

## Appendix 8. Conduit Flow Process (CFP2) Input File Documentation for New Capabilities of CFP2 Mode 1—Discrete Conduits

This appendix summarizes the variables, input data, and input file modifications needed for each of the new features in the second version of the Conduit Flow Process (CFP2). The CFP2 is backward compatible with the previous version of CFP (CFP1) if minor modifications are made to the CFP input file. These modifications are described in the “Modification and Increased Capabilities for Specifying Conduit Boundary Conditions” section. The updates in this version of CFP focus on CFP2 Mode 1, the CFP mode of operation in which users specify a discrete conduit network for the aquifer. Other CFP modes are described in the original CFP documentation (Shoemaker and others, 2008). Three different input files exist for Mode 1:

- CFP, the Conduit Flow Process input file (see Shoemaker and others, 2008, p. 27).
- CRCH, the Conduit Recharge input file (see Shoemaker and others, 2008, p. 30).
- COC, the Conduit Output Control file (Shoemaker and others, 2008, p. 30).

To clarify, item numbers in the following sections are not line numbers; they signify all required input data for each item. Thus, each item may be composed of more than one line of data. The number of lines for each item depends on the number of parameters that must be specified.

### New Capabilities for Simulating Conduit Storage and Flow

This section provides input instructions for implementing recent improvements to conduit storage and flow in CFP2 Mode 1. The purpose of CFP2 Mode 1 is to represent a conduit network as discrete elements (for example, tubes) that are connected through nodes within the model domain. The storage and flow improvements for CFP2 Mode 1 include Conduit Associated Drainable Storage (CADS), multiple-layer CADS (CADSML), and length-dependent exchange. In the input files, item 0 is a “#Required comment line” that can be useful for annotating package input. Item 1 is an integer value that specifies the CFP mode of operation. All newly added features in this version of CFP are for CFP2 Mode 1, thus item 1 of the input files has a value of 1.

#### Conduit-Associated Drainable Storage (CADS)

The Conduit-Associated Drainable Storage (CADS) functionality (see Reimann and others, 2014) is activated by the keyword CADS in item 2 of the CFP input file. The theoretical basis for CADS is provided in appendix 7 and shown in figure 7.3. Item 28 is an optional comment line to document data provided in item 29. Item 29 defines the node number (NO\_N) and exchange factor (K\_EXCHANGE) for each CFP node in both versions of CFP. In CFP2 with CADS, the width of the CADS is defined in the third column of input (W\_CADS). With this format, item 29 reads values for three variables: NO\_N, K\_EXCHANGE, and W\_CADS.

Example input file with  $W\_CADS = 0.25$  meter (m):

```

0.    #optional comment line
1.    1
2.    CADS
...
28.   #NODE K_EXCHANGE W_CADS
29.   1      0.000050      0.25
      2      0.000100      0.25
      3      0.000100      0.25
      4      0.000100      0.25
      5      0.000100      0.25
      6      0.000050      0.25

```

### Multiple-Layer CADS (CADSML)

Multiple-layer CADS (CADSML) is activated by the keyword CADSML in item 2 of the CFP input file. Item 29 is repeated for each CFP node. The values on each line of item 29 are  $NO\_N$ ,  $K\_EXCHANGE$ , and paired values of depth  $z$ , and  $W\_CADS$ , the associated width of the CAD storage (above the specified depth  $z$ ) for each vertical interval of CADS that is specified. Using this format, item 29 contains values for 10 variables:  $NO\_N$ ,  $K\_EXCHANGE$ ,  $Z1$ ,  $W\_CADS1$ ,  $Z2$ ,  $W\_CADS2$ ,  $Z3$ ,  $W\_CADS3$ ,  $Z4$ , and  $W\_CADS4$ . In CFP2, CADSML is limited to four CADS-layers, and layers without CADS must have  $W\_CADS$  defined as zero.

Example input file with  $W\_CADS = 0.25$  meter (m) for depth interval from 150 m to 30 m and  $W\_CADS = 0.50$  m from 30 m to 0 m:

```

0.    #Required comment line
1.    1
2.    CADSML
...
28.   #NODE K_EXCHANGE W_CADS
29.   1      0.000050      150 0.25 30 0.5 0 0 0 0
      2      0.000100      150 0.25 30 0.5 0 0 0 0
...
      5      0.000100      150 0.25 30 0.5 0 0 0 0
      6      0.000050      150 0.25 30 0.5 0 0 0 0

```

## CADS Recharge

The CADS recharge is parameterized in a second input file for CFP, the CRCH input file (see Shoemaker and others, 2008, p. 30). Item 3 of the CRCH input contains input for each CFP node; a node number and a value for the fraction of diffuse recharge, P\_CRCH, are specified on each line. CADS recharge is activated for a node by specifying an additional optional variable, P\_CDSRCH, on the line after the P\_CRCH value. The P\_CDSRCH variable is a real number equal to the fraction of diffuse areal recharge (entered in the MODFLOW-2005 RCH package) partitioned directly into CADS. If P\_CDSRCH is not set in the CRCH input file, the default value of 0.0 is used. In the following example, a value of P\_CRCH equal to 0.500 and a value of P\_CDSRCH equal to 1.0 indicate 100 percent of diffuse areal recharge is routed to CADS in node 1. For nodes 2 through 6, however, the default input for P\_CDSRCH effectively routes zero diffuse areal recharge to CADS.

Example CRCH input file (100 percent of diffuse areal recharge routed to CADS in node 1):

```
0.      #Required comment line
1.      1
2. #node P_CRCH P_CDSRCH
3.      1 0.5000 1.0
        2 0.500
        3 0.500
        4 0.500
        5 0.500
        6 0.500
```

## Length-Dependent Exchange

This option allows the water-transfer coefficient,  $\alpha_{ex}$ , to be applied per unit length  $l$ ; for example, input for this exchange is provided as  $\alpha_{ex} l^{-1}$ . Hence, it is not necessary to specify water-transfer coefficients to each node for which the node-associated conduit length varies (for example, if the spatial discretization of matrix cells is varying). The length-dependent exchange is activated by setting the SA-EXCHANGE flag (see Shoemaker and others, 2008, p. 28) to a value of 2 (item 14 in the example shown). In the following case with a 100-unit length tube, the  $\alpha_{ex}$  is 0.002 and the  $\alpha_{ex} l^{-1}$  is equal to the  $\alpha_{ex}$  divided by the length; thus,  $\alpha_{ex} l^{-1}$  is equal to 0.00002.

Example CFP input file (5 tubes with 100 length units, 6 nodes,  $\alpha_{ex}$  intended as 0.002 and  $\alpha_{ex} l^{-1}$  input as 0.00002)

```
13.     #SA-EXCHANGE flag setting follows: 2 = length-dependent exchange is active
14.     2
15.     #Required comment line
...
28.     #Required comment line
29.     1 0.00002
        2 0.00002
        ...
        6 0.00002
```

## Modification and Increased Capabilities for Specifying Conduit Boundary Conditions

CFP2 Mode 1 has several new boundary conditions that can be applied to each conduit. The new boundary conditions are fixed head-limited flow (FHLQ), well boundary and specified pumping from conduits by stress period, Cauchy boundary, limited head (LH) boundary, and time-dependent (TD) boundary. Each of these boundaries has a specific keyword to activate it. The keywords and input for each boundary condition are described in the corresponding sections. All additional boundary conditions, like the FHLQ boundary condition, are activated and defined in the CFP input file.

Activation of boundary conditions in one or more nodes in the simulation is enabled by specifying the keyword FBC (further boundary conditions) in item 2 of the CFP input file. Several keywords can be linked with a space or underscore, “\_” (for example, FBC\_CADS or FBC CADS). In item 27 in CFP1 Mode 1, the input parameters are the node number (NO\_N) and initial hydraulic head value (N\_HEAD). In CFP2 Mode 1, an additional keyword can be supplied to define the boundary condition type (BC\_TYPE). If no boundary conditions are defined for that node, the keyword “x” is mandatory to indicate no further boundary conditions need be considered for that node. For nodes that are specified with a boundary condition in item 27, BC\_TYPE (boundary condition type at specified node), the optional boundary condition value and related parameters must be specified.

The specific keywords and inputs for each boundary condition are provided in the boundary condition description for each boundary condition type. The CFP2 is backward compatible with models built using CFP1 after some minor modifications to the CFP input file. For models built using CFP1, item 27 must have the keyword “x” added to the third column to specify that none of the new boundary conditions are to be applied to the specified node number on that line.

### Fixed-Head Limited-Flow (FHLQ) Boundary Condition

For the fixed-head limited-flow boundary condition, the keyword “FHLQ” defines the node as having the FHLQ boundary. For each node with the boundary condition, after the FHLQ keyword, the limited-flow value (LQ) value must be provided. In the FHLQ format, item 27 for each node reads values for three or four variables: NO\_N, N\_HEAD, BC\_TYPE, and the optional LQ for the BC\_TYPE of FHLQ. N\_HEAD (column 2) can be defined as a fixed head by using positive values, or values less than or equal to -1 can be used to indicate that heads will be calculated during simulation.

Example CFP input file (fixed-head limited-flow boundary in node 6):

```

0.      #Required comment line
1.      1
2.      FBC
...
26.     #Node Head
27.     1      -1      x
        2      -1      x
        3      -1      x
        4      -1      x
        5      -1      x
        6      50.0   FHLQ 0.045

```

## Well Boundary Condition

The well boundary condition can be specified for one or more nodes in item 27 by using the keyword “WELL” in the third column of input values. The BC\_TYPE keyword “WELL” defines the associated node as containing a well boundary condition.

Example CFP input file (well boundary condition in node 5):

```

0.      #Required comment line
1.      1
2.      FBC
...
26.     #Node Head
27.     1      -1      x
        2      -1      x
        3      -1      x
        4      -1      x
        5      -1      WELL
        6      50.0    x

```

## Specified Pumping from Conduits

The CRCH input file allows definition of pumping rates for various stress periods. The intended pumping rates, variable QWELL (positive for inflow, negative for outflow), are added to item 2 formatted input rows following the value for P\_CRCH (see the “CADS Recharge” section). In the following example, a pumping rate of 0.25 length cubed per time is specified from a well boundary condition specified on node 5 (see well boundary condition example provided earlier). The input reads values for three variables: the node identifier (NODE\_NUMBERS), the percentage of diffuse conduit recharge (P\_CRCH), and the flow rate (QWELL). Please note that for conduits with the defined well boundary, QWELL needs a specified value greater than or equal to 0 (zero) for each time step in case the well is not active (that is, during a recovery period).

Example CRCH input file:

```

0.      #Required comment line
1.      1
      #node P_CRCH QWELL
2.      1 0.000
        2 0.000
        3 0.000
        4 0.000
        5 0.000 -0.25
        6 0.000

```

## Cauchy Boundary Condition

The CAUCHY functionality is activated by the keyword FBC in item 2 of the CFP input file, and boundary conditions are defined for individual nodes in item 27 by the keyword CAUCHY. In each line of item 27, the node identifier and hydraulic head at the specified node (for example, the Cauchy head, HCY, for nodes with the Cauchy boundary) are specified as the first two columns of input. For nodes where Cauchy boundaries are indicated, the keyword CAUCHY appears in column 3 and, when present, is followed by required values of the Cauchy conductivity (CCY) and the Cauchy limited inflow (CYLQ). For this format, each line in item 27 reads NO\_N, HCY, BC\_TYPE, CCY, and CYLQ (CCY and CYLQ are only required if the BC\_TYPE is CAUCHY).

### Example CFP input file (Cauchy boundary in node 6):

```

0.      #Required comment line
1.      1
2.      FBC
...
26.     #Node Head
27.     1      -1      x
        2      -1      x
        3      -1      x
        4      -1      x
        5      -1      x
        6      50.0   CAUCHY 2E-2 0.045

```

## Limited Head Boundary Condition (LH)

The LH functionality is activated by the keyword FBC in item 2 of the CFP input file, and boundary conditions are defined for individual nodes in item 27 (previously only “NO\_N, N\_HEAD” were input) by the keyword “LH” in third column. One line is provided for each node and the selected boundary condition. The head (HLH) value on line 1 of item 27 represents the limited head,  $H_{LH}$ , when the keyword LH follows the head value. Subsequently, each line in item 27 specifies values for three variables: NO\_N, HLH, and BC\_TYPE.

### Example CFP input file (Limited Head boundary in node 3):

```

0.      #Required comment line
1.      1
2.      FBC
...
26.     #Node Head
27.     1      -1      x
        2      -1      x
        3      60.0   LH
        4      -1      x
        5      -1      x
        6      50.0   x

```

### Time-Dependent Boundary Conditions (TD)

Time-dependent input data need to be saved in an external ASCII file. The name of this external file must be included in the MODFLOW Name File (NAM). In the following example, time-dependent boundary condition data are contained in the file named EXT1.txt. The first part of this example shows the contents of EXT1.txt. The second part of the example shows declaration of EXT1.txt in the MODFLOW NAM file.

For the time-dependent boundary condition file, item 1 specifies the number of specified boundary condition timesteps. Item 2 contains one line with two entries for each boundary condition timestep. Column 1 specifies the time, (t), as model time beginning at  $t = 0$  and continuing with one line for each model timestep for each dataset. Ensure that time-dependent data enclose the overall model time. The second entry on each line is the value for the boundary condition associated with that time. Boundary condition data are linearly interpolated between specified periods.

Example time-dependent boundary conditions data file:		
1.	3	
	# T-elap	BndyCond
2.	0	50
	1800	55
	3600	50

For the MODFLOW NAM file, the file EXT1.txt must be specified with the rest of the model input files with a unit number as shown in the example.

Example NAM file (file type DATA; here time-dependent data are provided by the file EXT1.txt with unit number 70):		
CFP	57	SC.cfp
COC	59	SC.coc
DATA	70	EXT1.txt

The time-dependent nature of boundary conditions is activated in the CFP input files (Shoemaker and others, 2008, p. 27) by the keyword “TD” (time-dependent). The TD symbol is directly appended to the boundary-type keyword (that is, to the value of BC\_TYPE—for example, FHLQTD). To specify a TD boundary condition for any boundary condition other than a well, replace the value of the variable that is to be time-dependent with the unit number of the external input file. For the well boundary condition with a TD boundary, the unit number is specified after the well boundary keyword (WELLTD). The examples that follow demonstrate the activation of TD input functionality for all supported types of boundary conditions.

Examples of CFP input files for Time-Dependent Boundary Conditions;  
file unit number for external TD boundary conditions input data is 70:

# Fixed head TD boundary in node 6 read from file unit 70 (Shoemaker and others., 2008, p. 27)

```
...
26. #Node Head
27. 1      -1      x
    ...
    6      70      TD
```

# FHLQ TD boundary in node 6 read from file unit 70

```
...
26. #Node Head
27. 1      -1      x
    ...
    6      70      FHLQTD 1.0
```

# Cauchy TD boundary in node 6 read from file unit 70

```
...
26. #Node Head
27. 1      -1      x
    ...
    6      70      CAUCHYTD 0.005 1.0
```

# Well TD boundary in node 5 read from file unit 70

```
...
26. #Node Head
27. 1      -1      x
    ...
    5      -1      WELLTD 70
```

## Modification and Increased Capabilities of CFP2 Output Files

### Time-Series Analysis (TSA) Output

This functionality provides an additional output file, TSA.out, containing a list that has all inflow and outflow terms of the conduits for every output time step specified in the file used to control CFP output, the conduit output control file (COC). The TSA output is specified in the COC file by assigning a negative sign to the NNODES value in item 2. NNODES is an integer number the absolute value of which is equal to the number of nodes for which flow and head values are desired in separate output files (see Shoemaker and others, 2008, p. 30). In the following example, NNODES is set to -6, signifying that the inflows and outflows for six nodes are to be written to the time-series analysis output file (TSA.out):

Example COC input file to provide TSA output (for 6 nodes)

```
0. #Required comment line
1. # NNODES value follows
2. -6
```

## Time-Series Analysis Along Nodes (TSAN) and Along Tubes (TSAT)

This functionality allows the generation of files that contain output data (time series) resulting from simulated processes along pathways of user defined nodes (TSAN) and tubes (TSAT), such as for all nodes and tubes of a specific conduit branch. To activate the TSAN functionality, item 2 of the COC input file (Shoemaker and others, 2008, p. 30), the number of TSAN nodes (NTSAN), is specified after the number of nodes (NNODES). To activate the TSAT functionality, item 8 of the COC input must contain the number of pipes (NPIPES) and the number of TSAT tubes (NTSAT). The default value for NTSAN and NTSAT is 0, the effect of which suppresses the writing of TSAN and TSAT output, respectively. Following item 13 in the COC input file, the intended node numbers for TSAN output (TSAN\_NODE\_NUMBERS), the TSAN output frequency (TSAN\_NTS), the intended tube numbers for TSAT output (TSAT\_TUBE\_NUMBERS), and the TSAT output frequency (TSAT\_NTS) need to be added.

The example that follows demonstrates the modifications to activate TSAN / TSAT (shown in red). In the example, N\_NTS is an integer value equal to the time-step interval for the output of node head and flow values. Here, N\_NTS equal to 2 activates node-specific output at each of the specified nodes (NODE\_NUMBERS) every two time-steps, and T\_NTS is an integer value equal to the time-step interval for output of pipe-flow rates and Reynolds numbers. In the example, T\_NTS equal to 2 activates pipe-specific output at each of the selected pipes (PIPE\_NUMBERS) every two time-steps.

Example COC input file to provide TSAN and TSAT output  
(NNODES is 6, TSAN for nodes 1, 2, and 4, and TSAT for tubes 2 and 3)

```

0.      #Required comment line
1.      #Required comment line
2.      6 3  #NNODES, NTSAN
3.      #Required comment line
4.      1 #NODE_NUMBERS
      ...
      6
5.      #Required comment line
6.      1 # N_NTS
7.      #Required comment line
8.      5 2 # NPIPES, NTSAT
9.      #Required comment line
10     1 # PIPE_NUMBERS
      ...
      5
11     #Required comment line
12     1 #T_NTS
13     #Required comment line / following TSAN_NODE_NUMBERS
14     1
      2
      4
15     #Required comment line / following TSAN_NTS
16     1
17     #Required comment line / following TSAT_TUBE_NUMBERS
18     2
      3
19     #Required comment line / following TSAT_NTS
20     1

```

## References Cited

- Reimann, T., Giese, M., Geyer, T., Liedl, R., Maréchal, J.C., and Shoemaker, W.B., 2014, Representation of water abstraction from a karst conduit with numerical discrete-continuum models: *Hydrology and Earth System Sciences*, v. 18, no. 1, p. 227–241, <https://doi.org/10.5194/hess-18-227-2014>.
- Shoemaker, W.B., Kuniatsky, E.L., Birk, S., Bauer, S., and Swain, E.D., 2008, Documentation of a conduit flow process (CFP) for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6–A24, 50 p., <https://pubs.usgs.gov/tm/tm6a24/pdf/tm6-A24.pdf>.