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Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow

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[1] In surface-water-irrigated western valleys, groundwater discharge from excess irrigation sustains winter streamflow at levels that exceed natural flows. This unnatural condition has persisted for so long that hydrologists, water managers, and water users consider it to be normal. Changing land uses and irrigation practices complicate efforts to manage groundwater discharge and, in turn, to protect instream flows. We examined the impacts on streamflow of (1) seasonal groundwater pumping at various distances from the Gallatin River and (2) improving irrigation efficiency in the Gallatin Valley, Montana. We show that the greater the distance from a seasonally pumping well to a stream, the less the stream depletion fluctuates seasonally and the greater the proportion of annual depletion occurs during the nonirrigation season. Furthermore, we show that increasing irrigation efficiency has implications beyond simply reducing diversions. Improving irrigation efficiency reduces fall and winter flows to a lower, but more natural condition than the artificially high conditions to which we have become accustomed. However, existing water users and aquatic ecosystems may rely upon return flows from inefficient irrigation systems. By strategically timing and locating artificial recharge within a basin, groundwater and surface water may be managed conjunctively to help maintain desirable streamflow conditions as land uses and irrigation practices change.

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1. Introduction

[2] Groundwater discharge sustains streamflow during critical low-flow periods. This is especially true in the western United States, where in most places spring snowmelt is the principal contribution to overland flow, whereas groundwater discharge maintains base flow through the summer, fall, and winter.

[3] Traditionally, hydrogeologists and groundwater managers have focused on achieving dependable supplies from wells. Contemporary concerns about maintaining instream flows, however, bring to the forefront new challenges in water management. As basin flows become fully allocated and water managers realize the connection between groundwater and surface water, attention is turning to developing strategies for managing limited groundwater and surface water resources conjunctively. Achieving the linked goals of obtaining sustainable groundwater supplies while at the same time maintaining desirable streamflow represents the most basic form of conjunctive groundwater and surface water management.

[4] Augmentation is a term water managers and lawyers use to describe a conjunctive groundwater/surface water management approach in which an existing diversion of surface water, with a water right, is retired to mitigate the stream depletion caused by new groundwater pumping. Long practiced in Colorado, augmentation is gaining popularity in other states as a legally enforceable approach for mitigating stream depletion caused by groundwater pumping. In most western states, all the available water is fully allocated, and no new supplies are available for new developments. In the ideal situation, the hydrogeologist determines the quantity, location, and timing of stream depletion that new wells will cause. Then, the developer locates existing surface water rights holders who are willing to sell or trade their rights. Finally, the hydrogeologist develops a mitigation plan that uses the existing surface water right to offset the stream depletion caused by the new groundwater pumping. Accurate mitigation conserves not only the quantity, but also the timing and location of groundwater discharge to associated streams.

[5] Mitigation plans, though, are being applied to a changing hydrologic regime. In many alluvial valleys, shallow aquifers are recharged primarily by irrigation. Discharge from those aquifers maintains instream flows during the nonirrigation season. Changing land uses and irrigation practices complicate efforts to manage groundwater discharge and, in turn, to protect instream flows.

[6] Irrigation practices induce seasonal groundwater stresses on aquifers. These stresses, although they fluctuate seasonally, historically have been relatively constant from year to year. During late spring through summer, irrigation diversions from surface water reduce natural streamflow. At the same time, excess irrigation water, especially from flood-irrigated cropland, infiltrates to the water table, where it recharges ground water. The groundwater slowly flows through the aquifer until it discharges to streams. Groundwater discharge from irrigated valleys maintains streamflow

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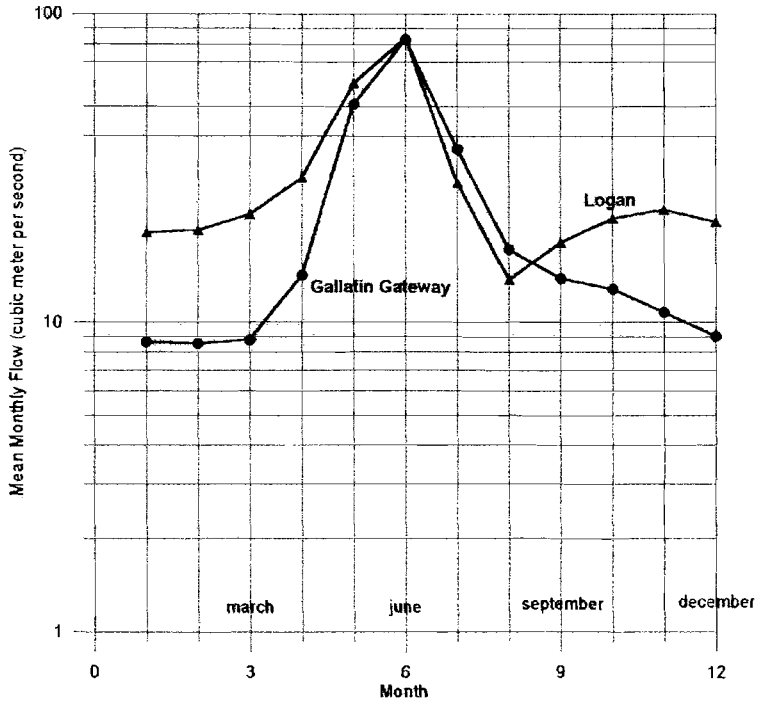

Figure 1. Average monthly flow of the Gallatin River at Gallatin Gateway (circles) and at Logan (triangles), Montana. Gallatin Gateway is above the irrigated Gallatin Valley (Figure 2); flow in the river at this point is largely unaffected by human activities, including irrigation. Logan is below the Gallatin Valley. At Logan, the river and its intervening tributaries are affected by all the human activities in the Gallatin Valley, especially irrigation.

well into the fall and winter, long after irrigation has ceased, and long after snow stops melting from the mountains. The resulting streamflow hydrograph (Figure 1, hydrograph for Logan, Montana), although not natural, is considered "normal" because it represents the average condition over the past 30 or more years. It is the condition to which we have become accustomed, and which supports the riparian systems with which we are familiar.

[7] Land-use changes in many parts of the west are changing the traditional pattern of irrigation. In urbanizing areas, irrigated land is converting to commercial and residential developments, many of which are supplied by groundwater. Much of the remaining cropland is converting from flood to sprinkler irrigation, and canals are being lined in an effort to improve irrigation efficiency.

[8] Irrigation efficiency is promoted worldwide as a means to increase limited water supplies. For example, in 2005, the *Bureau of Reclamation* [2006] contributed $4,314,033 to line or pipe more than 90 km (56 miles) of irrigation canals and ditches in order to "save" 36.7 million m^3 (29,726 ac ft) of water per year.

[9] However, this water "savings" comes at the expense of reducing or eliminating return flow. Thus improving irrigation efficiency is tantamount to decreasing groundwater recharge [*Scanlon et al.*, 2005] and, in turn, decreasing groundwater discharge to an associated stream. Usually, improved efficiency increases crop production by more uniformly distributing water to the root zone. Uniformly irrigated crops consume more water than nonuniformly irrigated crops [*Whittlesey*, 2002], leaving even less water available to recharge the aquifer. Increasing irrigation efficiency also may lead farmers to increase their irrigated acreage, thus consuming more and recharging less of the water diverted [*McMahon et al.*, 2003]. Less recharge means less discharge (or less return flow) to surface water once the aquifer system reestablishes equilibrium.

[10] Very few empirical studies document the impacts of changing irrigation efficiency on streamflow. One exception is in the Salt River Basin of western Wyoming [*Venn et al.*, 2004], where irrigators converted from flood to sprinkler irrigation on 75% of the irrigated cropland. The effect of this change was to increase streamflow by 34% in May and 50% in June, while decreasing flow by 15% in August, 14% in September, 8% in October, and 9% in November. At the same time, farmers in the basin reported 50–100% increases in crop yields.

[11] In another study, *Gannet and Lite* [2004] simulated the effects of canal lining on streamflow in the upper Deschutes Basin, Oregon. According to their model, the improved delivery efficiency achieved by reducing groundwater recharge from leaky canals took several decades to fully manifest as stream depletion.

[12] Improving irrigation efficiency reduces diversions, but also reduces groundwater recharge. The impacts of reducing the primary source of groundwater recharge (and its subsequent discharge to streams) in western valleys significantly change the streamflow hydrograph. Such widespread impacts deserve focused attention, especially in light

of concurrent efforts to manage groundwater and surface water conjunctively.

1.1. Purpose and Scope

[13] It is our purpose to investigate changes in irrigation efficiency on the associated streamflow. Rather than doing this in the abstract, we chose to do it using as a prototype the Gallatin Valley in Montana. The Gallatin River enters the valley from the mountains at Gallatin Gateway, where there is a long-term stream gage. Streamflow in the Gallatin River at Gallatin Gateway is largely unaffected by human activity, and is thought to represent the natural pattern of flow of many rivers in the west. The river flow at Gallatin Gateway is dominated by a period of spring runoff, followed by a more or less continual decline in flow. Within the Gallatin Valley, streamflow is diverted from the river and its tributaries for flood irrigation. The valley is underlain by a highly permeable alluvial aquifer. Irrigation return flow recharges the aquifer, and then flows back to the river through the aquifer. The valley provides an ideal prototype in which to illustrate our ideas.

[14] In the investigation we use a two-dimensional numerical model as our tool with which to analyze the transient effects of groundwater stresses from irrigation, pumping, and recharge on the flux of groundwater to streams. This is not a typical model study; we make no attempt to calibrate the model. However, we input into the model aquifer properties and boundary conditions that were determined by hydrogeologic studies of the Gallatin Valley. The model is simply our tool for making the analyses. As an introduction, we first examine the impacts of seasonal groundwater pumping on the consequent stream depletion, which depend on the distance from the well to the stream. We then consider the impact of changing irrigation efficiency on streamflow in the traditionally surface-water-irrigated Gallatin Valley. We explore the impact of return flow from irrigation on the stream hydrograph and show that lower efficiency irrigation systems maintain higher flows through the fall and winter. These results challenge the notion that improvements in irrigation efficiency are always beneficial. The study illustrates key factors that control the quantity, timing, and location of instream flows that are maintained by groundwater discharge.

1.2. Previous Work

[15] Much of the understanding of the source of water for wells stems from *Theis* [1940], who explained the principle of capture. The U.S. Geological Survey [*Lohman*, 1972] defines capture as follows:

> "Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the ground-water discharge into streams, lakes, and the ocean, or from that component of evapotranspiration derived from the saturated zone."

[16] Where a stream is hydraulically connected to an aquifer, capture can manifest either as an increase in recharge from the stream to the aquifer or a decrease in discharge from the aquifer to the stream, or some combination of both.

[17] Previous analyses of groundwater stresses on streamflow have focused primarily on impacts of pumping. *Theis* [1941] was the first to assess the impacts of pumping on an associated stream. *Glover and Balmer* [1954] and later *Jenkins* [1968] generalized Theis's analytical approach. In this approach, the stream becomes a line source for a well pumping in a semi-infinite space. One solves for the hydraulic head in the semi-infinite space at any particular time. Prior to pumping, heads are assumed to be uniform and equal to the stream stage. Applying Darcy's law at the stream boundary and integrating along the boundary, one can determine the capture from the stream at any time. If one then projects the pumping to infinite time, one can determine the ultimate stream capture, or stream depletion caused by the pumping. This method of analysis relies upon the mathematical principle of superposition [*Reilly et al.*, 1987], so the change in streamflow caused by a new pumping well is calculated independent of preexisting heads and preexisting groundwater flow to or from the stream.

[18] *Hantush* [1965] extended the linear model to consider an imperfect hydraulic connection between stream and aquifer. *Grigoryev* [1957] and *Bochever* [1966] developed more realistic models that account for both a partially penetrating stream and an imperfect hydraulic connection to the aquifer. *Zlotnik and Huang* [1999] and *Butler et al.* [2001] further extended the model to account for a finite width stream of shallow penetration adjoining an aquifer of limited lateral extent.

[19] *Wallace et al.* [1990] used the principle of superposition to analyze stream depletion caused by cyclic pumping. They summed the impact of single cycles of pumping superimposed one upon another to obtain a rather elegant general solution for cyclic pumping. More recently, *Singh* [2003] modified *Hantush*'s [1965] analytical model to consider partial penetration and semipervious streambed and banks, and used it to examine the impacts of cyclic pumping.

[20] With the advent of two- and three-dimensional groundwater flow models, the simplifications required for analytical modeling are no longer needed. However, the early numerical models were operated, almost without exception, in the superposition mode. The numerical model facilitated, but did not replace, the classic theoretical analysis, of which superposition was an integral part. Numerous published analyses, including *Longenbaugh* [1967], *Bredehoeft and Young* [1983], and *Young and Bredehoeft* [1972], used numerical models in the superposition mode to evaluate systems that use groundwater and surface water conjunctively.

[21] Using the principle of superposition, one can determine stream depletion. However, the depletion can occur either in a stream that is gaining water as outflow from an aquifer, or in a stream that is losing water to the aquifer, or as a combination of both through a given reach. In the case of a gaining stream, the gain will be decreased by the amount of stream depletion. Alternatively, in a losing reach, the stream loss will be increased by the amount of the stream depletion. The solution to the boundary value problem determines the stream depletion, but it does not indicate how the water will actually flow. One has to superpose the solution to the stream depletion boundary value problem on the water table as it would exist without the pumping causing depletion to

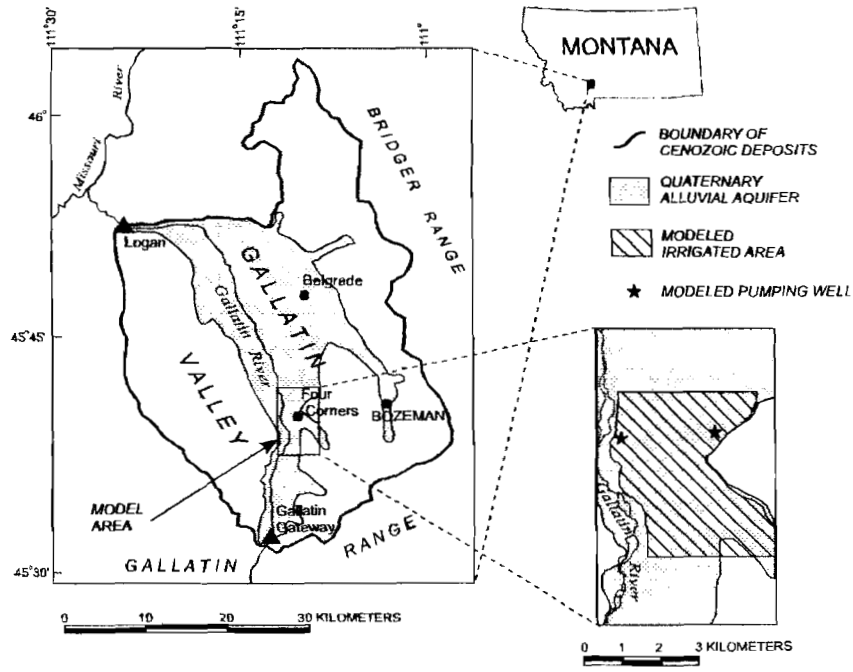

Figure 2. Location of (left) the Gallatin Valley and (right) the area modeled in this study.

determine the actual direction of flow: into or out of the stream.

2. The Gallatin Valley

[22] The 1350-km^2 (520-mi^2) Gallatin Valley (Figure 2) is an approximately north-south trending intermontane basin consisting of a broad alluvial plain ranging in elevation from about 1250 to 1400 m (4100 to 4500 feet), flanked by alluvial terraces up to 1900 m (6300 feet). Structurally, the valley is part of an eastward tilted graben filled with as much as 1800 m (6000 feet) of Cenozoic sediment. The northern, western, and southern basin boundaries are not marked by obvious faults, and may be depositional contacts between Cenozoic basin fill and pre-Cenozoic bedrock. The eastern boundary is a series of steep normal faults along the fronts of the Bridger and Gallatin ranges, which rise more than 1500 m (5000 feet) above the valley floor [*Kendy*, 2001; *Kendy and Tresch*, 1996].

[23] The climate of the Gallatin Valley is characterized by cold winters and mild summers. Average annual precipitation at Belgrade (Figure 2) (altitude 1360 m (4450 feet)) is 35.7 cm (14.1 inches) (Western Regional Climate Center, 1941–2005, http://www.wrcc.dri.edu). However, this belies the actual amount of water flowing through the valley. Precipitation in most of the valley's 4649-km^2 (1795-mi^2) drainage area far surpasses that in the valley itself. On the peaks of the Bridger and Gallatin ranges, annual precipitation exceeds 110 cm (44 inches). This precipitation falls primarily as snow, which accumulates in the mountains, so winter streamflow is very low. In the spring and early summer, snowmelt from the mountains feeds the Gallatin River and its tributaries. The Gallatin River, a tributary to the Missouri River, enters the Gallatin Valley at Gallatin Gateway and exits the valley at Logan (Figure 2).

[24] Land use in the Gallatin Valley is predominantly agricultural, dominated by hay and grain crops. The intensively irrigated alluvial plain is the main crop-producing area in Gallatin County. In 2000, farmers diverted 545.1 × 10^6 m^3 (441,900 ac ft) of surface water from the Gallatin River and its tributaries to irrigate 36,760 ha (90,840 acres) of pasture and cropland [*Cannon and Johnson*, 2004].

[25] Excess irrigation water infiltrates into the alluvial aquifer system. The shallow (14 to more than 18 m (45 to more than 60 feet) deep) Quaternary alluvial aquifer in the Gallatin Valley is highly permeable; transmissivity values range from 1100 m^2/d (12,000 feet^2/d) to more than 3200 m^2/d (35,000 feet^2/d). Recently, *Kaczmarek* [2003] determined a transmissivity of 1140 m^2/d (12,300 feet^2/d) and specific yield of 0.03 to 0.16, based on a 72-hour aquifer pumping test. Previously, *Hackett et al.* [1960] obtained transmissivity values ranging from 470 to 8400 m^2/d (5100 to 90,000 feet^2/d) and averaging 2400 m^2/d (27,000 feet^2/d). The shallow Quaternary alluvium is incised into much thicker (to 1800 m (6000 feet)), generally finer grained Tertiary alluvium, which fills the Gallatin Valley. Transmissivity of the Tertiary aquifer determined from four aquifer tests ranges from 3.7 to 210 m^2/d (40 to 2300 feet^2/d) [*Hackett et al.*, 1960]. The depth to groundwater generally ranges from about 2 to more than 125 m (6 to more than 200 feet) [*Kendy*, 2001]. Groundwater provides domestic supplies for more than 17,000 residents of the valley, but is not a major source of irrigation supply [*Kendy*, 2001].

[26] Virtually all of the groundwater beneath the valley discharges to the Gallatin River and its tributaries [*Hackett et al.*, 1960; *Kendy*, 2001; *Slagle*, 1995]. The Gallatin and its tributaries headwater in nearby mountain ranges and then flow across the Gallatin Valley, where they are subject to irrigation diversions and return flows.

[27] A comparison between average monthly hydrographs for the Gallatin River at Gallatin Gateway, where the river enters the valley, with the Gallatin River at Logan, where it exits the valley (Figure 1), illustrates the effect of irrigation diversion and return flow on the river flow at Logan. The upper stream gage, at Gallatin Gateway, represents a more or less natural hydrograph, indicating a long baseflow recession period following spring snowmelt. In contrast, the lower stream gage, at Logan, indicates a significant flow increase in the fall after irrigation diversions are shut down. The difference in the character of the hydrographs between Gallatin Gateway and Logan is the effect of the groundwater discharge of irrigation return flow from the Gallatin Valley on the river flow at Logan.

[28] Land use in the valley is undergoing major change. The population of Gallatin County increased from about 21,900 in 1950 to 67,831 in 2000 [*Montana Department of Commerce*, 2000], with almost all of the population increase occurring within the Gallatin Valley. Over the same period, the irrigated acreage decreased, making way for residential and commercial development. From 1964 to 2002, the area of farmland in Gallatin County decreased from about 410,000 to 290,000 ha (1,000,000 to 700,000 acres) [*National Agricultural Statistics Service*, 2004].

3. Groundwater Model

[29] We used a two-dimensional numerical model to help understand the changes in groundwater stresses in the Gallatin Valley as a result of these land-use changes. We focused on the rapidly developing Four Corners area (Figure 2) of the Gallatin Valley.

[30] In order to do the analysis, we used a two-dimensional groundwater code (JDB-2D/3D) that solves the same flow equations as MODFLOW [*Bredehoeft*, 1990]. The public domain model simulates a single, one-layer water table aquifer.

[31] Figure 2 shows the location of the modeled area within the Gallatin Valley. In the east-west direction, the cells are 97 m (330 feet) wide; in the north-south direction, they are 190 m (660 feet) wide. Overall, the grid consists of 48 cells in the east-west direction by 40 cells in the north-south direction.

[32] The grid spacing is fairly large in comparison with the stream width; however, because the modeled aquifer is homogenous and the geometry and stress patterns are simple, grid refinement did not affect the head or flow results significantly. We assumed that the shallow Quaternary alluvial aquifer has a transmissivity of 1,860 m^2/d (20,000 $feet^2/d$), and the surrounding Tertiary deposits have a transmissivity of 93 m^2/d (1,000 $feet^2/d$). Limited-duration pumping tests may underestimate the long-term yield characteristics of a water table aquifer [*Lohman*, 1979]. Therefore, assuming the 72-hour pumping test [*Kaczmarek*, 2003] generated minimum values, we modeled the system using a specific yield value of 0.2, a typical value for long-term drainage of unconfined aquifers [*Lohman*, 1979].

[33] We assumed the Gallatin River to be 30.5 m (100 feet) wide, with a streambed thickness of 1.5 m (5 feet), and a streambed hydraulic conductivity of 1.2 m/d (4 feet/d), based upon earlier studies (Levens, Russell, Montana Department of Natural Resources and Conservation, written communication, 2005). *Sophocleous et al.* [1995] found streambed clogging and the degree of partial streambed penetration to be important sources of uncertainty in modeling stream depletion. How one handles the stream-aquifer interconnection makes a difference in the results. In our case, the stream is hydraulically connected to the aquifer but it is not fully penetrating. In contrast to a fully penetrating stream, reducing the permeability of the streambed in our model has the effect of making the stream appear to be farther away from the stress than it really is. The boundaries of the model domain are assumed impermeable on all sides.

[34] We discretized each year modeled into 12 equal time steps of 30.44 days each. Adjusting the year into 12 equal time steps instead of using actual months simplifies the model without affecting the results significantly.

[35] The model is not calibrated to heads and flows. Instead, we used the principle of superposition to calculate the change in flows that would add to or subtract from preexisting flows. As indicated above, we input parameters and boundary conditions in the model that are known from earlier investigations. We also input a hypothetical irrigation distribution system. The model was our tool for analysis. The simulation results are intended to demonstrate concepts, rather than to accurately characterize the details of groundwater flow in the Gallatin Valley.

3.1. Single Well Pumping

[36] We first examine the impact on the river of a single well pumping, first located 0.3 km (0.2 mile) from the stream and then relocated 2.9 km (1.8 miles) from the stream. Our point in this exercise is to investigate the impacts of a single well and to demonstrate how the system responds.

[37] As mentioned earlier, *Wallace et al.* [1990] published a theoretical paper on stream depletion caused by cyclic pumping. *Wallace et al.* [1990] defined a condition of dynamic equilibrium in which the stream depletion in one cycle is equal to the quantity of water pumped during that cycle. The time required for the system to reach a state of dynamic equilibrium depends upon the distance from the well to the stream and the hydraulic characteristics of the aquifer. *Wallace et al.* [1990] presented an equation that describes the time needed for a well located a distance a from the stream to reach within 95% of dynamic equilibrium:

$$t_e = 127a^2S/T, \tag{1}$$

where S is the specific yield, T is the transmissivity of the aquifer, and a is the distance to a fully penetrating stream.

[38] In a semi-infinite system such as that used by *Wallace et al.* [1990], the system takes a long time to reach a new equilibrium state; for that reason, *Wallace et al.* [1990] defined the time to reach 95% of equilibrium. However, in a real system with lateral boundaries, dynamic equilibrium is reached when the impacts in one year are the same as in succeeding years; in this condition, the system is 100% in equilibrium. For our investigation, we use this more practical definition of dynamic equilibrium for real systems.

[39] *Wallace et al.* [1990] made a number of simplifications to facilitate a theoretical solution: (1) The stream is a straight line. (2) The river fully penetrates the aquifer. (3) The aquifer extends from the stream to infinity. In reality, the aquifer in the Four Corners area is bounded

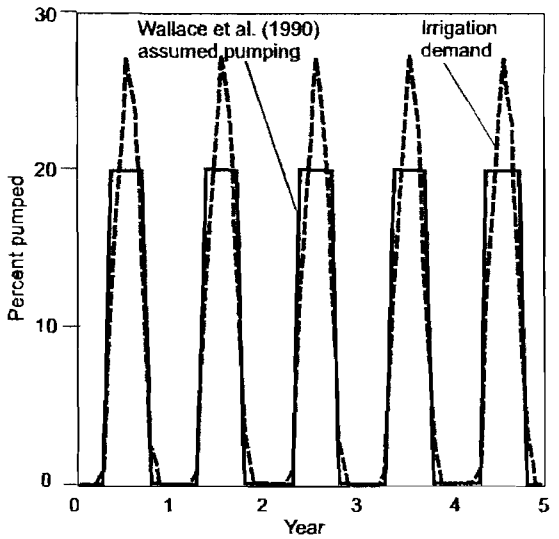

Figure 3. The square wave (solid curve) of cyclic pumping assumed in the *Wallace et al.* [1990] theoretical solution. In this example, 20% of the total demand is pumped in each of five months. The dashed curve is the irrigation demand of a proposed new well in the Four Corners area, expressed as the percent of the total demand pumped in each month. For example, 27% of the total water demand for irrigation occurs in July each year. The total amount pumped adds up to 100% under both curves.

not far to the east by alluvial fans of lower transmissivity. (4) The pumping is assumed to be an idealized square wave. Figure 3 contrasts the square-wave pumping scheme assumed by *Wallace et al.* [1990] with the actual irrigation demand of a proposed new well in the Four Corners area.

[40] Our modeling suggests that equation (1) is too conservative for determining how long the Gallatin Valley system takes to reach dynamic equilibrium, as we see below. The modeling shows that the system reaches a new dynamic equilibrium much quicker than equation (1) indicates. This is not surprising, given that neither the aquifer nor the pumping schedule in the Four Corners area fits the idealized theoretical model assumed by *Wallace et al.* [1990] particularly well. However, *Wallace et al.* [1990] correctly concluded that one must simulate a number of years of pumping to be sure that the system reaches a new equilibrium state. It is, after all, dynamic equilibrium that indicates the long-term impact of pumping on the stream.

[41] Figure 4 illustrates the stream depletion caused by one well pumping sufficient water to satisfy the crop demand for 2 ha (5 acres) of irrigated landscaping within a residential/commercial development in the Four Corners area of the Gallatin Valley. The well is located 0.3 km (0.2 mile) from the river (Figure 2). The bottom curve indicates the net groundwater pumping rate, i.e., the portion of withdrawal that the plants consume. Even if the well supplies residential and commercial demand, nearly all the consumptive use will be for landscape irrigation during the summer. It is assumed that unconsumed water returns to the aquifer instantaneously. The top curve indicates the consequent reduction in streamflow in the nearby Gallatin River.

[42] Since the well simulated in Figure 4 is only 0.3 km (0.2 mile) from the river, the stream depletion is in phase with the pumping. The amplitude of the depletion fluctuation is approximately one half of the amplitude of the pumping. During nonirrigation season, stream depletion is almost negligible. The depletion reaches a state of dynamic equilibrium in which annual stream depletion equals annual groundwater consumption after about 3 years of pumping.

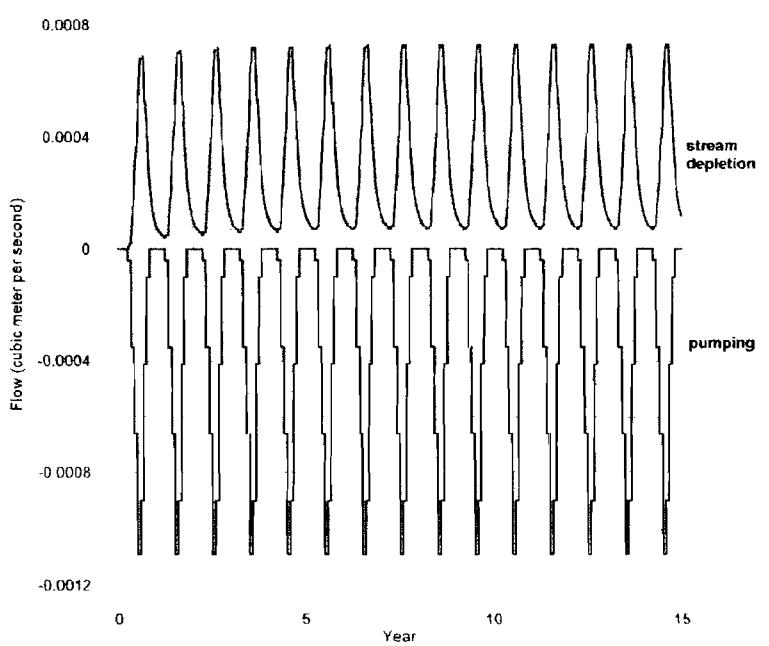

Figure 4. Plot of stream depletion caused by a single well pumping at a distance of approximately 0.3 km (0.2 mile) from the river, at the variable rate indicated to meet the crop consumptive demand for 2 ha (5 acres) of irrigated landscaping (one model cell).

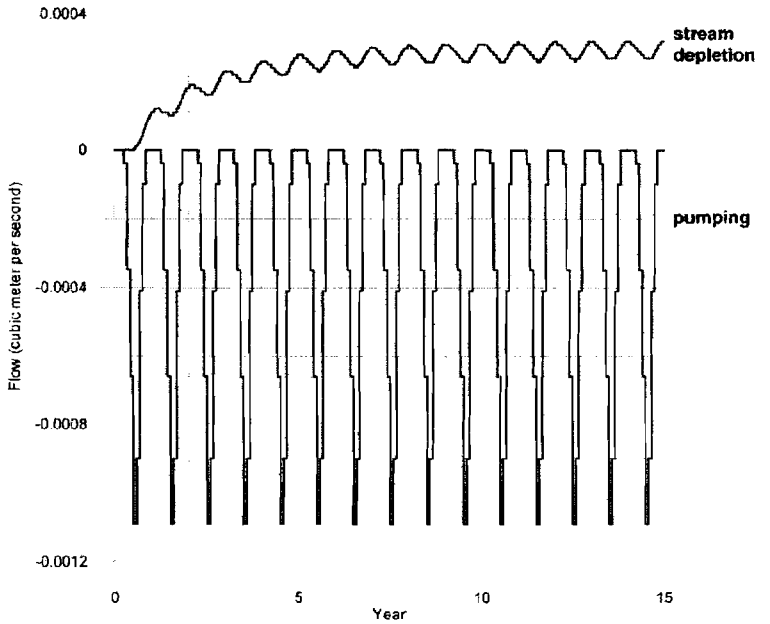

Figure 5. Plot of stream depletion caused by one well, located 2.9 km (1.8 miles) from the river.

[43] We also simulated a well located 2.9 km (1.8 miles) from the river (Figure 2) pumping an equal amount of water. Figure 5 shows the depletion associated with this more distant well.

[44] In the case of the more distant well, annual stream depletion reaches a more or less steady value, equal to the average value of the pumping spread throughout the entire year, after about 8 years. A small seasonal fluctuation occurs approximately 180 days out of phase with the pumping, so significant depletion occurs during the non-irrigation season, long after pumping has stopped. The maximum stream depletion occurs on 1 January.

3.2. Mitigation

[45] Figures 4 and 5 illustrate the mitigation problem. In Figure 4, where the well is situated near the river, the stream depletion has a large annual fluctuation, which is very nearly in phase with the pumping. The bulk of the depletion occurs during the irrigation season. In this instance, leaving a quantity of water in the stream equal to the stream depletion amount is a good method of mitigation. In other words, retiring a surface-water-irrigation right equal to the depletion by leaving the water in the river is an effective way to maintain the preexisting streamflow hydrograph, the result of surface water diversion and irrigation return flow.

[46] Figure 5 illustrates the mitigation problem when pumping effects are delayed. In this case, the stream depletion is more constant through the entire year. Leaving previously diverted irrigation water in the stream during the irrigation season will not provide mitigation for the depletion that occurs outside the season. Generally, water rights are available for sale or trade only during irrigation season, since only irrigators are willing to retire their rights. One option would be to use surface water instead of groundwater to irrigate the landscaped areas of the residential/commercial development. Although conceptually this seems to make sense, the engineering and construction costs of installing two sets of plumbing, one for drinking and bathing and another for irrigation, exceed the cost of mitigating stream depletion through artificial recharge.

[47] Recharging the aquifer with surface water in the vicinity of the pumping wells during the irrigation season will mitigate depletion throughout the year. Recharging in the area of the pumping has the opposite impact to the pumping, and spreads the flow back to the stream through the entire year, even if it only recharges during irrigation season. Artificial recharge to another part of the aquifer could be equally effective, so long as the aquifer materials are similar and the recharge site is at least the same distance from the stream as the pumping site. Also, the recharge site could not be located downstream from the affected stream reach, or so far upstream that intervening users could divert the recharged water.

[48] In summary, the impact of pumping groundwater depends upon the aquifer properties and the distance of the well from the stream. The most important factor is the distance from the well to the stream. Moving the well away from the stream makes the impacts become more constant and decreases the annual fluctuation so that the impacts of a distant well on the stream are relatively constant through time. Mitigating for a distant well requires a scheme that will also produce constant flow to the stream. One way to achieve this is though artificial recharge near the pumping site. With this background on pumping impacts, we now examine irrigation return flow.

3.3. Impact of Irrigation Return Flow on Streamflow

[49] We wish to examine the impacts of return flow from surface-water-irrigation on streamflow. Return flow occurs both as (1) surface water runoff back to the stream, more or less immediately, and (2) flow through the associated groundwater system. In the Gallatin Valley, the shallow aquifer is highly permeable: much of the return flow in the area occurs as groundwater flow through the aquifer. For

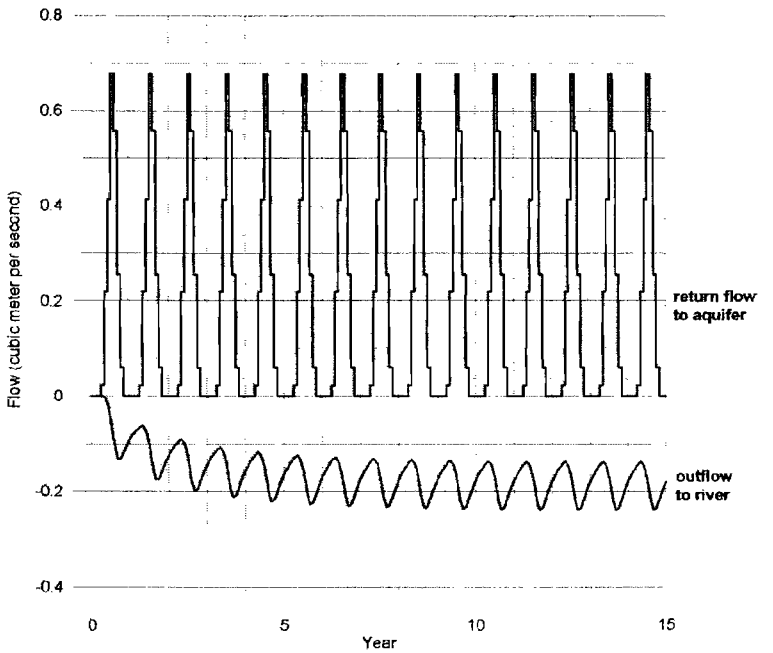

Figure 6. Simulated return flow to the river generated by irrigation that is 50% efficient (50% of the irrigation water recharges the aquifer and then returns to the river) on the area indicated on Figure 2.

this analysis, we assume that all of the return flow occurs through the aquifer. We also assume an irrigation system that is 50% efficient so that half of the diverted water recharges the aquifer, and crops consume the other half.

[50] We simulated an irrigated agricultural area of approximately 12.5 km^2 (3100 acres) with the model. The area of irrigation is indicated on Figure 2.

[51] Figure 6 shows the return flow generated by irrigation with 50% irrigation efficiency. The top curve represents the recharge rate of excess irrigation water from the irrigated land into the aquifer. The bottom curve shows the rate of groundwater discharge into the river.

[52] Recharge from excess irrigation water generates outflow to the river that persists throughout the year. The outflow is more or less constant about a mean value of about 0.18 m^3/s (6.5 cfs), on which is imposed a fluctuation with an amplitude of $\pm$ 0.1 m^3/s (3.5 cfs). The maximum outflow to the stream occurs toward the end of the irrigation season. The system takes approximately 8 years to reach dynamic equilibrium, in which the impacts are identical in succeeding years. The impacts resemble those of a single recharge well located at some distance from the stream, except that in this case the entire irrigated area overlying the aquifer contributes flow to the stream.

[53] Irrigation diversion and return flow change the temporal distribution of streamflow. In order to illustrate the impact of return flow, we took a monthly stream input hydrograph for our hypothetical stream reach that resembles the monthly streamflow of the Gallatin River at Gallatin Gateway. Because the river above Gallatin Gateway is relatively unaffected by human activity, we consider the flow of the Gallatin River at Gallatin Gateway to be natural streamflow for the area. We arbitrarily took 6% of the river flow at Gallatin Gateway as inflow to our hypothetical reach simply to illustrate our points; we did not want the results to be overwhelmed by too much streamflow. It turns out that 6% is just sufficient to leave some flow in the stream during the height of our hypothetical irrigation season.

[54] Using this streamflow as input to the reach, we calculated the impact of irrigating 12.5 km^2 (3100 acres), including both diversion and return flow (as illustrated in Figure 6 for 50% efficiency), on the streamflow. We considered two conditions: 50% efficient irrigation and 100% efficient irrigation. In both cases, the crops consume the same amount of water, but in the 50% case, twice as much water is diverted from the river to meet the crop needs and to recharge the aquifer. We recognize that 100% irrigation efficiency is unachievable; however, as the extreme of irrigation efficiency, it is instructive to analyze.

[55] Figure 7 shows the natural and calculated streamflows for our hypothetical reach during year 14, after dynamic equilibrium has been achieved.

[56] Compared with the natural hydrograph, diversions for irrigation decrease streamflow during the irrigation season. The more efficient the irrigation system, the less water needs to be diverted to satisfy crop needs, and the more water remains instream during the irrigation season.

[57] After irrigation season ends, the shape of the streamflow hydrograph depends on the efficiency of irrigation. In the case of 50% efficiency, water diverted during irrigation season returns slowly to the river, much of it during the nonirrigation season, as groundwater discharge. As a result, winter streamflow is greater than under nonirrigation conditions. The effect of the 50% efficient irrigation is to create return flow that maintains the streamflow through the fall and winter. With the return flow, there is approximately 30% more water in the river during the period October through February than under natural streamflow conditions. The modeled scenario is similar to the actual Gallatin River hydrograph at Logan (Figure 1).

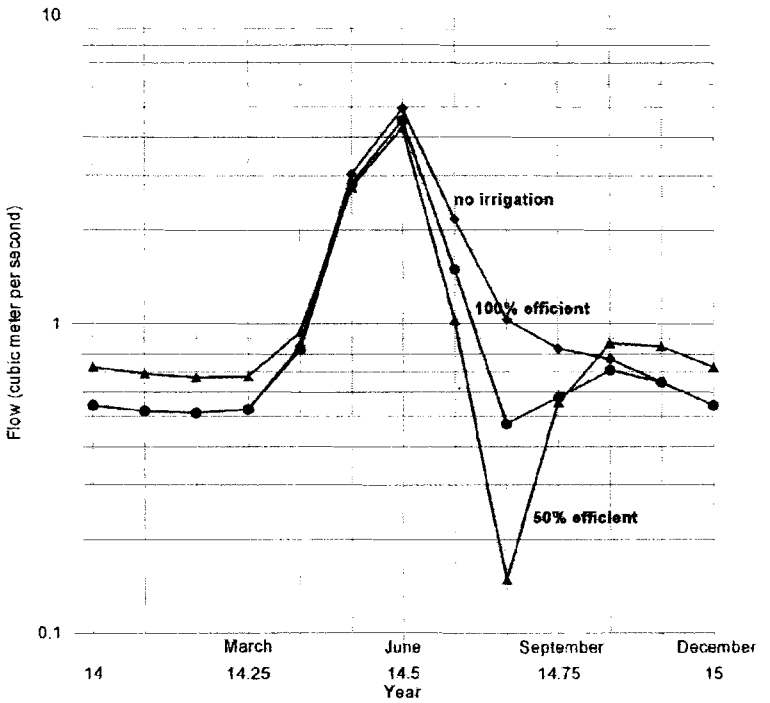

Figure 7. Computed streamflow in our hypothetical reach during one year, after dynamic equilibrium has been achieved. The curve with diamonds is set arbitrarily to 6% of the average monthly streamflow of the Gallatin River at Gallatin Gateway, which is located upstream from irrigation diversions and return flows. The curve with dots is streamflow from the reach with 100% irrigation efficiency on 12.5 km^2 (3100 acres) of cropland. (The 100% efficiency curve is the same as the nonirrigation curve except during the May through October irrigation season.) The curve with triangles is streamflow from the reach with 50% irrigation efficiency on the same cropland.

[58] Conversely, increasing irrigation efficiency has the effect of decreasing the fall and winter streamflow relative to inefficient irrigation systems; it moves the streamflow toward the natural condition. In our 100% efficiency example, crops consume all irrigation water applied, leaving no return flow to discharge to the river during the nonirrigation season. Thus, for 100% irrigation efficiency, the stream hydrograph is only affected by irrigation during the irrigation season; the winter streamflow hydrograph is the same as under natural, preirrigation conditions. This is quite different from the conditions to which we are accustomed.

[59] It is important to note that in all three cases plotted in Figure 7, total annual streamflow is the same. Changes in irrigation efficiency change the timing, but not the quantity, of annual flow. The only way to increase annual flows without importing water is to decrease water consumption within the basin. In our example, crops consume the same amount of water in each scenario, regardless of the amount applied. In reality, irrigation efficiency improvements such as sprinkler or precision irrigation systems tend to increase crop productivity, which increases water consumption, and consequently decreases annual streamflow.

4. Concluding Remarks

[60] Changing irrigation efficiency in alluvial valleys has implications beyond simply reducing diversions. So long as crop production does not decrease, irrigation efficiency improvements reduce groundwater recharge and associated discharge to streams. Impacts to downstream water users cannot be ignored.

[61] At the field scale, reducing or eliminating return flow can decrease late-season streamflow, shorten wetland hydroperiods, and deprive downstream users of late-season water supplies and hydroelectric generation capacity. These impacts may be avoided by taking into consideration the entire water balance, not just flow diversions, when contemplating future investments in irrigation efficiency projects. In some cases, it may prove more prudent to retain inefficient systems than to adversely affect downstream users by improving upstream irrigation efficiency.

[62] At the basin scale, an irrigation system taken as a whole may already be 100% efficient, even if the individual farms and canals within the system are not. In a basin like the Gallatin Valley, this is likely the case. If the system were not fully efficient, then excess (unallocated) water would be leaving the basin. In the Gallatin Valley, all water in the Gallatin River at Logan is claimed by downstream water rights. Even though individual farm efficiency could be improved, overall efficiency of the system would not improve. In fact, improving farm efficiency might result in more water consumption on some farms, which in turn would deprive their downstream neighbors of return flow that they counted on as part of their water supply.

[63] At the basin scale, as we have shown, irrigation efficiency affects the seasonality of river flows. When

irrigation systems deliver water inefficiently, excess water recharges the aquifer during irrigation season and discharges to basin streams after irrigation stops, boosting otherwise low fall and winter flows. This unnatural condition has persisted for so long that hydrologists, water managers, and water users consider it to be normal. It is this condition that supports present-day aquatic ecosystems. Improving irrigation efficiency reduces fall and winter flows to a lower, but more natural condition.

[64] Of course, other considerations, such as soil and water quality issues and operational costs for labor and energy, also come into play. Farmers may continue to improve delivery and application efficiency, regardless of the potential (or lack thereof) for saving water. Even in the absence of irrigation efficiency improvements, fall and winter flows decrease when irrigated cropland converts to residential and commercial use, thereby depriving the aquifer of summertime recharge from irrigation return flows. The policy question is whether such a change is desirable, or whether it is better to maintain existing conditions.

[65] Using conjunctive management approaches, systems can be engineered either to maintain or to change existing streamflow regimes. The applications of artificial recharge go beyond simply mitigating stream depletion from pumping wells, as we demonstrated in our example, to basin-scale water management. To maintain streamflow during the entire year, recharge facilities could be cited at some distance from the stream, enabling groundwater to discharge more or less constantly from the system to an associated stream throughout the year. Conversely, to supplement streamflow in the short term, recharge facilities could be cited near the stream, where the delay between groundwater recharge and discharge to the stream would be small.

[66] We do not imply that all irrigation efficiency improvements affect downstream users adversely. In some cases, minimizing diversions truly does save water. These are the cases in which excess water, which crops do not consume, leaves the hydrologic system or is not used beneficially. For example, if excess irrigation water discharges into a contaminated aquifer or into the ocean, or if it is consumed by nonbeneficial vegetation such as noxious weeds, then that water is worth conserving. *Molden and Sakthivadivel* [1999] modified the traditional water balance approach by classifying outflows from a hydrologic system according to availability or potential availability for additional use. Their "water-accounting" approach distinguishes excess irrigation water that returns to the system for further diversion from excess irrigation water that effectively leaves the system, either as unallocated outflow or as nonbeneficial consumption. *Peranginangin et al.* [2004] adapted their approach to groundwater management. Applying this concept to basin-scale water management, *Molden et al.* [2001] divide basins into hydronomic (hydro, water + nomus, management) zones, defined primarily according to the destination of the drainage outflow from water uses. Their classification distinguishes zones where water can be reused from those where it cannot, due to location and quality. Those are the zones to target for irrigation efficiency improvements.

[67] Water managers face complex challenges of supplying changing water demands while also restoring and maintaining aquatic ecosystems. A flexible water rights system that allows conjunctive management of groundwater and surface water provides the institutional framework for tackling these challenges. Hydrologists, armed with a clear understanding of the impacts of seasonal groundwater stresses on streamflow, can assist managers in either maintaining current streamflow conditions or, conversely, shifting the streamflow toward more natural conditions.

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Tony,

As you requested, attached please find the journal article by John Bredehoeft and myself, hot off the press.

Best regards,
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