Instruction Manual

Delayed Impact Calculator

For Well-Induced Stream Depletion and
Groundwater Return Flow from Deep Percolation

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Delayed Impact Calculator

Instruction Manual

for the

Delayed Impact Calculator

by

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Introduction

Creeks and rivers are often connected to adjacent permeable geologic deposits saturated with water. Together, they form stream-aquifer systems. For such systems, addition or withdrawal of water to or from the aquifer is an impulse that induces a response in the form of flow to or from the stream, that is, accretion or depletion. Under most circumstances, this phenomenon defies direct measurement. Transmission of water through the porous medium of the aquifer causes attenuation and delay. Accounting for these transient affects, with physically-based mathematical estimates improves conjunctive use of hydraulically connected groundwater and surface water.

As example, where water availability and use patterns are seasonal, the rate of stream flow can be maintained during critical periods, despite depletion from earlier well pumping, by release of water stored behind an embankment. Scheduling such an operation requires that the amount of stream depletion incurred each release period be estimated, since the amount of depletion generally does not match pumping. As another example, irrigation water that has seeped below the root zone and entered the aquifer can be reused later by diverting it from a connected stream as it exits the aquifer. Limiting such diversion to just the water due requires estimation of the amount of induced stream accretion each period.

The Delayed Impact Calculator is a Microsoft Excel 2010 workbook programmed to calculate accretion and depletion schedules. The Calculator has been subjected to peer-review and professional publication (Robinson 2020). Both the workbook and this manual are under copyright by the author, as of 2018, 2020, and 2025, and are distributed for free.   The workbook is intended to be treated like a desktop calculator, with just a few copies authorized per computer, from which input and output data can be retained by various means, including copy into a blank workbook. The Calculator was designed for intuitive use – without lengthy explanation. This manual provides supporting detail, describes the procedures employed by the workbook, and provides instruction to encourage successful calculation execution. Example scenarios are given in terms of input description and output interpretation.

The manual is intended to be used primarily as an Adobe portable document format (pdf) file with character recognition that is searchable. Therefore, the reader software Find or Search function is suggested as substitute for an index.

Groundwater Flow

Provided input data of sufficient detail and density, analysis of complex stream-aquifer systems including several aquifer layers can be accomplished with full-blown groundwater modeling software. Obtaining adequate data can be cost-prohibitive. As an alternative for less complex cases, where the chief groundwater transmission mechanism is differential piezometric head pushing water horizontally through a single principal aquifer, whether free, capped by an aquitard, or capped by an aquiclude, streamlined analysis can be accomplished right in Excel with the Delayed Impact Calculator.

The Calculator has modest input requirements and handles intermittent pumping schedules without any difficulty. A finite-difference approach is employed to quantify attenuation and delay incurred by specified groundwater impulses to stream-aquifer systems, in order to estimate stream gain or loss and provide response functions that can be superimposed on general aquifer dynamics. Where aquifer behavior varies so greatly that superposition is not appropriate, a regional groundwater model should be employed instead. The Calculator focusses on disturbance of baseline stream-aquifer system conditions, within a local geographic scope, caused by particular activities, such as pumping of specific wells.

The two principal elements of a stream-aquifer system, each contribute to system behavior. Aquifer contribution is analyzed by calculation of groundwater flow. Flow through the principal aquifer is taken by the Calculator to be horizontal and water transmission properties are taken as isotropic, meaning the same in one direction as another. Spatial variation of property values is allowed, and aquifer type can be unconfined, leaky (delayed-yield or aquifer capped by aquitard), or confined. Conditions can vary by cell, such as where a confined aquifer is depressurized, or made unconfined in a cell pumped by a well. The aquifer is represented as being bounded on the sides and bottom by impermeable material. Under

these conditions, application of Darcy's law and conservation of volume over time yield this transient groundwater flow equation (Bittinger 1967).

$$\frac{\partial}{\partial X}\left(Kh\frac{\partial H}{\partial X}\right) + \frac{\partial}{\partial Y}\left(Kh\frac{\partial H}{\partial Y}\right) = S\frac{\partial H}{\partial t} + \frac{Q}{(\partial X)(\partial Y)}$$ *Equation 1*

X	a horizontal distance, units of length
Y	the horizontal distance normal to *X*, length
K	saturated horizontal hydraulic conductivity of aquifer material, length/time
h	water-transmitting vertical thickness of the aquifer, length
H	aquifer potential energy as piezometric head relative to datum, length
S	Storage Coefficient of aquifer material, dimensionless
t	time
Q	rate of flow out of aquifer, cubic-length/time

Flow through the Streambed

Stream contribution to stream-aquifer system behavior is analyzed by calculation of flow through the streambed, whether of permissive or hydraulically restrictive material type, with the two receiving different mathematical treatment. The Delayed Impact Calculator considers every stream to be perennial, meaning that there is always at least some live water in-channel during analysis. The calculator takes stream head, or water level, to be constant through time, with adequate reach inflow to supply any calculated draft by the aquifer and adequate conveyance capacity to dispose of any outflow from the aquifer. For permissive-bed cases, aquifer head in stream or response cells is likewise constant, there being no bed-related head loss. For restrictive-bed cases, head in the aquifer beneath any stream varies with time in response to groundwater impulses. Aquifer head may be greater than or less than stream head in the same cell, as the two are separated by a distinct layer of bed material that causes head loss as flow passes through. The small amount of active elastic storage in the bed material is neglected. Bed material contribution to aquifer cell thickness for horizontal transmission of groundwater is also ignored. Restrictive channel sides, or banks, are characterized as impermeable, unless Complete incision adjustment is specified, as described by Appendix F.

Vertical flow through the streambed from stream to aquifer, or the reverse, is driven by the difference between stream head and aquifer head. This flux is governed by the physical characteristics of the bed, such as spatial dimensions and permeability of the material, according to Darcy's law. Parameters for calculating bed flow are described by Harbaugh (2005), from whom this equation was adapted, with slight nomenclature modification.

$$Q_R = \frac{K'L\,W\,(H - H_R)}{M}$$ *Equation 2*

Q_R rate of flow through riverbed or streambed from aquifer, cubic-length per time

K' saturated vertical hydraulic conductivity of streambed material, length/time

H aquifer potential energy as piezometric head relative to datum, length

H_R free water surface piezometric head in channel of river or stream, length

L bed length, the longer of ΔX and ΔY, length

W bed width, the shorter of ΔX and ΔY, or a smaller, user-specified value, length

M vertical thickness of bed material distinct from aquifer material, length

Should aquifer head beneath a stream fall below the bottom of the distinct layer of restrictive streambed material, the linkage between stream and aquifer could be subjected to unsaturated conditions that limit flow through the bed into the aquifer to a maximum rate based on available head differential across the saturated bed material. Whether this occurs is determined by a threshold at the bottom of the streambed, or some distance below it by user-specification to account for capillary action (matric suction). Beyond the threshold, further drawdown will not increase stream depletion. This does not mean that the system has been disconnected, just that the linkage includes limitation by an unsaturated condition (Fox and Gordji, 2007), so, the term Unsaturated Linkage is here offered as an apt replacement for the misnomer, Disconnection. Determination of the Critical Matric Suction value to be used, if not neglected, is left to be calculated outside the workbook, given such information as aquifer material air entry head, stream depth, etc. Appendix C contains further details.

Flow to or from storage in neighboring cells on all sides also contributes to aquifer head beneath a stream, so it is important that restrictive-bed configurations leave space around

streams to provide separation from domain boundaries, except where aquifer extent is physically limited.

Finite Difference Formulation

Without modification, *Equation 1* defies exact solution; however, accurate approximate solution can be obtained. This is accomplished numerically with Finite Difference formulation, representing the continuous function with discrete values corresponding to specific locations and times.

Horizontal distance is divided into a grid of rows and columns with increments in the X and Y directions. The volume encompassed by a set of spans and their corresponding thickness constitutes a grid cell, having a representative location or node at its horizontal center. The distance between nodes in adjacent cells is the average of the cell increment lengths along the axis of interest. The increment along the other axis is the same for each cell in the row, although it may vary from row to 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, an input and output period specified as 10 days can be subdivided into 5 steps for a calculation time step of 2 days. Lower case n is the time step index.

Figure 1: Finite Difference Distance Increments
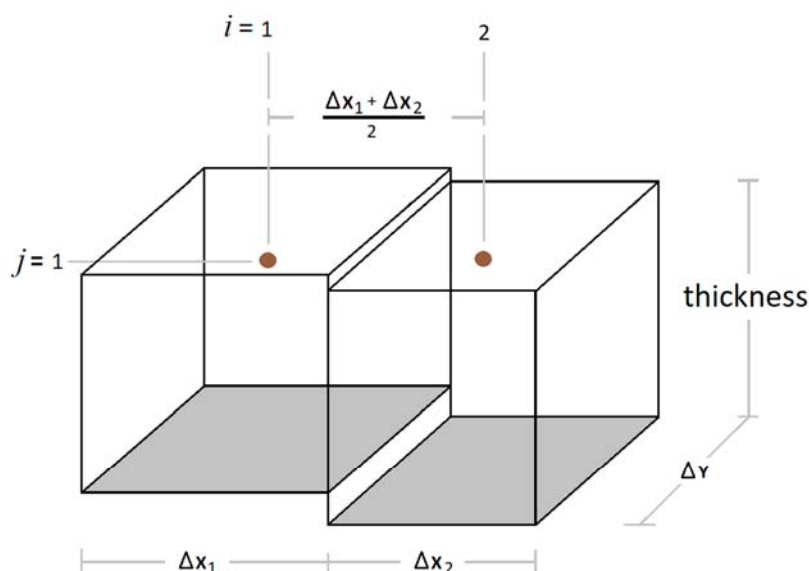
Aquifer thickness and hydraulic conductivity are characteristics that govern flow between cells, as opposed to storage properties, that relate to head within a cell. Therefore, it is appropriate to average thickness and conductivity values, where those differ from cell to cell. The form of averaging may be selected by the user from several options. For example, the distance-weighted arithmetic mean of the products of conductivity and thickness from each of two neighboring cells can be selected to give proportional representation to the span between adjacent cells. The Calculator also offers distance-weighted harmonic mean (Harbaugh 2005) and simple arithmetic mean options. A distance-weighted arithmetic mean formula is given here with nomenclature from above. Similar formulae are used for other spans, with only indices and signs changed.

$$\left(\overline{Kh}\right)_{i+1} = \frac{\left(Kh\frac{\Delta X}{2}\right)_i + \left(Kh\frac{\Delta X}{2}\right)_{i+1}}{\frac{\Delta X_i}{2} + \frac{\Delta X_{i+1}}{2}}$$

Equation 3

Implicit Representation

Discretization enables any of several available finite difference formulations, such as the explicit forward-difference representation of aquifer flow. Each of the various options offers some advantage. The Calculator employs a backward-difference approach that approximates flow during a time step based on differential head at the end of the time step. This formulation was selected for its robust stability, allowing successful computation with modest time step and grid resolution. Backward-difference representation of groundwater flow is implicit, meaning that the resulting equation is composed such that isolation of any future unknown gives a function of other future unknowns. Deterministic solution for a single location within an aquifer is not tenable; however, the relationships for a bounded group of contiguous locations go together as a system of equations that can be solved simultaneously for a given time step.

The backward-difference representation of *Equation 1* presented by Bittinger is adequate for uniform increments and permissive streambeds. In order to handle

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increment variation and restrictive beds, the equation was reconfigured and supplemented. Distances between nodes were substituted for uniform increment values, optional distance-weighted averages of *k h* products were employed, and streambed characteristics were incorporated. The latter provision was accomplished by expanding Q to two terms, Q_I, for impulse to or from groundwater, and Q_R for flow through the streambed, already given as *Equation 2.* Also, both sides were multiplied by *ΔY ΔX*, and factoring and cancelling were performed. The result is *Equation 4*, below, with modified expressions for coefficients and right-side constant.

$$A\,H_{n+1,j-1} + B\,H_{n+1,i-1} + C\,H_{n+1,j+1} + D\,H_{n+1,i+1} - E\,H_{n+1} = F \qquad \text{\textit{Equation 4}}$$

$$A = \frac{(\overline{Kh})_{j-1}\,\Delta X}{\left(\frac{\Delta Y_{j-1} + \Delta Y}{2}\right)}$$

$$B = \frac{(\overline{Kh})_{i-1}\,\Delta Y}{\left(\frac{\Delta X_{i-1} + \Delta X}{2}\right)}$$

$$C = \frac{(\overline{Kh})_{j+1}\,\Delta X}{\left(\frac{\Delta Y_{j+1} + \Delta Y}{2}\right)}$$

$$D = \frac{(\overline{Kh})_{i+1}\,\Delta Y}{\left(\frac{\Delta X_{i+1} + \Delta X}{2}\right)}$$

$$E = A + B + C + D + \frac{(\Delta X)(\Delta Y)\,S}{\Delta t} + \frac{K'\,L\,W}{M}$$

$$F = Q_I - \frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

For impulse cells, that hold wells or deep percolation areas, Q_I is a data input representing the net impulse to or from groundwater. For all other cells, Q_I is zero. For restrictive-bed response cells, representing streams, terms with K' in the numerator are active. For all other cells, those terms are zeros. Next-step aquifer head in permissive-bed cells equals stream head. Impermeable barrier cells are no-flow boundaries. The head values in both of these types of cells are kept constant by setting all coefficient and constant terms, aside from storage terms, equal to zero. Symbolic notation is,

otherwise, the same as for *Equation 1* and Figure 1. Δ is the span between locations or times a step apart in the dimension indicated by the neighboring symbol. Unspecified indices are *i, j, n*.

Future head values are determined by simultaneous solution of a system of equations composed per the form given by *Equation 4*. Then, resulting head values are used to compute response flow for determination of stream depletion or accretion by direct post-solution calculations.

<u>Matrix Composition</u>

Equation 4 is intentionally set in a form comprised of a series of terms consisting of known coefficient values multiplied by unknown future head values. The equation is written for each location in the finite difference grid, representing the aquifer, with reference to present and future head at that location and future head at each neighboring location. A factor of -1 is applied to both sides of each equation. The resulting coefficient values are used to populate a matrix with a row for each location and a column for each location. A single-column vector holds the values of the constant, F, for each cell. Symbolic representation of matrix format for a 3 by 3 aquifer grid, is presented, as Table 1. Each column label, *H*, for head, is here understood to carry an $_{n+1}$ subscript, not shown. Table 2 is a grid location subscript key.

Table 1 represents the system of equations for a single time step. Zeros and coefficient subscripts are omitted to aid legibility. The coefficient symbols represent distinct values in each row, meaning E in the first row does not necessarily stand for the same number as E in the second row. The values for each coefficient in each row correspond to the equation for the grid location represented by that row. The columns each correspond to the future head at a particular grid location.

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	$EQN_{3,3}$

Table 2: Grid Location Subscript Key for Preceding Matrix

	i=1	i=2	i=3
j=1	1,1	1,2	1,3
j=2	2,1	2,2	2,3
j=3	3,1	3,2	3,3

As explanation, the first row of the augmented matrix shown by Table 1 is for the far left location on the grid (as opposed to the near right corner), meaning the row represents the coefficients and constant from *Equation 4* formulated for location 1,1 from Table 2.   E is in the first column because it is the coefficient applicable to the future head at that same location. D is the coefficient applicable to the future head at the adjacent location to the right. C is the coefficient applicable to the future head at the adjacent location on the near side. F is in the constant column and does not apply to any unknown future value. The value of $\left(\overline{Kh}\right)_{j+1}$ used to compute C in this row is the selected average of the hydraulic conductivity of locations 1,1 and 2,1. The second row in the matrix is for the adjacent location to the right. Here, B is applied to the future

head at the adjacent location to the left, the first location described in this example, that is 1,1. A different value for E is calculated and applied to the future head at the second location, itself. D is applied to the right, and so on.

Solution Method

Several methods can solve the system of equations. Modified Incomplete Cholesky-Preconditioned Conjugate Gradient (MICCG) successive approximation is the numerical procedure used by the Calculator, because it gives outstanding computational efficiency (Hill 1990). The Calculator utilizes a head-closure and residual threshold of 1.0 x $10^{-\varepsilon}$, where ε may be selected from the range from 2 through 10. Since the threshold applies to row residual, resulting head estimates are typically several orders of magnitude more precise, and a maximum head estimate change minimum of 1.0 x 10^{-11} may preempt the specified threshold.   Also, at each important time step, a global volume budget is checked against an imbalance tolerance of 0.1% (0.001).

A simple example is given here. The columns of the matrix below are labeled for the corresponding unknown values $\underline{X_1}$ through $\underline{X_3}$ of the associated next-time-step variable array, to which the coefficients, $\underline{A}$, and constants, $\underline{b}$, apply by the equation $\underline{A} \cdot \underline{X} = \underline{b}$. The coefficient and constant values have been selected arbitrarily for clear exposition, as opposed to being representations of a physical system. Also, the method was described for sparse matrices of similar format to Table 1 that meet special criteria. This example does not contemplate all of those conditions; it is just intended to illustrate the steps of the procedure.   Although the method converges to solution for matrices like Table 1, it does not converge for some other types, so caution is advised.

$$
\begin{array}{ccc}
\underline{X_1} & \underline{X_2} & \underline{X_3}
\end{array}
$$

$$
\begin{bmatrix} 9 & 3 & 1 \\ 2 & 12 & -1 \\ 0 & 2 & 15 \end{bmatrix}
\begin{bmatrix} 14 \\ 27 \\ -11 \end{bmatrix}
\begin{array}{l} EQN_1 \\ EQN_2 \\ EQN_3 \end{array}
$$

$$
\underline{A} \qquad \underline{b}
$$

Preconditioning matrices are calculated from entries of the coefficients matrix $\underline{A}$. First, an upper triangular matrix, $\underline{U}$ is prepared. All entries below the diagonal are zero. All entries above the diagonal match $\underline{A}$. The diagonal is calculated as:

$$u_{11} = a_{11}$$

$$u_{22} = a_{22} - \frac{u_{12}^2}{u_{11}} - \frac{u_{12}u_{13}}{u_{11}}$$

$$u_{33} = a_{33} - \frac{u_{23}^2}{u_{22}}$$

$$\begin{bmatrix} 9 & 3 & 1 \\ 0 & 10.67 & -1 \\ 0 & 0 & 14.91 \end{bmatrix}$$

$$\underline{U}$$

Appendix H describes preparation of $\underline{U}$ for coefficient matrices of greater dimensions. Upon obtaining $\underline{U}$, its transpose, $\underline{U}^T$, is prepared. A diagonal matrix, composed of all zeros except the diagonals, which are given by $1/u_{ii}$, is also prepared. The product of the diagonal matrix and the upper triangular matrix is then found, and given the label $\underline{DU}$.

$$\begin{bmatrix} 9 & 0 & 0 \\ 3 & 10.67 & 0 \\ 1 & -1 & 14.91 \end{bmatrix}$$

$$\underline{U}^T$$

$$\begin{bmatrix} 1 & 0.333 & 0.111 \\ 0 & 1 & -0.094 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\underline{DU}$$

Arbitrary starting values are assigned to the entries of the variable vector, $\underline{X}$. The Delayed Impact Calculator employs present head input values as initial approximations of future head. In this example, zeros are assigned, for lack of obvious starting points.

Upon completion of these preparations, the procedure begins by multiplying $\underline{A}$ by the initial values of $\underline{X}$, and subtracting the product from $\underline{b}$ to get a vector of residual, $\underline{r}$. Here, the product is a vector of zeros, so $\underline{r}$ matches $\underline{b}$. Next, the first step to be iterated is performed. A vector, $\underline{v}$, is found by solving $\underline{U}^T \underline{v} = \underline{r}$ by forward substitution. This is a simple algebraic operation. For example, starting with the top row, $v_1 = 14/9 = 1.56$. $v_2 = (27-3(1.56))/10.67 = 2.09$, and so on. Then, a vector, $\underline{s}$, is found by solving $\underline{DU} \underline{s} = \underline{v}$ by backward substitution. For example, starting with the bottom row, $s_3 = -0.70/1 = -0.70$. A vector, $\underline{p}$, is initialized as equal to $\underline{s}$. Results of these steps are shown below.

X	AX	r	v	s	p
0	0	14	1.56	0.96	0.96
0	0	27	2.09	2.03	2.03
0	0	-11	-0.70	-0.70	-0.70

The procedure continues by computing the product $\underline{A} \underline{p}$. After that, the entries of $\underline{s}$ get multiplied by the corresponding entries of $\underline{r}$, and the sum of the products is taken to serve as numerator. The entries of $\underline{p}$ are multiplied by the entries of $\underline{A} \underline{p}$, and the sum of the products is taken to serve as denominator. The resulting ratio is α. Next, new approximations of the entries of $\underline{X}$ are found by adding α times the corresponding entries of $\underline{p}$ to the prior approximations of $\underline{X}$. Estimates of resulting residual, $\underline{r}$, are found by subtracting α times corresponding entries of $\underline{A} \underline{p}$ from the prior entries of $\underline{r}$. The numerator used to compute alpha is taken as denominator and a new numerator is computed with the new values of $\underline{r}$ and corresponding new values of $\underline{s}$, found as before, except using the new $\underline{r}$. The resulting ratio is β. New entries for $\underline{p}$ are computed by adding β times the prior entries of $\underline{p}$ to the new entries of $\underline{s}$. The results of these calculations are as shown next.

A p	α	X	r	v	s	β	p
14.00		1.00	-0.63	-0.07	0.00		0.02
26.95		2.12	-1.17	-0.09	-0.12		-0.08
-6.47		-0.73	-4.24	-0.29	-0.29		-0.30
	1.05					0.02	

The updated p values are then used to compute new $\underline{A}\,\underline{p}$ values, and the cycle repeats. Once calculated entries of $\underline{X}$ draw within the closure threshold of prior entries, and estimates of $\underline{r}$ diminish to less than the threshold, $\underline{X}$ is accepted as a solution. Convergence is achieved by the fifth iteration, shown below. Accurate computation requires greater precision; these round values just illustrate algorithm steps.

	Initial	First	Second	Third	Fourth	Fifth
X_1	0.00	1.00	1.02	1.00	1.00	1.00
X_2	0.00	2.12	2.04	2.00	2.00	2.00
X_3	0.00	-0.73	-1.01	-1.01	-1.00	-1.00

Modifications for Delayed-Yield Aquifer Type

The Calculator has been updated to include functionality for analysis of stream-aquifer systems with delayed-yield characteristics (Robinson 2025a). A separate subroutine is called to treat a grid with two layers: the primary aquifer and an aquitard above. Initial head is the same in both. The resulting system of equations populates a matrix with twice the number of rows that would be required for the other aquifer types, and an additional non-zero element per row, to give vertical flux. Aquitard coefficients are populated first, followed by aquifer coefficients. The horizontal flow coefficients for the aquitard are computed in like manner as those for the aquifer. The vertical flux coefficient, G, corresponds to the head difference between the aquitard and the aquifer at the same horizontal grid location. In the top half of the matrix, G is the rightmost coefficient, and in the bottom half it is the leftmost. G also adds to the diagonal term, E.

To calculate *G*, the interlayer average of the vertical hydraulic conductivity at play is multiplied by corresponding active horizontal cell area and divided by the vertical distance corresponding to the head differential between layers. Summation indicates aggregation of contributions from distinct portions of a cell's horizontal area, each with its own path distance and conductivity average, due to stream incision.

$$G = \sum \frac{(K_v A_h)}{d_v}$$
<div align="right">*Equation 5*</div>

The terms all update with changing head and status transitions, such as depressurization of the aquifer and dewatering of the aquitard. This can result in abrupt change to the value of *G*, leading to solution instability. As example, take a case of well pumping from the aquifer. The initial piezometric level of both aquifer and aquitard is equal to the stream head, several feet above the aquifer top. Uniform aquifer vertical conductivity is specified, as is the option to count Half of the saturated aquitard thickness as dissipating head when the aquifer is pressurized. At first, the distance in the denominator is the vertical distance between the center of the aquifer and the center of aquitard saturation. Once the piezometric head in the aquifer falls below the aquifer top by more than the Critical Matric Suction, if specified, the distance in the denominator becomes just the current saturated thickness of the aquitard, which can be a drastic reduction. In some instances, this causes oscillation from one solution iteration to the next, preventing algorithm convergence. To avoid procedure failure, when this occurs, the Calculator is programmed to modulate the distance to an intermediate value fixed throughout the problematic time step. When the aquitard is dewatered, except for any residual capillary fringe, the Calculator shows an aquitard head value equal to the aquifer top, less aquifer matric suction, and makes the value of *G* zero. When this occurs, the volume drained during the time step is divided by time step length and added to *F* for the cell beneath. Flux from the wet faces of neighboring cells that remain saturated may be passed to the aquifer beneath, as described by Appendix G. Should aquifer head thereafter rise above aquitard head, rewetting would occur and the coefficient *G* would again be computed.

Delayed Impact Calculator

Workbook Preparation and Input

A current version of the Calculator may be found free online in the HydroShare repository <www.hydroshare.org>. A simple search for "Delayed Impact Calculator" from the Discover page of the HydroShare site returns the correct resource. Readers should browse to the most recent version (e.g. Robinson 2025b). In case of unexpected service outage, an alternative server is available <www.guidewater.life/delay>. The Calculator may be copied to a convenient location on the local hard drive. The file is a Microsoft Excel spreadsheet workbook that opens with any recent version of the software. As a Macro-Enabled Workbook the "xl<u>sm</u>" name extension is required for proper function (underline added for emphasis).

Once the file is open, enable macros, as necessary, and, if applicable, unblock the file. In Microsoft Office, macros are procedures defined by Visual Basic for Applications computer code embedded in workbooks and other files. The primary computation procedures used by the workbook to make delayed impact calculations were programmed as macros using if-then statements and do-while type loops to process all of the input data organized by the workbook, implement the groundwater flow solutions described above, and output results. The macros in the workbook do not perform any other tasks, just those associated with stream-aquifer system analysis.

There are several available means of enabling macros. If a Protected View notice appears on opening, enable editing. In the event that a Security Warning message bar regarding macros appears, click to Enable Content. Another method is to start with the File ribbon tab, select Info, then Enable Content. Yet another is to select Macro Security from the Code group of the Developer ribbon tab and choose to enable all macros. To show the Developer tab, if not visible, in Excel 2010 and later, start with the File tab, select Options, Customize Ribbon, Main Tabs menu, and then select the Developer check box. Similar selections accomplish the task with other software versions. As soon as macros have been enabled, save and close the workbook.

Once the Delayed Impact Calculator has been saved after macros have been enabled, it can simply be opened and used over and over again like a calculator, without further file preparation, except for entry of input data. A single copy, or just a few copies, should be kept

in a convenient file directory or directories. Periodic download of a fresh update is recommended, improvement being a perpetual process.

Use of the workbook entails opening it, entering input data on several worksheets, and then executing the solution procedure by clicking a control button. Data of interest can be preserved and passed on by copy and paste of values into a blank workbook to be saved. Descriptions of the worksheets are given by the following sections. In addition to reading these sections of this manual, please read the notes given within the worksheets themselves.

As a general rule, Colored worksheet text, including bold white font over highlights, indicates required input. Most Input text is blue. Black font is indicative that text is not input. Red font warns of problems that can be solved by changing input data. Input proper data for every required field. Please select from available dropdown lists, wherever offered. Make quick preparation for calculation by viewing each of the following sheets, and providing input, where appropriate.

Notice

The workbook opens for the first time on the Notice tab. Here, information is provided to the operator prior to use. It is important to read and understand all notice items, instructions, and notes. This worksheet does not accept input. The operator must input data on the remaining tabs from Format through Time, making entries, where appropriate, on those tabs and on the tabs between, and then execute calculations from the Time tab.

Format

Click on the Format tab at the bottom of the workbook window to view the worksheet of the same name and specify the grid format used to represent the aquifer. There are several parameters to input.

Impulse Type

Select impulse type as Deep *Percolation*, *Well Injection*, or *Well Pumping*. This is helpful for managing plus and minus signs to yield intelligible nomenclature. Input to groundwater by deep percolation or well injection is taken as positive. Resulting stream

accretion is then given as positive. Withdrawal from groundwater by well pumping is also taken as positive, although it lowers piezometric head in the impulse cell or cells. Resulting stream depletion is likewise given a positive sign. Negative depletion is accretion, and negative accretion is depletion. For delayed-yield aquifer type, deep percolation is incident on the aquitard, whereas the other impulse types are incident to the aquifer. For the other aquifer types, all impulses are incident on the aquifer.

Impulse Units

Select either *Consistent* units or *Acre-feet*. With consistent units be sure that all inputs have the same length unit, whatever that is, meters, miles, or otherwise. Volumes are to have units of cubic length. As example, if using meters, input spatial increment lengths in meters, hydraulic conductivity in meters per day, thickness and initial head in meters, and deep percolation or well pumping in cubic meters per period. With acre-feet selected, length units are feet and volumes are acre-feet, consisting of 43,560 cubic feet. When *Consistent* units are selected, large numbers can be needed to express input time series volumes on the Time sheet, as necessary for appropriate head contributions.

Aquifer Type

Select either *Unconfined*, *Delayed-Yield*, or *Confined* aquifer type. Unconfined is the default. For unconfined aquifers, saturated thickness updates for each time step to account for water table change, cell by cell. For confined aquifers, thickness does not change, unless depressurization occurs, meaning that head falls below the top of the aquifer (less critical matric suction, if specified) and local behavior converts to unconfined. Delayed-yield aquifer type treats an aquifer initially confined by an overlying aquitard of some permeability that is, itself, unconfined. In otherwise confined cells, when head falls farther than the critical matric suction below the top of the confining unit, voids are considered to fill with air instead of developing greater negative pressure. Unconfined storage coefficient is Specific Yield, while confined storage coefficient is the product of Specific Storage times thickness. Unconfined

aquifers can be locally confined beneath restrictive stream beds. Confined aquifers can be unconfined where drawdown is substantial. When rising or falling head causes a transition in condition from the initial circumstance, a confinement change note posts on the Time tab to alert the user that part of the aquifer experienced a status transition.

Aquifer Property Mean Type

This is the form of average applied to *K h* products between adjacent cells. Select either *Weighted Arithmetic, Weighted Harmonic, or Simple Arithmetic* mean. The weighted means are preferred, as they allow proportionality where cell dimensions vary. The Weighted Arithmetic form is presented above as *Equation 3*. The Weighted Harmonic form is described by Harbaugh (2005). The Simple Arithmetic form is just one half of the sum of the products from two adjacent cells. *Weighted Harmonic* is default.

Aquifer Property Update Timing

Transient variation of the saturated thickness property of each aquifer cell makes significant contribution to groundwater transmission behavior in unconfined aquifers. For unconfined conditions, a couple of options for update timing are offered. The *Next Step* option uses thickness from the start of the step for calculation during the step, and then uses the resulting head values to calculate fresh saturated thickness values for the next step, as was done by Bittinger (1967). The other option, *Same Step*, starts that way, then repeats the process, using identical input as at first, except for saturated thickness, which is recalculated from the head results. In this way, end-of-step head is included in the coefficients applied during the same step. Recursion is iterated to convergence of the results. This is consistent with the backward-difference technique, as it approximates flow during a time step based on conditions at the end of the step, so *Same Step* is the default option. The procedure used for delayed-yield aquifers requires multiple recursions to treat confinement status transitions, so *Same Step* update timing is forced for that aquifer type.

Spatial Increments

Paper maps or mapping software facilitate domain selection, grid definition, and horizontal increment length specification. Although not necessary, a Geographic Information System, such as ArcGIS is well suited to these tasks. The most basic functions suffice. Once the grid is defined, input the number of spatial increments in the X direction, whether they are of uniform length, and what that length is or what other lengths, ΔX, they have. When called for, discrete X increment lengths are input in row 25 of the worksheet, starting with Column D. Avoid excessive difference in length from one increment to the next. Then, set the parameters for the Y direction. The spreadsheet can handle up to 50 increments in each direction. As specified numbers of increments increase, conditional formatting will cause the text to change color, a reminder that many increments require longer computation.

While bearing computation time in mind, the numbers and sizes of spatial increments should be chosen to give a clean representation of the system, with true effective distances, and should account for features such as narrow streams. For improved accuracy, use finer spatial resolution at and around wells. Allow ample analytical domain area without undue increase in computation time by specifying large increment sizes for cells located away from key features. Align the grid to the site, or to true north; either approach works. The grid extent, or domain, is treated as being a no-flow boundary, as is the bottom of the aquifer, and also any barrier cells. For analyses treating long times, domain boundaries should coincide with physical aquifer extent. Less extensive grids can suffice for shorter intervals.

Cell Classification

A *Cell Class* code must be input for every location in the grid. This can be accomplished in quick manner by manually entering codes into the Aquifer Representation Specification table, beginning with cell D27, and then selecting a cell or cells to duplicate, copying, selecting cells to hold the copied codes, right clicking, and selecting the Values paste option. For impulse and response class cells, the type is determined by the Impulse Type already input. The 4 class codes are given by Table 3.

Table 3: Cell Class Codes

Code	Class	Type	Flow (+)	Description
		Deep Percolation	Into cell from surface	Addition to Groundwater by Infiltration
1	Impulse	**Well Injection**	Into cell through well	Well Addition to Groundwater
		Well Pumping	Out of cell through well	Well Withdrawal from Groundwater
2	Response	**Stream Accretion**	Out of cell through bed	Groundwater Return Flow to Stream
		Stream Depletion	Into cell through bed	Groundwater Depletion of Stream
3	Transmission	**Ordinary Aquifer**	Through cell	Transmitting Aquifer, No Surface Flow
4	Barrier	**Impermeable**	None	Tight Formation Impeding Transmission

Use of these classes allows representation of a multitude of aquifer configurations. Basic requirements are that there be at least one impulse location and at least one response location. The number of locations set to each class is displayed in the Cell Classification Key and Audit Table in cells O7 through O13. A red zero indicates an inadequate number. That can be corrected by inputting the corresponding code for a location in the Aquifer Representation Specification table. Table 4a presents an example aquifer configuration with two different streams, a linear barrier, an adjacent deep percolation area, and one diagonal boundary. The cell colors are determined by conditional formatting formulae that reference Cell Class and Impulse Type. These are intended as a visual aid.

Delayed Impact Calculator

Table 4a: Example Aquifer Configuration

ΔY	j	i	1	2	3	4	5	6	7
1,320	1		3	3	3	3	3	3	3
660	2		3	3	3	3	3	3	3
100	3		2	2	2	2	2	2	2
660	4		3	3	3	3	3	3	3
660	5		3	3	3	3	3	3	3
660	6		3	3	3	3	3	3	3
660	7		4	4	4	4	3	3	3
1,320	8		1	1	1	1	3	3	3
1,320	9		3	3	3	3	3	3	3
1,320	10		3	3	3	3	3	3	3
1,320	11		3	3	3	3	3	3	4
1,320	12		3	3	3	3	3	4	4
100	13		2	2	2	2	4	4	4
660	14		3	3	3	3	4	4	4
1,320	15		3	3	3	4	4	4	4

The table provides a simplified plan view of the configuration. The streams are each 100 feet wide and the linear barrier is 660 feet wide. The deep percolation area is 1,320 feet wide. The *X* increment size is uniform, specified as 1,320 feet. The spatial increment dimensions used for calculation are not shown to scale by the table, or in other words, increment values are not used for spreadsheet cell size display. The same holds for head surface output configuration. Both are, therefore, to be understood as Not To Scale.

Barrier Cell Treatment

Domain boundaries and Class 4 cells, or impermeable barriers, receive special treatment by the solution procedure, as do cells next to them. A no-flow condition is imposed between the barrier and adjacent cells. Hence, heads in the cells next to the barrier cells do not depend on the heads in the barrier cells, so the corresponding coefficient value, A, B, C, or D, is set to zero. Heads in cells adjacent to barrier cells along different faces can be different from each other. Barrier cell head itself is output as it was input, unchanged for any step, to facilitate head surface output presentation. The grid extent or domain is given the same treatment, and acts as a no-flow boundary.

No special input on the Format tab is required for any of this, and the explanation here is just to inform the user of what the macro is doing once the compute button is clicked.

Ground

The Ground tab is for input of ground surface level relative to the datum. Ground data can be assembled from topographic maps. As shown by Figures 2 and 3, below, except where artesian pressure exceeds surface elevation, ground should be above head at each time step in each cell, otherwise an inundation note will post on the Time tab to provide an alert when the scenario is amiss.   Such may indicate that the available material cannot accept all of the water added by an impulse series. If initial head is higher than ground, conditional formatting will set font red, as a reminder. Please note that while the measurements shown by the figures are based on the down-positive convention, a factor of -1 is applied by the solution subroutine, such that higher levels are less negative, and therefore, greater.

Head

The Head tab is for input of initial head in the aquifer relative to the datum plane, as shown by Figures 2, 3a, and 3b, below. This use of the convenient term, "Head", takes distance from datum to piezometric surface as its meaning. Head data can be collected from well soundings and other types of geohydrologic measurements. Although physical circumstances can warrant otherwise in specific cases, for calculation of response functions, an initial condition of a flat, level, horizontal water table or piezometric surface is often appropriate. Therefore, the default specification method is Uniform.

A conditional format displays Discrete specification in orange as a caution. With Discrete specification, head equalization can contribute to response flow. Calculations with unequal head are allowed, as it may be useful to simulate drain-out of a surcharge or recovery from drawdown; however, response ratios and other secondary output are not provided for such cases, because proportionality is lost.

Except for special artesian circumstances, initial head should be specified as, and head should remain, below ground; otherwise, an inundation note will post on the Time tab. This

does not affect the groundwater calculations, it simply provides notice to scrutinize the impulse scenario, including: volumes, increment dimensions, initial heads, and ground specification.

For delayed-yield aquifers, initial aquitard head is assigned the same value as initial aquifer head in each cell. System response is computed starting from a static condition with artesian pressure in the aquifer equal to saturated thickness of the aquitard.

Although initial head is the only input on the tab, some output is also given. A grid of computed aquifer head values from a selected time step can be accessed at cell C77. Table 4b, shows an example of head output corresponding to a grid format similar to, although somewhat different from, that presented by Table 4a. The horizontal spatial dimensions of the table are not to scale. Head output units match initial head specification. For delayed-yield aquifer type, a similar output table is presented from column BD on. Also, a time series of head output can be generated (row 140) by specifying node indices for a specific location (Time tab), a feature that can be useful for calibration to pump test data.

Table 4b: Aquifer Head Output Sample

j \ i	1	2	3	4	5	6	7
1	10.1867	10.1881	10.1888	10.1895	10.1914	10.1931	10.1937
2	10.1863	10.1883	10.1893	10.1903	10.1931	10.1950	10.1954
3	**10.1858**	**10.1883**	**10.1895**	**10.1907**	**10.1940**	**10.1961**	**10.1963**
4	10.1942	10.1971	10.1986	10.2001	10.2041	10.2066	10.2065
5	10.2283	10.2342	10.2374	10.2406	10.2498	10.2536	10.2516
6	10.2399	10.2522	10.2604	10.2694	10.3075	10.3054	10.2933
7					10.3405	10.3251	10.3079
8	10.4301	10.5305	**10.8431**	10.5162	10.3591	10.3338	10.3146
9	10.4262	10.4881	10.5041	10.4751	10.3732	10.3418	10.3210
10	10.3680	10.3828	10.3828	10.3812	10.3615	10.3497	10.3322
11	10.2298	10.2446	10.2539	10.2639	10.3028	10.3387	
12	10.0917	10.1030	10.1158	10.1314	10.2512		
13	**10.0351**	**10.0388**	**10.0428**	**10.0485**			
14	10.0376	10.0399	10.0403				
15	10.0414	10.0420					

Thickness

The next tab is for input of aquifer thickness information that can be assembled from driller's logs, topography, and other data sources. The parameters that govern aquifer thickness, shown by Figures 2, 3a, and 3b, can be specified as a uniform value each or

separately for each parameter at each grid location. Aquifer Type is selected on the Format tab, and determines the thickness parameters for which input is required.

The Minimum Saturated Thickness is a watch threshold. It does not affect calculations. For well pumping scenarios, if the transmitting thickness of the principal permeable aquifer layer falls below the specified percentage of its first value at any location, a calculation note is output on the Time tab to advise of the fact. Specification of the minimum percentage is left to the operator.

Unconfined

For Unconfined aquifers, the total water transmitting saturated thickness used in calculations is determined for each time step as the difference between Head and Aquifer Bottom.

Figure 2: Parameter Definition Illustration, Unconfined Aquifer, Restrictive Streambed

Delayed-Yield

        For delayed-yield aquifers, the water transmitting saturated thickness of the aquitard is determined for each time step as the difference between Head and Aquifer Top. The water-transmitting thickness of the aquifer is just the difference between Aquifer Top and Aquifer Bottom, as shown by Figure 3a, unless depressurization occurs, as indicated by a confinement change note.

Figure 3a: Parameter Definition Illustration, Delayed-Yield Aquifer, Permissive Streambed

Confined

        For Confined Aquifers, the water-transmitting thickness used in calculations is just the difference between Aquifer Top and Aquifer Bottom, as shown by Figure 3b, unless depressurization occurs, as indicated by a confinement change note.

Figure 3b: Parameter Definition Illustration, Confined Aquifer, Permissive Streambed

Capillary Rise

Aquifer Capillary Rise acknowledges that, where unconfined, saturation can extend above the water table, and where confined, desaturation does not occur until depressurization exceeds the specified Critical Matric Suction below the aquifer top. Capillary action is evaluated as a two-regime process, neglecting variable saturation. Resaturation is treated as the reciprocal of desaturation, neglecting hysteresis, which can be important. Aquitard Capillary Rise is the same for a delayed-yield aquitard. Capillary rise is neglected by most delayed impact calculation tools, as effects can be minor. For this approach, specify None, or provide Critical Matric Suction input of zero. Otherwise, Critical Matric Suction for the aquifer material is calculated outside of the workbook and input here. Various publications give differing definitions and methods for estimation of the Critical Matric Suction. In general, the value is a function of air entry head and other factors. While definitions vary, a simple conceptualization is that of an idealized maximum capillary rise. Although this corresponds to a negative pressure, the convention of the workbook gives it a positive sign. The Critical Matric Suction affects status transition thresholds and saturated thickness computations. This factor may be important beneath a restrictive streambed (see page 38).

Conductivity

The Conductivity tab is for input of saturated *hydraulic conductivity*. Horizontal values are taken as isotropic. Vertical values require separate input, when appropriate. Units are length per day. If units are Acre-feet on the Format tab, the length must be feet, as explained by the paragraph on Impulse Units, above. The *Handbook of Hydrology*, edited by David Maidment (1992), presents coarse ranges of hydraulic conductivity for various material types as its Table 6.3.2. *Ground-water Hydraulics* (Lohman, 1972) gives conductivity values for alluvial materials of the Arkansas River Valley in Colorado as its Table 17. Examples from that source are presented here as Table 5.

Table 5: Hydraulic Conductivity Reference Values for Alluvial Material

Material	Hydraulic Conductivity
[ ]	[ft/d]
Gravel, Medium	950
Sand, Coarse	250
Sand, Medium	50
Sand, Fine	15
Clay	1

Whenever possible, parameterization from site-specific physical testing should be chosen over parameterization by selection from reference values or published ranges. Satisfactory determination of conductivity can be achieved by analysis of field data from aquifer tests carried out by well pumping (hence, called pump tests). Accurate characterization of conductivity is necessary to accurate delayed impact analysis.

Storage

The Storage tab is for input of aquifer characteristics used for the Storage Coefficient in the calculations. Whenever possible, parameterization from site-specific physical testing should be chosen over parameterization by selection from reference values or published ranges. Satisfactory determination of storage characteristics can be achieved by analysis of field data from aquifer tests performed by well pumping and carried out with the benefit of observation wells with appropriate locations relative to the pumping wells. Information of this type is essential to accurate delayed impact analysis.

Specific Yield

For unconfined conditions the Storage Coefficient is just the *Specific Yield*, a single, dimensionless parameter primarily dependent on effective porosity and also taken to include any minor elastic component. The *Handbook of Hydrology* (Maidment, 1992) presents coarse ranges of Specific Yield for various material types as its Table 6.3.4. *Specific yield – compilation of specific yields for various materials* (Johnson, 1967)

gives average values for unconsolidated water-table aquifer materials. Examples from that source are presented here as Table 6. Seek other sources for values from consolidated materials such as sandstones.

Table 6: Specific Yield Reference Values for Unconsolidated Material

Material [ ]	Specific Yield [ ]
Gravel, Medium	0.23
Sand, Coarse	0.27
Sand, Medium	0.26
Sand, Fine	0.21
Silt	0.08
Clay	0.02

Specific Storage

For confined conditions, the Storage Coefficient is the product of Specific Storage and layer thickness. Specific Storage is dependent on material elasticity. The *Handbook of Hydrology* (Maidment 1992) presents coarse ranges of Specific Storage for various material types in its Table 6.3.3. Specific Storage is typically orders of magnitude smaller than Specific Yield. Where confinement is manifest, delayed impact analysis is highly sensitive to variation of Specific Storage. Use of reference values is not appropriate in most instances. Therefore, example values are not presented here. Pump test results are required.

Should depressurization occur in any confined cell, and the critical matric suction be exceeded, the Storage Coefficient reverts to Specific Yield to account for the effect of active pore space storage as air occupies voids. Therefore, a Specific Yield input is on the tab, even when aquifer type is set as Confined. Confinement can also occur beneath incised streambeds in "unconfined" aquifers, so Specific Storage input is required for unconfined aquifer type as well. For time steps with pressurization or depressurization, E and F are customized.

Impulse

The Impulse tab is for input of information regarding the *spatial distribution of impulse* flow. Select either Uniform or Discrete specification, either by head equivalent or direct volume. Head equivalence accounts for cell properties, volumetric distribution does not. For delayed-yield aquifers, deep percolation is incident on the aquitard. Otherwise, impulses are all incident on the aquifer.

Uniform specification does not require further input. Each impulse cell will be allocated like share of each total influx or withdrawal of water, on the basis chosen. Discrete distribution is accomplished by entering numbers representing the relative magnitudes for each impulse cell. For 4 impulse cells, enter 1 for each of those cells, or 17 for each of those cells, and in either case, each cell will get 25 percent (1/4 or 17/68) of the total impulse during each period, if by volume. Should a particular cell get twice the impulse as the other 3, it would be represented by a 2 to their 1s, or a 40 to their 20s, or any other doubling. Then, that cell would get 40 percent (2/5) of each impulse while each of the other 3 impulse cells get 20 percent (1/5), instead of 25 percent. If negative magnitudes are specified, a cautionary conditional format will activate, as opposite signs may cause cancelling, so interpret with care.

Distribution by head accounts for cell size and storage coefficient. By Uniform distribution, a percolation cell having twice the storage coefficient, based on head at period beginning, as its otherwise identical neighbor would be allocated twice the volume, such that the resulting head impulse would be uniform. A percolation cell having the same storage coefficient, twice the area, and given twice the impulse of its neighbor by Discrete specification as head, would be given 4 times as much water.

Spatial proportionality on the chosen basis is maintained as specified throughout each period with a nonzero impulse value. Confinement transitions impact distribution during the first step of the next period. Time series impulse information is input on the Time tab.

Response

The next tab is for specification of *stream response zones* used to distinguish accretion or depletion spatially. As example, consider stream depletion incurred by a river and two creeks tributary to the river. An important water supply is served by a surface diversion

structure located on one of the creeks. The portion of the total depletion that is incurred above the structure is, therefore, of special interest. To parse out just the depletion above the diversion, select 2 response zones, start all response cells as zone 2 using the Reset command button in cell B13 to overwrite the existing Discrete Response Zone Specification table values, whatever they were, and then enter 1s for all response cells located above the structure location. One example of what that could look like is presented as Table 7.

Table 7: Response Zone Specification Example

j	i	1	2	3	4	5	6	7	8
1		2							
2		2							
3		2							
4		2							
5		2	2	2	2				
6		2			2	2	2		
7		2					2		
8		2					2		
9		2					2	2	2
10		2							
11		2							
12		2		1					
13		2	2		1				
14		2				1			
15		2					1		
16		2						1	
17		2							1
18		2							
19		2							
20		2							

Once the calculation is completed on the Time tab, the Stream Depletion, Zone 1 column will present amounts incurred on the reach of interest. The Stream Depletion, Total column will remain unaffected by zone specification.

When a single response cell has been designated and 2 zones are specified, the 2 will turn red as a reminder that it should be 1, since specification requires 2 or more response cells, and otherwise there can be only 1 zone. When 2 zones are specified, be certain that at least

one highlighted cell holds a 1 and at least one highlighted cell holds a 2. Regardless, output in the Total column remains true.

Streambed

The Streambed tab accepts input of information on properties governing flow of water into or out of the stream from or to the aquifer through the channel bed. ***Streambed Type*** can be Permissive (Fox, Heeren, and Kizer, 2010), meaning the bed material does not present additional hydraulic resistance to passage of water between stream and aquifer, or it can be Restrictive (Hantush, 1965), meaning the bed material is of relatively low hydraulic conductivity that contributes extra head loss, segregating stream head from cell head. For Restrictive bed type, ***vertical hydraulic conductivity*** of the bed must be input as a necessary characteristic of the distinct layer of bed material, per adaptation from *Equation 2* (Harbaugh 2005). ***Thickness of the bed material*** is another required parameter for restrictive beds.

Stream head is always at least as high as ***bed elevation***, given the perennial stream condition treated by the Calculator. Both are shown by Figure 2, above. Equivalent stream head matches initial aquifer head. Equivalent bed level matches stream head.

Uniform specification method applies a single value for each parameter to all stream cells, also called response cells, and is a quick and convenient method to enter characteristic values for simple scenarios. Alternatively, with Discrete specification selected, the user is to enter values for each parameter in each cell that is not grey in each of the tables provided, starting in rows 28, 88, 148, 208, 268, etc. as necessary, depending on specification option selections. This allows different bed characteristics on different stream reaches, and can be important to insightful impact analysis.

Equivalent ***bed width*** class sets the streambed as wide as the cell in which the stream segment is located. Specified width type takes user-input width data, allowing users freedom to specify stream widths that are narrower than the grid cells in which they are located. Values used for calculation are limited by the code to no more than cell width.

Bed length is taken as the cell dimension. For meandering streams or cells with type 2 neighbors at diagonals, such that stream length exceeds cell length, the ratio can simply be

applied to the width. For example, with "Simple" Incision Adjustment, a stream 10 meters wide that meanders a 120 m course through a cell 20 m wide by 100 m long, can be represented by a virtual width of 12 m to accompany the virtual length of 100 m, as this will give the same bed area as 10 m of width and 120 m of length. Shorter lengths can be treated in like fashion.

Incision Adjustment prompts the Calculator to account for different saturated thickness, storage behavior, and hydraulic connection adjacent to a streambed cut down into an aquifer system. For example, where a stream spanning ¼ of an unconfined cell is also cut ¼ of the way down into its saturated thickness, and head remains above the bed, the storage term for the cell is made just over ¾ of what it would otherwise be, since void space is not drained or filled under the bed and specific storage times the thickness beneath the bed is much less than specific yield. Also, the saturated thickness is adjusted to $^{15}/_{16}$ of what it would be, since ¾ of the width has full thickness and ¼ has ¾ thickness. These corrections represent bed confinement of the portion of the aquifer cell beneath. Incision Adjustment can be important for delayed-yield systems, as bed depth determines the layer or layers with which the stream has direct communication. Where an incised stream channel divides the full thickness of an aquitard cell, head calculation does not separate, so the grid should be reconfigured with bed width equal to cell width and correct response cell dimensions. When "None" is specified for Incision Adjustment, bed elevation and stream head are set to initial aquifer head, and no thickness or storage adjustments are made. When "Simple" is selected, thickness, storage, and communication adjustments are made, but streambanks are assumed to take up no space and be impermeable. For restrictive beds with "Complete" adjustment, cell properties are corrected to account for 3-dimensional space taken up by the stream channel, bed, and banks; plus, lateral flux is communicated through semipermeable banks to the aquifer and or aquitard, similar to the bank seepage mentioned by Rovey (1975). For permissive beds with "Complete" adjustment and channel cross-sections of substantial size relative to cell size, unimpeded lateral flux communication through channel sides keeps head in contacted cells equal to stream head.

Capillary Rise Below Bed is analogous to the issue described under the Thickness tab heading, except here the critical suction value applies beneath the streambed. This independent input allows for larger values under the bed, where stream head and other factors

may have influence, depending on the estimation approach used outside of the workbook. If suction is specified on the Thickness tab, whichever value is larger will govern below the bed, even if None is specified here. While effects of capillary action can be negligible, several publications (e.g. Fox and Gordji 2007) emphasize that, beneath a restrictive streambed, accounting for capillarity may be essential to accurate quantification of stream depletion.

Time

After the preceding steps have been taken to define the spatial grid and populate its characteristics to represent the physical stream-aquifer system and the conditions of interest, the Time tab serves as the final interface used to define the temporal schedule and calculate dynamic response behavior for specified impulses. There are several input parameters.

Basic Information

Input *site name* and *scenario designation* to provide unique identification for clear reference. Then specify the *solution threshold order*, a convergence threshold exponent magnitude for numerical solution, from the range between 2 and 10, inclusive. For Example, 6 gives a threshold of 1.0×10^{-6} or 0.000001 to call closure of successive estimates of head and of residual. Large exponent magnitude gives results of greater, often unnecessary, precision at cost of longer computation time.

Schedule Parameters

The next selection is *schedule type*. A *single impulse* schedule requires just one time series input, in cell D39. The rest of the input series is assigned zeros by the calculation procedure. Selection of this option allows development of an impulse-response function table for the stream-aquifer system. An *annual pattern* requires 12 or 365 time series inputs, depending on period units. The procedure cycles those values through the remainder of the series. Enough periods for 3 years or more are required for this option. The *uniform series* option requires a single time series input, which is then replicated for every period in the series by the calculation procedure. The *variable*

series option provides no automated input handling and instead requires operator attention to every period in the series.

The ***analysis periods*** input sets the length of the calculation time series and can be anything between 1 and 2,400. The value will turn red as a reminder to increase periods if less than 3 years of periods are set with the *annual pattern* schedule type. For more than 1,200 periods, the value will turn orange as a computation time caution.

Period units can be selected as *Days* or *Months*. Days are just that. Months are 365.25/12, or 30.4375 days, each. *Hours* is also an option for most schedule types, though typically just useful for calibration to pump test data; each hour is 1/24 day.

Units per period can be set to a whole number from 1 through 366. As example, for periods of 10 days each, with Days selected, enter that value. For periods of 3 months each, with Months selected, enter that value. This input is reflected by the End Time column of the impact schedule table below, the values of which should all be multiples of the units per period. A conditional format to red will be triggered for annual pattern schedules with more than 1 unit per period, since the programmed cycle for each year is based on single-unit periods.

Steps per period can be set to a whole number from 1 through 100. Steps divide each period to allow calculations with smaller increments of time. Early results can be sensitive to time step at some scales. Input 1 for a calculation time step equal to the period duration. Enter 2 for time steps equal to half the period. Time required for computations is a function of total number of steps, or steps times periods, so specify modest numbers of each to start, and then work up, as appropriate. Conditional format text colors give caution.

Impulse Arrival can be set to either Instantaneous or Steady. Instantaneous arrival applies all of the impulse each period at the very start of the first step for the period. Under unconfined conditions, the impulse contributes to the total transmitting thickness right from the start. Steady arrival divides the impulse for each period by the number of steps per period and then applies the result throughout each step, yielding a steady impulse throughout each period, although the impulse may be different from

period to period. As example, with period units as Days, units per period at 30, steps per period at 30, and an impulse of 90 acre-feet for a particular period, Instantaneous arrival applies all 90 acre-feet at the very start of the first day, whereas Steady arrival applies 3 acre-feet at a constant rate throughout each of the 30 days.

Secondary Output

Secondary Output is a post-processed result calculated from total stream depletion or accretion. Select the most interesting option from those available for the selected schedule type. A brief description of each secondary output option follows.

Single Impulse:	*Response Ratio* -	Stream response for each period divided by the sum of all groundwater impulse.
	Truncated Response -	Stream response for each period plus a uniform portion of the residual remaining at simulation end.
	Cumulative Ratio -	The sum of stream response from time series start through each period divided by the sum of groundwater impulse from time series start through the same period.
Annual Pattern:	*Impact Factor* -	Fraction of annual stream response incurred in corresponding period during penultimate year of simulation (proxy for dynamic equilibrium), computed on a rolling basis.
	Cumulative Ratio -	Described above.
Uniform Series:	*Period Ratio* -	Stream response for each period divided by the groundwater impulse during the same.
	Cumulative Ratio -	Described above.
Variable Series:	*Response Ratio* -	Described above.
	Cumulative Ratio -	Described above.
	Period Ratio -	Described above.

Changing the schedule type may necessitate changing the secondary output selection as well. A red conditional format will activate as a reminder if the selection needs to be updated. Secondary output is presented in the last column of the impact schedule table, unless initial head is specified with imbalance or some other fault occurs.

Chart Options

The *first period for impact schedule chart*, the *schedule chart gridline spacing*, and the *number of schedule chart periods* all determine the configuration of the time series column chart of impact schedule presented to the right of the Time Series Information block. Conditional format font colors warn of problems. These parameters can be updated on the chart, without repeating all calculations, by clicking the thin gray Update Chart command button located just under the chart.

Specified period for head surface is the input that determines whether and which calculated set of head values will be output in tabular form on the Head tab at cell C77. Input 0 to avoid head output. Input a value from 1 through the number of analysis periods to output the heads calculated for the end of the specified period. *Location for head time series* offers to output and plot a time series of head at a particular grid location, period by period for the entire scenario. An *i* index of 0, prevents this. Otherwise, input both *i* and *j* indices for the desired location.

Impulse Schedule

The final input is the impulse time series in the third column of the impact schedule table, starting with cell D39. This column is the place to enter the *well pumping*, *well injection*, or *deep percolation* schedule or the portion thereof required to be input for the selected schedule type. Blue text indicates required input, given the schedule information specified above. Impulse schedule information should come from water supply plan estimates or from analysis of water use records. Units are volume per period. As examples, the units could be acre-feet per 10 days, or cubic meters per month, depending on period definition (above on Time tab) and impulse unit

specification (Format tab). The blue impulse values will be processed by the calculation procedure, as described above, to form a complete time series for the specified schedule. Each will then be divided according to the impulse arrival specification, cell class configuration of the grid, and spatial distribution information.

As example, consider a grid with 4 input cells, all 660 feet by 660 feet, and all with 0.20 for storage coefficient. Impulse Arrival is Instantaneous. Impulse Distribution is Uniform by Head. For this case, a period impulse of 28 acre-feet of deep percolation is divided up and applied to the cells as 3.5 feet of head (0.7 feet of water) by the calculation shown here.

$$3.5_{ft} = \frac{28_{ac-ft}\ 43{,}560\ \frac{ft^3}{ac-ft}}{4 \cdot 660_{ft}\ 660_{ft}\ 0.2}$$

Had Impulse Arrival been Steady, instead, with 7 steps per period, the same impulse would have been divided up and applied to the cells as 1 acre-foot (43,560 cubic feet) per step for each by this calculation.

$$1.0_{\frac{ac-ft}{step}} = \frac{28_{ac-ft}}{4 \cdot 7_{steps}}$$

So, if the calculation time step is 1.0 day, each impulse cell gets a steady 43,560 ft³/d of deep percolation throughout the period. If the time step is 7.0 days, each impulse cell gets 6,223 ft³/d. If all impulses in the schedule are input as zeros, they will all turn red by conditional format to warn that there is no impulse from which to calculate a response. Calculation may still proceed with zero impulse, such as to calculate drain-out of built-up water table.

After proper input has been given for all parameters, and after the required impulse time series information is complete, the thin grey Compute Impact Schedule command button located between the time series information input block and the impact schedule table can be clicked to execute the calculation procedure.

Calculation Procedure and Output

When the Compute Impact Schedule button is clicked, a procedure is called to confirm that the workbook is up to date, verify that a few basic input requirements are met, and then call a sequence of subroutines to process the impulse time series data, perform the delayed impact calculations, and scale the impact schedule chart. All of these steps, and all of the calculations, were programmed into a Visual Basic for Applications module that is an integral part of the workbook. As the procedure executes, the mouse pointer should indicate that it is working. Be a little patient. As soon as the procedure concludes, diagnostic information is written to the Time sheet. In cell E31 the outcome is displayed, showing whether and when completion occurs, with status updates posted as the procedure works. Calculation notes advise of occurrences requiring contemplation or remedy.   The final computed cumulative ratio provides information useful to consideration of the adequacy of the number of periods analyzed and significance of residual impulse volume.

The time elapsed by previous computation is useful for understanding how long to expect the procedure to go. Scenarios with large numbers of spatial increments take longer to compute, as do scenarios with large numbers of periods and or steps per period. To avoid an unacceptable elapsed time, start with a small number of increments and periods. Increase them gradually, as insight regarding computation time with the computer at hand is gained.

Although prerequisite head values are computed first, the primary output of the computation procedure is volumetric impact incurred by the surface water stream or streams, either accretion or depletion, presented as the total for each period, in the 5th column of the impact schedule table of the Time sheet, starting with cell F39. According to the information input on the Response sheet, Zone 1 impact, can be given in the preceding impact schedule table column, as aggregated independently during the same procedural step that aggregates total impact. Both are plotted versus the input impulse time series on the column chart of impact schedule to the right of the time series information input block. This presentation of impulses and responses, side by side, gives a clear depiction of the degree of impact delay and of its effect on the schedule. An example is presented by Figure 4.

Delayed Impact Calculator
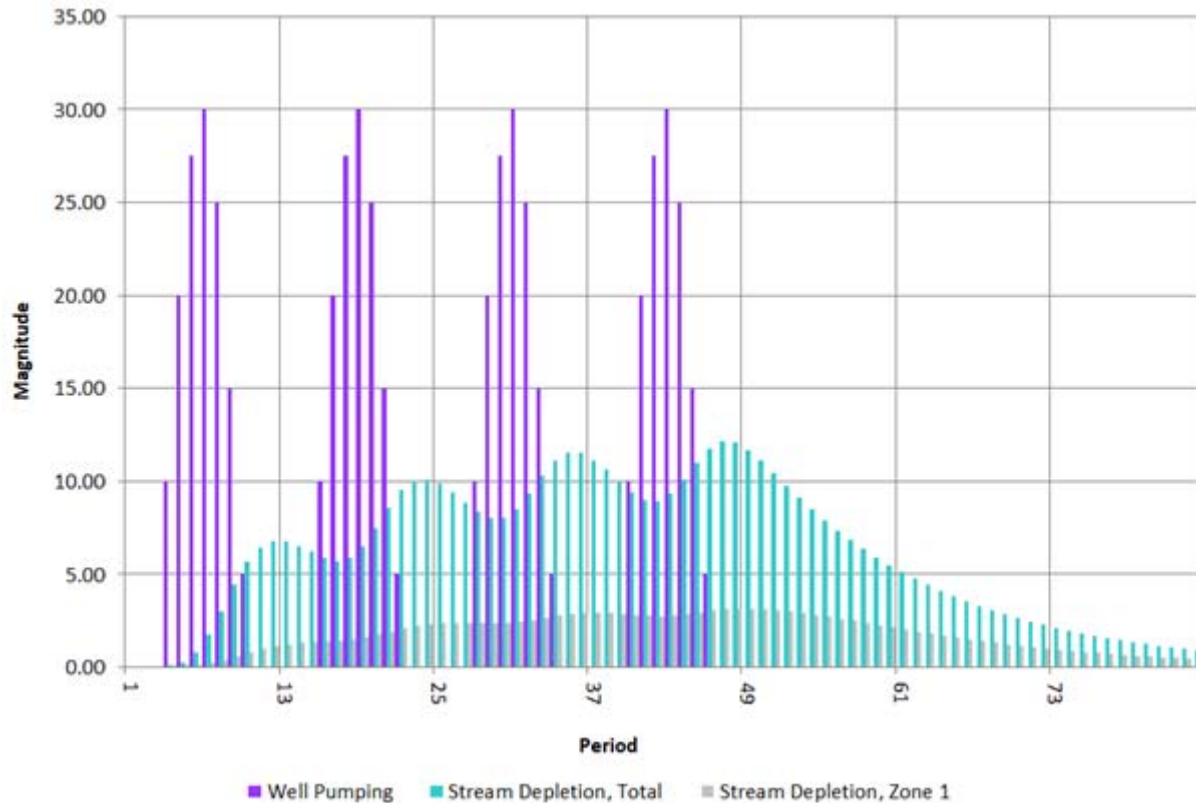
Figure 4: Sample Impact Schedule Chart

The purple columns represent well pumping with seasonality, such as might serve an irrigation use in a mid-latitude setting, over 4 cycles of 12, years and months. The cyan columns represent total stream-incurred depletion during 7 years of analysis. The shorter, grey, columns represent Zone 1 stream depletion, such as that incurred by a particular reach of interest. The seasonal pattern of depletion develops over the pumping period, beginning to approach dynamic equilibrium by the fourth year. The depletion pattern is different than the pumping schedule. Pumping peaks in the 7th period of each cycle (July) at a magnitude of 30 volumetric units for the month, whereas depletion peaks in the 11th period (November), at a magnitude of about 12 units. In this example pumping exceeds depletion throughout the irrigation season, and is exceeded by depletion throughout the non-irrigation season. Also, post-pumping depletion is significant, with non-trivial amounts occurring over 2 years after pumping ceased. Zone 1 experiences a portion of the impact, manifesting unique delay

characteristics, shown by dampened seasonality and a slower recession trend. These response schedule characteristics are the impact delays calculated by the workbook.

Secondary output is given in the last column of the impact schedule table, according to the selection made higher on the tab. Secondary output will be left blank when weighted average initial head or stream head of class 2 cells does not match the same average for classes 1 and 3, due to interference by head stabilization. Other scenarios can also end up with a blank secondary output column, for like reasons.

Although not the focus of the Delayed Impact Calculator, head values can confirm scenario validity and calculation quality, so the head chart is of some interest. The heads from the end of the specified period are output on the Head sheet, starting with cell C77. The head surface data allow for a quick, qualitative assessment and serve as a diagnostic tool. Head time-series data is given below the surface snapshot, and can be a valuable calibration resource.

Copy and paste values from information input cells and procedure output cells into a new sheet or blank workbook to preserve them for future duplication, modification, or comparison, and for further analysis or custom presentation, such as table formatting or chart preparation.

Practical Application

A few hypothetical examples are given here to illustrate use of the Delayed Impact Calculator, starting with maps and driller's logs, and progressing through calculation completion.

Irrigation Return Flow

The owners of a 34-acre parcel of land have asked how much their irrigation efforts contribute to streamflow after the irrigation season. An engineer has provided a soil moisture budget analysis that gives estimates of the amounts of deep percolation that pass the root zone and reach the water table as result of irrigation on the property. The estimates vary from month to month, always less than 0.2 feet of water in any month. The neighbor to the East irrigates similarly, as do those up and down the valley. Figure 5 is a map of the parcel and surrounding area.

Figure 5: Map of Irrigated Area
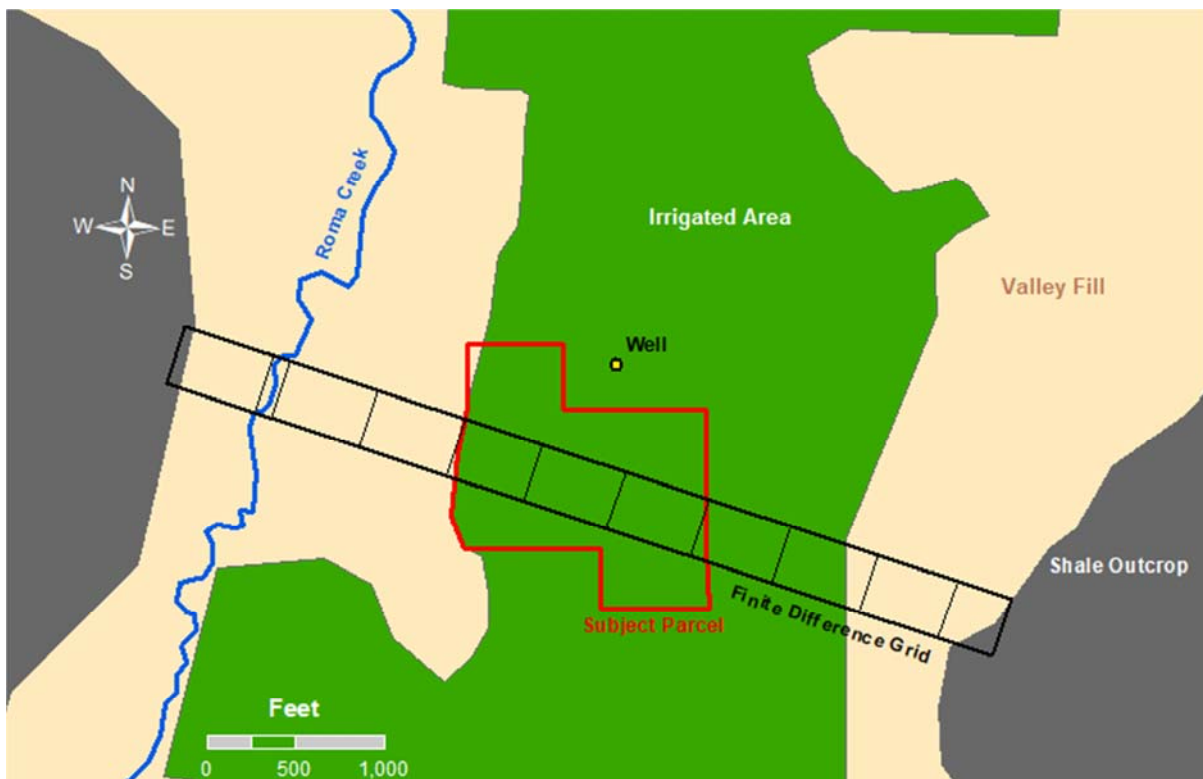
As shown, there is a well near the parcel. The Division of Water Resources maintains a database of well documents. The database includes a Well Construction report that contains this driller's log information from May 16th, 1997:

Table 8: Information from Example Well Construction Report

Depth	Note
0 – 71 feet	Gravels
71 – 80 feet	Gray Shale
45 feet	Water First Encountered
80 feet	Total Cased Depth of Completion
45 feet	Static Water Level

Although scant and dated, this information indicates that the aquifer in the vicinity is an unconfined alluvial aquifer. For this analysis, the datum is set at ground level, a uniform Ground input of 0 is specified, and a uniform Initial Head value (depth to water table) of 45 feet is entered. Aquifer bottom is set at 71 feet. Capillary Rise is set to None everywhere. No record of a detailed aquifer test is available, so, Hydraulic Conductivity and Storage Coefficient are unknown. The owners are advised that the delayed impact analysis can only be of limited use without the accuracy afforded by the necessary test results. They acknowledge the limitation, and request that the analysis be performed using reference values to give them a sense of the phenomenon that will help them decide whether to accept the additional expense of the test and associated activity. Conductivity is given as 950 ft/d by Table 5, and Specific Yield is given as 0.23 by Table 6. No streambed permeability information is available. Both permissive and restrictive cases will be considered, the latter with parameter values from another creek that could be similar, just to give a sense of the effect. Those parameters are vertical conductivity of 3 ft/d and bed thickness of 5 ft.

Since detailed input data is lacking, a simplified analysis is performed. Groundwater flow is treated as unidirectional, normal to the creek, so, a single row finite difference grid is adequate to approximate a slice of the area, as shown on Figure 5. Provided additional data, a

grid of greater dimensions, including all of the property, as well as neighboring area, could be appropriate.

Various permutations of workbook representation of the single row grid are presented as Table 9, on the next page. All employ an arbitrary representative row width of 340 ft and a column width of 100 feet for the stream cell, where the stream channel and adjacent shallow wetlands together span about that width. Table 9:A, yields acceptable results for the subject parcel, neglecting irrigation on the adjacent parcel. Correct results can be obtained by subtracting the results by 9:C from those by 9:B, taking care to use an impulse volume proportional to the number of impulse cells for each, and then dividing the monthly response differences by the difference in impulse volume to yield response ratios. That approach requires unjustified effort, hence 9:A. For the permissive streambed case only, 9:D will yield acceptable results. This is not true for the restrictive bed case, as flow to storage in the cell across the creek from the irrigated area is a factor. In other words, head propagates through the aquifer to the area West of the creek. Here, the contribution of this factor is quite small; however, the principle remains pertinent. 8:E yields incorrect results, even for the permissive bed case, because it does not allow head to spread to the East from the irrigated area, so it gives a false, accelerated response schedule. Successful application of 8:A depends on faithful transcription of the input data shown.

<div align="center">Table 9: Return Flow Grids</div>

A - Subject Parcel, As Mapped

Δ X	500	100	500	500	500	500	500	500	500	500	340
j i	1	2	3	4	5	6	7	8	9	10	11
1	3	2	3	3	1	1	1	3	3	3	3

B - Full Irrigated Width, As Mapped

Δ X	500	100	500	500	500	500	500	500	500	500	340
j i	1	2	3	4	5	6	7	8	9	10	11
1	3	2	3	3	1	1	1	1	1	3	3

C - Irrigated Width Without Subject Parcel

Δ X	500	100	500	500	500	500	500	500	500	500	340
j i	1	2	3	4	5	6	7	8	9	10	11
1	3	2	3	3	3	3	3	1	1	3	3

D - Subject Parcel, Equivalent Representation, Permissive Bed Only

Δ X	100	500	500	500	500	500	500	500	500	340
j i	1	2	3	4	5	6	7	8	9	10
1	2	3	3	1	1	1	3	3	3	3

E - Subject Parcel, Erroneous Representation

Δ X	100	500	500	500	500	500
j i	1	2	3	4	5	6
1	2	3	3	1	1	1

The volume of deep percolation must also be input. When deep percolation causes head to fluctuate by a large proportion of the aquifer thickness, just what the proportion is for the scenario of interest matters a great deal, because the contribution to transmitting thickness has an effect on flow transmission. In contrast, when deep percolation causes head to fluctuate by a small proportion of the aquifer thickness, just what the proportion is doesn't matter much, since the difference in transmitting thickness is negligible, so impact on flow transmission is tiny. Therefore, since monthly deep percolation is always less than 0.2 feet of water, or 0.87 feet of head (0.2 / 0.23 = 0.87), and the available information indicates aquifer thickness to be many times that, about 26 feet, a representative impulse of 0.1 foot of water will be used to calculate a characteristic response function. Alteration of response ratio output would not be meaningful were even twice that impulse employed. At about 10 fold, slight

effects are noticeable. The volume to enter in cell D39 of the Time tab is calculated from the selected 0.1 feet of deep percolation by multiplying by the number and dimensions of the impulse cells. 0.1 x 3 x 340 x 500 = 51,000. That is 51,000 cubic lengths, here cubic feet. The impulse volume will be distributed throughout the month. This is not a month-specific amount of deep percolation, just a representative impulse. Were 5 impulse cells employed the volume would be 85,000 for the same addition to head. Were only 2 employed, impulse volume would be 34,000.

To make calculations per the preceding discussion, enter the input values presented on the next page as Table 10, as well as "None" for Incision Adjustment and Capillary Rise, then click Compute Impact Schedule on the Time tab. The procedure takes just a second to work for this simple scenario. The final computed cumulative ratio for the permissive-bed case is 0.9993, meaning that over the span of 18 months, 99.93 percent of the 51,000 ft^3 of impulse was incurred as stream response, indicating that the number of periods was adequate to characterize the phenomenon to a high degree of completion. No calculation notes post, and outcome status is reported to be complete as the procedure finishes.

Table 10: Return Flow Calculation Input

Tab	Parameter	Input	Units
Format	Impulse, Type	Deep Percolation	
	Units	Consistent	
	Aquifer, Type	Unconfined	
	Mean, Type	Weighted Harmonic	
	Update, Timing	Same Step	
	X Increments, Number	11	
	Specification	Discrete	
	ΔX	Per Table 9:A	
	Y Increments, Number	1	
	Specification	Uniform	
	Length	340	[length] feet
	Cell Class	Per Table 9:A	
Ground	Specification	Uniform	
	Value	0	[length] feet
Head	Initial Head, Specification	Uniform	
	Value	45	[length] feet
Thickness	Aquifer Bottom, Specification	Uniform	
	Value	71	[length] feet
Conductivity	Hydraulic Conductivity, Specification	Uniform	
	Value	950	[length/d] feet/d
Storage	Specific Yield, Specification	Uniform	
	Value	0.230	[ ]
Impulse	Spatial Distribution, Specification	Uniform, Head	
Response	Number of Response Zones	1	
Streambed	Type	Permissive	
	Incision Adjustment	None	
	Stream Head Class	Equivalent	
Time	Site Name	Roma Valley	
	Scenario Designation	Irrigation Return Flow	
	Solution Threshold Order	3	
	Schedule Type	Single Impulse	
	Analysis Periods	18	
	Period Units	Months	
	Units per Period	1	[months]
	Steps per Period	4	
	Impulse Arrival	Steady	
	Secondary Output	Response Ratio	
	Deep Percolation, Total, Period 1	51,000	[length^3] feet^3

The resulting impact schedule table is presented as Table 11a. The stream accretion and response ratio columns are output. The response ratio column provides a classical response function that can be applied to deep percolation estimates to produce stream accretion estimates. Flow equivalent to 32 percent of deep percolation occurring during a given month reaches the creek during that same month. The equivalent of 27 percent is incurred during the following month, 14 percent the month after, and so on. As an alternate explanation, related groundwater return flow in October is 32 percent of October deep percolation plus 27 percent of September percolation, 14 percent of August, 9 of July, and so forth.

Table 11a: Example Return Flow Impact Schedule, Permissive Bed

Period	End Time	Deep Percolation Total	Stream Accretion Zone 1	Stream Accretion Total	Response Ratio
[ ]	[months]	[length^3]	[length^3]	[length^3]	[ ]
1	1	51,000.00	16,421.15	16,421.15	0.3220
2	2	0.00	13,867.71	13,867.71	0.2719
3	3	0.00	6,997.69	6,997.69	0.1372
4	4	0.00	4,512.76	4,512.76	0.0885
5	5	0.00	3,018.19	3,018.19	0.0592
6	6	0.00	2,027.15	2,027.15	0.0397
7	7	0.00	1,362.29	1,362.29	0.0267
8	8	0.00	915.62	915.62	0.0180
9	9	0.00	615.44	615.44	0.0121
10	10	0.00	413.68	413.68	0.0081
11	11	0.00	278.07	278.07	0.0055
12	12	0.00	186.92	186.92	0.0037
13	13	0.00	125.65	125.65	0.0025
14	14	0.00	84.47	84.47	0.0017
15	15	0.00	56.78	56.78	0.0011
16	16	0.00	38.17	38.17	0.0007
17	17	0.00	25.66	25.66	0.0005
18	18	0.00	17.25	17.25	0.0003

The response function can be used to answer the question: how much of the water in the creek in a given month, after the end of the irrigation season, is attributable to irrigation on the subject property during the preceding months? The irrigation season at the site spans April through October. What is the groundwater return flow contribution during November? The

answer can be estimated by application of the response function to monthly deep percolation estimates. The water use records and other information passed to the engineer's soil moisture budget analysis resulted in the following monthly estimates of deep percolation over the entire parcel during the preceding season.

Table 12: Example Scenario Deep Percolation Schedule

Month	Volume
April	2 ac-ft
May	5 ac-ft
June	3 ac-ft
July	1 ac-ft
August	1 ac-ft
September	2 ac-ft
October	2 ac-ft

November return flow is estimated as 0.2719(2) + 0.1372(2) + 0.0885(1) + 0.0592(1) + 0.0397(3) + 0.0267(5) + 0.0180(2) = 1.25 acre-feet, an amount equivalent to a steady flow averaging 9.5 gallons per minute throughout the month. Flow measurement from the creek can give context to the rate of groundwater return. Suppose a measurement taken just downstream that November was recorded as 120 gallons per minute. In such case, previous irrigation on the subject property contributed about 8 percent of the water, subject to the major accuracy limitations attendant to the use of reference values for aquifer parameters.

To make calculations for the restrictive-bed case, change the Streambed Type selection on the Streambed Sheet, select Uniform parameter specification method, Equivalent bed width, stream head, and bed elevation classes, and then input 3 [length/d, here ft/d] for vertical conductivity and 5 [length, here feet] for bed thickness. As with the case above, Incision Adjustment is "None". Click Compute Impact Schedule on the Time tab again. The final computed cumulative ratio for the restrictive-bed case is 0.9976, meaning that over the span of 18 months, 99.76 percent of the 51,000 ft^3 of impulse was incurred as stream response. After the first month, the response ratios are similar to the permissive-bed case, indicating that for such a wide creek, with the given bed conductivity, additional resistance makes just a modest contribution. The restrictive-bed impact schedule is presented as Figure 6 and as Table 11b.

Figure 6: Impact Schedule Chart, Single Impulse Irrigation Return Flow Example
Restrictive Streambed Scenario
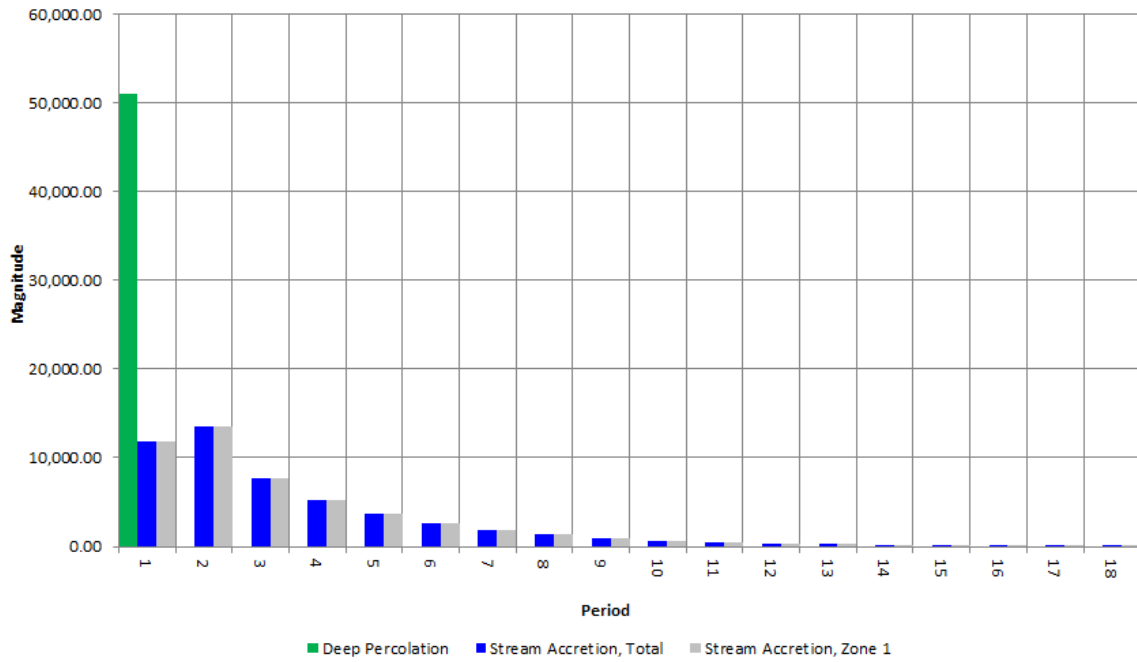
Table 11b: Example Return Flow Impact Schedule, Restrictive Bed

Period	End Time	Deep Percolation Total	Stream Accretion Zone 1	Stream Accretion Total	Response Ratio
[ ]	[months]	[length^3]	[length^3]	[length^3]	[ ]
1	1	51,000.00	11,762.39	11,762.39	0.2306
2	2	0.00	13,450.47	13,450.47	0.2637
3	3	0.00	7,656.13	7,656.13	0.1501
4	4	0.00	5,184.54	5,184.54	0.1017
5	5	0.00	3,678.71	3,678.71	0.0721
6	6	0.00	2,630.51	2,630.51	0.0516
7	7	0.00	1,883.38	1,883.38	0.0369
8	8	0.00	1,348.80	1,348.80	0.0264
9	9	0.00	966.04	966.04	0.0189
10	10	0.00	691.94	691.94	0.0136
11	11	0.00	495.62	495.62	0.0097
12	12	0.00	355.01	355.01	0.0070
13	13	0.00	254.30	254.30	0.0050
14	14	0.00	182.16	182.16	0.0036
15	15	0.00	130.49	130.49	0.0026
16	16	0.00	93.47	93.47	0.0018
17	17	0.00	66.96	66.96	0.0013
18	18	0.00	47.96	47.96	0.0009

The most noticeable difference between Table 11a and 11b occurs during the month of percolation, when the restrictive bed reduces the returned fraction from 32 percent to 23 percent. The other differences are less dramatic. Repetition of the arithmetic for November yields this computation. 0.2637(2) + 0.1501(2) + 0.1017(1) + 0.0721(1) + 0.0516(3) + 0.0369(5) + 0.0264(2) = 1.39 The same value can be obtained with fewer steps by changing the Impulse Units setting to Acre-feet, changing the Schedule Type to Variable Series, and putting the values from Table 12 (even though they are for the entire parcel...the difference to transmitting thickness has a negligible effect) right in the Deep Percolation column (starting with Period 4) prior to clicking Compute. The increase from 1.25 acre-feet for the permissive case to 1.39 acre-feet for the restrictive case in November is due to the restriction holding back early-time return, after which gradual relief of the retained head occurs over the following months of slightly greater return, an at first, counterintuitive, although true, circumstance. The comparison would be different, were the calculations made for October or another irrigation-season month.

Topics for further learning can be explored by modifying workbook input:

A) Demonstrate that, given scaled impulse volumes, solution by Table 9:B minus solution by Table 9:C is approximated well by solution by Table 9:D.

B) Demonstrate that solution by Table 9:E is not correct, even for a permissive-bed.

C) Demonstrate that the response ratios for an impulse equivalent to 0.2 feet of deep percolation in a month are essentially the same as for an impulse of 0.1 feet.

D) Demonstrate that the response ratios for an impulse of 5 feet of deep percolation are not quite the same as for an impulse of 0.1 feet.

E) Calculate September and December return flows for the case treated in the preceding demonstration, both with permissive and with restrictive streambeds.

Delayed Impact Calculator

Production Well Near Confluence

How much water will need to be purchased from an upstream supply to offset depletion of river flow by a proposed production well located near the confluence of rivers, where replacement is required to prevent diminution of the water supply to a top priority surface diversion? In this hypothetical example, the proponents of a solar panel manufacturing facility have asked how much water they need to make available on the Booming River during the typical periods of seasonal shortage to make up for depletion by their well. The well is planned to operate on a set pumping schedule to supply a consistent 5 acre-feet of water per month for indoor use at the facility, as well as double shifts during the long daylight period from May through July, as is sometimes necessary to fill orders. No portion of the pumped water is returned to the aquifer on site. The typical periods of shortage to the surface diversion are July through September and January through February. Bed permeability differs between rivers. Figure 7, on the next page, is a map of the well location and surrounding area.

The well has been drilled, together with a small observation well nearby, and an aquifer test has been conducted. An engineer has analyzed the field data and provided Hydraulic Conductivity and Storage Coefficient values of 27 feet per day and 0.19, in that order. Analysis of aquifer test data collected at sites located further from the confluence yielded markedly different bed characteristics for the two rivers. Where tested, the Quartz River exhibited effectively permissive bed characteristics. The Booming River, on the other hand, exhibited restrictive bed characteristics, represented by a vertical hydraulic conductivity of 0.1 feet per day, and a thickness of 5 feet. The Well Construction report contains information from September 2nd 2017, given by Table 13.

Figure 7: Map of Production Well Location
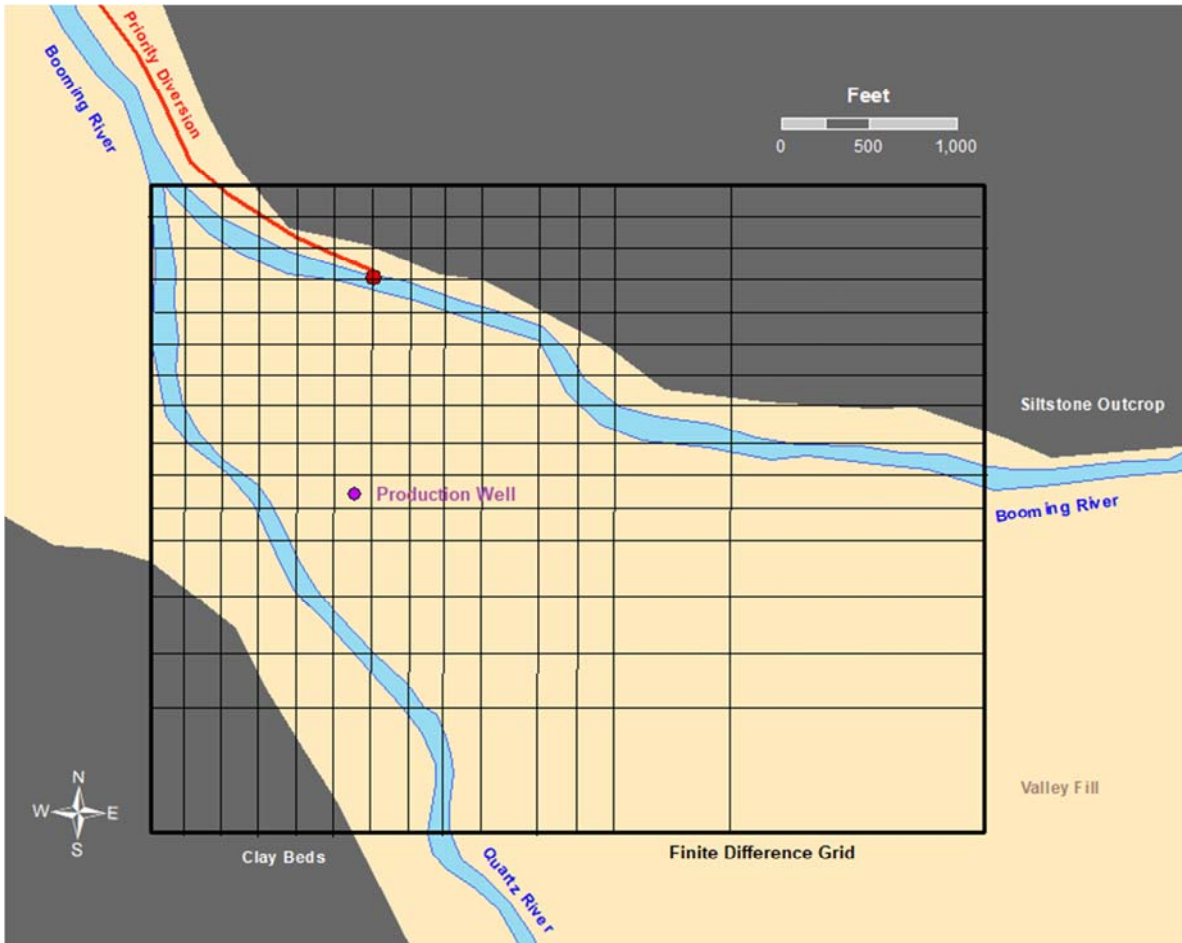
Table 13: Information from Hypothetical Well Construction Report

Depth	Note
0 – 5 feet	Soil
5 – 11 feet	Rocky Subsoil
11 – 23 feet	Cobble and silt
23 – 110 feet	Fine Sand and Gravel
110 – 118 feet	Blue Clay
118 – 122 feet	Red Siltstone
23 feet	Water First Encountered
120 feet	Total Cased Depth of Completion
22 feet	Static Water Level

Delayed Impact Calculator

The principal shallow aquifer in the vicinity is alluvial. The 1-foot discrepancy between the depth at which water was encountered, per Table 13, and the depth to the static water level could indicate a small degree of confinement by silt above the water table. It could also just be an artifact of the imprecision of the driller's perception. The aquifer is taken to be unconfined. Ground is set as Uniform at 0 feet, although the topography is varied, since a single value for the inundation watch will provide adequate assurance for this analysis. Initial Head is set as Uniform at 22 feet for this estimate of impulse response to be superimposed on regional groundwater dynamics. Construction Reports from nearby wells indicate that the slopes of the Siltstone Outcrop and Clay Beds continue below ground, and that there is diversity of material within the aquifer. Aquifer Bottom can be varied using Discrete specification to account for the slopes of the base formations as recorded in the reports. This is shown by Table 14 B, below. Streambed characteristics can be input likewise. Cells corresponding to the Quartz River can be assigned a vertical conductivity of 27 ft/d and a nominal bed thickness of 1 ft, to generally represent fairly permissive characteristics, while cells corresponding to the Booming River can be assigned vertical conductivity of 0.1 ft/d and bed thickness of 5 ft, from the aquifer test results obtained upstream, to represent the different character of that river. The confluence cell in the Northwest corner can be assigned the average values of 13.6 ft/d and 3 ft, for lack of better information. Bed width is set as Cell Width. Collection of geologic data and representation of the remaining heterogeneity, such has aquifer hydraulic conductivity, are left as opportunities for further study.

A rectangular finite difference grid of varied increment lengths is populated to represent the area, with focus, or higher resolution, meaning smaller increments, around the well and confluence of rivers, as shown on Figure 7. Larger increment lengths upstream, or South and East, allow the calculations to encompass adequate domain extent and response reaches using a minimum of grid locations. The Workbook representation of the grid is presented on the next page as Table 14, with Cell Class shown by A, Aquifer Bottom shown by B, and assignment of the reach of the Booming River above the surface diversion to Response Zone 1 shown by C. Bed permeability input is not shown; however, it is entered in like manner, with care to put values appropriate to the river to which each response cell corresponds.

Table 14: Well Near Confluence Grid

A – Cell Class and Increment Lengths

dX		200	200	200	200	200	200	200	200	200	300	200	200	660	1,320
dY	j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14
200	1	2	2	3	4	4	4	4	4	4	4	4	4	4	4
200	2	2	3	2	3	4	4	4	4	4	4	4	4	4	4
200	3	2	3	3	2	2	2	3	4	4	4	4	4	4	4
200	4	2	3	3	3	3	3	2	2	2	3	4	4	4	4
200	5	2	3	3	3	3	3	3	3	2	3	4	4	4	4
200	6	2	3	3	3	3	3	3	3	3	3	2	3	4	4
200	7	2	3	3	3	3	3	3	3	3	3	3	2	3	3
200	8	2	3	3	3	3	3	3	3	3	3	3	3	2	3
200	9	3	2	3	3	3	3	3	3	3	3	3	3	3	2
200	10	3	3	2	3	3	1	3	3	3	3	3	3	3	3
200	11	3	3	3	2	3	3	3	3	3	3	3	3	3	3
330	12	3	3	3	2	3	3	3	3	3	3	3	3	3	3
330	13	4	4	3	3	2	2	3	3	3	3	3	3	3	3
330	14	4	4	4	3	3	3	2	3	3	3	3	3	3	3
660	15	4	4	4	4	4	3	3	2	3	3	3	3	3	3

B – Aquifer Bottom Specification

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	39.5	37.0	38.0											
2	44.3	42.0	41.4	38.0										
3	50.1	51.0	50.8	41.4	37.0	41.4	37.0							
4	53.0	60.0	60.1	50.8	42.0	50.8	41.4	40.5	37.0	37.0				
5	56.5	70.0	69.5	60.1	51.0	60.1	50.8	53.0	42.0	41.4	38.0			
6	59.2	79.0	78.9	69.5	60.0	69.5	60.1	62.2	51.0	50.8	41.4	37.0		
7	62.1	77.0	81.0	78.9	70.0	78.9	69.5	69.5	60.0	60.1	50.8	41.4	36.2	37.0
8	65.0	75.0	80.0	88.3	79.0	88.3	78.9	80.0	70.0	69.5	60.1	50.8	41.1	41.4
9	59.0	67.0	70.4	80.0	88.0	107.0	88.3	86.0	79.0	78.9	69.5	60.1	51.0	50.8
10	51.0	61.0	70.3	70.4	107.0	109.0	107.0	114.0	98.0	88.3	78.9	69.5	59.2	60.1
11	41.0	49.0	57.0	70.3	92.4	107.0	92.4	102.0	107.0	107.0	92.9	78.9	69.5	69.5
12	35.8	38.0	41.0	58.0	80.3	92.4	80.3	91.3	84.0	93.0	105.1	94.1	78.9	78.9
13			36.0	42.0	68.2	80.3	68.2	74.0	79.0	86.0	102.0	101.0	92.9	88.3
14				32.0	56.1	68.2	56.1	69.0	68.8	78.3	93.0	87.4	105.1	107.0
15						56.1	50.0	68.9	63.0	68.5	74.7	71.8	102.0	93.0

C – Response Zone Specification

j \ i	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2	2												
2	2		2											
3	2			2	2	2								
4	2						1	1	1					
5	2									1				
6	2										1			
7	2											1		
8	2												1	
9		2												1
10			2											
11				2										
12				2										
13					2	2								
14							2							
15								2						

Delayed Impact Calculator

To make the calculations, enter the input values presented by Table 15, and then click Compute Impact Schedule on the Time tab. The procedure takes a few seconds to work for this scenario. An example time elapsed is 00:06. The final computed cumulative ratio is 0.9643, meaning that over the span of 60 months, 96.43 percent of the 375 ac-ft of well pumping is incurred as stream depletion. Post-pumping depletion to occur past the end of the analyzed time span is relatively minor. No calculation notes manifest, and outcome status is reported to be complete as the procedure finishes.

Figure 8a, on the page after next, shows the impact schedule. It is interesting to note that Zone 1 depletion peaks in August each year, although total depletion peaks in July. Differences like this are due to the heterogeneity of the system, in general, and in particular, the different streambed permeability characteristics.

The tabular data for the first 2 and last 2 years of the resulting impact schedule are presented on the page following the figure. The degree to which depletion for a given month matches depletion for the same month a year later confirms that the number of periods was adequate for dynamic equilibrium such that residual impact from earlier pumping is substantially represented in the response values presented for the last year. For example, July Zone 1 depletion was 1.20 acre-feet during period 43 and 1.20 ac-ft during period 55, a match.

The answer to the question posed at the outset of the example is found in the Table. Proposed well operation is estimated to deplete the flow available to the surface diversion by almost 2 ac-ft in January and February, together, and by 3.7 ac-ft in July, August, and September. These results were obtained by summation of monthly values from the Zone 1 column of output. For Example, August of the last year of calculation is period 56. Although well pumping that month is only 5 ac-ft, total depletion of the Rivers is 7.5 ac-ft, of which 1.3 ac-ft is incurred in Zone 1, above the diversion on the Booming River. The 1.3 is added to 1.2 from the preceding month, and 1.2 from the following month to yield 3.7, with rounding.

Table 15: Well Near Confluence Input

Tab	Parameter	Input	Units
Format	Impulse, Type	Well Pumping	
	Units	Acre-feet	
	Aquifer, Type	Unconfined	
	Mean, Type	Weighted Harmonic	
	Update, Timing	Same Step	
	X Increments, Number	14	
	Specification	Discrete	
	ΔX,Y	Per Table 14:A	
	Y Increments, Number	15	
	Specification	Discrete	
	Cell Class	Per Table 14:A	
Ground	Specification	Uniform	
	Value	0	[feet]
Head	Initial Head, Specification	Uniform	
	Value	22	[feet]
Thickness	Aquifer Bottom, Specification	Discrete	
	Values	Per Table 14:B	[feet]
	Minimum Saturated Thickness	80	[%]
Conductivity	Hydraulic Conductivity, Specification	Uniform	
	Value	27	[feet/d]
Storage	Specific Yield, Specification	Uniform	
	Value	0.190	[ ]
Impulse	Spatial Distribution, Specification	Uniform, Head	
Response	Number of Response Zones	2	
	Specification	Per Table 14:C	
Streambed	Type	Restrictive	
	Parameter Specification	Discrete	
	Bed Width Class	Equivalent	
	Hydraulic Conductivity	0.1, 13.6, or 27, per text	[ft/d]
	Distinct Thickness	1, 3, or 5, per text	[ft]
Time	Site Name	Quartz Mouth	
	Scenario Designation	Industrial Production Well	
	Solution Threshold Order	3	
	Schedule Type	Annual Pattern	
	Analysis Periods	60	
	Period Units	Months	
	Units per Period	1	[months]
	Steps per Period	4	
	Impulse Arrival	Steady	
	Secondary Output	Cumulative Ratio	
	Well Pumping, Total	Periods 5-7: 10, All Others: 5	[Acre-feet]

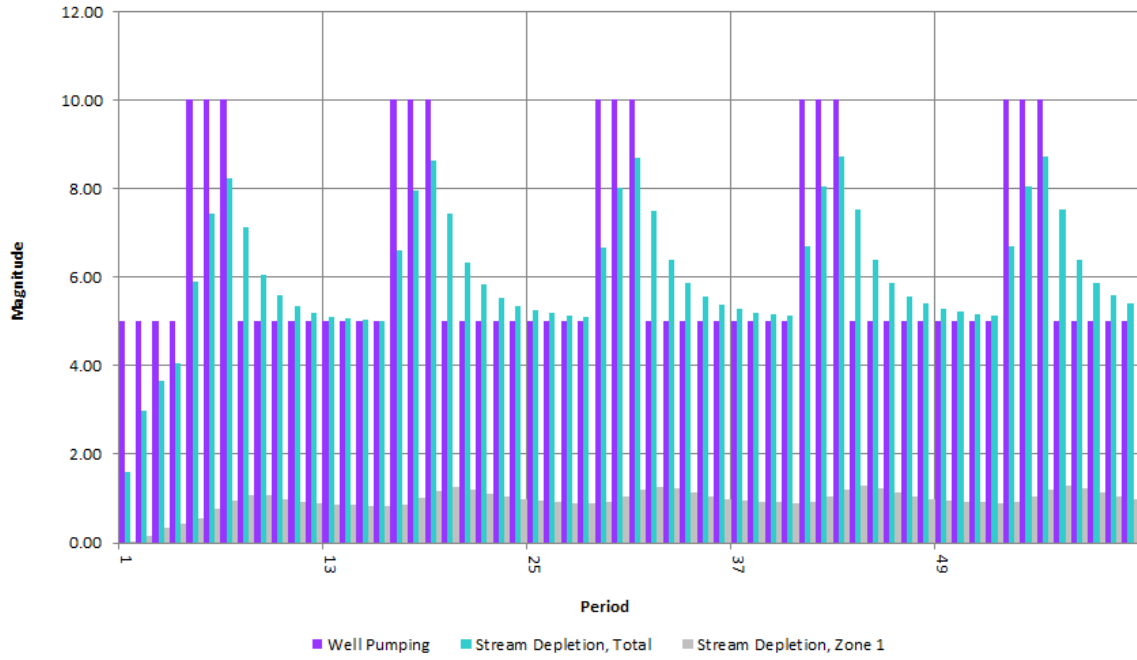Figure 8a: Impact Schedule Chart, Production Well Near Confluence Example

Figure 8b: Impact Schedule Chart, Opposite Streambed Characteristics,
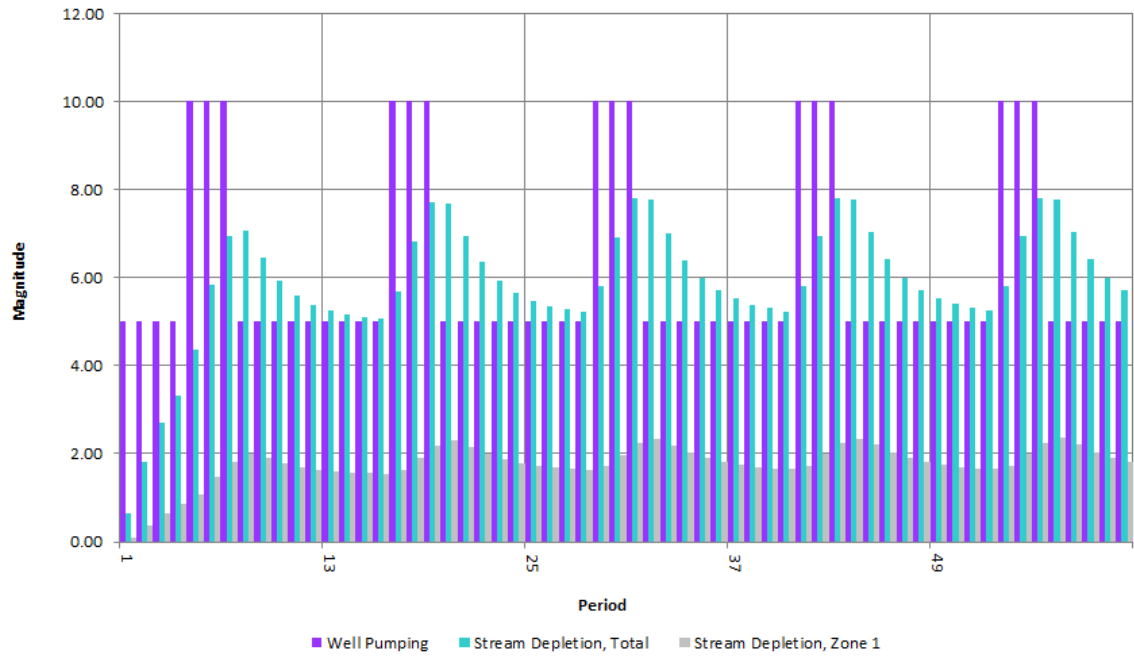for exploration topic B, described below

Table 16: Example Well Pumping Impact Schedule

Period	End Time	Well Pumping Total	Stream Depletion Zone 1	Stream Depletion Total	Cumulative Ratio
[ ]	[months]	[Acre-feet]	[Acre-feet]	[Acre-feet]	[ ]
1	1	5.00	0.03	1.58	0.3166
2	2	5.00	0.17	2.95	0.4534
3	3	5.00	0.32	3.63	0.5443
4	4	5.00	0.44	4.04	0.6101
5	5	10.00	0.56	5.87	0.6023
6	6	10.00	0.76	7.40	0.6367
7	7	10.00	0.96	8.20	0.6733
8	8	5.00	1.08	7.12	0.7416
9	9	5.00	1.07	6.07	0.7809
10	10	5.00	1.00	5.60	0.8071
11	11	5.00	0.94	5.35	0.8258
12	12	5.00	0.90	5.20	0.8400
13	13	5.00	0.87	5.11	0.8514
14	14	5.00	0.86	5.06	0.8609
15	15	5.00	0.85	5.03	0.8690
16	16	5.00	0.84	5.01	0.8760
17	17	10.00	0.87	6.58	0.8552
18	18	10.00	1.00	7.94	0.8499
19	19	10.00	1.15	8.61	0.8508
20	20	5.00	1.25	7.45	0.8754
21	21	5.00	1.20	6.34	0.8900
22	22	5.00	1.11	5.83	0.8999
23	23	5.00	1.04	5.54	0.9071
24	24	5.00	0.98	5.36	0.9126
37	37	5.00	0.96	5.28	0.9432
38	38	5.00	0.93	5.21	0.9453
39	39	5.00	0.92	5.16	0.9471
40	40	5.00	0.90	5.13	0.9487
41	41	10.00	0.92	6.67	0.9377
42	42	10.00	1.05	8.02	0.9326
43	43	10.00	1.20	8.69	0.9303
44	44	5.00	1.28	7.52	0.9405
45	45	5.00	1.24	6.40	0.9465
46	46	5.00	1.14	5.88	0.9504
47	47	5.00	1.06	5.58	0.9533
48	48	5.00	1.00	5.40	0.9554
49	49	5.00	0.96	5.29	0.9571
50	50	5.00	0.94	5.21	0.9584
51	51	5.00	0.92	5.16	0.9596
52	52	5.00	0.91	5.13	0.9607
53	53	10.00	0.93	6.68	0.9518
54	54	10.00	1.05	8.03	0.9474
55	55	10.00	1.20	8.69	0.9452
56	56	5.00	1.28	7.52	0.9530
57	57	5.00	1.24	6.40	0.9576
58	58	5.00	1.14	5.89	0.9606
59	59	5.00	1.06	5.59	0.9627
60	60	5.00	1.00	5.40	0.9643

Exploration topics:

A) Determine what portion of post-pumping depletion is incurred during the 12 months following cessation of pumping. To do this, choose the Variable Series schedule type, set analysis periods to 72, enter 0 Well pumping for periods 61 through 72, and compute the schedule. Then, compare the final computed cumulative ratio to 0.9643 and apply the fractions to the total groundwater withdrawal.

B) Investigate sensitivity of the results to the restrictive streambed approach employed for the example. As a first inquiry, try swapping the bed characteristics, meaning, set values in cells corresponding to the Quartz River equal to the original values for the Booming River, and vice versa, then repeat computation. Were circumstances reversed, would Zone 1 depletion in period 56 be much different than the 1.3 ac-ft mentioned above? What would be the change of amount and schedule of post-pumping depletion? Figure 8b illustrates the resulting impact schedule, and is presented on the same page as Figure 8a to facilitate comparison.

C) Pretend to gather geologic information from nearby wells and historical reports. Use Discrete characteristic specification to incorporate your findings. Repeat calculation of the example. How sensitive are the results to heterogeneity of the aquifer properties?

D) Reset all aquifer properties to those of the original example, except, set Aquifer Bottom to a uniform value of 85 feet. Repeat the calculation. Then, vary the grid configuration for comparison. Change the numbers and lengths of the increments, such that the spatial orientation of the features remains the same, but the resolution of representation differs. Repeat the calculations. How sensitive are the results to grid definition? Then, investigate sensitivity to time step variation.

Injection Well Behind Barrier

Groundwater overdraft has nearly eliminated base flow in an important hypothetical creek. Base flow is necessary to sustain ecological function and meet legal requirements for scheduled delivery downstream. The local water conservancy district has purchased a replacement supply, available at a constant flow rate amounting to 115 cubic meters per day. The water has been treated. The distance from the supply to the creek is long, and there has been a suggestion to build a pipeline to deliver the water. The district also owns several wells that were purchased and taken out of service during previous efforts to maintain base flow. A competing suggestion has been made, stating that the district should save the cost of the pipeline by injecting the water into the aquifer by pouring it down the nearest hydraulically connected well that is out of service, from where it would induce base flow via the aquifer. The suggestion occasioned several concerns. A principle concern regards timing, that is, how long before increased base flow will manifest at a rate similar to the rate of injection?

The well chosen as injection candidate is situated 2,015 meters from the creek. Geologic mapping of the area documents an igneous dike located between the well and the creek, oriented parallel to the creek. There are several gaps in the dike. Previous studies showed the gaps to extend down below the aquifer responsible for connection of the well and the creek. The aquifer is confined, with a nominal bottom elevation 165 feet below grade, top at 80 feet, and head typically about 50 feet from the surface in the area of the well. Near the creek, the mesa steps down. Prior pump test analysis estimated hydraulic conductivity at 31 meters per day, and Specific Storage at 0.0008 around another well nearby. Table 17 is a grid of the area. The *X* increment is set to 300 meters. Table 18 presents input for the scenario.

Table 17: Injection Well Grid

dY	j \ i	1	2	3	4	5	6	7	8	9	10	11
30	1	2	2	2	2	2	2	2	2	2	2	2
600	2	3	3	3	3	3	3	3	3	3	3	3
600	3	3	3	3	3	3	3	3	3	3	3	3
100	4	3	4	4	3	4	4	4	4	3	4	3
700	5	3	3	3	3	3	3	3	3	3	3	3
30	6	3	3	3	3	3	1	3	3	3	3	3
600	7	3	3	3	3	3	3	3	3	3	3	3
600	8	3	3	3	3	3	3	3	3	3	3	3
600	9	3	3	3	3	3	3	3	3	3	3	3
1,000	10	3	3	3	3	3	3	3	3	3	3	3

Table 18: Well Behind Barrier Input

Tab	Parameter	Input	Units
Format	Impulse, Type	Well Injection	
	Units	Consistent	
	Aquifer, Type	Confined	
	Mean, Type	Weighted Harmonic	
	Update, Timing	Same Step	
	X Increments, Number	11	
	Specification	Uniform	
	Length	300	[length] m
	Y Increments, Number	10	
	Specification	Discrete	
	Lengths	Per Table 17	
	Cell Class	Per Table 17	
Ground	Specification	Uniform	
	Value	0	[length] m
Head	Initial Head, Specification	Uniform	
	Value	50	[length] m
Thickness	Aquifer Top, Specification	Uniform	
	Value	80	[length] m
	Aquifer Bottom, Specification	Uniform	
	Value	165	[length] m
Conductivity	Hydraulic Conductivity, Specification	Uniform	
	Value	31	[length/d] m/d
Storage	Specific Yield, Specification	Uniform	
	Value	0.200	[ ]
	Specific Storage, Specification	Uniform	
	Value	0.0008	[/length] /m
Impulse	Spatial Distribution, Specification	Uniform, Head	
Response	Number of Response Zones	1	
Streambed	Type	Permissive	
Time	Site Name	Wahoo Township	
	Scenario Designation	Proposed Injection Well	
	Solution Threshold Order	3	
	Schedule Type	Uniform Series	
	Analysis Periods	156	
	Period Units	Days	
	Units per Period	7	[d]
	Steps per Period	7	
	Impulse Arrival	Steady	
	Secondary Output	Period Ratio	
	Well Injection, Total	805	[length^3] m^3

The default specific yield input is entered in case of depressurization; however, since there is no negative injection (groundwater withdrawal) in this case, it does not come into play. The well injection of 805 cubic meters per period is 7 times the supplied rate of 115 per day. The grid definition given by Table 17 does not need cells on the far side of the creek from the well, because the permissive bed allows dissipation of all built-up head there. Were the bed restrictive, analysis would be faulty without additional cells across the creek to store flow resisted by the bed.

After entry of all input, the compute button is clicked. This scenario takes some time to analyze. An example time elapsed is 3 seconds. There should be no calculation notes, and the outcome should post as complete. The results populate the Impact Schedule Table below the button, not shown here. After 52 periods of 7 days, that is to say after 1 year of injection, the Period Ratio output is 0.6387, meaning that absent loss to underflow beyond the domain analyzed, induced base flow is estimated to be about 64 percent of the rate of injection. After a second continuous year, the rate ratio is 86 percent. After a third year, the estimated ratio is 94 percent. On the next page, Figure 9 presents the impact schedule chart. There are certainly other questions to ask about the fate of injected water; however, provided the answers are encouraging, improvements to base flow could be expected at this estimated schedule with little additional expense. On the other hand, the pipeline could be built, for which cost, the delivery rate would be near 100 percent immediately upon completion.

Figure 9: Impact Schedule Chart, Injection Well Example
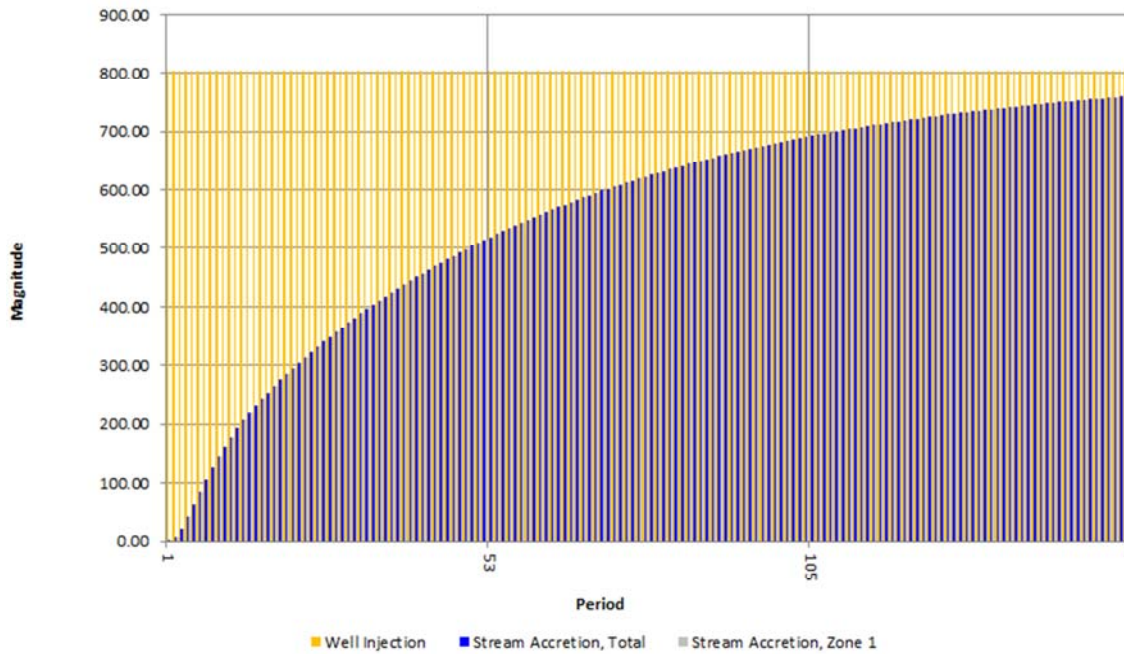
Exploration topics:

A) What if the pump test analysis was faulty, or the locations of the wells used for the test were not representative? How sensitive are the results of the delay analysis to the Specific Storage estimate? Repeat the calculations several times with different Specific Storage values and compare the results.

B) Set *X* increment specification to Discrete, and make all increment lengths 300, except the 6th column, with the well. Set that increment to 30 to allow consideration of better representation of the larger head accumulation nearer the well. Then reset the increment values of the 5th and 7th columns to 435 to make up the distance. Repeat the calculations. How much did the results change?

C) On the Time tab, set the Specified Period for Head Surface to 52, and then click to compute. Upon completion, view the table of output head values at B76 of the Head tab. Do the data confirm that perturbation of head propagates in a manner that makes sense? Change the Specified Period for Head Surface to 104 and repeat the calculations.   Do the changes make sense?

D) Change steps per period to 100. Then click Compute. Were the results different? How much accuracy is sacrificed for the abbreviated computation time afforded by a modest number of steps per period?

E) Change Steps per Period back to 7. Then, choose a different grid location for the well, adjust the spatial increment lengths, and repeat the calculations. What did you learn?

F) How sensitive is the analysis to calculation domain? The domain boundaries are treated as barriers. Move a boundary and repeat calculation as otherwise prepared for the original version of this example. For example, change the number of *Y* increments to 15, give each added increment a length of 2000 meters, input 3 as cell type for the additional cells, and click compute. Then compare results. How far into the simulation do the results start do differ significantly?

Adjacent Recharge Facilities

A hypothetical 80-acre piece of neglected land near a river is proposed to be used as a wet meadow habitat for water fowl brood rearing, with the dual purpose of providing a dependable full season supply of irrigation water to a smaller piece of crop land located down river a few miles, by retiming unappropriated water through induced aquifer recharge. The historical supply of irrigation water to the 80-acre parcel has been sold off. The only water that has not already been appropriated is the peak of the river's snowmelt runoff hydrograph, a supply not yet spoken for, but only available during a brief period in May. Analysis of hydrographic records indicates that even during low snowpack years, at least 264 acre-feet of water can be used. Legacy infrastructure includes a steel splitter box that divides the delivered water 5:1 between the different halves of the property. The water table is shallow, about 4 feet below grade. Would berms 40 inches high around each 40-acre area be adequate additional infrastructure for the scheme to succeed? How much retimed water would be made available to irrigate the crop land down river during the season from April through October?

Since at least 264 acre-feet are available every May, the calculations will be made as an annual series. 264 acre-feet is equivalent to 3.3 feet of water uniformly distributed across 80 acres. Although it may be delivered disproportionately and during the first 10 days of May, even the permeable local topsoil will take some time to allow the flow to percolate below the surface. At this level of analysis, a ponded condition will be taken to last throughout the month. The estimated loss to water surface evaporation is 0.5 feet. In addition, with an available water capacity of 0.2, 4 feet of soil will retain 0.8 feet of water that will be used by vegetation after ponding and temporary water table buildup have receded. That leaves 2 feet, or 160 acre-feet of water as induced recharge of the shallow aquifer.

The geologic log from a residential well nearby shows the bottom of the unconsolidated alluvium to rest on crystalline rock at a depth of 54 feet below ground surface. Analysis of a pump test on the same well resulted in a hydraulic conductivity estimate of 214 feet per day. There was no observation well, so storage properties are unknown. A well a few miles away in the same valley bottom was tested with benefit of an observation well. That test is the closest

known source of aquifer storage information, 0.20 for specific yield. Although not from the site, the estimate will be used for preliminary analysis, pending further investigation.

Table 19 gives the grid configuration for the scenario. Notice that the spatial distribution of impulse flow given by Table 19:B represents delivery through the legacy splitter box with 5 parts going to one half of the property for every 1 going to the other half. Table 20 presents other input for the scenario, on the following page.

Table 19: Adjacent Recharge Facilities Grid

A – Increments and Cell Classification

dY	j	i	dX 2,640 / 1	1,320 / 2	660 / 3	660 / 4	660 / 5	660 / 6	660 / 7	1,320 / 8	2,640 / 9
2,640	1		3	3	3	3	3	3	3	3	3
1,320	2		3	3	3	3	3	3	3	3	3
660	3		3	3	3	3	3	3	3	3	3
660	4		3	3	3	1	1	3	3	3	3
660	5		3	3	3	1	1	3	3	3	3
660	6		3	3	3	3	1	1	3	3	3
660	7		3	3	3	3	1	1	3	3	3
660	8		3	3	3	3	3	3	3	3	3
660	9		3	3	3	3	3	3	3	3	3
660	10		3	3	3	3	3	3	3	3	3
100	11		2	2	2	2	2	2	2	2	2

B – Spatial Distribution of Impulse

j	i	1	2	3	4	5	6	7	8	9
1										
2										
3										
4					5.00	5.00				
5					5.00	5.00				
6						1.00	1.00			
7						1.00	1.00			
8										
9										
10										
11										

Delayed Impact Calculator

Table 20: Adjacent Recharge Facilities Input

Tab	Parameter	Input	Units
Format	Impulse, Type	Deep Percolation	
	Units	Acre-feet	
	Aquifer, Type	Unconfined	
	Mean, Type	Weighted Harmonic	
	Update, Timing	Same Step	
	X Increments, Number	9	
	Specification	Discrete	
	Lengths	Per Table 19:A	[feet]
	Y Increments, Number	11	
	Specification	Discrete	
	Cell Class	Per Table 19:A	
Ground	Specification	Uniform	
	Value	0	[feet]
Head	Initial Head, Specification	Uniform	
	Value	4	[feet]
Thickness	Aquifer Bottom, Specification	Uniform	
	Value	54	[feet]
Conductivity	Hydraulic Conductivity, Specification	Uniform	
	Value	214	[feet/d]
Storage	Specific Yield, Specification	Uniform	
	Value	0.200	[ ]
Impulse	Spatial Distribution, Specification	Discrete, Head	
	Values	Per Table 19:B	
Response	Number of Response Zones	1	
Streambed	Type	Permissive	
Time	Site Name	Snowy River	
	Scenario Designation	Proposed Recharge Facilities	
	Solution Threshold Order	3	
	Schedule Type	Annual Pattern	
	Analysis Periods	60	
	Period Units	Months	
	Units per Period	1	[months]
	Steps per Period	4	
	Impulse Arrival	Steady	
	Secondary Output	Impact Factor	
	Well Injection, Total	Period 5: 160, All others: 0	[acre-feet]

As with the previous example, the grid definition given by Table 19:A does not need cells on the far side of the creek from the recharge site, because the permissive bed allows dissipation of all built-up head at the creek. Were the bed restrictive, analysis would be faulty without additional cells across the creek to store groundwater not accepted by the bed.

After all input has been entered, click the compute button. The calculation is "Ended" prematurely, and an "Inundated Ground" note posts. The note warns that the scenario is not tenable, as the aquifer and cover material cannot accept all of the water during May alone. Therefore, in answer to the first question under this heading above, berms alone are not adequate for the scheme to succeed, unless they are allowed to impound water past the end of the month, thereby incurring further evaporation loss. A probable cause of the fault is the disproportionate distribution of water between the two sub-parcels. Were the splitter box and lateral ditches leading therefrom altered in addition to berm construction, greater uniformity of application may be achieved and the aquifer may be able to accept all of the water as it is delivered. The simplest modification of the splitter may be to reconfigure to give equal shares to each lateral, and that may well be the winning plan. To continue this example, the hypothetical splitter will be changed to from 5:1 to 1.5:1 and impact schedule computation will be attempted again. This time the calculation succeeds!

What is the streamflow impact of the groundwater return flow induced by the reconfigured recharge facility? Figure 10 presents the Impact Schedule Chart. Table 21, presents a portion of the impact schedule data, including the impact factors.

Delayed Impact Calculator

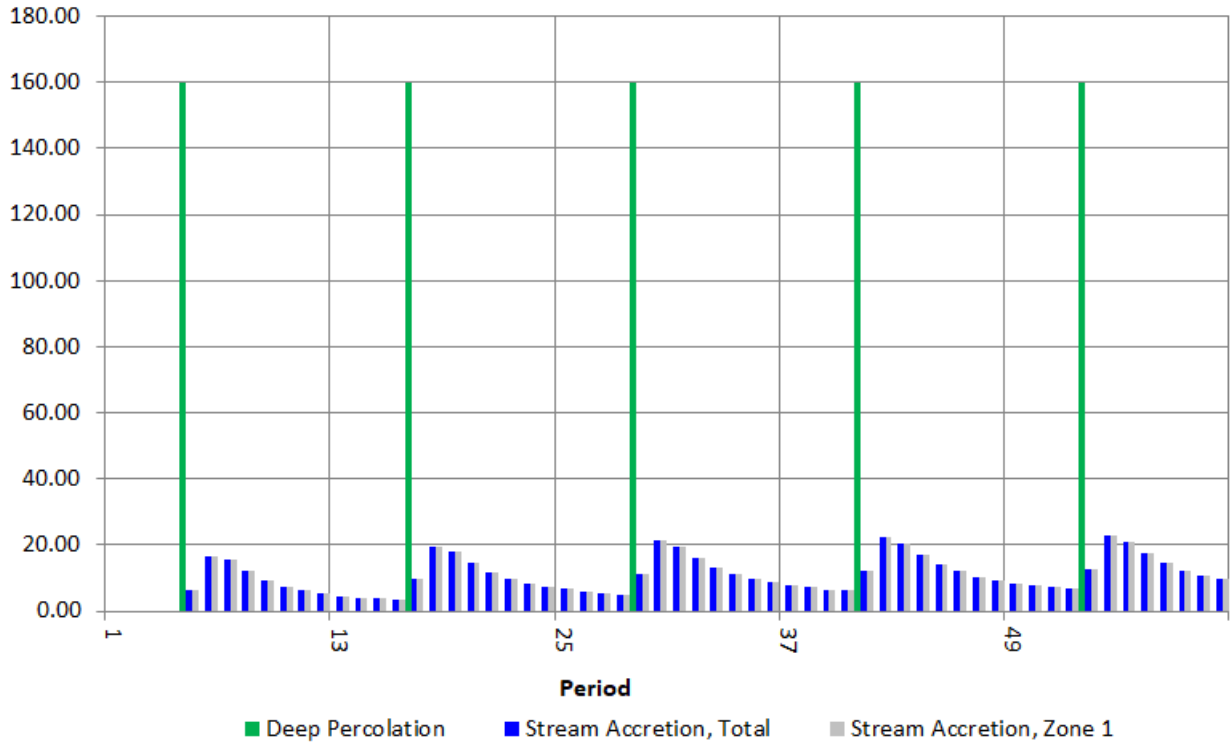Figure 10: Impact Schedule Chart, Injection Well Example

Table 21: Example Recharge Impact Schedule

Period	End Time	Deep Percolation Total	Stream Accretion Zone 1	Stream Accretion Total	Impact Factor
[ ]	[months]	[acre-feet]	[acre-feet]	[acre-feet]	[ ]
1	1	0.00	0.00	0.00	0.0552
2	2	0.00	0.00	0.00	0.0502
3	3	0.00	0.00	0.00	0.0462
4	4	0.00	0.00	0.00	0.0429
5	5	160.00	6.41	6.41	0.0848
6	6	0.00	16.68	16.68	0.1534
7	7	0.00	15.36	15.36	0.1414
8	8	0.00	12.00	12.00	0.1158
9	9	0.00	9.37	9.37	0.0957
10	10	0.00	7.52	7.52	0.0812
11	11	0.00	6.21	6.21	0.0706
12	12	0.00	5.28	5.28	0.0627

The impact factors are calculated from the second to last year of output, a proxy for dynamic equilibrium; however, they are presented at the top of the table to avoid the need to scroll. They do not correspond to the periods with which they are aligned, but to the position of those periods within the annual pattern. The 12 impact factors sum to 1. As example, the first impact factor of 0.0552 does not correspond to Period 1, but to January of any year after the establishment of dynamic equilibrium. To estimate January stream accretion in any such year, multiply 0.0552 by 160 acre-feet. Use the same approach to answer the question regarding retimed water made available during the growing season for irrigation down river, and get Table 22. Neglecting transit loss, the irrigation season supply sums to 114 of 160 acre-feet, or enough for the consumptive use of about 50 acres of irrigation, depending on details.

Table 22: Example Recharge Retimed Irrigation Supply

April	6.9
May	13.6
June	24.5
July	22.6
August	18.5
September	15.3
October	13

Exploration Topics:

A) After 60 months, the final cumulative ratio of response to impulse is only 0.7808. This means that the Impact Factors were computed before dynamic equilibrium dominated the system. Repeat the calculation through a span of 240 months. Compare the resulting Impact Factors, and factor-determined irrigation season impact. How much different are the first approximations from those obtained with the longer computation? What was the difference in computation time? Was it worthwhile for the degree of improved accuracy achieved?

B) What would the effect to the irrigation supply be were the modified 1.5:1 impulse distribution between the sub-parcel near the river and the sub-parcel farther from the river swapped?

Stream Depletion through Delayed-Yield Aquifer

A fictitious coarse sand aquifer is capped with a few meters of poorly sorted sand that is substantially less permeable. The two layers are abruptly pinched out by a very low permeability clay-bound gravel on all sides, leaving a permeable delayed-yield aquifer that is approximately circular.   A well pumps water from the edge of the aquifer, and a stream runs across the top, as shown by Table 23, presenting the cell classification pattern. All grid increments are 200 m, as given with the other scenario parameters on the page after next by Table 24. Capillary rise is set to None on both the Thickness and Streambed tabs. Update timing is Same Step. Weighted Harmonic aquifer property mean type is specified. Calculation results show that 96.3 percent of the water pumped from the aquifer was replaced from the stream during the period considered.

Table 23: Example Delayed-Yield Aquifer Configuration Cell Classification

j	i	1	2	3	4	5	6	7	8	9	10	11
1		4	4	4	4	3	3	3	4	4	4	4
2		4	4	3	3	3	3	3	3	2	4	4
3		4	3	3	3	3	3	3	3	2	3	4
4		4	3	3	3	3	3	3	3	2	3	4
5		3	3	3	3	3	3	3	3	2	3	3
6		1	3	3	3	3	3	3	3	2	3	3
7		3	3	3	3	3	3	3	3	2	3	3
8		4	3	3	3	3	3	3	3	2	3	4
9		4	3	3	3	3	3	3	3	2	3	4
10		4	4	3	3	3	3	3	3	2	4	4
11		4	4	4	4	3	3	3	4	4	4	4

Exploration Topics:

A) What if the aquifer had been assumed to be unconfined, or confined, instead of delayed-yield (leaky)? How does the response change after changing the Aquifer Type setting and computing again? Resulting Response Ratios (Simple incision) are presented as Figure 11. The confined response concludes within a few months, while the unconfined response continues well after 18 months.

B) What if "Complete" Incision Adjustment had been selected, instead of "Simple" adjustment? How does the calculated response change after changing the setting and computing again? Resulting Response Ratios (Delayed-yield) are presented as

Figure 12. For this example exercise, banks are characterized by saturated horizontal hydraulic conductivity of 20 lengths/d and thickness of 1 length unit. For the first few months, Complete adjustment gives higher response function output. As time proceeds further, Simple adjustment output makes up the difference. Including streambanks allows more accurate assessment of stream response, a reaction that is quicker than approximated with the faulty assumption of impermeable banks (unless artificially high bed conductivity is used).

Table 24: Delayed-Yield Example Input

| Tab	Parameter	Input	Units
Format	Impulse, Type	Well Pumping	
	Units	Consistent	
	Aquifer, Type	Delayed	
	X and Y Increments, Number	11	
	Specification	Uniform	
	Lengths	200	[length]
Ground	Value	5	[length]
Head	Value	10	[length]
Thickness	Aquifer Top, Value	14	[length]
	Aquifer Bottom, Value	34	[length]
Conductivity	Aquifer Horizontal Conductivity	40	[length /d]
	Aquifer Vertical Conductivity	4	[length /d]
	Aquitard Horizontal Conductivity	20	[length /d]
	Aquitard Vertical Conductivity	2	[length /d]
Storage	Aquifer Specific Yield	0.200	[ ]
	Aquifer Specific Storage	0.0001	[/ length]
	Aquitard Specific Yield	0.100	[ ]
	Aquitard Specific Storage	0.00001	[/ length]
Impulse	Spatial Distribution, Specification	Uniform, Volume	
Response	Number of Response Zones	1	
Streambed	Type	Restrictive	
	Incision Adjustment	Simple	
	Stream Head Class	Equivalent	
	Vertical Hydraulic Conductivity	0.5	[length/d]
	Distinct Thickness	1.0	[length]
	Bed Elevation	12	[length]
	Stream Width	10	[length]
Time	Solution Threshold Order	3	
	Schedule Type	Single Impulse	
	Analysis Periods	18	
	Period Units	Months	
	Units per Period	1	[months]
	Steps per Period	30	
	Impulse Arrival	Steady	
	Secondary Output	Response Ratio	
	Well Injection, Total	Period 1: 100,000	[length^3]

Figure 11: Response Ratio by Aquifer Type (Simple)
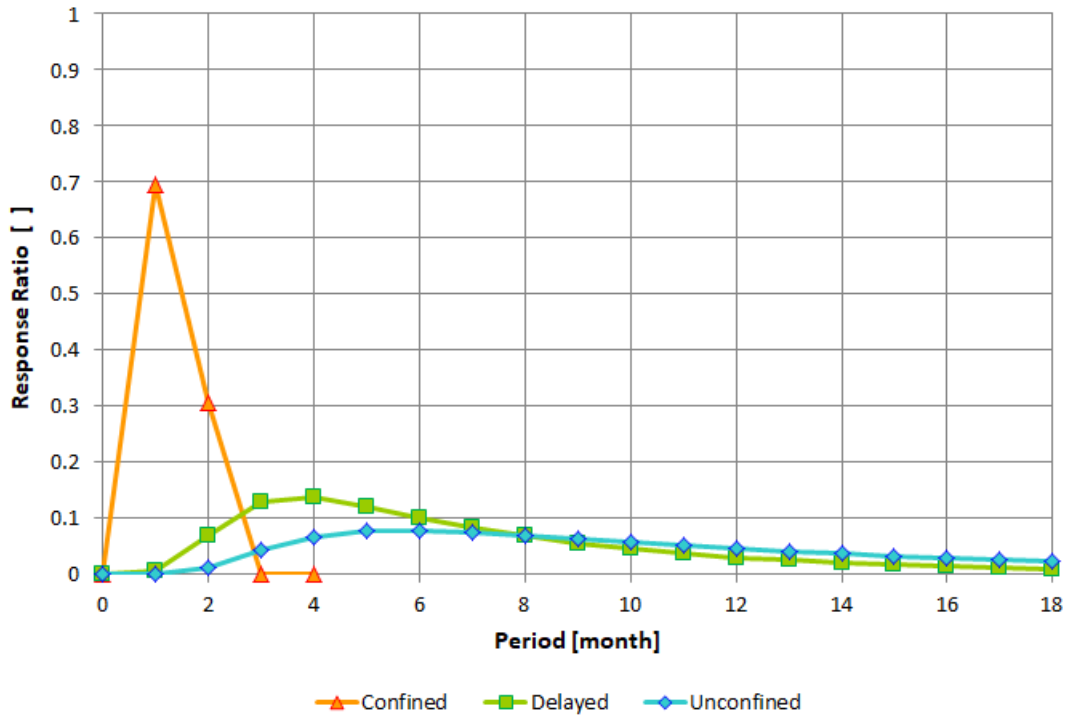
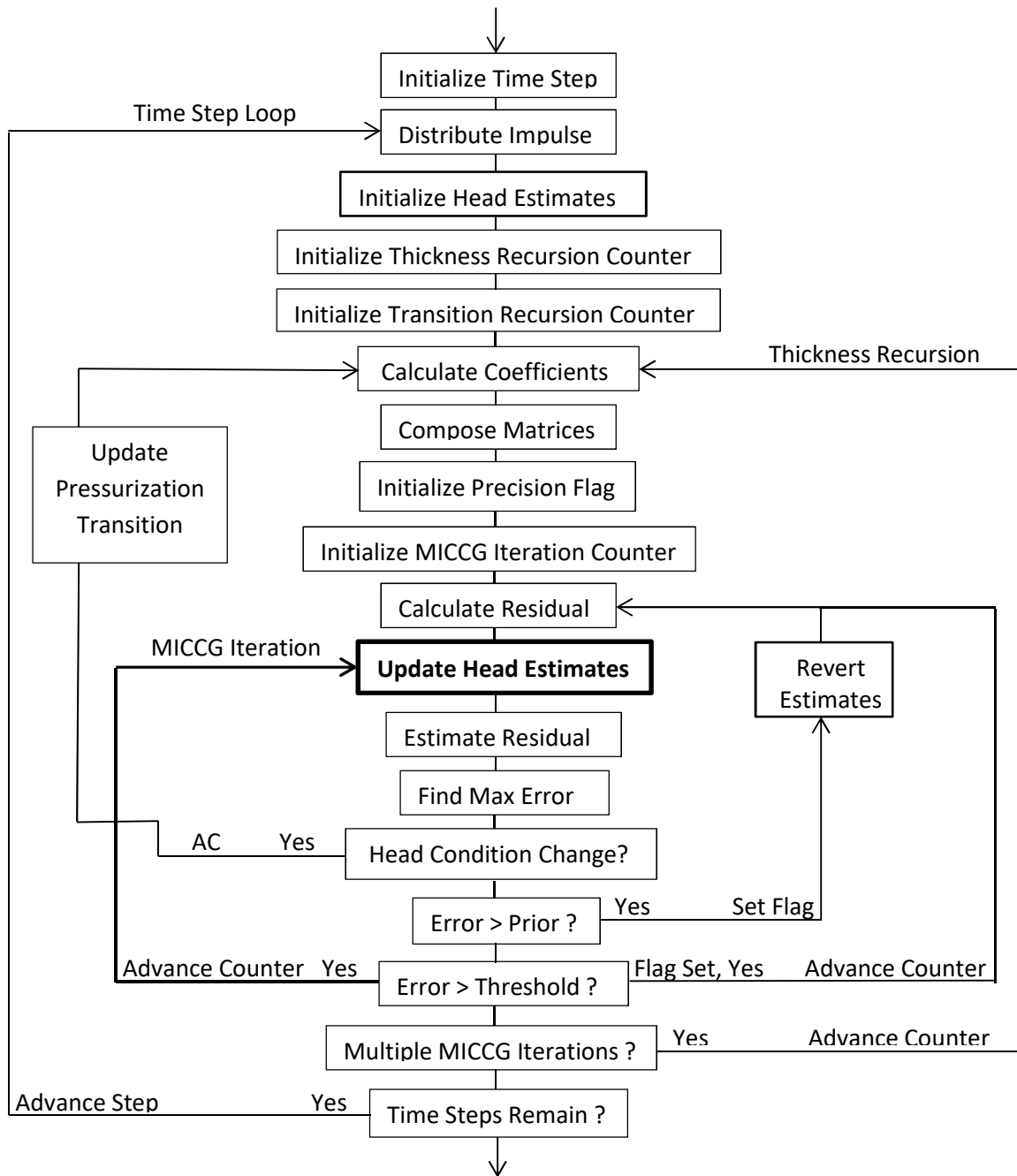Figure 12: Response Ratio by Incision Adjustment (Delayed-yield)

Delayed Impact Calculator
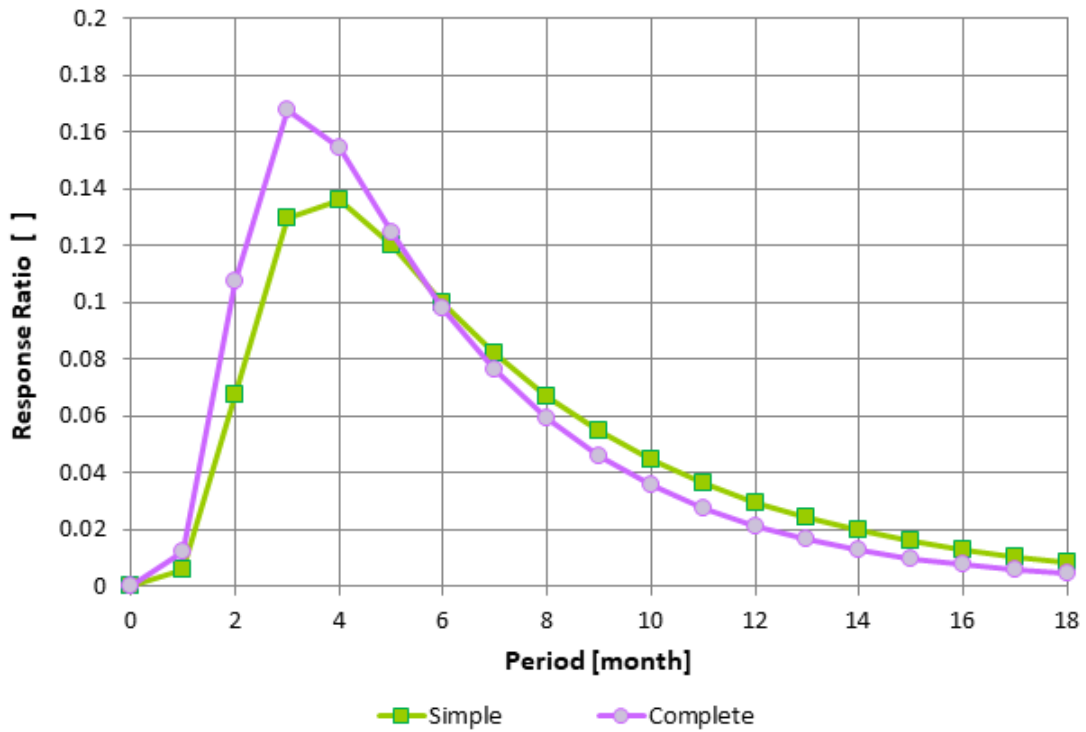
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Delayed Impact Calculator

Appendix A
Head Solution Loops
(simplified, all counters limited)

Initialize Time Step

Time Step Loop → Distribute Impulse

Initialize Head Estimates

Initialize Thickness Recursion Counter

Initialize Transition Recursion Counter

Calculate Coefficients ← Thickness Recursion

Update Pressurization Transition

Compose Matrices

Initialize Precision Flag

Initialize MICCG Iteration Counter

Calculate Residual

MICCG Iteration → **Update Head Estimates**

Revert Estimates

Estimate Residual

Find Max Error

AC   Yes   Head Condition Change?

Error > Prior ?   Yes   Set Flag

Advance Counter   Yes   Error > Threshold ?   Flag Set, Yes   Advance Counter

Multiple MICCG Iterations ?   Yes   Advance Counter

Advance Step   Yes   Time Steps Remain ?

Appendix B
Formulae Available to Average Spatially-Varied Characteristics

Distance-weighted Harmonic Mean

$$\left(\overline{Kh}\right)_{i+1} = \frac{\Delta X_i + \Delta X_{i+1}}{\left(\frac{\Delta X}{Kh}\right)_i + \left(\frac{\Delta X}{Kh}\right)_{i+1}}$$

Distance-weighted Arithmetic Mean

$$\left(\overline{Kh}\right)_{i+1} = \frac{(Kh\,\Delta X)_i + (Kh\,\Delta X)_{i+1}}{\Delta X_i + \Delta X_{i+1}}$$

Simple Arithmetic Mean

$$\left(\overline{Kh}\right)_{i+1} = \frac{(Kh)_i + (Kh)_{i+1}}{2}$$

Delayed Impact Calculator

Appendix C
Unsaturated Linkage of Stream and Aquifer

       With Streambed Type set to Restrictive and Capillary Rise Below Bed set to None, or with Critical Matric Suction set to zero, the Calculator bases coefficient values on ready infiltration of air preventing negative pressure conditions from occurring in the aquifer. Therefore, when aquifer head falls below the bottom of the distinct layer of less permeable streambed material, the link between stream and aquifer is subjected to unsaturated conditions at the bottom of the bed, and the difference in head across the bed to drive flux through the bed is limited to the difference between stream head and bed bottom elevation, meaning that flow through the bed remains constant at its maximum as aquifer head falls farther. This condition requires the following coefficient adjustments.

$$E = A + B + C + D + \frac{(\Delta X)(\Delta Y)\,S}{\Delta t} + \frac{K'L\,W}{M}$$

becomes

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

and

$$F = -\frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

becomes

$$F = -\frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t} - \frac{K'\,L\,W\left(H_R + (M - BED)\right)}{M}$$

where Q_i is neglected as it is zero and *BED* is the elevation of the streambed. These adjustments are applied in the course of the thickness recursion when Same Step update is enabled. When Next Step update is active, this is achieved by addition of a single-loop recursive step.

With Capillary Rise Below Bed set to Simple and a non-zero Matric Suction specified (on the Streambed tab or the Thickness tab), the Calculator bases coefficient values for circumstances with aquifer head falling below streambed bottom on air entry not imposing unsaturated linkage limitation until head falls farther below the bed than the specified Critical Matric Suction, ψ_{cr}, input in units of equivalent water level difference. This recognizes the important contribution of wicking, and gives improved results that account for greater maximum flux. The modest contribution of nonlinear behavior due to transition through varied degrees of saturation as suction exceeds the air entry value for the material is neglected. The coefficient adjustments that account for this phenomenon are the same as those described above, except that (M − BED) becomes (ψ_{cr} + M − BED).
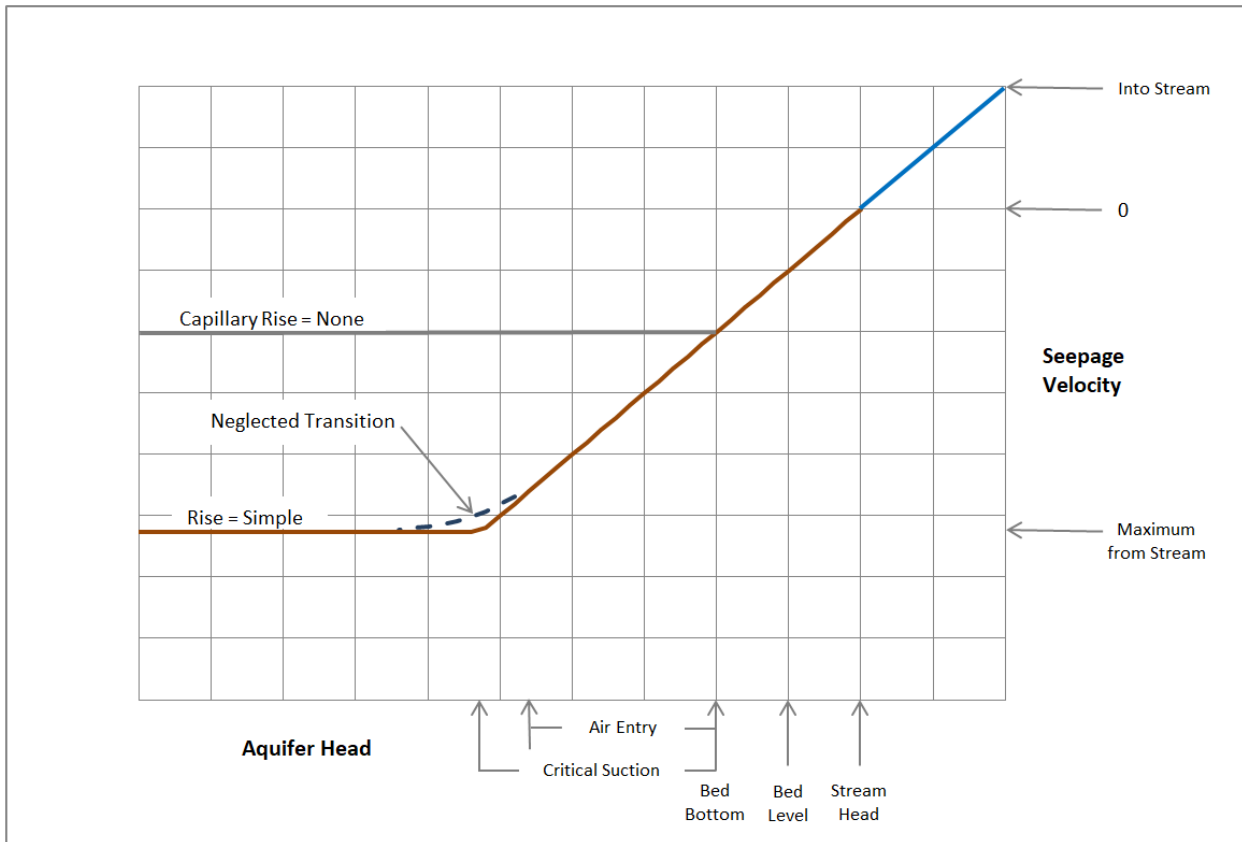
This conceptual diagram is similar to charts presented previously by Harbaugh (2005) and by Fox and Gordji (2007).

Appendix D
Permissive Bed and Barrier Cells

For the calculations carried out by the Calculator, groundwater potential energy in permissive bed cells and in barrier cells is independent of aquifer head in neighboring cells, as it remains constant. This condition is achieved with the following coefficient adjustments.

A, B, C, and *D* all become 0s.

also

$$E = A + B + C + D + \frac{(\Delta X)(\Delta Y)\, S}{\Delta t} + \frac{K'L\,W}{M}$$

becomes

$$E = \frac{(\Delta X)(\Delta Y)\, S}{\Delta t}$$

and

$$F = -\frac{(\Delta X)(\Delta Y)\, S\, H}{\Delta t} - \frac{K'\, L\, W\, H_R}{M}$$

becomes

$$F = -E\, H$$

Solution stability is then achieved by scaling the coefficients to similar magnitude as those computed for other rows in the matrix. For none or simple incision adjustment, cells that neighbor permissive bed stream cells have normal coefficients, since their head levels do depend on their neighbors, including stream cells, in the usual manner. Cells neighboring barriers have zeros for those coefficients that reference the barriers.

Flux through the bed into or out of a permissive stream is determined as a function of neighboring cell aquifer head and stream head. For complete incision adjustment, per Appendix F, cells contacted by permissive channel sides and ends are also treated to keep head equal to stream head. Then stream accretion or depletion is determined from the differential between the cells that neighbor the stream and the cells that neighbor the neighbors. These adjustments are not made for impulse cells. Where a well is located near an incised permissive bed stream, configure the grid to give at least one cell between the impulse cell and response cells. Also, where channel cross-section is small relative to cell dimensions, permissive bed complete incision is not appropriate. Reconfigure grid specification such that channel size better matches cell size.

Aquifer Pressurization Transitions

When rising or falling head passes the elevation of a confining layer, such as the top of a confined aquifer or the bottom of the streambed material in an unconfined aquifer with incision adjustment, (less critical matric suction, where specified) coefficients must be adjusted for the step and cell during which and where the transition occurs, in order to account for separate storage characteristics above and below the confining layer. This is achieved as follows. Here, σ signifies storage volume. In the interest of clarity, the sketches and $\Delta\sigma$ expressions are for cases with no critical matric suction, ψ_{cr}, specified. The coefficient expressions do show the ψ_{cr} terms.

Pressurization:
$$\Delta\sigma = \left(S_y(AqT - H_n) + S_s(AqT - AqB)(H_{n+1} - AqT)\right)(\Delta X)(\Delta Y)$$
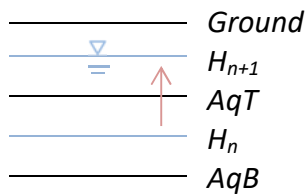
$$E = A + B + C + D + S\frac{(\Delta X)(\Delta Y)}{\Delta t} + \frac{K'L\,W}{M}$$

becomes

$$E = A + B + C + D + S_s(AqT - AqB)\frac{(\Delta X)(\Delta Y)}{\Delta t} + \frac{K'L\,W}{M}$$

and

$$F = Q_I - \frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

becomes

$$F = Q_I + \left(AqT\left(S_y - S_s(AqT - AqB)\right) + S_s(AqT - AqB)\psi_{cr} - (H_n + \psi_{cr})S_y\right)\frac{(\Delta X)(\Delta Y)}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

Depressurization:
$$\Delta\sigma = \Big(-S_y(AqT - H_{n+1}) - S_s(AqT - AqB)(H_n - AqT)\Big)(\Delta X)(\Delta Y)$$

—————— Ground
—————— H_n
—————— AqT
—————— H_{n+1}
—————— AqB

$$E = A + B + C + D + S\frac{(\Delta X)(\Delta Y)}{\Delta t} + \frac{K'LW}{M}$$

becomes

$$E = A + B + C + D + S_y\frac{(\Delta X)(\Delta Y)}{\Delta t} + \frac{K'LW}{M}$$

and

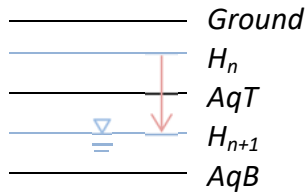$$F = Q_I - \frac{(\Delta X)(\Delta Y)\,S\,H}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

becomes

$$F = Q_I + \Big(AqT\big(S_s(AqT - AqB) - S_y\big) + S_y\psi_{cr} - (H_n + \psi_{cr})S_s(AqT - AqB)\Big)\frac{(\Delta X)(\Delta Y)}{\Delta t} - \frac{K'\,L\,W\,H_R}{M}$$

Where superposition of an incised restrictive streambed or bank occurs, similar treatment is used by taking the elevation of the bottom of the bed or bank material to be the confining layer, analogous to the aquifer top, and by applying confinement to just the portion of the cell beneath the bed or bank.

Where aquitard dewatering occurs, further coefficient adjustment is necessary. The volume drained from the aquitard during the dewatering time step is divided by time step duration and passed to the *F* term for the receiving aquifer cell beneath.

Appendix F
Channel Side Flux

Where the stream channel is very wide compared to its depth or very restrictive, meaning so resistant to flux that almost none passes through, calculated seepage into or out of the stream may not be altered much by flow through the sides, or banks, of the channel. Therefore, with exception of Rovey (1975), past efforts have made the mistake of neglecting side flux with the simplifying assumption that the banks are impermeable. This assumption is particularly problematic for delayed-yield aquifer systems, as bed flux must be attributed to one of two layers, and side flux may be incurred by either layer, or split between layers, depending on system geometry. For systems with moderate channel width and permeability, total stream depletion or accretion cannot be calculated with confidence without a method to formulate the groundwater equations such that each layer is given its due.

The Delayed Impact Calculator corrects this shortcoming by accounting for channel side flux using the "Complete" option for Incision Adjustment. Restrictive bed Complete adjustment adds terms representing channel side flux or streambank seepage to equations that are otherwise the same as for Simple adjustment, as described under Incision Adjustment in the Streambed section of the main text of the manual and given by Equations 2 and 4. For stream width less than cell width, terms are added for every response cell long dimension and for those short dimensions that do not abut another stream cell, boundary, or barrier and are consistent with bank continuity. Where X and Y cell dimensions are equal, the denomination Long is assigned to the dimension with the fewest abutting stream cells. For stream width equal to cell width, terms are added for every side of every stream cell that does not abut another stream cell, boundary, or barrier. Further explanation of bank communication is given by Appendix I. Thickness and storage properties of adjacent cells are adjusted for overlap of bank material.

For delayed-yield aquifers, wet portions of channel sides can be divided by the boundary between aquitard and aquifer; and for any aquifer, wet portions of channel sides change with rising and falling head. Also, flux through different parts of each channel side is driven by a different head relationship. Therefore, the Calculator tracks separate parts of each channel

side, computed for each time step. Example schematics follow, first a simple free aquifer, then a delayed-yield aquifer.
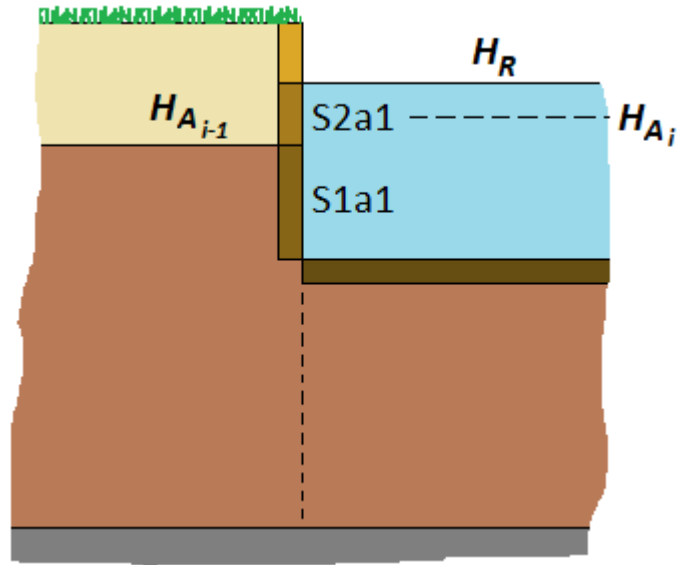
Example free aquifer streambank schematic, stream width equal cell width.
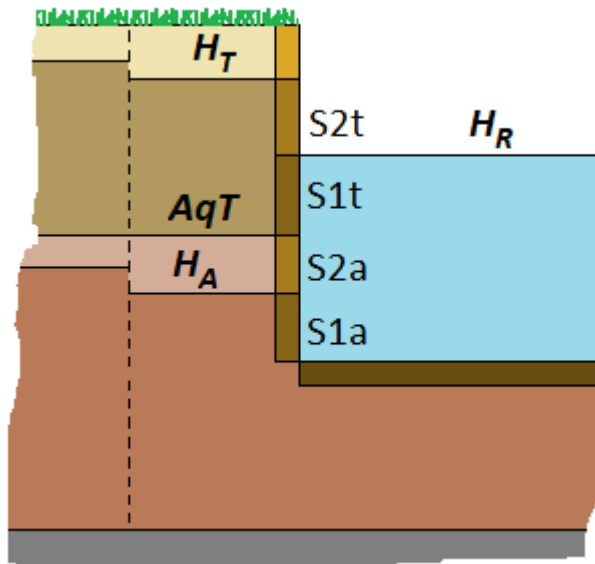
Example delayed-yield aquifer streambank schematic, stream width less than cell width.

The first image shows stream width equal to cell width. Aquifer head is below river head and lower in the cell on the left than in the cell with the stream. Flow through channel side part S2a1 is driven by $(H_R - H_{A\,i-1}) / 2$ plus matric suction of the aquifer material. Flow through channel side part S1a1 is driven by $(H_R - H_{A\,i-1})$ plus suction. Independent calculations are made for the other 3 sides, if warranted.

The second image shows stream width less than cell width. River head is below aquitard head, H_T, and aquitard head is above aquifer head, H_A. H_A is, for this example, below the top of the aquifer, AqT. Matric suction is active in both layers, but further mention is neglected for concise exposition. Flow through channel side part S2t is driven by $(H_T - H_R) / 2$. Flow through channel side part S1t is driven by $(H_T - H_R)$. Flow through channel side part S2a is driven by $(H_R - AqT + H_R - H_A) / 2$. Flow through channel side part S1a is driven by $(H_R - H_A)$. Symmetry allows rapid calculation for the opposite side, also driven by heads within the cell. Adjacent sides depend on neighboring cell heads, where applicable. This case is interesting, because given the transitory head conditions shown, stream accretion flows from the aquitard and stream depletion flows to the aquifer at the same time – for a moment the river is both gaining and losing from the same streambank in the same cell. After aggregation with the other sides of the cell, and with any other cells in the zone, the net is output by the spreadsheet. In most instances flow will just be into or out of the stream on a particular side, although it may occur that flow is out on one side and in on another side of a single cell.

Although development of delayed-yield aquifer capability prompted creation of "Complete" Incision Adjustment, the procedure also benefits free and confined aquifers. For confined aquifers, the fractures system or other means of hydraulic communication that connects the bed and the aquifer also connects the banks and the aquifer. Where matric suction is a factor, driving head relationships are adjusted to include the phenomenon, as the effect can be significant.

Delayed Impact Calculator

Appendix G

Wet Cell Face Flux

When the aquitard in a cell of a delayed-yield aquifer system dewaters, except for any residual capillary fringe, and its neighbor(s) retain effective saturated thickness, continuity for stable solution without abrupt loss of the corresponding horizontal flow component from the wet cell(s) may be enhanced by conveyance of a like flow seeping from the wet cell face(s) through the dry cell into the aquifer beneath. A "Yes." or "No." option on the Conductivity tab allows accomplishment of this by calculating the flux in a manner consistent with flow prior to dewatering. Flux through such a face between neighboring cells under saturated conditions is calculated by *Equation 4*, where the terms collected here appear, although separated.

$$Q = A \, (H_{n+1,j-1} - H_{n+1})$$

Upon dewatering of cell $_j$, $_i$, indices understood not shown, the expression undergoes modest modification.

$$qnoc = A_w(hx_{at,j-1} - hx_{at})$$

A_w is similar to A, just computed by feeding the average transmissivity formula a relatively small non-zero virtual thickness for the dry cell, $h = 0.00001 + UMAT - UMA$, with that last two terms signifying the ultimate matric suction (capillary fringe height) in the aquitard and aquifer, respectively, if employed. $hx_{at,j-1}$ is the prior iteration estimate of $H_{n+1,j-1}$ for the aquitard in the wet cell, and hx_{at} is the corresponding estimate for the dewatered cell.

The calculated flux is subtracted from the lower (aquifer) layer constant term of the cell with aquitard dry and added to the upper (aquitard) layer constant of the wet cell (to give the right signs, even though flow is from the upper layer).

$$F_{aq,j-1} = F_{aq,j-1} - qnoc$$

$$F_{at} = F_{at} + qnoc$$

This stability aid is not presented as a component of precise solution; however, in certain instances, such as where there is large drawdown in material with substantial matric suction near a stream, the option can be of use in quantifying system behavior estimates. Wet cell face flux can be very important for some cases that use arithmetic averaging of aquitard characteristics. For most cases, the contribution is negligible.

Appendix H

Preconditioner Algorithm

The Modified Incomplete Cholesky Preconditioned Conjugate Gradient method (MICCG) of successive approximation is a numerical method that depends on a preconditioner matrix adapted from the coefficient matrix of the system of equations to be solved, as described by Hill (1990, 2003). The sum of the elements of each row of the preconditioner matrix, $\underline{M}$, is equal to the sum of the elements of the same row of the coefficient matrix, $\underline{A}$. To accomplish this, the diagonal elements of the upper triangular matrix factor of $\underline{M}$ are calculated by a special algorithm. The upper triangular matrix is $\underline{U}$, and the diagonal elements of $\underline{U}$ are $u_{i,i}$. Above the diagonal, the elements of $\underline{U}$ are the same as the elements of $\underline{A}$. Below the diagonal, all elements of $\underline{U}$ are zero. The diagonal elements are calculated by this general algorithm.

$$u_{i,i} = (1 + \delta)a_{i,i} - \sum_{k=1}^{i-1} \frac{u_{k,i}^2}{u_{k,k}} - \sum_{j=1}^{i-1} f_{j,i} - \sum_{j=i+1}^{N} f_{i,j}$$

For $a_{i,j} \neq 0$,

$$f_{i,j} = 0$$

For $a_{i,j} = 0$,

$$f_{i,j} = \sum_{k=1}^{i-1} \frac{u_{k,i} u_{k,j}}{u_{k,k}}$$

Here, i is the matrix (not grid) row, and j is the matrix column. N is the number of matrix rows (or grid elements). Lower case δ is zero, unless a resulting value of $u_{i,i}$ turns out to be less than or equal to zero. Then, a non-zero value of δ would be determined by recursive calculation of an empirical formula until all $u_{i,i}$ are positive. The relaxation parameter, α (not to be confused with elements of the coefficient matrix, a), is not shown, as it is a multiplier given the value of 1.00, so it does not affect the result.

Delayed Impact Calculator

Although of tight and elegant appearance, as given, the general algorithm is not computationally efficient for the sparse matrices treated by the Calculator. Therefore, an alternative algorithm based on observed patterns of term occurrence and matrix symmetry is used to provide identical results with fewer computations required for the matrices under consideration. Series notation is replaced by for-next row index loops and if-then logic. Double index notation has been replaced by a single row index and terms C, D, and G from Equation 4 (and 5, in the body of the manual). To simplify presentation, u and a are limited to the diagonal terms of their respective matrices. For the same reason, several terms with Greek designators are defined for use here after adaptation from Hill. These definitions use an n subscript as generic stand-in for the purpose of this appendix. The number of columns in the grid is referred to as *L*. Delayed-yield systems are 2 layers, giving rise to the *N/2* terms. The code does not calculate and store values of the Greek terms (with the possible exception of δ), instead calculating u from a, *C*, *D*, *G*, and prior u.

$$xi = \xi_n = \frac{D_n{}^2}{u_n}$$
$$phi = \varphi_n = \frac{D_n C_n}{u_n}$$

$$tau = \tau_n = \frac{C_n{}^2}{u_n}$$
$$theta = \theta_n = \frac{D_n G_n}{u_n}$$

$$gamma = \gamma_n = \frac{G_n{}^2}{u_n}$$
$$psi = \phi_n = \frac{C_n G_n}{u_n}$$

Simplified code for the alternative algorithm is given with Visual Basic for Applications syntax on the next page. This preconditioner is valid for a two-layer system. A less-involved version works for single-layer aquifers. Although kept out of the snippet of code given, population of the above-diagonal terms of U and of the product DU may be accomplished by adding a few lines just above the bottom of the second for-next loop. For DU, each term of U is divided by the diagonal term of the same row. A subsequent loop is necessary for the transpose of U, designated U^T. The solution algorithm does not require calculation and storage of M, found as U^T DU; however, anyone interested could make the calculation and find that the row sums do match A.

```
LineTop:
For i = 1 to N
  u(i) = (1 + δ) * a(i)
Next i
For i = 1 to N
  If i - 1 > 0 Then
    u(i) =  u(i) - ξ(i-1) - θ(i-1) - φ(i-1)
      If i + N/2 - 1 <= N Then
        u(i + N/2 - 1) = u(i + N/2 - 1) - θ(i-1)
      End If
      If i + L - 1 <= N Then
        u(i + L - 1) = u(i + L - 1) - φ(i-1)
      End If
      If i - L > 0 Then
        u(i) =  u(i) - τ(i-L) - φ(i-L)
          If i + N/2 - L <= N Then
            u(i + N/2 - L) = u(i + N/2 - L) - φ(i-L)
          End If
      End If
      If i - N/2 > 0 Then
        u(i) = u(i) - γ(i-N/2)
      End If
  End If
  If u(i) < 0.001 Then
    If δ < Limit Then
      δ = 1.5 * δ + 0.001
      GoTo LineTop
    End If
  End If
Next i
```

Delayed Impact Calculator

Streambank Overlap

For Restrictive streambeds with Complete incision adjustment, where the combination of channel width and bank thickness equals or exceeds cell width, streambanks or channel sides, as described by Appendix F, contact adjacent cells and may overlap from the response cell into these neighboring cells. This allows stream head to be communicated to the adjacent cell(s) through just the bank material without further buffering through the response cell(s). Also, some portion of adjacent cell volume may be occupied by the bank material, and another portion of the cell volume can be confined beneath the bank material. These phenomena are accounted for by special functions that are called when Complete incision adjustment is specified.

Determination of those adjacent cells that are affected, is carried out by algorithms that process configuration characteristics including cell dimensions, stream dimensions, and response cell distribution. First, the orientation considered to be the "long" dimension of each response cell is found. Depending on response cell distribution, this may not be the longest side of the cell. As example, please consider the grid format shown here, with dimensions and cell class codes.

ΔY	j	ΔX	1,000	1,000	500	100	50	50	50	50	50	50	50
		i	1	2	3	4	5	6	7	8	9	10	11
1,000	1		3	3	3	2	3	3	3	3	2	3	3
500	2		3	3	3	2	3	3	3	2	3	3	3
100	3		3	3	3	2	3	3	2	3	3	3	3
100	4		2	2	2	2	2	2	2	2	2	2	2
50	5		3	2	2	2	1	3	3	3	3	3	3
50	6		3	2	2	2	3	2	2	2	4	3	3
50	7		3	3	3	2	3	2	3	2	4	3	3
100	8		3	3	3	2	3	2	2	2	4	2	3
100	9		3	3	3	2	3	3	3	3	4	3	3
500	10		3	3	3	2	3	3	3	3	4	3	3
1,000	11		3	3	3	2	3	3	3	3	4	3	3

The stream orientation algorithm gives results symbolized as 1 or 2, where 1 indicates that the "long" dimension is vertical on the page and 2 indicates horizontal orientation, as shown by the next image.

j \ i	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
4	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
5	0.0000	1.0000	2.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	2.0000	2.0000	1.0000	0.0000	2.0000	2.0000	2.0000		0.0000	0.0000
7	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000		0.0000	0.0000
8	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	2.0000	1.0000		1.0000	0.0000
9	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
10	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
11	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000

After the stream orientation algorithm, bank overlap occurrence is determined based on orientation, distribution, and channel dimensions. Where channel width plus bank thickness equals or exceeds cell width, contact and head communication occur on the "long" sides. In the case of exceedance, overlap also occurs on those sides. On the "short" side at the end of a series of response cells, even a series of just a single cell, contact and overlap likewise occur. Adjacent response cells are not considered to be separated by banks. The next image shows the number of overlapped sides in each cell for a full-width channel case.

j \ i	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	2.0000	0.0000	1.0000	0.0000
2	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	2.0000	0.0000	2.0000	0.0000	0.0000
3	1.0000	1.0000	2.0000	0.0000	2.0000	2.0000	0.0000	3.0000	1.0000	1.0000	1.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	2.0000	0.0000	0.0000	0.0000	2.0000	2.0000	2.0000	2.0000	1.0000	1.0000	1.0000
6	1.0000	0.0000	0.0000	0.0000	2.0000	0.0000	0.0000	0.0000		0.0000	0.0000
7	0.0000	1.0000	2.0000	0.0000	2.0000	0.0000	4.0000	0.0000		1.0000	0.0000
8	0.0000	0.0000	1.0000	0.0000	2.0000	0.0000	0.0000	0.0000		0.0000	1.0000
9	0.0000	0.0000	1.0000	0.0000	1.0000	1.0000	1.0000	1.0000		1.0000	0.0000
10	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000		0.0000	0.0000
11	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000		0.0000	0.0000

Where channel width plus bank thickness is less than cell width, banks do not contact or overlap on the "long" sides. Even for these cases, the "short" side at the end of a series has a bank overlap. In all cases, channel length is considered equivalent to the dimension of the "long" cell side. The next image shows the number of overlapped sides in each cell for a narrow-channel case.

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j \ i	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		1.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		1.0000	0.0000
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000

Communication and overlap on the "short" side at the end of a series is an option that can be disabled by selecting "None" for Stream End Banks on the Streambed tab when Complete incision adjustment is active. This changes the overlap results show above to those shown below.

j \ i	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
2	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000
3	1.0000	1.0000	2.0000	0.0000	2.0000	2.0000	0.0000	2.0000	1.0000	1.0000	1.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	2.0000	0.0000	0.0000	0.0000	2.0000	2.0000	2.0000	2.0000	1.0000	1.0000	1.0000
6	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000		0.0000	0.0000
7	0.0000	1.0000	2.0000	0.0000	2.0000	0.0000	4.0000	0.0000		0.0000	0.0000
8	0.0000	0.0000	1.0000	0.0000	2.0000	0.0000	0.0000	0.0000		0.0000	1.0000
9	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000		0.0000	0.0000
10	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000		0.0000	0.0000
11	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000		0.0000	0.0000

j \ i	1	2	3	4	5	6	7	8	9	10	11
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000	0.0000

Where there is bank overlap, width of overlap is found as either the width of the adjacent channel or the entire dimension of the cell side, depending on the orientation of the adjacent stream cell. Head relationships are then used to calculate flow between surface water and each cell with permeable geologic material in contact with at least one bank.

Thank you for reading this manual!

The End.

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