1/18-19/11 Bd Mtg Item 12
Reasonable Use Doctrine
Deadline: 1/13/10 by 12 noon

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January 13, 2011

Mr. Charlie Hoppin, Chair
and Members of the Board
State Water Resources Control Board
1001 I Street
Sacramento, CA 95814
Via Electronic Mail: commentletters@waterboards.ca.gov

Subject: **1/18-19/2011 BOARD MEETING – Item #12, Reasonable Use Doctrine**

Dear Mr. Hoppin and Members of the Board:

Thank you for the opportunity to comment on the Delta Watermaster Report "The Reasonable Use Doctrine & Agricultural Water Use Efficiency." I submit these comments on behalf of Trout Unlimited, the nation's oldest and largest coldwater conservation organization. We have more than 140,000 members and 10,000 members in California, and we have water lawyers, scientists and engineers working throughout the West to improve water use practices and streamflow.

We urge you to continue development of reasonable use measures to improve water use efficiency and to host a "Reasonable Use Summit" as recommended by the Watermaster. Trout Unlimited would be pleased to participate in such a summit.

As the report states, the Reasonable Use Doctrine is the "cornerstone of California's complex water rights laws." Unlike most other Western states, which have a comparatively unified approach to water right administration, California water law is fractured between the rules governing appropriations, riparian rights, and groundwater. The Reasonable Use Doctrine is the thread that runs throughout, and it offers perhaps the best hope at systematic solutions.

TU also agrees that the Reasonable Use Doctrine is available for proactive use, and we urge the Board to use it in a proactive manner. The experience with frost protection in the Russian River is illustrative. The rulemaking is not even complete, and it has had a remarkable beneficial effect on practices, with many landowners moving ahead of the rule to add off-stream storage or utilize wind machines as alternatives to direct diversions. It is worth stressing that the manner of diversion may be unreasonable even if the use of water itself is not. Again, the frost protection experience is illustrative. In both rivers, the effect of implementing the reasonable use doctrine is not to end diversions but to shift diversions from direct diversions to diversions to off-stream storage ponds.

Finally, we agree with the Watermaster that establishing a Reasonable Use Unit within the Division of Water Rights is a good idea.

We do have one note of caution. This will not come as news to you and your fellow Board members or to the Watermaster, but it is worth considering if the Summit moves forward. The Report states that the "underlying premise of this report is that the inefficient use of water is an unreasonable use of water." That may be so, if the inefficiency deprives other water users or instream beneficial uses of water. But not all efficiency is created equal. Where inefficient water use results in evaporation rather than crop production or return flows, it can be reduced in a way that benefits everyone. Similarly, some return flows carry pollution and exacerbate temperature impairments. But some "inefficient" water use makes its way downstream in a manner that benefits instream uses and downstream water right holders.

"Efficiency" is often defined to mean increasing crop production as a proportion of diversions. There is a natural tendency for irrigators to continue diversions at a given level even as they increase "efficiency." That might benefit society by increasing yields, but it could harm instream uses and other water right holders by reducing return flows and the amount of water available in a watershed. (It might be useful at the Summit to develop a workable definition of efficiency that keeps the focus on water lost to the stream system.)

Experience has shown that irrigation efficiency is a valuable tool in improving streamflows and water availability for other purposes, and TU has worked with farmers in ways that have resulted in meaningful improvements in streams. (See www.tu.org/conservation/western-water-project for a number of case studies and videos.) A common theme in our work is that the opportunity to use efficiency to improve conservation depends on local circumstances, and that efficiency must be paired with conscious efforts to improve streamflows in order to work. (See Eloise Kendy (2005) "Water-Balance Considerations for Instream Flow Restoration Design: Understanding Irrigation Return Flow." Report for Trout Unlimited, Western Water Project, Columbia River Transactions.) This paper and the others cited in this letter are attached.

Unfortunately, it is well documented that some well-intentioned programs to increase efficiency have had unintended consequences. In one influential study of the Salt River Basin in Wyoming, the transition from flood irrigation to sprinkler irrigation resulted in an overall increase in stream discharge and crop production, but it *decreased* streamflows during the critical late season as return flows dropped and farmers were able to effectively irrigate later into the year. (Venn, Brian J., Johnson Drew W. and Pochop, Larry O. (2004) "Hydrologic Impacts due to Changes in Conveyance and Conversion from Flood to Sprinkler Irrigation Practices." Journal of Irrigation and Drainage Engineering, Vol. 130, No. 3.)

More pessimistically, a paper published in the Proceedings of the National Academy of Sciences concluded that increased agricultural water use efficiency is unlikely to result in increased availability of water for instream uses or other water right holders in most circumstances. Rather it is likely to increase depletions unless efficiency is accompanied by simultaneous measures to decrease diversions. (Frank A. Ward and Manuel Pulido-Velazquez (2008) "Water conservation in irrigation can increase water use." PNAS 2008 105 (47) 18215-18220; published ahead of print November 17, 2008, doi:10.1073/pnas.0805554105.)

None of this is intended to suggest that increased efficiency is a bad thing, or that the Reasonable Use Summit should be rejected. But no one should assume that increasing "efficiency" automatically equates to "leaving water instream." (C.f. Watermaster Report, p. 12.) It takes conscious effort to make it so. Because many of the benefits of improved efficiency cited in the Watermaster Report are actually benefits of reduced diversions, and reduced diversions may—or may not—result from improved efficiency, it is important to be aware of the relationship between the two.

As the Ward paper states, "achieving real water savings requires designing institutional, technical, and accounting measures that accurately track and economically reward reduced water depletions." Trout Unlimited is very interested in working with the State Water Board to implement not only water use efficiency programs but also the institutional and technical measures necessary to realize real water savings.

In closing, we strongly encourage the Board to develop a proactive strategy to improve the reasonable use of water in California, starting with a Reasonable Use Summit. Thank you for your consideration of our comments.

Sincerely,

Brian J. Johnson

WATER-BALANCE CONSIDERATIONS FOR INSTREAM FLOW RESTORATION DESIGN: UNDERSTANDING IRRIGATION RETURN FLOW

Prepared for:

Trout Unlimited
Western Water Project
Columbia River Transactions

By:

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September 8, 2005

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Water-Balance Considerations for Instream Flow Restoration Design: Understanding Irrigation Return Flow

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Executive Summary

Irrigation return flow is the excess irrigation water that is not used by crops, but instead returns underground to its original source or another source of water. Reducing irrigation water use may not only reduce diversions from a target stream, as is often the restoration goal, but may also reduce irrigation return flow to the same or another stream. If downstream fisheries, irrigators, or other users rely on that return flow, then reducing irrigation water use may unintentionally defeat the restoration goal by dewatering other stream reaches. Therefore, it is important to consider irrigation return flow in streamflow restoration design.

The main questions about return flow to address before pursuing a change in irrigation water use are:

How much irrigation water recharges the aquifer?
When does return flow reach surface water?
Where does it return to surface water?
How much returns to surface water at any given time and place?
Who relies on the contribution of return flow to surface water?

Twelve case studies – eleven in Montana and one in Colorado -- illustrate the approaches and considerations involved in analyzing and understanding return flow processes.

The North Fork Blackfoot River and Lower Poorman Creek case studies illustrate the basic approaches for local-scale projects intended to re-water specific, relatively short dewatered stream reaches. These approaches include synoptic streamflow measurements (seepage runs), aquifer characterization, and periodic water-table measurements. In both cases, it was determined that the impacts of reducing return flows would not be severe, while the effects of reducing diversions would be highly beneficial.

The Flint Creek case study illustrates typical hydrologic patterns observed in irrigated areas in Montana. In spring and early summer, the water table rises in response to snowmelt, rainfall, and irrigation return flow. Water levels generally stay high throughout the irrigation season, as return flow continues to recharge the aquifer. This pattern contrasts with natural streamflow, which typically peaks in late spring, then quickly drops. In the fall, after irrigation season ends, ground-water levels gradually decline. When irrigation diversions cease, streamflow (in the absence of reservoir control) comes back up.

This pattern contrasts with that observed in the upper Big Hole basin. There, streamflow shows little or no recovery after diversions stop. Irrigation return flow has raised the water table so high that crops continue to consume ground water ("sub-irrigation") in the absence of surface application. It is not until the crops stop growing in the fall that return flow can discharge to the river without first being consumed by crops, and streamflow recovers slightly.

The Gallatin Valley and west Billings case studies illustrate several non-traditional analytical methods, including the analysis of stable isotopes of water to distinguish irrigation return flow from other ground water in an aquifer. The west Billings case in particular provides an excellent example of a comprehensive quantification of all aspects of the water balance, using a variety of approaches. Both the Gallatin Valley and west Billings are undergoing major land-use changes, from surface-water supplied flood irrigation to ground-water supplied residential and commercial development. If left unmitigated, the consequent changes in water use will decrease late-season streamflow, which depends on natural ground-water discharge. Strategies to reduce impacts to fisheries include adopting xeriscape techniques for landscaping, enhancing storm-water infiltration, and replacing irrigation return flow with artificial recharge to ground water.

Two studies of the Beaverhead River basin used numerical methods to quantify the lag time between irrigation diversion and return flow to surface water. One study examined long-term streamflow measurements in detail. It showed that even with incomplete datasets, a long historical record often divulges more about how a system responds to different hydrologic stresses than does a short, but complete record. The other study was a comprehensive analysis, using a variety of approaches to quantify the water balance as a function of time. In this case, ground-water age dating proved pivotal in accurately modeling irrigation return flow.

Two studies of the Greenfields Irrigation Division addressed water-quality impacts of irrigation return flow. Excess irrigation water from west of the Fairfield Bench mobilizes selenium from the underlying geologic deposits, posing a threat to Freezeout Lake, which receives the drainage. Excess irrigation water from the Bench itself discharges into the highly erosive Muddy Creek, causing extensive sedimentation problems downstream. But any strategy that reduces irrigation diversions to the Bench will also reduce the availability of ground water, the sole water supply for residents of the Bench.

The Flathead Indian Reservation case study illustrates the importance of geologic substrate in controlling seepage from canals. By concentrating efforts on areas underlain by permeable alluvium, 60 percent of canal leakage could be eliminated by lining only 9 percent of the Reservation's more than 56 million square feet of canals.

The Colorado Front Range case study illustrates the use of small-scale weighing lysimeters to measure return flow. Researchers determined this simple method compares well with other methods for field-scale investigations.

A common thread throughout the case studies is that each project is unique, and site-specific investigations are crucial. There is no standard "blueprint" for evaluating irrigation return flow for water leasing or any other water management strategy. Nevertheless, a few broad guidelines emerge.

First, do your homework. A wealth of maps, reports, and other information is available in libraries and on the internet, and should be compiled and consulted before going into the field. A list of key resources and how to find them is included in this report.

Second, visit the site. Record your observations on a map. Make note of dewatered stream reaches, diversions, pumps, irrigation drains, other manmade structures, natural springs and seeps, and other points of interest. Follow the major diversions up to where the irrigation water is applied. Note the condition of the ditches and canals that convey the water. Note areas that are unusually wet, where water from leaky ditches may be discharging to the land surface. In irrigated areas, note the crop types and conditions, the irrigation method, the amount of standing or flowing water, and where excess irrigation water flows. Think about how the diverse pieces you observe in the field fit together to balance the water budget. Note potential measurement sites. Importantly, visit with the locals to get the first-hand information on historical and current land and water-use practices, weather patterns, and streamflow conditions that cannot be found in maps and reports.

When the time comes to design the streamflow restoration project, consider the goals and scale of the project. For example, synoptic measurements might be adequate to address dewatering in a short stream stretch, whereas basin-wide management objectives could better be served by comprehensive water-balance studies and modeling. Geologic and hydrologic settings, as amply illustrated in the case studies, are major considerations for selecting restoration strategies. Social and legal issues such as water rights and political climate also play into project study and design.

Acknowledgements

The author gratefully acknowledges the contribution of DNRC hydrologist Mike Roberts, from helping to shape the content and direction of this report, to critically reviewing the final product, and for many enlightening discussions along the way. Many thanks also to DNRC hydrologist Terry Voeller for reviewing the draft report. Finally, special appreciation goes to Stan Bradshaw of Trout Unlimited for conceiving the idea for this project, obtaining support, and ensuring that the final product is useful and accessible to those whose work is dedicated to protecting instream flows.

Introduction

> "*The key question for water management in earlier decades was: how much water can we take from this river? The new question is: How much water do we need to leave in the river and how will the development of the resource in the watershed and globally change the amount that the river will provide? The science needed to answer the new question is very different from that which was needed for the questions of the past. When resources were relatively abundant compared to their level of use, the information needs were simple to satisfy. As competition for water intensifies, the need for information becomes much more significant. More and more, water is becoming a marketed resource, with market trades taking place among users. Evaluation of the impacts of these market decisions demands a new scientific capability to help society avoid unintended consequences from these tràdes affecting other uses or users. Flexible resource management depends on comprehensive information about the resource.*" (National Science and Technology Council Committee on Environment and Natural Resources Subcommittee on Water Availability and Quantity, 2004)

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Without water in streams, there can be no trout. It's that simple. For various reasons, numerous reaches of important Montana trout streams have become -- or are in danger of becoming -- dewatered. That's why Trout Unlimited focuses such intense effort on restoring and protecting instream flows.

As part of those efforts, Trout Unlimited often finds opportunities to lease irrigation water from farmers who no longer need to irrigate nearby parcels of land or are willing to change their irrigation practices in order to reduce their diversions. However, in many cases, excess irrigation water from that land may provide crucial water sources downstream. It may support wetlands and fisheries that otherwise would not exist, or it may support irrigation or other uses. Trout Unlimited wants to ensure that its work to solve dewatering problems upstream doesn't create new problems downstream. Understanding return flows is important for avoiding unintended consequences to the stream that an instream lease is supposed to benefit.

Predicting the fate of excess irrigation water is not a simple proposition. Nevertheless, several investigators have attempted to do just that, right here in Montana. This report reviews these cases, as a first step to informing Trout Unlimited of various options for evaluating return flow. After reviewing the cases, the report summarizes the important considerations for understanding and assessing the impacts of changing irrigation patterns. The report concludes with a reference table of analytical methods described in the text, cross-referenced to the case studies that employed each.

Water Balance and Return Flow Basics

In Montana, "return flow" is defined as "that part of a diverted flow which is applied to irrigated land and is not consumed and returns underground to its original source or another source of water, and to which other water users are entitled to a continuation of, as part of their water right. Return flow is not wastewater. Rather, it is irrigation water seeping back to a stream after it has gone underground to perform its nutritional function. Return flow results from use and not from water carried on the surface in ditches and returned to the stream" (Notice of Adoption and Amendment, Montana Administrative Register, 12/16/04).

Figure 1 depicts the flows into, out of, and beneath an irrigated area. Precipitation, *P*, and applied irrigation water, *I*, enter the field. Some of this water evaporates from plant and soil surfaces, and some is used, or transpired, by crops. Evapotranspiration, *ET*, represents the combination of these two processes. *ET* is the quantity of water that is consumed. The rest of the water that enters the field either runs off *(RO)* the land surface or drains through the root zone to the water table, where it recharges *(R)* the aquifer underground. The water table is the surface of the ground water, *GW*. Surface water *(SW_{in})* that flows into the area may be joined by *GW*, *RO*, and return flow *(RF)* before leaving the area as surface-water outflow *(SW_{out})*. These are the main components of the area's *water balance*. Quantifying return flow is almost always an exercise in estimating and calculating various components of the water balance.

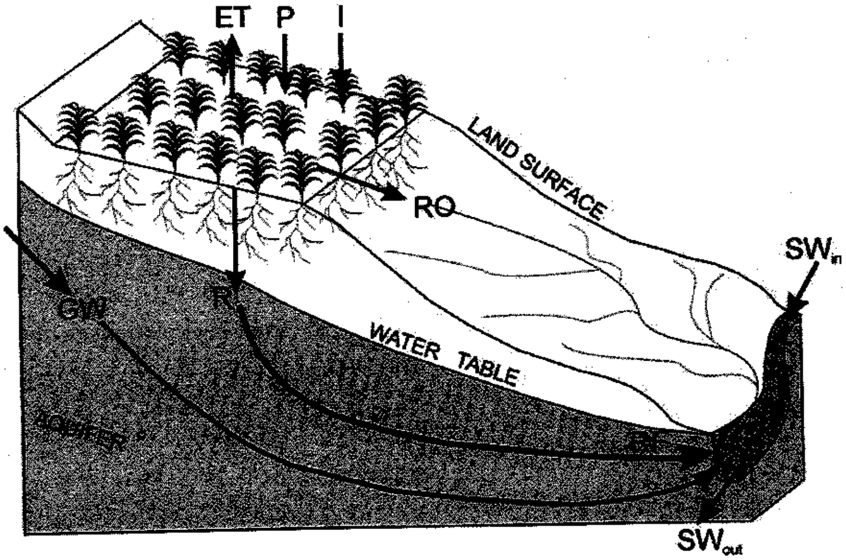


Figure 1. Schematic diagram of water-balance components of an irrigated field. Inflows: P = precipitation, I = irrigation. Outflows: ET = evapotranspiration, RO = runoff, R = ground-water recharge. GW = ground water recharged elsewhere. RF = return flow from the field to surface water.

Note that standard hydrologic definitions of irrigation return flow include *all* the artificially applied water that is not consumed by evapotranspiration and that either drains to the water table *or* runs off to a surface-water body. This report, however, adopts the Montana definition, so only the component that recharges the aquifer is considered.

The terms "recharge" and "discharge" also can be confusing. Because these terms describe flow directions into or out of a body of water, they need to be interpreted within the context of the sentence, and not generally as stand-alone terms. Recharge indicates flow into, and discharge indicates flow out of, a water body. For example, surface water may *discharge* from a stream into an adjacent aquifer. In that case, infiltrated surface water *recharges* ground water. Or, if the flow direction is reversed, ground water may *discharge* into a stream. *Ground-water recharge* refers to water that flows into, or replenishes, an aquifer; *ground-water discharge* refers to water that flows out of, or leaves, an aquifer. In figure 1, *R* represents ground-water recharge from the land surface, and *RF* represents ground-water discharge to the stream. *GW* represents an entire ground-water flow path, beginning with recharge from subsurface sources and ending with discharge to the stream.

Influence of Irrigation Return Flow on Instream Flows

Flow through aquifers occurs at a considerably slower rate than surface flow. A typical floodplain aquifer in Montana conveys ground water at a velocity of only a few feet per day. Movement through the aquifer effectively extends the time between irrigation water being applied to fields and excess water returning to streams. Thus, return flows can provide late-season irrigation water to farmers and ranchers who otherwise might be able to produce only one crop annually.

Why is return flow important for streamflow restoration? Because reducing irrigation water use may not only reduce diversions from a target stream, as is often the restoration goal, but may also reduce irrigation return flow to the same or another stream. If downstream fisheries, irrigators, or other users rely on that return flow, then reducing irrigation water use may unintentionally defeat the restoration goal by dewatering other stream reaches.

The main questions, then, to answer about return flow before pursuing a change in irrigation water use are:

How much irrigation water recharges the aquifer?
When does return flow reach surface water?
Where does it return to surface water?
How much returns to surface water at any given time and place?
Who relies on the contribution of return flow to surface water?

The following section explores how researchers have approached these questions in Montana, and what they have found.

Case Studies of Irrigation Return Flow Investigations

Twelve case studies – eleven from Montana and one from Colorado – have been selected to illustrate the approaches and considerations involved in analyzing and understanding return flow processes. The first few cases are described in greater detail than the others, in order to introduce the reader to standard methodologies and basic principles. Many of these methods are further explained in Boxes on pages 43 to 53. The subsequent cases highlight unique and innovative approaches.

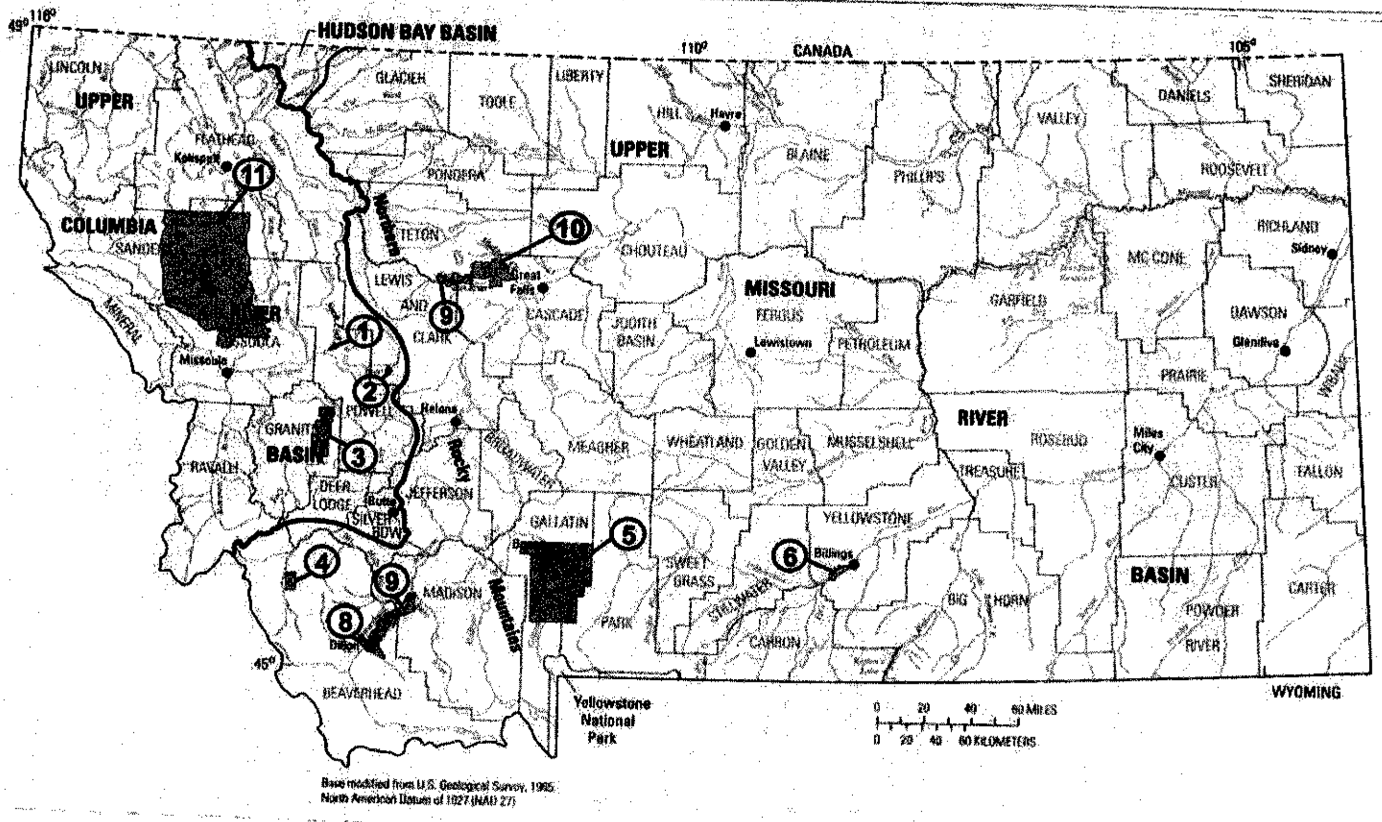
The methodologies used in these cases by no means comprise an exhaustive litany of all possible approaches. Many others have been used, and many are surely yet to be developed….. and their application will just as surely further our understanding of the role of irrigation return flow in sustaining instream flows.

1. North Fork Blackfoot River Valley: Targeting Efficiency Improvements

The North Fork Blackfoot River flows southwestward into the Blackfoot River, which is a tributary to the Clark Fork in western Montana (fig. 2). Its drainage area is about 275 square miles (176,000 acres). The approximately 25-square-mile Kleinschmidt Flat is the main crop-producing area in the basin. Water is diverted from the North Fork Blackfoot and its tributaries to about 2,000 irrigated acres at elevations ranging from about 4,100 to 4,500 feet. Excess irrigation water returns to the North Fork Blackfoot River.

In 1997 to 2000, hydrologist Mike Roberts and hydrogeologist Kirk Waren of the Montana Department of Natural Resources and Conservation characterized the hydrology and water use in the area, and identified stream and ditch reaches where measurable flow gains and losses occurred (Roberts and Waren, 2001). Although irrigation return flow was not a specific focus of investigation, results of the study lend insight to return flow processes in the basin.

Previously published geologic and topographic maps of the Kleinschmidt Flat area give clues to the hydrologic system. The Flat is almost completely surrounded by mountains and hills composed of Precambrian-age argillites and quartzites (siltstone and sandstone that have been subjected to intense heat and pressure deep underground), in some places capped by Quaternary-age glacial till (cobbles and boulders in a finely ground silty matrix). These are common geologic formations in northwestern Montana. The Flat itself is composed of Quaternary-age alluvium (heterogeneous deposits left by rivers and streams) and glacial outwash (coarse-grained deposits left by braided streams melting out of glaciers). Argillite, quartzite, and glacial till generally are "tight" rocks and deposits with little ability to convey ground water. In contrast, alluvium and outwash are relatively well-sorted, coarse-grained deposits, which easily transmit ground water. Therefore, it could immediately be surmised that ground-water flow occurs primarily within the "bathtub" of permeable alluvial and outwash deposits, which are "contained" within the much older, denser argillite and quartzite bedrock.



1. North Fork Blackfoot River valley (Roberts and Waren, 2001)
2. Lower Poorman Creek (Roberts and Levens, 2002)
3. Flint Creek valley (Voeller and Waren, 1997)
4. Upper Big Hole basin, Francis Unit, (Marvin and Voeller, 2000)
5. Gallatin Valley (Kendy, 2001)
6. West Billings area (Olson et al., 2002)
7. Beaverhead basin (Nicklin and Brustkern, 1983)
8. Upper Beaverhead basin (Uthman and Beck, 1998; Pope et al., 1999)
9. Greenfields Irrigation Division, Freezeout WMA (Nimick et al., 1996; Kendy et al, 1999)
10. Greenfields Irrigation Division, Muddy Creek (Osborne et al., 1983)
11. Flathead Indian Reservation (Slagle, 1992)

Figure 1. Locations of Montana case studies described in this report.

Although a detailed water-table map (Box 1) was not available prior to Roberts' and Waren's work, a solid initial guess was that ground water flows in roughly the same direction as surface water. This is almost always the case for permeable deposits like alluvium and outwash. So, even before any field work commenced, it could be deduced that excess irrigation water drains down to the water table, then moves laterally with ground water in a roughly southwesterly direction, toward the North Fork Blackfoot River at or near the downstream end of Kleinschmidt Flat. Because the bedrock areas are topographically higher, and are composed of less permeable geologic material than the Flat, it is likely that any irrigation return flow that leaves the Flat does so as surface water after discharging from the aquifer.

The investigators took a two-pronged approach to understanding interactions between surface water and ground water. The surface-water assessment focused on measuring stream and ditch flows, while the ground-water assessment focused on monitoring wells.

Surface Water Study

Synoptic streamflow measurements (Box 2) were the mainstay of the surface-water investigation of the North Fork Blackfoot. Continuous recorders operated by the Forest Service and U.S. Geological Survey (Box 3) at the upstream and downstream ends of the study area anchored a series of periodic measurements by Roberts at 14 additional sites.

Results of eight synoptic measurement events over three years (1997, 1998, 2000) indicate that streams and ditches in the northeastern, or upstream, part of Kleinschmidt Flat lose flow, while those in the southeastern part gain flow from ground-water discharge. In other words, seepage from surface water recharges ground water in the upper part of the Flat, while ground-water discharge feeds surface water in the lower part. For each synoptic measurement event, Roberts and Waren (2001) calculated streamflow gains and losses for the upper and lower reach of the North Fork.

Synoptic streamflow measurements also were used to determine seepage rates from individual canals. Average seepage rates ranged from about 15 to 61 percent of the diverted flow, with the highest rates occurring early in the irrigation season, when soils were dry.

Overall, ground-water discharge to surface water exceeded ground-water recharge from surface water on Kleinschmidt Flat, so ground water was coming from sources other than stream seepage. These sources may include subsurface flow into the aquifer, and seepage from irrigated fields.

Ground Water Study

The ground-water study consisted of compiling and evaluating geologic reports and drillers' logs (Box 4) to characterize the aquifer, and measuring water levels monthly in 19 wells.

Predictably, water-table maps (Box 1) based on measurements of the 19 monitoring wells indicate that ground water flows toward the southwest. In the southwestern (downstream) part of Kleinschmidt Flat, the flow direction turns more westward, toward the North Fork Blackfoot River. The water-table map also concurs with the conclusion based on synoptic measurements that the lower reach of the North Fork was gaining.

Every spring and summer, the ground-water reservoir grows in response to recharge from snowmelt, rainfall, and irrigation return flow. Every fall and winter, the reservoir shrinks as ground water drains from the aquifer. Increases and decreases in ground-water storage are manifested as the water table rising and falling, as indicated by ground-water hydrographs, or plots of water-table depth (or elevation) *vs.* time. Data for a hydrograph are obtained by measuring the depth to water in a well repeatedly over a period ranging from a single season to many years, in order to document water-level fluctuates.

Waren used ground-water hydrographs to calculate the quantity of water stored in and released from the aquifer seasonally. Over the winter of 1997-98, the water table dropped about 15 ft in the northeastern corner of the Flat, graduating down to 1 ft in the southwestern part, as recharge from the previous year drained from the aquifer. These seasonal water-table declines were plotted and contoured throughout the study area. Multiplying the land area by the water-level decline gives the volume of aquifer from which water released from storage, but not the volume of water itself. For that, the aquifer volume must be multiplied by the aquifer porosity, or specific yield (n or S_y, Boxes 5 and 7), since water only drains from pore spaces, not from the rock itself. Waren obtained S_y values from published literature. Ultimately, he found that the observed streamflow gains during this period "could reasonably be attributed to" release of ground-water storage as determined from their ground-water hydrograph analysis. It is important to note that this analysis does not distinguish irrigation return flow (*RF*, fig. 1) from other water in the aquifer (*GW*, fig. 1).

Lessons Learned

The study provides an accounting of water losses from the area. According to Blaney-Criddle calculations (Box 6), crops growing on Kleinschmidt Flat consume about 14.5 cubic feet per second (cfs) of water over the four-month growing season, compared to about 30 cfs diverted for irrigation. According to the streamflow measurements, the North Fork of the Blackfoot River naturally loses about 42 cfs from a four-mile stretch in the upper part of the basin (Roberts and Waren, 2001).

To increase instream flows during irrigation season, Roberts and Waren (2001) suggested improving conveyance efficiency of highly permeable canals in the upper part of Kleinschmidt Flat. It was their basin-scale water balance that focused their attention on the upper part of the basin, while their seepage runs on individual canals pointed them to specific reaches on which to direct conveyance improvement efforts.

Improving efficiency would reduce diversions from the upper reach, which would in turn increase streamflow. But increasing efficiency also would reduce ground-water recharge from excess irrigation. Return flows reenter surface water in the lower reach, where dewatering is not as serious as in the upper reach. Moreover, seepage from the upper reach of the river will continue to recharge the aquifer, providing ground-water recharge that will discharge later into the lower reach of the river. Therefore, the impacts of reducing return flows to the lower reach are unlikely to be severe, while the effects of reducing diversions from the upper reach could be highly beneficial.

2. Lower Poorman Creek: Restoring Upstream, Protecting Downstream

Poorman Creek is a tributary to Grantier Spring Creek, which flows into the Blackfoot River (fig. 2). Diversions from Poorman Creek irrigate about 340 acres, including 250 acres of sprinkler-irrigated and 90 acres of flood-irrigated land. Periodically, lower Poorman Creek runs dry, eliminating connectivity between important upstream and downstream aquatic biological communities. To maintain instream flows in the lower reach, a coalition of public and private interests proposed converting the 90-acre field from flood irrigation to more efficient sprinkler irrigation. The consequent reduction in water use would mean smaller diversions from Poorman Creek, and potentially more instream flow during irrigation season.

Changing from flood irrigation to sprinkler irrigation would require less water diversion, but also would reduce irrigation return flow. Downgradient from the 90-acre irrigated field slated for conversion lie a spring creek and wetland complex that are fed by ground-water discharge. It is imperative that any action to enhance the Poorman Creek fishery does not inadvertently harm the spring creek and wetlands.

In 2001, hydrologist Mike Roberts and hydrogeologist Russell Levens of the Montana Department of Natural Resources and Conservation characterized the timing and magnitude of flow in lower Poorman Creek. An important facet of their work was to anticipate downstream impacts of reduced irrigation return flow, should the flood-irrigated area be converted to sprinkler irrigation (Roberts and Levens, 2002).

Roberts and Levens (2002) conducted six synoptic streamflow measurements (Box 2) in June through August 2001 to locate and quantify streamflow gains and losses. They found that irrigation diversions greatly exacerbated natural streamflow losses, causing the stream to dewater completely in July and August. Even when diversions ceased in late August, seepage from the streambed continued and lower reaches of Poorman Creek remained dry. They concluded that the critical threshold of flow needed in the upper reach in order to preclude complete dewatering of the lower reach is between 1.8 and 6.5 cfs. This threshold potentially could be achieved by reducing diversions to the 90-acre flood-irrigated field.

The next question was how the consequent reduction in irrigation return flow would affect the spring creek and wetland complex downstream. Water-table maps (Box 1) based on observations in 6 monitoring wells indicate that during irrigation season, ground water flows from the 90-acre field toward (and presumably discharges into) the spring creek and wetlands. In late October, after irrigation has ceased, the flow direction shifts away from the wetlands. However, ground water from other areas continues to feed the wetlands. Under proposed sprinkler-irrigated conditions, ground-water flow is expected to be similar to that observed during late October. Therefore, Roberts and Levens (2002) concluded that although some small depletion may occur in the lower spring creek, the proposed change to sprinkler irrigation would not adversely affect the wetlands.

Lessons Learned

To address the dewatering problem, it was important to note that lower Poorman Creek stayed dry well into the irrigation season. No late-season response to irrigation return flow was observed. Therefore, it was concluded that any reductions in return flow caused by reducing diversions could not harm Poorman Creek any more than it was already being harmed. Still, excess irrigation water leaking out of ditches and seeping through irrigated soils had to go somewhere, so it couldn't simply be ignored. This explains why the focus of the return flow investigation was on the downstream spring creek and wetland complex, rather than on Poorman Creek itself.

Ultimately, the solution selected and implemented was to replace leaky ditches with a gravity-fed pipeline and to replace the flood-irrigation system with a center-pivot sprinkler system. The Montana Department of Natural Resources and Conservation, which facilitated the improvements, is currently monitoring Poorman Creek to document how these changes are increasing its connectivity to the Blackfoot River.

3. Flint Creek Valley: Understanding Irrigation Impacts

Flint Creek, a tributary to the Clark Fork, drains the Philipsburg and Drummond valleys in western Montana (fig. 1). Irrigation water is diverted from Flint Creek and its tributaries, and from East Fork Rock Creek Reservoir, which is located in an adjacent drainage basin. About 25,000 acres of land are irrigated, at elevations ranging from about 4,000 to 6,000 feet. Excess irrigation water returns to Flint Creek and to the Clark Fork.

In 1994 to 1996, hydrologist Terry Voeller and hydrogeologist Kirk Waren of the Montana Department of Natural Resources and Conservation quantified the amount and timing of return flow, assessed the potential for increased water availability through ground-water storage, and developed data for a numerical model of irrigation return flow processes in the Flint Creek valley (Voeller and Waren, 1997).

They relied primarily on a surface-water-balance approach requiring intensive data collection and analysis. Their parallel study of the ground-water system lent additional credence and insight to their results.

Surface-Water Study

The goal of the surface-water study was to determine return flow by accounting for all inflows and outflows, either by direct measurement or by calculation, during the post-irrigation season. Figure 3 conceptualizes Voeller and Waren's approach.

According to fig. 3,

$$\text{Inflow} - \text{Diversions} + \text{Return Flow} = \text{Outflow}$$

The study focused on the period from mid-October through December, after diversions and crop growth had ended for the year, so diversions and evapotranspiration need not be considered. Then, the equation reduces to:

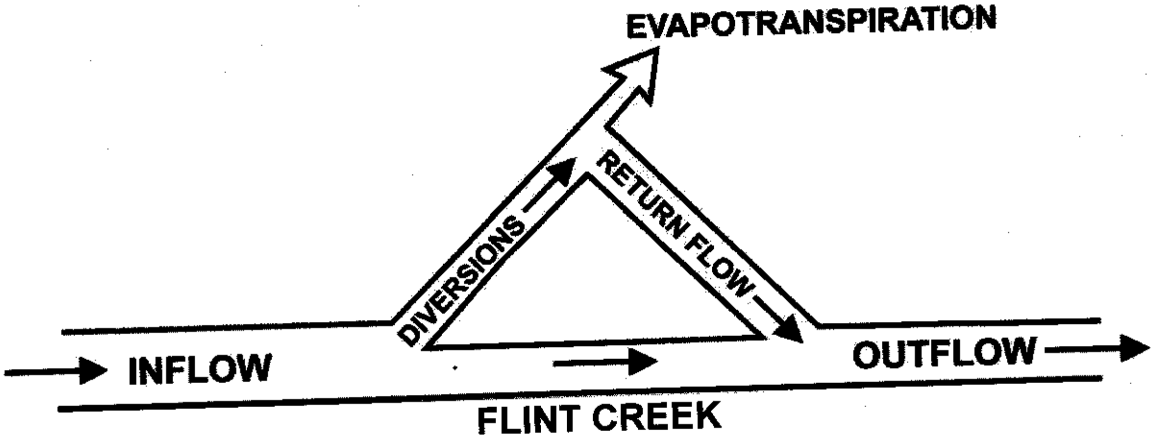


Figure 3. Conceptual representation of surface-water balance used to quantify return flows to Flint Creek. Inflows and outflows from each of four subareas were estimated or measured during the fall, after irrigation had ceased, so there were no diversions, and evapotranspiration was negligible. Return flow was then calculated as the residual. Modified from Nicklin and Brustkern (1983).

$$\text{Return Flow} = \text{Inflow} - \text{Outflow}$$

In addition to synoptic runs (Box 2), which consider a "snapshot" in time, Voeller and Waren (1997) also determined the *total* volume of flows throughout the post-irrigation season. Where they did not install continuous streamflow recorders, they estimated total seasonal flows based on periodic measurements, using standard statistical methods to correlate unmeasured with measured sites. Though obviously not as accurate as actual measurements, it is normal, acceptable procedure to estimate flows for unmeasured sites using generalized methods (Helsel and Hirsch, 1992) or methods developed specifically for western Montana (Parrett and Hull, 1985).

Total post-irrigation streamflow gains were 105 to 130 cfs, with effects of return flow in some areas persisting into the following irrigation season. In other areas, return flow extended only into November or December. The ground-water study helped explain why the areas behaved differently.

Ground-Water Study

Voeller and Waren used two hydrogeological methods to estimate the amount of return flow stored in and released from the aquifer: ground-water hydrograph analysis and the Darcy approach (Box 7). The two approaches yielded very different results, only one of which is consistent with the surface-water analysis.

Both methods required quantification of aquifer characteristics, which Waren estimated by examining drillers' logs of 129 existing wells (Box 4). In addition, he conducted four aquifer pumping tests (Box 5). The basin aquifers are fairly complex, consisting of confined and unconfined layers of clay, shale, and other deposits of glacial and fluvial origin. Geologic material proved to be important, as ground-water recharge appeared to be limited in areas underlain by poorly permeable deposits (Voeller and Waren, 1997).

The ground-water hydrograph analysis was essentially the same procedure as that followed for the North Fork Blackfoot River study (Roberts and Waren, 2001). Its result was consistent with the ground-water discharge determinations gleaned from the surface-water study.

For the Darcy approach, Waren relied on water-table maps (Box 1) he compiled from measurements in 87 wells. But even this large quantity of data was sufficient only to delineate regional flow paths, and not the detailed flow patterns that occur locally around irrigation drains, springs, and small channels. Consequently, return flow estimates based on the Darcy approach produced results about an order of magnitude smaller than expected. "Because of this problem, the evaluation of return flow by evaluating groundwater flux based on aquifer properties and gradients can produce unreliable results in certain situations. Accurate surface-water measurements are crucial to any evaluation of irrigation return flow" (Voeller and Waren, 1997).

Lessons Learned

Many of the observations that Voeller and Waren (1997) made in the Flint Creek valley apply to most, if not all, of Montana's irrigated areas. For example, many of their well hydrographs are quite typical (fig. 4). During spring and early summer, water levels rise in response to snowmelt, summer rains, and irrigation return flow. Water levels generally stay high throughout the irrigation season, dropping only a little or not at all during haying, when irrigation stops temporarily. This pattern contrasts with streamflow, which typically peaks in late spring, then quickly drops. In the fall, after irrigation season ends, ground-water levels gradually decline to a winter "base level" as excess irrigation water drains from the aquifer.

Typical streamflow responses to irrigation diversion and return flow are depicted in figure 5. The gray bars represent streamflow in Flint Creek under pre-development conditions, without irrigation or reservoirs. Natural flows peaked in late spring to early summer in response to snowmelt, and persisted at relatively high levels through the summer in response to rainfall and aquifer drainage. Flows decreased through the fall, reaching lowest levels around December.

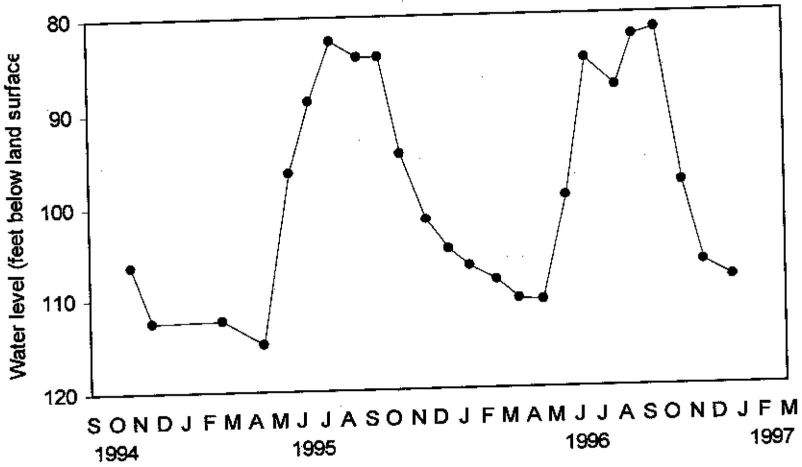


Figure 4. Hydrograph of water level in well FC19 in the Flint Creek Valley (data from Voeller and Waren, 1997).

The black bars depict the streamflow response to irrigation. Like the pre-development flows, these flows were calculated based on water-balance analysis. The effects of irrigation are twofold. First, streamflow severely decreases during the summer, when mainstem and tributary water is diverted onto irrigated land. Second, streamflow increases relative to pre-development conditions during the fall and winter, as irrigation return flow makes its way back to the river. Overall, annual streamflow is smaller under irrigation because irrigated crops consume water that otherwise would have contributed to streamflow.

The white bars depict the actual measured streamflow, with full irrigation *and* storage releases from East Fork Rock Creek Reservoir, from which water is transferred into the Flint Creek drainage. This interbasin water transfer dampens the effects of irrigation diversion, and enables irrigated crop production without drying up Flint Creek.

Figure 5 suggests that reducing irrigation diversions – for example, by converting from flood to sprinkler systems – would minimally impact irrigators who rely on water released from reservoirs. But the impact to irrigators who benefit from return flows would likely be significant, especially during drought years (Voeller and Waren, 1997). Those irrigators are concentrated in the lower part of the valley.

Hydraulic engineer Leslie Stillwater of the Bureau of Reclamation in Boise, Idaho (written communication, 2005) further refined the streamflow responses to irrigation return flow. Using data provided by Voeller and Waren (1997) and other sources, Stillwater developed a hydraulic model (*Modsim*) of surface-water flow in the Flint Creek valley. As part of this effort, she apportioned lag times between irrigation application and return-flow discharge into Flint Creek for each of the four major hydrologic units in the study area (figure 6).

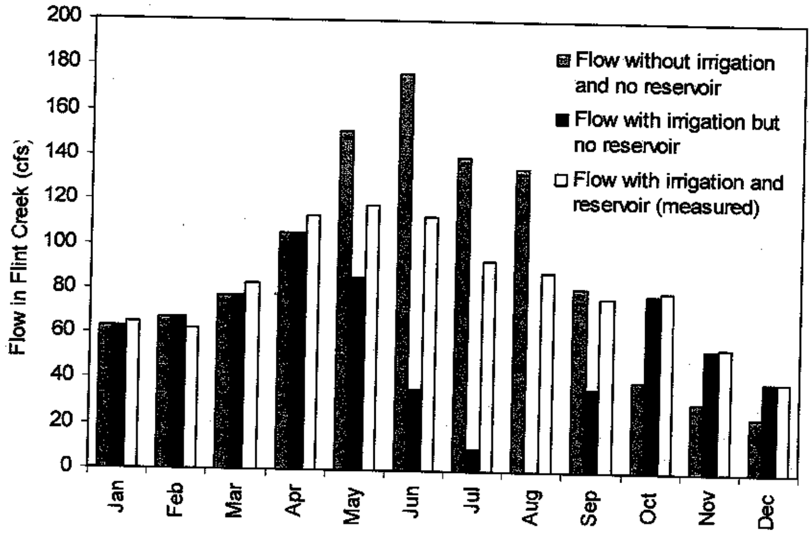


Figure 5. Calculated and measured flow in Flint Creek at Maxville, 1994, showing seasonal influences of irrigation and storage on streamflow. Modified from Voeller and Waren (1997).

Hydrogeologic conditions explain the different lag times. Return flows reach Flint Creek faster from floodplains with shallow water tables than from benches with deeper water tables and therefore greater capacity to store ground-water recharge. In contrast, areas with shallow water tables have little additional storage capacity to accommodate new recharge, so irrigation return flow quickly discharges from the aquifer.

To increase late-season water availability for irrigation, (Voeller and Waren, 1997) suggest increasing flood irrigation on new benchlands during spring runoff. Areas underlain by permeable deposits could be targeted to enhance recharge. Excess irrigation water would enter the aquifer where its storage capacity is the greatest and slowly drain to Flint Creek, arriving late in the season when it is needed the most.

Another strategy might be to lease late-season water rights from irrigators for instream flow, while continuing to allow early-season irrigation on the benches. Then, farmers could still harvest at least one crop. Early-season flows, which are not currently a problem, would be unaffected. Late-season flows would continue to benefit from return flow from early-season irrigation, in addition to the supplemental flow afforded by forgoing late-season diversions.

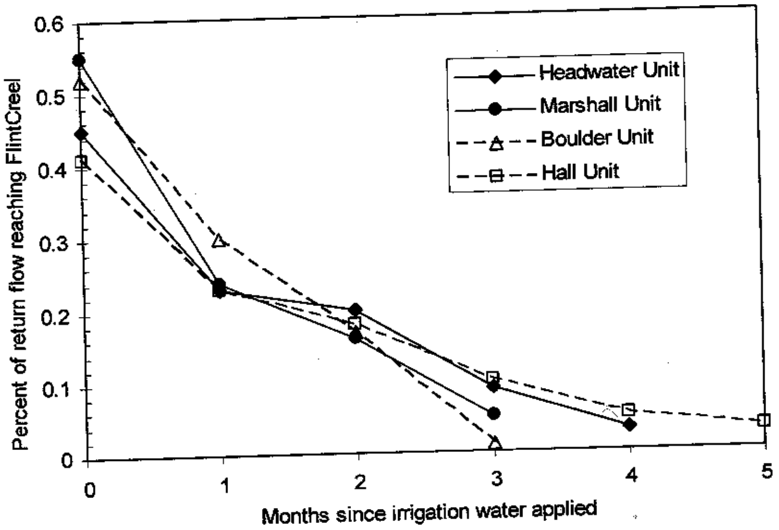


Figure 6. Return flow time lags for four major hydrologic units in the Flint Creek valley. Data from U.S. Bureau of Reclamation (Leslie C. Stillwater, written communication, 2005).

4. Big Hole Basin: Managing Evapotranspiration

The 130-mile Big Hole River drains 2,800 square miles of southwestern Montana before joining the Beaverhead River at Twin Bridges to form the Jefferson River, a major tributary to the Missouri (fig. 1). Diversion from the Big Hole and its tributaries irrigate about 520,000 acres of hay and pasture in the bottom lands of the broad Big Hole Basin, at elevations ranging from about 6,000 to 7,000 feet. The irrigated land is underlain primarily by permeable, Quaternary-age glacial outwash and alluvium.

Natural and human-induced changes in water-resource availability have generated considerable interest in improving water management in the Big Hole River basin. Many hay fields near Wisdom and Jackson that used to be irrigated only in the spring and early summer are now irrigated throughout the summer to support increased grazing. Forestry and agricultural practices have altered vegetation patterns and thus altered the hydrology of the basin. Recent droughts and elevated summer temperatures have heightened concerns about the survival of fluvial Arctic grayling and other fishery resources (http://www.mbmg.mtech.edu/env-assessment.htm).

In 1997 to 1998, hydrogeologist Rich Marvin of the Montana Bureau of Mines and Geology and hydrologist Terry Voeller of the Montana Department of Natural Resources and Conservation conducted a hydrologic investigation of the Big Hole River basin to document the effects of irrigation on the basin's water budget and to understand the interactions between ground water, surface water, vegetation, and climate. Two subareas – Francis Creek drainage in the upper basin and the irrigated area near Melrose and Glen in the lower basin – were studied intensively (Marvin and Voeller, 2000).

In addition to the traditional approaches of measuring ground-water levels and streamflows and conducting aquifer tests and synoptic runs, Marvin and Voeller (2000) focused special attention on climatic factors. Several precipitation gages were installed to determine the timing and variability of precipitation across the two subareas. Air and soil temperature, wind speed, relative humidity, incident solar radiation, net radiation, and barometric pressure were monitored to obtain evapotranspiration rates. Additional climate data, including snowpack, were obtained from a U.S. Bureau of Reclamation Agrimet station (Box 6), two National Weather Service climate stations, and several Natural Resource and Conservation Service snow telemetry (SNOTEL) and snow course sites.

From these data, Marvin and Voeller (2000) were able to account for all of the inflows to and outflows from the basin as they changed over time. The detailed quantification of evapotranspiration rates in particular proved pivotal in understanding the fate of return flow.

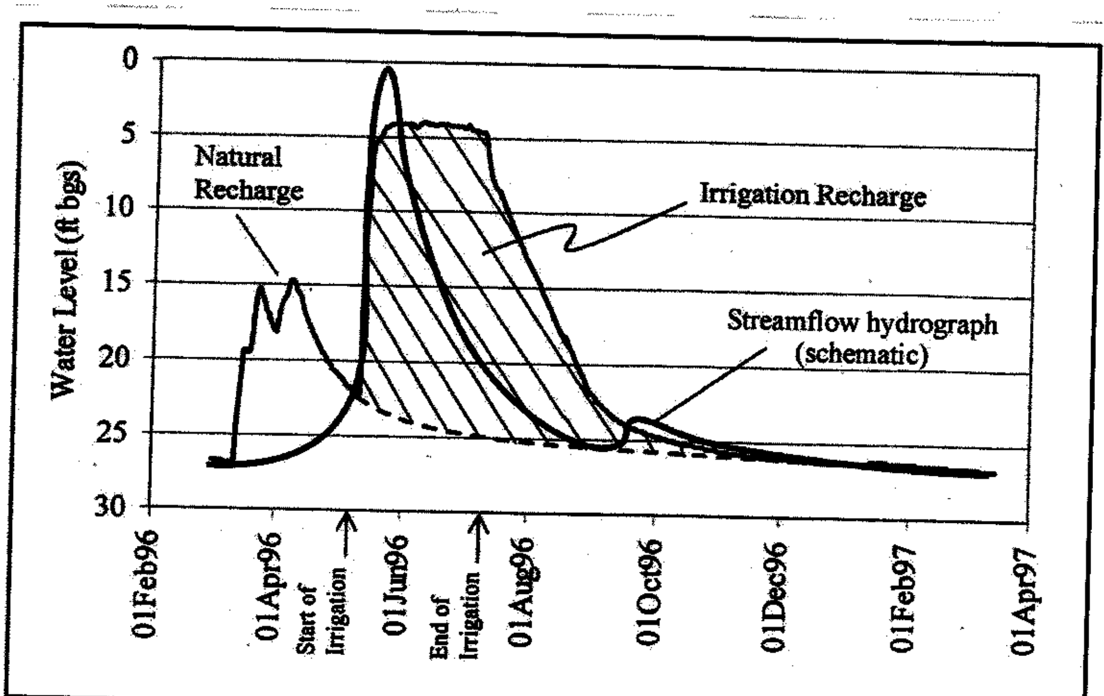


Figure 7. Well hydrograph (from Marvin and Voeller, 2000) and schematic streamflow hydrograph showing the interactions between irrigation, return flow, ground-water recharge and discharge, and streamflow in the

upper Big Hole Basin. Water-table depth is reported in feet below ground surface (ft bgs). Schematic streamflow hydrograph of the Big Hole River is not scaled.

Figure 7 illustrates the impacts of return flow and evapotranspiration on shallow ground water and the Big Hole River. In early spring, the water table rises in response to local valley snowmelt. After the low-elevation snowpack has melted, the water table begins to decline to baseflow conditions. In early-mid May, the mountain snowpack begins to melt, and streamflow in the Big Hole peaks in response. Irrigators begin to divert water as soon as it becomes available. Almost immediately, the water table rises as excess irrigation water recharges the aquifer, paralleling the rapid increase in streamflow. As irrigation season continues, the streamflow and ground-water hydrographs diverge. Streamflow declines rapidly, but the water table remains high.

In mid-summer, irrigation stops and the water table begins to decline. Surprisingly, the river shows no response. Instead of increasing as expected, streamflow continues to decrease, even though water is no longer being diverted for irrigation. What can explain this unexpected trend?

The small streamflow increase in early fall hints at the answer. By carefully quantifying evapotranspiration rates over time, Marvin and Voeller (2000) found that most of the irrigation return flow never makes it back to the Big Hole River. Excess irrigation water raises the water table so high that crop roots can tap directly into the aquifer for their late-season "irrigation". It is not until the plants stop growing in the fall that ground-water discharge can flow all the way to the river without being consumed along the way. Only then do return flows begin to supplement streamflow.

Lessons Learned

This discovery dashed hopes of increasing streamflow simply by reducing diversions to any willing irrigator. If diversions are reduced, but the cropped area remains the same, then less excess irrigation water would be available to recharge the aquifer. A deeper water table would put shallow ground water off limits to crops. Without access to subirrigation, ranchers may want to increase diversions to compensate.

Marvin and Voeller's study suggests that an effective water leasing strategy should focus initially on irrigated lands with deep water tables. If diversions to these lands cease, then actual water consumption would decrease because the crops would no longer have water. In contrast, if diversions to lands overlying shallow water tables ceased, then water consumption would remain unaffected because crops could continue to consume shallow ground water. As part of this strategy, it would be important to monitor streamflow to ensure that the leased water remains instream and is not diverted by downstream irrigators, whose water table may drop in response to diminished return flows. If the strategy is effective, then eventually the water table may drop sufficiently to expand the water leasing program to lands that currently benefit from high water tables.

It should be noted that Marvin and Voeller's study was conducted during a "normal" climate period. In the seven years subsequent to their study, the Big Hole has experienced severe drought. In addition, land use practices have been changing. When Marvin and Voeller conducted their study, most ranchers in the upper Big Hole stopped irrigating in early July after they harvested their hay crops. Now, many ranchers irrigate and grow pasture all season long, extending into early October.

The Big Hole is somewhat unique in that dewatering is a concern early in the season, when endangered Arctic grayling need high enough flows to fill side channels for spawning. Irrigation return flow is not as much a factor in maintaining this fishery as are the diversions themselves. The highest priority for water leasing is the major irrigators who divert water from just above the dewatered stretch, and whose excess irrigation water does not return to the river until much further downstream, where low flows are not as critical (Mike Roberts, DNRC, oral commun., 2005). This illustrates the importance of understanding site-specific conditions even when basin-scale hydrology is well-understood.

The key to managing flows in the Big Hole River is finding the right balance between water-table depths and surface-water diversion rates on a time-specific, site-specific basis. In some places, flow reductions at the headgate do result in immediate flow increases downstream (Mike Roberts, DNRC, written commun., 2005). In others, the consequent reduction in return flow would lead downstream irrigators to start diverting water at times of the year when traditionally they had no need. Recently changing practices -- from irrigating hay only until early July, to irrigating pasture (and maintaining high water tables) all summer long -- further complicate attempts to improve water management. Lacking a comprehensive model that incorporates all the interrelated feedbacks, it is unclear to what extent instream flow leasing would elicit the hydrologic responses desired.

Hydrogeologists Ginette Abdo and John Metesh are currently continuing this research in two parts, both of which are expected to be completed in 2006. The first part, funded by the Montana Department of Natural Resources and Conservation, involves collecting additional ground-water, surface-water, and climatic data from previously established field sites in the upper Big Hole basin. The second part, funded by the U.S. Bureau of Reclamation, establishes a new field site adjacent to the mainstem for studying the role of irrigation from tributary steams on basin hydrology. Based on the data collected, computer models will be developed and used to evaluate how possible changes in irrigation practices, recharge patterns, evapotranspiration, and ground-water use are likely to affect the hydrology of the upper basin. It is hoped that the information gleaned may lead to improved water-resource management and, ultimately, to increased summer and fall flows in the river (http://www.mbmg.mtech.edu/env-assessment.htm).

5. Gallatin Valley: Distinguishing Ground-Water Sources

The Gallatin Local Water Quality District (GLWQD) encompasses most of the 520-square-mile Gallatin Valley in southwestern Montana (fig. 2). Water is diverted from the Gallatin River and its tributaries to irrigate about 90,000 acres of cropland, at elevations ranging from about 4,000 to 5,000 feet. Excess irrigation water returns to the Gallatin River.

In 1997 to 1998, hydrogeologist Eloise Kendy of the U.S. Geological Survey investigated the magnitude, extent, and potential sources of nitrate in ground water in the GLWQD. One of the potential sources was fertilizer, which can make its way to ground water in irrigation return flow (Kendy, 2001).

Kendy (2001) analyzed nitrate isotopes (Box 8) to trace the source of nitrate in the aquifer. Nitrate molecules in water have different isotopic signatures, depending on whether they originated as feces (including livestock waste and septic effluent), fertilizers, soil organic nitrogen, or atmospheric nitrogen. The concentration of different isotopes of nitrate (and many other constituents) can easily be analyzed in water samples. Kendy (2001) found that fertilizers and soil organic nitrogen contributed most of the nitrate to ground water in the GLWQD. Irrigation probably facilitated the movement of nitrogen from fertilizers through permeable soils and into underlying aquifers.

An integral part of the investigation was to identify sources of ground water. Like nitrate, water molecules also have different isotopic signatures. Simple analyses of water isotopes (Box 8) in ground-water samples collected from wells can tell a great deal about the source of the ground water, including the elevation and temperature at which it recharged the aquifer, and whether or not it was stored in a reservoir prior to recharge (Clark and Fritz, 1997). If the watershed that provides irrigation water is located at a much higher elevation than the watershed that naturally recharges the aquifer beneath the cropland, then water isotopes – or, more precisely, the stable isotopes of oxygen and hydrogen ($\delta^{18}O/\delta D$) – provide an ideal means to distinguish native ground water (*GW* in fig. 1) from irrigation return flow. Likewise, if the irrigation water is stored in a reservoir, then $\delta^{18}O/\delta D$ (pronounced "oxygen-deuterium") analyses can be used to distinguish, and even to quantify, the two sources of recharge in an aquifer.

In addition to ground water, water isotopes also can be used to determine fractions of irrigation water in streamflow in a procedure known as isotopic hydrograph separation (Kendall et al., 1995). If irrigation return (*R*, fig. 2), other ground-water discharge *(GW)*, and streamflow (SW_{in}) from other sources are isotopically distinct, then the contributions of each water at any time can be calculated by solving the mass balance equations for the water and tracer fluxes in the stream. If no discharge measurements are available, then relative proportions of each water can be calculated (Kendall et al., 1995).

Based on stable isotopes of oxygen and hydrogen ($\delta^{18}O/\delta D$) in ground-water samples, Kendy (2001) showed that irrigation return flow was the primary source of ground water beneath the Gallatin Valley. This conclusion is consistent with an earlier water balance analysis (Hackett et al., 1960). Ground water beneath irrigated areas had the same isotopic "signature", or ratio, as the Gallatin River – the source of the irrigation water. In contrast, ground water beneath the unirrigated benches along the valley margins had different isotopic signatures. Interestingly, the $\delta^{18}O/\delta D$ data also indicated that irrigation diversions from the Gallatin River – not from the Madison River, as many people had previously suspected – are the primary source of recharge to the prolific deep aquifer beneath the Madison Plateau, which borders the Gallatin Valley on the west.

Lessons Learned

Land use is changing rapidly in the Gallatin Valley, from surface-water supplied flood irrigated cropland to ground-water supplied residential and commercial development. Together, the decrease in irrigation and increase in impermeable surfaces such as rooftops and pavement combine to reduce ground-water recharge. At the same time, ground-water pumping to supply the new developments increases artificial ground-water discharge. Overall, these changes, if unmitigated, will decrease late-season streamflow, which depends on natural ground-water discharge (Kendy, 2005).

The nitrate and $\delta^{18}O/\delta D$ analyses confirmed earlier work that identified irrigation return flow as the major source of ground-water recharge to the aquifer that feeds the Gallatin River, an important trout fishery. In order to protect that fishery, the amount and timing of ground-water discharge need to be maintained. Strategies to accomplish this include enhanced storm-water infiltration, xeriscape landscaping, and a legal framework for water-right changes that protects streamflow during key periods of the year by replacing irrigation return flow with artificial recharge.

If conditions are suitable, then $\delta^{18}O/\delta D$ analysis is the best approach to quantify the proportion of ground-water discharge attributable to irrigation return flow. Otherwise, the proportion is determined by independently estimating the quantities of recharge from various sources – an approach that almost always introduces significant uncertainty. Conditions are likely to be suitable for $\delta^{18}O/\delta D$ analysis if the different ground-water sources (including excess irrigation water) originated as precipitation that fell at distinctly different elevations or if one source was stored in a reservoir prior to recharge. Kendy (2001) did not attempt to quantify the proportion of irrigation return flow in ground water, although isotopic data provide the means to do so, as the next case study illustrates.

6. West Billings: Responding to Land-Use Change

The 79,000-acre West Billings area extends along the Yellowstone River from western Billings through Laurel to the western edge of Yellowstone County, in south-central Montana (fig. 2). Flood-irrigated cropland and pasture cover about half of the 3,200-ft study area. Water is diverted from the Yellowstone River and excess irrigation water also returns to the Yellowstone River. Over the past few decades, land use has been changing from surface-water supplied flood irrigation to ground-water supplied subdivisions.

In 1998 to 2001, hydrogeologists John Olson and Jon Reiten of the Montana Bureau of Mines and Geology evaluated the potential impacts of the land-use changes on the Yellowstone River and its alluvial aquifer. The changing role of return flow was a particular focus of the investigation.

Olson and Reiten (2002) began with the traditional approaches of measuring streamflow biweekly to monthly at 44 sites and measuring water-table elevations monthly in 80 wells for two years. They also conducted four 24- to 48-hour multiple-well aquifer pumping tests (Box 5) to help them understand the relatively complex site hydrogeology. They carefully mapped the distribution of a fine-grained surface layer -- in some places more than 20 feet thick -- which they suspected controlled ground-water recharge rates. Based on ground-water hydrograph analysis, they calculated ground-water recharge rates as a function of land use (proximity to ditches and irrigated fields) and geological setting (thickness of fine-grained surface layer). Then, they used some innovative approaches to help fine-tune their water balance of a 30,600-acre subarea.

To estimate leakage from canals, Olson and Reiten (2002) evaluated the responses of water levels in nearby wells. When major irrigation ditches are activated in mid-April, water levels rise not only in the ditches, but also in the underlying aquifer. Although their simple and elegant analytical method was developed in 1930s , it was rarely used until its reintroduction many years later (Lohman, 1979). Even now, it is still not a common approach in Montana. The method requires knowledge of aquifer hydraulic characteristics (Box 5) and site geometry. Applying this method to nine wells, Olson and Reiten (2002) estimated canal seepage rates of 0.1 to 1.0 acre-feet per day per mile. Extrapolating those rates to the area's 190 miles of canals, they determined that 14 percent of the total ground-water recharge for the area originates as seepage from canals.

Water that recharges eventually discharges. In most situations in Montana, ground water discharges to a surface-water body, such as a spring, lake or stream. If this ground-water discharge originated as irrigation water, then it is considered irrigation return flow. In some cases, ground water may discharge to pumped wells, or may be consumed by phreatophytes such as willows and cottonwoods, whose roots extract ground water from beneath the water table. Methods such as Olson and Reiten's canal leakage evaluation only quantify ground-water recharge. It is important to keep in mind that not all of that recharge necessarily will contribute baseflow to streams. Field reconnaissance – both on the ground and using aerial or satellite photography, if available – may identify any important "sinks" such as cottonwood stands or major well fields along the ground-water flow path, which need to be considered in the overall water balance.

Olson and Reiten (2002) used water-quality data to further refine the water balance. They collected samples from 22 wells and 9 surface-water sites and had them analyzed for a variety of constituents, including major and trace ions, nitrate, isotopes of several elements, tritium, and noble gases.

The isotopes of oxygen and hydrogen ($\delta^{18}O/\delta D$; Box 8) proved to be particularly useful for analyzing irrigation return flows. In most of the case studies, investigators did not distinguish irrigation return flow (*RF,* fig. 1) from other ground water *(GW*, fig. 1). Instead, they usually attributed all water-table rises and/or all ground-water discharges to irrigation returns, knowing that some, presumably small, component of these estimates actually represents ground water from other sources. In this study of West Billings, the investigators actually distinguished irrigation return flow from other ground water within an aquifer.

Irrigation water in the West Billings area is composed primarily of high-altitude snowmelt form the Yellowstone River, whereas the local precipitation is mostly low-altitude, late spring and early summer showers and thunderstorms. Consequently, the two sources have distinct isotopic compositions. The isotopic composition of ground water reflects the relative contributions of each recharge source. (For further explanation of $\delta^{18}O/\delta D$ applications, please read Gallatin Valley case study.) The isotopic compositions of 15 ground-water samples indicated that irrigation return flow contributed 84 percent of the ground water in the aquifer. To achieve this large percentage, only 10 percent of the local precipitation could have recharged the aquifer; 90 percent must have been lost to evaporation or runoff.

Stable isotope data have also been used to determine fractions of irrigation water in ground-water mixtures contributing to flow in the Snake River in Idaho. There, chlorofluorocarbon (CFC) and tritium/helium-3 ($^3H/^3He$) data were used to determine the age of the irrigation water fraction (Plummer et al., 2000). This information helped to establish the length of time for excess irrigation water to flow through the aquifer and discharge to surface water. (For further explanation of CFC and $^3H/^3He$ applications, please read Upper Beaverhead Basin case study.)

Olson and Reiten (2002) also used chemical data to estimate evapotranspiration *(ET)* rates. Chloride is a "conservative" ion that, once dissolved in water, tends to move with the water, rather than chemically reacting, precipitating, or attaching to soil. Only when water evaporates or is taken up by plants does it leave the chloride behind. If all chloride sources can be accounted for, then *ET* from the study area can be computed as:

$$ET = (1 - (Cl_r/Cl_{gw})) \times 100 \text{ percent}$$

where Cl_r = chloride concentration in recharge source
Cl_{gw} = chloride concentration in ground water

In the West Billings area, irrigation return flow is the only significant source of chloride in ground water. Based on the chloride data, only 17 to 31 percent of the irrigation water that did not run off actually recharged the aquifer; the rest was consumed by evapotranspiration. Generally, the thicker the fine-grained surface deposits, the greater the ratio of evapotranspired to recharged water. Conversely, the more permeable the land surface, the greater the propensity for excess irrigation water to become return flow, rather than evapotranspiring. This result is certainly transferable to other areas, and reinforces the importance of examining drillers' logs (Box 4) as a first step in any return-flow analysis.

Olson and Reiten (2002) did not determine the timing or location (specific stream reaches) of return flows discharging to surface water. But they did generate a detailed water balance of the area, accounting for all the components shown in Figure 1, as well as ground-water recharge from leaky ditches, lawn irrigation, and septic systems, and ground-water pumping for lawn irrigation and household use. They also made important observations about the relationship between geologic substrate and ground-water recharge rates.

Lessons Learned

Olson and Reiten (2002) concluded that the primary impact of the shift from agricultural to residential land use is a loss of ground-water recharge. Currently, almost all of the recharge is derived from irrigation return flow. When that source decreases and ground-water pumping concurrently increases, the water table drops and ground-water discharge to the Yellowstone River decreases accordingly – a repeat of the Gallatin Valley scenario described previously. With less clean recharge water available for dilution, dissolved constituents such as nitrate from septic effluent may increase in both ground water and the river. Surface-water quality would be most vulnerable during the winter baseflow period, when ground-water discharge supplies most of the flow (Olson and Reiten, 2002). Strategies proposed for the Gallatin Valley to mitigate the impacts of changing land uses would apply equally to the West Billings area. In addition, in west Billings, ground-water recharge could be enhanced by routing treated wastewater and storm runoff from low-recharge to high-recharge areas identified by Olson and Reiten (2002). Artificially recharging wastewater reduces the impacts of pumping domestic supply water out of the aquifer. Artificially recharging storm runoff has the added benefit of actually augmenting the ground-water supply, since, as Olson and Reiten (2002) discovered, only about 10 percent currently recharges aquifers; the rest runs off and evaporates. Capturing and recharging a greater proportion of local precipitation could be key to rebalancing the water budget in the face of land-use change. Recharge enhancement also would dampen extreme streamflow fluctuations caused by impermeable land surfaces, and filter runoff and wastewater naturally before they enter the surface-water system. Whether water leasing or artificial recharge strategies are used, Olson and Reiten's study provides ground-water flow rates and directions needed to help target and optimize those efforts.

7. Beaverhead Basin: Computing Return Flow Lag Times

The Beaverhead River begins at the Clark Canyon Dam, below the confluence of Horse Prairie Creek and the Red Rock River. The Bureau of Reclamation completed the Clark Canyon Dam and Reservoir Project in 1964, primarily to irrigate the 21,800-acre bench east of Dillon and to provide supplemental water to 28,000 acres of valley land. Irrigation return flow from the East Bench Unit returns to the Beaverhead River.

The irrigated land is underlain primarily by Tertiary-age sediments and the valley floor is underlain by more permeable Quaternary-age alluvium. Ground-water levels beneath the bench east of Dillon have risen as much as 100 feet since the construction of the main irrigation canal (Kendy and Tresch, 1996).

Irrigation return flows in the Beaverhead Valley have been addressed in several investigations (Nicklin and Brustkern, 1981, 1983; Pope et al., 1999; Uthman and Beck, 1998). Of the published return-flow studies completed in Montana, these are unique because they specifically examined the *timing* of return flows to surface water.

Numerical methods (Box 9) to accurately determine the timing of irrigation return flow require considerable data inputs to characterize the spatial and temporal complexities of interacting ground-water and surface-water systems. In Montana, such data requirements can rarely be met.

For his Ph.D. dissertation, hydrogeologist and civil engineer Michael Nicklin assessed the feasibility of applying a less data-intensive method to determine the timing of return flows to the Beaverhead River. Nicklin and Brustkern (1983) calculated irrigation return flows to the Beaverhead River from the East Bench irrigation unit using time series analysis.

Time series analysis is a major tool in hydrology. In short, it is the statistical analysis of how different parameters vary over time, and how their values relate to each other over time. Time series analysis is used for building mathematical models to generate synthetic hydrologic records, to forecast hydrologic events, to detect trends and shifts in hydrologic records, and to fill in missing data and extend records. Nicklin and Brustkern (1983) may have been the first to apply this tool to irrigation return flow.

In their analysis, they examined the relationship between irrigation return flow and irrigation diversions for the years 1966 through 1975. The only data required were records of daily inflows, outflows, and diversions from the river reach. Figure 3 (in Flint Creek case study) shows the physical relationship considered in the analysis. For each time, t, that measurements are available, return flow $R(t)$ is calculated according to the equation

$$R(t) = Outflow(t) - Inflow(t) + Diversions(t).$$

Nicklin selected the Beaverhead River as the site in Montana that came closest to meeting the data requirements. Where data were missing, they were synthesized using data regression. Even so, he found that data incompleteness hampered the time series analysis to the extent that it was only "moderately successful." He concluded that the approach should be attempted only where streamflow and diversion data are complete; that is, where measurements are available for every inflow, outflow, and diversion for every time step (typically daily) analyzed.

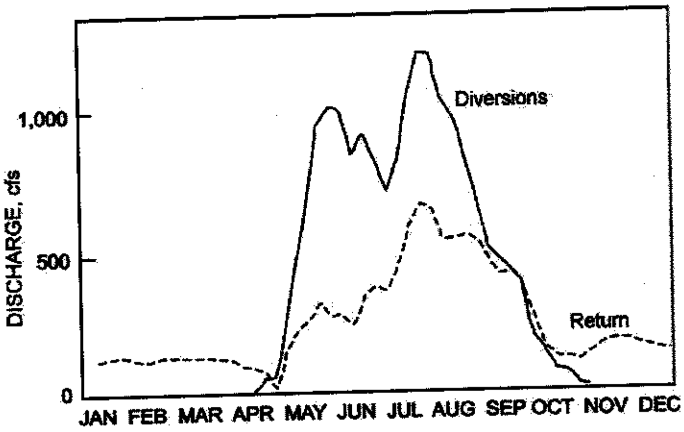


Figure 8. Mean weekly diversion and return flow hydrographs of the Beaverhead River between Clark Fork Canyon and Twin Bridges. Modified from Nicklin and Brustkern (1983).

Despite his disappointment with time series analysis, Nicklin's study did reveal several important relationships. Based solely on flow data, Nicklin and Brustkern (1983) found that, on average, 73.8 percent (range 62.5-84%) of annual diversions returned to the Beaverhead River; the remainder was consumed by crops. This value may be high because it includes ground-water discharge from sources other than irrigation, including precipitation and regional ground-water flow (*P* and *GW,* fig. 2). An average of 46.4 percent (range 34.3-61.8%) of returns reached the Beaverhead River during the irrigation season; the remainder returned after September 1. Although the average time delay between diversion and return flow was 61 days (range 52.9-78.2 days), ground water continued to discharge into the Beaverhead River throughout the year (fig. 8).

Lessons Learned

Time-series analysis, whether statistically rigorous, as Nicklin had intended, or somewhat less quantitative, which he ultimately used, is a useful first step in determining the lag between the time irrigation water is diverted and the time return flow discharges to surface water. An advantage of this type of analysis is that it provides useful, quantitative information from existing data without the need for additional field work. Even if field work is intended, time-series analysis *a priori* can help focus and guide field measurements.

A key question is whether sufficient data are available for a particular location. Nicklin concluded in the early 1980s that even the best site in Montana in terms of data availability did not have sufficient measurements to warrant the rigorous statistical approach. However, considerably more data have been collected in the intervening quarter-century. Moreover, Nicklin may not have considered smaller areas, for which data might have been available.

In any case, it is always worthwhile to examine existing flow data in and near a proposed water-leasing site, and time-series analysis offers a means to glean quantitative information about irrigation return flow from these historical data. Even with incomplete datasets, a long historical record often divulges more about how a system responds to different hydrologic stresses than does a short, but complete record.

8. Upper Beaverhead Basin: Modeling Irrigation Returns

The upper Beaverhead basin includes the Beaverhead River valley between Dillon and Barretts, and its tributaries, Rattlesnake Creek valley and Blacktail Deer Creek valley. The 5,000-6,000-foot valley drains an area of 2,895 square miles. More than 50,000 acre-feet of ground water is pumped from alluvial deposits, primarily in the Blacktail Deer Creek valley, to supply irrigation demands.

From 1991 through 1996, hydrogeologist Bill Uthman and civil engineer Jim Beck of the Montana Department of Natural Resources and Conservation conducted the Beaverhead Groundwater Project to determine the impacts of groundwater development on ground-water levels and surface-water availability (Uthman and Beck, 1998). In support of that study, hydrogeologists Daryll Pope, Dave Clark, and others of the U.S. Geological Survey (Pope et al., 1999) conducted geophysical, geochemical, and ground-water modeling investigations. The combined database provided ample input for well-calibrated numerical models by both groups of investigators. The work by Pope et al. (1999) in particular revealed important limitations about using numerical models.

The MODFLOW program (Box 9) calculates the water balance of an aquifer system as a function of time. The user inputs aquifer geometry and hydraulic characteristics, well pumping rates, and ground-water recharge. The program then computes ground-water levels and flow rates throughout the modeled area. To ensure that the model reasonably simulates actual conditions, the user "calibrates" the model by adjusting input parameters until the output matches actual water-level and flow measurements. Ground-water discharge rates determined from synoptic runs (Box 2) are thought to provide excellent targets for calibration.

Pope et al. (1999) decided to test that assumption. In addition to ground-water discharge rates from synoptic runs, they used chemical data to help calibrate the model. Chlorofluorocarbon (CFC), tritium (^{3}H), and tritogenic helium-3 (^{3}He) are "transient" tracers that humans introduced into the atmosphere at known rates (CFCs as refrigerants, aerosol propellants, cleaning agents, solvents, and blowing agents and ^{3}H-^{3}He as fallout from nuclear testing). Rain and snowfall that fell on any day since they were introduced had unique, known concentrations of these tracers. After the precipitation seeped through soils and became ground water, it retained this concentration. So, CFC and ^{3}H-^{3}He concentrations in ground water indicate the date that ground water recharged the aquifer.

Consider, for example, a ground-water sample with a CFC-11 concentration of 200 parts per trillion by volume (pptV) and a CFC-12 concentration of 375 pptV. (CFC-11 and CFC-12 are different types of CFC.) In which year did that water enter, or recharge, the aquifer? According to figure 9, those concentrations were present in atmosphere – and therefore in rain and snow -- in 1984. That is when the sampled water entered the aquifer (assuming no lag time between precipitation and ground-water recharge). If the recharge area is known, then the ground-water flow rate can be determined based on the time it took the water to flow from the recharge area to the sample location (sample date minus recharge date). Tritium and helium-3 analyses work in much the same way. Pope et al. (1999) determined ground-water flow rates by analyzing CFC and ^{3}H-^{3}He in about 50 ground-water samples, and mapping the resulting recharge dates along flow paths.

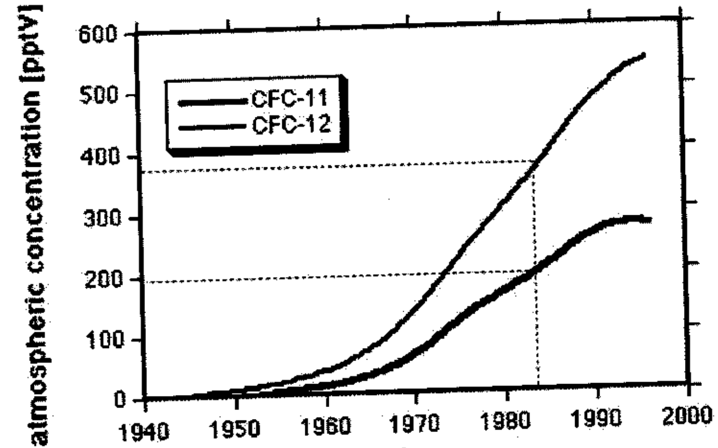


Figure 9. Concentrations (in parts per trillion by volume) of CFC-11 and CFC-12 in atmosphere, 1940-2000. Source: http://www.eawag.ch/research_e/w+t/UI/CFCdating.html, modified from (Busenberg and Plummer, 1992). Dashed lines show the concentrations in a ground-water sample that recharged the aquifer in about 1984.

Lessons Learned

Initially, Pope et al (1999) developed a "basic" ground-water flow model according to standard procedures. The model satisfactorily computed measured ground-water levels and ground-water discharge determined by DNRC (Uthman and Beck, 1998). It looked like a perfectly valid simulation of the natural system. Normally, at that point, the model would be complete. But then Pope et al. (1999) checked the model-calculated ground-water flow rates against the recharge dates they had obtained from transient tracer analysis, and found serious disagreement.[1] It wasn't until they adjusted the input for recharge from excess irrigation that they could at last calibrate the model to all known water levels and flow rates. This case illustrates the importance not only of properly accounting for irrigation return flow, but also of understanding the limitations of ground-water flow models, even in the presence of considerable data.

It also illustrates the utility of using age-dating techniques to help quantify the lag between the time excess irrigation water recharges the aquifer and the time it discharges to a stream. It should be noted, however, that CFC sampling requires highly specialized equipment that can be difficult to obtain and operate. For purposes of water leasing, especially on a local scale, it is probably not a practical analytical tool. But if age-dating information is already available from previous studies, it can definitely enhance the precision of any water-balance determination.

9. Freezeout Lake WMA: Assessing Water-Quality Impacts

In 1982, the U.S. Fish and Wildlife Service discovered dying waterfowl and waterfowl with birth defects and reproductive failures at the Kesterson National Wildlife Refuge in California. The cause of the problem was determined to be high levels of selenium in the irrigation drain water discharged into the reservoir. In late 1985, following intense media and congressional attention, the Department of the Interior developed the National Irrigation Water Quality Program (NIWQP) to investigate the extent and magnitude of the problem.

As part of an NIWQP investigation in Montana, U.S. Geological Survey hydrologists and U.S. Fish and Wildlife Service biologists assessed the impacts of irrigation drainage from the 83,000-acre Greenfields Irrigation Division (fig. 2) (Kendy et al., 1999; Knapton et al., 1988; Nimick et al., 1996). Irrigation water is diverted from the Sun River to the Greenfields Irrigation Division, most of which sits atop the gravelly Fairfield Bench. The westernmost 4,000 acres of irrigated land is lower in elevation and is underlain by glacial-lake deposits. This area drains into the Freezeout Lake Wildlife Management Area (WMA), a key staging area on the Pacific Flyway. About 6,000 acres of wetlands in the WMA are used by as many as 1 million migrating birds annually.

Selenium, a trace element that is essential in small quantities but toxic in large concentrations, occurs naturally in the fine-grained glacial-lake deposits. Under natural conditions, very little water seeped through the deposits. But when irrigation water is added, excess water seeps through, leaching selenium from the soil. Evapotranspiration from the root zone concentrates selenium in soil water before it drains through the soil profile. After it enters the aquifer, the drainage continues to dissolve and mobilize

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[1] The difference between model-calculated travel times for the basic simulation and the revised simulation ranged from 0 to 49 years. The revised simulation accounted for irrigation activities, whereas the basic simulation did not.

selenium. Selenium dissolved in ground water then discharges into wetlands in the WMA and enters the food chain.

To determine the quantity of selenium discharging into the WMA, the hydrologists first had to quantify the amount of irrigation drainage water discharging. Lacking continuous flow measurements of the numerous drains, they had to estimate. They obtained reasonable estimates based on the total volume of irrigation water delivered to farms and corresponding irrigation-efficiency estimates; total volume of direct spills from canals and corresponding estimates of spill percentages; total volume of canal deliveries and corresponding estimates of canal seepage; and total annual precipitation and corresponding estimates of precipitation runoff and infiltration. The estimates were based largely on interviews with the Greenfields Irrigation District managers. The knowledge of local farmers and water managers cannot be underestimated as a resource for understanding irrigation system dynamics, regardless of the amount of numeric data available.

Lessons Learned

This case illustrates the very real potential for irrigation water to dissolve and mobilize constituents from cropland via irrigation return flow. Although irrigation water is not the source of selenium, irrigation practices mobilized naturally occurring selenium from glacial-lake deposits and made it biologically available. In addition to naturally occurring constituents of soil and aquifer material, irrigation can mobilize soil amendments such as herbicides, pesticides, and fertilizers. Reducing the amount of applied irrigation water may have the added benefit of reducing concentrations of undesirable constituents in waters that receive return flow.

This case also underscores the importance of obtaining local knowledge for any investigation of irrigation return flow. Local water users know how and where water was historically diverted and applied, what crops have been grown, when crops were planted and harvested, what studies have already been conducted, and who might have additional information. In addition, locals often have a surprisingly good sense of the fate of excess irrigation water.

10. Muddy Creek: Separating Hydrographs

Muddy Creek is a tributary to the Sun River in west-central Montana. Irrigation runoff and return flow from the adjacent Fairfield (Greenfields) Bench (fig. 2) increases annual flow in Muddy Creek by 10 to 20 times over pre-irrigation conditions (Osborne et al., 1983). The increased flow has extensively eroded the fine-grained alluvial banks of Muddy Creek, increasing the annual sediment load in both Muddy Creek and the Sun River and impairing downstream water uses.

The Fairfield Bench consists of three Tertiary-age gravel terraces about 20-30 feet thick, deposited on top of Cretaceous- and Tertiary-age shale bedrock. Water is diverted from the Sun River via the Sun River Slope Canal to about 52,000 acres of irrigated cropland on the 58,000-acre Fairfield Bench at elevations ranging from about 3,700 to 3,900 feet. About 50,000 acres drain to Muddy Creek.

In 1981 through 1983, hydrogeologists Tom Osborne, Roger Noble, and others of the Montana Bureau of Mines and Geology conducted a detailed field investigation to understand the role of return flow from the Fairfield Bench in causing or exacerbating erosion in Muddy Creek (Osborne et al., 1983). Ground-water discharge from the Bench was monitored with flumes, weirs, and other channel controls for 2 years. Twenty-one observation wells were installed, 6 of which were monitored continuously. Additional water-table data were collected periodically from about 40 private domestic wells. Thirteen canal seepage tests (Box 2) and five aquifer pumping tests (Box 5) were conducted. Precipitation, evaporation, soil moisture, and crop water use data were obtained from the Montana Cooperative Extension Service. Ground-water recharge from irrigated fields was determined by measuring water-table fluctuations in response to irrigation at six selected study plots. Water-quality data from 19 wells, sampled three times each, helped the investigators understand ground-water flow paths. Water-quality data from irrigation drains and Muddy Creek helped them determine sources of the water. A numerical model was developed to synthesize all the data and check the detailed water balance.

The unique geological setting, with permeable gravel terraces directly overlying nearly impermeable shale bedrock, allowed Osborne et al. (1983, p. 48) to measure ground-water discharge from the Bench directly. No seepage runs were needed to account for unmeasured discharge because the drains and coulees that collect ground water from the Bench had eroded all the way down to the level of Muddy Creek. Below their outlets, virtually no ground water flows.

However, drains and coulees convey not only ground-water discharge, but also surface runoff (*RO*, fig. 2). To distinguish the ground-water component from the runoff component of Muddy Creek discharge, Osborne et al. (1983) used hydrograph separation (Meyboom, 1961).

A streamflow hydrograph is a graphical representation of the total amount of flow over time. The total amount is composed of the runoff, or surface-water, component and the baseflow, or ground-water discharge, component. Hydrograph separation is a graphical method of distinguishing these two components of a streamflow hydrograph. This approach can work well for rainfall-dominated streams like those in eastern Montana, but is often impossible to apply to snowmelt-dominated streams like those in western Montana, and to dam-regulated streams. The method is well-developed for rainstorm-dominated streams in the eastern United States, and may also work well for low-elevation streams in western Oregon and Washington.

Using this method, Osborne et al. (1983) determined that ground-water discharge, or baseflow, contributed 35 to 67 percent of the flow in Muddy Creek. It was also estimated that 15 to 20 percent of total precipitation contributed to ground-water recharge, based on water-table fluctuations in wells.

To determine leakage rates from canals, Osborne et al. (1983) conducted canal seepage tests on 13 canal reaches ranging from 800 to 3,000 feet in length. The canal reaches were dammed on both ends, water was pumped in to fill the reach, and allowed to soak in for 8 hours. Seepage rates, S, were then determined according to:

$$S = (Lw\Delta ht) / 3600$$

where S = seepage rate in cubic feet per second (cfs)
L = length of test section in feet
w= width of test section in feet
Δh = change in water surface (head) in feet
t = duration of test in hours
3,600 = conversion from hours to seconds

Seepage rates ranged from 0.45 to 4.7 cfs per mile, or a total of 37,000 acre-feet in 1982. This amounted to 26 percent of irrigation water brought onto the Fairfield Bench. In the same year, 31 percent of irrigation water seeped through irrigated fields. Only 14 percent of the irrigation water actually made it to the soil profile for crops to use. Fifty-eight percent of crop-water demand was met by subirrigation and precipitation (Osborne et al., 1983).

Lessons Learned

Although excess streamflow is the opposite problem from that which TU typically faces, the same questions must be answered, the investigative methods are transferable, and the proposed remedies are instructive. With 57% of irrigation water on the Bench simply bypassing crops and recharging the aquifer, great potential exists for reducing return flow. Based on their investigation, Osborne et al. (1983) proposed four categories of approaches for controlling irrigation-related runoff to Muddy Creek: (1) optimizing irrigation frequency and volume, (2) improving both on-farm and canal system efficiencies, (3) reusing runoff water, and (4) installing facilities to reduce peak flows, which cause most of the erosion.

The potential downside of the first two options in particular is that by reducing irrigation applications, they would also reduce ground-water recharge to the aquifer that supplies domestic water to residents of the Fairfield Bench. Before the Bench was irrigated, it is unlikely that a viable aquifer existed beneath it. To a large extent, the same is true of the valleys and basins of western Montana. Thus, it is important to consider the impacts of altering return-flow patterns not only on streamflow, but also on aquifers and the people who rely on them for water supplies.

11. Flathead Indian Reservation: Measuring Leaky Canals

The Flathead Indian Reservation in northwestern Montana (fig. 2) is irrigated via an elaborate network of distribution canals. About 250,000 acre-feet of water diverted from the Mission Range and Salish Mountains irrigate about 128,000 acres of cropland. Excess irrigation water, including leakage from the extensive canal system, recharges underlying aquifers, which supply water for domestic, stock, irrigation, and municipal uses (Slagle, 1992).

In 1986 through 1987, hydrogeologist Steve Slagle of the U.S. Geological Survey conducted field work to determine the quantity of leakage from the canals and to understand potential impacts to ground-water users if portions of canals were sealed to prevent leakage. More than 56 million square feet of irrigation canals traverse a diverse variety of terrain, represented by three principal geologic substrates: sandy, gravelly Quaternary-age alluvium; heterogeneous Quaterary-age glacial till; and silty, clayey Quaternary and Tertiary-age glacial lake deposits. To assess leakage rates, Slagle (1992) conducted detailed tests of 1-2 representative sites in each type of terrain.

At each site, Slagle (1992) installed 5-6 monitoring wells for conducting slug tests (Box 5), observing water-table fluctuations, and measuring temperature gradients. He installed stilling wells in the canals to record stage (surface-water elevation) fluctuations. He also conducted tracer tests in the aquifers and leakage tests in the canals to determine ground-water flow and leakage rates.

Temperature profiles in wells were used to examine the effects of canal leakage on ground-water temperature and the possible stratification of flow in the aquifer. However, the temperature data ended up being of limited use, as ground-water temperatures appeared to be influenced primarily by air temperature, and not by infiltrating canal water.

Tracer tests were conducted to determine the rate of leakage from canals, the ground-water flow rate, and hydraulic conductivity of the aquifer. Sodium-bromide tracer solution was injected into the canal bed at a known rate. At the same time, water samples were collected from monitoring wells. The concentration of bromide in these samples indicated the velocity of ground-water flow from the canal to the wells. Darcy's law (Box 7) was then used to calculate hydraulic conductivity.

Leakage tests to directly measure infiltration rates through the canal beds were conducted using seepage meters (fig. 10). Each seepage meter consisted of a 15-inch diameter, closed-top cylinder having two ports – one for attaching a water-supply bag and one for a vent to prevent air entrapment. The open bottom of the cylinder was embedded about 0.6 feet into the canal bed. The bag was submerged and a known volume of water supplied so that the water level in the bag was the same as in the canal. After a set period of time (6 to more than 100 hours, depending on the leakage rate), the volume of water loss from the bag was measured. The infiltration rate is the volume divided by the time period. Although this method accurately and directly measures canal leakage, it must be conducted repeatedly in different parts of a canal to account for variability in the substrate. In a heterogeneous environment, this can be extremely time consuming, especially if leakage rates are slow. Furthermore, the measured leakage rate is a function of water levels in the canal and the underlying aquifer, which change over the course of an irrigation season. Therefore, seepage meters are best used in canals with uniform bottoms, under "typical" water-level conditions, in conjunction with other methods of determining leakage rates from canals.

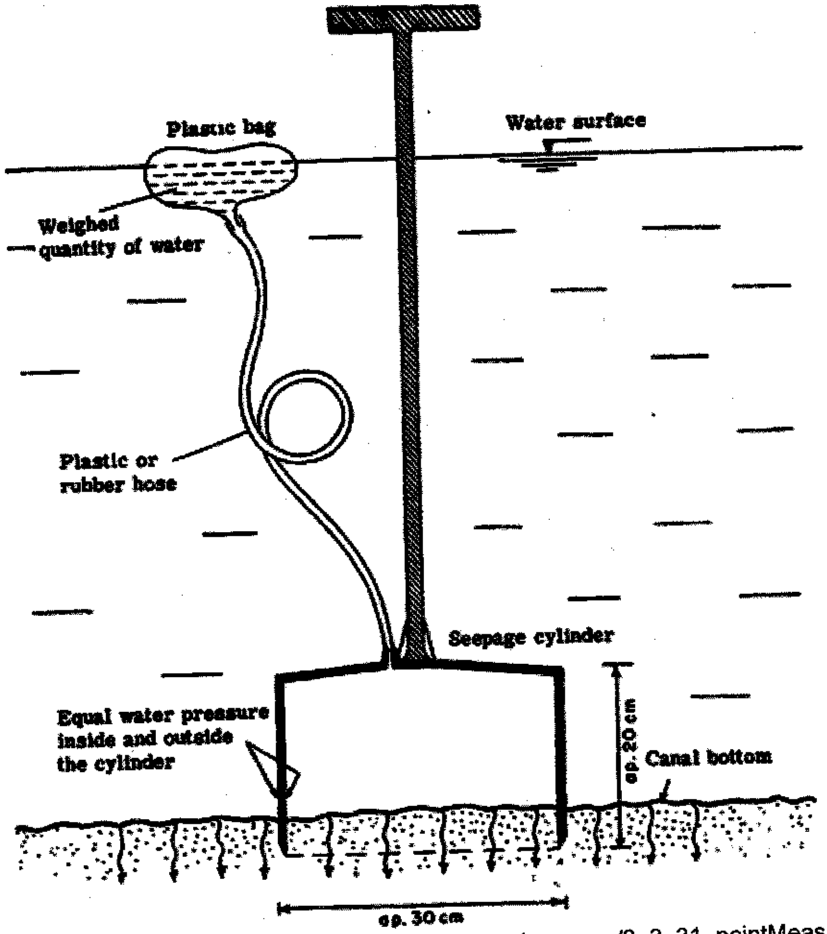

Figure 10. Seepage meter schematic. From http://ancid.org.au/seepage/3_3_31_pointMeasPrinc.html.

Slagle (1992) averaged hydraulic conductivity values from slug tests with leakage rates from seepage meters to determine the total amount of leakage from canals. Leakage rates of canals constructed on glacial till were similar to those of glacial-lake deposits, averaging 0.10 to 0.11 feet per day. In contrast, leakage from canals on the more permeable alluvium averaged 1.8 feet per day. Leakage from the entire canal system on the Reservation totaled about 314 acre-feet per day, or 48,000 acre-feet per year. Sealing the 9 percent of canals that traverse alluvial deposits would eliminate 60 percent of the leakage (Slagle, 1992).

Lessons Learned

The importance of geologic substrate in controlling ground-water recharge cannot be understated. As the west Billings case demonstrated, water leasing and other efforts to mitigate streamflow depletion are most effective if focused on areas with the thinnest surface layer of fine-grained deposits. The Freezeout Lake case showed how geologic substrate affects the chemistry of irrigation drainage. Here, Slagle (1992) determined on the basis of geologic substrate that 60 percent of canal leakage could be eliminated by lining only 9 percent of the Flathead Indian Reservation's more than 56 million square feet of canals.

12. Colorado Front Range: Weighing Lysimeters

Colorado Front-Range cities that obtain transmountain water transfers are entitled to use that water "to extinction", which means they claim the right to use return flow from lawn irrigation. To quantify return flow, most cities use small lysimeters to determine deep percolation as a function of the amount of water applied (Oad and DiSpigno, 1997). This method does not determine when or where return flow discharges to surface water, but offers an approach for quantifying ground-water recharge (*R*, fig. 1) that is not commonly used in Montana.

Weighing lysimeters consist of boxes containing plants and soil of known weight, embedded in the ground among similar plants and soil. Small weighing lysimeters are designed to be lifted out of the ground for periodic weighing; larger models have built-in scales that are read from underground viewing chambers.

Drainage lysimeters are a simpler variation of weighing lysimeters. Instead of capturing deep percolation, drainage lysimeters have permeable bottoms that allow excess water to flow out of the instrument. Drainage lysimeters are permanently installed flush in the ground.

A volume balance equation is used to calculate crop consumptive water use (*ET*):

$$ET = I + P - R - \Delta S$$

where I = applied irrigation water
P = precipitation
R = deep percolation, or return flow
ΔS= change in soil moisture.

I and P are measured independently. R is the quantity of water that drains through the lysimeter and accumulates in the bottom for periodic pumping (or drainage, depending on the design) and measurement. In weighing lysimeters, ΔS is determined by weighing the instrument before and after irrigation applications, and converting weight to volume. In drainage lysimeters, ΔS cannot be measured and must be assumed negligible (Oad and DiSpigno, 1997).

Although water-loss measurements from lysimeters are precise, their accuracy can be affected by the surroundings. If non-vegetated areas encircle the lysimeter, then vegetation in the lysimeter transpires more than if surrounding plants had reduced wind advection, as would be the case inside an irrigated field (Burman and Pochop, 1994). Likewise, a concrete or metal lysimeter frame extending above the land surface may heat up the lysimeter contents relative to the surrounding area.

Lessons Learned

Researchers at Colorado State University conducted experiments to compare estimates of deep percolation and evapotranspiration, and found considerable variation, depending on the approach used. Nevertheless, the researchers concluded that "the small lysimeters used by various cities are of acceptable accuracy compared to a large lysimeter and standard evapotranspiration equations for estimating consumptive use" (Oad and DiSpigno, 1997).

Deep percolation and evapotranspiration are important water-balance components to determine for understanding irrigation return flow. For field-scale projects, weighing lysimeters provide a relatively convenient, site-specific alternative to the more generalized methods described in Box 6.

Fundamental Considerations and Guidelines

As the widely varied case studies in this report demonstrate, there is no standard "blueprint" for evaluating irrigation return flow for water leasing or any other water management strategy. Nevertheless, a few guidelines do emerge from these cases, as summarized in this section.

Key Resources

First and foremost, do your homework. Even before visiting a new project site, try to obtain, at a minimum, the following:

- Topographic maps and aerial photos, available from a variety of sources, including Montana's Natural Resource Information System (NRIS), http://maps2.nris.state.mt.us/scripts/esrimap.dll?name=LocMap&Cmd=Map.
- Well drillers' logs, available from the Ground Water Information Center (GWIC) at the Montana Bureau of Mines and Geology, http://mbmggwic.mtech.edu/.
- Streamflow hydrographs, available from the U.S. Geological Survey (USGS), http://waterdata.usgs.gov/mt/nwis/sw.
- Water Resources Survey books, available at State and university libraries and on-line at http://www.dnrc.state.mt.us/wrd/home.htm (scroll to bottom of page). This outstanding resource – one for each county – contains detailed maps of irrigated lands, diversions, canals, and drains, accompanied by historical narratives and lists of water rights associated with each irrigation district.
- Soil Surveys, available from the Natural Resource Conservation Service (NRCS). http://soils.usda.gov/survey/printed_surveys/montana.html lists soil survey information by county.
- Historical climate data, available from the Western Regional Climate Center, http://www.wrcc.dri.edu/index.html.
- Water-right abstracts, available from the Montana Department of Natural Resources and Conservation (DNRC) Water Right Query System, http://nris.state.mt.us/dnrc/waterrights/default.aspx.
- Water-table maps, geologic maps, and hydrologic and geologic reports.

No central repository or clearinghouse exists for hydrogeologic maps and reports. However, for western Montana, a good place to begin is the reference manual, Geographic, Geologic, and Hydrologic Summaries of the Intermontane Basins of the Northern Rocky Mountains, Montana (Kendy and Tresch, 1996). For each intermontane basin or valley, this publication lists and summarizes every major -- and many minor -- geologic and hydrogeologic map and report available as of 1995.

Another good source is the Montana Water Center's searchable database of projects funded through the center, including numerous graduate student research projects: http://water.montana.edu/mwc/programs/research/projects/search.asp. The universities, conservation districts, U.S. Geological Survey, and Montana Bureau of Mines and Geology are also key resources.

Field Reconnaissance

Even armed with the latest and best maps, photos and reports, onsite visits are essential. Try to recognize the major features identified in the maps and reports. Get a feel for how the map scales translate on the ground. Decide which map to use as your main field reference, and write and draw your observations directly onto that map. If you take photographs, be sure to indicate on your map where you were standing and what direction you were facing when you took them. Likewise, cross-reference any notes you take to specific points on the map, if applicable.

Walk around the dewatered stream reach, or the stream reach of concern. Mark the reach on your map. Also observe and mark on your map any diversions, pumps, irrigation drains, other manmade structures, natural springs and seeps, potential or actual fish spawning areas, deep pools (for fish refuges during low flows), and any other points of interest.

Follow the major diversions up to where the irrigation water is applied. Note the condition of the ditches and canals that convey the water. If they are permeable and likely to leak, try to figure out where the leakage flows underground. Remember that the water table is often shaped like a subdued version of the overlying land surface or, more simply, "(ground) water flows downhill."

It is important to keep in mind that not all of leakage necessarily will contribute baseflow to streams. Field reconnaissance – both on the ground and using aerial or satellite photography, if available – may identify any important "sinks" such as cottonwood stands or major well fields along the ground-water flow path, which need to be considered in the overall water balance. Note areas that are unusually wet, where water from leaky ditches may be discharging to the land surface. Note whether the discharge you observe is beneficial (like in the Poorman Creek case) or non-beneficial (maybe it supports a lush weed patch) and therefore a prime candidate for canal sealing to save water.

When you reach the irrigated area, make the same types of observations as for the ditches and canals. Try to figure out where excess irrigation water goes, both underground and in surface drains. Think about the geologic substrate and how that might influence ground-water recharge and flow. Note the crop types and condition (dense, healthy crops consume more water than sparse, sickly crops), the irrigation method, and the amount of standing or flowing water.

Try to determine where surface drains and ground water that discharge into the dewatered stream reach originate. Examine the irrigated areas that contribute to them, and identify the diversions that serve that area. Think about how the diverse pieces you observe in the field fit together to balance the water budget.

Note potential measurement sites. Stream reaches with good access; even, confined flows; and ideally a bedrock outcrop work well. Any well potentially can be used for monitoring, with the owner's permission. Also note springs, seeps, and ponds that may represent the water table. Field-check benchmarks identified on topographic maps for later use in elevation surveys.

Perhaps most importantly, visit with the locals. If possible, have the water master or ditch rider and some local ranchers accompany you in the field. Pick their brains. Learn as much as possible from them about historical and current land and water-use practices, weather patterns, and streamflow conditions. Local knowledge is a priceless resource that rarely appears on maps and in reports.

Factors to Consider in Project Design

This section attempts to present general guidelines in the context of what we have learned from the case studies. That said, it is by no means an exhaustive or even prescriptive outline. Successful water managers recognize that every river, every project, and every community is unique, as are the solutions to their water-allocation challenges.

Goals and Scale of Project

First and foremost, understand the project goals. What are the amounts, locations, and timing of instream flows desired? The study objective, as well as the project timeframe and budget, largely dictate the approach. For example, for strictly concerns over connectivity in short reaches (e.g., North Fork Blackfoot and Poorman Creek case studies), synoptic measurements might be the best alternative. Basin-wide management objectives are better served by comprehensive water-balance studies and modeling (e.g., Flint Creek and upper Beaverhead River case studies).

Geologic Setting

How do aquifer characteristics and storage capacity control the amount of irrigation water that runs off relative to the amount that soaks into the ground and recharges the aquifer? How do they control the ground-water flow rate and direction, the lag time between irrigation and return flow, and the fate of seepage from fields and delivery systems? How does the geology affect the quality (chemistry) of return flow?

Hydrologic Setting

What are the historical flows in the basin, and why have they changed? How is the basin "plumbed", integrating natural and manmade systems? How long does the dewatered reach remain dry? If, like Poorman Creek, it remains dry well into the irrigation season, then any reductions in return flow caused by reducing diversions could not further harm that reach. Nevertheless, the fate of return flow needs to be determined in order to avoid harming others who may rely on it.

Legal and Social Issues

The economic and political climate of a basin play into the approaches taken both in investigating and in mitigating stream dewatering. Water-right issues that concern water leasing and return flow include seepage rights, enforceability of water-right changes, decree status, and locations of downstream priority users that require carriage water.

Monitoring

Follow-up monitoring of projects is essential before and after completion to assess their success and learn from their mistakes. For example, DNRC, in cooperation with TU, is currently monitoring Poorman Creek to assess the effectiveness of the conversion from flood to sprinkler irrigation in increasing connectivity of the creek to the Blackfoot River. Monitoring should assess not only the effectiveness of rewatering stream reaches, but also the impacts of reducing return flows.

Summary of Methods Used in Case Studies

The following table provides a cross reference between the various methods discussed in this report, the problems they address, and the case studies in which they were used.

SUMMARY OF METHODS FOR ANALYZING WATER-BALANCE COMPONENTS RELEVANT TO IRRIGATION RETURN FLOW

Estimated parameter	**Question**[2]	**Method**	**Case Study**
Ground-water recharge from irrigation / Amount of storage released from aquifer	A, B, D	Ground-water hydrograph analysis	North Fork Blackfoot Flint Creek West Billings Muddy Creek
Ground-water recharge from applied irrigation	A	Weighing lysimeters	Colorado Front Range
Source of ground water (irrigation return flow *vs.* other)	A, D	Isotope analysis (Box 8)	Gallatin Valley West Billings Upper Beaverhead
		Chemical analysis	Upper Beaverhead Freezeout Lake Muddy Creek
Evapotranspiration rate (Box 6)	A	Blaney-Criddle method	North Fork Blackfoot
		Evaporation pans, crop coefficients	Muddy Creek
		Intensive field instrumentation	Big Hole
		Chloride concentration in ground water	West Billings

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[2] Question addressed by method (parentheses indicate question indirectly addressed):
A. How much irrigation water recharges the aquifer?
B. When does return flow reach surface water?
C. Where does it return to surface water?
D. How much returns to surface water at any given time and place?

Estimated parameter	Question[3]	Method	Case Study
Leakage from canals	A	Seepage runs / flow measurements	Flint Creek Muddy Creek West Billings North Fork Blackfoot
		Canal ponding test	Muddy Creek
		Tracer test	Flathead Indian Res.
		Seepage meter	Flathead Indian Res.
Aquifer hydraulic characteristics (Box 5)	B, D (A,C)	Aquifer pumping tests	Flint Creek West Billings Upper Beaverhead Muddy Creek
		Slug tests	Flathead Indian Res.
		Well drillers' logs, published values	North Fork Blackfoot Flint Creek
Direction and rate of ground-water flow	C, (B)	Water-table map (Box 1)	North Fork Blackfoot Poorman Creek Flint Creek Big Hole Gallatin Valley Upper Beaverhead
		Transient tracers (^{3}H-^{3}He, CFCs)	Freezeout Lake Upper Beaverhead
Rate of ground-water flow	B	Darcy's law (Box 7)	Flint Creek Flathead Indian Res.
Quantity and location (reach) of ground-water discharge to surface water	B, C, D	Synoptic streamflow measurement (Box 2)	North Fork Blackfoot Poorman Creek Flint Creek Big Hole Muddy Creek Upper Beaverhead
		Hydrograph separation	Muddy Creek
Annual surface-water balance	D	Streamflow gaging, synthesis	Flint Creek Big Hole West Billings Beaverhead (Nicklin) Upper Beaverhead Freezeout Lake Muddy Creek
Timing of ground-water discharge to surface water	B, C, D	Time series analysis	Beaverhead (Nicklin)
		Modsim surface-water model	Flint Creek
		MODFLOW ground-water model (Box 9)	Upper Beaverhead Muddy Creek

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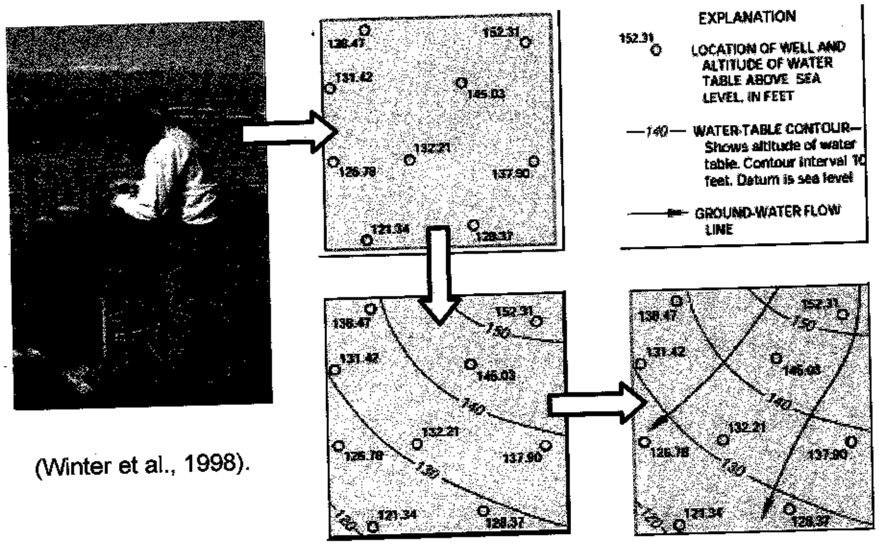
[3] Question addressed by method (parentheses indicate question indirectly addressed):
A. How much irrigation water recharges the aquifer?
B. When does return flow reach surface water?
C. Where does it return to surface water?
D. How much returns to surface water at any given time and place?

Box 1. Water-Table Maps

In almost all cases, ground water takes the shortest route "downhill", or down the slope of the water table. The only reliable way to determine the direction of ground-water flow – and thus the fate of irrigation return flow – is to plot a map of the water table or, more precisely, a potentiometric-surface map. Ground-water flow paths derived from water-table maps also help determine when return flow will reach surface water.

A water-table map is actually a topographic contour map, like the readily available USGS quadrangle maps that depict land-surface topography at the ground level, except water-table maps depict water-surface topography underground.



(Winter et al., 1998).

Water-table data consist of elevations of the water table at discrete points. Depending on the scale of the project area and the amount of detail required, water-table data may be acquired from a number of sources. The most reliable method is to measure the depth to water in shallow wells (photo above), since water in shallow wells rises exactly to the level of the water table. Any well may be used, so long as neither it nor surrounding wells have recently been pumped, and the well owner gives permission. Simple, small-diameter monitoring wells, or piezometers, may be installed expressly for measuring water levels. Another option is to survey the level of surface water in bodies that are known to be connected to the water table, such as gravel pits and, in some cases, seeps, springs, ponds, and streams. If less precision is required, then water levels may be gleaned from soil surveys, in combination with topographic maps. Soils information -- including lists of hydric soils, which are often associated with high water tables -- may be found at http://www.mt.nrcs.usda.gov/soils/. Water levels also may be obtained from drillers' logs (Box 4). It is important to remember that water levels fluctuate, sometimes by several tens of feet, so water-table data taken from sources such as drillers' logs and topographic maps are of limited use for small[4] study areas.

It is important that the elevation – not just the depth – of the water table be recorded at each site. Actual elevations are not necessary, but relative elevations are. If a benchmark is not available nearby, then the measuring points may simply be surveyed relative to each other. The only time a survey may not be necessary is if well locations can be plotted accurately on a detailed[5] topographic map.

Once all the measurements have been taken – ideally on a single day to avoid fluctuations – they are plotted on a map (upper middle graphic above). Lines of equal water-table elevation are then drawn between the plotted elevations (lower middle graphic). This should be done by a hydrogeologist, who will ensure that the final map is consistent with topographic and geologic features. Finally, going back to our original premise, water flows downhill. Lines drawn perpendicular to the water-table contours indicate the direction of ground-water flow (lower right graphic).

How many data points are needed? It depends on the scale of the project. It also depends on the complexity of the hydrologic system. Water levels at two points give the *relative* flow direction between the two points – toward either one point or the other. Water levels at three points give the *exact* flow direction, providing ground water actually flows in a straight line; three points situated on three sides of a mountain don't elucidate much of anything. The water table is often shaped like a subdued version of the overlying land surface. Therefore, well spacing should generally be close enough to define topographic features observed on the land.

There is no single repository or clearinghouse for water-table, or potentiometric-surface maps in Montana. Rather, almost all water-table maps are included as figures or plates in various reports. Therefore, the place to start looking for existing water-table maps is in hydrogeologic reports by consultants and government agencies. Maps of small areas may be associated with applications for water rights filed at the Montana Department of Natural Resources and Conservation (DNRC) and applications for subdivisions and ground-water discharge permits at the Montana Department of Environmental Quality (DEQ). Maps of larger areas in western Montana are listed in Kendy and Tresch (1996), along with their scales and contour intervals.

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[4] How small is "small"? If seasonal water-table fluctuations in individual wells exceed the difference in water levels between wells, then the area is too small to rely on historical measurements that were taken over a long period of time. For example, say the water table in the vicinity of wells A and B fluctuates 50 ft annually. Then say you find a driller's log for well A indicating a water level of 3,000 ft above sea level when it was measured in March and a driller's log for well B indicating a water level of 3,020 ft when it was measured in June. Since the reported water level in B is higher than the reported water level in A, does ground water flow from B to A? Maybe not. If the water level in A had also been measured in June, perhaps it would have been higher than 3,020 ft, which is reasonable, considering water levels fluctuate 50 ft annually. In that case, flow would be from A to B. Sometimes, long-term, continuous data from nearby wells can be used to "normalize" and make usable sporadic data from drillers' logs and other sources.

[5] How detailed is "detailed"? If uncertainty in the topographic contours affects the flow direction determined from the water-table measurements, then the topographic map is not sufficiently detailed.

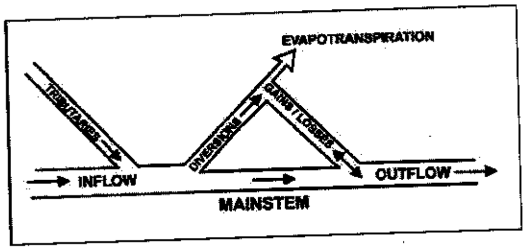
Box 2. Synoptic Streamflow Measurements, a.k.a. Seepage Runs

Inflows to and outflows from a stream reach may occur either as surface flows, which can be measured directly, or as ground-water flow (a.k.a. seepage), which cannot. The premise of synoptic streamflow measurements is that if all surface-water flows are accounted for, then ground-water flows – including return flow – can be calculated. The simple mass-balance equation, based on the graphic below, is:

$$Inflow + Tributaries - Diversions - Evapotranspiration \pm Gains/Losses = Outflow$$

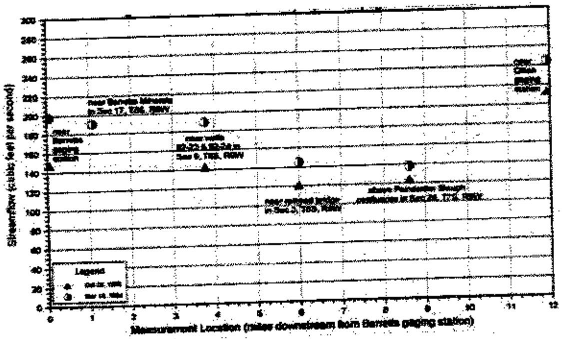
All variables in the equation are measured surface-water flows, except for the unmeasured *Gains/Losses* from/to ground water. Ideally, seepage runs are conducted when plants are dormant during late fall to early spring, so evapotranspiration and diversions may be considered negligible. Then, the equation reduces to:

$$Gains/Losses = Outflow - Inflow - Tributaries$$



"Synoptic" means presenting an account from the same point of view. A better word would be "concurrent", or at the same time. The idea is to take all the measurements at one time (or as close to one time as feasible) in order to obtain a snapshot of flow conditions within a stream or canal reach, unfettered by seasonal or other fluctuations

Conducting synoptic measurements in the fall accounts for post-irrigation season return flows. Results of two or more synoptic runs conducted over the course of a year shed light on the rate at which return flow drains from the aquifer system. For example, the graph below shows how the influence of irrigation return flow on the Beaverhead River diminished over the winter of 1983-84 (Uthman and Beck, 1998).



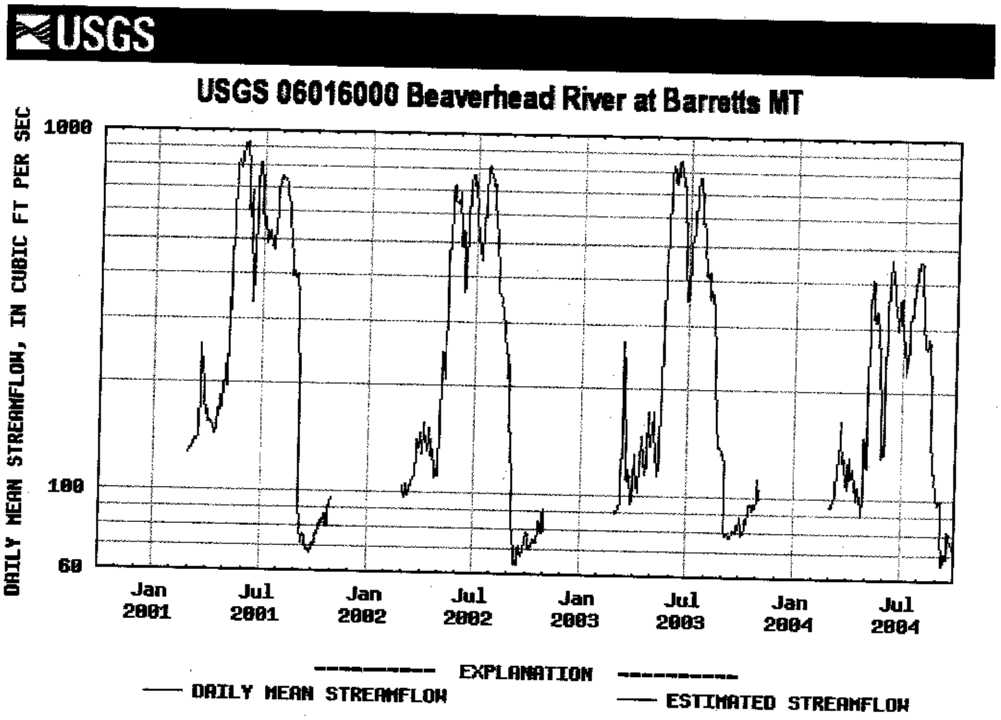
The closer together the mainstem sites are situated, the more precisely ground-water recharge and discharge areas may be located, so long as flows measurably differ between sites. Typically, streamflow measurements are at least five percent in error. These errors add up when using the equations above to calculate gains and losses. Therefore, it is important to measure mainstem flows at sites located close enough together to minimize the number of intervening tributary and diversion measurements, but far enough apart that the difference between inflows and outflows exceeds the sum of measurement errors. Conducting seepage runs outside the irrigation season avoids errors associated with measuring multiple diversions. Additionally, seepage runs must be conducted during periods free of storm and snowmelt events to assure steady flow conditions.

Box 3. U.S. Geological Survey Surface-Water Data

Over the years, the U.S. Geological Survey (USGS) has measured and recorded streamflow at hundreds of sites across Montana. Every active and discontinued site, along with its drainage area and period of record for each type of data (streamflow, chemistry, sediment, temperature) is listed at http://mt.water.usgs.gov/pub/MTStations.pdf. Historical and real-time data, statistical summaries, and hydrographs, or plots of streamflow *vs.* time, are available at http://waterdata.usgs.gov/mt/nwis/sw. This database is searchable by latitude/longitude, county, drainage area, and other attributes. It can also be searched by township, range, and section by specifying the USGS Site Name.

If USGS streamflow data are available for a site near a proposed return flow study, then every effort should be made to design the study around the USGS gaging site. USGS flow data are trusted and reliable. Often, they are located on large rivers that require special equipment and expertise to measure. Ideally, the study can be designed so that a single USGS gage measures the entire surface-water outflow from the area of interest.

Even if it is not practical to include a USGS gaging station within a return-flow study area, it is still prudent to determine the availability of data for nearby sites. Long-term streamflow data from nearby sites are useful for estimating flow at ungaged sites, which may be essential for understanding the local water balance.



Streamflow hydrograph downloaded from USGS website.

Box 4. Well Drillers' Logs and the GWIC Database

Every time a new well is constructed in Montana, the driller must complete and submit a well log to the State. All well logs on record are available at http://mbmggwic.mtech.edu/, in the Ground Water Information Center (GWIC) maintained by the Montana Bureau of Mines and Geology. The database is searchable by township and range, name of well owner, geologic unit, drainage basin, county, subdivision, and GWIC identification number.

A typical well log lists information about when and how the well was drilled and constructed, including the well depth, water depth, types of materials (sand, gravel, clay, etc.) encountered at various depths, and the well's response to pumping. This information lends insight to the aquifer's ability to transmit water. For example, ground water moves much faster through gravel and sand than through silt and clay. If the driller reported that the water level barely dropped when the well was pumped, then that's another indication that water may move quickly through the aquifer.

In addition to well logs, the GWIC site offers access to records of water levels measured in selected monitoring wells throughout the state. This information is crucial for understanding seasonal and long-term changes in ground-water flow and availability. Finally, GWIC (or its parent agency, the Montana Bureau of Mines and Geology) is a good place to start looking for published regional geologic maps and reports to help the geologist interpret local drillers' logs.

Examination of all drillers' logs, ground-water hydrographs, and reports on the area of interest provides a three-dimensional impression of ground-water movement through the local aquifer. By plotting reported water levels and geological units on maps, hydrogeologists obtain a first-cut representation of ground-water flow patterns in the area. Even if the area of interest lacks existing wells, drillers' logs from the surrounding area can help guide the placement of new, project-specific monitoring wells.

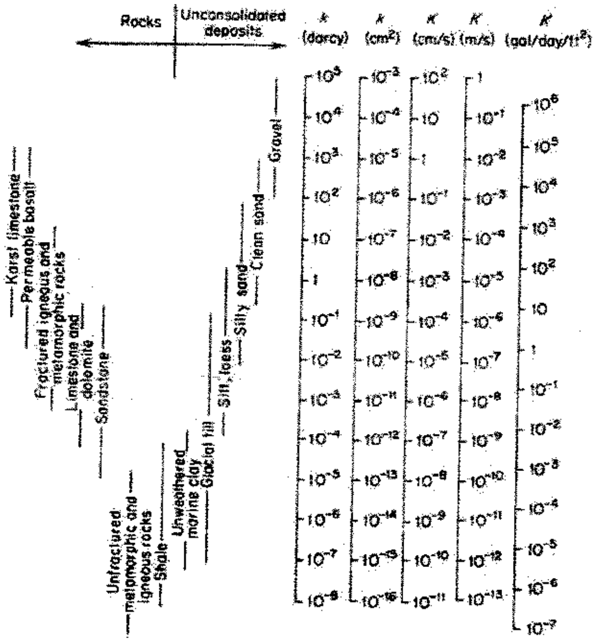
Montanans are fortunate to have this easily accessible, well organized database at their fingertips. It is a natural first stop for anyone interested in what's underground. And since return flow moves underground, GWIC is the place to start any return flow study.

Box 5. Determining Aquifer Characteristics

Hydraulic conductivity *(K)*, transmissivity *(T)*, permeability *(k)*, storage coefficient *(S)*, specific yield *(S_y)*, and effective porosity *(n)* are hydraulic characteristics that quantify an aquifer's ability to store and transmit ground water. They are constant values that do not change with time, but do vary from place to place, even within a single aquifer. These values are essential for determining ground-water flow volumes, velocities, and travel times, and the quantity of ground water stored in and released from aquifers.

Aquifer characteristics may be determined by a number of means, which range as much in accuracy as they do in effort and expense.... which is to say, a lot. From least to most accurate and reliable, these include:

- Obtaining published values from literature. This is a perfectly valid approach for an initial estimate and/or a small budget. Most hydrogeology textbooks list typical values associated with different geologic materials. The example below (Freeze and Cherry, 1979) shows the range of values of permeability (k) and hydraulic conductivity (K) found in nature. In Montana, the geologic materials that make up an aquifer may be gleaned from drillers' logs in the GWIC database (Box 4).



- Estimating *K* and *T* from pumping data reported on drillers' logs. The information that drillers provide to GWIC (Box 4) usually includes the results of short, single-well pumping tests, which hydrologists may use to estimate *K* and *T*. However, depending on the driller and testing method, this method can be notoriously inaccurate. Though the effort involved is greater than simply obtaining published values from literature, the result may not be any more reliable.

- Conducting laboratory tests. Core samples may be collected from the field and brought to the laboratory to measure *K*, *k*, *S_y*, *n*, and other characteristics. Although laboratory methods are fairly accurate, they only describe a tiny piece of the aquifer (the core sample), which may or may not represent the entire system. Because most aquifers – especially the alluvial and glacial aquifers that underlie most of the irrigated land in Montana – are extremely heterogeneous (non-uniform), hundreds of laboratory tests may be needed to characterize a study area.

- Conducting single-well aquifer pumping tests. Single-well tests in the field are an improvement over laboratory tests because they measure the characteristics of a larger piece of aquifer. A simple version is the slug test, in which a known volume is "instantaneously" inserted into or removed from the well, and the rate of water-level recovery is then recorded. Slug tests are handy when it is infeasible or cost-prohibitive to pump the well. Three disadvantages of single-well tests are that they only test the part of the aquifer in the immediate vicinity of the well, they don't account for hydraulic effects ("well loss"), and they cannot be used to determine values of S or S_y.

- Conducting multiple-well aquifer pumping tests. If money and time are no object, then multiple-well aquifer pumping tests, in which one well is pumped at a constant rate while water levels are measured in observation wells, is the best way to determine aquifer characteristics. The longer the pumping test runs, the larger is the volume of aquifer tested. (The relationship between pumping time and aquifer volume affected depends on the aquifer's hydraulic characteristics.) In addition to hydraulic characteristics, multiple-well tests can help locate aquifer "recharge boundaries" such as surface water bodies, from which the pumping well pulls water into the aquifer. Multiple-well tests may require professional hydrogeologists several weeks to plan and conduct the tests and analyze the results.

Box 6 . Estimating Crop-Water Consumption

Irrigation water that is applied to crops leaves the field in one of three forms: runoff, ground-water recharge, or evapotranspiration (*RO, R,* and *ET*, respectively, fig. 1). Since ground-water recharge, including irrigation return flow, is so difficult to quantify independently, it is commonly calculated as the residual in the water-balance equation, after determining *RO* and *ET* independently. *ET* is evaporation plus transpiration, or crop-water consumption. Several methods are available for estimating crop-water consumption. Only a few are mentioned here, generally in order of greatest to least accuracy.

Agrimet is a satellite-based network of automated agricultural weather stations located in irrigated agricultural areas throughout the Pacific Northwest, operated and maintained by the Bureau of Reclamation. The stations collect detailed climate and soil-water data needed for optimal farm-water management. Agrimet data, including daily *ET*, are accessible at http://www.usbr.gov/gp/agrimet/index.cfm. The web site also offers excellent explanations of how *ET* is calculated and how to make the most of Agrimet.

The **Penman-Montieth** equation uses temperature, humidity, wind speed, hours of sunshine, and crop data to calculate *ET*. The **Cropwat** program, developed by the Food and Agriculture Organization (FAO) of the United Nations, uses the Penman-Montieth method to calculate crop-water and irrigation requirements. The program may be downloaded from http://www.fao.org/ag/AGL/AGLW/cropwat.stm. Standard crop data are included in the program database, and climate data for 144 countries may be obtained from the FAO CLIMWAT database, http://www.fao.org/ag/AGL/AGLW/climwat.stm. Unfortunately, the United States is not one of those countries. However, it is not difficult to format climate data from other sources to use as input to Cropwat.

The SCS **Blaney-Criddle** TR21 method is widely used to calculate *ET* because it has relatively few climate data requirements; only temperature and precipitation are needed. The **Irrigation Water Requirements** software (Dalton, 2003), developed by the Natural Resource Conservation Service, inputs climate data directly from Montana weather stations and calculates crop-water use according to the Radiation Method (Doorenbos and Pruitt, 1977), the Temperature Method commonly referred to as the FAO-Blaney-Criddle method, and the SCS Blaney Criddle TR21 Method. The program may be downloaded from http://www.wcc.nrcs.usda.gov/nrcsirrig/irrig-mgt-models.html.

Box 7. Darcy's Law: Calculating Flow through an Aquifer

According to Darcy's Law, the volumetric ground-water flow rate increases with increasing *hydraulic conductivity, K* (or *transmissivity, T*), water-table slope, and aquifer thickness. That is, the thicker and more permeable the geologic material and the steeper the water table, the faster ground water can flow "downhill" through the aquifer. *K* and *T* are determined from aquifer-pumping tests (Box 5). The water-table slope, or *hydraulic gradient*, is determined from water-table, or potentiometric-surface, maps (Box 1). Aquifer thickness is determined from geologic information such as drillers' logs (Box 4).

Darcy's law is also used to determine ground-water travel times. Ground water only moves through pore spaces within the aquifer, and not through the rock itself. To account for this, the volumetric flow rate is divided by the aquifer *effective porosity*, or the proportion of aquifer material through which water flows, to compute flow velocity. The smaller the effective porosity, the faster the flow velocity. Effective porosity may be obtained from multiple-well aquifer-pumping tests.

K and *T* of natural geologic materials range over more than 10 orders of magnitude (Box 5). In heterogeneous material such as glacial till and alluvium, *K* and *T* may vary over several orders of magnitude within a single aquifer. This variation can lead to great uncertainty in flow calculations, and highlights the importance of determining these values at a sufficient number of sites to adequately characterize the aquifer. Understanding of the depositional processes that created geologic formations helps hydrogeologists decide where and how many aquifer tests to perform.

Given the uncertainty in ground-water flow rates calculated from Darcy's law, one might question why use Darcy's law at all? The information needed for a Darcy computation is usually readily available or easy to estimate near the onset of a project, so Darcy gives the investigator useful insight early on. Oftentimes, this insight helps guide the project. Darcy is usually one of several approaches used to characterize return flow processes in an area. Ideally, the different approaches will confirm each other, lending confidence to the results of each.

Box 8. Using Geochemistry to Trace Ground-Water Sources

Myth: Water = H_2O. *Reality*: Natural waters found in lakes, streams, and aquifers have a variety of constituents, both natural and anthropogenic, dissolved in them. As water flows across the ground, through soil, and into aquifers, it picks up minerals, salts, and contaminants along the way. So, natural water = H_2O + dissolved bits of almost everything it has encountered along its flow path.

That's why waters that originate from different sources have different chemical compositions. Geochemists view the unique chemical characteristics of different waters as natural tracers. For example, water from the east side of Montana's Bitterroot Valley is chemically distinct from west side water because of differences between the Sapphire Mountains on the east and the Bitterroot Mountains on the west. Water in the Bitterroot River contains concentrations of dissolved constituents in proportion to the contributions from its eastern and western tributaries.

Water beneath irrigated fields may contain nitrate from fertilizers. Nitrate is an excellent ground-water tracer because it is "conservative", so it moves with the water, rather than attaching to aquifer materials, precipitating out of solution, or chemically reacting. Moreover, nitrate from fertilizers is isotopically distinct from other nitrate sources such as septic effluent or livestock manure, so it can easily be identified in water samples.

What is meant by "isotopically distinct"? Isotopes are atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus. The naturally occurring elements give rise to more than 1,000 stable and radioactive isotopes (Coplen, 1993). Ground waters that were recharged at different times, in different locations, or that followed different flow paths are often isotopically distinct (Kendall et al., 1995).

The stable isotopes of oxygen and hydrogen ($\delta^{18}O/\delta D$ or "oxygen-deuterium"), the atoms that make up the water molecule, are functions of the temperature and elevation at which the water originated and of natural processes such as evaporation that may occur later. Thus, snowmelt high in the mountains has a different isotopic "signature" than low-elevation rainfall. Likewise, water that has been stored in a reservoir usually is isotopically distinct from nearby waters that flow freely. All of these waters maintain their isotopic signatures, even after they are used for irrigation and become return flow.

In certain situations, $\delta^{18}O/\delta D$ analysis can be used to determine the proportion of water derived from irrigation return flow. In order to do so, the irrigation source water must be isotopically distinct from the return flow receiving waters. Likely candidates include water diverted from another basin, water diverted from a high-elevation stream onto low-elevation benches, and/or water that has been stored in a reservoir. These situations are not unusual in Montana, especially in areas irrigated with mountain runoff.

The ratio of $\delta^{18}O/\delta D$ is not difficult or expensive to obtain. A water sample is collected without any special equipment and shipped to a qualified lab for analysis. Any potential source water, as well as the receiving water, should be sampled. Seasonal sampling can help determine changes in irrigation return flow over time. Isotopes are best suited for watershed-scale investigations because isotope tracers integrate, or generalize, small-scale variability within a basin (Kendall et al., 1995).

Box 9. Computer Models of Irrigation Return Flow

Determining *when* irrigation return flows discharge from the aquifer system into surface water is the most challenging aspect of understanding return flow processes. Excess irrigation water recharges the aquifer only during certain times of the year, and its flow rate in the aquifer changes as water levels respond to irrigation, precipitation, and other factors. Moreover, as return flow moves through the aquifer, it may encounter different geologic deposits with different abilities to transmit water. Therefore, the timing of return flow depends on simultaneous changes over both time and space. Analyses to account for these system complexities are too difficult for simple back-of-the-envelope calculations. Computer models are almost always needed to determine the timing of return flow.

Among these models is MODFLOW (McDonald and Harbaugh, 1988), the popular ground-water flow model that simulates the aquifer system explicitly (in detail) and surface water implicitly (as inputs and outputs to the aquifer). This approach is commonly used for regulatory purposes, even when few data are available, because of its relative ease of application by trained ground-water modelers. Even with scant field data, its ability to integrate site geometry and seasonal flow changes helps regulators and others understand ground-water flow and quantify water-balance changes over time. If stream hydraulics have been characterized, then MODFLOW can be linked to another program to simulate stream-aquifer relations (Prudic, 1989), thereby allowing for explicit modeling of the entire irrigation return flow process. It can also be linked to Geographic Information System (GIS) software such as ArcView to assist in data input and analysis. Although the MODFLOW program is freely available from the U.S. Geological Survey, commercial software to facilitate its use starts at about $1,200.

MIKE BASIN is a commercially available, ArcView GIS-based river basin network model that uses a time series method to model irrigation return flow. This model takes the opposite tack from MODFLOW in that it models surface water explicitly and ground water implicitly. "Technically, MIKE BASIN is a quasi-steady-state mass balance model, however allowing for routed river flows. The groundwater description uses the linear reservoir equation" and "MIKE BASIN is both a simulation and an optimization model" (http://www.dhisoftware.com/mikebasin/index.htm). The MIKE BASIN program lists at $4,600.

Some government entities have developed their own computer programs for evaluating irrigation return flow processes. For example, the U.S. Bureau of Reclamation used its own software, Modsim, to model return flow in the Flint Creek valley (written communication, Leslie Stillwater, Bureau of Reclamation, Boise, Idaho). However, these programs are not generally available for public use.

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Hydrologic Impacts due to Changes in Conveyance and Conversion from Flood to Sprinkler Irrigation Practices

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Abstract: Improvements in irrigation efficiency are well documented when changing from flood to sprinkler irrigation methods; however, other impacts to the watershed associated with this change are not well known. The resulting impacts to a river basin hydrology when irrigation and conveyance methods are changed are the focus of this study. In an attempt to improve water application and conveyance efficiencies in the Salt River Basin of western Wyoming, irrigation practices were changed from flood irrigation to sprinkler irrigation beginning in the late 1960s, with completion by the mid-1970s. Based upon a water balance, flow in the Salt River increased an average of 65.62 MCM/year. Return flow timing was also impacted by the conversion to sprinkler irrigation. Flows increased 34% in May and 50% in June, while decreasing 15 and 14% in August and September. These changes may have coincided with decreases in groundwater storage. However, analysis of changes in groundwater levels with time was inconclusive. Surface water total dissolved solids (TDS) appears unaffected by the conversion in irrigation practices, while limited groundwater quality data indicate that TDS values are lower in sprinkler irrigated areas.

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Introduction

The conversion from flood irrigation to sprinkler irrigation provides many benefits to farming communities including savings in water, energy, and labor, which are supplemented with the farmer's ability to produce increased crop yields (Guitjens and Goodrich 1994). Perhaps the greatest benefit to farmers resulting from changing irrigation practices is the increase in total irrigation efficiency. Irrigation efficiency is defined as the ratio of net volume of water beneficially used by the crops to the volume of water applied to the crops (Burt et al. 1997). Many climatic and geologic factors, such as wind, soil type, solar influences, and precipitation, influence irrigation efficiencies. Irrigation efficiencies reported for flood irrigation systems range from 45 to 60%, while sprinkler irrigation efficiencies range from 60 to 80% (Wolter and Bersisavlijevic 1991; Zalidis et al. 1997). Battikhi and Abu-Hammad (1994) found that, when converting from flood irrigation to sprinkler irrigation techniques, overall irrigation efficiency increased from 42% (citrus) and 53% (vegetable) with flood irrigation to 68 and 70%, respectively, for sprinkler irrigation. In most case studies, average irrigation efficiencies increase from approximately 50 to 70% after converting from flood to sprinkler irrigation.

The greater irrigation efficiency of sprinkler systems is the result of applying the water more evenly on the soil surface. The ability to distribute the water more evenly on the surface provides for maximization of water consumption and utilization. Flood or border irrigation distributes irrigation water unevenly over the fields; this increases the crop stress and lowers production. Deep percolation losses of water generally occur with flood irrigation, because overirrigation is necessary near the source to replenish the root zone of the soil farthest away from the source (Benjamin et al. 1998). Many crops, and especially alfalfa, are negatively impacted by oversaturated soil. In addition, flood irrigation water is often of a lower temperature than sprinkler irrigation water. The lower water temperature negatively impacts many crops (Saeed and El-Nadi 1997). Overirrigation can also lead to leaching of fertilizers and pesticides to groundwater (Benjamin et al. 1998), and the conversion to sprinkler irrigation may beneficially impact groundwater quality.

While improvements in irrigation efficiency are well documented when changing from flood to sprinkler irrigation, impacts to the watershed are not well known and are the focus of this study. The change from flood irrigation to sprinkler irrigation techniques affects a river basin hydrology through a variety of mechanisms including changes in seepage and deep percolation, evaporation, crop evapotranspiration, and phreatophyte consumption.

The objectives of this study are to quantify the potential hydrologic impacts to a watershed when irrigation systems are converted from flood to sprinklers and to relate these impacts to the various hydrologic components through which they occur. Specific objectives include the determination of changes in (1) return flow timing; (2) total annual river flow; (3) agricultural production; (4) surface water and groundwater quality; and (5) groundwater levels in the unconfined aquifer impacting river recharge.

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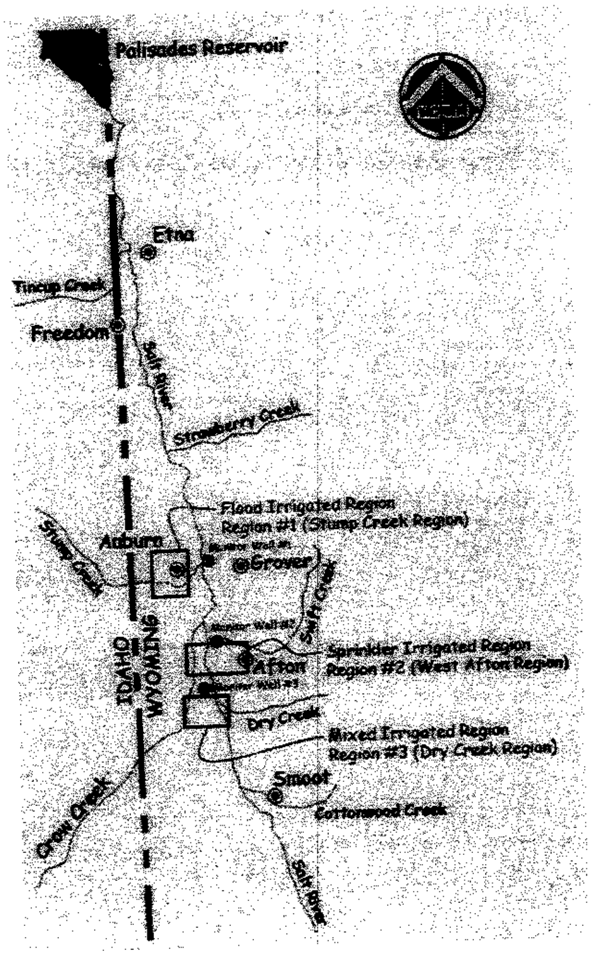

Fig. 1. Locations of Salt River and its tributaries, three monitoring wells, and three regions in study area analyzed for groundwater changes

Background

Site Description

The Star Valley in western Wyoming contains some of the richest farmland in the entire state, and as in other semiarid climatic regions, water for irrigation is a very important resource. Irrigation in the Salt River Valley in western Wyoming has taken place since the late 1800s. In an attempt to improve water application and conveyance efficiencies, irrigation practices were changed from flood irrigation to sprinkler irrigation beginning in the late 1960s, with completion by the mid-1970s. The change to sprinkler irrigation occurred on approximately 75% of the irrigated acreage and included installing several kilometers of underground gravity-pressurized steel and asbestos pipe. The pipes replaced the canal network as the means of conveyance of irrigation water to the fields. Water application with the sprinkler systems was more uniform and the amount of water applied was controlled better than with flood irrigation.

The Salt River Basin is located in the western part of Wyoming, near the Idaho border (Fig. 1). The valley's watershed covers approximately 2,147 km^2 (829 mi^2). The valley is nearly 88 km (55 mi) long and approximately 24 km (15 mi) wide. The Salt River and its tributaries provide irrigation water to the valley. The Salt River is formed from the Salt River mountain range on the east, the Gannett Hills on the south, and the Caribou and Webster ranges on the west. The river flows north to the Snake River, where it empties into the Palisades Reservoir on the Wyoming and Idaho border.

As of 1997, over 26,300 ha (65,000 acres) of agricultural land were used to produce crops in the Star Valley (SWWRC 1999). The two main crops, alfalfa hay and barley, are produced to support the dairy industry in the area. The crop irrigation requirements for the area are approximately 380 mm (15 in.) of water (Pochop et al. 1992). The Salt River and its tributaries must provide as much as 95% of the irrigation water used in Star Valley, amounting to about 120 million m^3 (MCM) (97,500 acre-ft) of water per year. Irrigation occurs throughout the duration of the growing season for the area, which is on average from May 1 to September 15. The majority of the soils in the valley are well-drained silty-sandy or gravelly loams (USDA-NRCS 1976). The valley has no reservoirs or surface storage capabilities, and the cropland is completely dependent on stream diversions and pumping of groundwater aquifers for obtaining irrigation water.

Because of its physical characteristics, the Star Valley presents a unique opportunity to study the hydrologic impacts of irrigation changes. The Greys River contains nearly the same flow as the Salt River and flows through a narrow drainage basin of approximately 1,160 km^2 (448 mi^2) on the adjacent side of the Salt River Mountain Range. However, unlike the Salt River, the Greys River has not been significantly impacted by changes in irrigation practices, because the river only provides water to about 200 ha (500 acres) of irrigated agriculture. As such, a comparison of flows in the two rivers before and after the application of sprinkler systems provides an excellent method to investigate impacts associated with changes in conveyance and application methods.

Methods and Procedures

Double Mass Balance Analysis

Double mass balance plots were created for analyzing the flow consistency over time of the Salt River, utilizing the Greys River as a control. The period of record analyzed was from 1954 through 2000. United States Geological Survey (USGS) stream gauges were used as the primary data resources. USGS station 13027500, located near Etna, Wyoming, above the Palisades Reservoir (latitude N 43°-04′; longitude W 111°-02′), was used to represent the Salt River flows. USGS station 13023000, located near Alpine, Wyoming, above the Palisades Reservoir (latitude N 43°-08′; longitude W 110°-58′), was used to represent the Greys River flows.

Cumulative average monthly flow values for the Salt River and the Greys River were calculated for each month over the period of record. The cumulative values for the two rivers were plotted against each other to graphically depict any changes that might have occurred to the Salt River's hydrology due to the change in irrigation practices. The Greys River was the control in the analysis, and it is assumed that climatic changes do not affect the plots, because climatic variables are considered essentially equivalent for each scenario. Changes in slope in the trend line over the period of record on the double mass balance plot represent changes in the ratio of Salt River flow to Greys River flow, which were attributed to nonclimatic factors, such as changes in irrigation practices.

Previously, in an attempt to identify if and when the Salt River flow responded to the conversion from flood to sprinkler irriga-

Table 1. Evaporation Coefficients, Average Monthly Evaporation, and Total Evaporation in Study Area

Month	Fraction of annual evaporation, C_1	Evaporation loss for conveyance to private property (MCM/year)	Evaporation loss for conveyance on private property (MCM/year)	Total evaporation loss (MCM/year)
May	0.115	0.26	0.32	0.57
June	0.131	0.30	0.35	0.65
July	0.171	0.38	0.46	0.84
August	0.156	0.35	0.42	0.77
September	0.115	0.26	0.31	0.57
		$\Sigma=1.55$	$\Sigma=1.86$	$\Sigma=3.41$

tion, a similar double mass balance analysis for the two rivers was performed by Sando et al. (Sando et al. 1985; Sando 1986). The Sando study covered the years 1954–1985. In this study, we follow the methodology of Sando but extend the period of years to 2000 and also quantify the flow changes and responsible mechanisms.

Streamflow Calculations

Generally, hydrologic modeling is utilized to demonstrate net changes in water balances for a particular area. Limited stream gauge data in the study area present difficulties in constructing a hydrologic model that would demonstrate changes in flow over time due to changes in irrigation practices. As a result, differences in flow ratios between the Salt River and Greys River are used to approximate the net change in annual flow in the Salt River resulting from changes in irrigation practices. Ratios of cumulative monthly flow in the Greys River versus cumulative monthly flow in the Salt River were calculated for flows prior to and after the change to sprinkler irrigation. The difference in ratios between the presprinkler and postsprinkler periods multiplied by the average monthly flow in the Salt River for a month represents the change of average streamflow in the Salt River for that month. The annual change in streamflow (i.e., the conservation of water) was calculated by summing the average monthly changes in flow for the months considered to be statistically significant. Student t-tests, with a confidence level of 95%, were performed to determine the statistical significance of monthly ratio changes.

Mass Balance Calculations

The conversion to sprinkler irrigation impacts the basin hydrology. A mass balance analysis provides a means of relating the changes in stream flows identified in double mass balance plots to changes in irrigation diversions, water use, and river basin hydrology. The mass balance for the system for each irrigation practice is described by

$$R_{\text{outflow}}=R_{\text{inflow}}-E-P-SI-ET+P_r-\Delta\text{Storage} \qquad (1)$$

where R_{outflow} = volume of water leaving the study area via the Salt River; R_{inflow} = volume of water entering the study area via the Salt River and its tributaries; E = total amount of water lost through evaporation within the study area; P = amount of water lost through phreatophytic consumption in the study area; SI = water lost via seepage and infiltration losses in the study area; ET = total amount of evapotranspiration occurring in the study area; P_r = annual precipitation in the study area; and ΔStorage = any change in storage within the study area. Because there are no surface water storage capabilities, ΔStorage accounts for any possible changes in aquifer storage. Each of these variables is an average annual value.

The change in stream flow in the Salt River due to the switch of irrigation conveyance and application methods can be described by

$$S=R_{\text{outflow-sprinkler}}-R_{\text{outflow-flood}} \qquad (2)$$

where S = total average difference in increased stream flow in the Salt River leaving the study area; $R_{\text{outflow-sprinkler}}$ = average annual flow of the Salt River when sprinkler irrigation was used; and $R_{\text{outflow-flood}}$ = estimated average annual flow of the Salt River if flood irrigation techniques were utilized over the same time period. The estimated flows are obtained from the development of flow ratios as described previously.

The parameters presented in Eq. (1) are affected differently by each irrigation practice. The sum of the net change for each parameter in Eq. (1) should account for the total change in annual streamflow in the Salt River after the switch to sprinkler irrigation techniques. Because of the change in conveyance methods (i.e., a change from open ditches to closed pipes), sprinkler irrigation practices in the study area are assumed to have minimal losses for phreatophytic consumption and seepage and infiltration losses in the conveyance process. Therefore, changes in streamflow due to changes in conveyance loss and field application can be calculated as

$$S=\Delta E+P_{\text{flood}}+SI_{\text{flood}}+\Delta ET-\Delta\text{Storage} \qquad (3)$$

where ΔE = change in evaporation due to changes in irrigation practices; P_{flood} = average annual phreatophytic consumption during flood irrigation; SI_{flood} = average annual seepage and infiltration losses occurring within the study area during flood irrigation; ΔET = change in evaporation; and ΔStorage = change in groundwater storage after the change in irrigation practices.

Evaporation Calculations

Evaporation loss calculations for the open canals were made for two of the larger irrigation districts, the Cottonwood Irrigation District and the Dry Creek Irrigation District. These calculations were then extrapolated to estimate the canal evaporation for the entire drainage basin. Values for canal evaporation losses (E_{flood}) were calculated from the fraction of total annual canal evaporation (C_1) for each month, total annual canal evaporation for the region (C_2), and the calculated total surface area, SA, of water exposed to the atmosphere in the flood irrigation canals as follows:

$$E_{\text{flood}}=C_1\cdot C_2\cdot SA \qquad (4)$$

C_1 values for each month are provided in Table 1. C_2 for the area is approximately 1.143 m (45 in.) (Lewis 1978). The total surface area, SA, of water within the irrigation canals for the two districts was calculated based upon information obtained from Application Permits for Diversion of Water, maintained by the Wyoming State Engineer's Office. These applications include details on each canal's length, width, slope, and wetted perimeter. From the information on the application permits, it was also possible to approximate the acres the canals supply for irrigation. The total acreage of cropland irrigated by the canals was calculated and used to create a ratio of total canal surface area required per irrigated acre of cropland. This ratio could then be applied to calculate the amount of surface area required to irrigate the 26,300 ha (65,000 acres) of irrigated land along the Salt River. The calculated surface area of the canals for the two irrigation districts was 34.6 ha (85.5 acres), while the irrigated acreage served by the canals was 4,580 ha (11,320 acres). The ratio of canal surface area to irrigated acreage was 0.0076 and canal surface area for the entire basin was 198 ha (490 acres).

Evaporation estimates were also calculated for conveyance on private land. The irrigators utilized V-shaped plows to construct the canals. The canals were approximately 0.30 m (1 ft) to 0.90 m (3 ft) wide and were installed every 30.5 m (100 ft) to 76.20 m (250 ft). Assuming the canals averaged a width of 0.61 m (2 ft) while being installed an average of 61 m (200 ft) apart, a total canal surface area of 219 ha (542 acres) was calculated for conveyance requirements on private property.

Groundwater Hydrology and Water Quality

The groundwater hydrology is impacted by changes in irrigation practices. Direct impacts to groundwater hydrology, such as changes in groundwater level, aquifer capacity, and the hydrologic cycle, occur due to changes in seepage and deep percolation. Deep percolation is the downward movement of water below the crop root zone, while seepage is the water that escapes from canals or on-farm ditches to the water table. During flood irrigation practices, water conveyance occurred within a canal network. For flood irrigation, the unlined irrigation canal network had an estimated length of 354 km (220 mi) traversing gravelly, sandy soils. Seepage and percolation rates in gravelly soils can be very high, and may result in large quantities of aquifer recharge and storage, especially during flood irrigation.

Few long-term monitoring or water supply wells exist in the study area, making it difficult to assess the impacts of changes in irrigation practices on groundwater levels. Well logs obtained from the Groundwater Division at the Wyoming State Engineer's Office for all wells installed in the Star Valley area were analyzed in an attempt to determine any impacts to the groundwater elevation. The well logs contained information on well owners, type of water use, initial static level of the groundwater, initial groundwater depth, well depth, main water bearing zone, approximate location of the well, geology of the soils enclosing the well, and drilling date of the well.

Approximately 25% of the basin was not converted to sprinkler irrigation. Three regions were analyzed to determine changes in groundwater levels over time (Fig. 1). The Stump Creek area, Region 1, was selected and analyzed as an existing flood irrigation area. The West Afton Region, Region 2, was analyzed as a sprinkler irrigated area. The Dry Creek Region, Region 3, contained both flood and sprinkler irrigated areas.

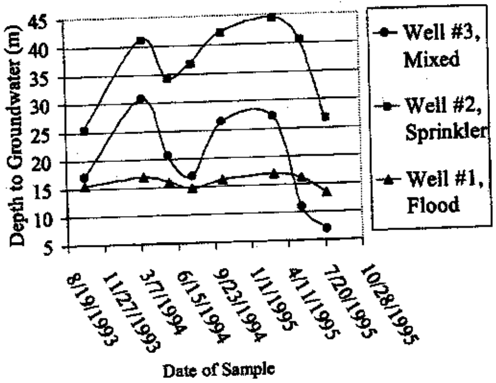

Fig. 2. Monitor well data for study area: monitor well 1 is located in a flood irrigated region; well #2 is located near a sprinkler irrigated area; well #3 is located with a mixed irrigation area

The analysis contained data from 160 wells located within the study area. The wells were selected based upon the density of wells in the study area and the type of irrigation practice. The criteria for selecting wells for comparison was as follows: (1) Wells must be located in close proximity of each other and sections based on township and range were chosen that contained the highest density of well data; and (2) the wells analyzed must be unconfined and likely to influence the recharge of the Salt River. Wells with a depth to the unconfined aquifer of no greater than 28 m (85 ft) from the ground surface for the sprinkler irrigated regions and no greater than 10 m (35 ft) for the flood irrigated regions were included in the analysis. These depth limitations were imposed to ensure selected wells were representative of unconfined aquifers.

Because groundwater elevations fluctuate due to the hydrologic cycle, it was necessary to normalize the groundwater levels for seasonal variations to obtain an accurate prediction of trends over extended periods of time. Monitoring wells located within the study area, which contained only a few years of record, were used to normalize the static water level information obtained from the well logs. Using the groundwater levels for the winter months of February and March as a baseline, a ratio between these months and other months was calculated and used to correct for seasonal variation in groundwater levels (Fig. 2). Plots of seasonally corrected static well levels versus time were created to identify any changes with time in groundwater levels in each of the three designated regions.

The changes in irrigation practices may also have impacts upon the water quality within the watershed. Star Valley contains large saline deposits (Walker 1965), and the leaching of salts during irrigation may cause water quality concerns with respect to domestic and agricultural use. The gauging station, USGS stream gauge No. 13027500, utilized for streamflow analysis on the Salt River contained data on water quality, including salinity, total dissolved solids, and conductance for the period 1965–1975.

Seepage Calculations

The conversion to sprinklers eliminated a majority of canal seepage that occurred prior to the conversion from flood to sprinkler irrigation. During flood irrigation, water was carried to the irrigated fields via an unlined canal network resulting in a large amount of seepage loss.

The soil types in the Star Valley vary depending on location. Soil types were determined from information obtained from per-

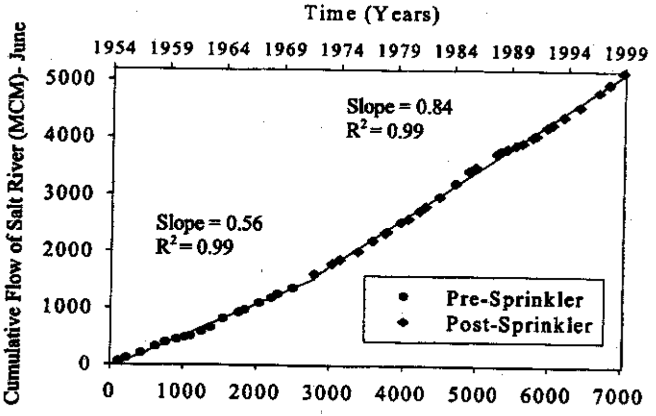

Fig. 3. Double mass balance plot for month of June

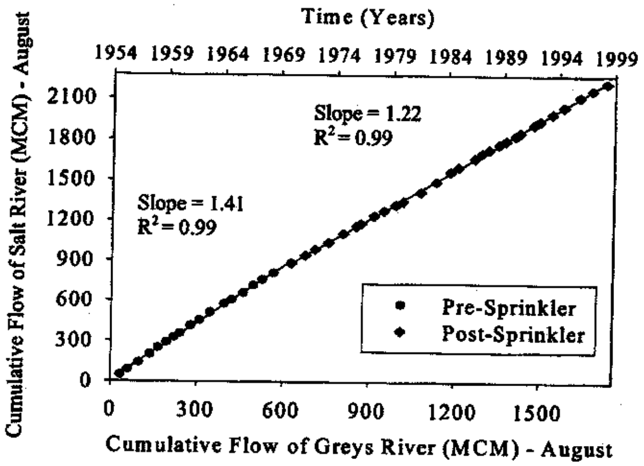

Fig. 4. Double mass balance plot for month of August

mits to divert water and from a soil survey (USDA-NRCS 1976). The permits also include information on canal length, canal wetted perimeter, and the number of acres served by the canal. Using this information, the contact area per acre irrigated was calculated for the two major irrigation districts. This ratio was applied to the entire acreage within the Star Valley to estimate the total seepage area for the flood irrigation system. This area was then multiplied by a soil seepage coefficient of 0.30 m^3/m^2-day for sandy loam soil (Finkle 1982) to obtain the seepage estimate for the presprinkler period. The value of 0.30 m^3/m^2-day was chosen because it most closely relates to the average type of soil located in the study area. Postsprinkler conveyance seepage losses are assumed negligible because water conveyance is with a pipe network.

Results and Discussion

Double Mass Balance Plots

The results of the double mass balance analysis of the Salt River flows versus the Greys River flows are presented for the months of June (Fig. 3) and August (Fig. 4). Double mass balance plots for all months can be found elsewhere (Venn 2002). Inspection of the double mass balance figures reveals a break in the trend line slope beginning in approximately 1971. This time corresponds to the time irrigation practices were changing from flood to sprinkler. To determine if the observed changes in flow ratios were statistically significant, Student t-tests for all months were conducted on the calculated average ratios for both the presprinkler and postsprinkler periods using a 95% confidence interval (Table 2).

The early irrigation months of May and June show increases of flow in the Salt River relative to the Greys River, after the conversion to sprinkler irrigation (Table 2). The later irrigation months of August and September and the nonirrigation months of October and November show decreases in flow of the Salt River relative to the Greys River after the conversion to sprinkler irrigation. The August through November changes are likely due to changes in groundwater return flow timing due to flood versus sprinkler irrigation practices. This evidence clearly shows changes in hydrology to the Salt River directly related to the conversion from flood to sprinkler irrigation practices and that groundwater levels may be changing in the area. Impacts to groundwater levels are discussed in more detail in the Groundwater Analysis section of this paper. The slopes of the double mass plots for the remaining months of July and December through April reflected little or no change to the return flow of the Salt River relative to the Greys River, and the resulting t-tests for these months estimate confidence levels below 95%.

Stream Flow Changes

Calculations based on the difference in flow ratios provide a means for determining average monthly and yearly amounts of

Table 2. Student t-Test Results of Flow Ratios Determining Statistically Significant Months

Month	Time period	Average flow ratio	Standard deviation	Confidence interval	Student t-test	Significant
January	Pre/post	2.210/2.069	0.251/0.292	0.119/0.106	0.091232	No
February	Pre/post	2.197/2.134	0.212/0.288	0.101/0.105	0.400483	No
March	Pre/post	2.044/2.083	0.226/0.310	0.107/0.113	0.628803	No
April	Pre/post	1.647/1.593	0.387/0.401	0.184/0.146	0.655327	No
May	Pre/post	0.787/1.055	0.167/0.293	0.079/0.107	0.000284	Yes
June	Pre/post	0.538/0.808	0.151/0.193	0.072/0.070	0.000005	Yes
July	Pre/post	0.875/0.913	0.103/0.147	0.049/0.053	0.306508	No
August	Pre/post	1.426/1.216	0.144/0.123	0.068/0.045	0.000021	Yes
September	Pre/post	1.899/1.627	0.124/0.152	0.059/0.055	0.000000	Yes
October	Pre/post	2.061/1.917	0.142/0.140	0.068/0.051	0.002172	Yes
November	Pre/post	2.335/2.137	0.135/0.234	0.071/0.085	0.000342	Yes
December	Pre/post	2.352/2.183	0.297/0.253	0.141/0.092	0.058433	No

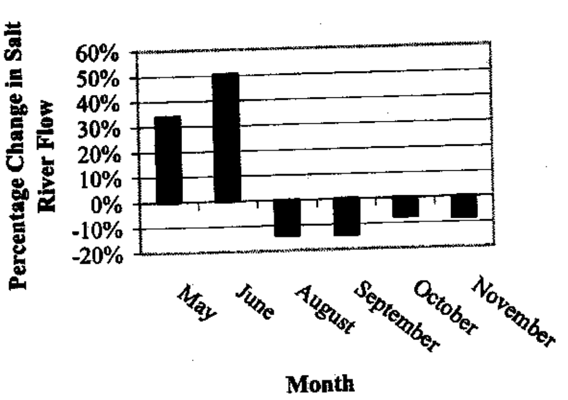

Fig. 5. Annual average percentage of increase or decrease in Salt River flow per statistically significant month due to changes in irrigation practices

water conserved or lost due to eliminating open canals and converting to sprinkler irrigation. The amount of water conserved or lost each month as a percentage of average volume for the month is shown in Fig. 5. The months of May and June show average increases of 34 and 50% in streamflow of the Salt River, respectively, while the months of August and September show average decreases of 15 and 14%, respectively. The overall average annual increase of flow in the Salt River is approximately 65.62 MCM (53,200 acre-ft), which is calculated from the summation of flow changes for each of the statistically significant months. The 65.62 MCM/year of additional water flowing in the Salt River after conversion to sprinkler irrigation is approximately 55% of the average annual consumptive irrigation requirements in the study area, and approximately 10% of the average annual flow of the river.

Crop Yields

The conversion from flood to sprinkler irrigation beneficially impacted crop yields, which increased from 50 to 100% (Sando 1986). As shown in Fig. 6, crop production yields for alfalfa hay increased from an average of 3.6 ton/ha (1.6 t/acre) to an average of 4.7 ton/ha (2.11 ton/acre) after the switch to sprinkler irrigation (USDA-NASS 1999). The increased yields are attributed to more efficient water application and are directly related to the increase in overall irrigation efficiency. Farmers indicated that they are able to produce a greater crop yield on the same amount of land, because they could deliver irrigation water evenly to the entire field. Second cutting yields of crops by Star Valley farmers increased nearly 100% as compared to second cuttings with flood irrigation practices, which explains the increases in total crop yield.

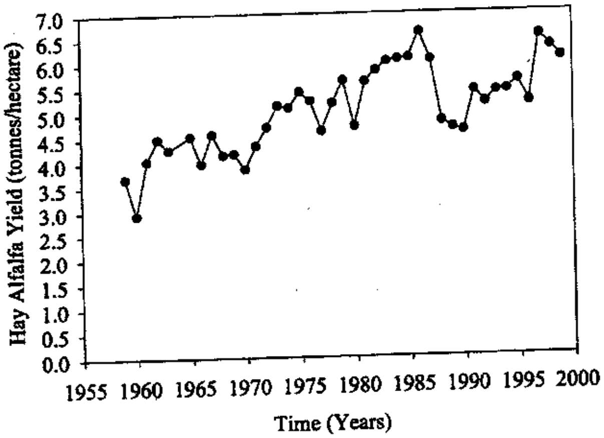

Fig. 6. Crop production yields for hay alfalfa in study area

Evaporation

Canal evaporation, which occurred with the flood irrigation systems, accounts for some of the 65.62 MCM (53,200 acre-ft) annual increase in Salt River flow after conversion to sprinkler irrigation. Estimates of monthly and total canal evaporation that occurred during the flood irrigation period for the entire study area are shown in Table 1. The conveyance evaporation occurring in the basin was approximately 3.4 MCM/year (2800 acre-ft/year) during flood irrigation. It should be noted that evaporation from open canals and ditches could have a higher evaporation loss per unit area than a large open body of water (Burt et al. 1997) because the canal water is moving and mixes more readily with the air, resulting in a higher evaporation rate. The preceding estimates for evaporation are based on reservoir evaporation coefficients; therefore, the evaporative losses for the Star Valley shown in Table 1 are conservative estimates.

There are application evaporation losses with sprinkler methods. Thus, changes in streamflows are affected by both eliminating canal evaporation that occurred during the flood irrigation period and by increasing application evaporation losses during sprinkler irrigation. Sprinkler evaporation losses are typically less than 2% of the discharged water (Thompson et al. 1993). Assuming 2% losses, the evaporative losses from sprinkler evaporation in the study area would result in losses of roughly 1.5 MCM (1,200 acre-ft) of water. The evaporation estimates for conveyance and application during flood irrigation are more than double the amount of evaporation for conveyance and application during sprinkler irrigation. A reasonable estimate for the excess Salt River flow through reduction in evaporation is the difference in the estimates of evaporation for the different irrigation practices. The difference in evaporation estimates is 1.9 MCM per year (1,540 acre-ft). This value can account for some of the increase in streamflow of the Salt River.

The preceding estimated value of evaporation occurring during the presprinkler period only accounts for conveyance and on-field canal networks. Other mechanisms may increase the total amount of evaporation occurring during flood irrigation as compared to sprinkler irrigation. During the presprinkler period, crop irrigation required flooding the entire field in order to irrigate the higher reaches of land. Therefore, some of the crop land was oversaturated and standing water in the oversaturated areas was susceptible to evaporation.

Evapotranspiration (ET) is the combination of evaporation from soil, plant surfaces, and standing water as well as transpiration from plants. Evapotranspiration from plant surfaces and transpiration from the plants should be equivalent for both irrigation techniques. However, early in the growing season, there is a lack of sufficient crop canopy for infant barley and hay crops, and these crops are unable to transpire the entire amount of water provided by the flood irrigation canals and soil surfaces. Under these conditions, a greater amount of water may be lost due to evaporation with flood irrigation techniques as opposed to sprinkler irrigation techniques. ET losses are known to be higher with flood irrigation as compared to sprinkler irrigation, assuming similar conditions and acreage (Guitjens and Goodrich 1994).

Published grass reference ET values exist for the study area, but these values do not differentiate between transpiration from the plants and evaporation from the soil. Hence, it is difficult to estimate how evaporation would change with different application techniques.

Many areas in the Star Valley contained high groundwater levels before the installation of sprinklers. Flood irrigation created many boggy and swampy situations throughout the valley. Several acres within the area had standing water through much of the irrigation season. Evaporation could have also occurred from these standing bodies of water.

Seepage Analysis

The piping network utilized after the conversion to sprinkler irrigation eliminates the majority of seepage that occurred in the canals used with flood irrigation. Seepage refers to the water lost from the canal network in conveyance to the crops, while deep percolation refers to the water escaping the root zone during field application. When utilizing flood irrigation, large quantities of water seep from flood canals and percolate into groundwater aquifers (Voeller and Waren 1997). Some of the water that is applied to the fields may also escape the root zone and percolate. Because of uneven application, percolation may be different between the two applications practices.

The change in canal seepage due to the change in conveyance is approximately 50 MCM (40,000 acre-ft). This represents 42% of the average annual consumptive irrigation requirement for the study area. This estimate agrees well with other reported values. For this region within the State of Wyoming, canal and lateral losses are typically 38–42% of the total diversion for flood irrigation (ADMP 1946). The reduction in seepage that occurred with sprinkler irrigation directly impacted the groundwater hydrology in the Star Valley. The volume of water conserved through reduction in seepage is approximately 76% of the average annual increase of flow in the Salt River after the conversion to sprinkler irrigation practices. However, this estimate cannot be directly applied as true savings, because it is assumed that a large fraction, but not all, of the seepage water eventually returned to the Salt River. The fraction that did not return can be considered the true savings of water that was previously lost through evaporation, phreatophytic vegetation consumption, and to irrecoverable groundwater.

Phreatophytic Vegetation Consumption

Phreatophytic vegetation can be considered to include all the vegetation not utilized by farmers in the Star Valley for productive uses. Through seepage and infiltration mechanisms and the creation of low-lying bogs, the canal network and flood irrigation practice present in the flood irrigation period provided water for phreatophytic vegetation, which included willows, cattails, weeds, cottonwood trees, and grasses. These phreatophytes consumed water and reduced the return flow to the Salt River. Some of the increased Salt River water flow was achieved with the changes in irrigation practices, because phreatophytes were no longer able to utilize irrigation water from the old canal network. It is difficult to accurately estimate the total amount of phreatophytic consumption during flood irrigation, but evidence exists to indicate it was significant. Through interviews with residents and information provided by the Farm Service Agency in Afton, it is known that the amount of phreatophytic vegetation has decreased since the change in irrigation practices. Many boggy wetland areas that existed during flood irrigation are gone today. This would be consistent with the higher efficiency of the sprinkler irrigation system and suggests a decrease in the groundwater level may have occurred.

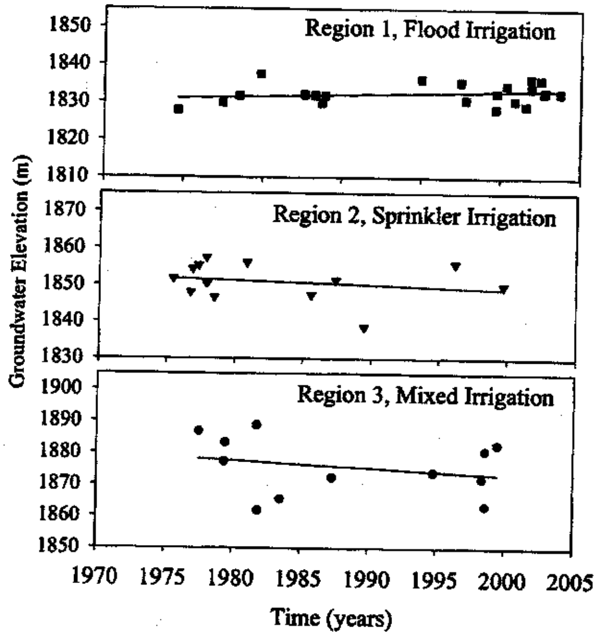

Fig. 7. Scatter plots of groundwater elevation versus time for regions with different irrigation practices

Groundwater Analysis and Changes in Storage

Previous studies have shown that groundwater tables and aquifer storage are influenced by changes in irrigation practices. Winger et al. (1995) found that, during 50 years of operating a canal network in central Nebraska, some areas experienced groundwater rises up to 35 m. With the elimination of flood irrigation in the Star Valley, significant quantities of the water are no longer reaching groundwater aquifers and a decrease in groundwater levels can be expected. In order to fulfill the yearly mass balance on the watershed and account for the increased streamflows based upon the sprinkler irrigated acreage within the study area, a decrease in groundwater levels of approximately 0.31 m/year (1.02 ft/year) would be required. Over a period of 30 years, the groundwater table would be expected to show decreases of 6.0 m (20 ft).

Regions in the Star Valley currently containing either sprinkler or flood irrigation practices were analyzed to determine the effects of the conversion on groundwater levels in unconfined aquifers. The unconfined aquifers in the regions were analyzed because they are the main contributing mechanisms of river recharge in the area. Groundwater elevations versus time for areas with different irrigation methods are shown in Fig. 7. There is a large amount of scatter in the groundwater elevation data presented. Some of the scatter can be attributed to the varying well locations within the regions. To minimize this effect, regions were chosen such that elevations do not vary greatly within the narrowly defined regions. Some of the scatter may also be due to different climatic effects with time. Regardless, the amount of scatter in the figure makes determination of changes in the groundwater table for the different areas difficult, and the data does not indicate that statistically significant changes in the groundwater regime have occurred.

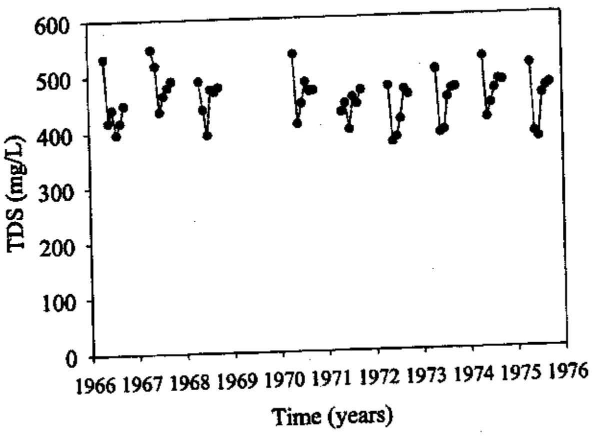

Fig. 8. Total dissolved solids concentrations for Salt River for irrigation months (April–September) during period before and after conversion to sprinkler irrigation

Long-term monitor wells are the most conventional means for determining changes in groundwater elevations over time. In addition to the data used in the groundwater analysis section, there are also three monitoring wells that exist within the study area, each limited to data for a period less than 3 years taken in the early 1990s. Monitor well 1 is located in the flood irrigated region, monitor well 2 is located near the sprinkler irrigated region, and monitor well 3 is located in the mixed flood and sprinkler irrigated region (Fig. 1). The three monitoring wells provide information on seasonal groundwater level fluctuation, but cannot be used to investigate long-term changes in groundwater levels. Fig. 2 shows that groundwater depths fluctuate significantly in sprinkler regions as compared with the flood irrigated region. Monitor well 1 shows annual groundwater fluctuations of less than 1.2 m (4 ft), while the monitoring wells in the sprinkler region and combined region show annual groundwater fluctuations of approximately 5–6 m (14–20 ft).

Very few conclusions can be drawn from the limited monitor well data. One observation might be that the low annual fluctuations in groundwater depth in the flood irrigated region indicates that the aquifer is usually at a high water level and flow is from the aquifer to the river throughout the year. On the other hand, the larger depth fluctuations during the year in the sprinkler and combined regions may be due to deep percolation during the irrigation season, return flows, and perhaps even recharge from the river. However, as stated, the monitor well data is too limited to draw conclusive observations.

Groundwater and Surface Water Total Dissolved Solids

TDS data for the seasonal irrigation months was tabulated and plotted (Fig. 8) for comparisons of the presprinkler and postsprinkler periods. Dissolved solids concentrations within the Salt River for the sprinkler period remained within 10% of the concentrations measured for the presprinkler period. Therefore, no significant impacts to the surface water TDS in relation to the change in irrigation practices in the study area could be documented.

Groundwater quality data was also very limited due to the lack of wells within the study area. TDS concentrations for three groundwater wells located in sprinkler irrigated regions and one located in a flood irrigated region are shown in Table 3. The well in the flood irrigation region had a TDS value more than 250 mg/L higher than the sprinkler wells and average river values. It is difficult to accurately predict the changes in groundwater quality due to changes in irrigation practices based on the limited data. The limited results, however, imply that groundwater quality is improved in sprinkler irrigated regions as opposed to flood irrigated regions. This effect on groundwater quality has been well documented in other groundwater quality studies related to different irrigation practices (Beke et al. 1993; Miller and Andersen 1993; Ghassemi et al. 1994).

Table 3. Groundwater Quality for Wells Located within Study Area

Well permit number	Irrigation practice	Date of sample	Total dissolved solids (mg/L)
P84521W	Sprinkler	7/16/1991	246
P99886W	Sprinkler	9/27/1996	267
P38291W	Mixed	11/2/1977	340
P64767W	Flood	11/1/1983	520

Summary and Conclusions

The objectives of this study were to quantify the potential hydrologic impacts to a watershed when irrigation systems are converted from flood to sprinklers and to relate these impacts to the various hydrologic components through which they occur. Specific objectives included the determination of changes in (1) return flow timing; (2) total annual river flow; (3) agricultural production; (4) surface water and groundwater quality; and (5) groundwater levels in the unconfined aquifer impacting river recharge.

Return flow timing was impacted by the conversion to sprinkler irrigation. Streamflows increased 34% in May and 50% in June, while decreasing 15 and 14% for August and September. These changes are related to how on-field application efficiency of irrigation water increases with sprinkler irrigation. Because conveyance for sprinkler irrigation now occurs in a pipe network, deep percolation, seepage, and groundwater recharge related to the former flood irrigation practices are eliminated. The change in magnitude and timing of return flows has the potential to influence streamflows and hamper irrigators in the lower end of the valley, because the river flow has decreased during the later part of the irrigation season. Practical solutions for reducing the impacts of the return flow timing include installation of catchments. The early spring runoff could be stored and utilized more beneficially to alleviate the 15% decrease in available in-stream flow at the end of the irrigation season.

The average annual Salt River Flow is approximately 722 MCM (575,000 acre-ft), and the 65.62 MCM of excess flow represents 9% of the average annual Salt River flow. The increased flow is substantial, as it represents approximately 55% of the average annual consumptive irrigation requirement in the study area. These changes may have coincided with decreases in groundwater storage. Analysis of changes in groundwater levels with time was inconclusive; however, if occurring, changes could be very important to the long-term water production of the area.

The increased annual flow occurred even with an increase in crop yields. After the conversion from flood irrigation to sprinklers, average crop yields increased from 1.6 t to 2.1 ton/acre. Crop yields increased because farmers can now more evenly distribute irrigation water to their fields and irrigate higher reaches of their fields.

The surface water quality appears unaffected by the conversion in irrigation practices. Dissolved solids concentrations within the Salt River for the sprinkler period remained within 10% of the concentrations measured for the presprinkler period. The results of the limited groundwater quality data indicate that TDS values are lower in sprinkler irrigated areas.

The observed impacts to the river basin hydrology are mainly due to canal evaporation, evapotranspiration, phreatophytic consumption, unlined canal seepage, and possible changes to the aquifer system. Unlined canal evaporation estimates account for approximately 1.25 MCM/year (1,500 acre-ft/year) of the increased annual flow. Unlined canal seepage losses were estimated to be 50 MCM/year (40,000 acre-ft/year). The volume of water conserved through reduction in seepage can account for 80% of the increased flow in the Salt River. However, this estimate cannot be directly applied as true savings, because it is assumed that a large fraction but not all of the seepage water eventually returned to the Salt River later in the year. Conclusions of this study are based on limited groundwater information. In the future, a more in-depth study of the changes in groundwater hydrology is necessary. Lysimeters in the study area have been installed in the last 5 years, which should provide additional information on the impacts to the groundwater hydrology.

Water in the semiarid western United States is a vital resource. In an attempt to conserve this valuable commodity, irrigation practices in the Star Valley in western Wyoming were converted from flood to sprinkler irrigation to improve application and conveyance efficiencies. The changes in conveyance and conversion from flood to sprinkler irrigation increased agricultural production, caused changes in return flow timing, appeared to increase annual river flow, and possibly impacted groundwater levels and water quality.

Notation

The following symbols are used in this paper:

C_1 = fraction of annual evaporation for each month;
C_2 = total annual evaporation;
E = volume of water lost through evaporation;
ET = volume of water lost through evapotranspiration;
P = volume of water lost through phreatophytic and hydrophytic consumption;
P_r = volume of water entering study area as precipitation;
R_{inflow} = volume of water entering study area;
R_{outflow} = volume of water leaving study area;
S = annual increased stream flow of Salt River;
SA = surface area of water in irrigation canals;
SI = volume of water lost due to seepage and infiltration;
ΔE = change in evaporation;
ΔET = change in evapotranspiration; and
$\Delta\text{Storage}$ = change in storage within study area.

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Water conservation in irrigation can increase water use

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Climate change, water supply limits, and continued population growth have intensified the search for measures to conserve water in irrigated agriculture, the world's largest water user. Policy measures that encourage adoption of water-conserving irrigation technologies are widely believed to make more water available for cities and the environment. However, little integrated analysis has been conducted to test this hypothesis. This article presents results of an integrated basin-scale analysis linking biophysical, hydrologic, agronomic, economic, policy, and institutional dimensions of the Upper Rio Grande Basin of North America. It analyzes a series of water conservation policies for their effect on water used in irrigation and on water conserved. In contrast to widely-held beliefs, our results show that water conservation subsidies are unlikely to reduce water use under conditions that occur in many river basins. Adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge. Policies aimed at reducing water applications can actually increase water depletions. Achieving real water savings requires designing institutional, technical, and accounting measures that accurately track and economically reward reduced water depletions. Conservation programs that target reduced water diversions or applications provide no guarantee of saving water.

agriculture | sustainability | institutions | hydrology

Easterling (1) recently observed that a great challenge facing 21st-century political and scientific leaders will be to increase the world's food supply to accommodate a world growing to 10 billion or more people while also facing climate change. Water in the right quality, amount, time, and place is essential for ecosystems and for economies. Much of the world's food production depends on water for irrigation. Natural ecosystems are adapted to stream discharge, precipitation, and evaporation patterns. So, adjustments in the water cycle to climate, weather, and land-use change will have large and complex effects on economic and ecological systems

Many countries have inadequate water supplies to meet their current urban, environmental, and agricultural needs. In the face of increased water scarcity, population and water demands continue to grow (2, 3). The challenge is to grow enough food for 2 billion more people over the next 50 years while supplying growing urban and environmental needs for water (4, 5). Some analyses have estimated that 60% of added food required will come from irrigation (6). Raising food production to support this larger world population requires sustaining improved performance of irrigation (7–12).

As pressure mounts for irrigated agriculture to produce more crop per drop, there is a widespread belief in environmental and water policy circles that if irrigators made more efficient use of water then there would be more water for environmental uses and for cities (12, 13). More than a billion people worldwide lack safe affordable drinking water (8). A considerable number of informed individuals, large development organizations, and much popular belief subscribes to the view that measures to increase irrigation efficiency[*] will result in additional water for uses outside agriculture (16, 17). Numerous public policies have been implemented and billions of dollars in public and private investments spent to promote water conservation in irrigated agriculture. However, many of these investments have not made additional water available to new users. Although water conservation intentions carry considerable political weight, there is all too often little serious evidence on conservation outcomes that would be produced by water conservation programs in policy debates, funding opportunities, and the popular press. Moreover, studies that connect water use efficiency with wet[†] water savings are rare. Notable exceptions include the works of Hussain *et al.* (16), Huffaker and Whittlesey (17), Peterson and Ding (18), Huffaker and Whittlesey (19), and Schierling *et al.* (20).

This contribution of this article is to analyze agricultural water conservation subsidies with respect to their effect on water used in irrigation and on conserved water available for other uses. A basin-scale hydroeconomic optimization model is presented linking biophysical, hydrologic, agronomic, economic, policy, and institutional dimensions of the Upper Rio Grande Basin of North America (the Basin), shown in supporting information (SI) Fig. S1. Results of that model are used to examine farm income-maximizing choices regarding crop mix, irrigation technology, water demand, consumptive use, return flows, income, and taxpayer costs of a water-conserving program. The cost effectiveness of a range of conservation subsidy arrangements for reducing water depletions is also identified.

Materials and Methods

Water Conservation. Evapotranspiration (ET) from the watershed's surface is the depletion[‡] or loss of water from a hydrologic basin associated with plant water use. Water diverted from its natural course through a canal, pipe, or other conveyance measure and applied in irrigation in excess of ET is not lost because it returns into the basin from which it was withdrawn via surface runoff or deep percolation. This water can be available to other users at other

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Author contributions: F.A.W. and M.P.-V. designed research, performed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

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[*]Many definitions of irrigation efficiency have been proposed (14, 15). For this article, efficiency is the ratio of water depleted by plant evapotranspiration (ET) to water diverted from the stream. ET is the consumed fraction of water diverted. As technologies or management practices are adopted that bring the ratio closer to 1, irrigation efficiency increases. Much of this article focuses on what happens to the nonconsumed fraction.

[†]The term wet water savings refers to real water compared with paper water, i.e. water rights.

[‡]Some writers prefer the term "consumption" to "depletion," because depletion suggests the unsustainable action of drawing down on a stock (22). By contrast, consumption occur as a part of sustainable income. We use the term depletion because it contrasts with water diverted from the stream or water applied to the crop. Water diverted and water applied can return to a closed hydrologic basin. Depletion cannot.

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Table 1. Crop water use, price, yield, and cost per acre, Lower Rio Grande, NM, 2006

Crop	Water applied*		ET*		Deep percolation*		Price		Yield, quantity/acre†		Production cost (0% capital drip irrigation subsidy), \$/acre/year		Production cost (100% capital drip irrigation subsidy), \$/acre/year‡	
	Flood	Drip	Flood	Drip	Flood	Drip	\$/Unit	Yield units	Flood	Drip	Flood	Drip	Flood	Drip
Alfalfa	5.0	2.7	2.2	2.7	2.9	0.0	130.00	Tons	8.0	10.0	884	1,357	884	993
Pima cotton	2.8	1.5	1.2	1.5	1.6	0.0	1.05	Lbs	750.0	937.5	979	1,324	979	960
Upland cotton	2.8	1.5	1.2	1.5	1.6	0.0	0.75	Lbs	1,000.0	1250.0	1027	1,261	1027	897
Spring lettuce	2.5	1.4	1.1	1.4	1.4	0.0	5.84	Cartons	475.0	593.8	3001	4,398	3,001	4,034
Fall lettuce	3.3	1.8	1.4	1.8	1.9	0.0	6.23	Cartons	500.0	625.0	2,638	3,971	2,638	3,606
Fall onions	4.7	2.5	2.0	2.5	2.7	0.0	6.63	Sacks	1,200.0	1500.0	5,762	8,848	5,762	8,484
Midseason onions	4.0	2.9	2.3	2.9	1.7	0.0	6.38	Sacks	675.0	843.8	3,722	5,708	3,722	5,344
Spring onions	4.8	3.4	2.7	3.4	2.0	0.0	6.43	Sacks	825.0	1031.3	4,455	6,871	4,455	6,506
Grain sorghum	2.0	1.1	0.9	1.1	1.1	0.0	3.70	Cwt	40.0	50.0	615	728	615	364
Wheat	2.5	1.4	1.1	1.4	1.4	0.0	3.75	Cwt	92.0	115.0	718	929	718	565
Green chile	4.6	2.5	2.0	2.5	2.6	0.0	285.00	Tons	11.0	13.8	2,275	3,356	2,275	2,992
Red chile	5.0	2.7	2.2	2.7	2.9	0.0	0.72	Lbs	3,500.0	4,375.0	2,004	2,851	2,004	2,486
Pecans	6.0	3.2	2.6	3.2	3.4	0.0	2.28	Lbs	1,158.1	1,447.7	1,731	3,114	1,731	2,750

*Acre-feet per acre per year.

†Each crop is specified to have a linear relationship between water use (ET) and crop yield across irrigation technologies.

‡Includes annualized cost per acre of drip irrigation, operation, and maintenance.

times in other locations.[§] One user's water inefficiency often serves as the source of another user's water supply.

On-farm adoption of drip irrigation is one measure widely believed to conserve water. Drip irrigation allows for precise application of water into plants' root zones, with little loss to runoff or deep percolation. A linear relationship is typical between ET and crop yield over a wide range of crops and water applications (21). So, irrigation technologies that apply water at optimal times and locations in plant root zones increase crop consumptive use of water and crop yield as irrigation efficiency increases. When yield goes up, ET typically rises.

Water losses through deep percolation or surface runoff will be reduced, possibly to nearly 0, through drip technology, but more ET will be used by the plant in supporting its reduced plant stress and higher yield. More efficient irrigation systems reduce diversions from streams and increase crop both yield and gross revenue (18). Depending on the cost of installing drip irrigation, costs and returns of production, and the price of water, the farmer who uses the technology may experience increased yield and higher income per unit of land. From the farmer's economic view the new water-conserving technology is good. However, basin-level consumptive use of water can increase.

Study Area. The Basin is that part of the area drained by the Rio Grande and its tributaries that flow from its headwaters to ≈70 miles south of the border cities of El Paso, TX and Ciudad Juárez, Mexico (Fig. S1). Surface water from the river meets the primary water needs of Albuquerque, NM, El Paso, and Juárez. In addition, it serves 1 million acres of irrigated land in the U.S. and Mexico. In fall 2004, water storage in Elephant Butte, the largest reservoir in the Basin, was <5% of capacity. After an unprecedented 25-year period of full-water supplies, water allocations during 2003 were reduced to just one-third of full-supply conditions.

Data. Table 1 shows the most important hydrologic, agronomic, and economic data for irrigated agriculture used by our analysis. Depending on the crop, water applied under drip irrigation is approximately half as much as under flood irrigation. However, crop ET is higher under drip irrigation, which reflects higher water depletions that support the typically greater yields experienced by irrigators who use this technology. ET under flood irrigation is typically less than half of water applied; the rest either seeps to deep percolation or returns to the stream as surface return flow. The table also shows that production costs per acre are typically much higher under drip than under flood irrigation, although that cost elevation is considerably reduced as the public subsidy of drip irrigation increases from 0 to 100%.

Modeling Framework. The hydroeconomic analysis developed for this article is a basin-scale accounting of the Basin's essential hydrologic relationships, institutions, and economic sectors. This integrated model is formulated as a mathematical optimization problem. The objective is the sum of net economic benefits[¶] from basin water diversions, for off-stream uses, and for net benefits of water environments. The objective is to maximize the discounted value of net economic benefits over a 20-year time horizon. Constraints are used to characterize the basin's hydrology and its institutions. Our basin-scale approach extends similar previous work by Vaux and Howitt (24), Booker (25), and Hurd *et al.* (26), all of whom developed integrated basinwide hydrologic models for policy analysis containing an economic objective.

The model is formulated and solved on an annual time step, with reservoir storage and other hydrologic and economic conditions carried forward to each next time period. Fig. S2 shows a schematic of the basic hydrologic–agronomic balance at the field-stream level. Mathematical documentation of earlier versions of the model has been published elsewhere (27, 28). Although the model and its documentation were developed for the Basin, it was designed to be adaptable to other basins, cultures, and economic environments that characterize the economic value of water.

Hydrology. Basin hydrology is based on the principle of water mass balance, defined in both flows and stocks. The most important flows tracked by the model include headwater flows, streamflows at the basin's important stream gauges, water diverted, water applied to crops, water depleted, reservoir releases, groundwater pumping, seepage to aquifers, return flows to streams, reservoir evaporation, and reservoir releases. Important stocks include reservoir and aquifer levels. A hydrologic mass balance for both surface water and groundwater is enforced for all flows and stocks. The model includes major functions that influence any of the flows described above. The mass balance for reservoir stocks is given by starting storage minus reservoir releases plus river inflows to the reservoir minus evaporation. Changes in any period's groundwater stock are represented through effects of seepage, water applied, and water pumped.

Institutions. The U.S.–Mexico Treaty of 1906 is an important international treaty. Under it, the U.S. is obliged to deliver 60,000 acre-feet per year to Mexico at the El Paso–Ciudad Juárez border. Historically, in severe drought

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[§] A fraction of water diverted in a basin may return to the basin too late, too far away, or in too low a quality to be of economical use or because the water flows into an irretrievable sink such as the ocean or saline lakes (23).

[¶] Excluded are costs associated with the public subsidy of drip irrigation's capital cost. From a national view, a public subsidy incurs opportunity costs because those resources typically have alternative uses.

periods, U.S. deliveries to Mexico have fallen below 60,000. Nevertheless, our model enforces a good-neighbor policy by requiring delivery of 60,000 acre-feet to Mexico in all conditions.

Various U.S. Federal laws affect use of the Basin's water. Our model enforces the Endangered Species Act of 1973 (ESA), which allocates the Basin's water to produce sufficient streamflow in the San Acacia reach of the Rio Grande (Fig. 1) to protect from extinction the endangered Rio Grande silvery minnow. The model enforces this constraint by requiring streamflows at the San Acacia gauge to exceed 240,000 acre-feet per year.

In the western U.S., numerous interstate compacts have been signed since 1922 signing of the Colorado River Compact. The Rio Grande Compact (the Compact), signed in 1938 by Colorado, New Mexico, and Texas, divides the river's annual flow among those states. It obliges each upstream state to make larger annual deliveries to the downstream state in wetter periods. Each state receives a specified percentage of headwater flows, so the Compact spreads the risk of drought or climate change among the three states. Our model allocates water among the states according to the Compact's written rules.

In many of the world's water-stressed regions, neighbors have agreed to share scarce supplies in drought periods. Since the early 1950s, the New Mexico and Texas have agreed to share water delivered by the Rio Grande Project. Based on historical agricultural acreage in production in southern New Mexico and Texas at the time of the Project's construction, U.S. lands in New Mexico receive up to 57% of any year's allocation, and lands in Texas have received up to 43%.

Economics. ***Benefits.*** The model's economic analysis accounts for both water use-related benefits and the benefits of a higher-quality water environment. Benefit functions were developed to approximate water users' willingness to pay for water-related services. The two urban water-use nodes in the model are Albuquerque and El Paso. For both of those cities, the value of water is measured by water's price times the number of units sold to its customers plus any related consumer surplus. Consumer surplus is measured as the area beneath the urban water demand function and above actual price charged. For environmental benefits, willingness to pay is measured as the maximum price that could be charged to visitors at the Basin's six major reservoir-based recreation sites.[||] More details on the economics of urban and environmental values are presented in refs. 27 and 28.

Irrigation benefits. The agricultural analysis is based on estimating how income-optimized cropping practices adjust to various subsidies of drip irrigation. The agricultural analysis of water is based on estimating how acreage in production by crop and irrigation technology adjusts to various capital cost subsidy levels of drip irrigation, ranging from 0 to 100%. As is common worldwide, drip irrigation in the Basin is considerably more expensive than flood irrigation. It also requires less water applied per acre and produces greater crop yields. The answer to the question of whether or not drip irrigation is economically attractive to irrigators turns on what combination of economic and water supply conditions make it profitable to choose drip over flood irrigation.

Irrigators' choices are based on what provides the highest discounted net present value of farm income. Agronomic–economic data include price by crop, production cost and yields per acre by crop and irrigation technology, and total acres in production. The hydrologic relations included ET, water applied, deep percolation, and surface return flow per acre by crop and crop irrigation technology. The Basin's water supply is defined by average historical headwater flows as well as reservoir and aquifer starting conditions for 2006.

Other benefits. The basinwide model identifies water use patterns and water decisions that maximize discounted present value of net benefits. The model was designed to identify water use patterns that maximize the discounted net present value of economic benefits over water uses, locations, and time periods. Part of that total basin-scale net benefits includes farm income as described above. Gross benefits are defined for urban, agricultural, and environmental uses. Although the major focus of this article is the economics of water conservation in agriculture, the model views agriculture as only one of three water uses (29, 30).

Costs. Production costs of irrigated agriculture. Increased stream diversions or depletions typically require additional costs to be incurred to make suitable for human use the increased water used. For agricultural groundwater-pumping nodes, the largest incremental costs are those incurred for energy and for related operation, and maintenance. Costs are broken into variable and fixed costs, described below.

Variable costs vary with the scale of the irrigation enterprise (e.g., acres) and with the management decisions made, such as the type of field or irrigation technology chosen. They also vary with the intensity of any single input on a given land unit. Variable costs occur because of the decision to purchase additional inputs for use in production. In the long run, all costs are variable in the sense that given a long enough period, they can be varied. In the short run, such as a single year, revenues must exceed variable costs, or it is more profitable to cease production. Shutting down is always a choice for an irrigator facing growing water scarcity. At a point in time near the end of the irrigation season, nearly all costs are fixed in the sense that they have already been incurred, so the incremental revenue coming in from a crop is likely to be considerably higher than the additional variable costs needed to harvest the crop.

Other costs. For urban areas, there are considerable costs for purification to make the water safe and healthy for human consumption. Treatment costs are considerably higher than for agriculture, but urban treatment costs are typically lower for pumped water than for diverted river water. Urban delivery cost data were obtained from the Albuquerque and El Paso water utilities, and agricultural water cost data were obtained from published farm enterprise cost and return budgets. Both urban and environmental costs are included in the objective function as negative terms when costs are subtracted from benefits.

Net environmental benefits are measured as gross environmental benefits minus added gross environmental management costs needed to assure a higher quality environment. Data are scarce on costs of managing the water environment. As a first approximation, we measured those costs as management costs incurred by the New Mexico State Parks Department for maintaining fishing facilities and for supporting larger numbers of anglers in the face of reservoir volume increases.

Discounted net benefits. Discounted net present value is expressed in its standard algebraic form:

$$NPV = \sum_{u}\sum_{t}\frac{NBu_{ut}}{(1+r_u)^t} + \sum_{e}\sum_{t}\frac{NBe_{et}}{(1+r_e)^t} \qquad [1]$$

where the u and t indices refer to benefits and costs of water use and the water environment, respectively; r_u and r_e are rates for discounting water uses and water environments; and NB_{ut} and NB_{et} are net benefits from water uses and water environments. Water use in the Upper Basin is heavily constrained by scarce water supplies and by existing institutions. The four existing institutions described earlier are incorporated into the model. The discounted net present value includes the summed stream of net use-related benefits and net environmental benefits. Total basinwide economic benefits defined in this way are maximized subject to the constraints defined by hydrology and water allocation institutions described above. The objective as well as those water allocations and system operations that serve to maximize it are based on standard microeconomic welfare economics. Similar economic optimization models at the basin scale are described by Booker and Young (31), Draper *et al.* (32), Pulido-Velázquez *et al.* (33), and Booker *et al.* (34).

Solving the Model. We formulated the model as a dynamic nonlinear optimization model, for which the objective was to maximize discounted net present economic value summed over water uses, water environments, irrigation technologies, locations, and time periods. In the model, reservoir contents, pumping, water use patterns, and on-farm irrigation technologies are optimized over the model's time horizon, in which the hydrologic input is headwater inflows as well as starting values for reservoir and aquifer levels. The model accounts for physical interactions among uses (irrigation, urban, and environmental), storage (reservoirs and aquifers), flows (diversions, pumping, water applied, water depleted, and return flows), and losses (field, conveyance, and reservoir evaporation).

Results

Table 2 shows hydrologic impacts for the river, farm, and aquifer associated with various levels of public subsidies of drip irrigation. Impacts shown in the table are limited to the 89,000 acres served by the Elephant Butte Irrigation District (EBID) of southern New Mexico. The base case is defined by a policy of 0 subsidy. Under this scenario, farmers are predicted to apply 364,000 acre-feet, of which pumped groundwater supplies 91,000 acre-feet. Some acreage of all 13 crops shown in Table 1 enter the optimal solution under at least some of the public subsidy levels. For the base case, these include alfalfa on 18,760 acres,

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[||] Important excluded environmental values include benefits produced by instream flows at nonreservoir nodes and any environmental values, such as option, existence, or bequest values influenced by variations in reservoir levels or by other water decisions.

Table 2. Water conservation in irrigated agriculture for selected drip irrigation subsidies, Lower Rio Grande, NM, annual average, 2006–2025, hydrologic outcomes

		Hydrologic outcomes, 1,000 acre-feet/year									
		On farm				River					
Subsidy, % capital*	Subsidy, \$/acre/year†	Water applied	ET	Water Pumped	Reservoir release, inflow	Stream diversions	Surface return flow	Aquifer outflow (river gains if >0)	Downstream delivery (outflow)	Aquifer, change in storage	Total water conserved
0	0	364	167	91	555	273	0	32	314	74	0.0
10	36	371	171	86	566	285	0	34	315	80	−3.7
20	73	362	168	87	558	274	0	32	316	75	−0.6
30	109	328	176	56	555	272	0	29	312	67	−8.5
40	146	318	181	51	549	268	0	26	307	61	−13.6
50	182	318	187	52	533	267	0	24	290	56	−19.5
60	219	319	197	58	534	262	0	19	292	45	−29.6
70	255	324	203	66	532	258	0	17	291	39	−35.9
80	291	324	203	64	535	259	0	17	292	39	−36.0
90	328	324	203	69	513	255	0	15	273	36	−36.0
100	364	324	204	63	535	261	0	17	292	40	−36.7

*Total costs include Program Cost of Water Conservation subsidy.

†Total costs exclude Program Cost of Water Conservation subsidy.

pima cotton on 3,216 acres, upland cotton on 8,218 acres, fall lettuce on 4,467 acres, onions on 3,573 acres, wheat on 1,072 acres, green chile on 2,680 acres, red chile on 2,680 acres, and pecans on 25,906 acres. Under that base case, total optimized agricultural income is \$34.1 million per year. Under the optimal base case solution, flood irrigation is used for ≈90% of the service area in actual production with drip irrigation used for just <10%. This corresponds approximately to actual 2006 EBID conditions.

We identified effects of a range of cost-sharing arrangements by varying the proportion of the average annualized irrigation system improvement capital cost paid by the public agency versus the farmer. That part of capital cost paid by the public agency was parametrically increased from 0 to 100% in 10% increments.

Table 2 shows the hydrologic outcomes of 10 scenarios associated with alternative drip irrigation subsidy levels. The unconsumed part of irrigation water diverted from the stream is presumed fully available for other uses, either for downstream surface water use or as aquifer recharge that would be available for use in current or future periods. Drip irrigation produces higher ET than flood irrigation, while also producing higher crop yields. Raising the subsidy on drip irrigation induces more drip acreage and more total acreage into production when the Basin's reservoirs start very low as they were in early 2006. Total water applied (pumped plus diverted) falls from 364,000 acre-feet under the baseline to 324,000 under a 100% capital subsidy. Surface return flows are always 0. Groundwater pumping for irrigated agriculture falls considerably, from 91,000 under baseline to 63,000 under maximum subsidy. Aquifer-to-river gains fall from 32,000 acre-feet under baseline to 17,000 under the highest subsidy. Aquifer storage gains fall from 74,000 acre-feet under no subsidy to 40,000 under maximum subsidy. The net effect overall is greater water depletion (greater ET), which produces a negative conservation of ≈36,700 acre-feet per year under the highest subsidy compared with a defined 0 conservation with no subsidy. We find that a progressively increasing public subsidy of drip irrigation considerably reduces water applied to farmlands. However, it increases overall water use. These findings support the conclusions of Schierling *et al.* (20) as well similar findings published by Huffaker (35), Huffaker and Whittlesey (19), and Ahmad *et al.* (36). They also concur with the recent conclusions of Molden (37).

An important finding is that as the subsidy increases, water depletion never falls below base-level depletion. As the subsidy increases, the ratio of depletion to water diverted from the stream increases. The ratio of depletion to water diverted rises to 80% under a 100% subsidy from a base case of 61%, while water pumped is reduced from 91,000 acre-feet to 63,000 acre-feet.

Table 3 shows land use and economic outcomes produced by the same drip irrigation subsidy scenarios. Results show that as subsidy levels increase, net farm income increases from \$34.1 million under the base case to \$45.5 million under the highest subsidy. At the 100% subsidy, level drip irrigation is used for 46,000 of 87,000 acres in production, or 53%. Overall, results suggest that a water conservation subsidy policy is unlikely to reduce water depletions under any of the scenarios. In fact, water depletions, yields, and acreage are all predicted to increase if total water use is not constrained to base levels by the various water authorities. If total irrigated acreage is also allowed to increase, the potential increase in water depletions is even higher. We conclude that in river basins where downstream users and future generations depend on the unconsumed portion of diversions in the form of returns to the stream and raised aquifer storage, subsidies for conservation technology investments are unlikely to bring about a new supply of water but will likely lead to increased depletions.

Results of Table 3 show that subsidies do encourage a shift to more water-efficient technologies. By paying for a part of the capital cost, the program reduces farmers' irrigation costs. Because of reductions in water applied to crops, increased program subsidies also lead to savings in other variable costs, including energy and groundwater pumping. As the subsidy rises and as its implementation promotes a change in technology, results show continued reductions in water applied to crops. At the same time, net farm income increases because of the subsidy itself and because of the subsidy's impact on altered technology and increased crop yields.

Table 3 presents 5 indicators of total economic benefits in addition to farm income and program cost: These indicators include (*i*) net benefits of water use including costs of irrigation subsidies in total costs (national view); (*ii*) net benefits of water use excluding the irrigation subsidy cost (basin view); (*iii*) net benefits produced by the water environment; (*iv*) total net benefits of water use plus benefits of the water environment

Table 3. Water conservation in irrigated agriculture for selected drip irrigation subsidies, Lower Rio Grande, NM, annual average, 2006–2025; land use and economic outcomes

Land use outcomes (1,000 acres/year)					Economic outcomes ($1,000/year)							
Subsidy, % capital	Subsidy, $/acre/year	Land in drip irrigation	Land in flood irrigation	Total land under irrigation	Farm income	Program cost	Net benefits from water use A*	Net benefits from water use B†	Net benefits from water environment	Total net benefits A*	Total net benefits B†
0	0	7	68	75	34,102	0	519,848	519,848	23,273	543,121	543,121
10	36	8	69	77	34,723	309	520,211	520,519	22,465	542,676	542,985
20	73	9	66	76	34,770	690	519,826	520,517	23,204	543,030	543,720
30	109	25	52	77	35,242	2,794	518,190	520,984	23,253	541,443	544,238
40	146	32	47	79	36,219	4,613	517,348	521,961	23,313	540,661	545,274
50	182	36	45	81	37,499	6,475	516,686	523,161	22,877	539,564	546,038
60	219	42	42	84	38,903	9,185	515,514	524,699	22,807	538,322	547,506
70	255	45	42	87	40,473	11,422	514,848	526,269	22,821	537,668	549,090
80	291	45	42	87	42,171	13,131	514,836	527,968	22,775	537,612	550,743
90	328	45	42	87	43,632	14,773	515,446	530,219	23,046	538,492	553,265
100	364	46	42	87	45,506	16,571	514,663	531,234	22,795	537,458	554,029

*Total costs include Program Cost of Water Conservation subsidy.

†Total costs exclude Program Cost of Water Conservation subsidy.

including subsidy costs (national view); and (*v*) total net benefits of water use plus the water environment excluding subsidy costs (basin view). This last economic indicator is the objective function maximized for this analysis.

An important trend is the nearly uniform increase in the Basin's total net benefits with rising irrigation subsidies. Total net benefits from the Basin's view increase from about $0.543 billion per year with no subsidy to about $0.554 billion per year under a 100% subsidy, as farm incomes in the Basin increase from $34.1 million with no subsidy to $45.5 million with a 100% subsidy. From the national view, the story is different. Where the taxpayer's cost of the irrigation subsidy is included in total costs, national net benefits fall from a high of $0.543 billion with no subsidy to a low of $0.537 billion with a 100% subsidy. So, although the irrigation water conservation subsidy is economically good for the Basin, it is a weak economic performer for the nation.

Conclusions

Lubchenco (38) described a social contract between science and society, in which advances in science inform society's important decisions. Her observations certainly characterize the elusive search for policies that would stretch the world's effective supply of water by promoting water conservation in irrigated agriculture. Our findings from the Rio Grande Basin suggest that water conservation subsidies are unlikely to reduce water depletions by agriculture under conditions likely to occur in many river basins. These findings suggest that some programs subsidizing irrigation efficiency are likely to reduce water supplies available for downstream, environmental, and future uses. Although water applied to irrigated lands may fall, overall water depletions increase. Our findings suggest reexamining the belief widely held by donors that increased irrigation efficiency will relieve the world's water crisis.

The world's single biggest water problem is scarcity (13). Reducing wet water scarcity requires accurate measurement of water use at different scales, including better estimates of return flows and ET. It also requires defining water rights, water transfers, water use, and water accounting overall in water depletions rather than water applications. With better crops, higher yields, and more even distribution of water, our results show that resulting crop water depletions increase. For example, in recent years crop yields have increased dramatically in the upper part of the Basin in southern Colorado. Alfalfa, potato, and grain yields in this part of the Basin have increased considerably since the mid 1980s. Those increased yields coupled with changing irrigation practices have worked to increase overall water depletions.**

Our findings also suggest that where return flows are an important source of downstream water supply, reduced deliveries from the adoption of more efficient irrigation measures will redistribute the basin's water supply, which could impair existing water right holders who depend on that return flow. Our results indicate that water conservation subsidies will not provide farmers with economic incentives to reduce water depletions and therefore are unlikely to make new water available for alternative uses. In fact, depletions are likely to increase as a result of subsidies. Drip irrigation is important for many reasons, including greater water productivity and food security (12, 15), but does not necessarily save water when considered from a basin scale (37).

What measures can be taken to promote real water savings? A first step could be accurate accounting of basinwide water use. Water accounting analyzes use, depletion, and productivity of water at the basin scale (37). Accurate accounting and measurement of water use can help identify opportunities for water savings, increase water productivity, and improve the rationale for water allocation among uses (37). Other measures include reducing or converting nonbeneficial evaporation from soil or supply sources to beneficial crop ET, restricting acreage or water use expansion in cropped areas, switching to lower water-consuming crops, or irrigating current crops at a deficit (39, 40).

Careful definition and administration of water rights can play a role. Water rights, water markets, water transfers, and water accounting need to be defined in terms of water depleted, not just water applied. Without defining water use in terms of depletions, individual farmers who invest in more efficient irrigation systems recognize that they apply less water per acre. They may believe their water right is no longer fully used and may claim that the unused water is available for beneficial use. A common reaction among private irrigators and even among

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**There are important cases where policies designed to reduce applied water successfully reduce depletions. These occur where irrigation return flows travel to a saline body such as the ocean, a saline lake, or brackish groundwater. In these cases, most applied water is consumptively used because unused irrigation water is lost for future freshwater use. Water-marketing efforts, such as those between southern California cities and California's Imperial Irrigation District, which drains into the saline Salton Sea, have successfully achieved water conservation in agriculture while providing incentives for more efficient water use in all sectors from both local private and regional social views. We thank an anonymous reviewer for this insight.

public water conservation program administrators is to create a new use of water or expand the current water use to a larger number of acres or to higher water-consuming crops. The U.S. National Resources Conservation Service Environmental Quality Incentives Program (41) revolves around the premise that if irrigators install a more efficient irrigation system and irrigate 2 parcels instead of 1 with the same water right, increased efficiency in water use results. Water rights administrators can guard against this error. Where water rights are administered based on water depletions, water right administrators will not permit investors in irrigation efficiency to presume that water is saved. Indeed, where hydrologic realities of a river basin are implemented into law, the right to acreage farmed and to water applied will be reduced after measures are taken to increase irrigation efficiency.

A major question for efficient public policy is whether or not the increase in net farm income compensates the forgone benefits of reduced return flows and seepage (12). This is a question facing water science, water policy, and water administration. Where reduced return flows and lost aquifer seepage block another's water use, conservation poses a serious question for water rights administration because those effects are often hard to measure and often occur with considerable delay. Answering this question requires sorting out conflicting impacts of water application versus water depletion and an understanding of the transmission of those effects at the basin scale.

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