Final Report
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Designing River Basin Storage Along The Lower South Platte Using StateMod And Optimization

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1 Executive Summary

This research provides quantitative information to undergird a decision regarding the optimal location, type and size of additional unappropriated water storage along the Lower South Platte River. In order to identify a location for increased water storage, we use flow data produced by StateMod as input to a mixed-integer linear optimization model. This program minimizes the cost to meet all shortages by assigning network flow while adhering to the constraints that force the physical and topographical structures of the river. The program solutions contain a location/s and amount of water storage that mitigates the shortages over a given time horizon. Storage methods considered include: (1) expanding existing reservoir capacity by raising the height of dams, (2) constructing new surface reservoirs, and (3) constructing Aquifer Storage and Recovery (ASR) facilities. Reservoir costs used in this study are obtained from estimates associated with like projects in Arizona, California and Colorado. We have also considered upstream pumping via pipeline and these cost estimates are obtained using a pipeline tool developed by the State of Texas. Dredging, as a method of expansion, has not been included in our analysis because the costs are much greater than our considered methods. Feasible locations of underground storage are obtained from the CWCB Underground Water Storage Study [1].

Using historical flow data from 1962 through 2012, we extend the capability of StateMod by considering solutions with the following characteristics: (1) a single-reservoir solution, (2) a solution in which we only expand existing reservoirs, and (3) a hybrid solution without the constraints in (1) or (2). We conclude that, for the time horizon considered, the optimal method to mitigate shortages is with the construction of a series of smaller surface and sub-surface reservoirs (i.e., hybrid solution). The total increased storage volume is 25,378 acre-feet (AF) which mitigates all shortages identified by StateMod and does not require upstream pumping.

Contents

2 Introduction

In order to provide insight about additional reservoir storage locations, the Colorado School of Mines sought a Water Supply Reserve Fund (WSRF) grant in the fall of 2016. Our goal is to use existing tools and data (e.g., StateMod and historical flow data), coupled with optimization, to identify the most cost effective ways to mitigate shortages in a given river basin drawing on data from a specific time horizon. At that time, the Lower South Platte River Basin was chosen as a case study based on the demand for such information and the data set available for use with StateMod.

Faced with determining the location of new storage when considering 150 miles of river is challenging and time consuming. Questions arise such as (1) whether or not there is excess physical water available and where it might be, (2) the locations of the unmet demand, (3) types and sizes of available storage, (4) upstream pumping considerations, and (5) where to conduct in-depth, site-specific studies. This work produces what could be the first step in answering these questions.

3 Methodology

We take an existing river basin simulation model (StateMod), which uses historical flow and the physical characteristics of the basin, as well as doctrines and policies, to identify where excess supply and unmet demand are located along the river and in time. In other words, StateMod accounts for the water in the river during a given time period, at a given location, and identifies: (1) excess supply available for use (if any) by the junior water right holder, and (2) unmet demands. Using the aforementioned data, our optimization model minimizes the cost of fulfilling the unmet demands employing available supply over a time horizon of 50 years by prescribing flows and adding infrastructure for storage. We determine the types, locations and sizes of additional storage by considering: (1) increasing the existing reservoirs' capacities by raising dams, (2) constructing new surface reservoirs, (3) building new ASR facilities, and (4) erecting new pipelines to pump water upstream. For the instances we solve, these considerations are contingent upon the historical location of excess supply and unmet demand (Figure 1). Our work is undergirded by traditional water supply analysis techniques which use existing flow and assume that historic and hydrologic trends of the past will continue; for the purposes of this study, we assume the same [2].

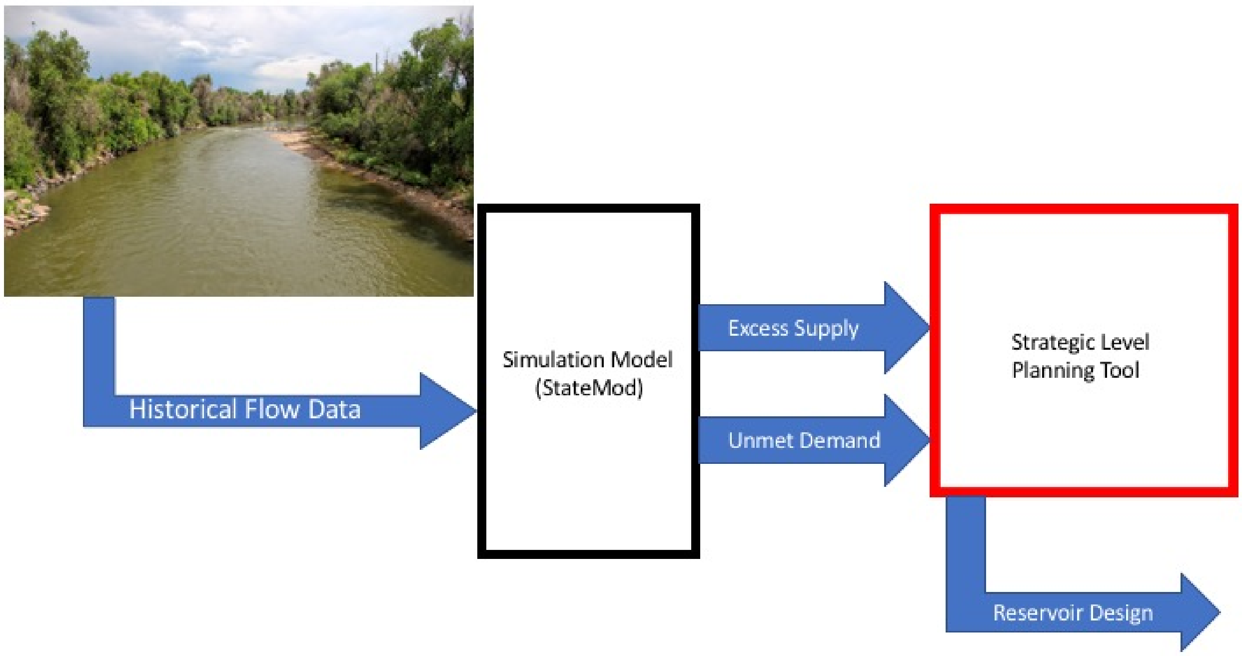


Figure 1: Flow chart of the reservoir design process [3], [4]

3.1 Shortfalls

We recognize the limitations of this methodology such as: (1) the absence of site-specific information (e.g., soil conditions at proposed reservoir sites), and (2) the location of future water purchasers. However, our work can be used as a strategic analysis tool by planners and engineers to quickly identify the most effective reservoir locations, types and capacities, as well as pipeline locations and sizes, rather than examining every potential storage site.

3.2 Simulating River Flow

StateMod is used to simulate flow from the Lower Latham Ditch to the Nebraska border from January of 1962 through December of 2012 using historical data. The points at which flow is simulated can represent stream flow gauges, irrigation diversions, reservoir diversions, tributary flow and/or return flows related to reservoirs and augmentation plans (Figure 2). Appendix A depicts the latitude and longitude of each point (i.e., node).

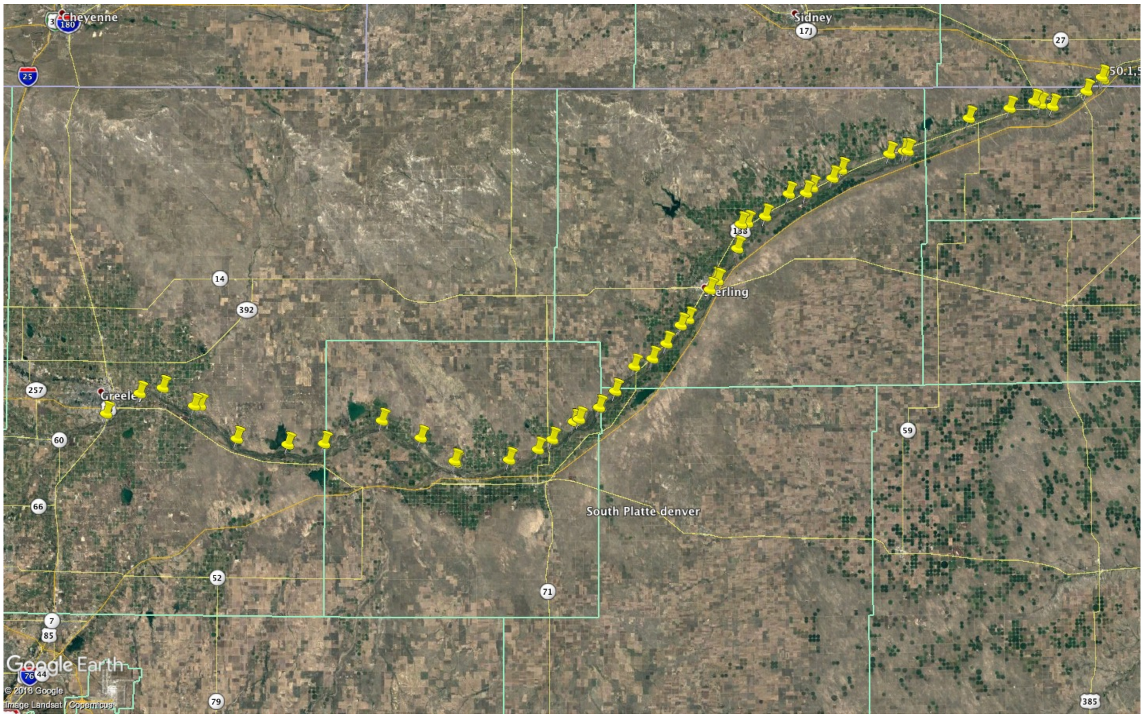


Figure 2: Points at which StateMod simulates flow

3.3 Transforming Simulation Output into Optimization Model Input

The data collected at each node includes excess supply, unmet demand, flow in and out, as well as diversions (if any). In the case of existing reservoirs, diversions in and releases from are also collected. The excess supply data represents all unappropriated water during a given time period at a given node. This data is disaggregated to translate cumulative flow at a given location to the quantity of water that originated at said node. The unmet demand data represents the shortage at a given node during a given time period and is associated with a specific water right held by its owner. Therefore, each shortage is coupled with a penalty which increases with water right seniority. Figure 3 depicts an abbreviated, notional example of how the excess supply and unmet demand data is obtained along the Lower South Platte.

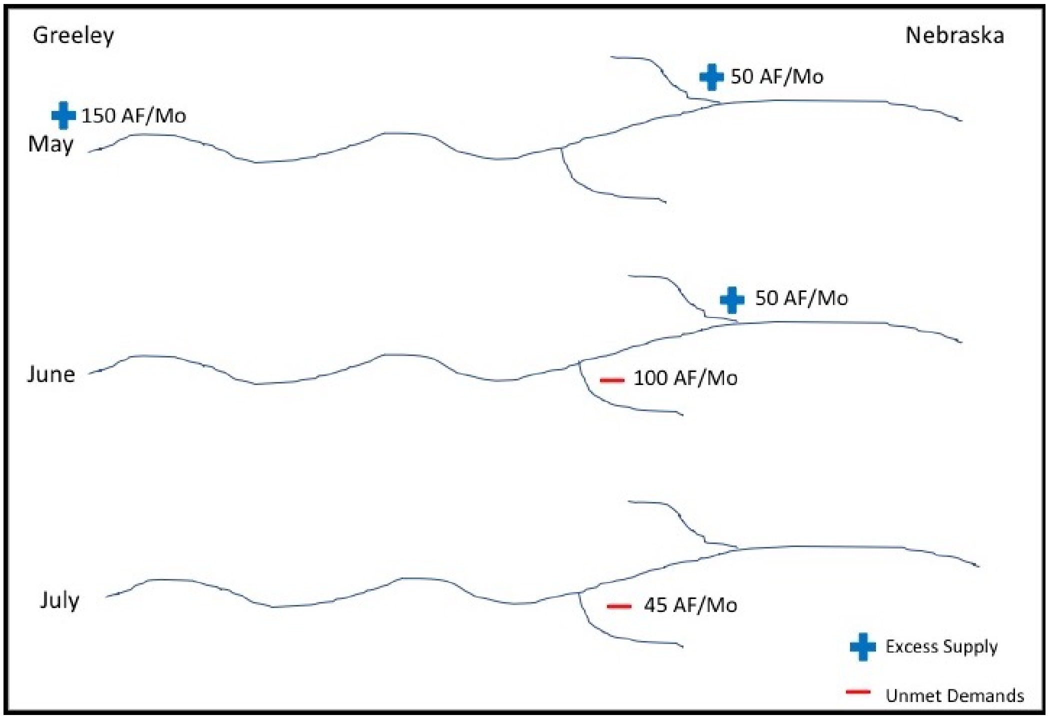


Figure 3: Abbreviated, notional example of how excess supply and unmet demand are captured from StateMod output

For this example, in May, there are 200 AF of excess unappropriated water that will flow into Nebraska if it is not utilized upstream. In June and July, there are unmet demands because there are no upstream excesses during each month. So, excess water in May should be stored to meet unmet demands in June and July. As this example is extended to incorporate 50 years of flow data (on a monthly time step), 150 miles of river characteristics, and multiple storage and pumping options, the problem becomes quite large. Appendix D describes the size of the problem.

4 Storage and Pumping Options

Within this lower portion of the river, there are six existing reservoirs considered for an expansion of up to 50,000 AF: (1) Riverside, (2) Empire, (3) Jackson, (4) Prewitt, (5) North Sterling, and (6) Julesburg (Figure 4). We also consider the following new sites: (i) 31 surface reservoirs, each with a maximum capacity of 150,000 AF, and (ii) 31 sub-surface storage locations (ASRs), with varying capacities based on the geological characteristics in each area [1] (Figure 5). New site locations were chosen based on the data collection sites depicted (i.e., nodes) in Figure 2. We use four pumping rate options, based on the daily flow rates of the South Platte River as measured near Julesburg: (1) 72 AF/month, (2) 140 AF/month, (3) 2,795 AF/month, and (4) 5,270 AF/month.

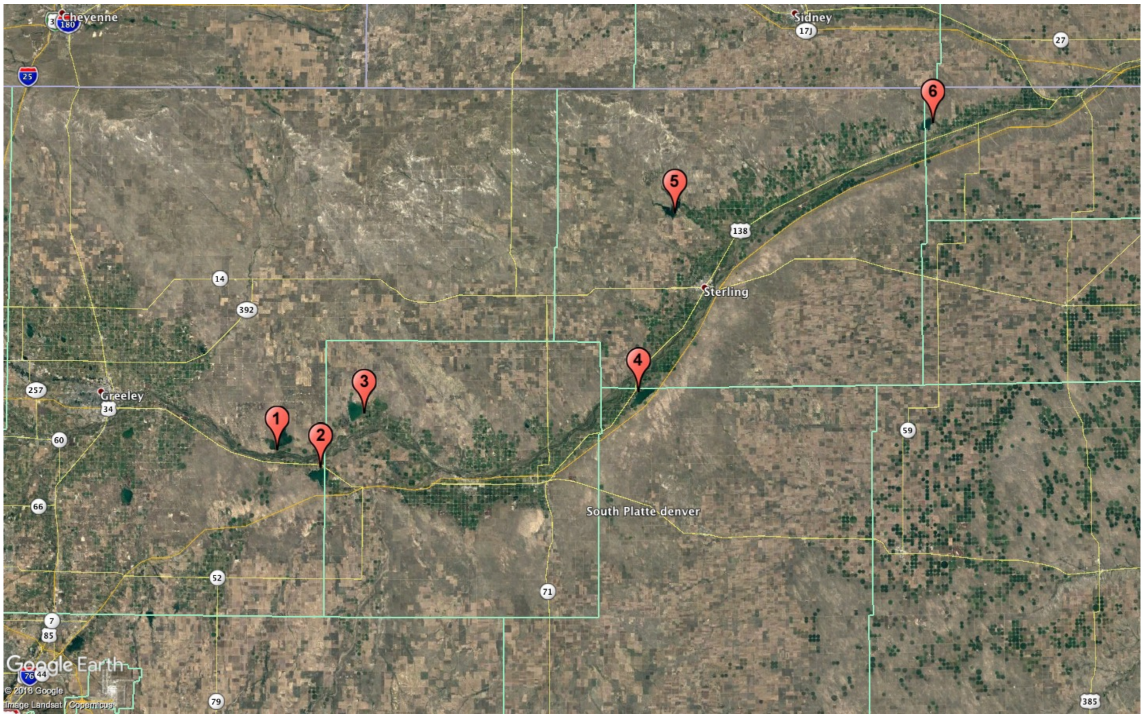


Figure 4: Existing reservoirs considered for expansion: (1) Riverside, (2) Empire, (3) Jackson, (4) Prewitt, (5) North Sterling, and (6) Julesburg [5]

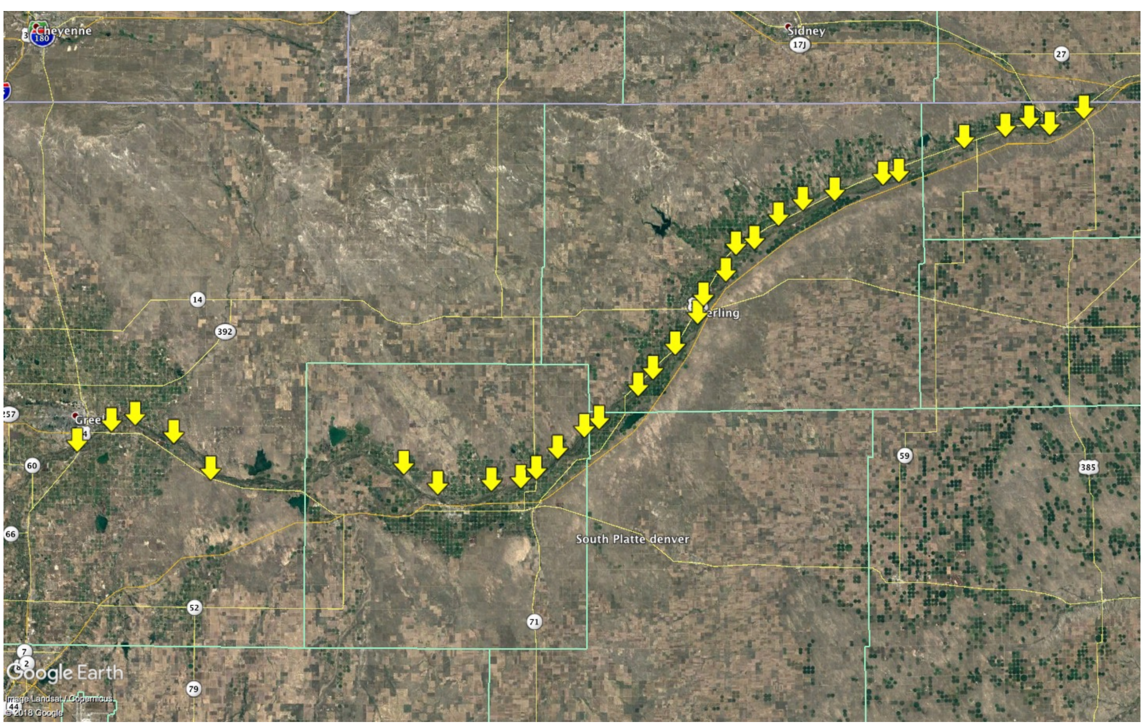


Figure 5: Locations considered for new surface and sub-surface reservoirs [5]

5 Cost Estimates

Our research develops a strategic planning tool for reservoir design and does not use site-specific information (e.g., topography and soil quality) a priori. Instead, we calculate the median cost value from a prespecified set of valid construction scenarios. These suffice for strategic planning but need refinement for any subsequent detailed analysis.

5.1 Reservoir Costs

The cost estimates used for both new reservoir construction and existing reservoir expansion derive from projects in Arizona, California and Colorado (Appendix B). For new construction, costs can vary based on many characteristics, some of which are: (1) the distance of the reservoir from the river, which impacts how far water must be conveyed via pipeline or channel and whether or not pumping is required, (2) permitting, and (3) infrastructure that must be relocated such as roadways and power transmission lines. Expansion costs are associated with projects in which dams are raised, thus increasing the size of the reservoir. Dredging is substantially more expensive than the aforementioned options and is not included as a means of reservoir expansion [6]. In a cost-minimizing model such as ours, a dredging solution would not be chosen unless forced because there are numerous, cheaper storage options from which to choose. Table 1 depicts the median construction and operation and maintenance (O&M) costs in this project.

Median Costs of New Storage Capacity		
Project Type	**Construction ($/AF)**	**O&M ($/AF/mo)**
New surface reservoirs	3,120	2.50
New sub-surface (ASR) reservoirs	390	0.27
Existing reservoir expansion	2,226	0.33

Note 1: All costs are in 2014 dollars using inflation calculator http://www.usinflationcalculator.com/

Table 1: Median costs of new storage capacity used in computation

5.2 Pipeline Costs

Unlike reservoir cost estimates, for which project uncertainties are consolidated by using the median value from numerous projects, pipeline costs are developed using a tool that incorporates more site-specific information pertaining to the pipelines [7]. Based on the location of each potential or existing reservoir and the distance and elevation difference between them, we compute the pipe length and slope. To determine the pipe diameters, we evaluate daily flow rates from the lower-most point on the river and select four options: (1) 72 AF/Mo, (2) 140 AF/Mo, (3) 2,795 AF/Mo, and (4) 5,270 AF/Mo. Using the Unified Costing Model [7], we fit these rates to various pipe sizes to evaluate pressure and velocity with the final diameters chosen as 12-inch, 20-inch, 54-inch, and 66-inch pipe. We estimate the land needed for pipeline right-of-way to be 10 feet wide and contain seven parcels per mile while consisting of 40% farmland, 40% irrigated cropland, and 20% pasture with a weighted average cost of $2,560 per acre [8]. Becasue there are four potential pipe diameters connecting each downstream node to every other upstream node, there are too many pipeline costs to list individually; however, Table 2 provides samples.

Example Pipeline Cost Estimates					
Pipeline	**Capacity (AF/mo)**	**Length (Miles)**	**Construction ($)**	**Maintenance ($/mo)**	**Operation ($/mo)**
Estimate 1	72	0.81	1,242,000	20,000	5,000
Estimate 2	140	4.8	3,018,000	40,000	28,000

Note 1: All costs are in 2014 dollars using inflation calculator http://www.usinflationcalculator.com/

Table 2: Example pipeline cost estimates

5.3 Penalties

Along with construction and O&M costs, we apply penalties to enforce prior-appropriation doctrine. Therefore, each unmet demand is coupled with a penalty, which increases with water right seniority and is always larger than the cost to divert into a new reservoir. In other words, the model chooses meeting demands over incurring unmet demand penalties. Thus, the priority of this model is minimizing the cost of shortage mitigation.

6 Optimization

Because the problem is too large to be solved by hand, we use a mathematical program (i.e., optimization model) to minimize the cost of shortage mitigation over a time horizon. These types of models are especially useful when: (1) there are many unknown values to be determined, (2) there exist complex relationships between the unknown values, (3) there are many tradeoffs, and (4) a repeatable, quickly obtained, objective solution is needed. Our model combines costs, penalties, excess supply, unmet demands and topography to determine the location of new storage and corresponding flow needed to meet demand. Appendix C contains a detailed description of our optimization model.

7 Solutions

The data collected at each point along the river, combined with previously mentioned costs, capacities and penalties, are used as inputs to our optimization model. The model is quite large in that the corresponding instances contain more than 6,000,000 variables and more than 1,900,000 constraints. After tuning the model to reduce numerical instability and solve time, most instances solve in approximately one minute. Appendix D describes the specialized software used to both code and solve the model.

We consider the following three pragmatic alternatives: (1) constrained to a single reservoir, (2) constrained to the expansion of existing reservoirs only, and (3) a hybrid solution not constrained by (1) or (2) which can use any combination and quantity of reservoir types. Each solution consists of the location and size of new storage capacity; the size corresponds to the maximum volume of water stored in said reservoir during our time horizon. As an example, Figure 6 shows the inventory level for the single-reservoir constrained solution (Section 7.1). Appendix B depicts the reservoir and pipeline cost estimates used *in* the model as well as the costs produced by the model for each solution.

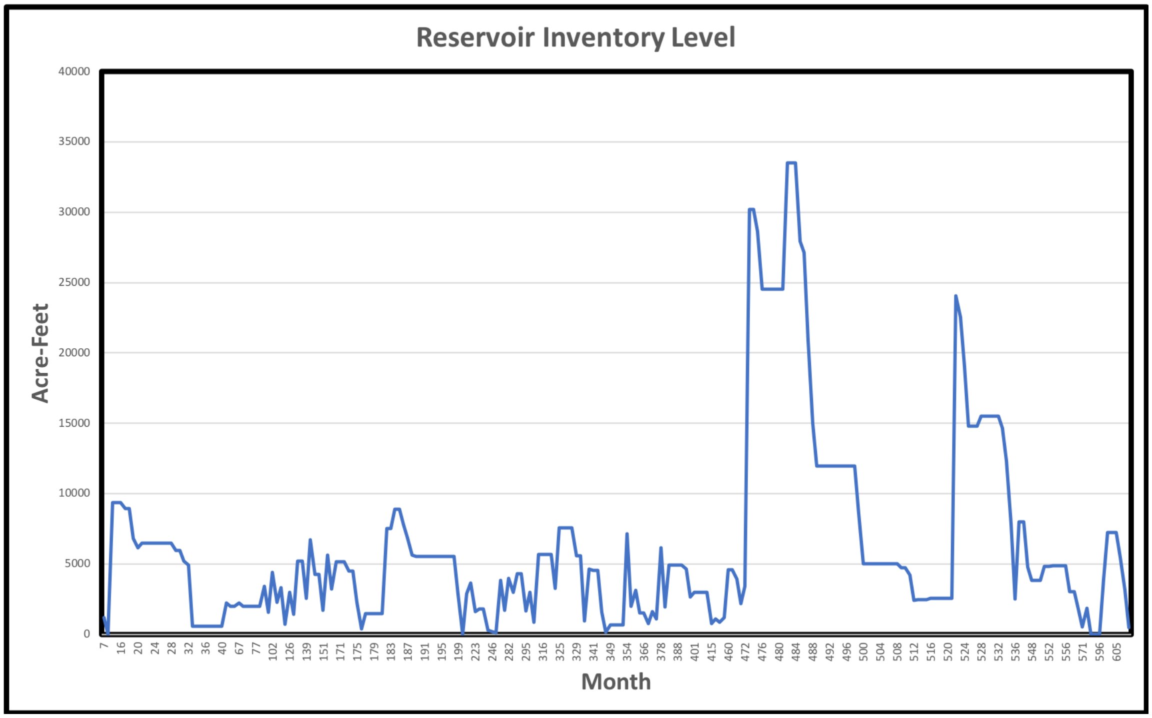


Figure 6: Reservoir inventory level

7.1 Single-Reservoir Constrained Solution

To reduce the number of required permits, we constrain our optimization model to the construction of a single reservoir, which it places just downstream of La Salle (Latitude 40°21′41.9″N, Longitude 104°42′12.3″W), on the uppermost part of our section of river, with a capacity of 33,508 AF. All demands are met with no upstream pumping.

7.2 Existing-Reservoir-Expansion Constrained Solution

To preclude the need for new construction permits altogether, our results show the expansion of three reservoirs to be optimal– those at Riverside, Jackson and Prewitt by 1,561 AF, 8,630 AF, and 16,516 AF, respectively (Figure 4). This solution meets 99.3% of all unmet demands with a cumulative increased storage volume of 26,707 AF and does not use upstream pumping. However, Prewitt reservoir leaks stored water into the ground at a faster rate than the other selected reservoirs. Therefore, expanding reservoirs other than Prewitt may be preferred. In this case, we would expand Riverside, Empire and Jackson reservoirs by 1,631 AF, 30,610 AF, and 278 AF, respectively. This option requires more water be stored in the aforementioned reservoirs, and a cumulative increased storage volume of 32,519 AF, but still mitigates 99.3% of all unmet demands. Were we to expand a single reservoir, it would be Jackson Reservoir by 32,524 AF. This solution meets 98.7% of all unmet demands. These scenarios employ dam raising, rather than its cost-prohibitive alternative, dredging [6]. But, if a dredging solution were sought, the reservoirs chosen for expansion would likely change because of differences in relative costs.

7.3 Unconstrained Solution with Respect to Number and Type of Reservoirs

A solution in which we neither preclude the construction of reservoirs nor constrain their number mitigates all shortages by prescribed flows without upstream pumping. A series of 10 smaller surface and sub-surface reservoirs cumulatively increases storage volume by 25,378 AF (Figure 7). Appendix E contains the type, volume, latitude, and longitude of each reservoir.

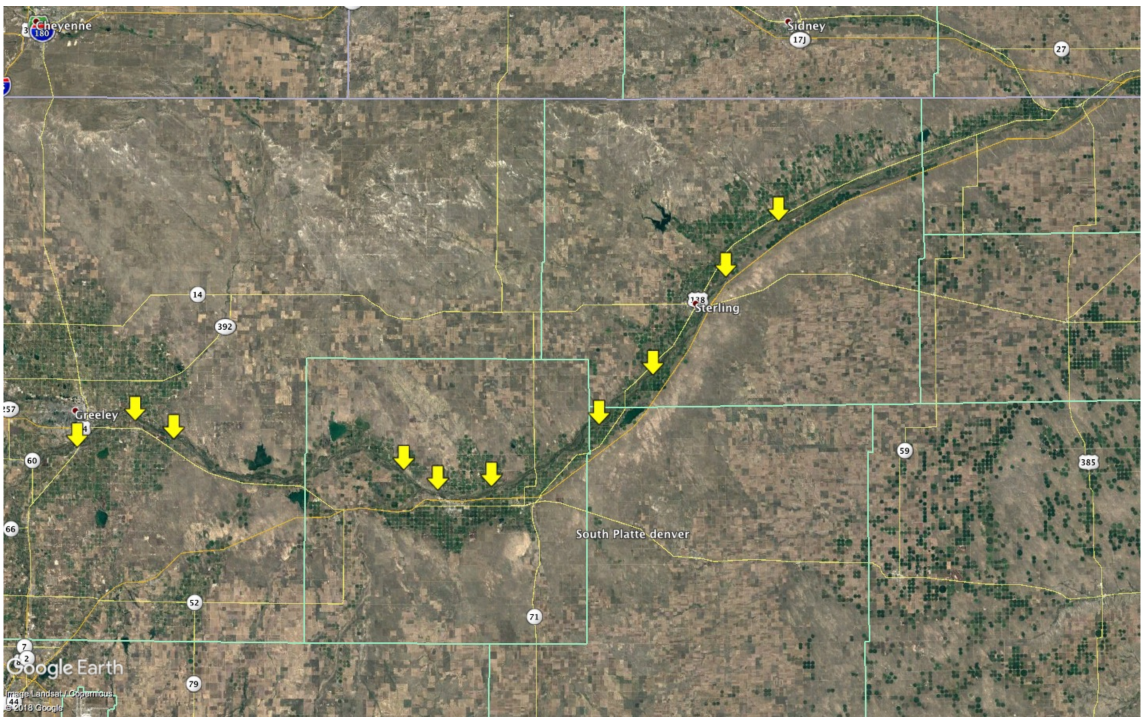


Figure 7: Unconstrained solution with respect to number and type of reservoirs showing the 10 smaller surface and sub-surface reservoirs

7.4 Future Climate Scenario Solutions

The three preceding solution types only consider weather and growth scenarios as represented by historical river flow from 1962 through 2012. Recently, as of the time of this writing, the Colorado Water Conservation Board (CWCB) developed five scenarios for the purposes of long-range water planning [9]. Our current work incorporates part of the assumptions contained in the first three scenarios (e.g., that observed trends of the past remain the same). As a natural extension of this work, we chose to adjust the historical data to represent conditions not depicted by historical flow. To do this, we reduced the excess supply and increased the unmet demands by incremental percentages to see if the model would re-locate reservoirs from those described in the unconstrained solution (Section 7.3). The percentage was increased up to 50% before changes in reservoir locations manifested in the solution. In other words, the excess supply and unmet demands were reduced by 50% and increased by 50%, respectively, before unconstrained-solution reservoirs were re-located. In order to depict early runoff, we retarded historical flow across our time horizon by one month (i.e., May flow data is used in April) and resolved the model. In this case, seven of the ten reservoirs were re-positioned into adjacent locations.

8 Conclusions

We have used an existing simulation model, StateMod, to produce data as input for our optimization model. Whereas river basin simulation models evaluate existing networks, our optimization model yields the best way to mitigate shortages by determining the location, type and size of storage, as well as the amount of upstream pumping and prescriptive flows while balancing cost. This work is a paradigm shift in that an optimization model is coupled with an existing simulation model to design improvements to a basin, not just to evaluate its current state. Based on our results, we conclude that the most cost-effective way to mitigate shortages is by storing smaller amounts of water in multiple locations, rather than a large amount in a single location.

9 Acknowledgements

We thank the following individuals for their direction and insights: (1) Carl Brouwer, Northern Water, (2) Sean Conway, South Platte Basin Roundtable, (3) Erica Fleishman, Center for Environmental Management of Military Lands, Colorado State University - Fort Collins, (4) Joe Frank, South Platte Basin Roundtable, (5) Craig Godbout, Colorado Water Conservation Board, (6) Andres Guerra, Department of Civil and Environmental Engineering, Colorado School of Mines, (7) Mandy Hering, Department of Statistical Sciences, Balor University, (8) Tissa Illangasekare, Department of Civil and Environmental Engineering, Colorado School of Mines, (9) Sonia Kreidenweis, College of Engineering, Colorado State University - Fort Collins, (10) Emily LoDolce, formerly of the Colorado Water Conservation Board, (11) Steve Malers, Open Waters Foundation, (12) Dinesh Mehta, Department of Computer Science, Colorado School of Mines, (13) Andy Moore, Colorado Water Conservation Board, (14) Dave Nettles, Colorado Department of Natural Resources, (15) Chip Paulson, Stantec, (16) Randy Ray, Central Colorado Water Conservancy District, (17) Brent Schantz, Colorado Department of Natural Resources, (18) Mike Slusher, Davis, Martin, Powell and Associates, Inc., (19) Enrique Triana, formerly of Stantec, (20) Garrett Varra, South Platte Basin Roundtable, (21) Regan Waskom, Colorado Water Institute, Colorado State University - Fort Collins, and (22) Jim Yahn, Colorado Water Conservation Board.

A Data Point Locations

Nodes are numbered from west to east.

Node	Latitude	Longitude
1	40°21'41.93"N	104°42'12.39"W
2	40°24'3.43"N	104°37'12.26"W
3	40°24'42.93"N	104°33'45.85"W
4	40°22'42.69"N	104°29'2.27"W
5	40°22'44.91"N	104°28'7.95"W
6	40°19'1.80"N	104°22'36.12"W
7	40°18'25.37"N	104°15'0.10"W
8	40°18'33.60"N	104° 9'34.64"W
9	40°21'12.68"N	104° 1'0.14"W
10	40°19'17.00"N	103°55'13.01"W
11	40°16'39.49"N	103°50'9.71"W
12	40°16'28.92"N	103°50'2.34"W
13	40°16'49.48"N	103°42'4.40"W
14	40°16'50.47"N	103°42'6.08"W
15	40°18'0.40"N	103°37'47.87"W
16	40°19'8.12"N	103°35'40.24"W
17	40°21'8.86"N	103°32'26.72"W
18	40°21'8.86"N	103°32'26.72"W
19	40°21'26.99"N	103°31'40.99"W
20	40°22'44.92"N	103°28'45.40"W
21	40°22'47.15"N	103°28'41.96"W
22	40°22'47.15"N	103°28'41.96"W
23	40°24'37.44"N	103°26'17.77"W
24	40°27'25.69"N	103°23'27.45"W
25	40°28'17.94"N	103°20'44.99"W

Node	Latitude	Longitude
26	40°29'59.84"N	103°18'39.55"W
27	40°32'4.42"N	103°16'31.03"W
28	40°32'44.66"N	103°15'24.11"W
29	40°36'6.25"N	103°12'9.54"W
30	40°37'7.04"N	103°10'59.99"W
31	40°37'15.51"N	103°11'19.59"W
32	40°40'46.06"N	103° 8'1.17"W
33	40°43'31.54"N	103° 7'26.90"W
34	40°43'40.63"N	103° 6'30.51"W
35	40°44'24.04"N	103° 3'48.84"W
36	40°46'56.69"N	103° 0'14.51"W
37	40°47'2.00"N	102°57'39.51"W
38	40°47'38.84"N	102°56'44.31"W
39	40°48'42.67"N	102°53'40.05"W
40	40°49'38.95"N	102°52'19.74"W
41	40°51'25.56"N	102°45'3.96"W
42	40°51'44.36"N	102°42'51.73"W
43	40°51'44.41"N	102°42'16.82"W
44	40°55'26.04"N	102°32'58.91"W
45	40°56'31.56"N	102°26'47.05"W
46	40°57'17.71"N	102°23'1.52"W
47	40°56'57.72"N	102°22'3.77"W
48	40°56'42.60"N	102°20'15.10"W
49	40°58'23.94"N	102°15'2.66"W
50	40°59'58.74"N	102°12'40.07"W

B Project and Solution Cost Estimates

New Reservoir Construction Costs		
Project Name	**Location**	**Cost ($\frac{\$}{AF}$)**
Windy Gap Firming Project option 2	Colorado	3,008 [10]
Windy Gap Firming Project option 3	Colorado	3,232 [10]
Windy Gap Firming Project option 4	Colorado	3,398 [10]
Windy Gap Firming Project option 5	Colorado	3,874 [10]
Northern Integrated Supply Project option 1	Colorado	6,533 [11]
Northern Integrated Supply Project option 2	Colorado	2,556 [11]
Sites Reservoir option 1	California	2,976 [12]
Temperance Flat Reservoir option 1	California	2,006 [12]
Existing Reservoir Expansion Costs		
Moffat Collection System	Colorado	2,281 [13]
Los Vaqueros Reservoir	California	2,171 [12]
San Luis Reservoir	California	2,783 [12]
Shasta Reservoir	California	1,700 [12]

Note 1: All costs are in 2014 dollars using inflation calculator http://www.usinflationcalculator.com/

Note 2: [Bracketed numbers] represent the citation associated with each estimate

Note 3: Options represent the various construction alternatives within the Environmental Impact Statement

Table 3: Increased Surface Capacity Construction Costs

New Subsurface Reservoir Construction Costs (ASR)		
Project Name	**Location**	**$/AF**
GRUSP, CAVSARP, Sweetwater	Arizona	100 [14]
GRUSP, CAVSARP, Sweetwater	Arizona	130 [14]
Water In the West	California	390 [15]
South Platte Storage Study	Colorado	524 [16]
South Platte Storage Study	Colorado	1,001 [16]

Note 1: All costs are in 2014 dollars using inflation calculator http://www.usinflationcalculator.com/

Note 2: [Bracketed numbers] represent the citation associated with each estimate

Table 4: Increased Subsurface Capacity Costs

Surface Reservoir O & M Costs		
Project Name	**Location**	**$/AF/Mo**
Windy Gap Firming Project option 2	Colorado	0.88 [10]
Windy Gap Firming Project option 3	Colorado	1.54 [10]
Windy Gap Firming Project option 4	Colorado	1.93 [10]
Windy Gap Firming Project option 5	Colorado	2.50 [10]
Northern Integrated Supply Project option 1	Colorado	3.00 [11]
Northern Integrated Supply Project option 2	Colorado	1.92 [11]
Sites Reservoir option 1	California	0.45 [12]
Temperance Flat Reservoir option 1	California	8.00 [12]
Existing Surface Reservoir Expansion O & M Costs		
Moffat Collection System	Colorado	0.33 [13]
Subsurface Reservoir O & M Costs		
GRUSP, CAVSARP, Sweetwater	Arizona	0.27 [14]

Note 1: All costs are in 2014 dollars using inflation calculator http://www.usinflationcalculator.com/

Note 2: [Bracketed numbers] represent the citation associated with each estimate

Note 3: Options represent the various construction alternatives within the Environmental Impact Statement

Table 5: Project Operation and Maintenance Costs

Model Solution Costs for Various Alternatives		
Solution Name	**O&M ($)**	**Construction ($)**
Single Reservoir	92,441,870	100,792,064
Expansion (Riverside, Jackson, Prewitt)	9,701,013	59,449,782
Expansion (Riverside, Empire, Jackson)	11,782,266	72,443,450
Expansion (Jackson only)	11,847,192	72,398,424
Unconstrained	12,710,756	15,332,388

Note 1: All costs are in 2014 dollars.

Table 6: Model solution costs for various alternatives

C Optimization Model

A Mixed-Integer Linear Program integrates costs, supplies, demands and topology to determine the location of new storage and flow needed to meet demand in dry months. The objective function minimizes: (1) construction as well as operation and maintenance costs of new infrastructure, (2) unmet demand penalties, and (3) the use of elastic variables inserted to handle atypical events while adhering to constraints that force the physical and topographical structures of the river.

C.1 Sets

$t \in \mathcal{T}$	set of all monthly time periods
$t \in \mathcal{T}'$	set of all time periods in which the South Platte Compact applies
$d \in \mathcal{D}_t$	set of all demand sites at time t
$n \subset \mathcal{D}_t$	set of all demand nodes at time t and within the lower half of the river (District 64) that hold a water right junior to that of the South Platte Compact
$r \in \mathcal{R}$	set of all reservoirs which includes existing and potential, where r' is a downstream reservoir from r
$\mathcal{E} \subset \mathcal{R}$	set of existing surface reservoirs
$\mathcal{P}^s \subset \mathcal{R}$	set of potential surface reservoirs
$\mathcal{P}^u \subset \mathcal{R}$	set of potential underground reservoirs
$s \in \mathcal{S}_t$	set of all supply sites at time t
$j \in \mathcal{J}$	set of all pipeline flow capacities

C.2 Parameters

$f_{jr'rt}$	fixed cost to construct a pipeline with flow level j from reservoir r' to upstream reservoir r in time t (\$)
$\hat{f}_{jr'rt}$	fixed monthly cost to maintain a pipeline with flow level j from reservoir r' to upstream reservoir r in time t (\$)
$\mathring{f}_{jr'rt}$	fixed monthly cost to operate a pipeline with flow level j from reservoir r' to upstream reservoir r in time t (\$)
$\breve{u}_{rt}$	per unit cost to store water in reservoir r in time t (\$/AF)
$\mathring{u}_{rt}$	per unit cost to operate and maintain reservoir site r in time t (\$/AF)
$\hat{c}_{st}$	capacity of supply site s in time t (AF)
$\bar{c}_{rt}$	maximum capacity of reservoir r in time t (AF)
$\underline{c}_{rt}$	minimum capacity of reservoir r in time t (AF)
c^s_r	capacity of the reservoir discharge ditch r (AF)
c^r	capacity of the South Platte River (AF)
c^p_j	capacity of a water pipeline with flow level j (AF)
c^d_r	capacity of the intake diversion ditch at reservoir r (AF)
d_{dt}	demand at site d in time period t (AF)
v^+_{dt}	volume of river water entering demand site d in time period t (AF)
v^-_{st}	volume of river water leaving supply site s in time period t (AF)
v^d_{rt}	volume of river water already diverted into diversion ditch at reservoir r in time period t (AF)

v^r_{rt}	volume of river water already released by reservoir r in time period t (AF)
p_{dt}	unmet demand penalty at site d in time period t ($/AF)
p^e	demand exceedance penalty ($/AF)
M	"sufficiently large" value

C.3 Variables

$X_{rdt} =$	amount of water released from reservoir r to downstream demand site d in time t (AF)
$\bar{X}_{sdt} =$	amount of water diverted from supply site s to demand site d in time t (AF)
$\tilde{X}_{srt} =$	amount of water diverted from supply site s to reservoir r in time t (AF)
$\hat{X}_{r'rt} =$	amount of water pumped from reservoir r' to upstream reservoir r in time t (AF)
$\check{X}_r =$	maximum flow from reservoir r across all time periods (AF)
$\mathring{X}_{rt} =$	maximum flow from reservoir r by time t (AF)
$Z^+_{dt} =$	amount in excess of demand at site d in time t (AF)
$Z^-_{dt} =$	amount of the unmet demand at site d in time t (AF)
$I_{rt} =$	inventory amount for reservoir r in time t (AF)
$\check{W}_{rt} =$	maximum size of reservoir r in time t (AF)

$$Y_{rt} = \begin{cases} 1 \text{ if reservoir } r \text{ is used by time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$\mathring{Y}_{rt} = \begin{cases} 1 \text{ if operation and maintenance costs are incurred at reservoir } r \text{ by time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$\tilde{Y}_{jr'rt} = \begin{cases} 1 \text{ if a pipeline with flow capacity } j \text{ is constructed between reservoir } r' \text{ and} \\ \quad \text{upstream reservoir } r \text{ in time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$\tilde{Y}'_{jr'rt} = \begin{cases} 1 \text{ if a pipeline with flow capacity } j \text{ is constructed between reservoir } r' \text{ and} \\ \quad \text{upstream reservoir } r \text{ by time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$\tilde{Y}''_{jr'rt} = \begin{cases} 1 \text{ if a pipeline with flow capacity } j \text{ is used between reservoir } r' \text{ and upstream} \\ \quad \text{reservoir } r \text{ in time period } t \\ 0 \text{ otherwise} \end{cases}$$

$$\alpha_{rt} = \begin{cases} 1 \text{ if the amount of water stored in reservoir } r \text{ in time period } t \text{ is greater than} \\ \quad \text{the minimum capacity of } r \\ 0 \text{ otherwise} \end{cases}$$

$$\beta_{dt} = \begin{cases} 1 \text{ if the total amount of water allocated to demand site } d \text{ in time period } t \\ \quad \text{exceeds the requirement of the South Platte Compact} \\ 0 \text{ otherwise} \end{cases}$$

$$W_{rt} = \begin{cases} 1 \text{ if reservoir } r \text{ is first used at time period } t \\ 0 \text{ otherwise} \end{cases}$$

C.4 Objective Function

$$
\begin{aligned}
(\mathcal{P})\ \text{minimize}\ & \sum_{j\in\mathcal{J}}\sum_{r'\in\mathcal{R}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} f_{jr'rt}\tilde{Y}_{jr'rt} + \sum_{j\in\mathcal{J}}\sum_{r'\in\mathcal{R}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} \hat{f}_{jr'rt}\tilde{Y}'_{jr'rt} \\
& + \sum_{j\in\mathcal{J}}\sum_{r'\in\mathcal{R}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} \mathring{f}_{jr'rt}\tilde{Y}''_{jr'rt} + \sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} \breve{u}_{rt}\breve{W}_{rt} \\
& + \sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} \mathring{u}_{rt}\mathring{X}_{rt} + \sum_{d\in\mathcal{D}_t}\sum_{t\in\mathcal{T}} p^e Z^+_{dt} + \sum_{d\in\mathcal{D}_t}\sum_{t\in\mathcal{T}} p_{dt} Z^-_{dt}
\end{aligned} \tag{1}
$$

C.5 Constraints

Capacities (see Section C.5.1)

$$\sum_{d\geq r} X_{rdt} \leq (c^s_r - v^r_{rt})Y_{rt} \qquad \forall \quad r\in\mathcal{R} \text{ and } t\in\mathcal{T} \tag{2a}$$

$$I_{rt} \leq \bar{c}_{rt}Y_{rt} \qquad \forall \quad r\in\mathcal{P}^u \text{ and } t\in\mathcal{T} \tag{2b}$$

$$\sum_{s\leq r} \tilde{X}_{srt} \leq (c^d_r - v^d_{rt})Y_{rt} \qquad \forall \quad r\in\mathcal{R} \text{ and } t\in\mathcal{T} \tag{2c}$$

$$\hat{X}_{r'rt} \leq \sum_{j\in\mathcal{J}} c^p_j \tilde{Y}''_{jr'rt} \quad \forall \quad r', r\in\mathcal{R} \text{ and } t\in\mathcal{T} \tag{2d}$$

$$\sum_{s\leq d} \bar{X}_{sdt} + \sum_{r\leq d} X_{rdt} \leq c^r - v^+_{dt} \qquad \forall \quad d\in\mathcal{D}_t \text{ and } t\in\mathcal{T} \tag{2e}$$

$$\sum_{d\geq s} \bar{X}_{sdt} + \sum_{r\geq s} \tilde{X}_{srt} \leq c^r - v^-_{st} \qquad \forall \quad s\in\mathcal{S}_t \text{ and } t\in\mathcal{T} \tag{2f}$$

Penalties (see Section C.5.2)

$$Z^+_{dt} \geq \sum_{r\leq d} X_{rdt} + \sum_{s\leq d} \bar{X}_{sdt} - d_{dt} \quad \forall \quad d\in\mathcal{D}_t \text{ and } t\in\mathcal{T} \tag{3a}$$

$$Z^-_{dt} \geq d_{dt} - \sum_{r\leq d} X_{rdt} - \sum_{s\leq d} \bar{X}_{sdt} \quad \forall \quad d\in\mathcal{D}_t \text{ and } t\in\mathcal{T} \tag{3b}$$

Flow Balance (see Section C.5.3)

$$\hat{c}_{st} = \sum_{d\geq s} \bar{X}_{sdt} + \sum_{r\geq s} \tilde{X}_{srt} \quad \forall \quad s\in\mathcal{S}_t \text{ and } t\in\mathcal{T} \tag{4a}$$

$$\sum_{d \geq r'} X_{r'dt} + \sum_{r < r'} \hat{X}_{r'rt} \leq I_{r',t-1} \quad \forall \quad r' \in \mathcal{R} \text{ and } t \in \mathcal{T} : t > 1 \tag{4b}$$

$$\sum_{d \geq r} X_{rdt} = 0 \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} : t = 1 \tag{4c}$$

$$\sum_{r < r'} \hat{X}_{r'rt} = 0 \quad \forall \quad r' \in \mathcal{R} \text{ and } t \in \mathcal{T} : t = 1 \tag{4d}$$

Inventory Flow (see Section C.5.4)

$$I_{rt} = I_{r,t-1} + \sum_{s \leq r} \tilde{X}_{srt} + \sum_{r' > r} \hat{X}_{r'rt} - \sum_{d \geq r} X_{rdt} - \sum_{r' < r} \hat{X}_{rr't} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{5a}$$

$$I_{rt} \leq MY_{rt} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{5b}$$

$$I_{rt} \geq \underline{c}_{rt} - M(1 - \alpha_{rt}) \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{5c}$$

$$\sum_{d \geq r} X_{rdt} \leq M\alpha_{rt} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{5d}$$

Total Quantity of New Infrastructure (see Section C.5.5)

$$\sum_{j \in \mathcal{J}} \sum_{t \in \mathcal{T}} \tilde{Y}_{jr'rt} \leq 1 \quad \forall \quad r', r \in \mathcal{R} \tag{6a}$$

$$\sum_{r \in \mathcal{P}^s} Y_{rt} \leq 1 \quad \forall \quad t \in \mathcal{T} \tag{6b}$$

$$\sum_{r \in \mathcal{E}} Y_{rt} \leq 1 \quad \forall \quad t \in \mathcal{T} \tag{6c}$$

$$\sum_{r \in \mathcal{P}^u} Y_{rt} \leq 1 \quad \forall \quad t \in \mathcal{T} \tag{6d}$$

$$Y_{rt} \leq Y_{r,t+1} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} : t \leq |\mathcal{T}| - 1 \tag{6e}$$

Construction of Reservoirs (see Section C.5.6)

$$\breve{W}_{rt} \geq \breve{X}_r - M(1 - W_{rt}) \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{7a}$$

$$Y_{rt} - Y_{r,t-1} = W_{rt} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{7b}$$

Construction of Pipelines (see Section C.5.7)

$$\tilde{Y}''_{jr'rt} \leq \sum_{t'=1}^{t-1} \tilde{Y}_{jr'rt'} \quad \forall \quad j \in \mathcal{J}, r', r \in \mathcal{R} \text{ and } t \in \mathcal{T} : t \geq 2 \tag{8}$$

Operation and Maintenance of Reservoirs (see Section C.5.8)

$$\breve{X}_r \geq I_{rt} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{9a}$$

$$\breve{X}_r \leq \mathring{X}_{rt} + M(1 - \mathring{Y}_{rt}) \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{9b}$$

$$Y_{rt} \leq \mathring{Y}_{r,t+1} \quad \forall \quad r \in \mathcal{R} \text{ and } t \in \mathcal{T} : t \leq |\mathcal{T}| - 1 \tag{9c}$$

Operation and Maintenance of Pipelines (see Section C.5.9)

$$\tilde{Y}''_{jr'rt} \leq \tilde{Y}'_{jr'rt} \quad \forall \quad j \in \mathcal{J}, r', r \in \mathcal{R} \text{ and } t \in \mathcal{T} \tag{10a}$$

$$\tilde{Y}'_{jr'rt} \leq \tilde{Y}'_{jr'r,t+1} \quad \forall \quad j \in \mathcal{J}, r', r \in \mathcal{R} \text{ and } t \in \mathcal{T}, t \leq |\mathcal{T}| - 1 \tag{10b}$$

South Platte Compact (see Section C.5.10)

$$\sum_{r \in \mathcal{R}} X_{rdt} + \sum_{s \in \mathcal{S}_t} \bar{X}_{sdt} + \sum_{s \in \mathcal{S}_t} + \hat{c}_{st} \geq d_{dt} - M'(1 - \beta_{dt}) \quad \forall \quad d \in \mathcal{D}_t \text{ and } t \in \mathcal{T}' \tag{11a}$$

$$\sum_{r \geq n} \sum_{n \in \mathcal{D}_t} X_{rnt} + \sum_{s \geq n} \sum_{n \in \mathcal{D}_t} \bar{X}_{snt} \leq 0 + M'\beta_{dt} \quad \forall \quad d \in \mathcal{D}_t \text{ and } t \in \mathcal{T}' \tag{11b}$$

Non-Negativity and Binary Restrictions (see Section C.5.11)

$$X_{rdt}, \hat{X}_{r'rt}, \bar{X}_{sdt}, \tilde{X}_{srt}, \mathring{X}_r, \breve{X}_{rt}, I_{rt}, Z^+_{dt}, Z^-_{dt}, \breve{W}_{rt} \geq 0 \;\; \forall \;\; r', r \in \mathcal{R}, d \in \mathcal{D}_t, s \in \mathcal{S}_t, \text{ and } t \in \mathcal{T} \tag{12a}$$

$$Y_{rt}, \tilde{Y}_{jr'rt}, \tilde{Y}'_{jr'rt}, \tilde{Y}''_{jr'rt}, \mathring{Y}_{rt}, \alpha_{rt}, \beta_{dt}, W_{rt} \text{ binary } \;\forall\;\; r', r \in \mathcal{R}, j \in \mathcal{J}, d \in \mathcal{D}_t, s \in \mathcal{S}_t \text{ and } t \in \mathcal{T} \tag{12b}$$

C.5.1 Capacities

If a new reservoir is created and/or an existing reservoir is expanded, constraints (2a) ensure that the total flow released from a reservoir in each time period does not exceed the available capacity of the discharge ditch. Constraints (2b) make certain that the inventory levels of newly created reservoirs and expanded reservoirs do not extend beyond the maximum capacity. Constraints (2c) safeguard the total volume released from all upstream supply nodes to each reservoir such that the available capacity of each reservoir intake ditch in each time period is not surpassed. Constraints (2d) guarantee that the pumped water volume is less than pipe capacity. Constraints (2e) ensure that the cumulative water released to meet demand does not violate the available river capacity. Constraints (2f) make certain that the cumulative volume released from each supply node is within the available river capacity.

C.5.2 Penalties

Constraints (3a) apply a penalty if demand is exceeded. If demand goes unmet, constraints (3b) apply a penalty, increasing with the seniority of the water right.

C.5.3 Flow Balance

Constraints (4a) empty each supply node into storage and/or to meet demand. Constraints (4b) ensure that the removal of water from new reservoirs in a given time period does not exceed the inventory balance of said reservoirs in the preceding time period. Constraints (4c)-(4d) preclude the release of or pumping water from any reservoir in time period 1.

C.5.4 Inventory Flow

Constraints (5a) preserve inventory balance. Constraints (5b) ensure that inventory is only held in constructed reservoirs. Constraints (5c)-(5d) maintain the minimum required reservoir volume.

C.5.5 Total Quantity of New Infrastructure

Constraints (6a) construct pipelines between nodes only once. Constraints (6b)-(6d) enforce the specified number and type of reservoirs to be considered. Constraints (6e) ensure a constructed reservoir incurs operational costs in all future time periods.

C.5.6 Construction of Reservoirs

In order to calculate the reservoir construction costs, the maximum reservoir size is needed. Constraints (7a)-(7b) apply the corresponding cost during the initial time period of use.

C.5.7 Construction of Pipelines

Constraints (8) ensure pipeline construction costs are incurred in the time period preceding first use.

C.5.8 Operation and Maintenance of Reservoirs

Constraints (9a)-(9b) apply the reservoir operation and maintenance cost using the maximum size of the new reservoir at the time of construction. By constraints (9c), the operation and maintenance costs are incurred in every year following construction.

C.5.9 Operation and Maintenance of Pipelines

Constraints (10a)-(10b) apply the operation and maintenance costs for pipeline use during the initial time period of use and in every time period thereafter.

C.5.10 South Platte Compact

The South Platte Compact with Nebraska is enforced annually from April through October in District 64 (lower portion) of the river. Constraints (11a)-(11b) enforce the South Platte Compact with Nebraska and only apply at node 50 (Nebraska border) in the amount of 7244 AF/month.

C.5.11 Non-Negativity and Binary Restrictions

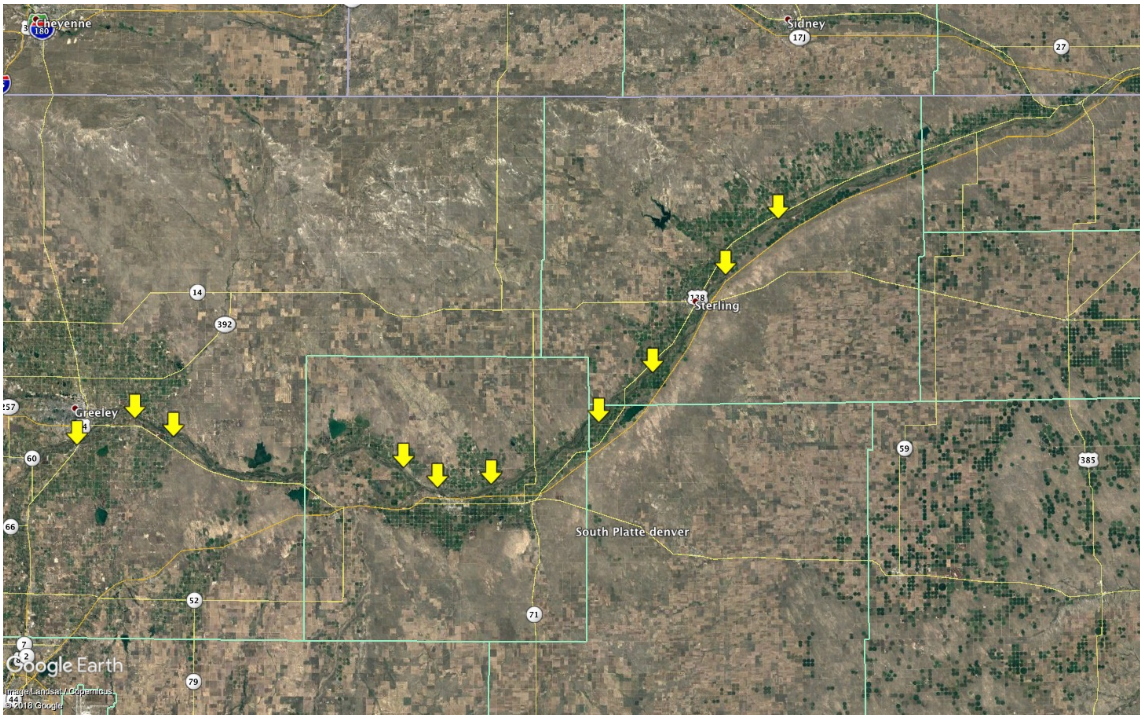
Constraints (12a) dictate the non-negativity of continuous variables. Constraints (12b) guarantee the appropriate variables are binary.

D Software and Tuning

The model runs on a SuperServer 1028GR-TR with a 1TB hard drive, 3 Intel Xeon-PHI coprocessors and 164GB of RAM operating under a Linux environment. We code model instances in AMPL ([17], [18]) and solve them with CPLEX version 12.7.0.0 ([19], [20]); these instances contain more than 6,000,000 variables, of which at least 98,000 are binary, and more than 1,900,000 constraints. CPLEX parameter settings are used to reduce the effect of numerical instability. Specifically, we decrease the integrality and feasibility tolerances from the default settings, and turn off certain cuts that are more prone to numerically unstable behavior, e.g., Gomory cuts, mixed-integer rounding cuts, and zero-half cuts; additionally, we use eight threads. Using an initial feasible solution obtained via a sliding time window heuristic (e.g., [21], [22]), our particular instances solve to optimality in fewer than 20 seconds.

E Unconstrained Solution Characteristics

Nodes are numbered from west to east.



Node	Type	Volume (AF)	Latitude	Longitude
1	Surface	53	40°21'41.93"N	104°42'12.39"W
3	Surface	1308	40°24'42.93"N	104°33'45.85"W
5	ASR	3306	40°22'44.91"N	104°28'7.95"W
10	Surface	715	40°19'17.00"N	103°55'13.01"W
12	ASR	4745	40°16'28.92"N	103°50'2.34"W
14	ASR	4577	40°16'50.47"N	103°42'6.08"W
23	ASR	7422	40°24'37.44"N	103°26'17.77"W
26	ASR	2376	40°29'59.84"N	103°18'39.55"W
32	ASR	582	40°40'46.06"N	103° 8'1.17"W
36	ASR	294	40°46'56.69"N	103° 0'14.51"W

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