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Front Cover: South Platte basin. Photo by Bill Cotton
This Page: Aerial view of the South Platte River west of Weldona, Colorado. Photo by Bill Cotton

Introduction

by Reagan Waskom, Director, Colorado Water Institute

The South Platte basin is one of the most complex water use and administration basins in Colorado, with a long management history and some 18,600 decreed points of diversion. Much of Colorado's historical water law and administration stemmed from this basin and continues to evolve to this day. There is rarely enough water to satisfy all of the demands in this growing basin, where the majority of Colorado's citizens reside.

A century and a half of irrigation development in the S. Platte basin has resulted in an extensive network of diversion ditches, canals, and reservoirs, all of which seep large amounts of water into the alluvial aquifer. As a result, groundwater has been extensively utilized for irrigation in the basin going back to the 1930s. Return flows from irrigation make a large contribution to stabilizing river flows and are a critical component of water rights and utilization in this basin. Prior to 2003, approximately 8,200 high capacity irrigation wells pumped on average nearly 500,000 AF/yr from the alluvial aquifer. After the fall out from the 2000 Empire Lodge case and subsequent legislation and litigation, there are now approximately 6,500 high capacity wells in the alluvial aquifer, and total annual groundwater pumping in the basin is now closer to 450,000 AF/yr, with agricultural pumping estimated at about 400,000 AF/yr. To comply with the strict groundwater administration implemented after the year 2000, extensive groundwater recharge projects have been developed to augment out-of-priority groundwater diversions or withdrawals.

In recent years, homeowner reports of high groundwater levels in the Sterling and Greeley areas have begun to surface. Wet years in 2009, 2010, and 2011 increased the frequency and locations of these complaints. Homeowners reported failing septic systems and flooding basements in areas that had not previously had such issues. Local attempts to address flooding concerns were not successful, as inadequate information existed to isolate the cause of the waterlogging. Parties in the S. Platte basin appealed to the state Legislature in 2011 and 2012, asking if there was a way to insert some institutional mechanisms to deal with high groundwater and provide more opportunity for agricultural groundwater users. Homeowners with flooded basements asked why recharge structures continued to operate when the local water table was near the surface. Eventually, the Legislature passed HB12-1278, requiring the Colorado Water Institute at CSU to conduct a study of these problems and propose solutions.

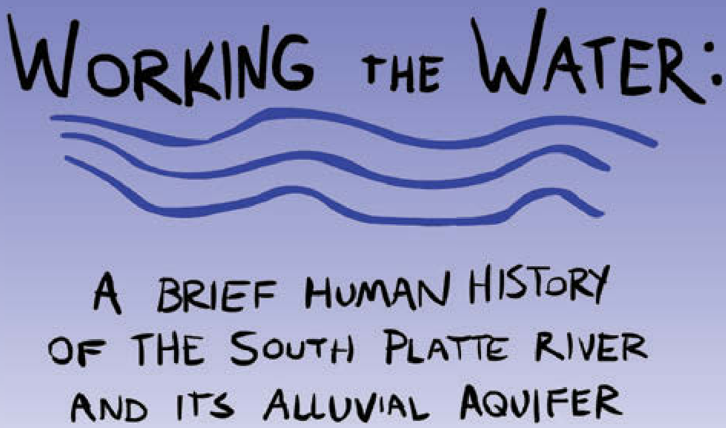
The problems of groundwater management are complex and controversial from a number of viewpoints. The challenge of sustainably using tributary groundwater without impairing the senior rights of surface water diverters is made more difficult by the lack of comprehensive and readily available data, models that accurately simulate actual conditions, and a common technical platform used by all water managers in the S. Platte basin. Due to the time lags involved with detecting groundwater movement and change, it is difficult to react in real time to excess groundwater depletions or accretions from recharge, sometimes resulting in undesirable third-party impacts, such as fluctuating groundwater levels. In the S. Platte, concerns have arisen in recent years from conflicting viewpoints about over-pumping, as well as loss of the ability by some to utilize groundwater, excess augmentation leading to high water tables, and augmentation water not adequately replacing depletions. While the system is working well for many water users, the question remains as to whether we can improve the system for the good of Colorado while maintaining our commitments to preventing injury to senior water users, the South Platte Compact, and the Platte River Endangered Species Recovery and Implementation Program.

The South Platte is an extremely complicated system that resists simple solutions. Much of the total economy of Colorado is generated in this water-short basin, requiring us to find ways to stretch our water supply for the good of all water users and the natural environment. Future expected growth and development in the basin only heightens the need to find and implement measures to sustain the economy and the surface and groundwater system. This special issue of *Colorado Water* summarizes some of the findings from the HB1278 study on water use in the S. Platte basin in order to better understand the current status and potential opportunities for additional alluvial groundwater utilization in the basin.

Working the Water

A Brief Human History of the South Platte River and its Alluvial Aquifer

MaryLou Smith, Policy and Collaboration Specialist, Colorado Water Institute



Addressing the dual challenge of maximizing beneficial use and protecting property rights in the South Platte basin has to start with an understanding of the history that got us to the point we are today. The HB12-1278 team set out to tell the story succinctly but accurately in two forms—a "brief" 17-page history entitled A Brief Timeline of Groundwater Management in the South Platte Basin *and an animation based on the timeline. Both are available at http://cwi.colostate.edu/southplatte.*

Here are the script and some clips from the animated version.

Introduction The South Platte River and its Alluvial Aquifer form the scene of a modern day conundrum. The state legislature wants to know: can groundwater be put to beneficial use while respecting senior surface rights? This brief animation attempts to highlight the events that led us to this place.

Pre-European Settlement Before European settlement, the Arapaho and Cheyenne migrated through the South Platte basin following game. They likely moved on each year when the South Platte's flows disappeared in late summer. And they probably dug into the sandbar aquifers to get cooler and better tasting drinking water.

1860s Individuals, some of them brought west by the Colorado Gold Rush and the Homestead Act, began growing crops. They dug ditches to divert water directly from the South Platte River and its tributaries.

1870s Then, irrigators wanted to irrigate farther from the river, requiring a larger network of ditches. The capital cost was more than one individual could bear. Where did the money come from?

- Big corporations, some from Europe—one was Traveler's Insurance Company
- Groups like Greeley's Union Colony
- Mutual Ditch Companies—groups of farmers to pooling their resources and labor

1874 There was an altercation on the Poudre River. Fort Collins farmers were upbraided by Union Colony farmers because they were taking all the river flow. Fort Collins farmers were further upstream, but they didn't get there until after the Union Colony farmers had already dug their ditches. Altercations like this led to the Doctrine of Prior Appropriation—"first in time, first in use" regardless of where you are on the river.

1876 Colorado became a state, and the Doctrine of Prior Appropriation was written into its constitution.

1890s Trans-mountain tunnels were dug to bring water from the Grand River and the Laramie River to bolster the flows of the South Platte. This was long before the bigger projects such as CB-T did the same thing in the mid 1900s.

1886 The first known irrigation well in the S. Platte basin was drilled in 1886. Mr. Hurdle, east of Eaton, used a centrifugal pump powered by a steam engine to help irrigate his farm.

1893 Mr. Hurdle's neighbor, Mr. McClellon, sued him, charging that the well pumping was affecting his ability to get his surface water. The court agreed that a well must not be allowed to injure a senior right, but Mr. McClellon still lost his suit because the court said the evidence of injury was too vague.

1900s Reservoir construction got underway—a means of storing the spring snowmelt flows. Otherwise, irrigation for the year would be over by mid to late summer. Reservoirs also opened up for irrigation a quantity of land on the lower end of the river that previously could not be irrigated.

1922 Professor Ralph Parshall published a study that showed all the surface irrigation on the South Platte was causing two significant changes: increased streamflow and an increase in the groundwater table.

1923 Colorado signed an interstate compact with Nebraska apportioning the waters of the South Platte River.

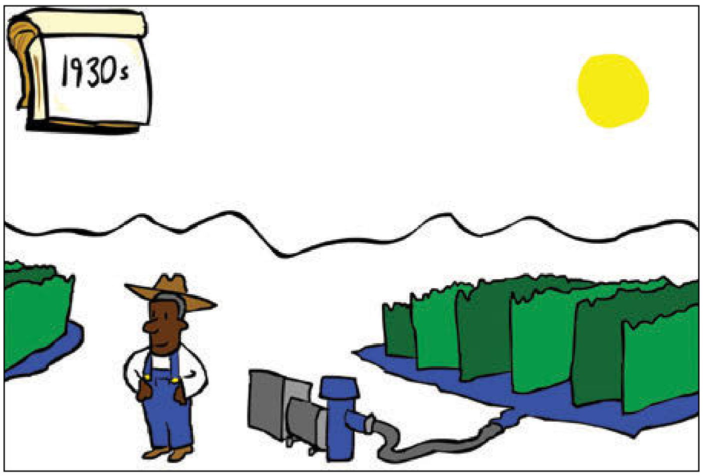


Illustration by Noah Besser

By 1930 300 high capacity wells were in operation in the South Platte alluvium.

1930s During the 1930s, an estimated 1,400 more high capacity wells were put into service, many by farmers with surface water rights who recognized that wells supplemented their surface supplies, greatly increasing reliability, especially during drought.

1940s Wells really took off in the South Platte basin because of two developments: rural electrification and the invention of the turbine pump.

1943 An irrigation engineer with joint appointments with CSU and USDA, W.E. Code, pointed out that 80 percent of the groundwater pumping at that time was being done in conjunction with surface water irrigation. He warned that legislation to strictly limit pumping could harm surface irrigators, to the overall economic detriment of the region.

1950s Another drought spurred the move toward even more wells being drilled. Drought brought low stream flows. Surface water irrigators and reservoir owners with water rights dating back to the late 1800s and early 1900s began to notice that they didn't have enough water to irrigate while their neighbors with wells COULD irrigate. Some became suspicious that wells were drawing water away from the stream.

1956 Ralph Parshall pointed out that things had dramatically changed on the South Platte. He said all the irrigation wells installed in the 30 years since his 1922 study were using up the seepage return flow that earlier had benefitted the senior direct flow and reservoir storage rights downstream.

1957 In response to complaints about wells taking water from senior surface users, the Colorado legislature passed the Colorado Groundwater Law of 1957. (This replaced their first attempt at regulating ground water in 1953.) Now you had to get a well permit from the state in order to drill a well. But the permit didn't grant you a water right. For that, you had to take your permit along with the evidence of when you first drilled your well to court, and you could get a water right with that priority date.

1965 The legislature passed the Colorado Groundwater Management Act, which gave the state engineer authority to deny a well permit application if there was no unappropriated water or if the proposed well would injure existing water rights.

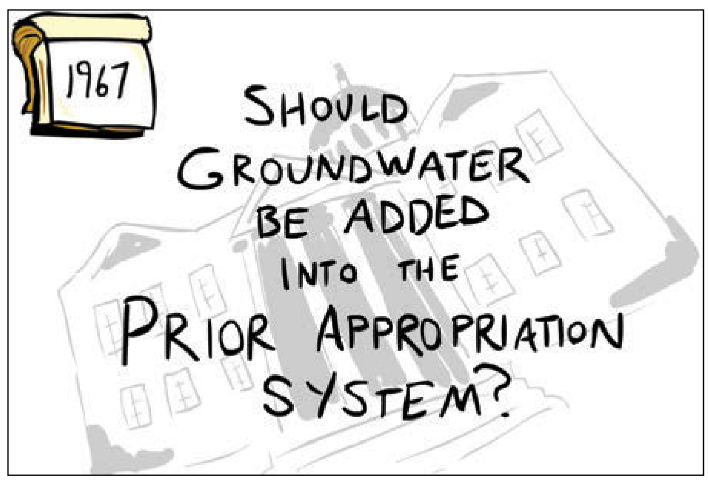


Illustration by Noah Besser

1967 The legislature authorized a two-year study to find out if legislation was needed to bring groundwater into the "prior appropriation" system.

1968 Mort Bittinger and Ken Wright conducted the study. They found that the South Platte "groundwater reservoir" contained about ten million acre-feet of water, but it was being utilized in only a haphazard and unplanned way. They said that distribution of the water in the aquifer was a problem, not the amount of water. They also found that while groundwater pumping was causing some infringement of senior rights, it was not as severe as some had thought. They pointed out that groundwater pumping was actually helping stabilize water supplies in the South Platte basin.

While it is important to recognize vested water rights of surface diverters, they said, it is also important to efficiently manage the whole water resource, both surface water and groundwater.

1968 The case of Fellhauer vs. the People came before the Colorado Supreme Court. It ruled that the state had to come up with orderly rules and regulations regarding groundwater; it couldn't just arbitrarily shut off wells to provide more water for surface users. Justice Groves brought up a new concept. He said that while it is important that we prevent injury to senior water rights, we have to also integrate into the law the concept of "maximum beneficial use."

1969 A big year for groundwater in Colorado. The legislature passed an act called the Colorado Water Right Determination and Administration Act. It is often referred to as simply "The 1969 Act."

This act said that a well user could pump water out of priority, but only if he replaced that water in time, location, and amount to prevent injury to water rights owners senior to him. The means of replacing that water became known as "augmentation." The legislation required well users to submit augmentation plans to be adjudicated by the courts.

Illustration by Noah Besser

1970s-1980s Well pumpers began to submit augmentation plans. For instance, in 1972, several augmentation plans in the Fort Morgan area were adjudicated. But many others operated under "substitute water supply plans" that the state engineer allowed. The state engineer's right to approve these temporary plans was the subject of legislation in 1974 and 1977 and became a major issue, as we will see later. Two organizations formed to help well users in the South Platte meet the new requirements. One was called GASP—Groundwater Appropriators of the South Platte. The other was formed by the Central Colorado Water Conservancy District on behalf of its members. It was called Central GMS—Groundwater Management Sub-district. Both of these organization collected dues from their members and began to find augmentation water. In some cases they bought permanent supplies, but because it was so expensive, they often leased water from those who had excess. (There was excess water to lease because these were unusually wet years.) During this time, GASP and Central GMS operated under temporary substitute water supply plans.

Illustration by Noah Besser

2001-2002 THE PERFECT STORM. Two major events happened to turn things around big time. The first event was the Empire Lodge Case. Water was a side issue in the case, but it lead to a Supreme Court ruling that the state engineer did not have the authority to issue substitute water supply plans indefinitely. Well owners must file for court adjudicated augmentation plans in order to continue the operation of their wells.

The second event was drought—big time. The biggest drought since the 1930s. Senior surface water users kept a call on the river almost constantly in 2002, 2003, and 2004, but they still received very diminished supplies. GASP and Central GMA couldn't keep up with their members' commitments because the availability of lease water virtually disappeared.

Illustration by Noah Besser

2003-2006 The "perfect storm" created by these two events—major drought and the Empire Lodge Case—resulted in tremendous upheaval on the South Platte River. Many who had relied on use of their wells to irrigate crops could no longer do so. The ensuing conflict lead to attempts to give relief to well users while protecting the rights of senior surface users. Legislation gave well users additional time to get into compliance, but the lack and expense of available augmentation supplies was a huge detriment to the continued operation of a number of wells. Protests mounted, including a big meeting in 2006 that brought Governor Ritter to Wiggins to listen to angry well users.

2007 Governor Ritter convened a neutral South Platte Wells Task Force to listen to testimony and see if they could come up with any solutions. Some testified that senior surface rights must be protected at all cost. Others argued that the level of augmentation required under the new rules was too severe, and that shutting off wells was damaging the state's economy. This polarized debate led to little change, but the Task Force did make 10 recommendations. Two of the recommendations were eventually adopted: streamlining of the Water Court to improve efficiency, and forgiveness of current depletions caused by pre-1974 pumping.

2007-Current Now we are in what we could call the "Full Augmentation Era." Though approximately 1,200 wells remain partially or fully curtailed for various reasons, many well users have found supplies to fully augment their groundwater use. One way is by purchasing surface water rights to flow into the river directly. Another way is to build recharge ponds. These are engineered to deliver water to the aquifer in a manner that replicates the time, place, and volume it would have originally reached the river through surface irrigation return flows.

2008—2012 A significant number of reports has been made of high groundwater levels causing flooding of basements and crop damage. Many believe this to be caused by excessive augmentation of the aquifer and lack of groundwater pumping. Others believe it has more to do with the high water years we have had, or that people are building new structures in areas with naturally high water tables. Some believe the partial augmentation levels achieved between 1974 and 1999 were sufficient to prevent injury, and that today's stricter requirements cause over-augmentation.

2012 The state legislature approved HB12-1278, funding the Colorado Water Institute at CSU to do a study of the situation. This is the most comprehensive study of the South Platte River basin authorized by the legislature since the study that led to the 1969 Act that brought wells into the prior appropriation system.

Illustration by Noah Besser

The HB12-1278 Study What does the legislature want this new study to find out? First, is groundwater recharge causing the high water tables, and if so, what is the remedy? Second, what have we learned from the past 45 years since we passed the 1969 Act? Is it possible that we could be employing new technologies and knowledge to manage groundwater and surface water in a way that is beneficial for both senior surface users and well-pumpers? Are our rules keeping us from using improved operation and management tools that we didn't know about when those rules were passed? Preventing injury to private property rights is critical. But could we meet the dual goals of maximizing the economic beneficial use of the whole water resource while still protecting water rights from injury?

Modeling the Influence of Conjunctive Water Use on Flow Regimes in the South Platte River Basin Using the SPDSS Groundwater Flow Model

Domenico Baú, Department of Civil & Environmental Engineering, Colorado State University

Using the South Platte Decision Support System groundwater flow model, researchers modeled 2,500 square miles of the South Platte basin with the long-term goal of evaluating the model for capabilities, strengths, and weaknesses.

The South Platte Decision Support System (SPDSS) Alluvial Groundwater Model was developed by CDM Smith on behalf of the Colorado Water Conservation Board (CWCB) during the period 2003-2013. Its main objectives included improving our understanding of the regional flow regime and providing a tool that may assist stakeholders in the evaluation and planning of water resources of the regional aquifer system. The SPDSS modeled area is around 2,500 sq. miles, and the simulation period spans from 1950 to 2006. A modified version of MODFLOW, a widely used U.S. Geological Survey finite-difference groundwater flow model, was developed by CDM Smith to simulate historical fluxes into and out of the South Platte groundwater system.

The long-term goal of this project is to provide the CWCB with an independent evaluation of the SPDSS groundwater flow model, highlighting model capabilities, strengths, and weaknesses. The activities carried out at CSU during the first year consisted of a thorough examination and visualization of the data included in the input files developed to construct the aquifer model, with comments regarding the functioning of the model.

In addition, preliminary model runs were performed to gain insight into the tool and assess its general capabilities. In these runs, the model was used to simulate some hypothetical scenarios, in which historical well extractions and injections are reduced and increased in order to verify the responses of the models for water levels, stream-aquifer intra-flux, and evapotranspiration. The goal of these preliminary runs was to assess the numerical robustness and stability of the model, as well as create expertise and provide training opportunities to improve the human capital and skills required for using the SPDSS groundwater model.

Model Input Files

Table 1 lists 14 MOFLOW input files that describe structural, parametric, and mass fluxes of the simulated region. The structural input files include the domain discretization, temporal discretization, time steps, boundary conditions, and initial boundary conditions. The input files also include information about the geometry of the aquifer (ground surface and bedrock elevations) and hydrogeological parameters (conductivity, specific storage, etc.). Water fluxes in and out of the alluvial aquifer are described by the well, stream, recharge, evapotranspiration packages.

Figure 1 shows the locations of the wells used in the model. While several wells represent actual groundwater pumping, a large portion of them is used to represent inflow or outflow from the Denver Basin aquifers that constitute the bedrock base for the alluvium. Another relatively large number of wells is also used to represent prescribed lateral-flow boundary conditions. The total number of wells activated varies over stress periods, but remains relatively constant. For example, the number of wells activated for the last stress period (December 2006) is equal to 52,363.

While lumping together actual groundwater well pumping, flux exchange across the bedrock, and lateral flow boundary conditions does not affect the accuracy of the model, it may limit the ability of other users to modify the input files, for example to simulate different management scenarios of well pumping. In addition, such a practice makes it difficult to interpret mass balance results.

The map presented in Figure 2 shows the location of injection, extraction, and inactive wells in the month of June 2006. From Figure 2, it possible to observe that the Denver aquifer withdraws water from the alluvium, while water is provided to it through most of the lateral boundary. Figure 3 provides a map of the basin with the location of the monitoring wells mentioned above.

Output Files

Table 2 lists six MODFLOW output files that describe the SPDSS groundwater model results, which include spatial-temporal groundwater level distributions, cell-to-cell water budget and mass fluxes in and out of the region, and stream stage at each reach. A post-processing step is required to analyze the cell-to-cell budget file in order to summarize system mass balance at each time step. The prescription of the output data to be printed out is controlled using the P5_tr.oc file. In particular, this file specifies the times at which the output is saved and the format, either binary or ASCII, with which it is produced.

Simulated Mass Balance

The model output provides a cell-to-cell flow budget for all prescribed stress periods. These results demonstrate that the numerical solution obtained by MODFLOW is globally accurate. The most important observation that can be made from the mass balance output relates to the components of aquifer recharge, aquifer discharge into the stream network, and extraction wells. In general, aquifer recharge progressively increases through the growing season, and aquifer discharge into streams is shown to decrease until the month of June and increase in the second half of the year. These results can be explained by observing that there is a gradual increase in well extraction rates during the growing season. However, this is a qualitative conclusion, since well extraction accounts not only for groundwater pumping, but also for exchange flows of water with the aquifer across the lateral boundary and the portion of the lower boundary where it connects with Denver Basin's bedrock aquifers.

Data included in the file P5_tr06.ccf have been used to derive time-series profiles for the period 1950-2006 on the water budget components. These "hydrographs" are compared to the corresponding results obtained under different conditions of well pumping.

Scenarios for Modified Well Pumping Conditions

To test the numerical stability and robustness of the SPDSS groundwater model and, at the same time, gain insight into its ability to simulate changes in hydrological and anthropogenic stress conditions, a number of additional hypothetical simulation scenarios are considered. In these scenarios well injection and extraction rates as prescribed in the baseline simulation are modified by: reducing extraction rates by 20 percent (Scenario 1); increasing extraction rate by 20 percent (Scenario 2); reducing injection rates by 20 percent (Scenario 3); and increasing injection rates by 20 percent (Scenario 4). These hypothetical scenarios are thus compared to the baseline conditions. In Scenario 1, where well extraction rates are reduced by 20 percent (see the green-line profiles), there is an overall increase in aquifer storage, along with an increased flow out of the aquifer across general boundary condition grid cells. Recharge volumes do not change since in these simulations, recharge conditions are left unchanged and therefore are not affected by varied conditions of pumping. The volume of water discharged from the aquifer in the stream network is decreased.

Table 1. *Input Files for the SPDD groundwater model*

No.	File Type	File Name	Description
1	DIS	P5_tr_mod_20100729.dis	Discretization package
2	HED	P5_tr06_stable.hed	Initial head file
3	BA6	P5_tr.ba6	Basic package
4	LPF	P5_tr_run.lpf	Layer property flow package
5	SFR	sfr_output_tr_por_20110608_90ke.sfr	Stream flow package
6	WEL	P5_SPDSS_TR_WEL_MODFLOW_20100812_por_mask_s5.wel	Well package
7	OC	P5_tr.oc	Output control package
8	RCH	RCH_Full_POR_20090428.rch	Recharge package
9	PCG	P5_tr.pcg	Preconditioned conjugate gradient solver
10	GMG	p5.gmg	Geometric multigrid solver
11	GHB	P5_tr_20110616.ghb	General head boundary package
12	ETS	output_ets_50_to_06_20111219.ets	Evapotransportation package
13	GGE	gage_20100521.gge	Stream gage locations
14	HOB	HOB_clean_valid20110606.hob	Head observation package

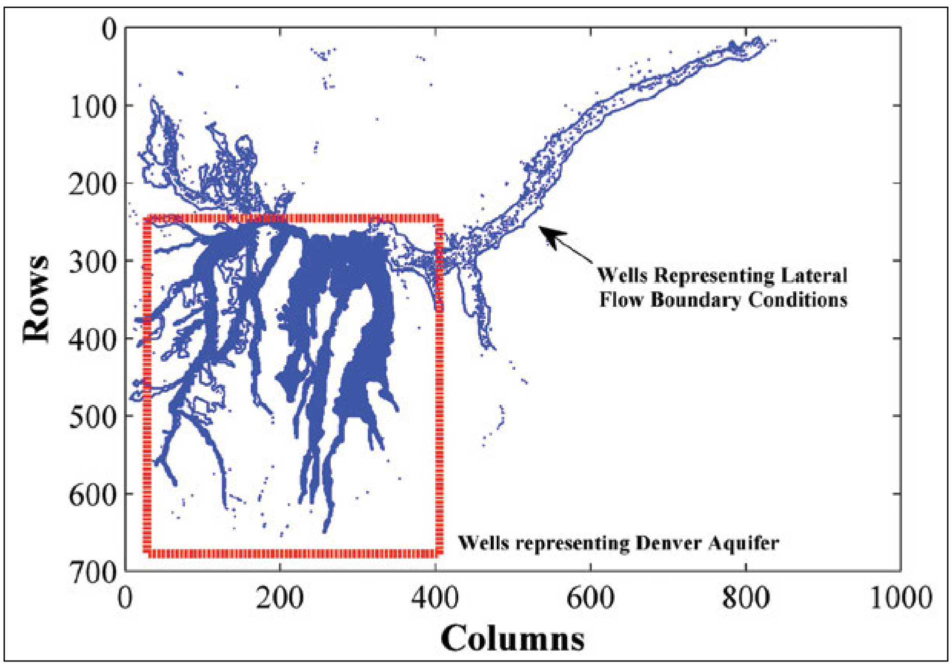


Figure 1. *Wells Locations and Boundary Conditions*

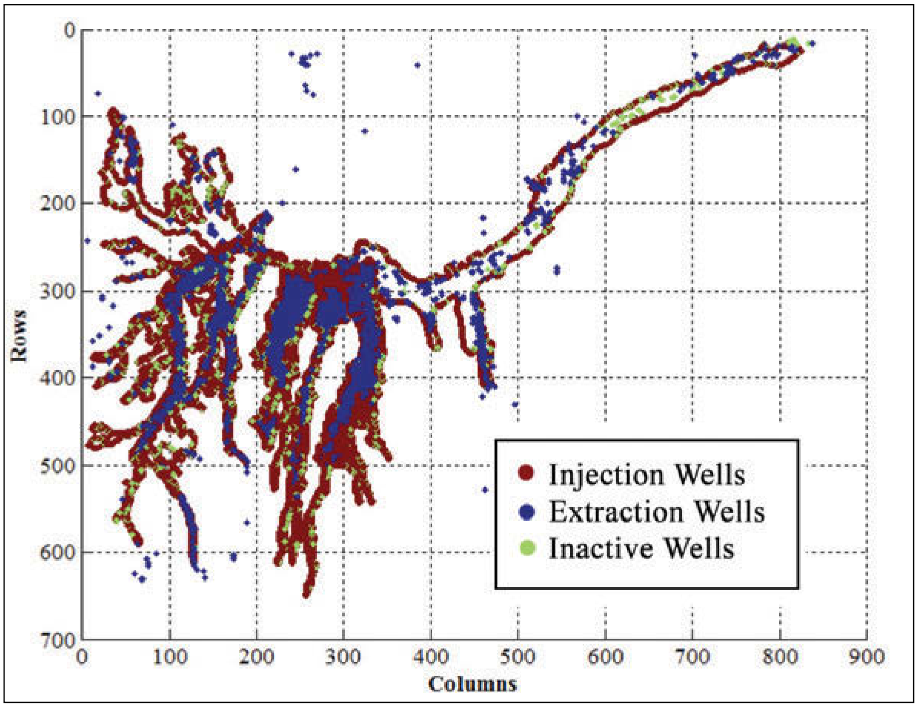


Figure 2. *Location of injection, extraction, and inactive wells as of June 2006*

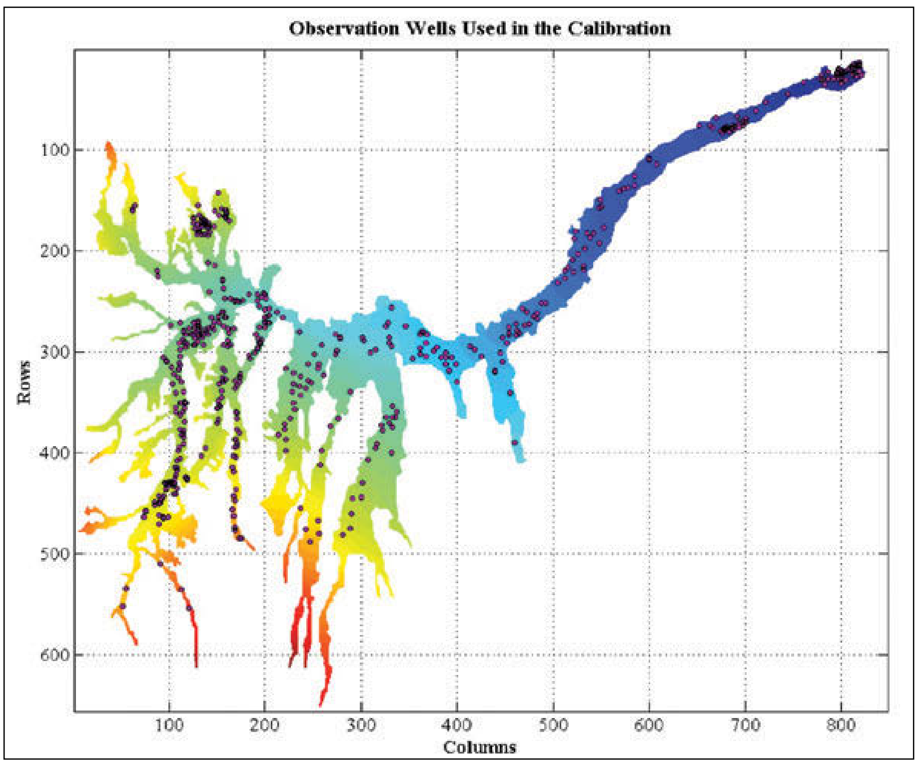


Figure 3. *Location of observation wells used in the calibration*

Table 2. *Output Files produced by the SPDD groundwater model*

No.	File Type	File Name	Description
1	GLO	P5_tr06.glo	Global file
2	HED	P5_tr06.hed	Simulated head
3	CCF	P5_tr06.ccf	Cell to cell budget
4	DAT	P5_tr06_stream.dat	Stream flow output
5	SG1	gage_tr06_out.sg1	Stream flow downstream end
6	SG2	divert_tr06_out.sg2	Stream flow downstream end

Evapotranspiration volumes increase slightly with respect to the baseline conditions (blue-line profiles). Most of these results can be explained in terms of an average increase of the water table elevations. Only the decrease in the water globally discharged from the aquifer into streams network is difficult to justify. In this case, a more thorough spatial analysis of the components of the mass balance is necessary and likely to explain these results.

When compared to the baseline condition, Scenario 2, which is characterized by well extraction rates increased by 20 percent (see the green-line profiles), shows results that are substantially opposite to Scenario 1.

In Scenario 3, where well "injection rates" are reduced by 20 percent (see the pink-line profiles), the overall volume extracted through pumping units (actual wells, lateral boundaries, and bedrock aquifers) is highly reduced. Globally this produced a small decrease in groundwater storage. The volume of water lost through general boundary condition grid cells is decreased. The volume of water discharging form the aquifer into streams decreases significantly, and evapotranspiration losses are reduced. These results can be explained in terms of an average decrease of the water table elevations. When compared to the baseline condition, Scenario 4, which is characterized by well "injection" rates increased by 20 percent (see the black-line profiles), shows results that are opposite to Scenario 3.

The purpose of these simulations is to gain familiarity with the SPDSS groundwater model and verify its capabilities in terms of providing results that can be well understood and foreseen, from a perspective of global mass balance. It is however important to emphasize that the results presented in the above scenarios are valid only within the context of groundwater model. In reality, changing the well flow rates cannot be done without affecting the conditions of aquifer recharge, since usage of water resources is highly dependent on water availability and strictly regulated by water rights.

Overall, the results obtained from this set of simulations with modified pumping scenarios indicate that the SPDSS groundwater model is numerically robust and provides results that can be explained in terms of a basic application of the mass balance equations.

Model Calibration

Based on information provided by CDM-Smith, the SPDSS groundwater model was initially calibrated under steady-state conditions using field observations available for the period 1991-1994. The calibration was then refined under transient-state conditions using field data collected between 1999-2005. In both phases, calibration was performed automatically by combining the MODFLOW code with the optimization package PEST. Finally, the model calibration was fine-tuned manually to resolve numerical issues associated with the occurrence of dry cell conditions and ultimately provide a better matching between simulated variables and observed variables. Field data used in the calibration included head observations, stream gauge readings, and remote sensing based estimations of ET. Based on the SPDSS model files, it was possible to retrieve the head observations (file HOB_clean_valid20110606.hob), as well as stream flow data at the downstream end of the SPDSS groundwater model domain (files gage_tr06_out.sg1 and divert_tr06_out.sg2). ET satellite data were not made available in the files.

The parameters that were calibrated included the hydraulic conductivity field and the bed conductance spatial distribution. Since the number of active cells is large, it is computationally prohibitive to calibrate the conductivity field directly. Therefore a pilot method was used, in which the hydraulic conductivities at 270 points were used as the target parameters of the calibration. The hydraulic conductivity field was then estimated by spatial interpolation of the pilot point conductivity values. In this interpolation, only points within a specified zone were used. For this purpose, the aquifer domain was subdivided into 16 zones. It is not possible to make any conclusions on this approach since it was not specified how these zones were delineated.

All together, the calibration process required the estimation of a total number of at least 270 parameters. Although the range of variability of each parameter was somewhat constrained using the interpolation technique mentioned above, the number of parameters seems quite large. In these conditions of over parameterization, the calibration procedure is typically affected by problems of non-uniqueness of the solution. Such calibration procedures are widely accepted and used in the standard practice. However, they do not exclude the existence of other parameter sets that can make the model reproduce the observed data with the same accuracy.

What Knowledge Can Be Gained?

It is very important to highlight that the SPDSS groundwater model simulates water flow over a very large area and over a particularly long period of time. A regional model of this size is rarely found in the literature. In our opinion, the size of the grid cell that forms the SPDSS model is such that it cannot be used to represent water flows at the local scale with accuracy, but can be fundamental to gaining insight into the water regimes and balances at the regional scale. While imitating reality for small-scale models is also difficult, the predictive ability of large-scale models is influenced by uncertainties due to the high degree of heterogeneity and complexity of the systems and the hydrological processes. Ideally, the principle of parsimony is in favor of simplified models, in which the majority of systems' uncertainty can be attributed to few parameters. However, oversimplified models are also limited in their ability to give reasonable answers. In summary, we consider the SPDSS groundwater model an important start for a continuous effort toward effective management of water resources in the South Platte.

A realistic approach to construct reliable regional groundwater models is to deal with them as evolving tools that simulate and explain the dynamics of the hydrologic system. These tools should be flexible enough to receive continuous updates and improvements to cope up with new data and observations and reduce model uncertainties. In our opinion, the SPDSS groundwater model is a valuable tool for regional water management but will need constant upgrading as new data are collected and made available. These data should be adequate for the scale of the model. For example, an interesting approach for further validation of the SPDSS model would be to integrate in it remote sensing measurements, such as GRACE data, which can provide monthly estimates of regional changes in subsurface water storage.

One another possible application of the SPDSS model is to provide a base for the development of "child" models, that is, local models characterized by a much higher level of resolution that can be used to understand with more detail the interrelations between water use, groundwater storage and stream flows in any particular area of interest within the SP River Basin. These child models, which would not be any less complex than the full-scale model, could be coupled to the regional SPDSS groundwater model and together would form a modeling framework that could be used to manage groundwater resources both at the regional level and at the local level.

Research Team Members

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Groundwater Levels
Historically and Now

Panagiotis Oikonomou, PhD Candidate,
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The HB1278 study utilized publicly available data from six groundwater observation networks that are currently active in the basin. Wells were included that had a consistent record of measurements in the time period of 2000-2012 and at least one measurement in the last two years. The data show more increasing water levels over the recent decade than declining water levels. Future data collection will verify whether the trend will continue, or whether the levels have reached new equilibrium.

Aerial view of the Riverside Canal on the South Platte River east of Kersey, Colorado.
Photo by Bill Cotton

Introduction

The South Platte River basin, as other basins in semi-arid parts of the world, has undergone a huge transformation due to land use change, agricultural development and population increase. The spread of irrigated agriculture that started around the late 1870s and the development of the required infrastructure (ditches, canals, reservoirs, etc.) as well as the transbasin water importations that augmented and stabilized the water supply, converted the ephemeral South Platte River, which often run dry during late summer, to a perennial one.

Water management of the basin has changed through the years. There are three major water management eras: 1) from the 1930s to 1972, where significant volumes of groundwater were pumped without augmenting the depletions; 2) from 1972 to 2002 where the depletions were partially augmented, as many wells operated under Groundwater Appropriators of the South Platte (GASP) and Central Colorado Water Conservancy District (CCWCD)'s substitute water supply plans (SWSPs); and 3) from 2002 till today, with full enforcement of augmentation of depletions and curtailment of wells lacking court adjudicated augmentation plans following the Empire Lodge Case and the drought of 2002. This of course affected the alluvial's aquifer levels, since the natural seasonal hydrologic patterns were disrupted. The ability to detect and interpret changes in groundwater levels is essential for sustainable use of groundwater resources but also critical for efficient and effective integrated surface water and groundwater management.

Previous Groundwater Studies

USGS Water Supply Paper 1378 (1957) mapped groundwater levels in basin. The study began in 1947 and was published in 1957 using data derived from 189 observation wells, 62 of which were from the CSU network established by W.E. Code. Drilling logs were obtained for 1,767 additional existing wells. Water Supply Paper 1378 reported that the alluvium varies in thickness from a foot at the edge of the valley to 293 feet deep.

The Bittinger Wright 1968 progress report stated (on page 28) that long-term observation well records collected by Colorado State University (CSU) show a stable water table over the 35-year period from 1933 to 1968. The typical annual cycle of fluctuation observed was such that the water table was generally at its highest in the fall and lowest in the spring. Wright concluded this pattern indicated that surface water additions from ditches, reservoir, and fields during irrigation season exceeded net withdrawal of water through wells at that time. During the winter, the river serves as a drain, lowering the water table built up during the previous crop season.

Active Observation Well Networks

The HB1278 study utilized publicly available data from six groundwater observation networks that are currently active in the basin (Figure 1). These include: CCWCD, CSU, Colorado Division of Water Resources (DWR), the Lower South Platte Water Conservancy District (LSPWCD), S. Platte Decision Support System (SPDSS), and USGS National Water Quality Assessment (NAWQA). Data were obtained from each of these networks and checked it in detail to determine if there were missing values, duplicates, or values that needed verification.

While the spatial extent of the observation wells in the six groundwater level monitoring networks covered the mainstem of the S. Platte, they were not aligned temporally in terms of the period of record nor the number and frequency of observations, making it difficult to easily draw inferences across the six networks. Additionally, the network had data gaps (some very large) as well as missing and duplicate observations that had to be reconciled. Only the irrigation wells in the CSU, DWR, and CCWCD networks had records that reached back prior to 1969. Irrigation wells provide the least reliable data, particularly when sampled only once or twice a year, as individual observations are likely to be skewed by recent pumping, recovery, and recharge. In spite of these limitations, the six observation networks provide valuable data on water levels in the basin over time (Table 1).

Methods and Procedures

As part of the HB12-1278 Study, it was attempted to analyze each set of data for recent trends to address the question of whether recent changes in surface and groundwater management were indeed driving groundwater levels upwards. A preliminary approach to investigate possible groundwater level changes

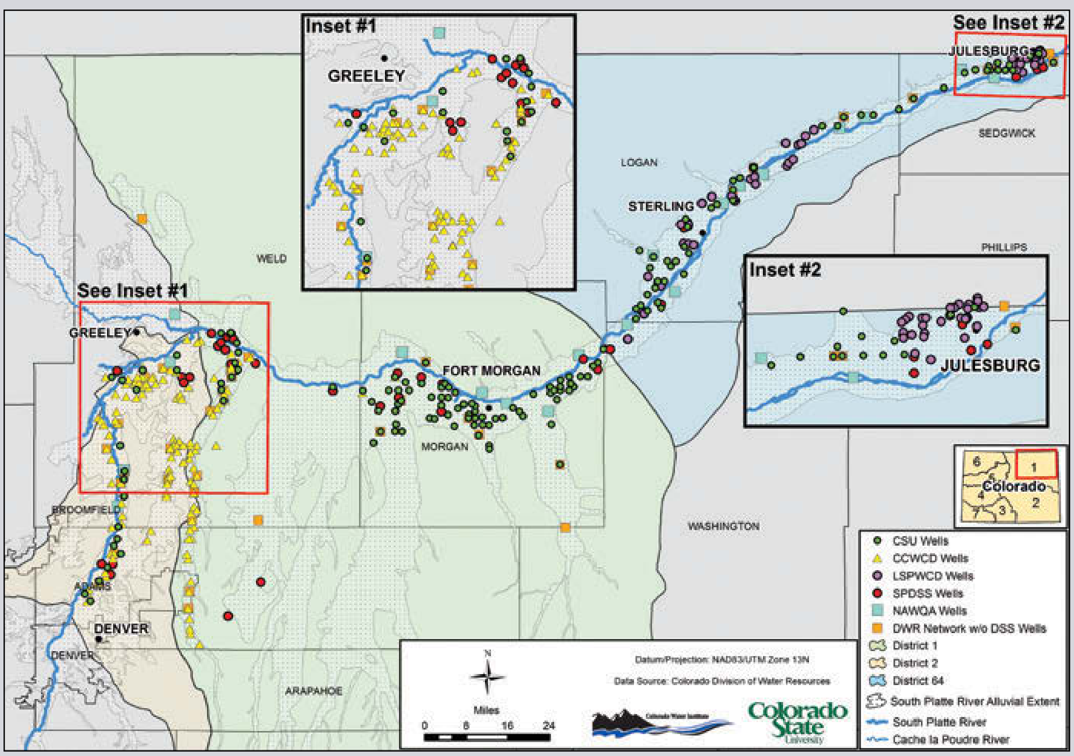


Figure 1. *Observation & Monitoring Wells of the South Platte River Alluvial Aquifer*

Table 1. *Composition of well types of the six observation networks.*

Network	Well Type				Total
	Irrigation	Monitoring	Recharge Monitoring	Unknown	
CCWCD	138	16	-	-	154
CSU	150	-	-	-	150
DWR	54	4	-	-	58
LSPWCD	19	26	20	17	82
SPDSS	-	38	-	-	38
USGS-NAWQA	-	19	-	-	19
Total	361	103	20	17	501

in the S. Platte was to investigate for monotonic trends in the observation well data that had been collected from HydroBase (version 20130710) and S. Platte water agencies. The wells investigated for trends are part of five major networks, including the CCWCD network, the LSPWCD network, the DWR network, and the CSU network. The USGS NAWQA network of 19 dedicated monitoring wells was installed in 1994 for the South Platte NAWQA, but given the incomplete period of record for these wells, these were not included in the analysis.

The wells that were included in the analysis were those that had a consistent record of measurements in the time period of 2000-2012 and at least one measurement in the last two years. The data do not allow for a longer period of analysis due lack of systematic measurements during earlier years.

Analysis was performed based on bi-annual (spring and winter) data for CCWCD, DWR, and CSU networks and monthly measurements for SPDSS and LSPWCD networks in order to determine if long-term systematic trends existed by utilizing the non-parametric Mann-Kendall (Kendall 1975; Mann 1945) test with a significance level of five percent. It was decided to keep the monthly time-series for SPDSS and LSPWCD so as not to lose important information by degrading them into bi-annual. A non-parametric trend test was chosen because the data are not required to follow a normal distribution. The other assumption that Mann-Kendall test requires is that the data not be serial correlated. Serial correlation can influence the accuracy of the Mann-Kendall test resulting in statistical errors (Wang et al. 2005). If the data are not independent, then the results of the Mann-Kendall are not accurate, resulting in statistical errors. As Wang and Swail (2001) have shown, prewhitened data reduces the magnitude of trend. The method used to avoid this problem was proposed by Zhang et al. (2000) and refined by Wang and Swail (2001)and gives almost unbiased estimates of lag-1 autocorrelation coefficient and slope.

Results

Although each observation well network has its own limitations, we attempted to analyze each set of data for recent trends to address the question of whether recent changes in surface and groundwater management were indeed driving groundwater levels upwards, as was required under HB1278. First, it is important to determine if there are statistically significant trends in water table levels.

The CCWCD observation network included a total of 154 wells, but 18 wells were excluded from our analysis because they did not have any measurements the last two years (2011 or 2012). We used a time series of two measurements per year, and the average percentage of missing measurements in the 136 remaining wells was about 32 percent. Our evaluation indicated that of the 136 wells, 69 wells had no statistically detected trend, 12 wells had a significant decreasing trend (p-value five percent) and 55 wells had a significant rising trend (p-value less than five percent). Thus, for the CCWCD network, 40 percent of the wells showed a rising trend over the past twelve years while half showed no statistically significant trend.

The DWR observation network contains 58 wells, but only 42 wells were used in trend analysis for the period of 2000-2012. Sixteen wells were excluded because they did not have measurements for the last two years (2011 or 2012). Again the time series used had two measurements per year, and the average percentage of missing measurements in the 42 wells was 22.5 percent. Of the 42 wells tested, 26 wells had no statistically detected trend, two wells had a significant decreasing trend (p-value five percent), and 14 wells had a significant rising trend (p-value less than five percent). Thus, for the DWR network, 33 percent of the wells show a rising trend, and 62 percent show no detectable trend for the past twelve years.

The CSU observation well network is the oldest of the six networks, containing 150 wells, but it also has some of the most significant data gaps. Of the 150 wells, only 81 were used in the 2000-2012 trend analysis (2000-2012) due to the gaps in the data. The time series used had two measurements per year and the average percentage of missing measurements in the 81 wells was 68.5 percent. A majority of the CSU wells have a measurement gap from winter 2003 till spring 2009, making our statistical analysis much less powerful. Due to these data gaps we found that 79 of the 81 wells showed no statistically detected trend and only two wells in this network could be shown to have a statistically significant rising trend (p-value less than five percent) for the past twelve years.

The LSPWCD observation network in Logan and Sedgwick Counties has a total of 33 wells. We were able to construct a time series for 2002-2012 for 31 of these wells. Two wells were excluded because they did not have any measurements over the last two years (2011 or 2012). Note that we could not begin this time series with the year 2000 as the wells did not have observations prior to 2002. This resulted in a time series that started and ended with drought. The time series for the wells included had 12 monthly measurements per year with an average of 8.7 percent missing measurements in the 31 wells. Of the wells included, six wells had no statistically detected trend, no wells showed a significant decreasing trend (p-value five percent) and 25 wells had strong significant rising trend (p-value less than five percent) for a total of 80 percent of the wells showing a rising trend. Caution is warranted in this evaluation as the data show that shallow observation wells in the basin react quickly to drought and 2002 is a low point in most of the recent data. The wells in Pawnee Ridge, LWU, and LLWU were not used in the analysis due to their short temporal span of measurements.

For the analysis of the SPDSS monitoring wells we utilized 36 of the 38 wells, excluding two wells from the analysis for the period of 2003-2012 because they did not have complete data for the last two years (2011 or 2012). The time series used 12 monthly minimum measurements per year, and the average percentage of missing measurements in the 36 wells was 24.2 percent. Twenty-four wells had no statistically detected trend, while three wells had strong significant decreasing trend (p-value five percent) and nine wells had strong significant rising trend (p-value less than five percent), for a total of 25 percent of the wells showing a rising trend (Figure 2).

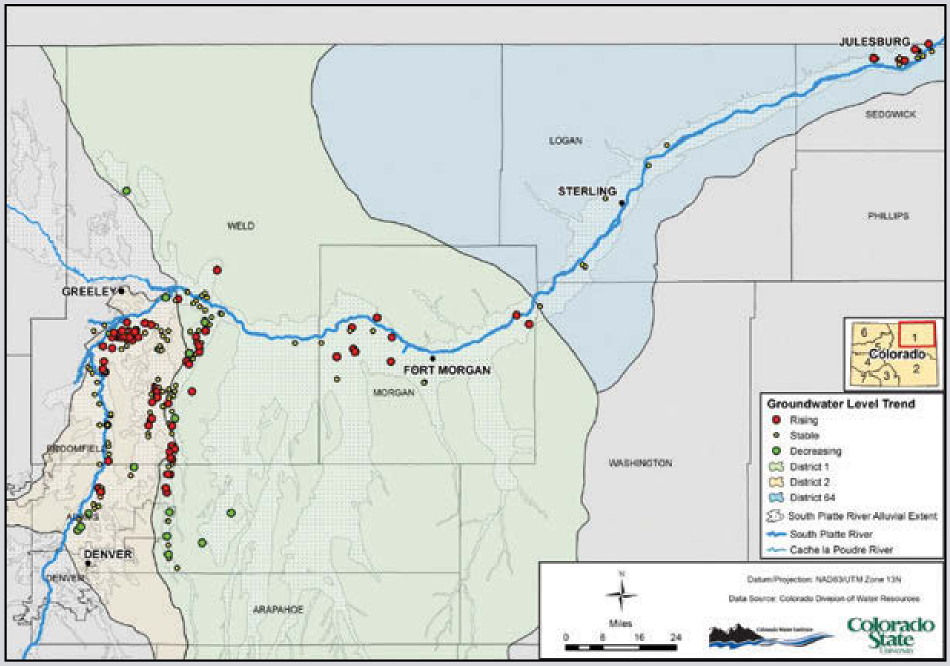


Figure 2. *Groundwater Depth Trends Over 2000-2012 for Observation Wells with Complete Records for the Period, where red dots indicate rising water levels over the past decade.*

Discussion

Localized high groundwater levels have been reported in the basin going back to the early 1900s and at one time, there were drainage districts in the South Platte to keep fields from waterlogging. Both the DWR and CSU networks, which overlap to a significant degree, contain the longest record of water table levels and thus provide information over a longer period of groundwater development and administration. In looking at water levels going back to the 1920s, 1930s, and 1940s before extensive development and pumping occurred in the basin, it is clear that high groundwater levels existed at that time after some 50-70 years of surface water development.

The 2012 drought provided a valuable observation year for the HB12-1278 study, as many observation wells showed a decline that year and did not continue the rising trend observed over the past decade, indicating that unusually large lagged return flows from post-2005 administration were not in transit back to the river or to unfortunate homeowners' basements, at least on a regional scale. Some wells show that water levels have risen within ten feet of the ground surface, a point at which non-beneficial evaporative up-flux can occur, waterlogging soils and causing salinization. On the whole, the majority of the observation wells either did not have an adequate data record or there was too much noise in the data to detect a statistically significant trend. However, there are a much greater percentage of the 326 observation wells, used in the trend analysis, showing increased water levels over the recent decade rather than declining water levels. This is not surprising, as we know this period started at a drought induced low point and that pumping decreased significantly while recharge increased significantly. More time and more data will be needed to verify if this trend results in the establishment of a new post-2002 equilibrium, or whether this upward trend will continue.

Groundwater Use and Augmentation

Reagan Waskom, Director, Colorado Water Institute

The HB1278 study evaluated groundwater pumping and consumptive use in the South Platte basin and found seasonal and long-term variability due to improvements in irrigation, changes in augmentation requirements, and other environmental factors. The changes in administration of wells have also led to increases in augmentation amounts over time.

All groundwater in the South Platte basin that is not either designated basin groundwater or Denver Basin groundwater is presumed to be tributary groundwater, in direct hydraulic connection to the surface stream system. Prior to 2003, an average of nearly 500,000 acre-feet (AF) of groundwater was pumped annually in the S. Platte basin from approximately 8,200 high capacity wells. Agricultural pumping between 1950-2000 was calculated to average 438,000 AF/yr with municipal and industrial pumping growing to approximately 50,000 AF/yr during this same period. There are now approximately 6,500 high capacity wells in the basin and total annual groundwater pumping in the basin is now closer to 450,000 AF/yr, with agricultural pumping in the 400,000 AF/yr range. Central Colorado Water Conservancy District has approximately 1,200 wells in the WAS and GMS plans that are on a quota system and not able to pump anywhere near 100 percent of full crop ET (GMS quota has been about 35 percent since 2006; WAS quotas have been even less). Most of the other irrigation wells in adjudicated augmentation plans have full or near full allocations in most years. While rules now require well owners to meter and provide pumping records, it will likely be several years before we have accurate accounting of well metering records to determine exactly how much individual wells are pumping and how much water is extracted from the various reaches of the alluvium in the basin.

For the purposes of augmentation plans, two methods are generally used to determine the amount of stream

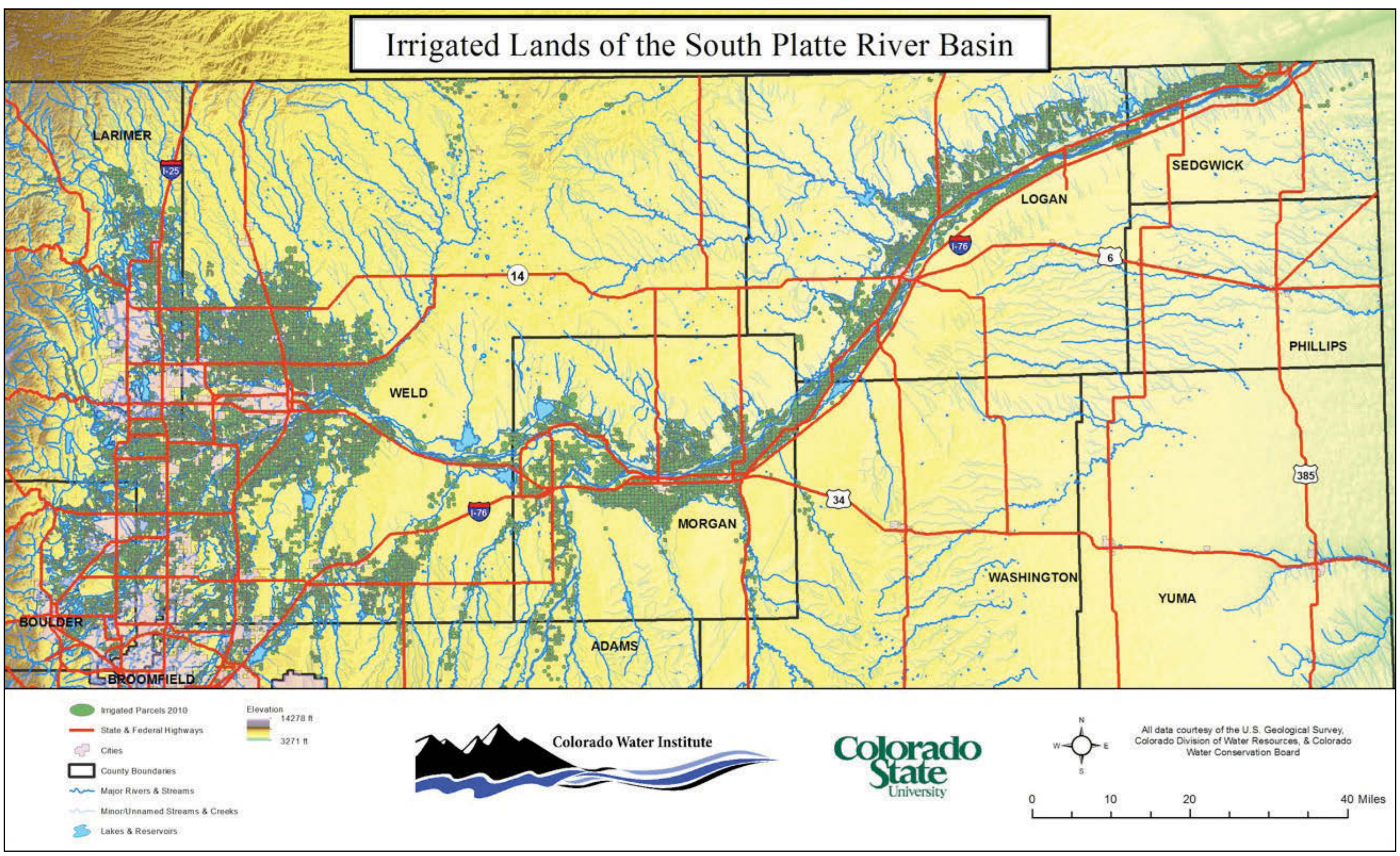


Figure 1. *Irrigated lands in the S. Platte basin of Colorado.*

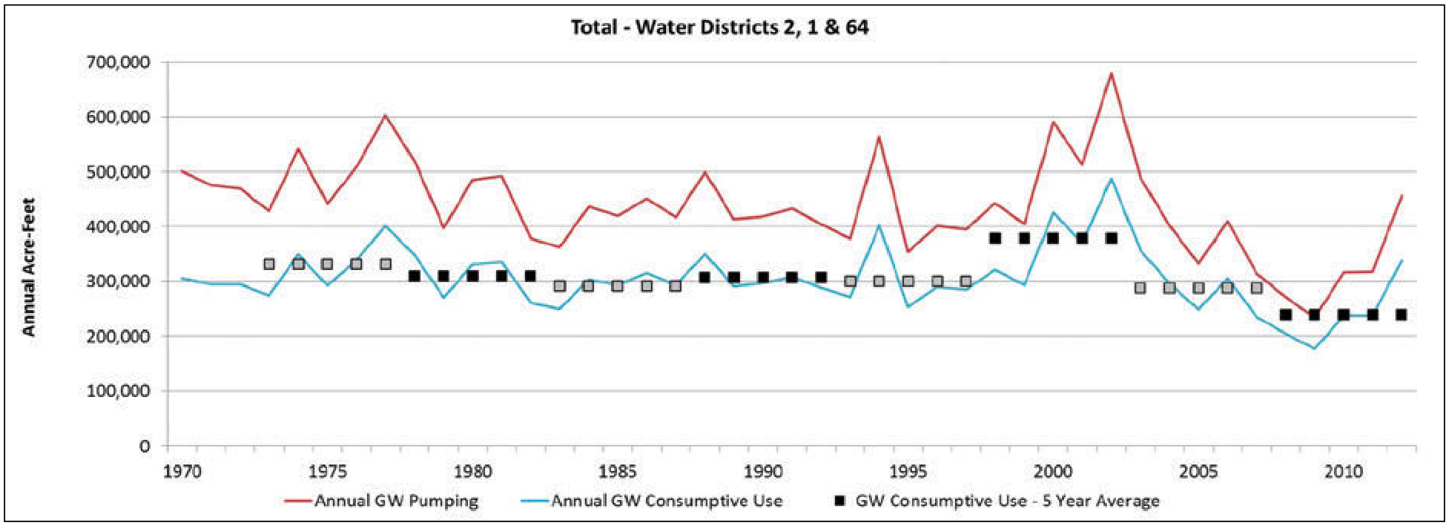


Figure 2. *Total Estimated Annual Pumping and Groundwater Consumptive Use in Water Districts 2, 1, and 64. Data Source: CO DWR HydroBase Version 20130710.*

depletion caused by well pumping: 1) crop potential consumptive or 2) presumed depletive factor (PDF). The most commonly used method for estimating stream depletion is the PDF. In this method, well volume is recorded or calculated, and a specified percentage of that pumping is assumed to be consumptively used by the crop depending upon irrigation method (and hence the streamflow depletive amount). In most plans, sprinkler irrigation is assumed to have an 80 percent PDF, and surface irrigation is assumed to have a 60 percent PDF.

The amount, timing, and location of stream depletion due to pumping depend on proximity of the well to the stream, the pumping rate and duration, the direction and rate of groundwater flow, the amount of groundwater recharge, and hydraulic properties of the aquifer. Whether a pumped depletion causes injury depends on if it impacts the stream while under administration and if senior diverters are thereby shorted by the out-of-priority pumped depletion.

The method used for our analysis for estimating agricultural pumping where groundwater is the sole source is based upon crop consumptive use and an estimation of irrigation efficiency using 80 percent for sprinkler irrigation and 60 percent for flood irrigation. The average annual agricultural pumping demand for the period of 1991 to 1994 is estimated at 432,838 AF per year. Annual pumping rates are known to vary as a function of streamflow, precipitation, and ET; thus, modeled estimates attempt to incorporate these variables. Well curtailments since 2005 have resulted in agricultural pumping somewhere in the neighborhood of 400,000 AF for Division 1, as estimated by the Division 1 Engineer. Pumping rates for agricultural wells ranges from zero during the non-growing season months, generally November through March, to peak values in July of each year. Annual agricultural pumping values range from 176,000 AF in 1951 to 714,000 AF in 2002 in Division 1. The month of July has the highest average pumping rate, at 127,000 AF, followed by August, June, and September.

Irrigated lands have decreased in the S. Platte basin since reaching a peak of slightly over one million acres in the mid-1970s to approximately 830,000 acres presently (Figure 1). Much of this loss of irrigated lands is a result of urban growth over agricultural lands along the Front Range/I-25 corridor, but some of it can also be attributed to the purchase of senior agricultural surface water rights and the subsequent dry up of these lands.

We estimated pumping amounts based on crop irrigation water requirements plus an on-farm application efficiency value associated with flood and sprinkler application methods less any surface water supplies, as estimated by the StateCU analysis developed for the SPDSS (Figure 2). The difference between pumping and consumptive use reflects the portion of pumping that is not consumed by the crops and therefore returns to the river or aquifer. The difference between annual pumping and consumptive use generally decreases over time, reflecting the gradual increase in sprinkler irrigation over the past several decades.

Annual variability of the pumping volumes can be attributed primarily to varying climate conditions, plus some changes in irrigated acreage. The variability and increased pumping for the 2000 through 2012 average seen in Water District 64 can be attributed primarily to climate variability. The greatest pumping and consumptive use occurs in Water District 1, which correlates with the large amount of acreage served only by groundwater in that district. Reduced pumping in Water District 2 after the 2002 drought occurred because many wells were not fully covered under augmentation plans and were forced to reduce pumping. Water District 64 has the most recharge and surface augmentation sources, and increased pumping reflects limited surface water

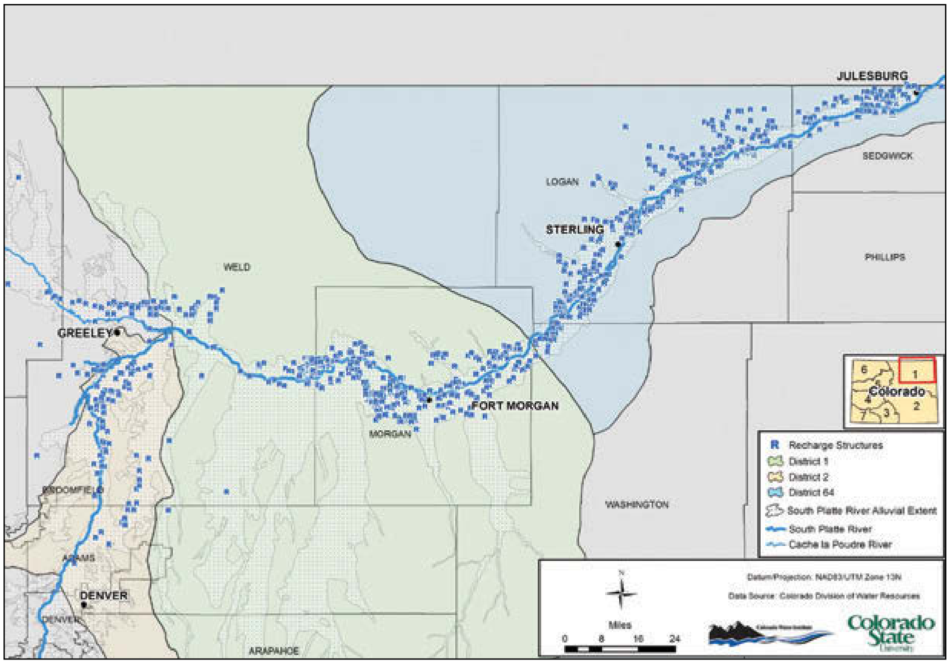


Figure 3. *Location of existing recharge structures in the S. Platte basin. Data Source: CO DWR HydroBase Version 20130710.*

due to drier conditions. It is important to note that consumptive use values shown in these graphs do not take into account the lagged depletive impact at the river. Five-year averages are used to smooth out the data and indicate the effect of lagged depletions. Note that groundwater pumping has shown an increase since 2009 as additional augmentation supplies have been acquired and adjudicated.

Augmentation

Plans for augmentation allow diversions of water out-of-priority while ensuring the protection of senior water rights. Decreed water rights receive a replacement water supply that offsets the out-of-priority depletions caused by well pumping. Replacement water can come from any legally available source of water, such as mutual ditch company shares, reservoir storage releases, successive use of transbasin water, nontributary water, augmentation wells, and/or artificial recharge of aquifers to generate augmentation credits. Where surface water is fully appropriated, Colorado law presumes that groundwater depletions through well pumping will result in injury to senior appropriators absent a showing to the contrary. The S. Platte basin is fully appropriated and thus the presumption of injury accompanies all out-of-priority depletions by tributary wells.

Elements of a well augmentation plan typically include:

- Accounting of river depletions in time, amount, and location due to well pumping
- Replacement/augmentation sources for all injurious depletions
- The plan for operation of augmentation water to cover depletions

The most cost effective method of augmentation is to develop recharge structures that can take surface water during times of free river and allow the water to seep into the aquifer and back to the river. These structures may be ponds, unlined ditches, or low lying areas that overlie the alluvium and are hydraulically connected to the river, are permeable, and have enough unsaturated material above the water table to allow recharge. The goal is to time the recharge so that it will flow underground back to the river coincident with the timing of injurious well depletions hitting the river. The returned recharge water is then available to senior surface water rights in lieu of the river baseflow that was taken out-of-priority by well pumping. The accuracy of calculating the timing of this recharge water return flow to the river is important, as it determines whether the recharge suitably replaces water in the river at the time it is needed by senior water rights.

The most common approaches for estimating the effects of groundwater pumping on streamflow are the Glover solution (Glover and Balmer, 1954), the stream depletion factor method (Jenkins, 1968; Hurr and Schneider, 1972; Schroeder, 1987), and numerical methods such as MODFLOW (McDonald and Harbaugh, 1988). While these analytical methods have been widely accepted in water rights cases, it is recognized that they simplify physical conditions such as vertical and horizontal aquifer properties (Fox et al., 2002; Miller et al, 2007). Despite recent advancements in numerical solutions for stream depletion analysis, it is likely that the established Glover methods will continue to be widely used in existing and new augmentation plans, particularly as they are accepted by both the court and opposers.

Augmentation plan decrees typically specify an assumed period of senior call that must be protected from injury, often for the duration of the irrigation season. The plan may also be required to demonstrate that depletions from irrigation, augmentation, and recharge wells can all be replaced, if necessary, for the entire year. Plan operators are required to submit monthly reports of their daily depletion and accretion accounting to the Division Engineer. Net out-of-priority well depletions are calculated by multiplying the sum of net depletion by the percentage of time the wells were out-of-priority. Shortfalls in accretions to cover net depletions necessitate replacement with alternative augmentation water or curtailing well pumping to the extent needed to avoid a deficit. Augmentation plan operators are bound by the terms and conditions of the decree, and the Division Engineer has the nondiscretionary responsibility to enforce the terms and conditions of the decree upon the wells and the lands included in the decree, as well as the successors and assignees, until all obligations under the decree have been fulfilled.

Augmentation supplies can be divided into two general categories:

- Recharge Augmentation Supplies include water diverted for in-ditch recharge or to recharge ponds. The lagged timing of these recharge supplies is not specifically considered. Instead, the monthly diversions to recharge are summed on an annual basis, and trends are considered based on a five-year average. Note that recharge augmentation supplies accrue to the river regardless of whether a call requires augmentation during that time period.
- Surface Augmentation Supplies include controlled water released from a storage reservoir, water diverted and released to the river via an augmentation station, and reusable effluent. Surface augmentation supplies only are released to the river when a call requires augmentation.

Recharge structures in the S. Platte are designed to introduce water into the alluvium that will result in water accretions to the river. The structures are optimally sited at a distance from the river that most efficiently covers lagged pumping depletions that are incurred during the summer growing season, but may hit the river days, months, or years later, during a period when the river is under administration. A recharge structure may be a designated section of unlined ditch or canal, or a pond or group of ponds that receive water designated for recharge or augmentation. Flow

A pump house in the South Platte River basin, Hillrose, Colorado.
Photo by Bill Cotton

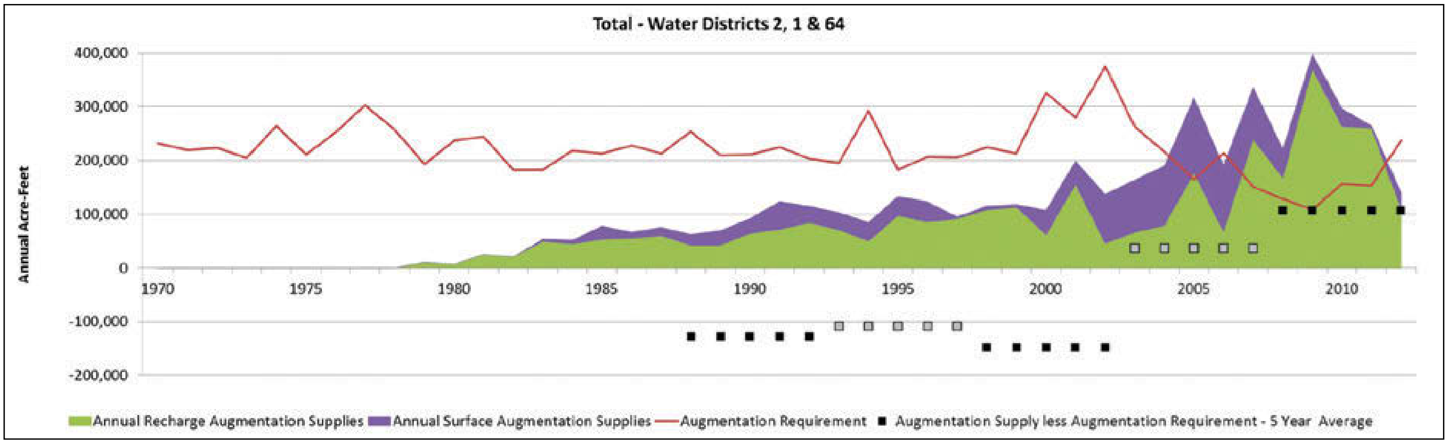


Figure 4. *Total annual surface and groundwater augmentation supplies versus estimated potential augmentation requirements, and five-year average augmentation supplies less potential augmentation requirement in water districts 2, 1, and 64.*

into and out of each recharge structure must be metered and equipped with a continuous flow recorder or similar approved equipment. Recharge water must be deemed fully consumable, and accretions are calculated as inflow minus evaporation plus consumptive use by vegetation plus water retained and outflow. Recharge accounting is done on a daily time step with monthly summations provided to the Division Engineer within 30 days of the end of the month.

Potential augmentation requirements were determined for the HB1278 study by summing the depletions from wells associated with an augmentation plan based on the HydroBase association table. As discussed above, not all groundwater pumping causes depletions to the river, and depletions do not require augmentation if there is not a senior call on the river. The annual potential augmentation requirements do not represent lagging or periods that the river is not under call. The result is that the lack of lagging underestimates depletion, while the assumption of 100 percent call overestimates the owed depletions. A calibrated groundwater model is needed to more precisely quantify lagged augmentation requirements at this scale.

The increase in recharge augmentation supply in the 2000s is a result of an increase in recharge areas constructed in the basin, specifically in Water District 64 and to a slightly lesser degree in Water District 1 (Figure 3). District 2 has seen the development of many lined gravel pits which may or may not provide augmentation water, but do not serve as a source of recharge. Augmentation supplies in District 2 are inadequate to serve the needs, so wells remain on restricted quotas. Surface augmentation supply reflects releases for augmentation from direct release from reservoirs such as Jackson Lake and Prewitt Reservoir, groundwater diversions from augmentation/recharge wells, bypassed diversions measured at augmentation stations, reusable effluent, and other sources of direct augmentation.

The five-year averages shown in Figure 4 indicate that potential estimated augmentation requirements exceeded augmentation supply prior to the more strict administration that began after the drought in the early 2000s. However, since days of administrative call were considerably less in these water districts prior to 2000, the

Table 1. *Average surface diversions, pumping, consumptive use groundwater pumping, and augmentation for water districts 2, 1, and 64 for 2008-2012.*

	WD 2	WD 1	WD 64	Total
	----- Average (2008-2012) in AF/yr ----------			
Total Surface Diversion	376,583*	673,869	257,766	1,308,217
Total Pumping	31,195	177,490	110,612	319,298
CU GW Pumping	23,138	134,872	80,781	238,791
Surface Augmentation	18,487	6,067	5,493	30,047
Recharge Augmentation	11,166	131,287	91,819	234,271
Total Augmentation	29,653	137,354	97,312	264,318

Table 2. *Average surface diversions, pumping, consumptive use groundwater pumping, and augmentation for water districts 2, 1, and 64 for 1999-2004.*

	WD 2	WD 1	WD 64	Total
	------ Average (1999-2004) in AF/yr -----------			
Total Surface Diversion	397,916	573,433	209,553	1,180,902
Total Pumping	89,840	277,685	145,095	512,620
CU GW Pumping	62,418	205,907	102,630	370,954
Surface Augmentation	9,105	30,961	25,861	65,927
Recharge Augmentation	3,786	46,432	36,653	86,871
Total Augmentation	12,891	77,393	65,514	152,798

actual augmentation requirement would have been much less than the potential maximum requirement based upon consumptive groundwater pumping.

Augmentation from recharge in excess of requirements may occur because junior recharge rights are only in priority during short time windows and thus, augmentation plan operators must recharge as much as possible when they are in priority. Since recharge operators cannot know when the next drought period will occur, they are compelled to operate as if drought could occur next year, or for the next six years, depending upon the court decree. Additionally, timing of when recharge rights are in priority may not match the lagged timing of water need for irrigation. The locations of recharge ponds and other recharge facilities relative to irrigation wells also may present timing difficulties for augmentation plans. For example, if recharge structures are located closer to the river than to irrigation wells in an augmentation plan, the recharge credits reach the river more quickly than the depletions. In these cases it is difficult to recharge only the amount of water ultimately needed to offset the well depletions. As a result, many augmentation plans have excess capacity to provide adequate supplies to cover depletions year round. A good augmentation plan must have a blend of recharge structures close to the river for use following dry periods and structures further away to provide much longer recharge credits for protection during prolonged drought periods. Tables 1 and 2 show the changes in pumping and augmentation before and after strict administration of wells. Augmentation through recharge has greatly increased between these two time periods.

HB12-1278 Delivered More than the Contracted "Deliverables"!

In the process of meeting the requirements of the legislation laid out in the House Bill, the HB1278 research team developed a number of contributions that will help policy makers and researchers going forward include:

Google Earth Maps and Flyover: User-friendly GIS maps and a narrated flyover of the basin are cataloged online at www.cwi.colostate.edu/southplatte/.

South Platte Point Flow Tool: We developed a TSTool command to perform a general point flow analysis for daily, monthly, and annual data.

Animated History of Well Development: We provided a history of well development in the South Platte to give context for the policy decisions that need to be made today. We hired an animator to make it into a video available online.

Proposed Groundwater Monitoring Network Plan: As we accessed data from various entities, it quickly became obvious that there is a keen need to bring together all the various data collection points and collectors. We developed a statistically valid monitoring plan that was included in our final report.

Website: We could have just emailed our report to the legislature on December 31 and counted our job done, but we wanted to keep interested parties informed of our progress along the way. And we wanted to provide links to what we were collecting in the way of reports, articles, maps, and any number of other resources. Additionally, we wanted to create a way for stakeholders to share their values and beliefs about the issues. We developed and maintained a robust website to do that. You can interact with it at www.cwi.colostate.edu/southplatte/

Phreatophyte Mapping and ET estimates: The study team replicated and validated the Groeneveld 2001 phreatophyte study, then extended it back to 1990 and forward to 2010 with an enhanced methodology.

Updated SPDSS TSTools: Major TSTool enhancements made for the HB1278 project included adding support for the USGS NWIS groundwater Web services; improved handling of water level data from HydroBase, including calculating statistics on water levels; adding features to read and process tables from any database and Excel, which allowed queries of plan/recharge data; and diversion record enhancements to evaluate recharge.

Bibliography of South Platte Groundwater: Literally hundreds of reports, articles, maps, graphs, and other resources were gathered and analyzed as part of this study. See how many of the 1,167 entries you are familiar with!

Online Excel Spreadsheets of Groundwater Data: It's one thing to put the data we developed on our website. We went a step further and put them there in a format that allows the viewer to manipulate the variables themselves. Most of our spreadsheets allow this capability.

50-year Climate Data Summary: The Colorado Climate Center developed 50 years of precipitation and snowpack data, now available online for researchers and consultants.

The South Platte River Basin between Platteville and Sterling, Colorado.
Photo by Bill Cotton

Surface Water Diversions and Administration

Reagan Waskom, Director, Colorado Water Institute

South Platte diversion trends have changed in recent decades, with significantly more water diverted in the off-season and shoulder seasons for augmentation. Analysis of the call data from 1982-2012 show that administration of the river has changed in the recent decade, with many more days of administrative call compared to previous decades, decreasing the number of days of free river.

Flow Trends

Flow on the mainstem of the S. Platte from Denver to Julesburg is measured by ten principal stream gages maintained by the U.S. Geological Survey (USGS) and Colorado Division of Water Resources (DWR) (Figure 1). Many developments have altered flow trends over the period of time that gage records have been kept on the S. Platte, including new reservoirs, transbasin diversions, and well pumping. We conducted a statistical analysis of streamflows for the Kersey and Julesburg gages over five time periods to detect trends in flow records and to determine if the observed trends were statistically significant. In order to identify any possible streamflow changes in the S. Platte, we investigated monotonic trends of discharges, without accounting for either climatic or anthropogenic variation. Two key streamflow gages at Kersey and Julesburg were chosen, and trend testing for five time periods was performed. The decision to test for multiple time periods was based on water management shifts in the S. Platte basin.

Trend analysis for the annual (irrigation year Nov. 1-Oct. 31) and monthly streamflow was performed by utilizing the non-parametric Mann-Kendall (Kendall 1975; Mann 1945) test and a significance level of five percent. We found that from 1969 to 1999, the average annual river flow at Kersey was 927,323 acre-feet (AF), primarily due to very big flow years in 1970, 1973, 1980, 1981,1983, 1984, 1985, 1995, and 1987, all of which exceeded one million AF. The average annual river flow at Kersey from 2000-2012 was 553,773 AF. Interestingly, the annual flow at Kersey in the drought year of 2012 (394,588 AF) was 45 percent higher than the drought year of 2002 (272,075 AF). However, it should be noted that nearly 500,000 AF of groundwater was pumped in Water Districts 2 and 1 in 2002 with 80,000 AF of augmentation, compared to 290,000 AF of pumping and 185,000 AF of augmentation in 2012. No statistically significant monthly or annual trend, either positive or negative, was detected in flows measured at the Kersey gage from the period of 2000-2012.

The average annual flow at the Julesburg gage near the state line averages 380,070 AF for the entire period of record from 1924-2012. Large variation in flow occurs within and between years (Figure 2). No statistically significant trend in flow at Julesburg was detected over the entire period. For the period of 1967-1999, a positive but non-significant trend was observed over the period, with a significant positive trend (at p<.05) during August, September, and October. The average annual flow for the period of 1967-1999 was 589,313 AF. In contrast, the average annual flow for the period of 2000-2012 was 213,446 AF, due mainly to drought conditions in 2001-2008 and 2012, and increased diversions for recharge. These data provide no evidence that Julesburg flow trends in the past decade are increasing. It should be noted that in 1997, Colorado, Nebraska, and the U.S. Department of the Interior made a cooperative agreement to develop and implement a recovery program for four endangered species: the whooping crane, the least tern, the piping plover, and the pallid sturgeon. Colorado has committed to making 10,000 AF of water available between April and September of each year by adjusting the timing of water flows using an augmentation scheme managed at the Tamarack Ranch State Wildlife Area (Freeman 2011). Correspondingly, we detected

Figure 1. *Major streamflow gages on the S. Platte mainstem below Denver.*

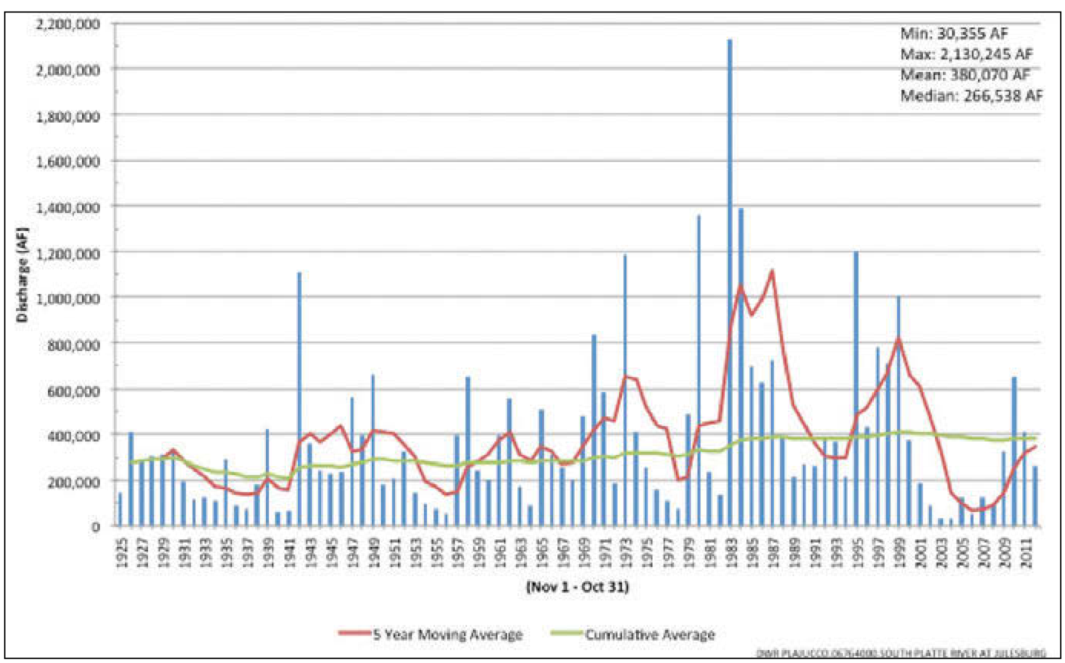


Figure 2. *Annual S. Platte River flows at Julesburg, CO, 1925-2012. Data Source: CO DWR HydroBase Version 20130710.*

Table 1. *Average Total Annual Diversions for 56 Major Ditches in Water Districts 2, 1, and 64. Data Source: CO DWR HydroBase Version 20130710.*

Period	Irrigation Season (Apr-Oct)	Off-Season (Nov-Mar)	Irrigation Year (Nov-Oct)
	----------------	AF/yr	----------------
1969-1999	818,151	151,479	969,630
2000-2012	901,600	343,912	1,245,512

a positive trend for the months of July and August in the 2000-2012 period.

Surface Water Diversions

There are 56 major surface water diversion canals along the mainstem of the S. Platte in Water Districts 2, 1, and 64. Minor ditches, alternative points of diversion, and augmentation structures are not included in this number. The largest change that can be observed in surface water diversions over this period is the post-1969 diversions in the November to March period, when canals are taking water for reservoir filling and augmentation purposes. We analyzed mean annual diversion records and irrigation and reservoir season diversion records for the periods of 1950-1968, 1969-1999, and 2000-2012, as well as 1950-2012 and 1969-2012, to detect the presence or absence of trends, either positive or negative, and used the Mann-Kendall test to determine if the trends were significant.

Comparing mean annual canal diversions for the 1950-2012 period to the 2000-2012 period, we observe that about a third of surface water diversions show some increase in mean annual diversion amounts between the periods. In Water Districts 1 and 64, these increases can mostly be attributed to increased reservoir fill season (Nov. – March) diversions for the purpose of augmentation accretions. It is important to note that prior to the 1980s, river commissioners were not uniformly kept on the job year-round, and off-season diversion records are incomplete.

Reservoirs and Transbasin Diversions

Water management organizations in the S. Platte basin have developed an extensive system of reservoirs throughout the basin to enable storage of spring runoff and winter water. Total reservoir storage capacity in the basin exceeds two million AF of capacity. These reservoirs tend to fill during average years and years of plentiful snowpack. In addition, S. Platte water users benefit from some 14 transbasin diversions that import an average of 386,000 AF annually during the period from 1969-2012 (Figure 3).

River Calls

Tributary groundwater users are responsible for repaying injurious river depletions taken out-of-priority during times the river is under senior call or administration. Among the many changes that have occurred in the basin over time, the percentage of time during which the river is under administration, particularly outside of the typical irrigation season, has changed. At one point there was a so-called “gentlemen’s agreement” in the S. Platte for how surface reservoirs would be filled during the off-season. That agreement held that following the normal irrigation season, surface reservoirs would begin storing river flows from the top of the basin down, and lower river seniors would avoid making a priority call. This resulted in minimal wintertime call on the river, and the wintertime stream depletions caused by pumping from the previous years did not have to be replaced by irrigation well owners. This was a major benefit for well augmentation plans and particularly, for Groundwater Appropriators of the S. Platte (GASP) and the Central Colorado Water Conservancy District. The gentlemen’s agreement began to break down in the late 1990s as more artificial recharge projects were developed for augmentation plans, taking advantage of free river periods when reservoirs were filling under the gentlemen’s agreement. Loss of the agreement increased time period during which the river was under call, and hence, the depletions owed back to the river system by well users. Division 1 staff still attempts to facilitate upstream reservoir fill by working with water users to encourage cooperation and efficiency in the spirit of the gentlemen’s agreement, but this only works if adequate water is available in the river.

The S. Platte Compact with Nebraska was settled in 1923. Between April 1 and Oct 15 of each year, Colorado has full use of the river except in District 64, where the right of the Western Canal to divert 120 cfs under its 1897 right is recognized. Thus, Colorado is required by the compact to curtail all diversions in District 64 junior to June 14, 1897 when the Julesburg gage falls below 120 cfs during the irrigation period. Times when the river falls below 120 cfs during this period are registered as a S. Platte Compact call. Flows less than 120 cfs are not uncommon during summer. The annual period subject to the compact is 198 days, and the lower river is currently under compact administration an average of 116 days per year over the past decade.

Analysis of the call data from 1982-2012 show that administration

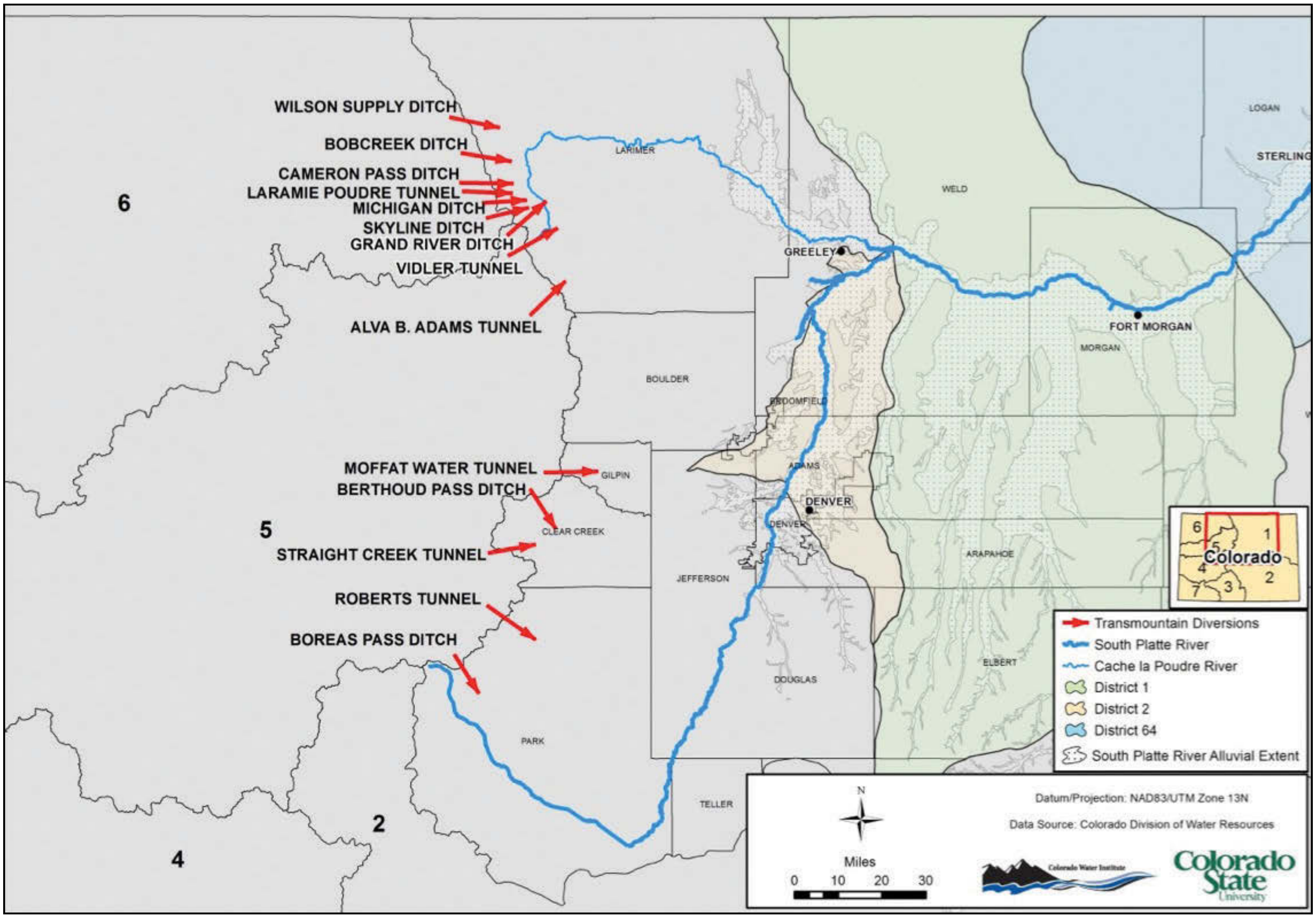


Figure 3. *Transbasin diversions to the S. Platte basin.*

of the river has changed in the recent decade. In the past, the number of days the river was under administration was typically a function of water supply from snowpack and precipitation. This changed beginning in 2000 when additional calls were put on the river in the irrigation season and the reservoir filling season. The average days under call in the period of 2002-2012 has tripled in District 2, quadrupled in District 1, and more than doubled in District 64 when compared to the 1982-2001 period. Off-season calls account for much, but not all of this change in administration. The net impact is a double whammy of more days that well depletions must be repaid and fewer days of free river when junior augmentation rights can be exercised.

It should be noted that not all calls impact irrigation wells. Most of the high capacity irrigation wells in the basin have 1930s-1960s adjudication dates. Any call junior to a well's adjudicated priority date would not trigger augmentation requirements for those depletions. The oldest augmentation calling right on the river is the 1972 Fort Morgan Plan. Post-1972 augmentation plans include recharge rights that occasionally are in priority as the calling right—wells senior to that date do not have to replace these depletions called by augmentation plans. In most cases, these operate as by-pass calls to senior users. Recharge calls almost all operate as bypass calls to rights senior to most wells when there was enough water to meet the senior demand, but not enough to go to free river. These calls maximize beneficial use by allowing the well depletions to be in priority and not require augmentation, but keep the most junior rights out of the river so that the call does not yo-yo between senior calls and free river. The Division 1 Engineer estimates there are approximately 6,000 cfs of decreed water rights in Districts 1 and 64 for recharge and augmentation with post-1972 priority dates. Recharge and recharge calls happen primarily in two periods, the spring and fall shoulder months, when neither direct use nor storage are at their peaks, or in the dead of winter, when diversions down very long ditches to storage can be problematic due to icing (reducing storage demand), but running water for in-ditch recharge and over shorter distances to recharge ponds can be done with less difficulty.

Using SPDSS Tools to Process Data for the South Platte River

Steve Malers, Chief Technology Officer and Systems Engineer, Open Water Foundation

The HB1278 project team used SPDSS data and software tools, including TSTool, and a data-centered approach, allowing for automated and reproducible procedures. TSTool was used in combination with other tools, like GIS, Microsoft Excel, and others, to automate data access and time series processing for various data types, including streamflow, diversions, well levels, and climate data.

Historical point flow analyses showed that the South Platte is generally a gaining river, benefitting from the return flows from agriculture and recharge.

The South Platte Decision Support System (SPDSS) is the most recent basin modeling effort that is part of Colorado's Decision Support Systems (CDSS, see http://cdss.state.co.us). SPDSS and other decision support systems have been developed with funding from the Colorado Water Conservation Board (CWCB) in order to help the CWCB and the Division of Water Resources (DWR) understand water resource issues and make decisions about these resources. The HB1278 project has leveraged SPDSS data and software and enhanced SPDSS tools in order to streamline project efforts.

CDSS utilizes a "data-centered" approach where important data resources, such as the State of Colorado's HydroBase database, form the basis of analysis input, and automated procedures are implemented for analysis. HydroBase is the State of Colorado's database that contains important water resource data such as water rights, diversion records, streamflow data, river calls, and many other associated data types. The data-centered approach, illustrated in Figure 1, was developed because of the need to efficiently process large amounts of data into usable formats, including model input files and data analysis products. The data-centered approach is:

- Automated – utilizes CDSS software tools like TSTool and StateDMI data management interfaces (DMIs)
- Repeatable – utilizes "command files" as input to control processing
- Self-documenting – data processing output files include command file instructions and other metadata in comments

In this approach, a significant portion of the analysis effort is spent up front understanding data

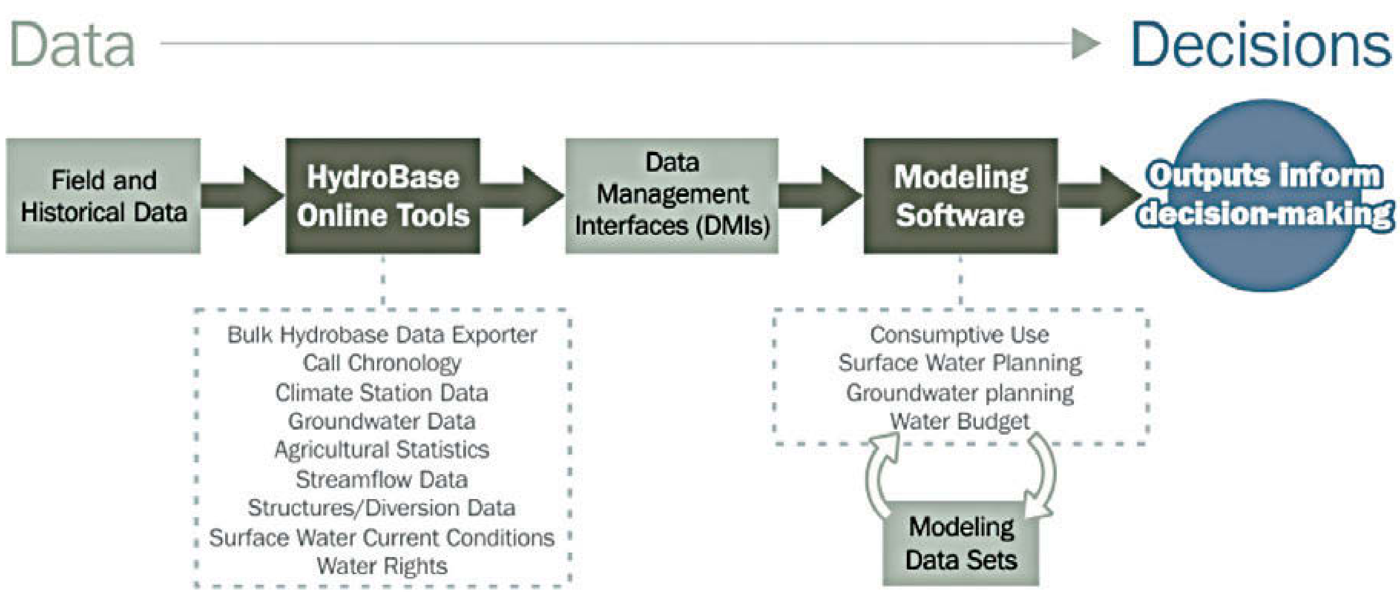


Figure 1. *Data-centered analysis approach (from the CDSS website).*

availability and limitations and determining how to process data into desired products. The resulting process is encoded in command files, which can then be run as many times as required to fine-tune the analysis process. The initial investment in defining the automated process provides a return on time invested, because re-execution of the analysis process is rapid and leverages the initial investment. In contrast, previous efforts involving manual editing of data files or developing one-off data-processing software resulted in tools that could not be reused. The data-centered approach and automation also encourage the development of best practices that can be reproduced, shared, and updated over time.

The TSTool software, so named because it was originally developed to reformat time series data from the HydroBase database into model dataset formats, is a workhorse in CDSS and was used extensively on HB1278 to access and process data. At its heart, TSTool provides features to configure a workflow of commands (see command types in Figure 2) in order to sequentially process data. Basic steps in processing typically include:

1. Read data from input sources, including HydroBase and other databases, data files, and web services
2. Quality control data
3. Fill and otherwise manipulate data, if necessary for analysis
4. Perform analysis
5. Generate output products including output files and visual data products

The main data objects handled by TSTool include time series (essentially arrays of date/time and value pairs),

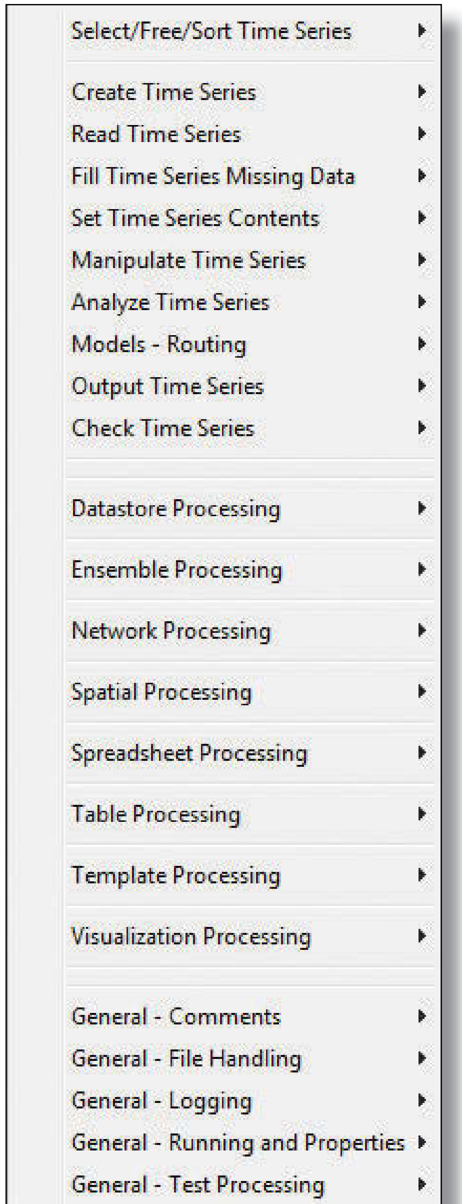


Figure 2. *Command types within TSTool.*

tables (e.g., corresponding to database queries), and increasingly, map layers. Standard conventions are enforced in order to ensure that the hundreds of processing commands provide a common interface to software users. For example, each time series is identified by a standard "time series identifier" that contains location identifier (e.g., station identifier), data source (e.g., agency such as "DWR"), data type (e.g., "Streamflow"), data interval (e.g., "Month"), and optionally, a scenario. These conventions have been utilized to implement interfaces to many data sources, including Internet Web services for United States Geological Survey (USGS), Regional Climate Center Applied Climate Information System (RCC ACIS), Natural Resources Conservation Service (NRCS), and State of Colorado. In addition to providing access to time series, TSTool provides a way to automate queries of the State's Microsoft SQL Server HydroBase database tables and views using Structured Query Language (SQL), without requiring the installation of additional database viewing software.

TSTool was used in the HB1278 project to automate data access and time series processing for various data types, including streamflow, diversions, well levels, and climate data. In some cases TSTool performed the analysis completely, and in other cases it was used in conjunction with other tools, such as GIS, Microsoft Excel, or model and analysis tools. In cases were multiple tools were used, the data-centered, automated approach and standard data formats were used to ensure that the data analysis process was automated and repeatable.

The HB1278 authorization language recognized a need for analysis but also recognized that insufficient funding and time were available to perform full modeling. Consequently, it was important to leverage existing SPDSS data, tools, and modeling work. As part of the HB1278 project, the SPDSS consumptive use model dataset for the StateCU model was extended through 2012. However, the water allocation model (StateMod) is being completed as part of the SPDSS surface water modeling project, and development of the MODFLOW groundwater model is continuing as a separate component

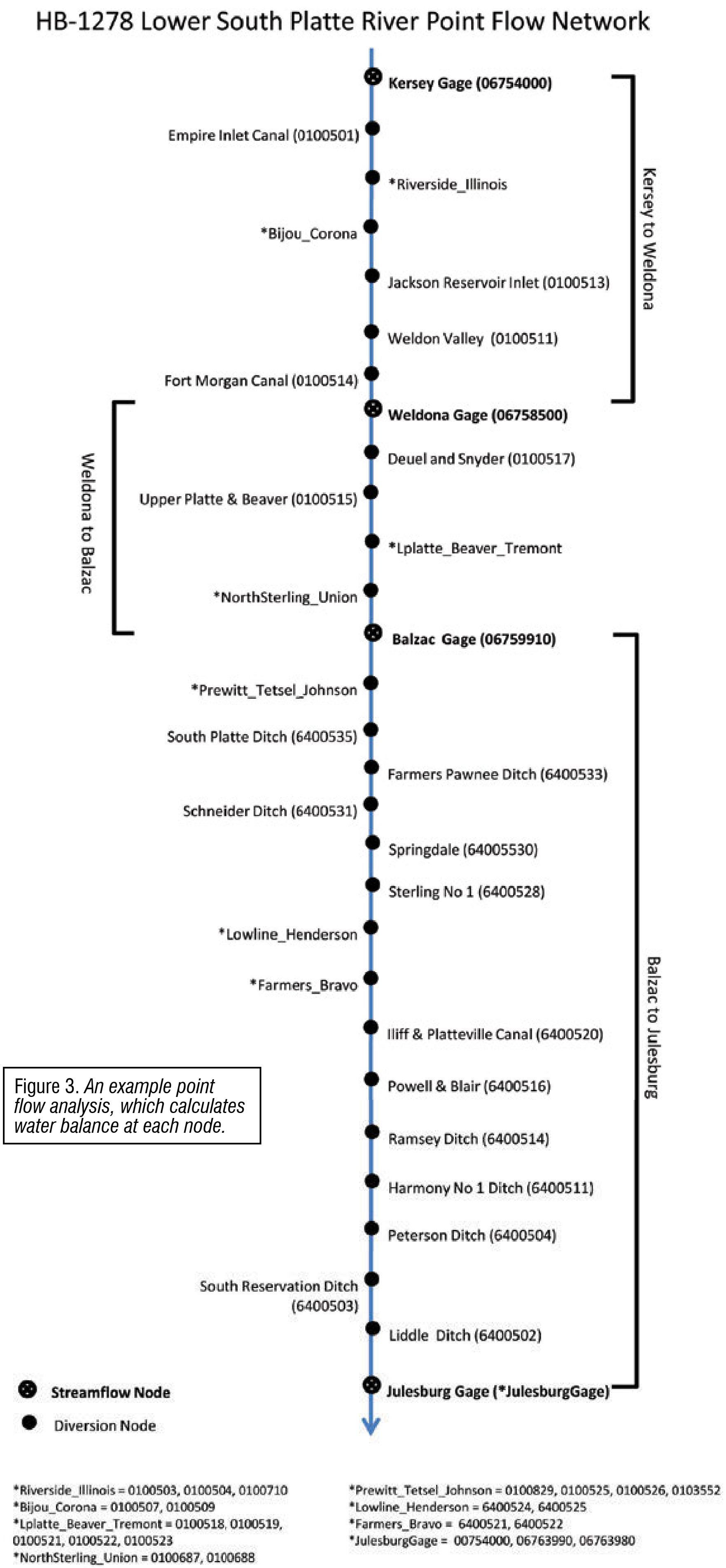


Figure 3. *An example point flow analysis, which calculates water balance at each node.*

of SPDSS. A middle-tier analysis was needed between data analytics (such as can be performed with existing TSTool commands, Excel, etc.) and full modeling (StateMod, MODFLOW) in order to understand historical changes of water resources in the South Platte, in particular gains and losses attributed to natural and administrative changes in the basin.

To meet this need, and again, to leverage existing SPDSS tool capabilities, TSTool was enhanced to provide a point flow analysis capability via the new AnalyzeNetworkPointFlow command. A point flow analysis represents the system as a simple "node network," as shown in Figure 3. In such a representation, water balance is computed at each node, accounting for inflow from the upstream node, diversion or inflow at the current node, and calculating each node's outflow. Whereas the flow at a node is known at stream gages, the river flow typically is not measured at diversion points and must be estimated by subtracting diversions and adding inflows. The error at the downstream gage resulting from calculations within the river reach is distributed back to intervening nodes as the reach gain or loss. The error is prorated by assuming a constant gain/loss rate over the reach while considering stream mile distance between nodes.

Similar to other TSTool commands, the AnalyzeNetworkPointFlow command is executed as a step in a workflow, which involves the following procedure:

1. Read the river network definition from an Excel file
2. Read time series associated with the network nodes from various sources (HydroBase, USGS web services, DWR web services, RCC ACIS Web services)

3. Process the time series as needed for input to the analysis (e.g., merge historical diversion records in HydroBase with real-time "administrative gage" data from the State's Web services in order to obtain a full historical period)

4. Perform the point flow analysis using the AnalyzeNetworkPointFlow() command

5. Create output products

The network was defined in an Excel workbook using the Lower South Platte Water Conservancy District (LSPWCD) Visual South Platte point flow tool as a guide. Whereas the Visual South Platte tool focuses on real-time tracking of the river, the TSTool analysis performed the analysis for 1987 to 2012 and consequently time series data needed to be processed from various sources, requiring that the network worksheet include data source information for the multiple sources.

Existing TSTool commands were used to automate data retrieval and processing. The network definition and point flow analysis command were designed to allow the analysis to be performed using daily, monthly, or annual time series. A monthly analysis was used for final analysis because daily data showed extensive flow variability due to daily operations, lagged impacts from one timestep to another, etc. Figure 4 illustrates the computed gain/loss for the Balzac to Julesburg reach (the gain/loss in the reach above the Julesburg gage). The dips in the graph are explained by periodic hydrologic events resulting in temporary extremes in the water balance, as well as occasional data issues. Further data improvements are possible by building on the results of the SPDSS surface modeling efforts that are currently in progress.

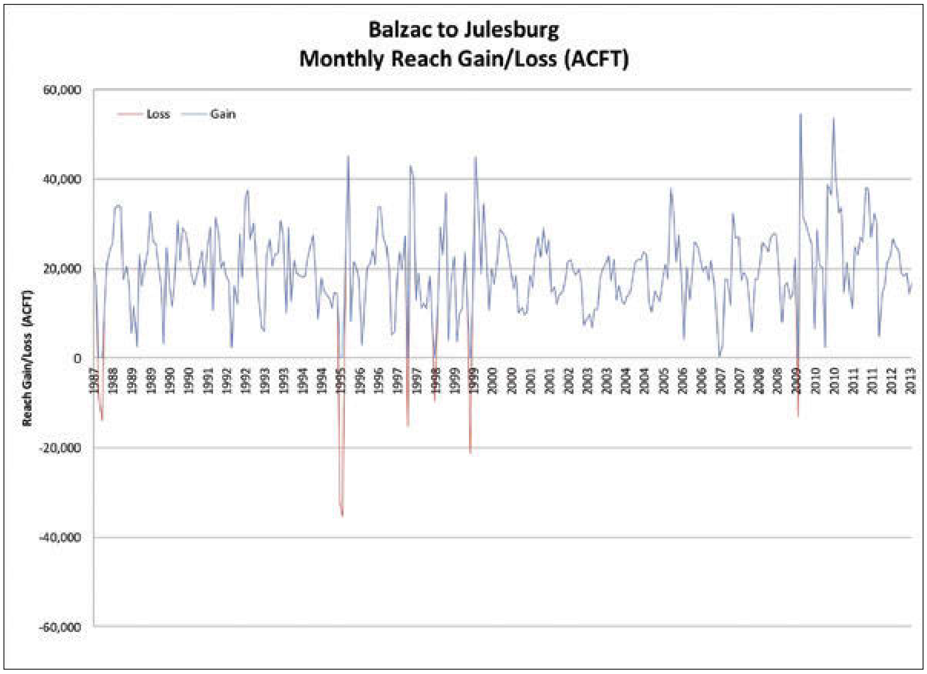


Figure 4. *An example gain/loss computation created from TSTool commands.*

The resulting output time series from the analysis were further analyzed to analyze trends and compare with precipitation, streamflow, and recharge. The results of the point flow analysis showed that there have been changes in reach gain over time; however, the data are noisy. The South Platte is generally a gaining river, benefitting from the return flows from agriculture and recharge. The river responds quickly to surface water returns and consequently the impacts from precipitation, irrigation, and recharge must be considered together. Hydrologic conditions including high flow years and drought greatly impact the natural and managed river and mask trends associated with changes in administration. Reuse of return flows increases progressively through downstream reaches, and forms a significant part of the supply for the lower reach to Julesburg. The historical point flow analysis is useful for understanding the trends and relative magnitudes of gain and loss but is impacted by the network definition and limited availability of historical time series data in some cases.

Utilizing SPDSS data and software tools, including TSTool, allowed the HB1278 project team to efficiently access and process data. The data-centered approach encourages implementation of procedures that can be automated and reproduced. This will allow the HB1278 work to be updated and improved in the future. A combination of historical point flow analysis tool, real-time point flow analysis tool, and full basin modeling, implemented using a consistent network definition and data, can provide guidance on a variety of questions about water management and administration.

The synthesis of all of the analyses performed in the HB1278 project forms the basis for recommendations, accessible in full on the HB1278 website: http://www.cwi.colostate.edu/southplatte/index.shtml.

Significant parts of the point flow analysis were implemented by Mark Mitisek of Leonard Rice Engineers, with input from Kara Sobieski of the Wilson Water Group.

The Climate of the South Platte Basin

A Lesson in Variability

Wendy Ryan and Nolan Doesken, *Colorado Climate Center, Department of Atmospheric Science, Colorado State University*

The South Platte basin includes high mountain regions where snowpack accumulates in winter, as well as lower elevation dry flatlands near the eastern Colorado border.

The basin exhibits highly variable annual weather patterns, making it difficult to model and predict patterns. Additionally, long-term monitoring stations are closing throughout the basin, causing gaps in data.

Introduction

The South Platte basin lies in the northeastern portion of Colorado. The headwaters of this basin originate in high mountains that rise to over 14,000 feet. The basin then stretches far onto the plains into the northeast corner of the state where the elevation drops to only 3,500 feet at the Nebraska border This terrain defines the climate characteristics of the basin. The high mountains capture frequent winter and spring storms, which build snowpack that later becomes the water supply for the rest of the basin. The South Platte is home to 3.5 million people (in Colorado only) mainly concentrated along the Front Range corridor from Ft. Collins to Denver. It is also home to extensive areas of high-production, irrigated agriculture. Meeting the water needs of both the population centers and agricultural industry are of the utmost importance in the basin.

Precipitation

Precipitation varies widely across the South Platte basin (Figure 1). The higher terrain along the westernmost edge of the basin receives from 30 to as much as 52 inches on average, while east of the mountains the plains receives as little as 10-15 inches in the driest areas of Weld and Morgan counties. Precipitation also varies widely temporally (Figure 2). At individual locations, annual precipitation totals can range from less than half the long term average to nearly double the average in extremely wet years. This makes water supply planning a real challenge for resource managers and water providers. Drought is a frequent visitor and can bring extended dry periods that sometimes end abruptly and sometimes continue for several years.

The high mountain areas to the west capture snow when the prevailing westerly winter winds bring storms into Colorado from the Pacific. As the air rises up and over the terrain, moisture condenses into clouds and falls as snow, creating a frozen reservoir of water supply. The majority of the cold-season precipitation falls along and west of the Continental Divide but extends eastward into the headwaters of the S. Platte basin. Then, as the air descends the east flank of the Rockies, the air warms and precipitation rapidly diminishes, causing the lower portions of the basin to be in a winter snow shadow. During the fall, winter, and spring, the best chance for precipitation at lower elevations comes when low pressure systems track south of this area, helping to create upslope flow (winds from the east). These patterns occur infrequently but allow moisture from the Gulf of Mexico to reach the Colorado Front Range. Winds push the moist air mass up against the eastern slope of the mountains, where the air cools, condenses, and can create large snowstorms or widespread fall or spring rains along the Front Range and eastern plains.

Precipitation patterns are highly seasonal, with the mountains receiving the majority of their moisture from October-May. The South Platte is unique in the fact that high elevations tend to receive beneficial moisture from late season storms (April/May) more than any other basin in the state (Figure 3 and 4). As a result, this makes the snowpack/runoff relationships that are used to predict seasonal water supplies less reliable in the South Platte than in other parts of Colorado. Using peak snowpack yields only slightly better results than April 1 or May 1 snow water equivalent as runoff predictors, but the correlations are still weak in terms of predictability of runoff volume.

Precipitation on the plains is also highly seasonal (Figure 3), with the majority coming in the spring and early summer months as the seasons and jet stream are changing. Much of the annual precipitation on the plains comes from just a few big storms. In some cases, these storms come as large snowfall events that

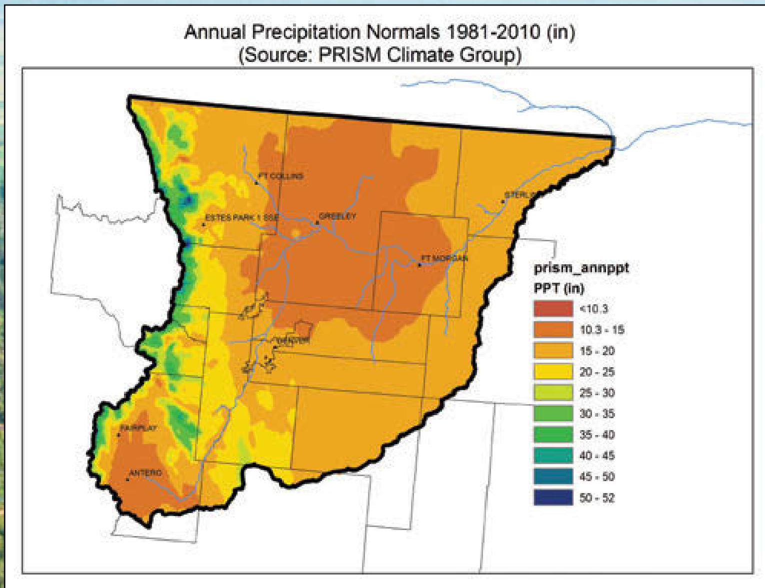


Figure 1. *South Platte basin annual normal precipitation (in).*

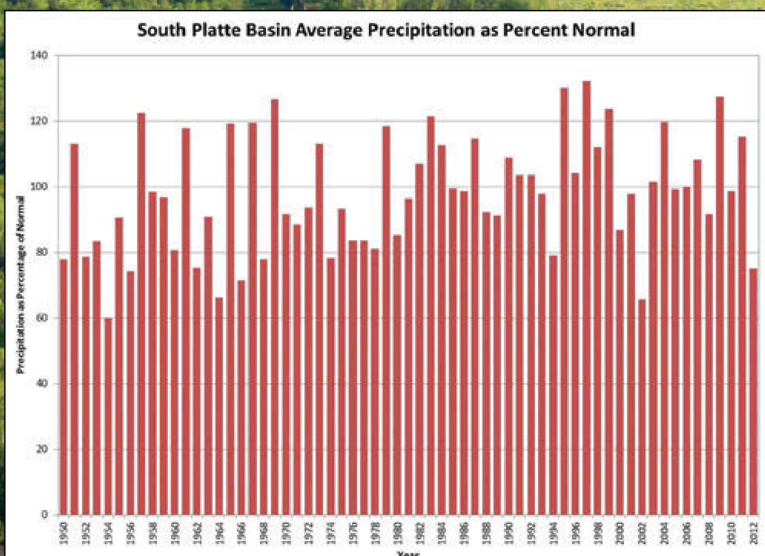


Figure 2. *South Platte annual precipitation as a percentage of normal time series.*

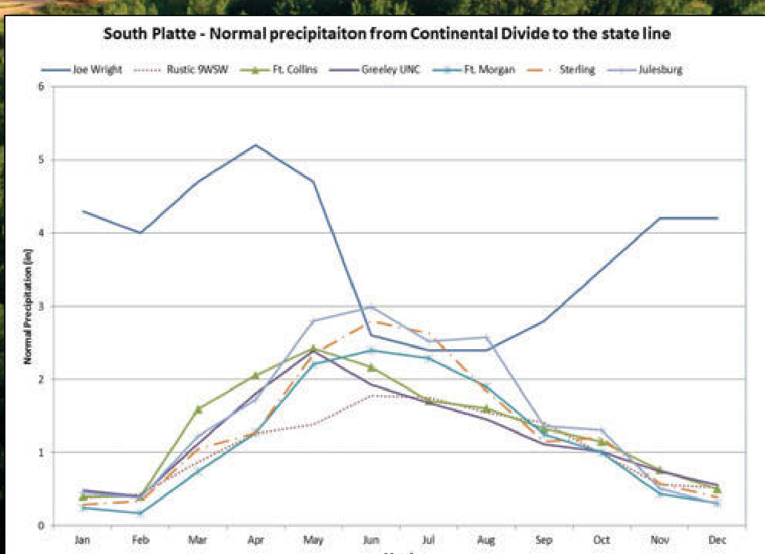
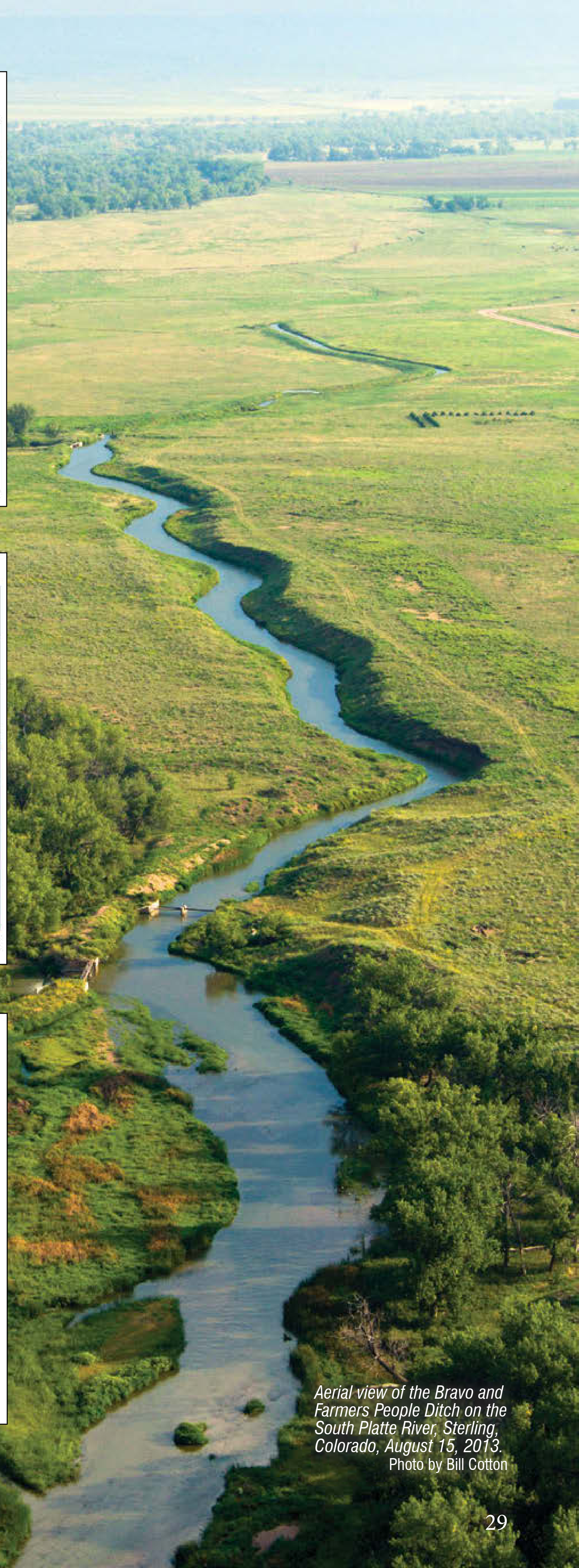


Figure 3. *Normal precipitation patterns across the South Platte basin from the Continental Divide to the state line.*



Aerial view of the Bravo and Farmers People Ditch on the South Platte River, Sterling, Colorado, August 15, 2013.
Photo by Bill Cotton

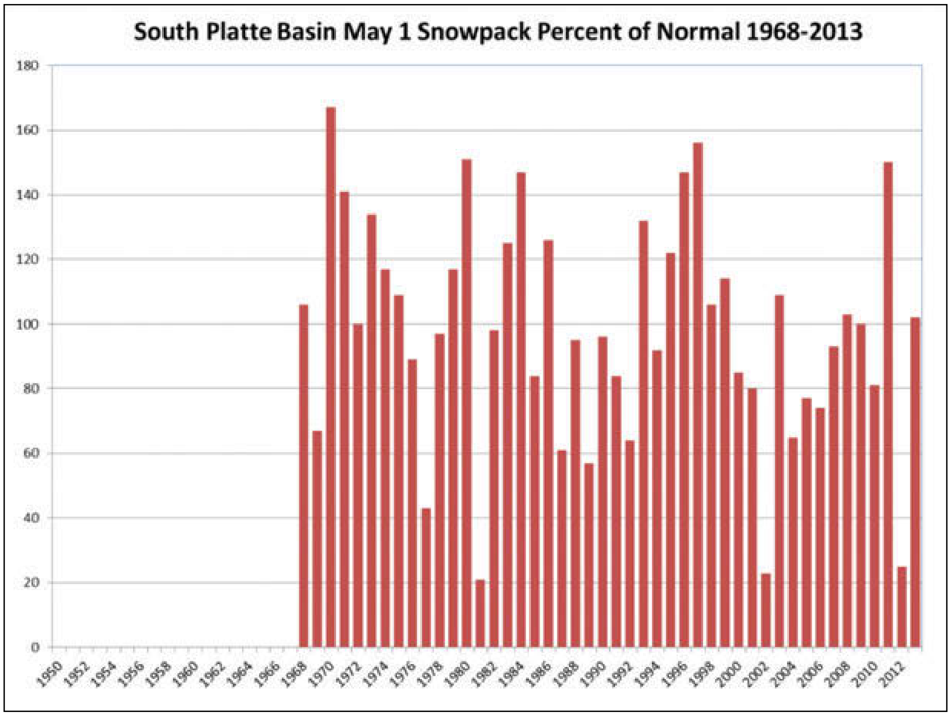


Figure 4. *May 1 snow water equivalent as a percentage of normal for the South Platte basin (1968-2013).*

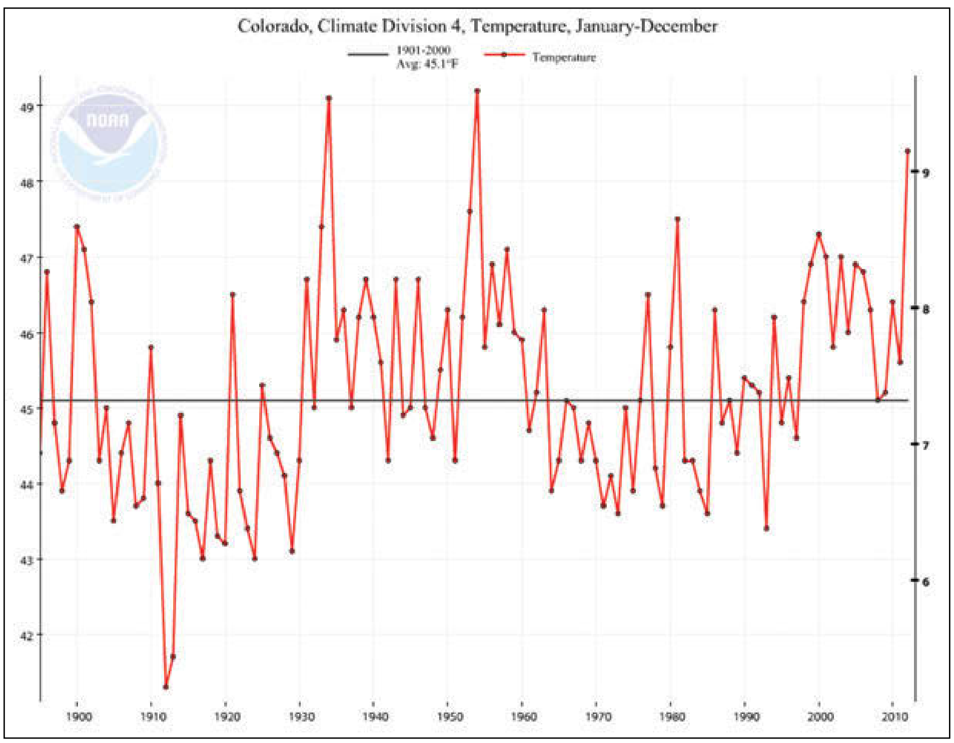


Figure 5. *Basin-wide annual average temperature time series 1895-2012.*

can shut down roads and collapse roofs (March 2003), but they can also come in the form of rain storms. Once the summer rolls around, precipitation transitions to more convective in nature and can be localized but heavy. In some cases, these types of events cause catastrophic flooding (Big Thompson flood of 1976 and Fort Collins and Pawnee Creek floods of 1997 are good examples), damaging hail, extreme precipitation, and in some cases, tornadoes. The South Platte generally does not have much influence from the North American monsoon (not as much as the southern basins), but in some years wet conditions associated with the monsoon season can bring generous amounts of moisture in July and August.

Temperature

Figure 5 shows the temperature history using a composite of all stations in the South Platte. The basin average annual temperature is about 45°F but has varied four degrees in both directions from that average value in specific years. Temperatures show a warming trend of 1.1 degrees F over the past century.

Temperature in the basin is highly dependent on elevation. Air cools approximately 3.5 degrees Fahrenheit for every 1000 feet of elevation gain. The high mountains have much cooler temperatures than the plains during all seasons. The dry climate that dominates the South Platte creates large diurnal variations in temperature at all elevations with few clouds and limited moisture to absorb energy for evaporation, which causes quicker changes in sensible heat (i.e. the temperature we feel). At night with clear skies, heat easily escapes near the surface, causing rapid cooling. In winter, temperature can be highly influenced by the amount of snow cover present. In low lying areas, cold air can pool when winds are light, and this is intensified when snow cover is present. The high albedo of snow causes the sun's energy to be reflected back into the atmosphere rather than be absorbed by the earth's surface. Areas like Greeley tend to exhibit cold air pooling in the presence of snow cover and low lying proximity to the river. In summer, temperatures can be quite warm on the plains, and reaching the 100 degree F mark is not uncommon. High temperatures and low humidity creates a large atmospheric demand for available water. The South Platte is a water-limited system in terms of the demand from the atmosphere being greater than the amount of precipitation received. Figure 6 shows the average water deficit, Precipitation minus Evapotranspiration (ET), for the basin. This deficit ranges from 5 to nearly 25" of water using 30 year climate normals (1981-2010) derived by NOAA and using those to calculate Blaney-Criddle ET.

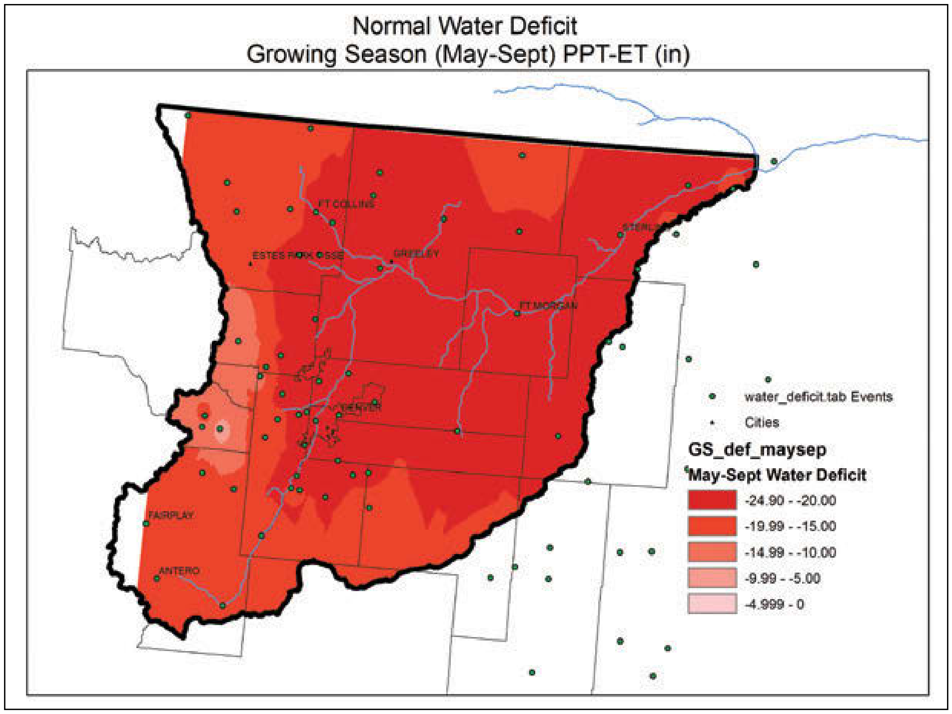


Figure 6. *Using climate normal and the Blaney-Criddle evapotranspiration (ET) calculation, the map shows the normal water deficit of the South Platte basin by subtracting ET from precipitation.*

Monitoring Gaps

In recent years, long-term NOAA Cooperative stations along the mainstem of the South Platte have been closed for a variety of reasons. These stations serve as the climate monitoring backbone of not only the basin, but the entire country. The discontinuation of these stations makes long term climate analysis difficult, particularly for the lower elevations east of Greeley (Figure 7). Other networks have come on line in recent years, but do not have the climate record or consistency that these Cooperative stations have. CoCoRaHS (Collaborative Community Rain, Hail, and Snow Network) serves the purpose of high spatial density precipitation monitoring, but they do not measure temperature and have short periods of record. Automated stations (CoAgMet – Colorado Agricultural Meteorological Network) measure temperature well, but not year round precipitation. Federally funded monitoring programs are being cut at alarming rates and if the State of Colorado intends to continue quality, long term climate monitoring in this basin, collaborative efforts should be made to restore observations at these locations.

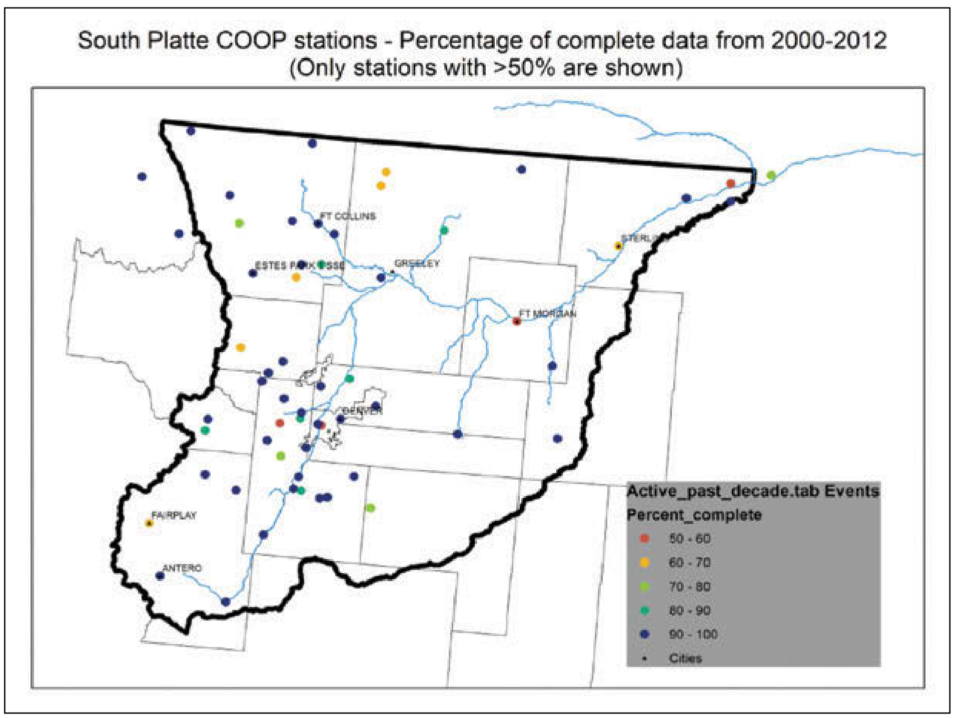


Figure 7. *Date completeness for the NOAA Cooperative stations in the South Platte (2000-2012).*

Summary

The climate of the South Platte is wildly variable and quite fascinating. Large changes from year to year, season to season, day to day and even hour to hour are common. Monitoring and observations are key to understanding changes and investigating issues that arise not only in the South Platte, but across the entire state.

Using Surface Energy Balance to Estimate Evapotranspiration of Irrigated Crops and Phreatophytes of the South Platte River Basin

Ahmed Eldeiry, Department of Civil and Environmental Engineering, Colorado State University

Using remote sensing and multiple weather stations' data, crop and phreatophyte evapotranspiration were calculated for the South Platte basin. Irrigated lands were estimated at 850,549 acres, while the total area of the phreatophytes was estimated at 201,632 acres. Phreatophyte evapotranspiration was estimated at 348,321 acre-feet.

Introduction

Water resources management is important in agricultural production in order to face the daunting challenges from population growth with the existing limited resources of water. Crop water use, also known as evapotranspiration (ET), represents soil evaporation and the water used by a crop for growth and cooling purposes. As the growing season progresses and canopy cover increases, evaporation from the wet soil surface gradually decreases. When the crop reaches full cover, approximately 95 percent of ET is due to transpiration and evaporation from the crop canopy, where most of the solar radiation is intercepted. Prevailing weather conditions, available water in the soil, crop species, and growth stage influence crop water use. ET is the largest user of irrigation water, and accuracy in ET estimation can be very valuable for better irrigation management.

Most conventional methods in estimating ET are based on point measurements with limited ability to capture the spatial variability at the area of interest. ET varies spatially and seasonally according to weather and vegetation cover conditions. Remote sensing has the potential to estimate ET and has several advantages over the traditional methods. It has the ability to capture spatial variability, and it can provide regional estimates of actual ET at low cost. ET models based on surface energy balance (SEB) with remote sensing (RS) data estimate actual ET with a spatial resolution equal to the pixel size of the image used. SEB algorithms are based on the rationale that ET represents a change in the state of water, from liquid to gas/vapor, by a process that requires available energy (net radiation minus the energy into the ground) in

the environment for the vaporization of water. There are several SEB models in the literature, which mainly differ in the way sensible heat flux (H) is calculated. SEB index is based on the contrast between wet and dry areas. All the semi-empirical algorithms use weather data from a single weather station located within the satellite image. For semi-empirical models, information gathered from single weather stations does not accurately represent weather conditions such as those created by topographic and/or microclimatic conditions within the coverage of a satellite scene.

ReSET Model

The use of single weather station data was extended to the use of multiple weather stations in the ReSET model. Elhaddad and Garcia (2008) proposed a methodology to incorporate multiple weather stations into a SEB model called RS of ET (ReSET) in order to address the variable weather conditions per location encountered by the RS platform's coverage area at the time of overpass. ReSET is a SEB model built on the same theoretical basis of its two predecessors, METRIC (Allen et al. 2007) and SEBAL (Bastiaanssen et al. 1998), with the additional ability to handle data from multiple weather stations. This enhances regional ET estimates by taking into consideration the spatial variability of weather conditions through data acquired from different weather stations. ReSET can be used in both the calibrated and the uncalibrated modes. The calibrated mode is similar to METRIC in which the reference ET from weather stations is used to set the maximum ET value in the processed area, while in the uncalibrated mode, the model follows a similar procedure to SEBAL wherein no maximum ET value is imposed.

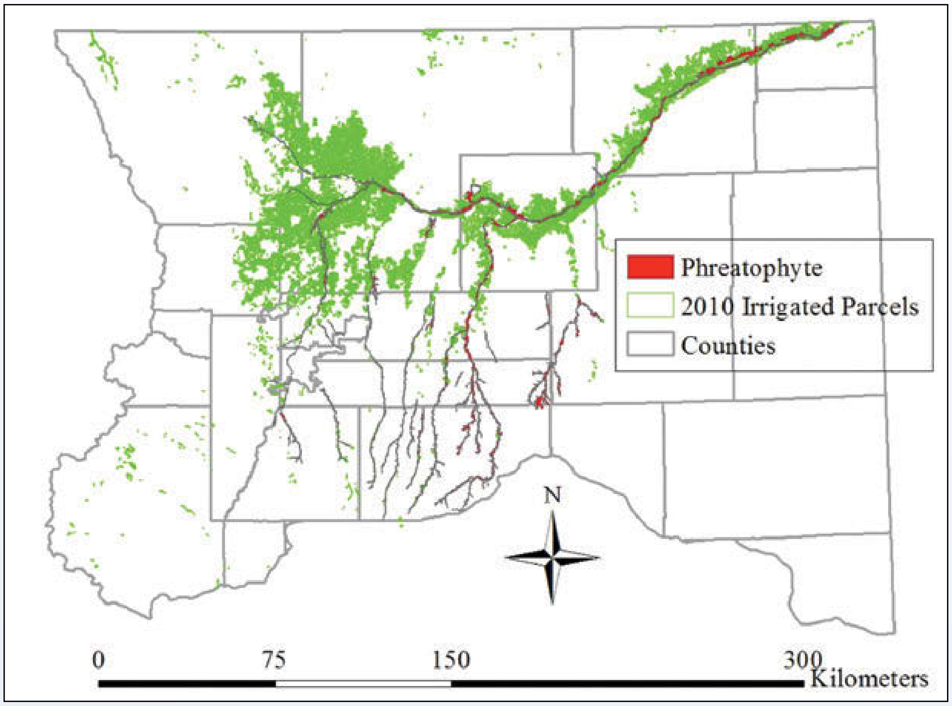
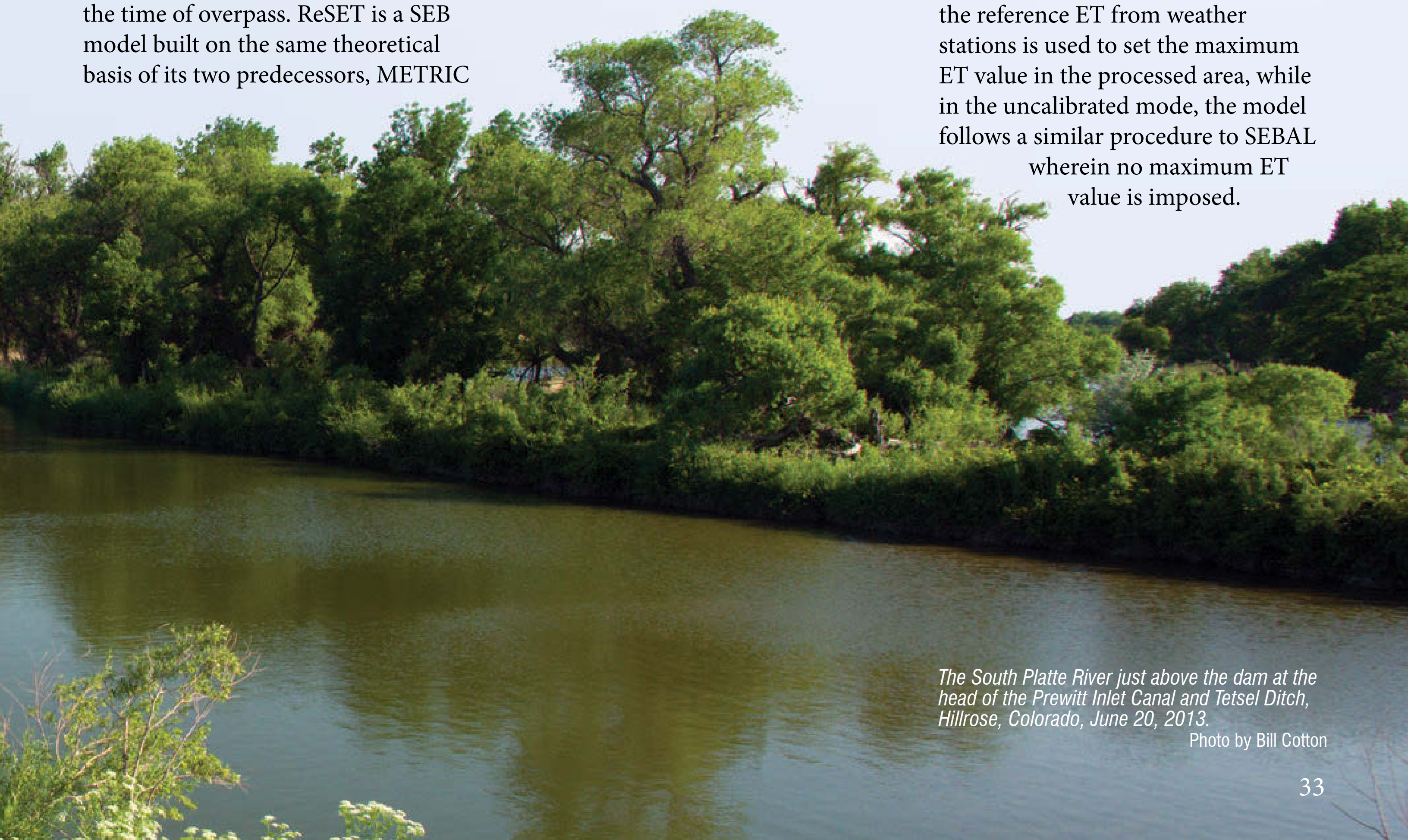


Figure 1. *Irrigated Parcels of 2010 and phreatophyte shapefiles.*


The South Platte River just above the dam at the head of the Prewitt Inlet Canal and Tetsel Ditch, Hillrose, Colorado, June 20, 2013.
Photo by Bill Cotton

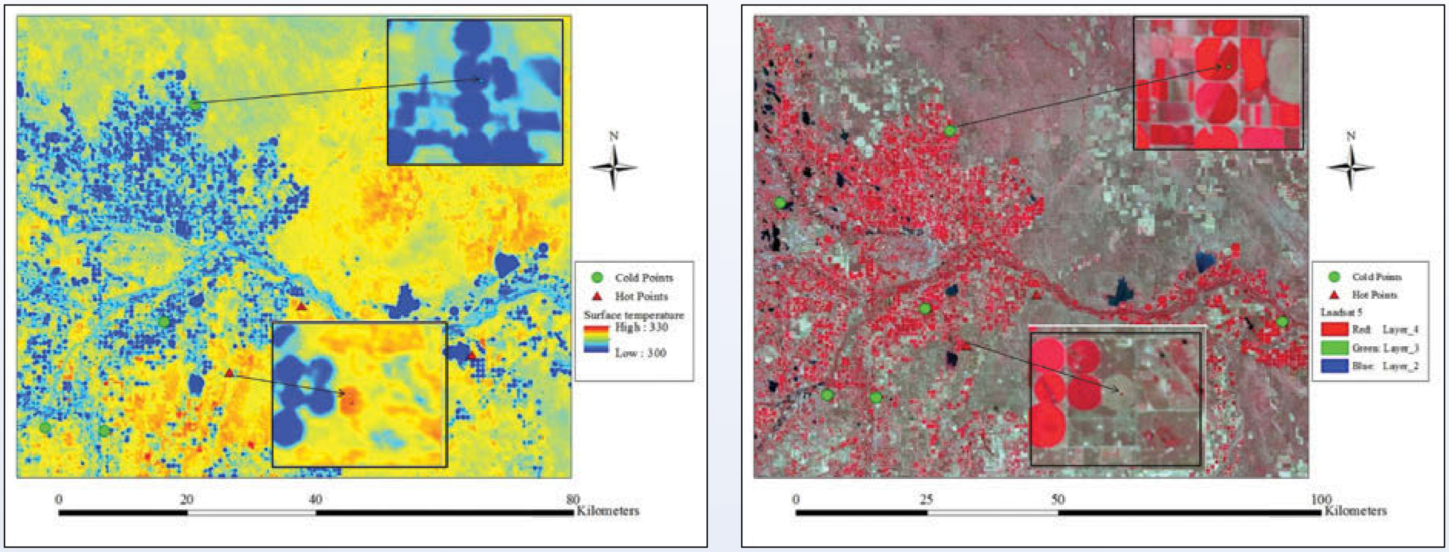


Figure 2. *Examples of cold and hot points displayed on surface temperature raster (left) and on the original landsat 5 image (right).*

Weather Station Data

Weather station data were collected from Northern Colorado Water Conservancy District (NCWCD). Data from 21 weather stations were considered for generating ET using the ReSET model. Reference ET at the hour and day of each image acquisition date were considered as well as daily wind run. After generating ET for each image, the daily reference ET and temperature of the whole season were considered for interpolating the developed raster of each image to generate the seasonal ET.

Irrigated Parcels

Figure 1 shows the shapefile of the irrigated parcels and phreatophytes in the South Platte River basin. Both shapefiles of the irrigated crops and phreatophytes were obtained from the South Platte Decision Support System (SPDSS). The number of irrigated parcels as presented in the shapefile of the irrigated parcels is 24,950 parcels with an area of 850,549 acres, while the total area of the phreatophytes is 201,632 acres. The irrigated parcels and the phreatophytes are obtaining their consumption water from surface water, groundwater, or both.

Selecting Cold and Hot Points

Models that use reference ET as a calibration method place some conditions on the selection of the cold pixel. Allen et al. (2005) recommend the cold pixel be close to the weather station (20 to 30 km) in METRIC model calibration. They also recommend that the image should be split into several subareas, and that each subarea should be processed with its own hot and cold pixels when significant variation in weather conditions exists. This solution provides better estimates for ET than the use of one reference cold and hot pixel for the whole image. Figure 2 shows an example selecting the model for cold and hot points. The model selects these points on a search radius of 10 kilometers for the closest weather station. The selection of cold points should be in a well irrigated field, and the selection of hot points should be in a fallowed field. Figure 2 shows the hot and cold points with the surface temperature raster as a background on the left and with the original landsat 5 image as background on the right.

Generating ET Using ReSET Model and Landsat 5 Images

The ReSET model is applied in this article to estimate ET using several Landsat 5 scenes. ET is computed for each pixel in the satellite image for the instantaneous time of the image. The process is based on a complete energy balance for each pixel where ET is predicted from the residual amount of energy remaining from the classical energy balance. The algorithm used to calculate the components of the surface energy equation from Landsat imagery can be summarized as follows: Landsat imagery contains visible bands (1, 2, 3), infrared bands (4, 5, 7), and a thermal infrared band (6). From the visible and infrared bands, surface albedo is derived. The normalized difference vegetation index (NDVI) is derived from bands 3 and 4, and the surface temperature is derived from the thermal infrared band (band 6). These three components are combined with the digital elevation models (DEM) and surface roughness to calculate the net radiation (Rn) based on a function developed by Bastiaanssen (2000). The soil heat flux (G) is calculated empirically using albedo, NDVI, surface temperature, and sensible heat flux. Clouds affect the calculations of

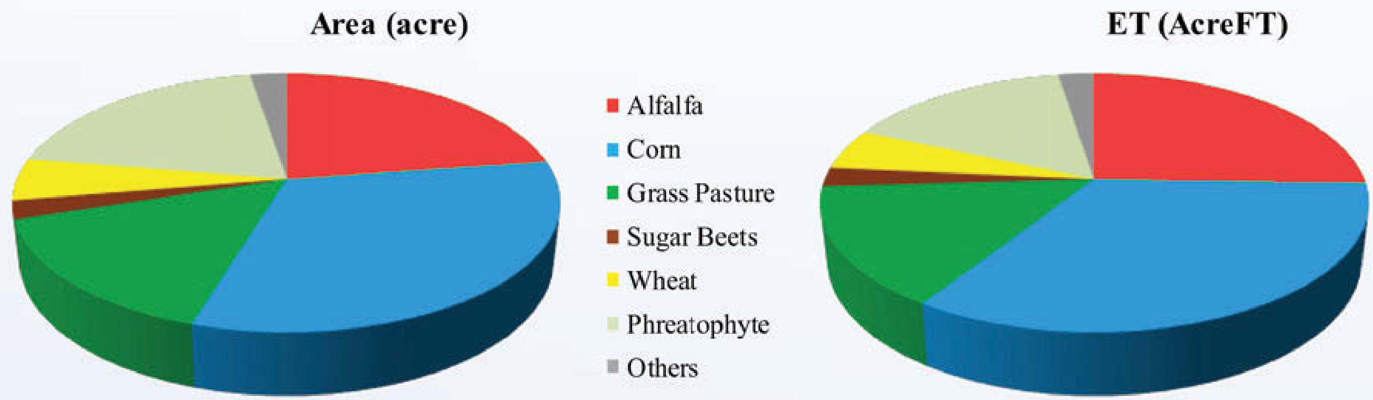


Figure 3. *The area and ET of all irrigated crops and phreatophytes of the South Platte River Basin.*

ET when using remote sensing. Even a thin layer of clouds will produce an error in the calculations, since the areas covered by clouds will reflect as cool areas, which would be misclassified as actively growing areas with high ET values. The cloud cover in the seven Landsat scenes used ranged from zero to 14 percent. A cloud mask was created for each image to eliminate areas covered by clouds or cloud shadows.

ET Acre-Feet of Irrigated Crops and Phreatophytes

Figure 3 as well as Table 1 show the area and ET of each individual irrigated crop as well as the phreatophytes of the South Platte River basin. Crops that made up an area less than one percent of the total were combined as "others" for easy comparison. These crops include: barley, blue grass, dry beans, small grain, sorghum grain, sunflower, and vegetables. The total area of corn, 325,161 acres, includes corn (319,376) and corn grain (5,785). Corn and alfalfa are the dominant crops in the area, followed by grass pasture. Alfalfa has the highest average ET (2.4), while phreatophyte has the lowest average (1.73). The total area of the irrigated crops and phreatophytes of the South Platte exceeds one million acres, while the ET exceeds two million acre-feet.

Conclusions

Most of the previous SEB developers have recommended that these models be applied in areas having constant wind and constant reference ET because they were using data for one weather station. This can create a limitation on the application of these models in areas with high spatial variability in weather parameters. The ReSET model used in this article incorporates the spatial variability of wind and reference ET into the model as grids. Such an approach ensures that each cell is modeled on the basis of its spatial location, taking into consideration all the spatial variability that impacts the calculation of ET. In a study done by Groeneveld et. al, 2007 to estimate the phreatophyte coverage of the South Platte, Landsat images were used for only the peak of the season to generate the stretched normalized difference vegetation index (NDVI*) and data from four weather stations (reference ET and precipitation) to generate the phreatophyte ET. They estimated the whole phreatophyte ET as 255,413 (AcreFT), while the estimation in this article was 348,321 (AcreFT), a 27 percent difference. This difference is due to the fact that Groeneveld et. al used Landsat images only during the peak of the season while in this article, several images were used from the beginning to the end of the season. Also, Goreneveled et. al used the average weather station data to obtain ET, while in this article, the data from 21 weather stations were used at the hour and date of acquiring each individual image. Also, the weather station data were used while interpolating the images from the beginning to the end of the season.

Table 1. *The area and ET of all irrigated crops and phreatophyte of the South Platte River Basin.*

Type	Area (acre)	ET (AcreFT)	Avg. (AF/Acre)	% of Total
Alfalfa	231,159	555,782	2.40	23.32%
Corn	325,161	732,269	2.28	32.81%
Grass Pasture	156,342	327,811	2.10	15.77%
Sugar Beets	23,378	51,804	2.22	2.36%
Wheat	53,426	110,805	2.07	5.39%
Phreatophyte	201,632	348,321	1.73	20.34%
Others*	26,294	54,511	2.07	2.60%
Total	1,017,393	2,181,303	2.14	100.00%

Dialogue instead of Debate

Setting the Tone Through HB12-1278 Community Meetings and Website Input

MaryLou Smith, Policy and Collaboration Specialist, Colorado Water Institute

Community meetings and a dedicated HB12-1278 website allow for community input and interaction with study findings.

On a South Platte tour in October, 2012, Governor Hickenlooper said we need more knowledge of the aquifer, and cooperation on all sides moving forward. He said "Smart people willing to compromise can figure this stuff out."
Courtesy of The Greeley Tribune

Can thoughtful dialogue take precedent over polarized debate on a subject as contentious as the operation of alluvial wells in conjunction with surface water on the South Platte River? Believing that it could, the Colorado Water Institute (CWI) at Colorado State University set about to provide such an opportunity through community meetings and a process for website input as part of its HB12-1278 study.

Colorado House Bill 12-1278 was passed in 2012, authorizing the first comprehensive groundwater study in the state since the landmark study of 1968 that preceded the "Water Right Determination and Administration Act of 1969." The 1969 act was Colorado's attempt to bring groundwater under the same prior appropriation system as surface water rights. The HB12-1278 study was authorized by the legislature, in part, to shed light on whether the strict augmentation of water supplies now required of those who use wells is actually over-augmenting the alluvial aquifer, causing damage from high water tables.

Knowing that the issue is contentious and polarizing, CWI set about to design and implement a process to inform stakeholders and the public about its study and to encourage them to bring creative thinking to the issue through two means—community meetings and an opportunity for input via a dedicated HB12-1278 website.

Community Meetings

January meetings in the communities of Longmont, Gilcrest, and Sterling drew significant audiences. Basic information about the HB12-1278 study and how it is being conducted was followed by a well-received animated human history of the South Platte River and its alluvial aquifer, and the events that led up to the current issues under study. Joe Frank and Robert Sakata, two state water leaders often seen to be on opposite sides of the issue, engaged in a facilitated-dialogue highlighting their respective views, as a means of modeling for the audience the difference in dialogue and debate. Their tone—listening to and exhibiting curiosity about the other's views—set the tone for the public input part of the program. The use of cards with lead statements for members of the audience to complete ahead of speaking, assisted in promoting thoughtful expression of values and beliefs. Those statements included such leads as "I am concerned that…", "I need more information to help me understand," and "We need to preserve…." Different perspectives were shared, but the technique did not lend itself to diatribes and accusations; instead, it allowed for an even-handed expression of various interests.

Stakeholder Input on the Website

In addition to the opportunity to share views at the January community meetings, stakeholders were given the means for sharing their views anonymously via the HB12-1278 website. More than 300 individual statements were contributed and can be viewed online at http://www.cwi.colostate.edu/southplatte/dialogue.shtml. The website also gave those who have experienced adverse effects from high groundwater levels the opportunity to register the specifics of their experience as a means of input to the study team.

Reagan Waskom, director of the Colorado Water Institute and the HB12-1278 study, expressed that the hope of the approach taken with the community meetings and the website stakeholder input was to "raise the level of conversation from contentious debate to respectful dialogue—an important role of a land-grant university."

Website as an Educational Tool

The HB12-1278 website also serves as a means to educate the public about the multitude of issues surrounding the South Platte River and its alluvial aquifer as well as the experiences of other places with similar issues.

- A resources page includes presentations made at a conference on the South Platte issues in November 2012 as well as a number of previous studies, including the 1967 Bittinger-Wright study leading up to the 1969 Act.
- Links to other pertinent websites are provided, including a link to the Colorado Division of Water Resource's groundwater page and the Groundwater Atlas of Colorado by the Colorado Geological Survey.
- A Google Earth flyover of the South Platte River gives the public a chance to take a virtual trip down the South Platte with commentary pointing out major canals and diversions, stream gages, recharge structures, and more.
- A You-Tube video can be accessed on the website. This animation is called Working the Waters: A Brief Human History of the South Platte River and its Alluvial Aquifer, and gives viewers a practical guide to understanding the background of today's issues.
- At the conclusion of the study, the website houses the report to the legislature (the full report as well as an executive summary version) and all the appendices provided as a part of the report.

John Stulp, Reagan Waskom, and Bob Sakata listen as Glenn Fritzler, agricultural producer near LaSalle, shares his thoughts on the South Platte groundwater issue at one of three HB1278 Community meetings.
Photo by Stephen Smith

Aerial view of the South Platte River northeast of Kersey, Colorado.
Photo by Bill Cotton

Where Do We Go From Here?

Reagan Waskom, Director, Colorado Water Institute

The S. Platte basin has been in a state of flux since the early settlers began diverting flows for mining and agriculture in 1859. A number of variable climate, hydrologic, and human factors interact to create an extremely complicated set of conditions impacting the alluvial aquifer. The complexity of interacting factors in the basin makes it challenging to attribute the effect of single factors, such as reduced pumping or increased augmentation on groundwater levels. Additionally, the data record, particularly groundwater levels and pumping volumes, is incomplete and irregular. While variations in the data record introduce some uncertainty in exact amounts of pumping or other parameters, various trends are apparent that allow us to make a number of observations, which taken together reveal certain generalizable findings that warrant further consideration and action. Specifically, the observation well record shows a large percentage of wells with observed rising water levels in the past decade, particularly near Greeley along the mainstem, and in Morgan, Logan, and Sedgwick Counties. As a likely response to curtailment of pumping after 2002 and increased recharge, groundwater levels have increased over the last decade (2003-2012).

Our evaluation of the data leads to the conclusion that current administration of groundwater in the basin works well for the majority of water users, and that senior surface water users are protected from material injury due to well pumping by current administration. Groundwater users in Water District 2 and parts of District 1 have been adversely impacted by the shortage of affordable augmentation supplies to offset pumped depletions. Presently, high groundwater conditions impacting landowners appear to be localized and thus, local solutions are recommended. In the consideration of any changes to the system, it should be acknowledged that senior water rights must be protected in any adjustments to the system and that wells cannot be relieved from the obligation to replace out-of-priority depletions that cause material injury to senior water rights.

Mitigating High Groundwater

Several areas on the S. Platte mainstem, most notably Sterling and the Gilcrest/LaSalle regions, are experiencing high groundwater conditions that should be mitigated to prevent further damage to property and loss of water through non-beneficial consumptive use. There are over 500 recharge projects now in place in the S. Platte basin. According to Division 1 staff, as many as 800 total recharge structures are planned in existing augmentation plans, so there are potentially many more facilities yet to be constructed. Future groundwater recharge projects should be designed, located, constructed, and managed so as to avoid creating groundwater mounds that cause harm to third parties. When the State Engineer and the water court currently evaluate a recharge project, they are primarily determining whether it will offset out-of-priority depletions, with no explicit responsibility to

The South Platte River at Highway 63, Atwood, Colorado.
Photo by Bill Cotton

determine if recharge is at risk of causing property damage to others in the flow path of recharged groundwater.

Recharge structures should only be placed near urbanizing areas after an analysis of potential impact to down gradient properties. In some cases, more complete geotechnical analysis is warranted to identify aquitards, perched water tables, confining layers or clay lenses, and consideration of flow paths that may affect return time to the river. A spacing interval between recharge structures may need to be established to avoid cumulative impacts. The State Engineer's Office (SEO) should be authorized to work with local parties to establish remedies that allow augmentation plans to continue operating without causing impact from high groundwater levels.

The Colorado Division of Water Resources has instrumented the two areas in the S. Platte basin with known high groundwater levels (Sterling and Gilcrest/LaSalle). With two years of data collected (2012-2013) to characterize water level behavior, these areas are primed for implementing pilot tests to evaluate alternative strategies for groundwater management. Pilot approaches may include permitted pumping or decreased recharge as determined to be locally appropriate to test alternative management strategies. Groundwater levels and surface diversions in the pilot areas must be accurately monitored in real time to determine impacts from the pilot management approach, and a plan to augment any injurious depletions must be established. Calibrated numerical groundwater models should be developed and tested against analytical methods in the pilot project areas.

The SEO should be authorized to work with recharge site operators in pilot project areas with mounded groundwater to replace injurious groundwater depletions in ways that will achieve the goals of augmentation plans without further raising water levels. Additionally, a stakeholder group should be authorized to develop local input to the SEO for alternative management in the pilot project areas. The pilot projects should sunset after a three to five year period, and an analysis of what was learned should be provided to the Legislature.

Increased Administrative Flexibility

HB1278 required an evaluation of whether the use of water in the basin could be improved by affording the State Engineer additional authority to administer water rights. Developments in water court and administrative practice have diminished the Division Engineer's ability to play a management role in the distribution of water supplies. As we have already adjudicated most of the augmentation plans for high capacity irrigation wells likely to be developed within Water Districts 2, 1 and 64, the mass movement of irrigation wells into augmentation plans is widely considered to be nearly completed. The decrees are considered final and to the extent that any room exists for adjustment in augmentation requirements, it has to do with the administrative call. Augmentation plans respond to the administrative call, and this is the one moving part that is not fixed in the decrees. Reducing the number of days of administrative call on the river system will allow for additional groundwater use and allow more days of free river, whereby well users can acquire recharge supplies.

Reducing the winter call period was once accomplished in the S. Platte under the gentlemen's agreement. The goal was to fill all the reservoirs and use Colorado's full compact entitlement, but avoid putting a call on so that upstream reservoirs could fill with an agreement to keep North Sterling, Empire, Jackson, and Jumbo whole if water ran short. The call regime is often governed by water rights low in the basin, which does not maximize opportunities for efficiency. However, downstream senior rights cannot be shorted and must have guarantees that they will not be harmed if they operate without placing a priority call.

Development of criteria for implementation of increased management will require the Division Engineer to rely heavily upon available real time data and forecasts. Some monitoring of key basin elements is in place and can be utilized immediately. The HB1278 study recommends specific additional monitoring and data management measures. Datasets related to both surface and groundwater should be used by the Division Engineer to guide the development of an annual management plan, which could then be adjusted throughout the season in response to changing conditions. For areas in the basin experiencing damaging high groundwater conditions, there is the potential for rules to establish standards to determine when portions of the alluvial aquifer are "full" and additional augmentation or curtailment is wasteful. In these regions, it is likely that the aquifer's accretive contributions to the river have reached maximum potential, and additional replacement or curtailment merely contributes to evaporation or evapotranspiration losses without any increase in water supply for senior rights. At such times, the Division Engineer could set the administrative call affecting the augmentation plan so that additional replacement is not required and/or authorize pumping to mitigate damaging conditions and return the aquifer to optimal accretive levels.

Basin Wide Management

Achieving optimum conjunctive use of surface and groundwater in the S. Platte that is sustainable over the long term is best accomplished through implementation of a basin-wide approach that would have the goal of fuller utilization of the river and the alluvial aquifer for all water users' benefit. Presently, no one organization in the basin has the responsibility of managing the whole system for the benefit of all. Admittedly, there are many political, jurisdictional, and funding impediments to implementing basin-wide management in the S. Platte, but it must be understood that this basin faces the most critical water supply gap in the future, and meeting that gap requires us to optimize the use of the resource. Water lost downstream in the recent flood of 2013 and the inability to more effectively use the aquifer during the 2012 drought demonstrates that we are not best positioned to deal with extreme hydrologic events or future shortages.

A new entity such as a South Platte Water Conservation District with a mandate to work with water users across the entire basin could work towards augmenting water supplies and facilitating more flexible management in the basin. The basin-wide entity could be charged to work toward determining the sustainable yield of the aquifer, making a plan for the distribution of sustainable yield by priority, determining how we could operate recharge more effectively in certain areas, and developing water not committed to a specific water right for a water bank or spot market. It could capture and store groundwater and put it in the river in times of drought and replenish it in times of plenty. A regional authority for basin-wide water management is not a new or original idea. Members of the Governor's 2007 South Platte Task Force proposed it, as did the Bittinger/Wright study in 1968. Perhaps the time is right to give this concept more serious consideration as we prepare for the future water supply gap in the basin.

All potential solutions to increase management effectiveness involve greater recognition and use of the alluvial aquifer and development of true conjunctive use. One possible pathway is to define sustainable yield and distribute it according to priority using surface diversions and widespread groundwater withdrawals to insure against hydrologic variability. Alternatively, we could develop provisions to use the sustainable yield of the aquifer for drought only, not to exceed two or three years out of ten within a certain zone or withdrawal rate. Another possible approach is to develop provisions for emergency use of the aquifer during drought with accountability to repay future injurious depletions. A management entity could assess these scenarios, as well as others, in an effort to identify strategies to protect existing rights and maximize beneficial use.

The management entity could operate the real time monitoring network, continue the HB1278 study, build a home for real time management of the system, and this institution could become the champion for the S. Platte Decision Support System (SPDSS). Water users would run the organization and tasks could include:

- Build and operate new storage projects, including underground storage
- Serve as the water banker and develop a fully operating spot market for the basin
- Develop more augmentation water supplies
- Create a basin-wide augmentation bank
- Provide ongoing data collection, analysis, and display
- Provide SPDSS oversight
- Develop an annual river forecast and operating plan that determines sustainable yield
- Develop annual plans for distribution of sustainable yield by priority, using surface and groundwater withdrawals
- Work with the SEO to keep the call period minimized through cooperation and communication
- Find and protect environmental flows
- Implement phreatophyte management
- Provide coordination and communication among water users

Better Monitoring and Models

In an age when water is becoming increasingly scarce and supplies uncertain, robust data networks and decision support tools are critically needed for day-to-day operations and to build a long-term data archive to serve the needs of the people of the State of Colorado. The HB1278 study has revealed that our groundwater monitoring data collection network is irregular and incomplete but could rather easily be substantially upgraded. Better management decisions require higher quality and more easily accessible data. We need to install, instrument, and maintain a groundwater level monitoring network that can be used for real time management decisions. Additionally, water management organizations in the basin should share data and collaborate on data collection. The USGS has developed a statistically robust groundwater monitoring network as part of the HB1278 study based on existing monitoring wells that can greatly improve our ability to track and manage groundwater for very low initial cost. The complete network, consisting of three subnetworks, includes wells managed by federal, state, and local agencies, demonstrating the need to gather community resources collaboratively in a unifying manner to establish an optimal network for the region.

Aerial view of the Farmers Pawnee Ditch on the South Platte River, Atwood, Colorado. Photo by Bill Cotton

We also need a basin-wide model and a common technical platform that all water users in the basin agree to employ. The SPDSS is the best mechanism to provide this platform over time. However, the Colorado Water Conservation Board needs to work with basin water interests to develop stakeholder ownership of the SPDSS to ensure it continues to improve and meet the needs of basin water users. In addition, the current status of climate data collection in the S. Platte is problematic. Long-term stations are simply too few and too far apart. In light of current federal budgets, relying on National Weather Service and the Natural Resources Conservation Service to fill these gaps and bring back records to some locations is likely not feasible. A more robust and adequately funded network of weather stations with high spatial representation across the state should be considered to ensure Colorado meets the data needs of stakeholders across the state. Improving the monitoring network is in the interest of all water users and could be coordinated under the basin-wide entity.

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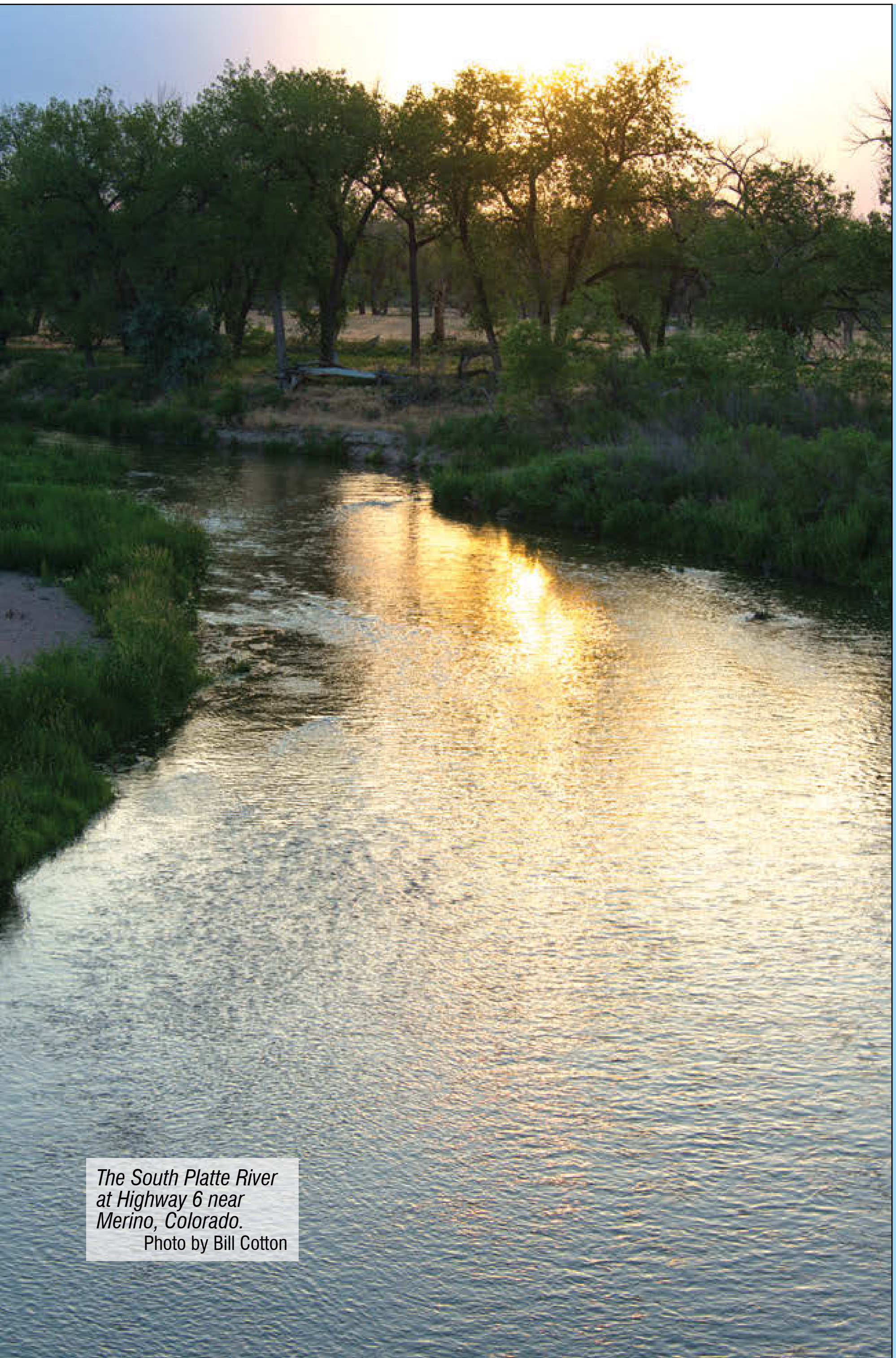

The South Platte River at Highway 6 near Merino, Colorado.
Photo by Bill Cotton

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