Predicting When the Well Will Go Dry: A Review of Commonly-Used Models for Water Supply Planning and Management

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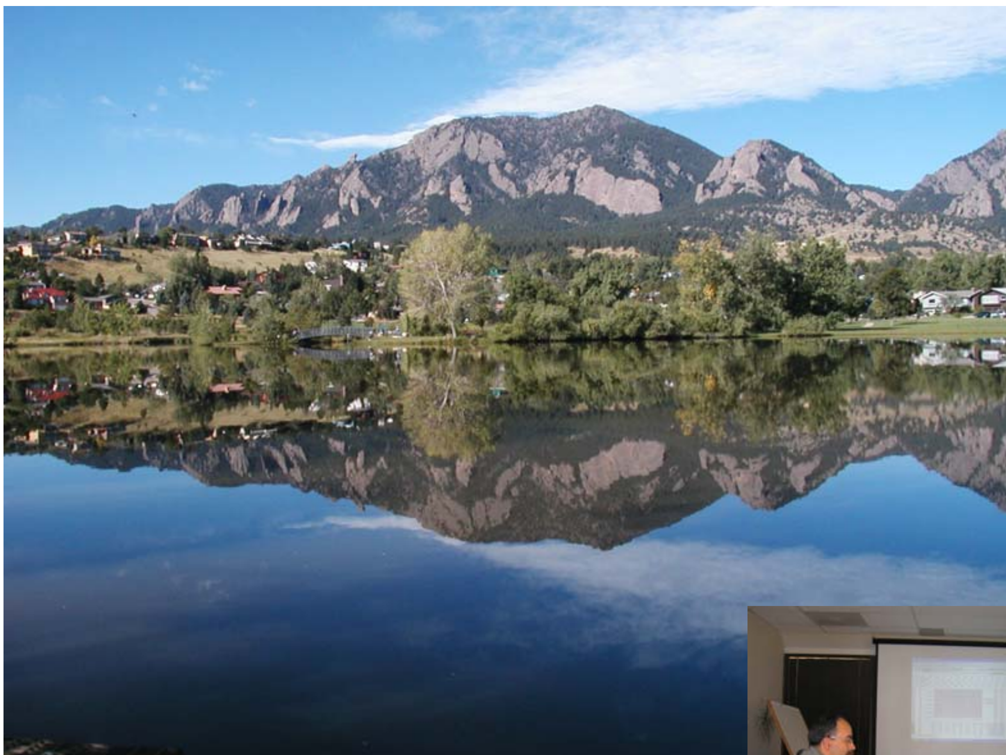


Debug a Model

INTRODUCTION

"***Water promises to be to the 21st century what oil was to the 20th century: the precious commodity that determines the wealth of nations***." **–**Fortune Magazine (May 15, 2000)

While there are alternatives to oil as an energy source, there is no substitute for water as a supply for human uses or agricultural purposes. This paper reviews the state of the art of water resources management in the United States in general, with specific examples from the Rocky Mountain west.

Overview of Water Rights

Water rights in the United States are generally administered according to one of two legal structures, either the riparian doctrine or the prior appropriation doctrine. The riparian doctrine is typically used east of the 100th meridian, where rainfall is generally more than 20 inches per year. The prior appropriation doctrine is commonly applied west of the 100th meridian, where, generally speaking, there is insufficient rainfall for non-irrigated agriculture. Each doctrine is defined more clearly below.

- The riparian doctrine specifies that a landowner adjacent to waterways may use the water as they wish, so long as they do not diminish the quantity or quality needed by downstream users.

- The prior appropriation doctrine holds that anyone anywhere in the state can use water from a stream, with those having the most senior decreed rights having the first right of use.

While some states use a pure doctrine and others use blended systems, the more interesting variation from a water rights management perspective is how aggressively the state administers the water rights laws that are in place. Some states, like Oklahoma, are relatively lax in administration because they have enough water and thus conflicts are rare. Others, like New Mexico, have been lax in the past but are having to step up their administration of water rights because conflicts are increasing. Still others, like Colorado, actively administer water to allocate available supplies as close to the letter of the law as possible.

Water Rights in Colorado

"***Whiskey*'s for *drinking, water*'s *for fighting about.***" -- *Mark Twain*

Colorado arguably has the most sophisticated and complex water administration systems of the 50 states. Water rights in Colorado are based on the prior appropriation system, where those with the oldest decree have the first right to use what water is available. This "*first in time, first in right*" system is based on the premise that when there is not enough water to satisfy all users, sharing the available water would be of little value to any user (Rice and White, 1987).

Water rights in Colorado are broadly classified into two categories: direct flow water rights and storage rights. Direct flow rights provide the holder the right to divert water and put it to immediate use or with a very short delay, which in general practice is less than 72 hours. The most valuable direct flow rights are those that are senior enough to be in priority for the majority of the growing season in many, if not most years. The longer the right is in priority, the more water it can divert and therefore the more valuable it usually is. Direct flow rights that are not often in priority are not reliable enough to have as much value as a water supply, either for irrigation or for municipal use. Water that is diverted under a direct flow water right but is not consumed must be returned to the stream for the benefit of downstream users. Direct flow water rights are decreed for a specific flow rate, typically measured in cubic feet per second (CFS).

Storage rights allow the holder to divert water at times when water is available and store it until it is needed. These are valuable on streams where the only reliable flows occur during the runoff seasons, such as snow-melt driven streams, or on streams where senior direct flow rights divert all but the highest flows during the peak of the spring runoff. Storage rights typically allow for a single filling of a storage reservoir each year and are limited to the volume of the reservoir, most commonly measured in acre-feet (AF).

Water rights are also decreed for specific types of use, such as irrigation, domestic, municipal, industrial, fire fighting, recreation, environmental and power generation. Depending on the type of use, limitations regarding the timing of use come into play. For example, irrigation rights are typically only diverted during the growing season.

Water rights are real property, and may be bought, sold or leased by willing sellers and buyers.

- Water rights can be transferred from one location to another, from one use to another, and even from one time of year to another, as long as no water rights decreed at the time of the change are injured. Such changes in water rights generally must be adjudicated in the State Water Court to preserve their continued operation.
- Water rights can be lost through non-use. In Colorado, water rights without a record of use for an extended period of time may be placed on the State Engineer's abandonment list. Rights that cannot show use may be declared abandoned and permanently lost to the holder.

- Water rights cannot be increased beyond their decreed amount through adverse possession. New decrees can be filed, but the new water right will be junior to rights previously filed.

Colorado is a signatory to nine compacts with individual downstream states and nine multi-state or multi-national compacts, more than any other state in the nation (Waterknowledge, 2008).

WATER SUPPLY PLANNING AND MANAGEMENT TOOLS

*"**Plans are nothing; planning is everything**." -- Dwight D. Eisenhower*

As water use in the west increases, the need for administration will also grow and evolve. In addition, more complete use of the resource will mean that changes in water rights and modifications to operations will be analyzed in ever-increasing detail to demonstrate that the change will not injure other water users. To meet this demand for precision and accuracy, analyses based on modeling will become more common, and existing models will become more sophisticated.

Models are already used extensively by water resources engineers to simulate potential conditions and predict hydraulic and hydrologic outcomes. These include commercial models that calculate the theoretical parameters for open channel and pipe flow, stormwater detention and streamflow routing. However, because raw water collection and diversion systems are all unique, most water users use one of a few model engines or build their own custom model.

Models are used to quantify changes in streamflows and reservoir operations and predict answers to questions about:

- which users will divert water, how much and when
- changes in yield to a particular user
- how much storage is needed to maintain a certain operation
- what-if questions about changes in operations or facilities
- water rights accounting

Models used by select water users and regulators are listed in Table 1.

Table 1: Water Supply Planning and Management Models used by Selected Water Entities in Rocky Mountain West

Entity	Modeled System	Model Engine
Colorado Dept Water Resources, in-state	Major river basins (3+)	BESTSIM
Colorado Dept of Water Resources, interstate with Kansas	Arkansas basin	Custom Fortran
New Mexico Office of the State Engineer, Interstate Streams Commission	Pecos River Basin	Riverware
Denver Water, CO	Raw water system	BESTSIM
Colorado Springs Utilities, CO	Raw water system	MODSIM
Aurora Water, CO	Raw water system	ExcelCRAM
City of Boulder, CO	Raw water system	ExcelCRAM
City of Fort Collins, CO	Raw water system	MODSIM
City of Greeley, CO	Raw water system	MODSIM
City of Loveland, CO	Raw water system	MODSIM
Pueblo Board of Water Works, CO	Raw water system	Spreadsheet
City of Cheyenne, WY	Raw water system	None
City of Laramie, WY	Raw water system	None
City of Albuquerque, NM	Raw water system	Spreadsheet

Selecting the Right Model

*"**Remember that all models are wrong**; **the practical question is how wrong do they have to be to not be useful**." -- George Box*

Water planning models are typically used to determine how systems will respond to change, with the goal of cost-effectively maximizing yield. Models are increasingly being used to study the uncertainty associated with long-term droughts identified in tree-ring reconstructions, with potential changes in hydrology due to climate change, and with new environmental or legal mandates. A variety of water resources planning models are available, each designed for a particular purpose and user group, and often with capabilities that overlap.

Water supply planning models can be classified by the type of solver used. Linear models add and subtract inflows and depletions in a predetermined order. Network flow models, an efficient form of linear programming, allocate water to provide the greatest value for the system as a whole, based on user-specified priorities within a single time step. Optimization models allocate water to maximize the delivery of water to defined needs over multiple time steps. Models typically have a daily, weekly, or monthly time step and impose potential operations or facilities on historical or virgin hydrology.

Hydrologists and engineers have many alternatives to select from when choosing a raw water planning model. This paper compared seven commonly used models, each of which is described in the following paragraphs. A graphical summary of the models is presented in
Figure 1.

- RiverWare, a product of CADSWES at the University of Colorado, is based on linear programming and has three simulation modes: pure simulation, rule-based simulation, and optimization. In pure simulation, all but one operational parameter is specified by the user, and the model calculates the unknown. In rule-based simulation, the user delineates and prioritizes rules for operations and then the model allocates inflows to meet the rules. In optimization mode, the model allocates water to meet demands in a priority order. RiverWare is expensive, the extensive user interface can be difficult to master, and the optimization solver is not well suited for complex water rights (CADSWES, 2008).

- MODSIM, available from Colorado State University, is a network flow model with a priority-based solver that mimics water rights allocations. MODSIM is linked to MODFLOW and QUAL2E to calculate groundwater/surface water interactions and water quality. MODSIM has a friendly user interface. MODSIM's limitations include its inability to split yield from a single water right between multiple owners, difficulty implementing rule-based operations, and its data storage format can make it difficult to ensure quality assurance and quality control of input data for large networks (ColoState, 2008).

- WRAP, publicly available from Texas A&M University, is a linear accounting model with an exceptionally good reliability and frequency functionality. WRAP calculates the natural hydrology of a basin and then allocates water based on the water rights priorities specified by the user. The user interface is primarily a file manager; all file creation and editing is done through other spreadsheet, text, and word processing programs. It is the only model in this discussion without a graphical user interface (TWRI, 2008).

- BESTSM, a proprietary model from Boyle Engineering Company, is designed to allocate water to demands based on the prior appropriation system. BESTSM is capable of modeling water quality for conservative constituents. Based on linear programming, the model uses simplified physical processes (e.g., return flow calculations), does not optimize, and does not calculate channel hydraulics (Boyle, 2008).

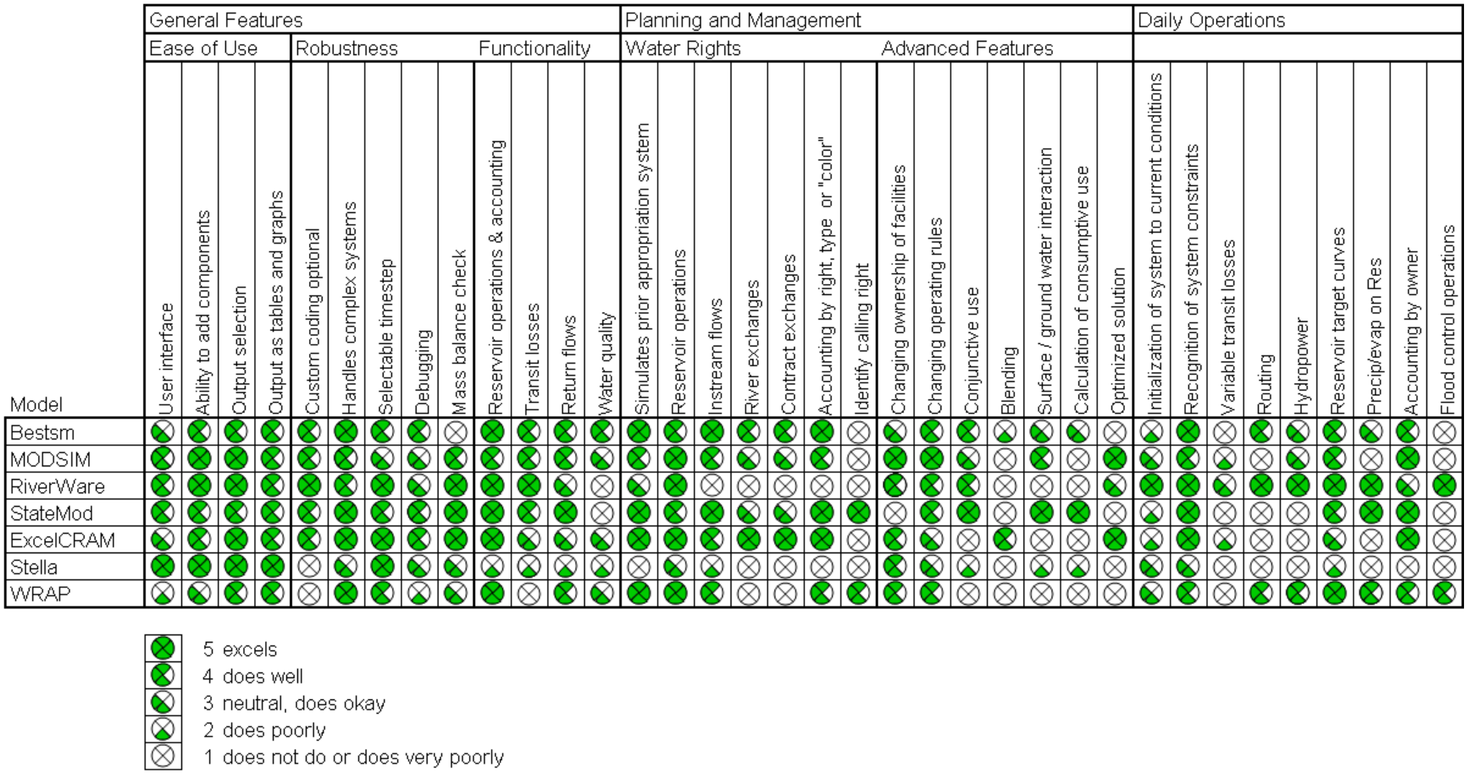
- StateMod is a free version of BESTSM, available from the Colorado Department of Natural Resources. StateMod differs from BESTSM in that it is equipped with enhanced surface water/groundwater routines for agricultural operations. In addition, StateMod cannot model water quality and does not perform routing calculations (CO SEO, 2008).

- ExcelCRAM, a proprietary model available from AMEC Earth & Environmental, is a network flow model based in Microsoft Excel. ExcelCRAM can repeatedly simulate the same timestep, which allows the model to accurately simulate extremely complex systems and to track water quantity and quality from different sources. Designed for the advanced modeler, the ExcelCRAM interface can be daunting to modeling novices (AMEC, 2008).

- Stella, a proprietary model developed by ISEE Systems, is a systems dynamics model based on linear programming. It can be applied to any problem by inexperienced users. Stella has a friendly graphical user interface with very good graphical output. But because it was not designed as a water-resources planning tool, it has no predefined water-related facilities, such as reservoirs. All water-resources constructs - reservoirs accounting, losses, routing, etc. - must be developed from scratch (Stella, 2008).

This chart is most useful for comparing general capabilities between models, not determining an absolute value for a specific capability of a particular model. For example, daily operations are generally best performed by RiverWare and WRAP, advanced agricultural operations are modeled well by StateMod, and water rights are addressed well by BESTSM, MODSIM and ExcelCRAM.

Figure 1 provides a graphical comparison of model attributes. The rating was developed through discussions with water resources modelers who are familiar with one or more of the models.



	User interface	Ability to add components	Output selection	Output as tables and graphs	Custom coding optional	Handles complex systems	Selectable timestep	Debugging	Mass balance check	Reservoir operations & accounting	Transit losses	Return flows	Water quality
median	4	4	5	4	4	5	4	3	3	5	4	4	3
mean	4	4	5	4	3	4	4	3	3	4	3	4	2

	Simulates prior appropriation system	Reservoir operations	Instream flows	River exchanges	Contract exchanges	Accounting by right, type or "color"	Identify calling right	Changing ownership of facilities	Changing operating rules	Conjunctive use	Blending	Surface / ground water interaction	Calculation of consumptive use	Optimized solution
median	5	5	4	3	3	4	1	4	4	3	1	2	1	1
mean	4	4	4	3	3	4	2	4	4	3	2	2	2	2

	Initialization of system to current conditions	Recognition of system constraints	Variable transit losses	Routing	Hydropower	Reservoir target curves	Precip/evap on Res	Accounting by owner	Flood control operations
median	3	5	1	1	3	4	3	5	1
mean	3	4	2	2	3	4	3	4	2

Figure 1: Comparison Chart for Water Supply Planning and Management Models

FUTURE TRENDS

*"**Prediction is very difficult, especially if it's about the future**." --Niels Bohr*

The common consensus is that water administration and analysis will, overall, become more complex in the future. This will include both the number and level of processes represented by models.

The future trends in water rights modeling, operations and administration listed below are derived from numerous sources, including public meetings, private conversations and various published materials.

- ***More Complex:*** To capture as many facets of the physical system as possible, models will become more complex, simulating ever-increasing levels of details of both the practical and theoretical processes. With the uncertainty of the future climate, models will be built to simulate physical processes, including precipitation-runoff, stream channel routing, surface water – ground water interactions and water rights allocations. These processes are all presently contained in models, but in the future more of these processes will be calculated by the same model. This will allow a model to calculate the fate, transport and allocation of water from raindrop to flocculation tank.

- ***More Complete:*** The acceptable standards for models, like all technology, will continue to increase over time. Increased computing power will allow models to continue to grow in complexity so they will better represent physical processes. Models will include more detailed calculations related to gains and losses, accounting and water quality. While the models can become as detailed as imaginable, they will only be as good as the data used to populate them.

- ***More Accurate:*** The increase in modeling standards will also be reflected in models that more accurately simulate transit loss, return flows, evaporation, bank storage, water quality and other factors that are generally currently represented only in coarse forms, if at all.

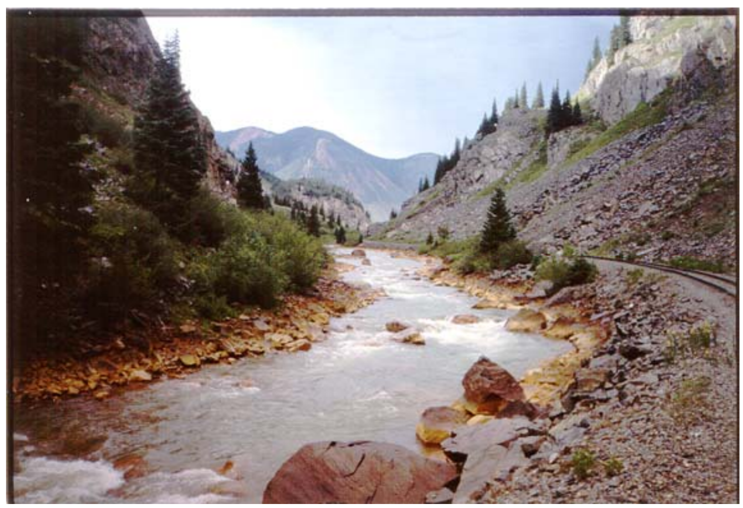
- ***New Tools:*** Just as new tools will be developed to solve more complex problems, so too will new tools be developed to further our understanding of the tools' function. For example, data output has changed dramatically from time series to table to graph, and cutting edge output is now reviewed as an animation. Examples of this can be seen in automated pipe networks and in 3-dimensional CADD tours of buildings as they are being designed.

Management Implications

*"**Models come and go, but data are forever**" -- Ben Harding*

Because of increasing scrutiny, models will play an ever increasing roll in water resources planning, management, operations and administration. Water resources practitioners will have to become comfortable with modeling, whether it is using models themselves, or learning to review model output for accuracy.

Of the various models currently available, each has different strengths. Some are better for simulating operations while others are better at simulating water rights allocations. Choosing the best model for a specific purpose may require contracting for services from a particular consulting firm.



Being a technology product, models are prone to change over time as hardware and software capabilities improve. Modeling efforts should be viewed as projects that will produce a product that will never be 100 percent complete nor 100 percent accurate, and that will be replaced with something better in the near- to mid-term, commonly every 5 to 15 years. Budgeting for staff time and monetary resources should be done keeping this impermanence in mind.

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