MODELING DROP 2 STORAGE RESERVOIR OPERATIONS WITH HEC-RAS, IMPERIAL COUNTY, CALIFORNIA

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Abstract

Drought and climate change in the Colorado River Basin are the business drivers for increased system efficiency and provide the impetus for construction of the Drop 2 Storage Reservoir. An average of 70,000 acre-feet of Colorado River Water is annually delivered to Mexico in excess of the 1944 Treaty requirement of 1.5 million acre-feet per year. Excess flow that cannot be stored at Senator Wash or elsewhere on the system is also known as "non-storable flow." In December 2007, Reclamation signed the Record of Decision for the *Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead,* along with agreements to provide funding of the reservoir in exchange for system efficiency intentionally created surplus. The primary objective of the Drop 2 Storage Reservoir is to add approximately 8,000 acre-feet of additional system storage and system efficiency to capture non-storable flow. Operations of the Drop 2 Storage Reservoir are modeled using an unsteady flow model in HEC-RAS, a one dimensional flow model developed by the United States Army Corp of Engineers. Non-storable flows are modeled through the All-American Canal and diverted to the Drop 2 Storage Reservoir by programming gates to open and close at critical junctions, such as the Coachella turn out, and at Cells 1 and 2 at the storage reservoir. System conditions for February 2009 were simulated to demonstrate programming rules at gates. Base flow conditions and non-storable flows are entered into the unsteady flow editor as a flow hydrograph boundary condition.

INTRODUCTION

The recent drought in the Colorado River Basin (2000 to present), coupled with changing temperature and precipitation patterns, has provided impetus to increase Colorado River system efficiency. The Drop 2 Storage Reservoir (D2SR) satisfies part of this need for greater system efficiency.

Drought, Climate Change, and Water Supply

Drought on the Colorado River system is not uncommon. Meko et. al. (2007) reconstructed annual flows on the Colorado River at Lees Ferry from A.D. 762 through A.D. 2005, by analyzing the tree ring record in the Upper Colorado River Basin. A time series plot of the 25-year running mean of reconstructed annual flow from A.D. 762 to present reveals natural variability in the system, including both wet periods and dry periods. One of the wettest cycles occurred in the early 20th century, and may have influenced water supply assumptions for the Colorado River Basin when the Colorado River Compact was developed. However, the 25-year running mean also reveals periods of prolonged, severe drought, such as the Medieval Climate Anomaly. A mega-drought in the mid-1100's may have lasted at least 60 years (Figure 1).

According to Reclamation (2009) the recent drought in the Colorado River Basin has resulted in the driest 10-year period[1] of the 100-year historical record on the Colorado River at Lees Ferry.[2] The drought began in water year 2000 and continues through water year 2010. Although there have been at least two years with above average flow, it is not uncommon to have a few wet years during prolonged dry periods. Water years 2000 through 2009 were all

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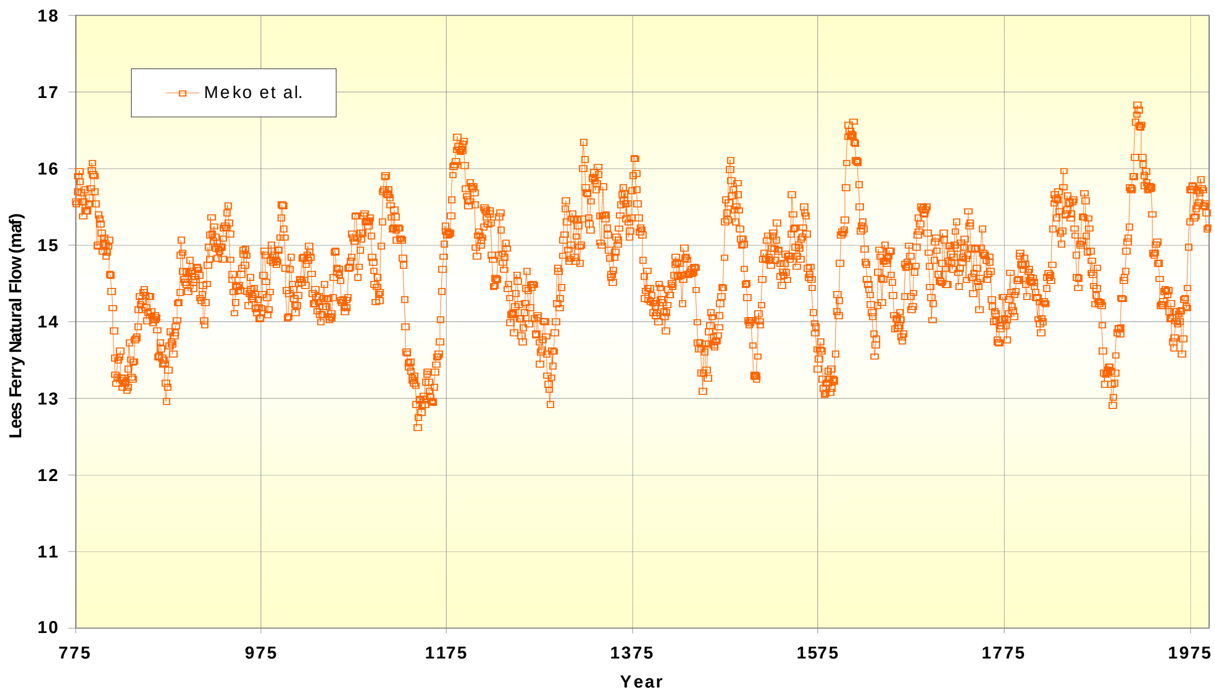
[1] Water year 2000 to 2009, inclusive

[2] The basis for the 100-year Colorado River flow data at Lees Ferry is from the natural flow database, located at http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.



Drought conditions have been exacerbated by the affects of climate change. Miller and Piechota (2008) report that temperature and precipitation patterns are changing for both the Upper and Lower Colorado River Basin. Increasing temperature trends were most significant from January through March. One result is increasing stream flow trends from January through March, contributing to higher, earlier runoff and increased variability in stream flow earlier in the season.

Operations and Water Demand

While the current drought is diminishing water supply into Lake Powell, and while climate change is altering temperature and precipitation patterns throughout the Colorado River Basin, Lake Mead and other main stem reservoirs in the Lower Colorado Region are operated primarily to supply water to both municipal and agricultural users in the Lower Division States[3] and Mexico.

Once Colorado River water is released from Lake Powell, the water courses through the Grand Canyon and is stored in Lake Mead for delivery to the Lower Basin states and Mexico. The Secretary of the Interior (Secretary) serves as the water master of the Colorado River below Lee Ferry, or the Compact Point, between the Upper Colorado River Basin and Lower Colorado River Basin. One primary goal of the Secretary is to deliver 9.0 million acre-feet of water to the Lower Basin and Mexico, as dictated by the "Law of the River," a complex series of legislation, treaties, and agreements that divides the Colorado River water among the basin states and Mexico, last updated by Nathanson (1978), and currently being updated again.

According to Reclamation (2000 to 2009, 2000 to 2009a), approximately 6.87 million acre-feet[4] of Colorado River water is released from Parker Dam, and at most 6.49 million acre-feet[5] is regulated at Imperial Diversion Dam, just north of Yuma, Arizona, for irrigation and other uses in California, Arizona and Mexico. That water must be

[3] Arizona, California, and Nevada, as defined in the Colorado River Compact.
[4] Average annual release from Parker Dam, water year 2000 to 2009, inclusive, from Reclamation's 24-month study.
[5] Average annual release from Parker Dam, minus average annual consumptive use between Parker Dam and Imperial Dam, water year 2000 to 2009, inclusive, from Reclamation's 24-month study and Colorado River Accounting and Water Use Reports, Arizona, California, and Nevada. System gains and losses between Parker Dam and Imperial Dam are not included.

released from storage in Lake Mead, travel approximately 65 miles south to Davis Dam, another 82 miles south to Parker Dam, and another 143 miles south to Imperial Dam, a total of approximately 290 miles. It takes approximately five days for water released from Lake Mead to reach Imperial Dam (or approximately three days from Parker Dam to Imperial Dam). By the time the water arrives at Imperial Dam, the water users that scheduled it may not be able to put it to beneficial use due to changed weather conditions, high runoff into the river, or a number of other factors (Figures 2 and 3).

Colorado River water may be stored in Senator Wash Reservoir, a pumped-storage facility about two miles upstream from Imperial Dam on the California side of the Colorado River. Senator Wash Dam was constructed with a capacity of approximately 13,863 acre-feet at elevation 251 feet, specifically to manage fluctuating flows at the lower end of the Colorado River. However, elevation restrictions have been placed on Senator Wash Reservoir since 1992 due to potential piping and liquefaction of foundation and embankment materials at West Squaw Lake Dike and Senator Wash Dam. Currently Senator Wash Reservoir is restricted to 9,000 acre-feet at elevation 240 feet. Further, Senator Wash reservoir levels must not exceed elevation 238 feet for more than 10 days. The facility consists of six 200 cfs capacity pumps that can pump at most 1,200 cfs at full capacity. Senator Wash must have both adequate space and pump capacity to divert Colorado River water released from Parker Dam. Colorado River water that cannot be diverted at Imperial Dam or stored in Senator Wash Reservoir is called "non-storable" flow.

Colorado River water reaching Imperial Dam is routed through the desilting works and into the AAC for delivery to both the Imperial Irrigation District (IID) and the Coachella Valley Water District (CVWD), and to other users between Imperial Dam and Pilot Knob. At Pilot Knob water may be diverted to Mexico for delivery at the Northerly International Boundary (NIB). Water not diverted at Pilot Knob continues west in the AAC for delivery to IID and CVWD. Non-storable flows are planned to be diverted at the Coachella Canal turnout and into a 6.6-mile Inlet Canal. At the westerly end of the Inlet Canal is a planned forebay/afterbay structure which regulates flow into and out of the 8,285 acre-foot D2SR. The new D2SR/AAC system is designed to convey at most 1,800 cfs of non-storable flow. At this conveyance rate, the D2SR would fill in about 3 days.

<u>System Efficiency and Intentionally Created Surplus</u>

Since the current drought began in 2000, approximately 741,482 acre-feet of non-storable Colorado River water has flowed to Mexico[6]. This is in addition to approximately 1,116,337 acre-feet of water from the Wellton-Mohawk Irrigation and Drainage District that bypasses the Colorado River and is discharged to the Cienega de Santa Clara in Mexico.

To address non-storable flows, Reclamation and the Lower Division States conducted a study to identify additional regulatory storage opportunities below Parker Dam. The study determined that building a small reservoir near the AAC in Imperial County, California, was the best alternative to meet the objectives for conserving Colorado River water. A study performed by Reclamation concluded that 70,000 acre-feet on average of non-storable flow could be saved annually.

Reclamation (2007) and the Secretary signed the Record of Decision (ROD) for the *Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead*, also known as the Shortage Guidelines. Key to this ROD was the implementation of intentionally created surplus, where stakeholders could create surplus on the Colorado River through system efficiency projects, or through water conservation.

Also in December 2007, Reclamation (2007a, 2007b) signed funding agreements for the construction of the D2SR. In exchange for project funding, the Southern Nevada Water Authority (SNWA), the Central Arizona Water Conservation District (CAWCD), and the Metropolitan Water District of Southern California (MWD) received

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[6] Average values for non-storable flow and bypass flow to Mexico, water year 2000 through 2009 inclusive, Colorado River Accounting and Water Use Reports, Arizona, California, and Nevada. Values for calendar year 2009 were based on the December 21, 2009 end of year consumptive use forecast.

Figure 2. Colorado River system downstream of Parker Dam, showing location of the Drop 2 Storage Reservoir just north of the Northerly International Boundary with Mexico.

Figure 3. Oblique aerial view taken from Google Earth (2009) looking north across the Northerly International Boundary from Mexico. Flows are modeled from Imperial Dam through the All-American Canal to the Drop 2 Storage Reservoir, located far left immediately north of the Northerly International Boundary.

system conservation intentionally created surplus. The estimated construction cost at the time of funding was $172 million. SNWA agreed to pay most of the project's cost (including the cost of construction of the confluence structure of the project), as well as its operation and maintenance costs for a specified period of time. In return, SNWA will receive 400,000 acre-feet of water, at a maximum of 40,000 acre-feet a year, until 2036.

The MWD and CAWCD provided $28.6 million each (for a total of $57.2 million) for construction of the project. In return, both MWD and CAWCD will receive 100,000 acre-feet of water each (200,000 acre-feet total), a maximum of 65,000 acre-feet a year, from 2016 through 2036. CAWCD's delivery may be reduced by the amount of water used by SNWA and/or the MWD in any given year.

MODEL DEVELOPMENT

Construction of the D2SR is expected to be complete by Summer 2010. The Engineering Services Office (ESO) of Reclamation's Lower Colorado Region modeled unsteady flow operational scenarios of the D2SR and the AAC using the latest version of HEC-RAS, a one-dimensional steady and unsteady hydraulic model developed by BUSACE(2008) at the United States Army Corp of Engineers (USACE). Non-storable flows reaching Imperial Dam were modeled through the AAC and into the D2SR.

HEC-RAS is a hydraulic model comprised of a graphical user interface with separate components to analyze hydraulics, store data, and report graphic and numeric output. The program has three hydraulic analysis components, namely, steady flow, unsteady flow, and moveable boundary sediment transport computations. Brunner (2008) indicates these three analysis components use common geometry data and common geometric and hydraulic computation routines.

The unsteady flow component was used to simulate conditions on the AAC and D2SR system. Mixed flow regime calculations are simulated including subcritical and supercritical flow, and hydraulic jumps. Hydraulic structures such as bridges, culverts, storage areas, gates, and diversions are also included in the model. The computational procedure solves for a one-dimensional energy equation, where energy losses from friction and contraction/ expansion losses are incorporated into system conveyance computations. The momentum equation is used for rapidly varied flow situations, such as hydraulic jumps, hydraulics adjacent bridges, and junctions.

The unsteady flow model was constructed by Brown and Caldwell by entering the physical geometry data of the existing AAC from Imperial Dam to a point east of Drop 3, including inline structures such as Drop 1, Drop 2, and Pilot Knob, a total distance of approximately 46 miles of canal. The HEC-RAS geometry editor was also used to input proposed structures, such as the newly lined sections of the AAC, the Coachella Canal turnout, the Inlet Canal, the forebay/afterbay structure, the off-line storage structure (OLS), the D2SR, the outlet canal and pipeline, and other structures. Gates are input at existing and proposed structures and programmed in the HEC-RAS unsteady flow editor. This is a new feature to HEC-RAS and is designed to simulate operations associated with the opening and closing of gates in unsteady flow conditions (Figures 4, 5, and 6).

MODEL SCENARIOS

The ESO was retained to develop modeling scenarios to recreate February 2009 system conditions assuming the D2SR was operational. The February 2009 time frame was chosen because non-storable flows were delivered to Mexico, in excess of treaty requirements, and provides an example of programmable gates within HEC-RAS.

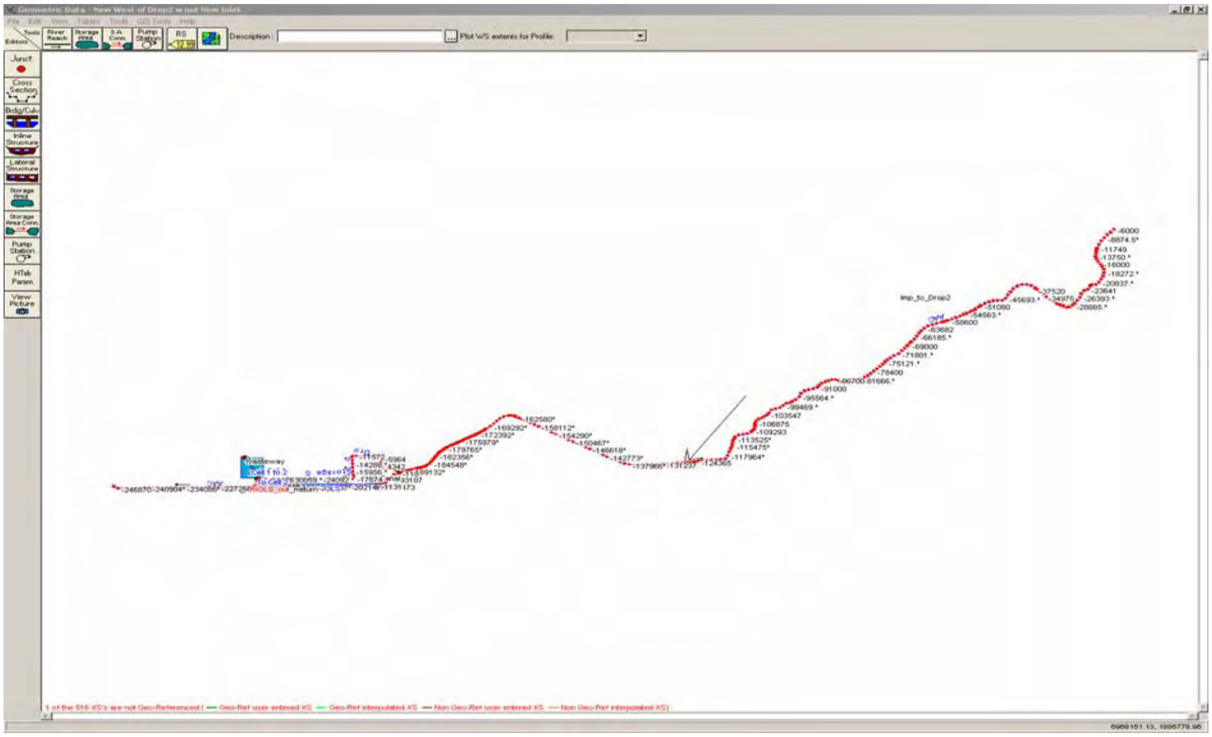


Figure 4. Model configuration from HEC-RAS geometry editor. Approximately 46 miles of the All-American Canal were modeled from Imperial Dam to Drop 3, west of the proposed Drop 2 Storage Reservoir. The Drop 2 Storage Reservoir is the blue storage area to the left, whereas Imperial Dam is located to the far right. Flow in the All-American Canal is from east to west, north is to the top.

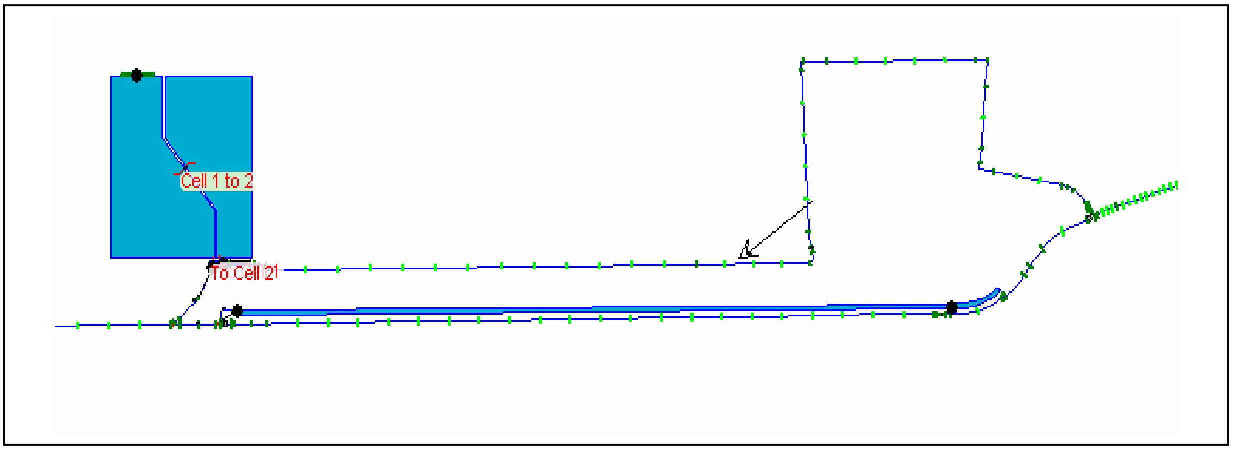


Figure 5. Model configuration from HEC-RAS geometry editor. Approximately 6.6 miles of Inlet Canal was modeled from the Coachella turnout to the proposed Drop 2 Storage Reservoir. Non-storable flow conveyed in the All-American Canal is diverted into the Inlet Canal, to a forebay/afterbay structure, and into or out of Cell 1 and Cell 2 of the Drop 2 Storage Reservoir. Flow is from east to west, north is to the top.

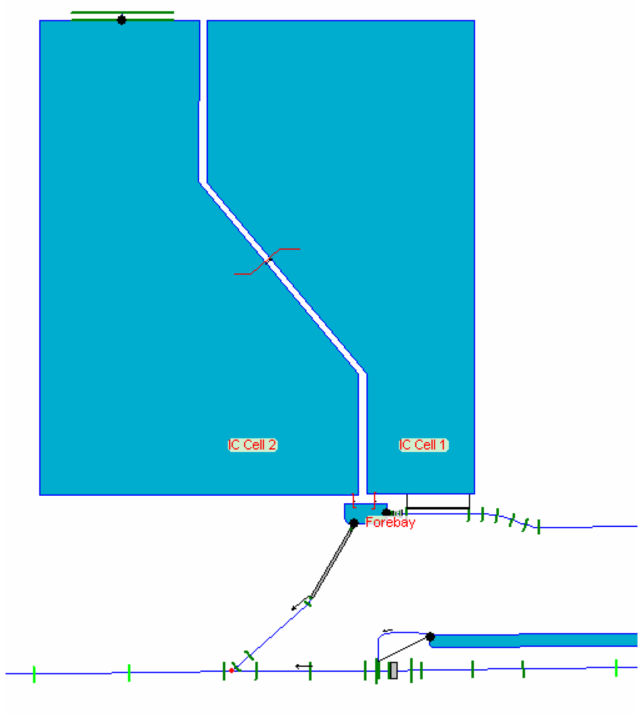


Figure 6. Model configuration in the vicinity of Drop 2 Storage Reservoir from HEC-RAS geometry editor. Gates within the model are located before each cell, at the forebay/afterbay structure, and at the outlet canal, and are programmed to open or close depending on the flow scenario.

Yuma Operations

Operations at Imperial Dam are complex, especially when a winter or summer storm contributes inflow to the system. During a rainstorm event, flows released from Parker Dam may reach Imperial Dam after water orders are cut. Space may or may not be available in Senator Wash to store the additional flows, depending on stored volume in Senator Wash versus the volume of inflow to Imperial Dam, or the rate of inflow past Senator Wash. Senator Wash pumps are limited to 1,200 cfs at most, therefore flowrates in the Colorado River higher than 1,200 cfs at Senator Wash cannot all be delivered.

Yuma Operators typically divert Colorado River water through the Gila Gravity Main Canal to Arizona users, and through the AAC for the California users. Deliveries to the NIB at Mexico are usually made through the AAC and diverted at Pilot Knob, depending on the time of the year. However, if orders are cut in California, operators may open any or all of the three California Sluice Gates at Imperial Dam, diverting Colorado River water south through Laguna Dam, and through the old Colorado River channel to NIB. Operators typically manage water orders that may be in excess to Mexico by contacting water users to see if additional water can be delivered. Additional water that cannot be delivered would then be sent to D2SR for storage, or become excess flow to Mexico.

February 2009 Scenarios

The forecast from February 4th to February 7th indicated a major rain event for southeastern California, western Arizona, and southern Nevada (Figure 7). The gridded precipitation forecast is illustrated by various color patterns; for example the areas covered in grey forecast light rain versus the areas covered in red forecast more intense rainfall. The forecast was generated from the Colorado Basin River Forecast Center (CBRFC) for the entire Colorado River Basin.

Table 1 summarizes operations at Imperial Dam for the first half of February 2009. Releases on February 4th of 6,495 cfs reach Imperial Dam on February 7th. Senator Wash on February 7th is already full. Parker releases are reduced significantly until February 10th and then begin to increase. Both IID and CVWD decrease orders significantly by February 8th. The decrease in water ordered, a full Senator Wash, and large flows being released out of Parker Dam require the California Sluice Gates at Imperial Dam to be opened on February 7th, and remain open until February 12th. The California Sluice Gates release water which is conveyed to the NIB via the Colorado River. Table 2 summarizes water ordered but not delivered that becomes excess flow to Mexico. This excess flow was modeled in the boundary conditions of the HEC-RAS unsteady flow model.

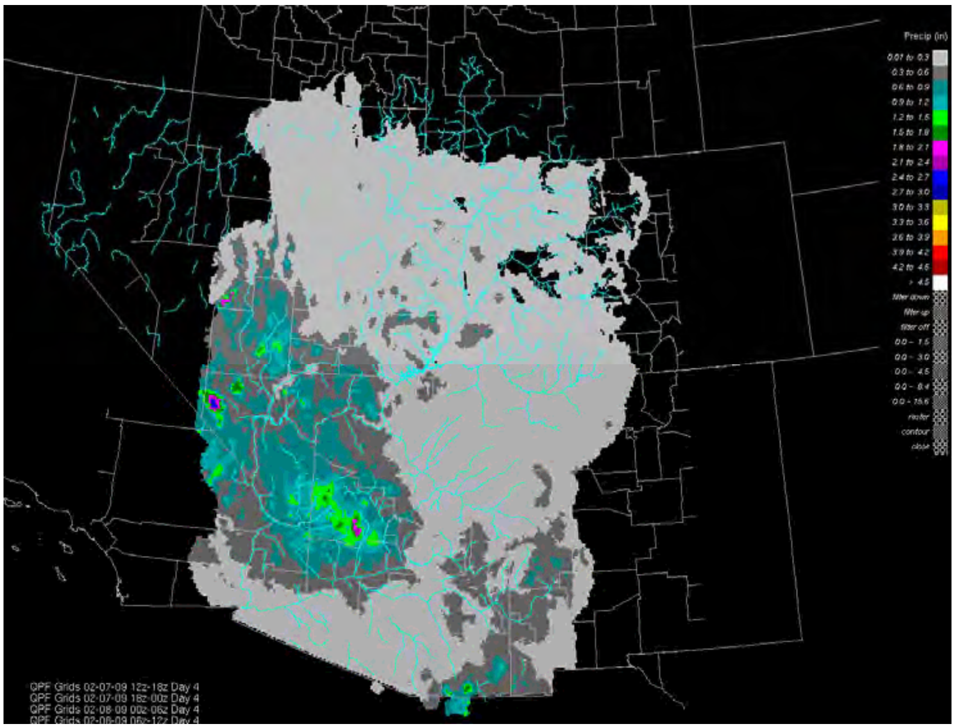


Figure 7. 3-day forecast on February 4th indicating rain and snow over most of the Colorado River Basin[7].

Table 1. Summary of Operations at Imperial Dam, February 2009

February	Daily Mean Flow	California	PK Check	IID	CVWD	Parker
1	4837	257.69	1521	2121	285	6,514.01
2	5483	0.00	1588	2277	376	6,505.27
3	5560	0.00	1538	2550	452	6,657.06
4	5698	0.00	1544	2550	458	6,495.54
5	5791	0.00	1550	2646	373	6,096.84
6	5299	0.00	1565	2542	317	5,969.56
7	4332	1380.27	1469	2056	174	5,908.67
8	2622	2696.65	808	1323	110	5,320.12
9	3145	2803.92	700	1056	151	4,844.10
10	3580	2492.88	700	1388	204	3,926.41
11	3750	2115.83	700	1358	251	4,948.71
12	4178	49.88	885	1683	257	4,565.00
13	4823	0.00	1540	1775	236	5,020.94
14	4782	0.00	1588	1627	167	5,084.74
15	4545	0.00	1529	1344	242	5,492.64

[7] From the Colorado River Basin Forecast Center

Table 2. Non-storable flow modeled, February 2009.

February 2009	Total ordered flow, IID and CVWD, past station 1117+00 (cfs), Pilot Knob	Total ordered flow, IID and CVWD, past station 1117+00, Pilot Knob + Non storable flow (cfs)	Non-storable flow (cfs)
1	2406	2406	0
2	2653	2675	22
3	3002	3002	0
4	3008	3008	0
5	3019	3019	0
6	2859	2875	16
7	2230	2230	0
8	1433	1891	458
9	1207	1983	776
10	1592	2201	609
11	1609	2054	445
12	1940	2114	174
13	2011	2011	0
14	1794	1794	0
15	1586	1586	0

Boundary Conditions

The HEC-RAS unsteady flow model simulated February 2009 system conditions by routing non-storable flows through the AAC to the D2SR. Non-storable flows were routed to D2SR in addition to the water ordered by IID and CVWD. A flow hydrograph boundary condition was input into the unsteady flow editor at an hourly time step. This hydrograph simulated base flow in the AAC from February 1 to February 15. Non-storable flows were added to the flow hydrograph at an assumed maximum of 300 cfs/hr ramp up and ramp down rate (Figure 8). The non-storable flows were then diverted through the Coachella turnout gates to the D2SR. Each gate was simulated using a series of programmable rules that adjust the gate opening depending on values in the model at a given time step. Following are examples of how the gates operate in the model.

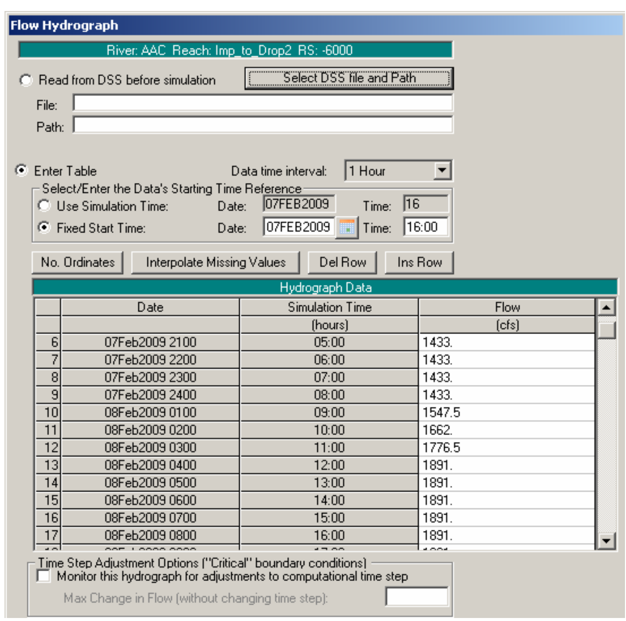
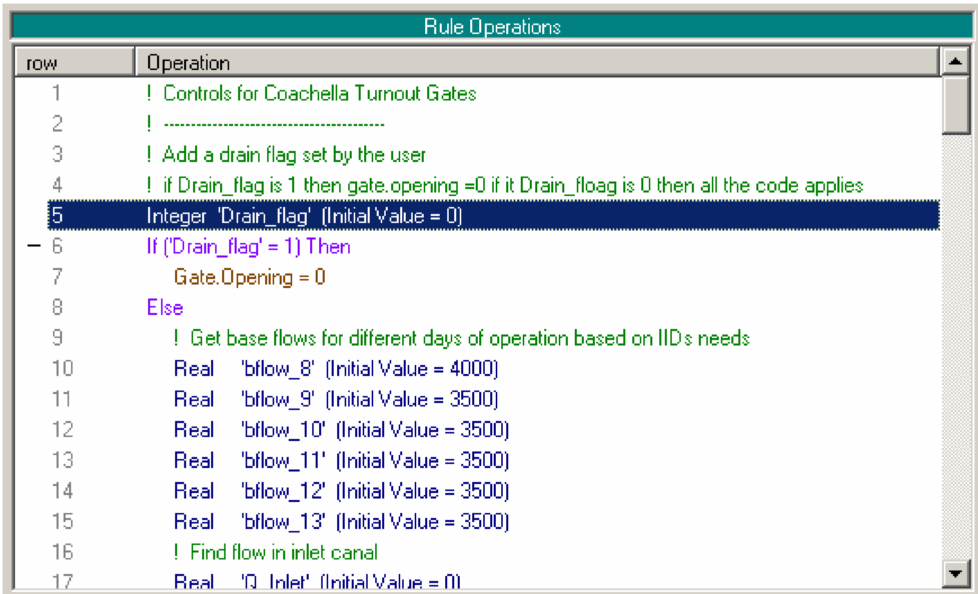


Figure 8. Flow hydrograph boundary conditions in the HEC-RAS unsteady flow editor.

Coachella Turnout Gates

The Coachella turnout gates operate the Inlet Canal. A flag was added to program the gates to turn on or off. This flag tells the rules whether the D2SR is draining or filling. If the flag is turned on it is a draining scenario and the gates to the Inlet Canal remain closed. If the flag is turned off it is a filling scenario. In a filling scenario the user can define a base flow for each day. This base flow is the flow that will continue through the AAC, and not be diverted to D2SR. The gates to the Inlet Canal are operated to allow the total flow that is in the hydrograph minus the base flow (non-storable flow) to pass the gates, into the Inlet Canal and to D2SR. The rules also restrict the base flow from increasing at more than 300 cfs an hour (Figure 9).



Rule Operations

row	Operation
1	! Controls for Coachella Turnout Gates
2	! --
3	! Add a drain flag set by the user
4	! if Drain_flag is 1 then gate.opening =0 if it Drain_floag is 0 then all the code applies
5	Integer 'Drain_flag' (Initial Value = 0)
6	If ('Drain_flag' = 1) Then
7	Gate.Opening = 0
8	Else
9	! Get base flows for different days of operation based on IIDs needs
10	Real 'bflow_8' (Initial Value = 4000)
11	Real 'bflow_9' (Initial Value = 3500)
12	Real 'bflow_10' (Initial Value = 3500)
13	Real 'bflow_11' (Initial Value = 3500)
14	Real 'bflow_12' (Initial Value = 3500)
15	Real 'bflow_13' (Initial Value = 3500)
16	! Find flow in inlet canal
17	Real 'Q_Inlet' (Initial Value = 0)

Figure 9. Coachella turnout gate rules for February scenarios.

Drop 1 Gates

The gates at Drop 1 are programmed to open and close to allow a given flow through the AAC. This flow is the base flow that was defined by the user in the Coachella turnout rules. The rules are written to allow this base flow to pass the gates at Drop 1. The user can adjust this base flow for each day by adjusting the base flow defined at the Coachella turnout. In the February scenarios, the Drop 1 gates pass all but the non-storable flow diverted to D2SR.

Gates into Cell 1 and Cell 2

Cell 1 and Cell 2 gates are two separate sets of gates but operate in the model exactly the same. The drain flag described in the Coachella turnout gate rules is also part of these rules. If the flag is turned on it is a draining scenario. The draining is tied to a desired flow rate that is given by the user. This is the variable 2Q in the rules (Figure 10). The rules first look to see if one or both of the cells is empty (see lines 13 and 17 of Figure 10). If one cell is empty and the other cell is not the rules will open the gates to the cell which is not empty and allow it to drain at the flow rate that was defined by the user (see line 19 of Figure 10). The cell will drain at this flow rate as long as there is enough head to produce the given flow. Once the head no longer produces the user defined flow rate it will flow at the maximum allowable flow rate for the given head. If neither cell is empty then it will allow half of the user defined flow rate through each set of gates as long as there is enough head to support that flow (see line 16 of Figure 10). If the drain flag is turned off and it is a filling scenario, the rules test to see if either cell is full (see lines 27 and 30 of Figure 10). If one cell is full it allows the entire flow into the cell that is not full until both cells are filled. If both cells are not full it allows the gates to be open equally to fill both cells at the same rate until both cells are full.

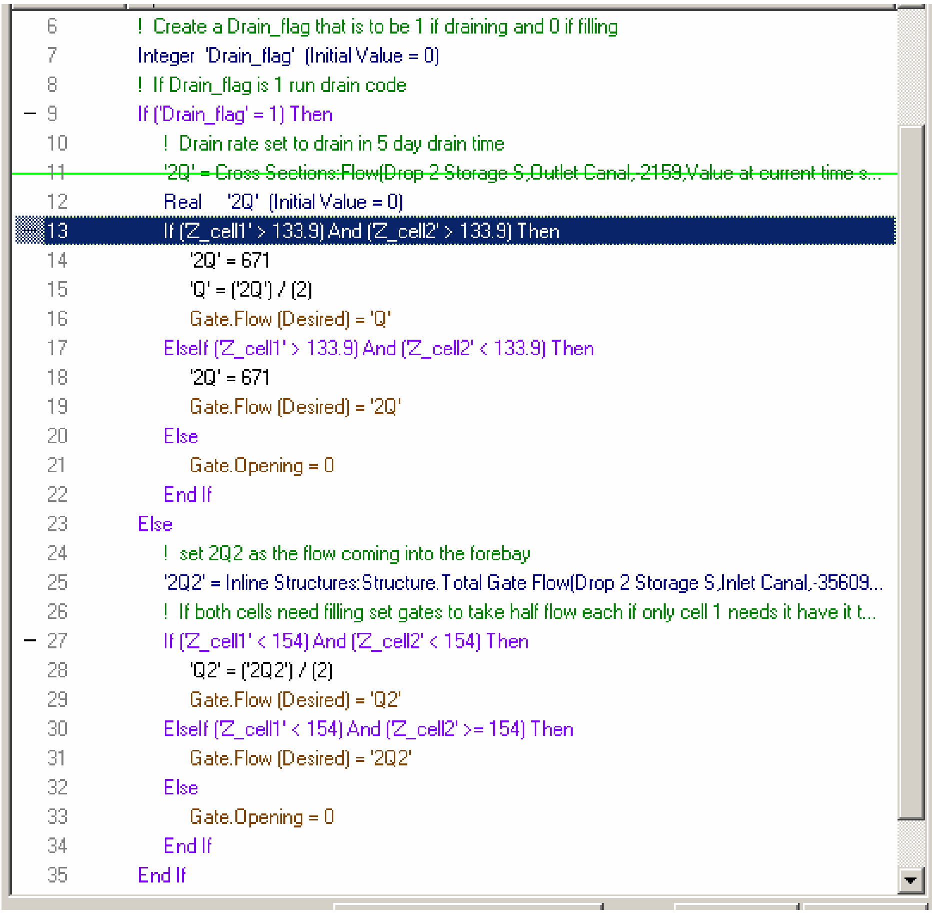


Figure 10. Gate rules for Cells 1 and 2 for February scenarios.

Outlet Canal Gates

The outlet canal gates also have the drain flag. If the drain flag is on these gates open to allow draining. The user can set the draining flow rate which should match the flow rate set for the draining of the Cell 1 and Cell 2 gates. If the flag is turned off it is a filling scenario. The rules are set to keep these gates closed until both cells have been filled. At that point the gates open to allow flow equal to the flow in the inlet canal. This avoids any over filling or spilling of the canal.

CONCLUSIONS

Use of HEC-RAS to simulate non-storable flow delivery to D2SR is a good first step in simulating operations. Programmable rules to simulate gate operations in HEC-RAS is a new feature of the latest version that allows the user greater insight on day to day operations. The unsteady flow model simulated conditions well and was fairly stable. Model stability was maintained by not over increasing or decreasing conveyance parameters between cross sections, structures, or within the boundary conditions. The AAC and D2SR were designed for smooth conveyance and steady flow operations, therefore the unsteady flow model and programmable gates functioned fairly well.

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