# Return Flow and Well Depletion: Protecting Streams from Groundwater Impact

**Samuel Collin Robinson, P.E., M.ASCE**[1]

[1]Professsional Engineer, Guide Water, Post Office Box 4033, Grand Junction, Colorado 81502, United States; e-mail: collin.robinson@guidewater.life

## ABSTRACT

Freshwater supply development can cause relative scarcity of a resource vital to environmental function, public health, and stable economic activity, plus innovation – elements essential to flourishing civilization. Effective conjunctive allocation of heavily draughted stream-aquifer system resources must account for groundwater return flow and stream depletion from well pumping, including attenuation and delay of these dynamic processes. Engineering analysis of delayed impact is based on treatment of the groundwater flow equation. Available methods of impact schedule calculation include: direct simplified solutions, developed by Glover, Hunt and others; software, developed by the United States Geological Survey; and the Delayed Impact Calculator, an Excel spreadsheet, programmed for the purpose. In Colorado, calculated impact schedules give basis to usage and replacement approaches that protect streamflow. Protective strategies are the principal terms of statutorily-defined Substitute Water Supply Plans and Augmentation Plans. Example schedule calculations for a return flow situation and a well depletion scenario are described.

## INTRODUCTION

Withdrawal of freshwater resources by diversion of surface water or extraction of groundwater to supply crops, municipalities, and industry reduces the availability of water for sustaining ecological function and serving future uses. In some arid and semi-arid regions, existing use has reached or exceeded full employment of renewable resources. As use progresses toward induction of relative scarcity, efficient allocation becomes essential (Jones and Cech 2009).

Often, surface water and groundwater are connected, as where creeks and rivers are hydraulically coupled to adjacent permeable geologic deposits saturated with water, forming stream-aquifer systems (Barlow and Leake 2012). For such systems, addition or withdrawal of water to or from the aquifer is an impulse that causes a response in the form of increased or reduced flow to or from the surface water network. Except where special conditions are met, this is a transient, unsteady, or dynamic process. As hydraulic stress propagates from the impulse, water is transmitted through the porous medium of the aquifer, which dampens and lags manifestation as streamflow. Attenuation and delay are determined by physical characteristics (Barlow and Leake 2012). Recognition of the delayed linkage between surface water and groundwater resources allows efficient conjunctive use whereby integration of their allocation and administration enables maximization of overall benefit from finite supplies (Colorado General Assembly 1969). In Colorado, the connection has been accepted since at least the 1960s. It is a topic of ongoing progress in various places where increasing need is met by limited water resources (Alley and Alley 2017, Corum 2018).

As an example of integration of groundwater and surface water administration, a fraction of the water applied during irrigation seeps below the root zone and enters the aquifer, inducing increased streamflow. Where the irrigation supply originated at another place or time, such as outside the basin or during a prior period of surplus, the subsequent flow increase can be appropriated without further impact to natural flow (Oad and DiSpigno 1997). This is accomplished by diversion from the stream that collects the groundwater return. Integrated administration protects natural flow required for preexisting uses by limiting the amount taken to a schedule that matches return.

As another example of integration, an acceptable rate of streamflow can be maintained during dry periods, despite depletion from well pumping, by foregoing surface diversion of water that would have been diverted to a pre-existing use. Planning such an operation requires that the schedule of well depletion be calculated, since, depletion does not necessarily match pumping, yet must be kept within the amount schedule of the former diversion. Diminution of flow can continue even after pumping has been halted (C.R.S. 37-92-305(8)(c)).

In Colorado, administration of highly utilized stream-aquifer systems must account for groundwater return flow and also for well depletion, including quantification of their attenuation and delay dynamics (C.R.S. 37-92-305(4)(C)(III) and (8)(C)). Formal purview of administration of water resources is given to the State Engineer (C.R.S. 37-92-301).

## GROUNDWATER FLOW TOOLS

Groundwater return flow and well-induced stream depletion are not apt for direct measurement. Aquifer test results, such as from well pumping tests, give information that can be used to estimate these impacts. Engineering analysis to quantify delayed impact is based on treatment of the groundwater flow equation. Derivation of the full generalized transient three-dimensional nonlinear differential equation has been presented before. Harbaugh cites a published derivation, and gives the equation outright, expressed in the dimension of $\text{Time}^{-1}$ (Harbaugh 2005). To date, exact solution of the full equation has not been published, to this author's knowledge, if ever achieved. The void is partly filled by several available solutions of alterations of the equation.

**Analytical Solutions**. Analytical and semi-analytical approaches have been established by several contributors, including Theis, Glover and Balmer, Glover, Hantush, and Hunt. Description of several of these, with reference citations, was given by a previous publication (Hunt 2014). They are direct solutions, made possible by idealizing assumptions. Hence, applicability is limited to scenarios that substantially conform to simplification. For example, linearization of the differential equation is achieved at expense of approximation by neglecting or holding constant certain terms assumed to undergo only trivial change (Glover 1974).

The solutions generally derive from very basic stream-aquifer system configurations. Some have incorporated more involved features, such as restrictive streambed and partial penetration; however, those configurations are otherwise simple. The utility of the solutions can be extended by use of negative withdrawal rates, the principal of superposition, image theory, calibrated parameterization. For example, image theory can be employed to adapt a semi-infinite aquifer solution for use in a narrow valley with an impermeable boundary parallel to the stream (Schroeder 1987). Still, relatively few configurations are available.

For an example of this class of groundwater flow treatment, as of writing, a tool offering several of these solutions for well depletion is available from the environment body of the regional council of Canterbury, New Zealand, as a Microsoft Excel workbook named "Streamdepletionv3.xls" that can be acquired online without charge.

https://www.ecan.govt.nz/your-region/your-environment/water/tools-and-resources/

**Geological Survey Software**. Where interbedded aquitards, vertical flow, heterogeneity, anisotropy, irregular impermeable boundary, deviated stream location, or other complications make significant contributions to behavior of stream-aquifer systems, approximation by the idealizations necessary to the analytical solutions can introduce substantial error. Provided input data of sufficient detail and density can be obtained, analysis of systems marked by such complexity can instead be accomplished with special software. The accepted standard is MODFLOW, originally developed as the United States Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (Harbaugh 2005).

The finite-difference approach consists of discretizing space and time into set increments. This allows approximation of the full groundwater flow equation with detailed representation of complexity. Often, field acquisition of input data adequate to highly detailed modeling is prohibited by cost. MODFLOW can be used with scant input data by making more assumptions and representing fewer specifics. This leaves advantages of the model unrealized.

Over decades of development, revision, and extension, MODFLOW has incorporated comprehensive functionality. A robust body of literature describes the program. As an example, for the release of a new version, a principal developer completed a lengthy report on the groundwater flow process (Harbaugh 2005). In addition to the program and supporting documentation, various graphical user interfaces have been created, and MODFLOW has been incorporated with integrated water management computation tools (Gassman *et al.* 2007). Commercial software offering enhanced data management and visualization can be purchased.

The Geological Survey offers a program called ModelMuse that provides an example of interface software capable of accommodating a great range of physical complexity, given a proficient user. As of writing, ModelMuse, including installation files, MODFLOW, interface documentation, and tutorials by Richard Winston, can be secured online *gratis*.

https://water.usgs.gov/nrp/gwsoftware/ModelMuse/ModelMuse.html

**Impact Calculator**. An impact delay calculator was developed by the author as an alternative to the other tools. The calculator is a Microsoft Excel 2010 workbook programmed to estimate accretion and depletion schedules using finite-difference strategies applied inside a modest scope of complexity by acceptance of a subset of the basic conditions that allow analytical solution. The spreadsheet was inspired by a prior effort (Bittinger 1967). Although its minimum input requirements are unimposing, the calculator still allows irregular dimensions, freedom to specify barrier and stream alignments, and heterogeneity.

Accepted simplifications are that: stream and aquifer share a clear hydraulic connection; flow transmission occurs by differential piezometric head pushing water horizontally through a single principal layer; hydraulic conductivity is isotropic, meaning independent of direction; and the aquifer is bounded on the sides and bottom by impermeable material. While honoring limitation to these conditions, the calculator can handle a breadth of system configurations determined by site, scenario, and available input data. The only software requirements are access to and basic familiarity with Excel.

The Delayed Impact Calculator and its instruction manual can be obtained online for free.

https://www.guidewater.life/delay

## FINITE-DIFFERENCE FORMULATIONS

The Delayed Impact Calculator offers two solution methods, described in brief here, beginning with the equation and discretization from which both arise. Given the accepted conditions, application of Darcy's law and conservation of volume yields a modified version of the groundwater flow equation, still in a nonlinear differential form, as given by Morton Bittinger in his dissertation, *Simulation and Analysis of Stream-aquifer Systems,* (1967).

$$\frac{\partial}{\partial X}\left(kh\frac{\partial H}{\partial X}\right)+\frac{\partial}{\partial Y}\left(kh\frac{\partial H}{\partial Y}\right)=S\frac{\partial H}{\partial t}+\frac{Q}{(\partial X)(\partial Y)} \qquad (1)$$

Finite-difference forms of Eq. (1) allow numerical treatment by representing the continuous function with discrete values corresponding to specific locations and times. Aquifer dimensions are divided into increments in the *X* and *Y* directions. The volume encompassed by a set of increments and their corresponding thickness constitutes a cell, having a representative point, or node, on the head datum plane in the horizontal center. For unconfined aquifers, transmitting thickness is thickness plus head. Figure 1 illustrates the nomenclature.

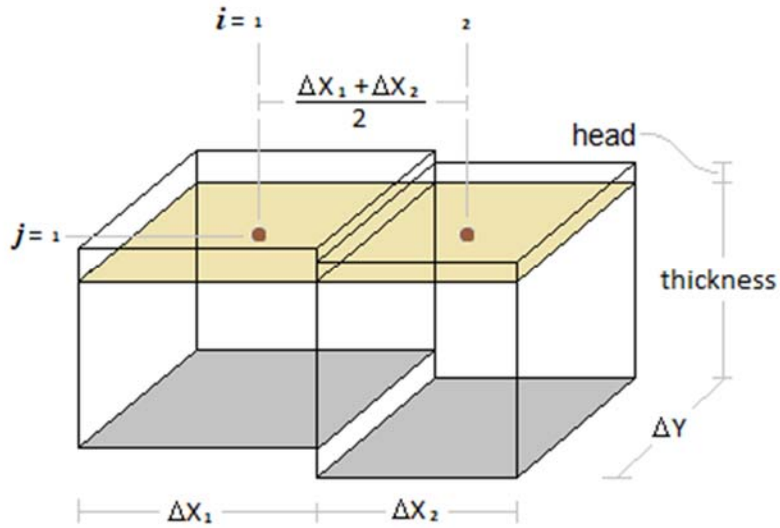


**Figure 1. Finite-Difference Distance Increments**

The distance between nodes in adjacent cells of the resulting grid is the average of their increments along the axis of interest. As currently programmed, the increment along the other axis is the same for each cell in the row, although it can vary by row. Lower case *i* and *j* are the node indices along the axes, *X* and *Y*, in that order. Time is divided into periods and then subdivided into steps. As example, a period specified as 10 days can be subdivided unto 5 steps for a calculation time step or time increment of 2 days. Lower case n is the time step index.

**Explicit Representation**. The forward-difference approach approximates flow during a time step based on differential head at the start of the time step, allowing explicit solution, meaning that the resulting equation can be solved directly for the future value of a single unknown. The explicit formulation is not mathematically stable, because extrapolation errors accumulate.

Therefore, time increments must be kept small, in order to avoid calculation failure. This is accomplished with a large number of steps per period. Computation time is relatively brief.

The forward-difference form of Eq. (1) presented by Bittinger is adequate for uniform spatial increments. In order to handle variation of increment lengths, the equation is reconfigured. Distances between nodes are substituted for single increment values and distance-weighted averages of $k\ h$ products are applied between cells in place of simple product averages. Also, both sides are multiplied by $\Delta Y\ \Delta X$, and terms are factored and cancelled. The result is Eq. (2), arranged for expression as head. Unspecified indices are understood to be *i, j,* and *n*. Eq. (2) is used to project heads for a group of contiguous locations one step into the future from a time at which their values were all known. For determination of depletion or accretion, the equation is manipulated to isolate Q, and applied for each response cell, allowing no response cell storage.

$$H_{n+1} = H + (Q_A + Q_B + Q_C + Q_D - Q)\frac{\Delta t}{(\Delta X)(\Delta Y)S} \tag{2}$$

$$Q_A = \frac{\left((k\,h\,\Delta Y)_{j-1} + (k\,h\,\Delta Y)_j\right)\Delta X\left(H_{j-1} - H_j\right)}{2\left(\frac{\Delta Y_{j-1} + \Delta Y_j}{2}\right)^2}$$

$$Q_B = \frac{\left((k\,h\,\Delta X)_{i-1} + (k\,h\,\Delta X)_i\right)\Delta Y\left(H_{i-1} - H_i\right)}{2\left(\frac{\Delta X_{i-1} + \Delta X_i}{2}\right)^2}$$

$$Q_C = \frac{\left((k\,h\,\Delta Y)_{j+1} + (k\,h\,\Delta Y)_j\right)\Delta X\left(H_{j+1} - H_j\right)}{2\left(\frac{\Delta Y_{j+1} + \Delta Y_j}{2}\right)^2}$$

$$Q_D = \frac{\left((k\,h\,\Delta X)_{i+1} + (k\,h\,\Delta X)_i\right)\Delta Y\left(H_{i+1} - H_i\right)}{2\left(\frac{\Delta X_{i+1} + \Delta X_i}{2}\right)^2}$$

**Implicit Representation**. The backward-difference approach approximates flow during a time step based on differential head at the end of the time step, and is implicit, meaning that it expresses the relationship such that isolation of any particular future unknown gives an expression in terms of other future unknowns. Direct solution is not tenable; however, the equations for adjacent locations go together as a system that can be solved simultaneously. The implicit formulation is mathematically stable, even for relatively large increments of space and time, and can use relatively few steps to avoid long computation time.

As with the other approach, the backward-difference form of Eq. (1) presented by Bittinger is adequate for uniform spatial increments. In order to handle variation of increment lengths, this equation too is reconfigured, substituting distances between nodes for single increment values, and employing the distance-weighted average of $k\ h$ products between locations. Also, both sides are multiplied by $\Delta Y\ \Delta X$. Factoring and cancelling are performed. The result is Eq. (3), expressed in terms of flow. Unspecified indices are again *i, j,* and *n*. For determination of stream depletion or accretion, next-time-step head values must be determined by simultaneous solution; then Eq. (3) is arranged to isolate Q, and applied from the perspective of each response cell, allowing no response cell storage.

$$A\,H_{n+1,j-1} + B\,H_{n+1,i-1} + C\,H_{n+1,j+1} + D\,H_{n+1,i+1} - E\,H_{n+1} = F \tag{3}$$

$$A = \frac{\left((k\,h\,\Delta Y)_{j-1} + (k\,h\,\Delta Y)_j\right)\Delta X}{2\left(\frac{\Delta Y_{j-1}+\Delta Y_j}{2}\right)^2}$$

$$B = \frac{\left((k\,h\,\Delta X)_{i-1} + (k\,h\,\Delta X)_i\right)\Delta Y}{2\left(\frac{\Delta X_{i-1}+\Delta X_i}{2}\right)^2}$$

$$C = \frac{\left((k\,h\,\Delta Y)_{j+1} + (k\,h\,\Delta Y)_j\right)\Delta X}{2\left(\frac{\Delta Y_{j+1}+\Delta Y_j}{2}\right)^2}$$

$$D = \frac{\left((k\,h\,\Delta X)_{i+1} + (k\,h\,\Delta X)_i\right)\Delta Y}{2\left(\frac{\Delta X_{i+1}+\Delta X_i}{2}\right)^2}$$

$$E = A + B + C + D + \frac{(\Delta X)(\Delta Y)\,S}{\Delta t}$$

$$F = Q - \frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t}$$

**Matrix Composition**. Eq. (3) is intentionally set in a form comprised of a series of terms consisting of determinate coefficients, each multiplied by an unknown future head. The equation is written for each location in the finite-difference grid representing the aquifer, with reference to parameter values and present head at that location, as well as parameters and future head at that and each adjacent location. The resulting coefficient values and constant terms are used to populate a matrix consisting of a row for each equation in the system. An example is shown symbolically for a simple 3 by 3 aquifer grid as Table 1.

**Table 1: Augmented Coefficient Matrix from System of Equations**

| $H_{1,1}$ | $H_{1,2}$ | $H_{1,3}$ | $H_{2,1}$ | $H_{2,2}$ | $H_{2,3}$ | $H_{3,1}$ | $H_{3,2}$ | $H_{3,3}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| E | D | - | C | - | - | - | - | - | F | $EQN_{1,1}$ |
| B | E | D | - | C | - | - | - | - | F | $EQN_{1,2}$ |
| - | B | E | - | - | C | - | - | - | F | $EQN_{1,3}$ |
| A | - | - | E | D | - | C | - | - | F | $EQN_{2,1}$ |
| - | A | - | B | E | D | - | C | - | F | $EQN_{2,2}$ |
| - | - | A | - | B | E | - | - | C | F | $EQN_{2,3}$ |
| - | - | - | A | - | - | E | D | - | F | $EQN_{3,1}$ |
| - | - | - | - | A | - | B | E | D | F | $EQN_{3,2}$ |
| - | - | - | - | - | A | - | B | E | F | $EQN_{3,3}$ |

This augmented matrix represents the equations for passage of a single time step. Within the brackets, hyphens replace 0s and subscripts were omitted to aid legibility. The letters represent distinct values in each row, meaning $E$ in the first row is not necessarily the same number as $E$ in the second row, as example. The columns left of the vertical bar each correspond to the next head at a particular grid location.

**Simultaneous Solution**. Together, the equations of the system can be solved. Several techniques exist. Performing Gaussian Elimination and backward substitution on the augmented coefficients matrix is an effective and reasonably efficient method using simple row operations. For the matrix format shown by Table 1, the elimination and substitution steps can be skipped for certain columns in each row, those beyond the reference range of the associated grid location. This streamlining measure reduces computation time. The workbook effects skipping by index limitation in the Visual Basic code that carries out the procedure.

The elimination and substitution procedure, thus modified, is the technique employed by the Delayed Impact Calculator. The procedure was adapted from the basic elimination and substitution algorithms explained in numerical methods texts, such as *Numerical and Statistical Methods with SCILAB for Science and Engineering* by Gilberto Urroz (2001). In referring to that book, please be aware of the typo on page 169, where "(equation1–(4/2)…)" should be "(equation3–(4/2)…)".

**Response Output.** The primary result of either treatment of aquifer impulse is approximate volumetric stream response time series information. An impact schedule table gives the computed volume of stream accretion or depletion incurred each period as result of water introduced into or removed from the aquifer. Both total and zone impact are presented, allowing segregation by stream reach. Secondary output, such as total cumulative impact through each period is also presented. Response output is plotted versus impulse input on a column chart of impact schedule, giving a visual side-by-side presentation for clear relationship depiction, showing attenuation and delay characteristics. An example chart is presented as Figure 2.

The example shows a variable series made up of 4 years of well pumping, with seasonality, and 4 years following cessation of pumping. Depicted stream depletion lags, approaches dynamic equilibrium, and then recedes. Fractions of total depletion incurred on the reach of interest follow similar trends, although exhibiting greater lag and marked suppression of seasonal fluctuation. Pumping exceeds total depletion throughout high-demand seasons, and is exceeded by total depletion throughout low-demand seasons. Post-pumping depletion is significant long after pumping ceased. Calculator results like these match output from analytical solutions and MODFLOW well.

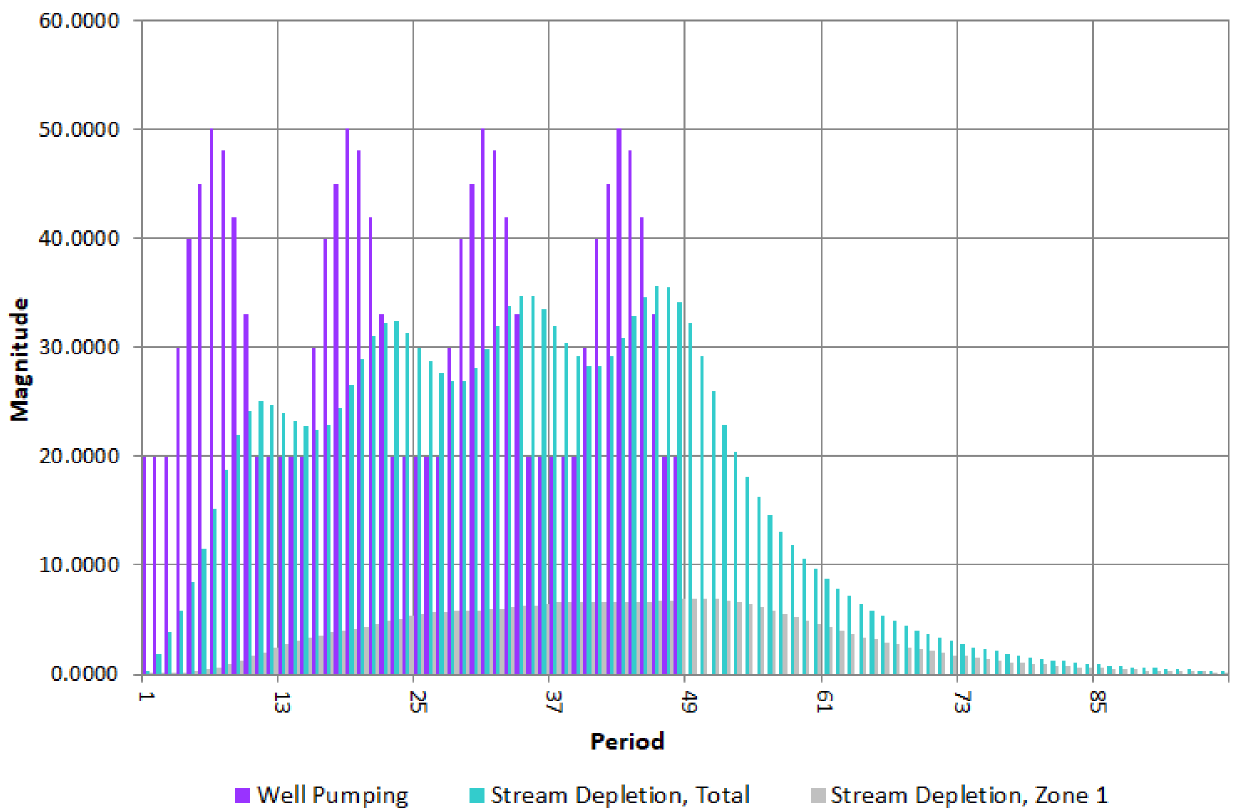


**Figure 2: Impact Schedule Chart**

**STREAM PROTECTION**

Recognition and quantitative characterization of stream-aquifer connection establish sound basis for stream protection. Protective actions can include use restriction and depletion replacement.

**Use Restriction**. Limiting out-of-channel use of water, whether by outright prohibition against taking water, direct reduction of diversion, or a more subtle approach, is a basic method to effect stream protection and adherence to sustainability. Manifold benefits are attributable to this practice, including enhanced reliability of supply for priority uses. A disadvantage is that the practice presents an obstacle to development of water uses conceived as technology, economic context, and demography evolve.

Use restriction can and should be practiced voluntarily, by conscientious water users acting as good neighbors and resource stewards. This approach depends on people exercising self-restraint and kindness, and is a preferred alternative that is often effective. When shortage is not borne equitably or communication breaks down, assistance can be necessary. In Colorado, the State Engineer has authority to curtail or order discontinuation of withdrawal of water from streams and wells, among other activities (C.R.S. 37-92-301, 37-92-502). The engineer can stop water users from taking water when it would reduce streamflow below rates required to serve rights that existed prior to theirs. Ramifications can also limit changes of use of senior rights.

Although adequate in many cases, reactionary use restriction does not provide effective stream protection in every instance. As example, consider a well situated such that 80 percent of the stream depletion caused by pumping during a given month is incurred by the stream in subsequent months. Post-pumping depletion prevents cessation of use from providing prompt protection. To yield timely effect, interruption of pumping would have to occur in advance of the onset of need. Here, practical stream protection requires planning.

**Depletion Replacement**. Another method of stream protection and sustainable utilization involves impact offset. This principle allows continuation of water uses and development of new water uses causing impact to over-appropriated streams. Diminution of flow required for pre-existing beneficial uses is considered injury requiring replacement. Depletion replacement provisions that cancel out net stream impact are useful for cases where groundwater delay prevents use restriction alone from providing practical means of stream protection.

This alternate protection approach is achieved in Colorado with statutorily defined Substitute Water Supply Plans and Augmentation Plans (Alley and Alley 2017). Substitute Water Supply Plans are intended to be provisional, as opposed to permanent (C.R.S. 37-92-308, and subsections). Requests for such plans are reviewed and approved under the supervision of the Office of the State Engineer, who is head of the Division of Water Resources. Augmentation Plans fill the need for lasting arrangements. Applications for augmentation plans go through a court process requiring approval by a judge (C.R.S. 37-92-302, *et seq.*).

The framework given by either type of replacement plan provides that stream depletion caused by new or junior uses be replaced with water that would not otherwise be in the stream there and then. To gain approval, replacement water must satisfy several other requirements: the replacement source must be legally obtained water, it must be of quality adequate to meet the needs of the existing uses, it must be of quantity equivalent to depletion, timing of delivery must match timing of depletion, and location of introduction of the water to the stream must be suitable. Also, control and adequacy of replacement supply must be demonstrated prior to realization of the beneficiary use.

A few examples of replacement supplies include water stored in reservoirs during times of plenty, water imported from other drainage basins, and water acquired by retirement and change of higher priority uses. Change of use is governed by a court process that also imposes no-net-impact conditions, such as replication of historical return flow, when necessary to protect surface streams. The protection and flexibility facilitated by depletion replacement plans are beneficial. Prevention of allocation becoming stagnant is a substantial advantage. Economic pressure to change historical uses, in order to provide replacement supplies for new uses, can be a disadvantage when the older uses contribute to sustainable land management practices, food and fiber production capability, and ecosystem services.

## EXAMPLE CALCULATIONS

Examples illustrate impact schedule calculations and zero-net-injury strategies applied to groundwater return flow from irrigation and to well depletion of a particular reach.

**Return Flow**. As mentioned by the introduction, under certain circumstances, groundwater return flow from irrigation can be used later without reducing natural stream discharge. Consider a hypothetical crop, watered by a junior priority direct-flow irrigation right that is prohibited from diverting during the important crop growth stage month of August. A reservoir is constructed to store water available in abundance during May, so that it can serve crop demand left unmet in August. Soil moisture budget analysis gives an estimate of the amount of August irrigation that will infiltrate beneath the root zone to reach the water table and induce stream accretion. The farmer desires to use the return flow attributable to the reservoir water for supplemental irrigation of a different crop to be planted on a field served by a diversion located several kilometers downstream. Limiting this new use to the schedule of return incurred allows maximum beneficial use overall, by protecting the river from diminution of the quantity of water naturally available to serve preexisting uses.

The Delayed Impact Calculator estimates the amount of water reaching the stream during August, September, and October as a result of deep percolation during August. To prepare for these calculations, the workbook is configured to represent the initial place of use of the reservoir water. Figure 3 presents a simplified site map showing the layout of the irrigated field and surrounding area, including the alignments of the river and a low-permeability shale outcrop.

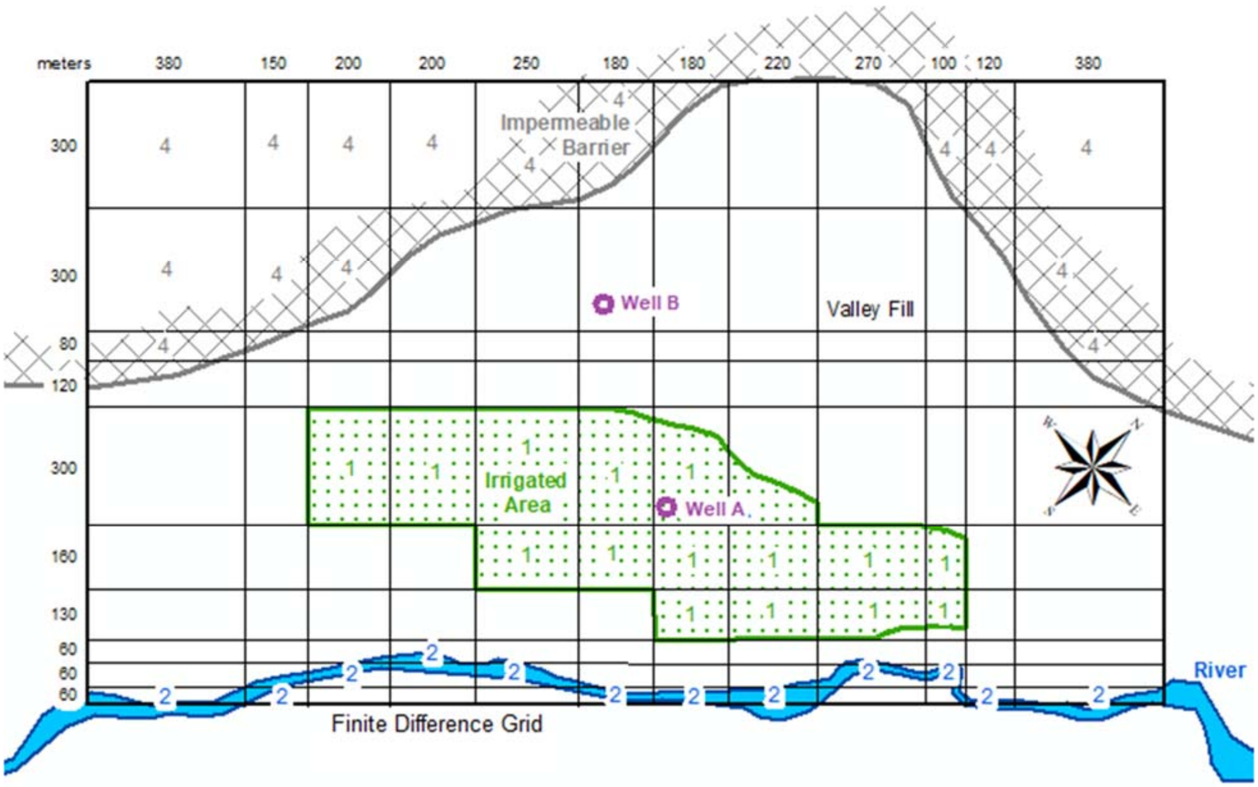


**Figure 3: Return Flow Site Map**

Figure 3 includes locations of nearby wells, because driller's logs and aquifer test records from wells provide vital site-specific information regarding aquifer characteristics. A pump test report and records of monthly water level measurements for Well A were provided by the farmer. No log was found. Analysis of the test data yielded a hydraulic conductivity estimate of 12 meters per day. The level measurement records show a seasonal pattern of a meter or two of increase from April through July, followed by the level remaining about the same for several months, before receding from December through March. For Well B, a pump test analysis, including driller's log, was found in the Division of Water Resources database. The pump test was conducted with the benefit of an unmarked observation well located near the pumped well. The analysis provided estimates of 8 meters/day for saturated horizontal hydraulic conductivity and 0.18 for specific yield. The log of Well B documents that the well was drilled in February, and that the bit passed through 3 meters of soil and cobble, hit sand, continued to 5 meters, encountered water, continued through saturated sand to a depth of 53 meters below ground surface, passed through shale to 55 meters, and stopped. After completion, the static water level was 5 meters below ground.

A simple example of possible finite-difference grid configuration has been defined for the calculations, as shown by Figure 3. A grid of greater width would be preferable for purposes beyond this demonstration. Horizontal increment lengths are given in meters along the northwest and southwest sides of the grid. A cell class code of 1, 2, or 4 is specified for several cells to signify that they represent impulse, response, or impermeable flow barrier locations. Cells without shown code are Class 3, ordinary transmitting aquifer. A simple way of incorporating the limited available hydraulic conductivity information is assignment of 8 m/d to the 4 northwest rows, and 12 m/d to the remaining rows. Upon consideration of the available driller's log and well sounding records, plus the season of analytical focus, the head datum is set at 3 m below ground; therefore, thickness is set to 50 m, and cover is set to 3 m. Initial head is set to 0. The only available, locally-determined specific yield is employed to characterize storage behavior throughout the grid. Spatial distribution of the groundwater impulse is specified as uniform, and a single stream response zone is specified.

The implicit finite-difference formulation is selected, along with weighted average treatment of aquifer characteristics. 12 simulation periods are specified, each 1 month long, and each divided into 15 steps. A single impulse is applied, with even distribution throughout the first month, August. Response ratio secondary output is specified in order to get results in the form of stream accretion for each period divided by the overall impulse total. 29,755 cubic meters of water are given as the deep percolation impulse during the first period, followed by 0 impulses thereafter. The equivalents of the percolation volume, spread over the irrigated area at one time, would be 0.05 m of water or 0.277 m of head, after dividing by the storage coefficient. A click on the command button to Compute Impact Schedule executes the procedure. A period of about 24 seconds elapses, and return flow schedule estimates have been posted.

The response ratios give estimates of the fractions of August deep percolation accrued by the stream system and available to divert: 0.2264 in August itself, 0.2419 in September, 0.1211 in October, and so on. In other words, 22.64 percent or 6,737 $m^3$ of credit attributable to reservoir supply accrues to the river in August after first use. In September, the volume available to the farmer to meet consumptive crop demand is 7,197 $m^3$, neglecting transit loss. During the first 12 months, 91.25 % of August deep percolation is estimated to be received by the river as groundwater return flow.

**Reach Depletion**. The other example from the introduction involves maintenance of the natural rate of streamflow during dry periods, despite depletion due to pumping water from a hypothetical groundwater well. Water that would have been diverted to a pre-existing irrigation use upstream remains in the river to replace the portion of required flow lost to well depletion. A limited schedule of credit attributable to the former use became available when the irrigated fields were lost to a multi-lane highway project. The owner of an industrial project purchased the credit and had a well drilled. The well is proposed to serve a need for supplemental water from June through November, when 5,000 $m^3$ of water is to be pumped per month at a steady rate. Pumping is to be 0 throughout the other months. Wastewater is disposed of off-site. A gaging station monitors discharge, west to east, at the bottom of the critical reach of river. A substantial creek joins the river just downstream of the gage, where it adds flow that mitigates localized relative scarcity. The well is located just east of the gage, and a couple of hundred meters south. An intrusive body of low-permeability granite is located near the well, extending south and west. Flow in the critical reach drops to just the amount required, and sometimes less, during the period from July through September of a typical dry year.

Depletion replacement planning requires estimation of the injurious depletion schedule, accomplished here by the Delayed Impact Calculator. Figure 4 presents a simplified map of the well location, and surrounding area, prepared to facilitate configuration of the workbook. The figure shows river alignment, barrier location, and example finite-difference grid format information for depletion calculations. Cell class codes are shown, as explained for the return flow example, above. The difference here is that some coded cells are shown with a subscript, $2_1$. These are designated as Response Zone 1 to distinguish depletion of the river reach above the gaging station. They are formatted as Class 2, and then their response zone is set to 1 on the separate Response worksheet. All other Class 2 cells are given 2 as their response zone.

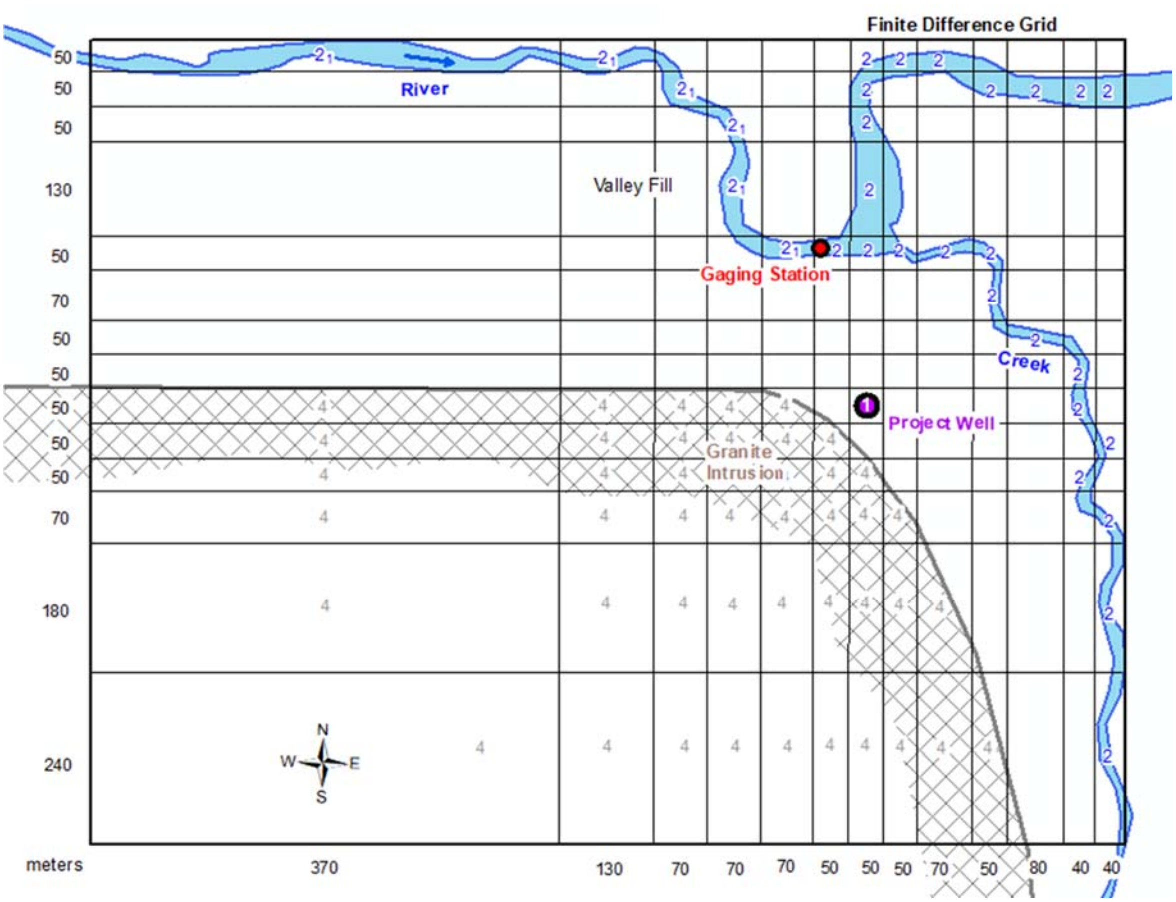


**Figure 4. Well Depletion Site Map**

An aquifer test has been conducted by pumping the project well and monitoring water level in a small diameter observation well nearby. An engineer has analyzed the field data and given 5 meters per day and 0.24 as estimates of hydraulic conductivity and specific yield. The Well Construction Report found as an appendix to the pump test analysis included driller's log information establishing that the principal shallow aquifer in the vicinity is alluvial, with a free water table found 25 m above a basement layer of blue clay when the well was drilled. The static water level was about 10 m below ground. Absent information on aquifer heterogeneity, uniform characteristic values from the report and appendix are specified based on a head datum set 10 m below ground surface. Thickness is set to 25 m, cover is 10 m, and initial head is set to 0. The conductivity and storage estimates from the pump test are employed throughout the grid. Spatial distribution of well pumping is uniform, as only pertinent to a single impulse cell.

The explicit finite-difference formulation is selected, and 48 simulation periods are specified, each 1 month long, and each divided into 30 steps. Daily or weekly calculations could be made instead. Also, were hydraulic conductivity higher, the explicit procedure would fail, without a larger number of steps. Hundreds can be required. Well pumping is characterized as distributed throughout each period, and an annual pattern of pumping is specified, per the seasonal need described above. In this example, the first month is January. A click on the Compute Impact Schedule button starts calculation. Soon the depletion schedule is output.

Inspection of the Impact Schedule Chart indicates that the calculation period was adequate to establishment of a state near dynamic equilibrium. Therefore, by the last year of results, depletion estimates include most residual from prior pumping. This is indicated by how little depletion output increased for each month from the penultimate year to the final year. The portion of induced depletion occurring in Zone 1 from July through September reduces the flow available to meet the requirement in the critical reach above the gage.

Consider the volume required to be scheduled for July of a dry year. July of the last calculation year is period 43. Well pumping is 5,000 $m^3$ for the month; however, stream depletion was just 2,852 $m^3$, due to attenuation and delay. The injurious portion, incurred above the gage, was 456 $m^3$, and is the amount of replacement required. The volume of replacement for August is taken from period 44 as 653 $m^3$. September replacement is 768 $m^3$. October replacement is 0, although Zone 1 depletion is 838 $m^3$, because, by October, flow in the river has historically always been adequate to requirements, plus projected well depletion. Were the river below objective during a winter month, another means of replacement delivery would be required, since depletion continues and the irrigation use retirement credit is out of season. Confronted with just the described critical period, a replacement plan with confirmation that the injurious amount schedule can be offset by use retirement credit, adjusted for transit loss, can protect the river from overdraft, so that it will remain a viable resource for future generations.

As an exercise to prompt further exploration, the response zone for the first cell west of the gage is set to 2. The calculation is repeated. The fresh Zone 1 results exclude depletion incurred on the lowest 70 m of the reach of interest. The portion due farther upstream during July is just 126 $m^3$, or less than a third of the result above the gage before modification. With a less expensive source that could be delivered at least 70 meters above the gage, a significant benefit ratio enhancement could be realized.

## CONCLUSION

Conjunctive allocation of highly utilized stream-aquifer system resources can effect protection of streamflow. No-net-injury strategies that treat groundwater return flow and stream depletion from well pumping are based on quantification of delayed impact schedule. Several types of groundwater flow tools, including useful simplified solutions, are available to perform schedule calculation for stream-aquifer systems. The Delayed Impact Calculator is an Excel spreadsheet, programmed to employ finite-difference solutions that allow analysis of a broad variety of physical configurations, with modest input data and software requirements. Used to efficiently estimate custom impact schedules, the calculator facilitates current effort to protect streams, giving reborn, and significantly extended, utility to prior work by Bittinger. Where need overcomes economic limitation, analysis of aquifers exhibiting significant vertical flow, or defined by several distinct layers, remains a domain for more elaborate tools.

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This paper includes material from the Delayed Impact Calculator Instruction Manual. Both documents were written by this author, and both include source references for citations of fact. Janet Alcon of Mesa County Libraries facilitated access to reference literature. Thank you, Janet!

## NOTATION

This paper presents mathematical equations expressed with these symbols:

$H$ potential energy as piezometric head relative to datum, units of length;
$h$ water-transmitting vertical thickness of the aquifer, a length;
$i$ node index along x axis;
$j$ node index along y axis;
$k$ saturated horizontal hydraulic conductivity, a length/time;
$n$ time step index;
$Q$ rate of net flow out of aquifer, a cubic-length/time;
$S$ Storage Coefficient, dimensionless;
$t$ time;
$X$ a horizontal distance, a length;
$Y$ the horizontal distance normal to $X$, a length; and
$\Delta$ the difference in value between locations one step apart.

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