Streamflow-Routing Package

The Streamflow-Routing Package (Prudic, 1989) has been modified for use in MODFLOW-2000 (Harbaugh and others, 2000, and Hill and others, 2000). Streambed conductance can be defined using parameters, and streamflow observations can be specified. Note that the current version of STR does not support the "FREE" option of the Basic Package, so input must be entered in fixed-field format where indicated.

This version of the Streamflow-Routing Package supports time-varying parameters. Parameters may be designated as time-varying by specifying the optional keyword "INSTANCES" as described below. Each parameter designated as time-varying may include either one or multiple instances, where each instance is a list of reaches and properties that is associated with an instance name. When a time-varying parameter is activated for a stress period, one of the instances defined for that parameter must be specified, and the parameter, for that stress period, applies to the reaches and properties associated with the selected instance. Parameters not designated as time-varying are defined and activated without the need to specify instance names.

Ground-Water Flow Process Input Instructions

Input to the modified version of the Streamflow-Routing (STR) Package is read from the file that has file type "STR" in the MODFLOW name file. Optional variables are shown in brackets. All variables are read with fixed format except as noted.

FOR EACH SIMULATION
0.   [#Text]
        Item 0 is optional -- "#" must be in column 1. Item 0 can be repeated multiple times.

1.   [**PARAMETER**   NPSTR   MXL]
        This optional record is read with free format; it must start with the word "PARAMETER".

2. MXACTS NSS NTRIB NDIV ICALC CONST ISTCB1 ISTCB2
      I10   I10 I10   I10   I10   F10.0   I10   I10

3. [PARNAM PARTYP Parval NLST   [**INSTANCES** NUMINST]]
        Item 3 is read with free format. If PARNAM is to be a time-varying parameter, the keyword "INSTANCES" and a value for NUMINST must be entered.

4a. [INSTNAM]
        Item 4a is read only if PARNAM is time varying. NUMINST repetitions of Item 4 (parts a and b) are read. After each repetition of Item 4a, NLST repetitions of Item 4b are read.

4b. [Layer Row Col Seg Reach Flow Stage Condfact Sbot   Stop]
      I5   I5   I5   I5   I5   F15.0 F10.0   F10.0   F10.0 F10.0
        NLST repetitions of Item 4b are required.   The NLST repetitions of Item 4b follow each repetition of Item 4a when PARNAM is time varying. Repeat Items 3 and 4 for each of NPSTR parameters.

FOR EACH STRESS PERIOD
5. ITMP   IRDFLG   IPTFLG
     I10   I10   I10

```
6. Layer Row   Col   Seg   Reach  Flow    Stage     Cond      Sbot    Stop
    I5    I5    I5    I5    I5    F15.0   F10.0     F10.0     F10.0   F10.0
```

Item 6 is repeated ITMP times if NPSTR=0. If ITMP<0, Item 6 records are used from the previous stress period.

```
7.  [Pname [Iname]]
```
Item 7 is repeated ITMP times if NPSTR>0. Free format is used. Iname is read if Pname is a time-varying parameter.

[Note that either Item 6 or Item 7 may be read, but not both.]

```
8. Width    Slope    Rough
   F10.0    F10.0    F10.0
```
Item 8 is read only if ICALC > 0, in which case Item 8 is repeated for every stream reach. The records must be is the same order as the stream reaches.

```
9.  Itrib(NTRIB)
    10I5
```
Item 9 is read only if NTRIB > 0, in which case Item 9 is repeated NSS times in sequential order of the segments. Each record contains NTRIB values.

```
10.  Iupseg
     I10
```
Item 10 is read only if NDIV>0, in which case Item 10 is repeated NSS times in sequential order of the segments.

Explanation of Variables Read by the STR Package

Text - is a character variable (199 characters) that starts in column 2. Any characters can be included in Text. The "#" character must be in column 1. Except for the name file, lines beginning with # are restricted to the first lines of the file. Text is printed when the file is read.

NPSTR - is the number of stream parameters that will be defined.

MXL - is the maximum number of stream reaches that will be defined using parameters. MXL must equal or exceed the sum of NLST x NUMINST for all parameters.

MXACTS - is the maximum number of stream reaches that will be in use during any stress period. MXACTS includes reaches that are defined using parameters as well as reaches that are defined without using parameters.

NSS - is the number of stream segments

NTRIB - is the number of stream tributaries that can connect to one segment. The program is currently dimensioned so that NTRIB cannot exceed 10.

NDIV - is a flag, which when positive, specifies that diversions from segments are to be simulated.

ICALC - is a flag, which when positive, specifies that stream stages in reaches are to be calculated.

CONST - is a constant value used in calculating stream stage in reaches. It is specified whenever ICALC is greater than 0. This constant is 1.486 for flow units of cubic feet per second and 1.0 for units of cubic meters per second. The constant must be multiplied by 86,400 when using time units of days in the simulation.

ISTCB1 - is a flag and a unit number for the option to write seepage between the stream reaches and model cells into the list file or an unformatted (binary) file.

> If ISTCB1>0, it is the unit number to which seepage between each stream reach and the corresponding model cell will be saved whenever the variable ICBCFL in the Output Control Option is set.
>
> If ISTCB1=0, seepage between each stream reach and the corresponding model cell will not be written into any file.
>
> If ISTCB1<0, streamflow for each reach and seepage between each stream reach and the corresponding models cell will be written into the LIST file whenever the variable ICBCFL in the Output Control Option is set.

ISTCB2 - is a flag and a unit number for the option to store streamflow out of each reach in an unformatted (binary) file.

> If ISTCB2 > 0, it is the unit number to which streamflow in each stream reach will be saved whenever the variable ICBCFL in the Output Control Option is set.
>
> If ISTCB2 ≤ 0, streamflow in each stream reach will not be stored in a disk file.

PARNAM – is the name of a parameter. This name can consist of 1 to 10 characters and is not case sensitive. That is, any combination of the same characters with different case will be equivalent.

PARTYP - is the type of parameter to be defined. For the STR Package, the only allowed parameter type is STR, which defines values of streambed conductance.

Parval - is the parameter value. This parameter value may be overridden by a value in the Sensitivity Process input file or by a value generated by the Parameter Estimation Process.

NLST - is the number of stream reaches that are included in each instance defined for the parameter.

INSTANCES – is an optional keyword that designates a parameter as time varying. The keyword is case-insensitive; that is, it may be entered in any combination of upper- and lower-case letters. If *INSTANCES* is present, it must be followed by a value for NUMINST. If *INSTANCES* is absent, PARNAM is non-time-varying and NUMINST should not be present.

NUMINST – is the number of instances that are included in the definition of a time-varying parameter, where each instance is a list of stream reaches and associated properties. If the keyword *INSTANCES* is present, NUMINST must be present. If the keyword *INSTANCES* is absent, NUMINST should not be present.

INSTNAM – is the name of an instance associated with the parameter PARNAM specified in the corresponding Item 3. The name can consist of 1 to 10 characters and is not case sensitive. That is, any combination of the same characters with different case will be equivalent. Names entered for INSTNAM must be unique for any given parameter, but names may be reused for instances associated with different parameters.

Layer - is the layer number of the stream reach.

Row - is the row number of the stream reach.

Col - is the column number of the stream reach.

Seg - is a number assigned to a group of reaches. Segments must be numbered in downstream order and are read into the program in sequential order.

Reach - is a sequential number in a segment that begins with 1 for the farthest upstream reach and continues in downstream order to the last reach in the segment. Reaches must be read in sequentially because the order in which reaches are read determines the order of connection.

Flow - is the streamflow entering a segment. This value is used only for the first reach of each segment. The value should be specified as either 0 or blank when the reach number (Reach) is not 1. When the inflow to the first reach of a segment is the sum of the outflow from upstream tributary segments, Flow should be specified as -1. When the segment is a diversion, the Flow for the first reach is the amount to divert; however, there will be no diversion if the segment from which the diversion is obtained contains less than the value of Flow.

Stage - is the stream stage. The value of Stage is not used if ICALC>0.

Condfact - is the factor used to calculate streambed hydraulic conductance from the parameter value. The conductance is the product of Condfact and the parameter value.

Sbot - is the elevation of the bottom of the streambed.

Stop - is the elevation of the top of the streambed. The value of Stop is used if the option to calculate stream stage is active (ICALC>0) or when the streambed has zero flow.

ITMP - is a flag and a counter. Its meaning depends on whether or not stream parameters are being used.

> If STR parameters are being used (NPSTR>0), ITMP is the number of stream parameters being used in the current stress period.
> IF STR parameters are not being used (NPSTR=0), ITMP is the number of stream reaches for which data will be read in the current stress period. If ITMP < 0, STR data from the preceding stress period will be reused.

IRDFLG - is a flag, which when positive, suppresses printing of the stream input data for a stress period. The input data are printed if IRDFLG is 0 and ICBCFL in the Output Control Option is set.

IPTFLG - is a flag, which when positive, suppresses printing of stream results for a stress period. Results are printed if IPTFLG is 0, ICBCFL in the Output Control Option is set, and ISTCB1 < 0.

Cond - is the streambed hydraulic conductance.

Pname - is the name of a parameter that is being used in the current stress period. ITMP parameter names will be read. They must be specified in an order that meets the downstream ordering requirements for Seg and Reach.

Iname – is an instance name that is read only if Pname is a time-varying parameter. Multiple instances of the same time-varying parameter are not allowed in a stress period.

Width - is the width of the stream channel. It is read only when stream stage is calculated (ICALC>0).

Slope - is the slope of the stream channel. It is read only when stream stage is calculated (ICALC>0).

Rough - is Manning's roughness coefficient. It is read only when stream stage is calculated (ICALC>0).

Itrib - contains the segment number for each tributary that flows into a segment. NTRIB values are read for each segment. Unused values of Itrib should be set to 0. Itrib records are read only when NTRIB>0.

Iupseg - is the number of the upstream segment from which water is diverted. If the segment is not a diversion, Iupseg should be specified as 0. Iupseg records are read only when NDIV>0.

Parameterization in the STR Package

For each stress period in which streams are to be simulated by the STR Package, input describing the correspondence between layer, row, and column numbers and segment and reach numbers is required. In the original STR-Package documentation (Prudic, 1989, p. 28), this correspondence was included in data item 3. In Modflow-2000, this correspondence can be entered either as part of parameter definitions in item 4b or as non-parameter input in item 6. Note that if any STR parameters are defined, all stream segments and reaches must be defined using parameters. The list of cells, segments, and reaches defining this correspondence must be in sequential order from upstream to downstream, first by segments and then by reaches, as described by Prudic (1989). When parameters are used to define STR segments and reaches, the same ordering requirement applies. When parameters are used, the order of segments and reaches is determined by the order in which parameter names are listed in item 7; for each parameter listed in item 7, the order of segments and reaches is as listed in the parameter definition.

The ordering requirement can be problematic when using parameters in the STR Package. For example, in a case where the modeler might want to define STR parameters based on underlying geology or soil types, devising a parameter-definition scheme that honors the geologic or soils information and simultaneously satisfies the stream-ordering requirement may not be possible. In situations where the stream-ordering requirement can not be met with the desired parameterization, an alternative would be to define the STR input without using parameters and to use UCODE (Poeter and Hill, 1998) or PEST (Doherty, 1994) to parameterize the STR input, calculate sensitivities, and estimate parameters.

The STR Package does not support the additive property of parameters as described in Harbaugh and others (2000, p. 16-19). Multiple parameters may be used to simulate distinct segments in the same cell or group of cells. When this is done, the streamflow in each stream is accounted for individually (and correctly). However, the streambed conductance of a particular segment and reach cannot be defined to be the sum of contributions from multiple parameters. If this approach is attempted (as by specifying the same segment and reach in definitions of different parameters), the streamflow is not accounted for properly, and the resulting heads and flows likely will be wrong.

Calculation of Simulated Equivalents to the Observations

In the Streamflow-Routing Package, flow at each finite-difference cell specified is calculated using equation 8 (Hill and others, 2000), except when the hydraulic heads falls below the bottom of the streambed or if there is insufficient water in the stream. Mathematically, for finite-difference cell n, this is expressed as:

$q_n = C_n(H_n - h_n)$ $\qquad$ $h_n > RBOT_n$, flow entering the reach $\geq C_n(H_n - h_n)$

$q_n = C_n(H_n - RBOT_n)$ $\qquad$ $h_n \leq RBOT_n$, flow entering the reach $\geq C_n(H_n - RBOT_n)$ $\qquad$ (1)

$\qquad\qquad\qquad\qquad\qquad$ flow entering the reach insufficient for the above

q_n = flow entering the reach

If a measured gain to the surface-water body is represented using more than one finite-difference cell, the calculation is summed for the cells involved, using equation 9 (Hill and others, 2000).

Calculation of Observation Sensitivities

In the Streamflow-Routing Package, sensitivities are calculated as they are for the General-Head Boundary Package, except as noted by the second and third situations noted in eq. 1. For cells in which these conditions occur, the contribution to eq. 10 (Hill and others, 2000) is replaced by:

$\dfrac{\partial q_n}{\partial b_\ell} = \dfrac{\partial C_n}{\partial b_\ell}(H_n - RBOT_n)$ $\qquad$ $h_n < RBOT_n$, flow entering the reach $\geq C_n(h_n - RBOT_n)$ $\qquad\qquad$ (2)

$\dfrac{\partial q_n}{\partial b_\ell} = 0.0$ $\qquad\qquad\qquad$ flow entering the reach insufficient for the above.

Observation sensitivities are used in sensitivity analysis and regression as discussed by Hill (1998, p. p. 14-16, 38-42, 58).

Observation Process Input Instructions

Input for the Observation Process STR Package is read from a file that is specified with "STOB" as the file type listed in the name file. Free format is used throughout.

```
0.   [#Text]
```
Item 0 is optional and can include as many lines as desired. Each line needs to begin with the "#" character in the first column.
```
1.   NQST  NQCST  NQTST   (free format)
2.   TOMULTST  EVFST  IOWTQST   (free format)
```
Read items 3, 4, and 5 for each of NQST groups of reaches for which streamflow-routing observations are to be specified.
```
3.   NQOBST  NQCLST  (free format)
```
Read item 4 for each of NQOBST observation times for this group of reaches. STATISTIC and STAT-FLAG are ignored if IOWTQST is greater than zero.
```
4.   OBSNAM  IREFSP  TOFFSET  HOBS  STATISTIC  STAT-FLAG    PLOT-SYMBOL
```
Read item 5 for each of |NQCLST| reaches in this group.
```
5.   SEGMENT  REACH  FACTOR   (free format)
```
Read items 6 and 7 if IOWTQST is greater than 0.
```
6.   FMTIN  IPRN  (free format)
7.   WTQ(1,1), WTQ(1,2), WTQ(1,3), ... , WTQ(1,NQTST) (format: FMTIN)
     WTQ(2,1), WTQ(2,2), WTQ(2,3), ... , WTQ(2,NQTST)
     ...
     WTQ(NQTST,1), WTQ(NQTST,2), WTQ(NQTST,3), ... , WTQ(NQTST,NQTST)
```

Explanation of Variables

Text—is a character string (maximum of 79 characters) that starts in column 2. Any characters can be included in Text. The "#" character needs to be in column 1. Text is printed when the file is read and provides an opportunity for the user to include information about the model both in the input file and the associated output file.

NQST—is the number of reach groups for which streamflow-routing observations are listed. A group consists of the reaches needed to represent one flow measurement (eq. 9, Hill and others, 2000).

NQCST—is greater than or equal to the total number of reaches in all reach groups. NQCST must be greater than or equal to the sum of all |NQCLST|.

NQTST—is the total number of streamflow-routing observations for all reach groups. NQTST must equal the sum of all NQOBST, which are specified in repetitions of item 3 in the input file.

TOMULTST—is the time-offset multiplier for streamflow-routing observations [-- or T/T]. The product of TOMULTST and TOFFSET must produce a time value in units consistent with other model input. TOMULTST can be dimensionless or can be used to convert the units of TOFFSET to the time unit used in the simulation.

EVFST— is the error variance multiplier for observations represented using the Streamflow-Routing Package, and is used to calculate the weights as described below in the explanation of STATISTIC. EVFST makes it easy to change the weights uniformly for all flow observations represented using the Streamflow-Routing Package.

IOWTQST— is a flag that indicates that the variance-covariance matrix on STR-Package flow observations is to be read into array WTQ of item 7. If IOWTQST equals zero, weights are calculated using STATISTIC of item 4; if it is greater than zero, items 6 and 7 are read and used to calculate the weights.

NQOBST—is the number of times at which flows are observed for the group of reaches.

NQCLST—is a flag, and the absolute value of NQCLST is the number of reaches in the group. If NQCLST is less than zero, FACTOR = 1.0 for all reaches in the group.

OBSNAM—is a string of 1 to 12 nonblank characters used to identify the observation.
IREFSP—is the reference stress period to which observation times are referenced. The reference point is the beginning of the stress period.

TOFFSET—is the time offset of the observation, from the beginning of stress period IREFSP [T]. TOFFSET must be in units such that the product of TOMULTST and TOFFSET is in time units consistent with other model input. TOFFSET and TOMULTST from the STOB file and values of PERLEN, NSTP, and TSMULT from the DIS file are used to determine the stress period, time step, and time during the time step for the observation. To specify that an observation is for a steady-state model solution, specify IREFSP as the stress-period number of the steady-state stress period, and specify TOFFSET such that TOMULTST×TOFFSET is less than or equal to PERLEN for the stress period; if PERLEN is zero, set TOFFSET to zero. If the observation falls within a time step, the simulated equivalent is calculated by linearly interpolating between values for the beginning and end of the time step. If the first stress period is transient and the observation falls within the first time step, the simulated equivalent from the end of the time step is used because no flow from the beginning of the time step is available for interpolation.

HOBS—is the observed streamflow-routing-boundary gain (if HOBS is negative) or loss (if HOBS is positive) $[L^3/T]$. The terms 'gain' and 'loss' are from the perspective of the surface-water body, so that gains occur when water leaves the ground-water system, and losses occur when water flows into the ground-water system.

STAT—is the value from which the weight for the observation is calculated, as determined using STAT-FLAG. STATISTIC is ignored if IOWTQST is greater than zero, in which case WTQ of item 7 is used to define the weighting.

STAT-FLAG—is a flag identifying what STATISTIC is and how the weight is calculated. STAT-FLAG is ignored if IOWTQST is greater than zero.

> STAT-FLAG = 0, STATISTIC is a scaled variance $[(L^3/T)^2]$, weight = $1/(STATISTIC \times EVFST)$
> STAT-FLAG = 1, STATISTIC is a scaled standard deviation $[L^3/T]$, weight = $1/(STATISTIC^2 \times EVFST)$
> STAT-FLAG = 2, STATISTIC is a scaled coefficient of variation [--], weight = $1/[(STATISTIC \times HOBS)^2 \times EVFST]$

PLOT-SYMBOL—is an integer that will be written to output files intended for graphical analysis to allow control of the symbols used when plotting data.

SEGMENT—is the segment number of a streamflow-routing cell included in the cell group.

REACH—is the reach number of a streamflow-routing cell included in the cell group.

FACTOR—is the portion of the simulated gain or loss in the reach that is included in the total simulated gain or loss for this reach group (f_n of eq 9, Hill and others, 2000).

FMTIN—is the Fortran format to be used in reading each line of the variance-covariance matrix used to calculate the weighting. The format needs to be enclosed in parentheses and needs to accommodate real numbers.

IPRN—is a flag identifying the format in which the variance-covariance matrix is printed. If IPRN is less than zero, the matrix is not printed. Permissible values of IPRN and corresponding formats are:

Output requires more than 80 columns		Output fits in 80 columns	
IPRN	FORMAT	IPRN	FORMAT
1	10G12.3	6	5G12.3
2	10G12.4	7	5G12.4
3	9G12.5	8	5G12.5
4	8G13.6	9	4G13.6
5	8G14.7	10	4G14.7

WTQ—is an NQTST by NQTST array containing the variance-covariance matrix on STR-Package flow observations [$(L^3/T)^2$]. For elements WTQ(I,J), if $I \neq J$, WTQ(I,J) is the covariance between observations I and J; if I = J, WTQ(I,J) is the variance of observation I. Note that the variance-covariance matrix is symmetric, but the entire matrix (upper and lower parts) must be entered.

REFERENCES

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