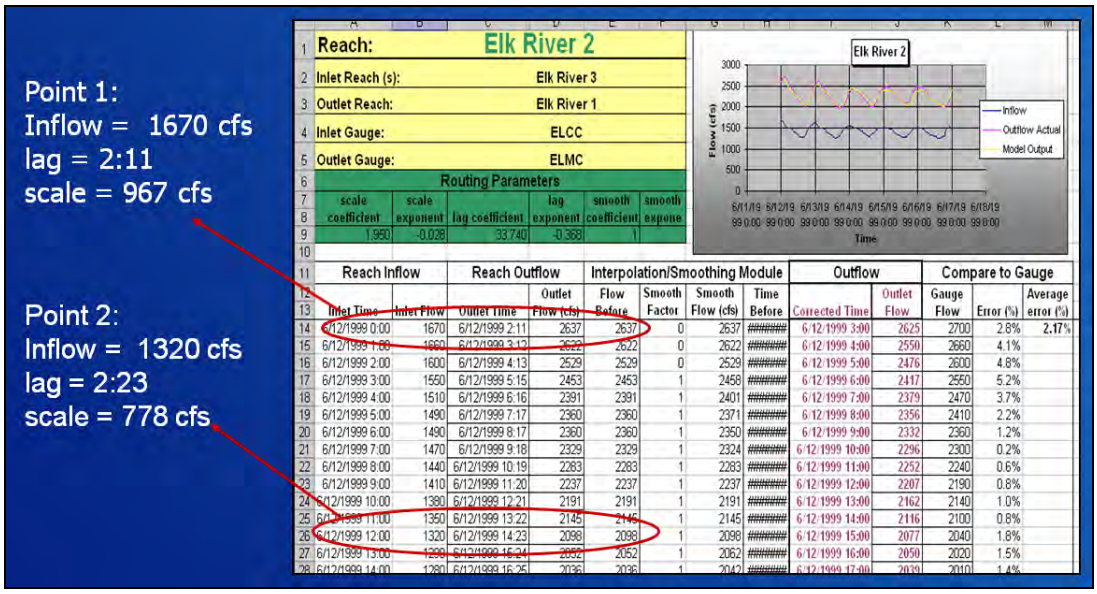

Figure 7 Routing Method Example.

Calibration of Stream Network: For each reach in the network, the inflow hydrograph is operated on by the two mapping functions f_1 and f_2 to lag and scale it and generate an outflow hydrograph. Then reach-by-reach these parameters are tuned to fit the most recent realtime observed gage flow data at the next downstream gage. After each reach throughout the basin has its parameters tuned, the stream network is calibrated and can take inflows at the input nodes and rout them through the system thus making a forecast (of 96 hours plus travel time down to the node) at every node within the basin. This calibration process usually takes approximately 20 minutes, is largely automated, and can be reasonably done on a daily basis. Once this calibrated network is set, hypothetical release schedules can be used as input and will propagate almost instantaneously throughout the network to show forecasted results up to six days into the future on an hourly scale.

Sample Uses for Model: Two brief hypothetical examples are given here showing how the modeling system has been used to improve operations of river systems and reservoirs. First, a water manager may know that a release increase will be initiated at a particular time in the next 4 days that is intended to be a delivery of water to a certain takeout point downstream. With the model the manager can make a very accurate estimate of the time that the release increase will reach its intended destination and the diverter can begin to take the released water. The manager can also make a very precise estimate of how much the release increase will have to be in order to deliver the appropriate amount of water to the takeout given the most current gains and losses occurring in the system. Estimates of the travel time of operational changes like this made by this modeling system are generally accurate to within one hour, and almost never more than two, even if the travel time through the river system is 48 hours or more. Being able to use this tool in this way results in much more efficient use of stakeholders' water as diversions of just the right amount can be delivered and taken at the precisely the time that they arrive at the point of diversion.

Another example of how this system is used is when natural inflows to a river need to be augmented by releases of stored water in order to meet a downstream target for environmental or other reasons. If, for example, the natural unregulated flow is decreasing over the coming few days, then ideally the releases of stored water would increase over the same period, but only as needed to maintain the target flows downstream and no more. Using this modeling system, managers can design high-precision release schedules on an hourly scale to optimally meet, but not exceed, the flow targets, thereby saving water that often is over-released due to a lack of precise knowledge of when and how much water to release to meet the target.

IMPLEMENTATION

Truckee River Travel Time Report: In the Truckee River basin, this model is run regularly and its output is used to generate a daily travel time report that is available to stakeholders, and the general public on an ongoing basis. This report can be seen at www.troa.net under the reports tab. Figure 8 shows the report as it is displayed on the internet.

The travel time report lists the travel time between several significant locations on the river. The report is generated directly out of the Watermaster's database. The modeling system is run regularly (usually weekly) and the optimized routing parameters are entered into the database. The database then calculates the average flows through the river and uses the mapping function f_1 on a reach-by-reach basis to calculate the travel time through each of the reaches defined within the model. Then within the database, these travel times are combined appropriately to calculate the travel times between the nodes in the travel time report. The Watermaster has the option to let the travel time calculation for each reach be automated based on the average flow in the reach over the past six hours, which is the default automated method, or if he knows that a significant change to the flows in the river is imminent, like a coming release change, he can manually enter in to the lag calculation a flow of his choice. The travel times are then recalculated using the expected flow in the river. Then on a weekly basis the routing parameters are recalibrated using the model and entered into the database.

Figure 8 Screenshot of the Travel Time Report Website

The travel time report is new as of the beginning of 2010 . It has been used by the Watermaster to determine when release increases intended for use in the Truckee Canal can be actually be taken by the Truckee Carson Irrigation District at Derby Dam at the mouth of the Truckee Canal. It will be used to precisely time releases of water for endangered species in the reach below Derby Dam to compensate for the initiation of a diversion at Derby Dam into the Truckee Canal such that the physical flows below Derby dam do not fluctuate greatly up or down to the detriment of the threatened and endangered species in these lower sections of the river. The Truckee Meadows Water Authority (TMWA), the water purveyor for much of the Reno/Sparks metropolitan area, will use the travel time report to time the releases of its Privately Owned Stored Water in the upper reservoirs in order to precisely deliver water to their run-of-the-river power generation facilities and M&I takeouts in the Truckee Meadows.

Springtime Operations of Flaming Gorge Reservoir: The model was originally developed to support the springtime operations on Flaming Gorge Reservoir. The Green River below Flaming Gorge Reservoir is home to three endangered fish species. A cooperative effort between the United States Bureau of Reclamation, the United States Fish and Wildlife Service, and others resulted in a comprehensive recovery plan being developed. One of the primary operational objectives set forth in the recovery plan is for Flaming Gorge Dam to be operated to achieve prescribed peak flows and durations in a critical section of the river that is over 100 miles downstream from the dam, and 30 miles downstream from the Yampa confluence. To optimally achieve these flow targets without wasting water by over-releasing, the peak releases from the reservoir must be timed to precisely coincide with the natural spring peak flow from the unregulated Yampa River. Successfully implementing this operation requires forecasting the Yampa peak roughly 3 days ahead of time, the capability to set release changes from the dam to reach the confluence (18-24 hour travel) at precisely the right time, and the ability to set and adjust the release magnitudes such that the downstream targets are met but not exceeded. In

some instances the flow targets and durations require releasing water that bypasses the power generating system at Flaming Gorge. When this occurs, it is critical that the bypass releases initiated are precisely timed and in the exact amount needed, but no more, to minimize the loss of power generation revenue. This was accomplished by the operators of Flaming Gorge Reservoir using this model very successfully in the springtime of 2006. This modeling system has been used by the operators of Flaming Gorge Dam successfully since 2004.

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