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Matchmaking for water Innovation
MAR Solutions - Managed Aquifer Recharge Strategies and Actions (AG128)

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Introduction to MODFLOW Packages

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FREEWAT
Free and Open Source Software Tools for Water Resource Management
EU HORIZON 2020 Project

FREEWAT

This lecture presents an introduction to MODFLOW Packages, highlights the important features and mainly provides references to the most useful literature and webpages! It does not pretend to be a complete MODFLOW manual!

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 642224

GROUNDWATER FLOW (GWF) Packages

- Packages each represent a type of system feature. Some examples:
  - Package that defines model layers and properties:
    - Layer-Property Flow (LPF) Package
    - BCF Package
      - One of the two needs to be defined
  - Packages used to add/remove water at a specified rate:
    - Well (WEL)
    - Recharge (RCH)
  - Packages that add/remove water based on head in the aquifer:
    - General-Head Boundary (GHB)
    - River (RIV)
    - …

How Processes and Packages Interact

	GWF Process	OBS Process
LPF Package	Define K and S properties, possibly using parameters. Calculate contributions to the matrix equations	No observations are now defined for the LPF Package. Possible observations are internal flows.
RIV Package	Define river properties, possibly using parameters. Calculate contributions to the matrix equations.	River gain and loss observations can be defined.

In MODFLOW, subroutines are named using the three-letter identifiers for processes and packages. For example, GWF1LPF6RP

Modflow Packages

- Basic
- Global
- Output Control
- Flow Package
  - BCF
  - LPF
  - HUF
- River
- Drain
- General Head
- Well
- Changing Head Boundary
- Horizontal Flow Barrier
- Stream-Aquifer Interaction
- Recharge
- Evapotranspiration
- Solvers
  - SIP
  - SSOR
  - PCG
  - LMG

Packages from MODFLOW88/96

	Package Name	Abbreviation	Package Description	
required	Basic	BAS	Handles those tasks that are part of the model as a whole. Among those tasks are specification of boundaries, determination of time-step length, establishment of initial conditions, and printing of results.	
required	Block-Centered Flow	BCF	Calculates terms of finite-difference equations which represent flow within porous medium; specifically, flow from cell to cell and flow into storage.	Flow Component Packages
	Well	WEL	Adds terms representing flow to wells to the finite-difference equations.	Stress Packages / Flow Component Packages
	Recharge	RCH	Adds terms representing areally distributed recharge to the finite-difference equations.	Stress Packages / Flow Component Packages
head dependent BCs	River	RIV	Adds terms representing flow to rivers to the finite-difference equations.	Stress Packages / Flow Component Packages
head dependent BCs	Drain	DRN	Adds terms representing flow to drains to the finite-difference equations.	Stress Packages / Flow Component Packages
head dependent BCs	Evapotranspiration	EVT	Adds terms representing ET to the finite-difference equations.	Stress Packages / Flow Component Packages
head dependent BCs	General-Head Boundaries	GHB	Adds terms representing general-head boundaries to the finite-difference equations.	Stress Packages / Flow Component Packages
	Strongly Implicit Procedure	SIP	Iteratively solves the system of finite-difference equations using the Strongly Implicit Procedure.	Solver Packages (1 is required)
	Slice-Successive Overrelaxation	SOR	Iteratively solves the system of finite-difference equations using Slice-Successive Overrelaxation.	Solver Packages (1 is required)

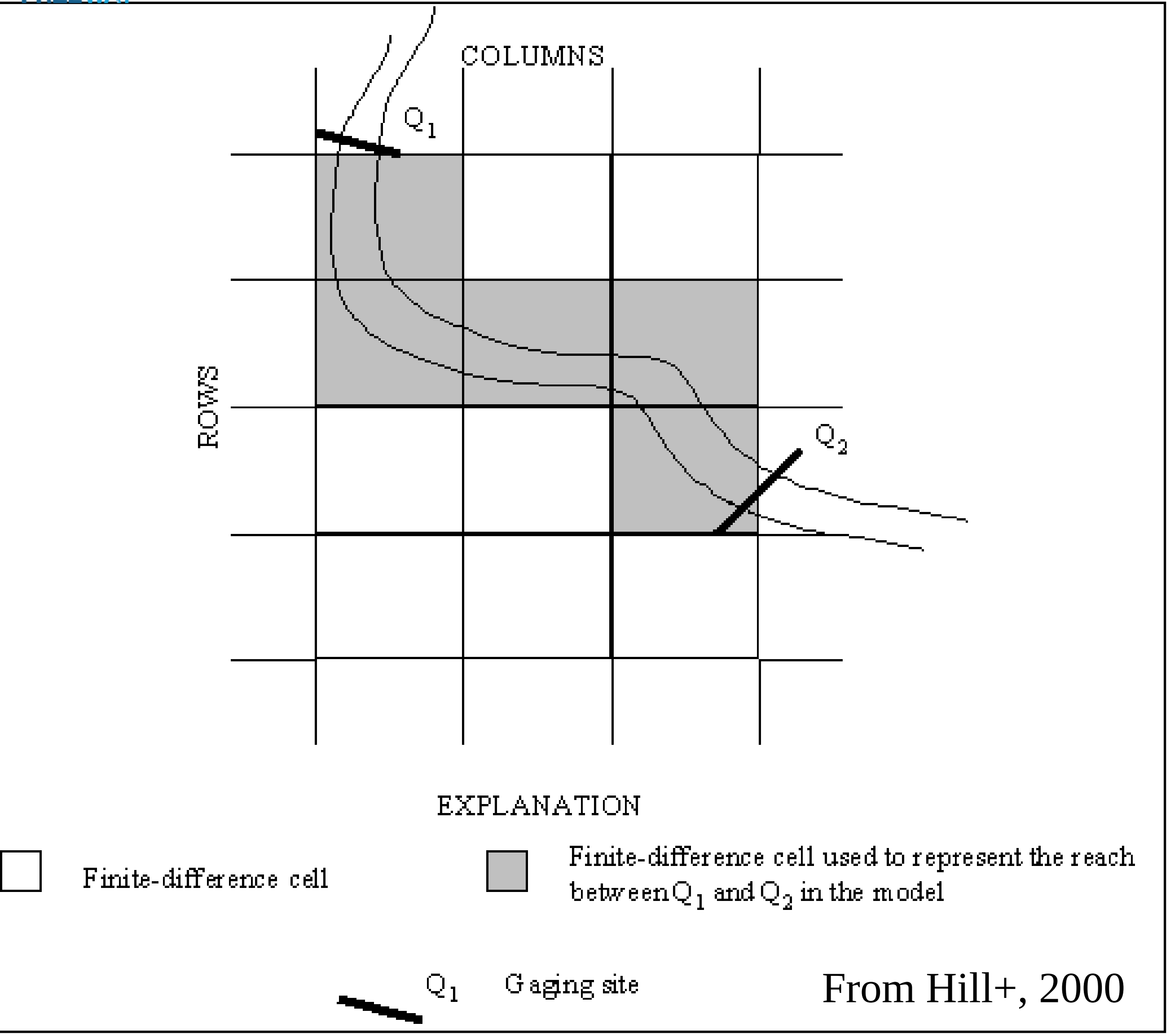
& PCG2

How do the packages work?

- Some examples:

1) WEL package
2) RIV package
3) DRAIN package
4) GHB package
5) LAK package
6) SFR package

Head-dependent boundaries



From Hill+, 2000

Generally use many cells to define a feature. Here, shaded cells are used to simulate flow to compare to measured flow Q_2-Q_1.
Other cells would be used to define the rest of the river.

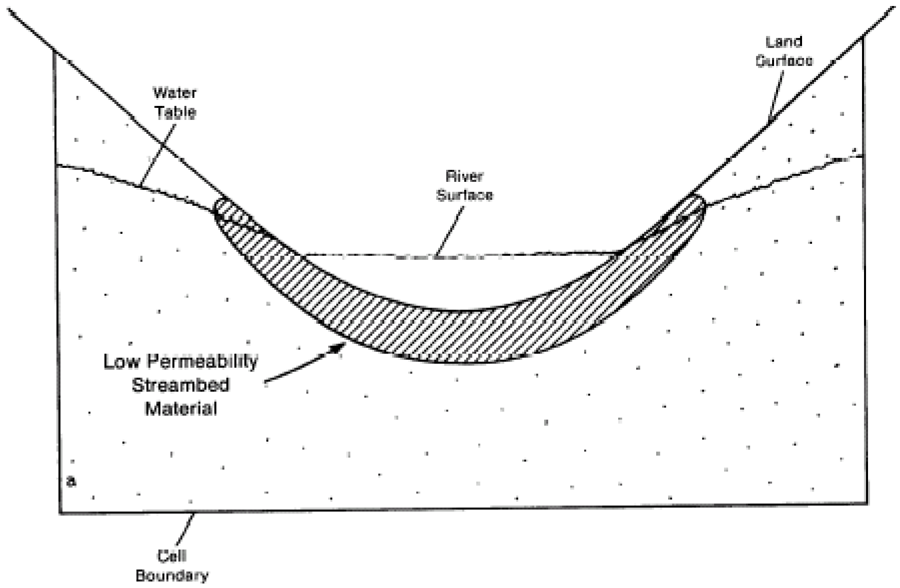
Packages for Head Dependent Boundaries implemented in FREEWAT

$Q = C \Delta h$ where C is the Conductance term

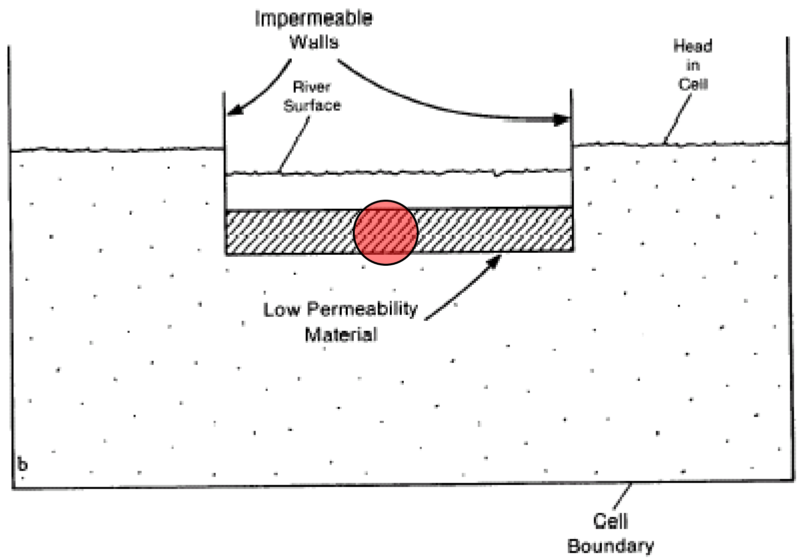
- River Package (RIV)
- Drain Package (DRN)
- General Head Boundary (GHB) Package
- ET Package (EVT and ETS)
- Streamflow routing Package (SFR)
- Lake Package (LAK)
- Unsaturated zone flow package (UZF)
- …

MODFLOW RIV Package/1

http://water.usgs.gov/ogw/modflow/MODFLOW-2005-Guide/index.html?riv.htm



Field setting



Representation in the model

MODFLOW RIV Package/2

MODFLOW RIV Package simulates river/aquifer seepage, depending on the head gradient between the river and the groundwater system.

The riverbed is made of low permeability material and the water level in the model cell stays above its bottom.

The flow between the river and the aquifer in reach *n* is given by:

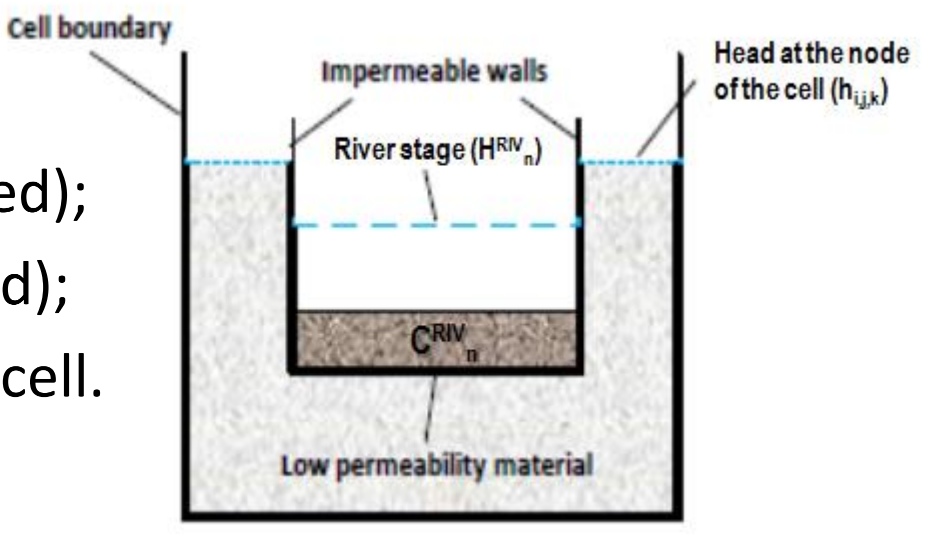
$$Q_n=C^{RIV}_n(H^{RIV}_n-h_{i,j,k}),$$

where:

C^{RIV}_n is the conductance of the riverbed material (user-defined);

H^{RIV}_n is the river stage (user-defined);

$h_{i,j,k}$ is the head at the node of the cell.



MODFLOW RIV Package/3

C^{RIV}_n depends on the hydraulic conductivity of the riverbed and on its geometry, according to the following equation:

$$C^{RIV}_n = K_n L_n W_n / M_n \qquad (1)$$

where:

K_n is the hydraulic conductivity of the riverbed material;

L_n is the length of reach;

W_n is the width of the river;

M_n is the thickness of the riverbed.

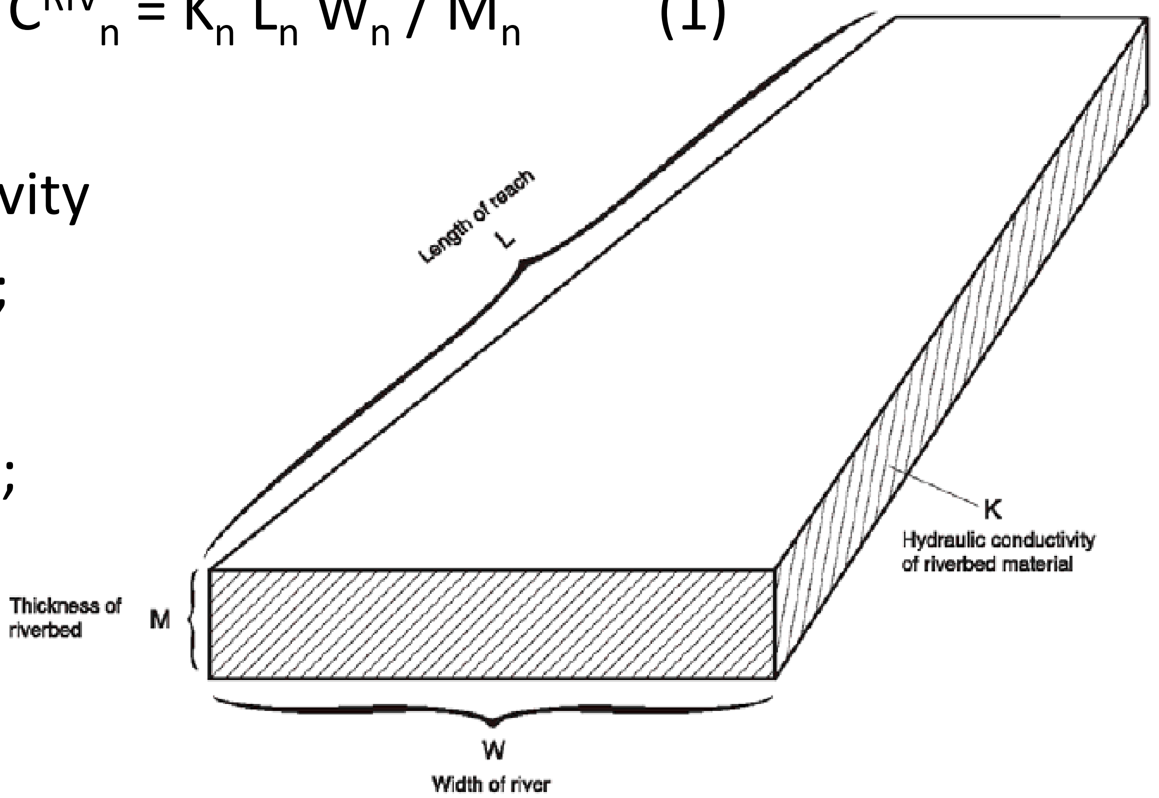
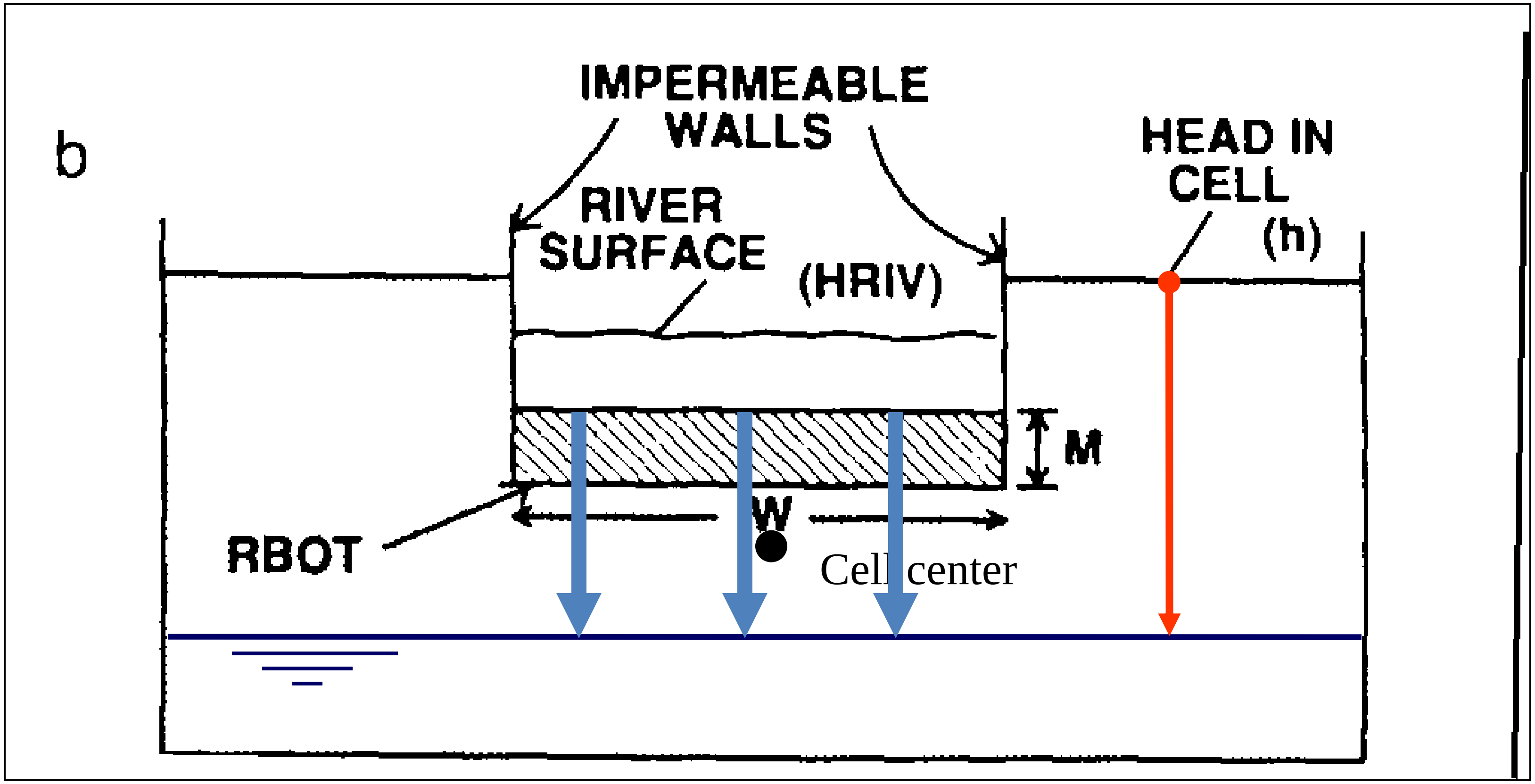


Figure from Harbaugh AW (2005) *MODFLOW-2005, the U.S. Geological Survey modular ground-water model – the Ground-Water Flow Process*. U.S. Geological Survey Techniques and Methods, 6-A16.

MODFLOW RIV Package/4

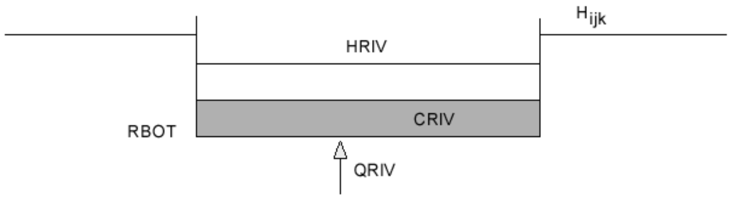
RIV Package with h_n below $RBOT_n$ (h_n<$RBOT_n$): river loosing water toward the aquifer



MODFLOW RIV Package/5

- Summary of river/aquifer conditions:

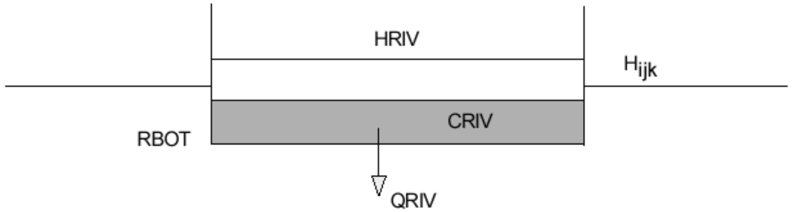
Stage above water table



$$QRIV = CRIV * (HRIV - H_{ijk})$$

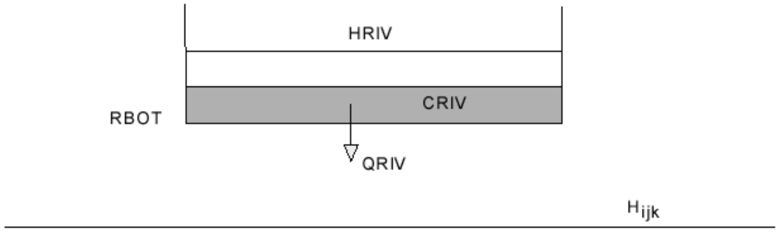
(-Q signifies flow out of cell)

Stage below water table



$$QRIV = CRIV * (HRIV - H_{ijk})$$

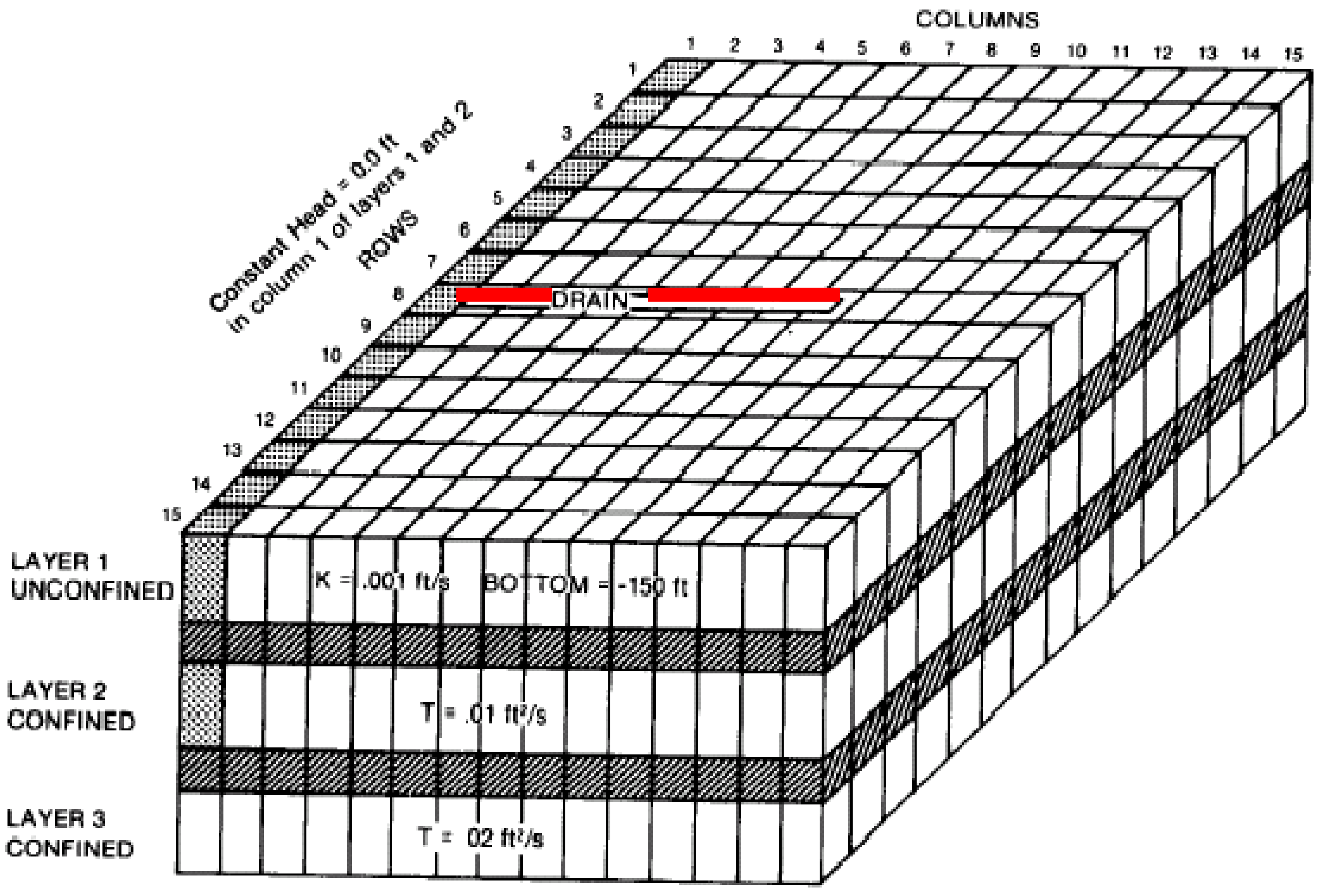
Water table below river bed



$$QRIV = CRIV * (HRIV - RBOT)$$

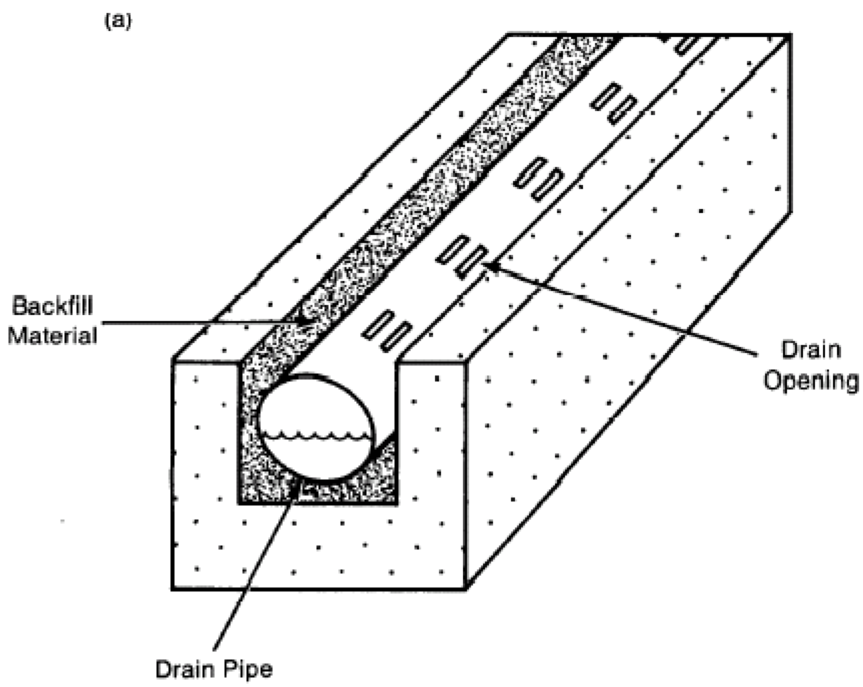
MODFLOW DRN Package/1

http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/



MODFLOW DRN Package/2

MODFLOW DRN Package simulates drain/aquifer seepage, depending on the head gradient between the drain and the groundwater system. The DRN differs from RIV because the drain is only allowed to gain water and it is never loosing water.



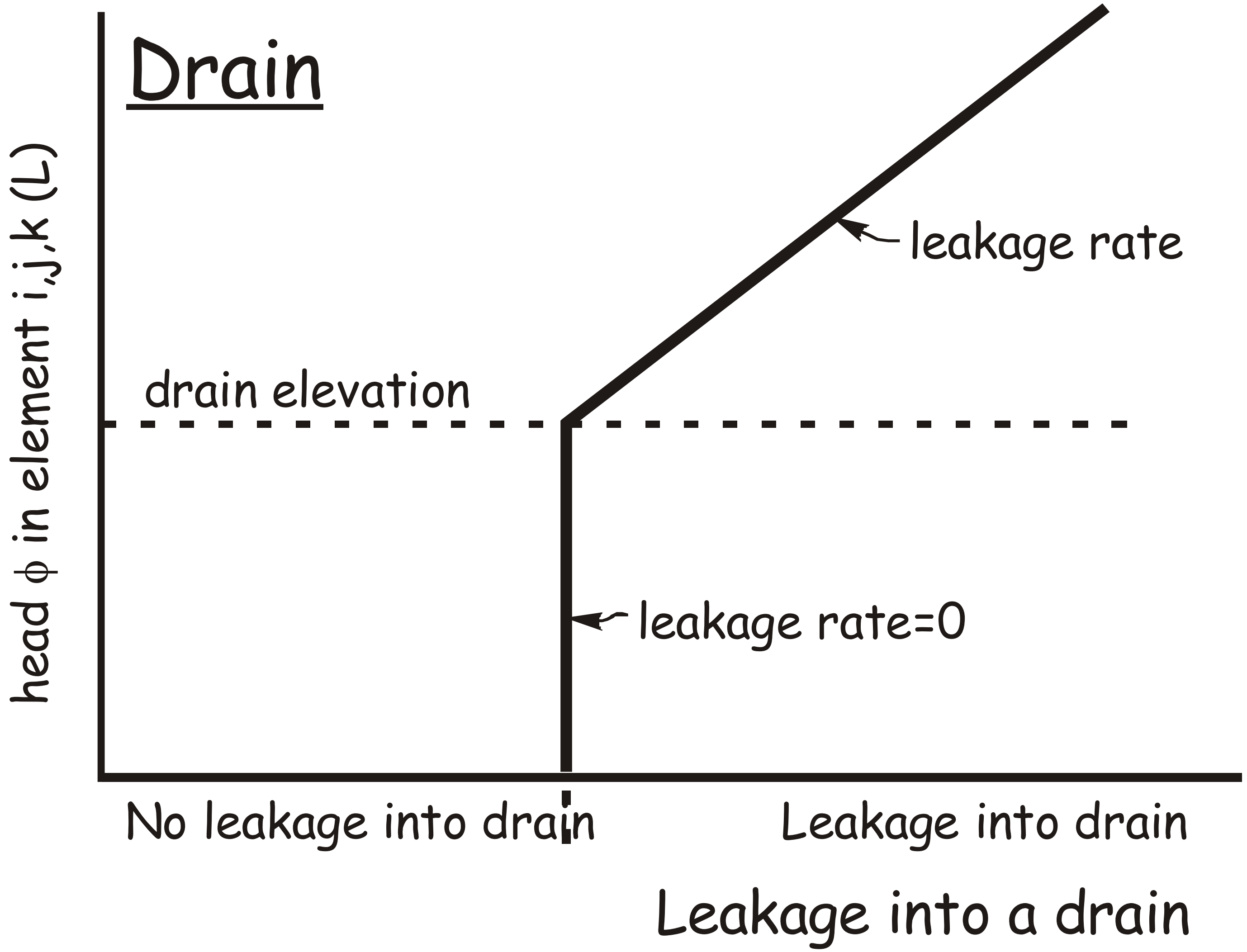
$Q = C\,(h_{ijk} - d)$

where d = head in the drain.

$Q = 0$ if $h_{ijk} < d$

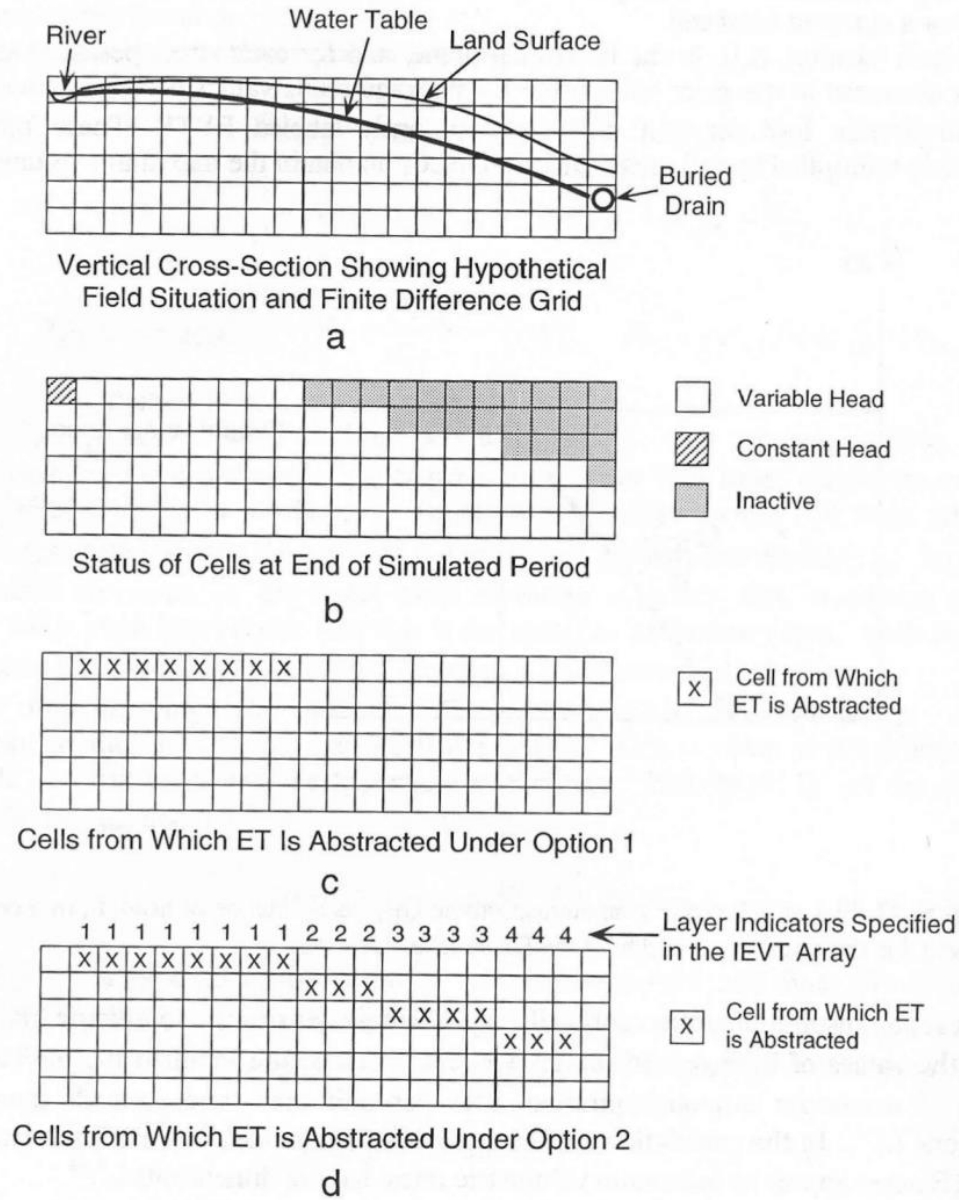
MODFLOW DRN Package/3

Similar to other head dependent packages:

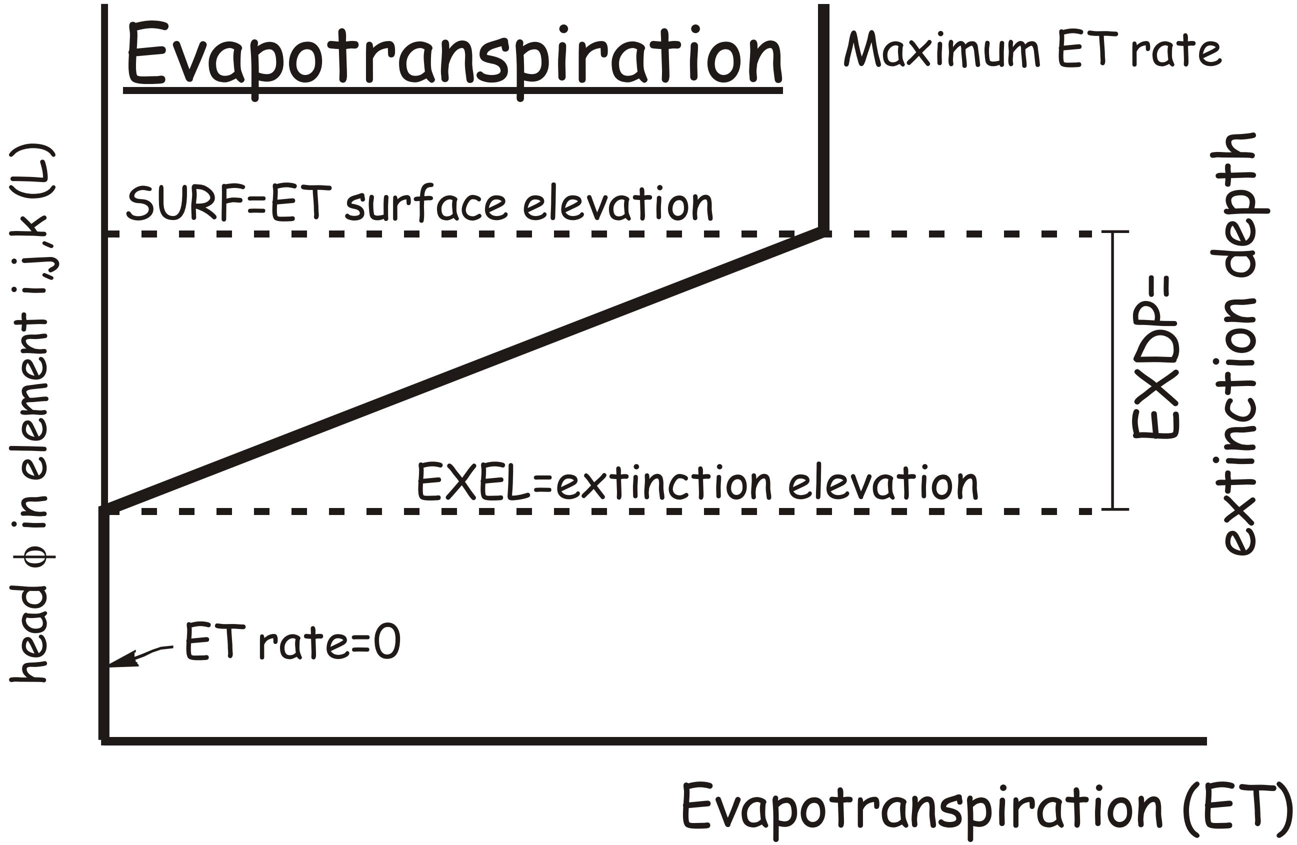


MODFLOW EVT Package/1

- Allows ET only when water table depth is shallow
- Can allow ET only from uppermost cells



MODFLOW EVT Package/2



MODFLOW GHB Package/1

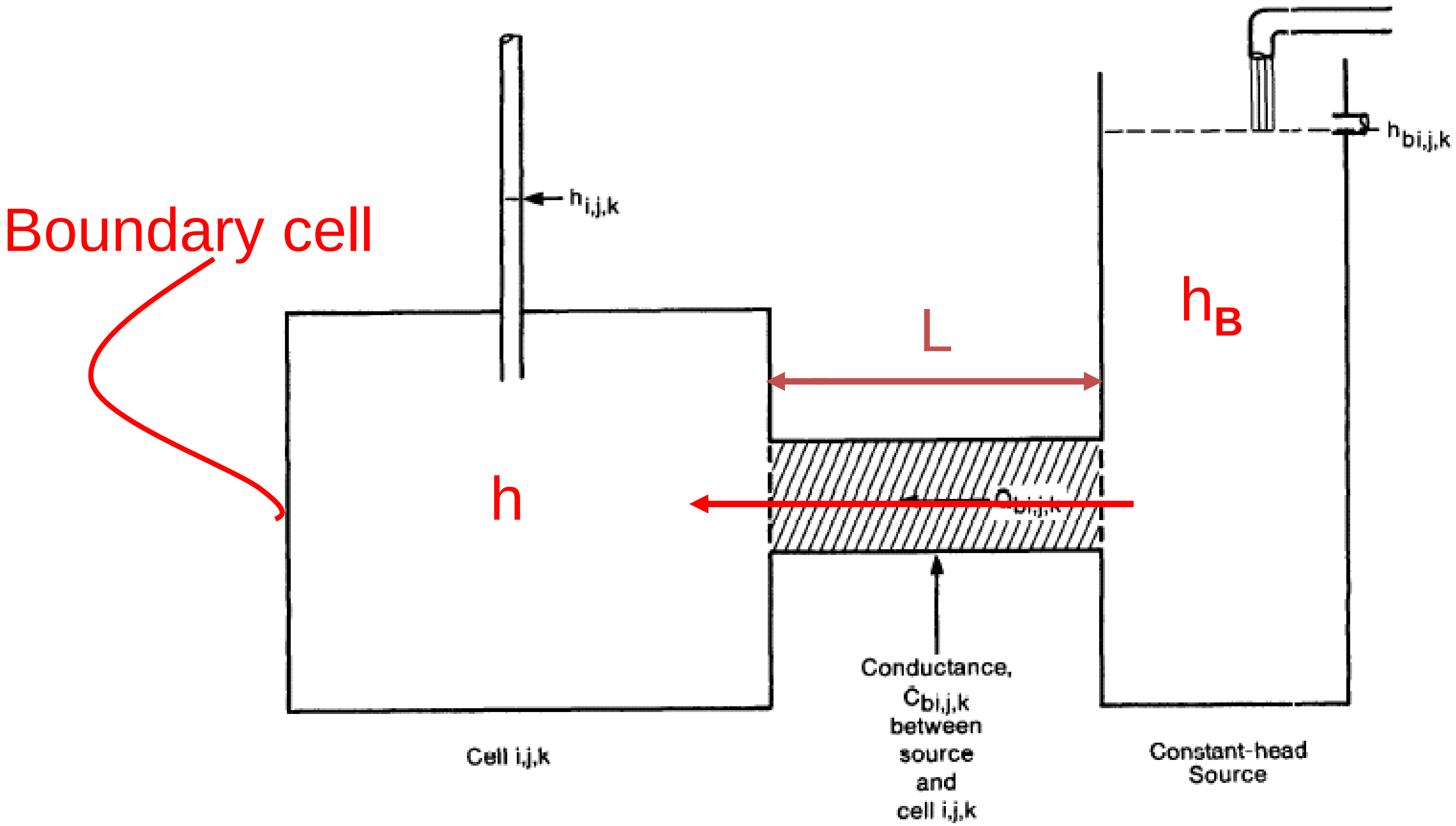


Figure 44.—Schematic diagram illustrating principle of general-head boundary package.

$Q = C\,(h_B - h)$

C = Conductance = K A/L

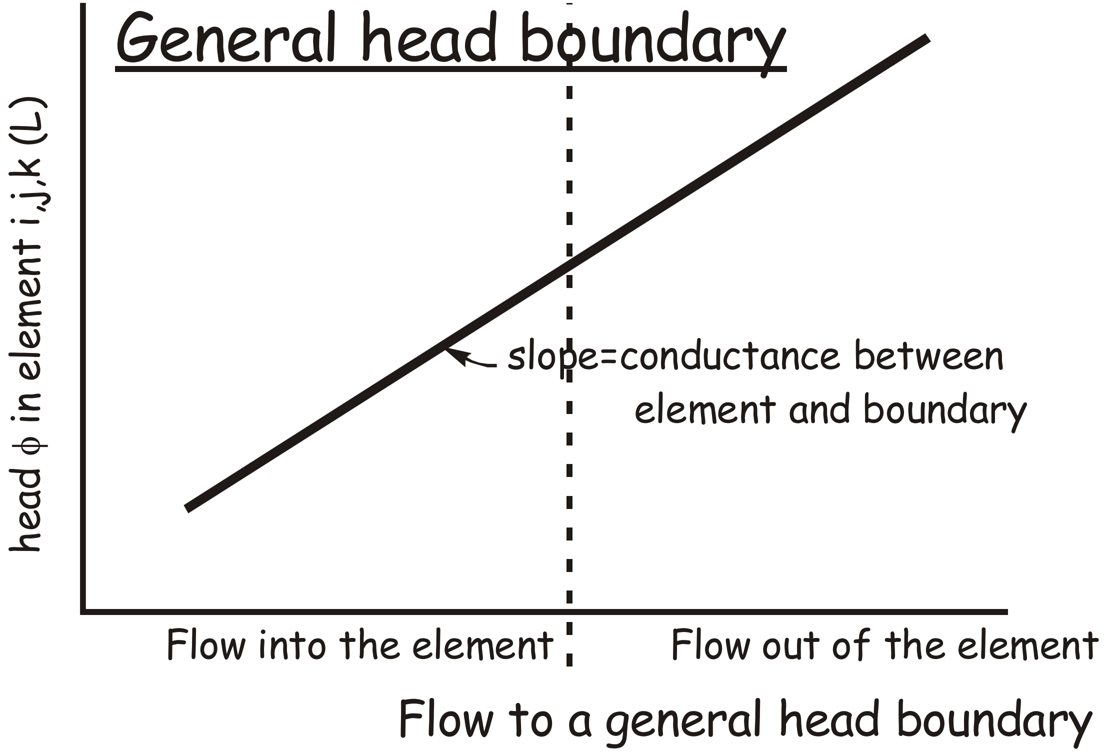
K is the hydraulic conductivity of the aquifer between the model and the lake;

A is the area of the boundary cell, perpendicular to flow.

MODFLOW GHB Package/2

Concept similar to RIV and DRAIN

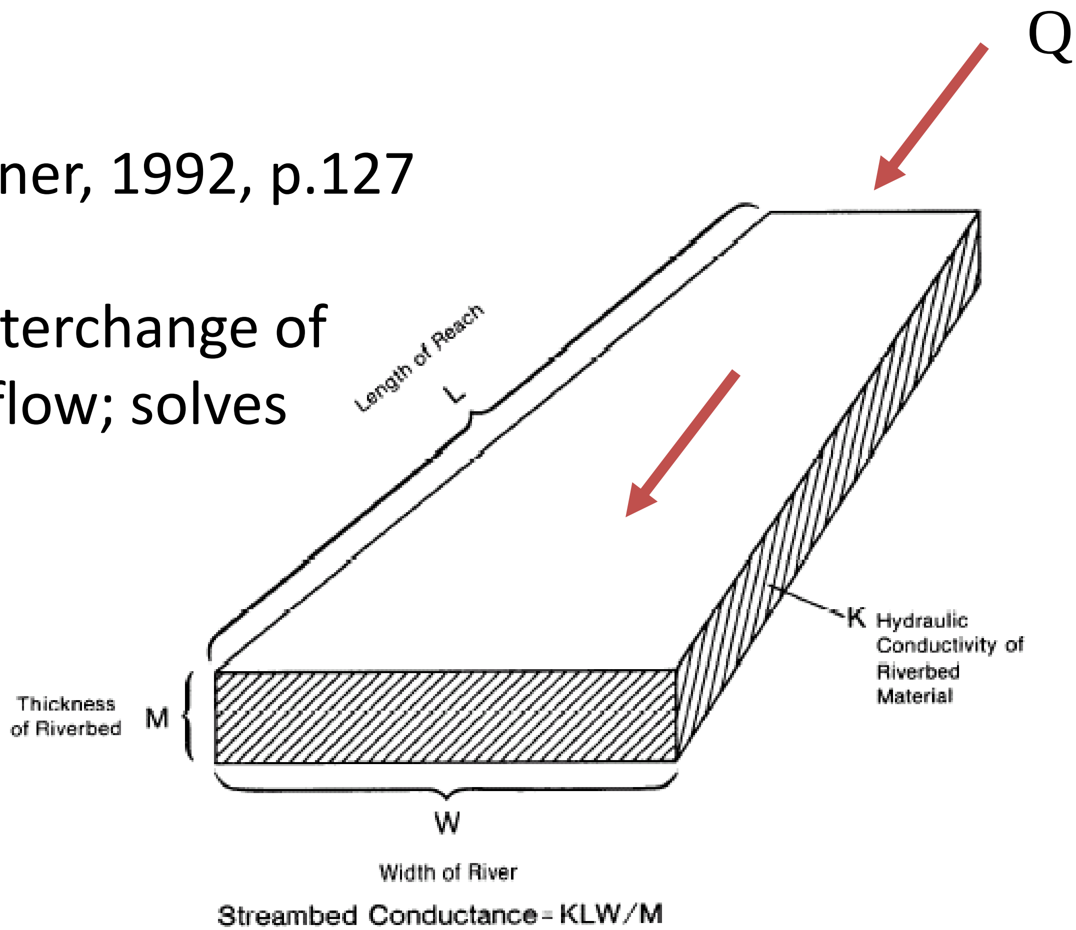
http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/index.html?ghb.htm



Stream Routing Package (STR)

Prudic, 1989
See Anderson and Woessner, 1992, p.127

STR allows for dynamic interchange of groundwater and streamflow; solves for stream stage.



Manning's Equation:

$$d = (Q\, n / C\, w\, S^{1/2})^{3/5}$$

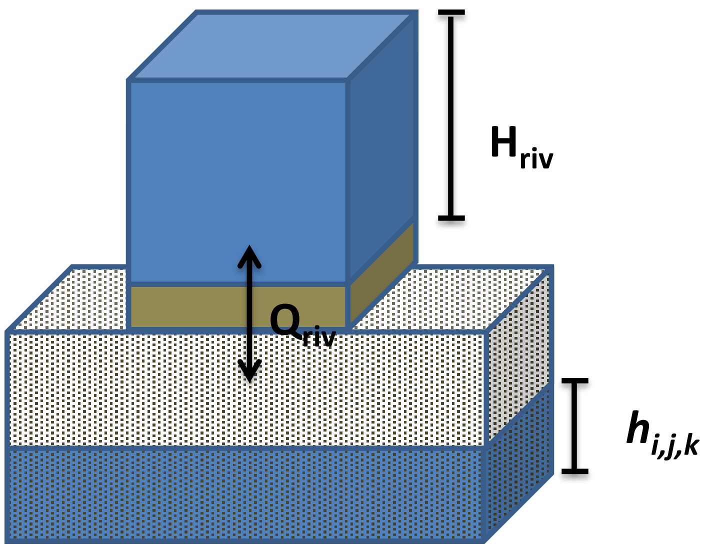
n is Manning's Roughness coefficient

Streamflow Routing Package SFR/1

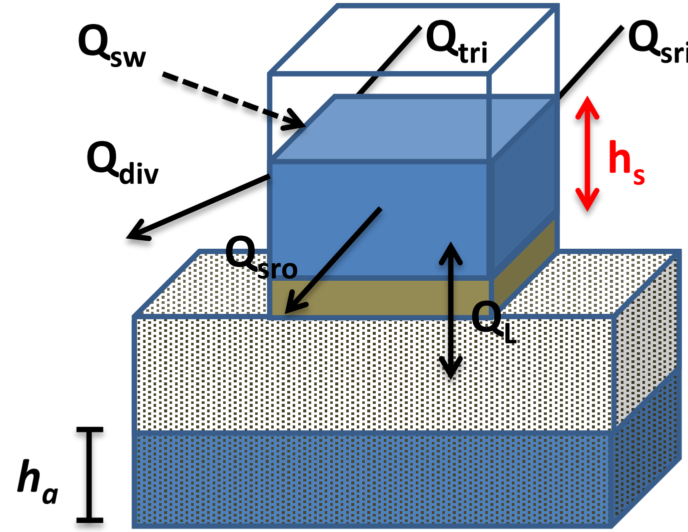
Prudic et al., 2004

RIV and SFR comparison

RIV



SFR



$$Q_{riv} = C_{riv}(H_{riv} - h_{i,j,k})$$

$$C_{riv} = \frac{K\ L\ W}{M}$$

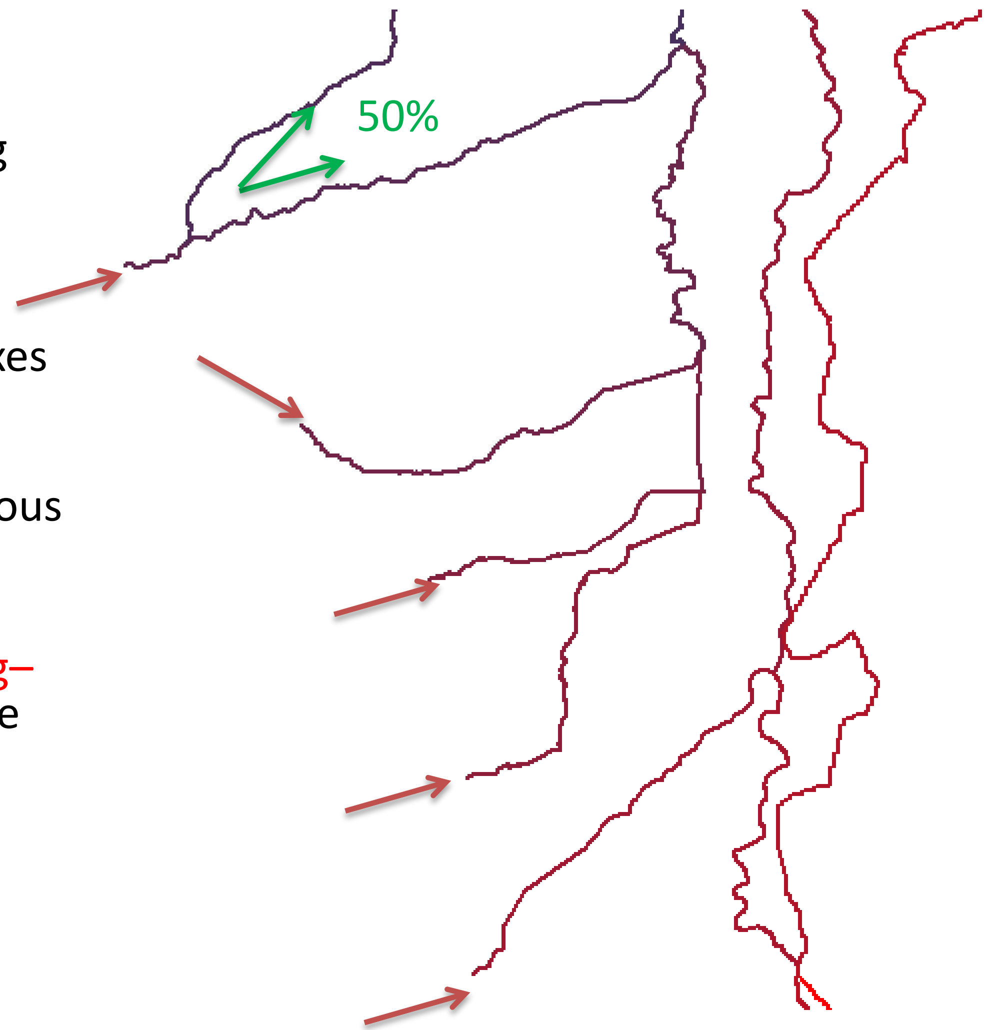
$$Q_L = \frac{KLW}{m}(\boldsymbol{h_s} - h_a)$$

$$Q_{mdpt} = Q_{in} + Q_{out} + 0.5(Q_L)$$

$$Q_L = \left(\frac{C}{n}\right) w \boldsymbol{h_s}^{5/3} S_o^{1/2}$$

SFR package: basic concepts

1. SFR is much less a boundary condition than the RIV package
2. Stream dimensions and starting and ending heights are defined
3. Stream Stage interpolated between two points
4. Diversions based on known fluxes or statistic distribution
5. Inflow to each stream segment can be defined, we use a previous streamflow regression

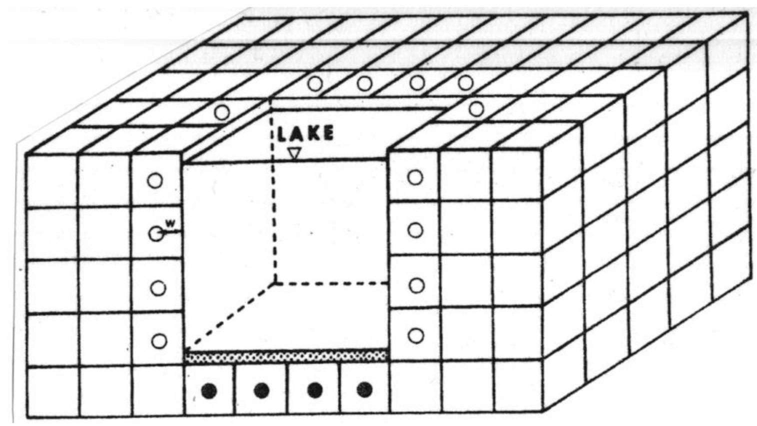


SFR is solving the Gauckler–Manning–Strickler equation and calculating the actual discharge in the river

MODFLOW LAK Package/1

(Cheng and Anderson, GW,1993)
(Council, 1998)
(**Merritt and Konikow, 2000**)

Solves for lake levels

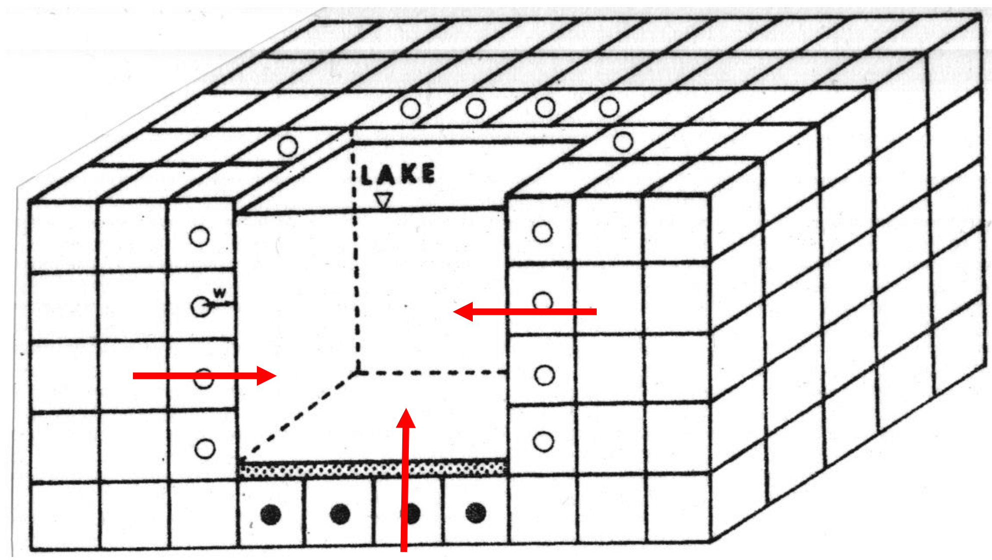


Other packages:

- **Wetland Module**
  (Restrepo et al., GW,1998)

- **MODBRANCH**
  (Swain, 1993)

MODFLOW LAK Package/2



Change in Storage = Outflow - Inflow

Change in lake level = Change in Storage/Area

MODFLOW RCH Package/1

MODFLOW Recharge (RCH) Package simulates areally-distributed direct recharge to groundwater, usually used for rainfall recharge.

The user must define, for each SP, the recharge flux to be applied to the map area, in units of length per time [L/T]. This recharge flux is then multiplied internally by the area of each cell, to get the recharge flow rate at each cell, then expressed as a fluid volume per unit time [L^3/T].

The user must also specify if the areal recharge has to be applied:

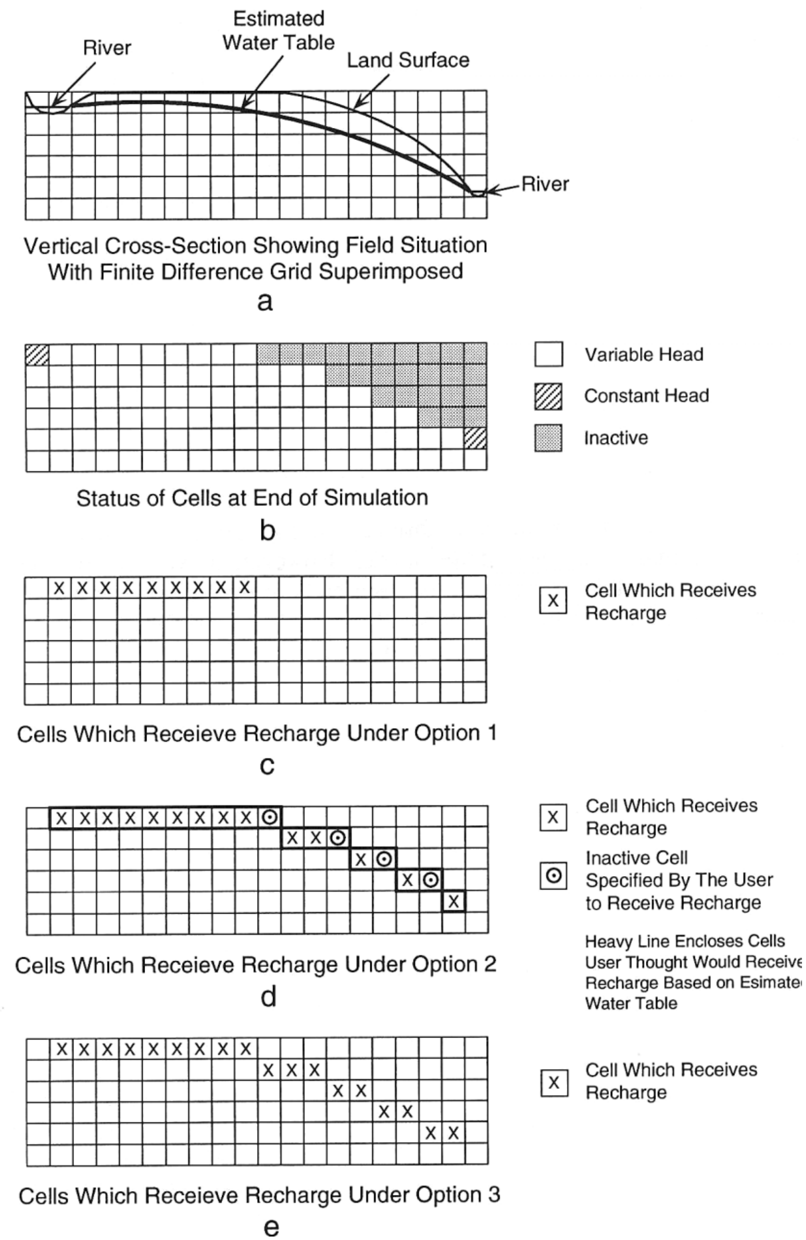
(1) to the upper model layer,

(2) to the uppermost variable-head cell in each vertical column, or

(3) to any cell in each vertical column belonging to the user-defined model layer.

MODFLOW RCH Package/2

- One value assigned to each vertical column
- RCH can be assigned to the uppermost cell or to a specified layer



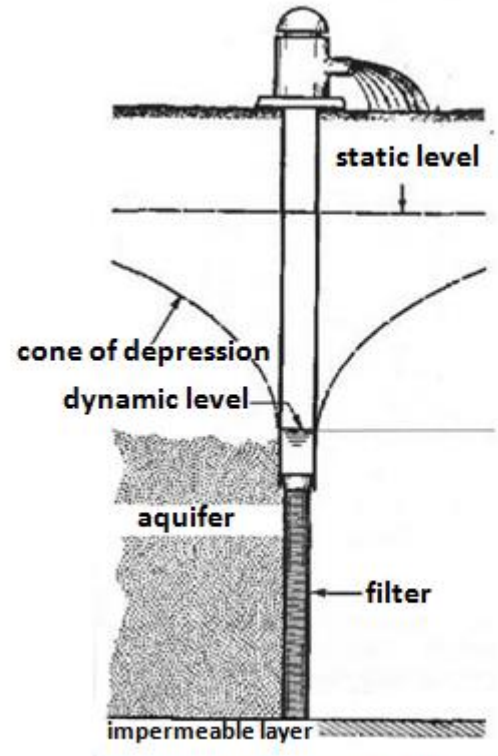
MODFLOW WEL Package/1

MODFLOW WEL Package simulates wells that withdraw water from or add water to the aquifer at a constant rate during a SP.

The user must define, for each stress period, row, column and layer number of the cell in which the well is located and its extracted/recharge flow rate (Q).

Q is expressed as a fluid volume per unit time [L^3/T].

Negative values for Q are used to indicate well pumping, whereas positive values for Q indicate a recharge well.

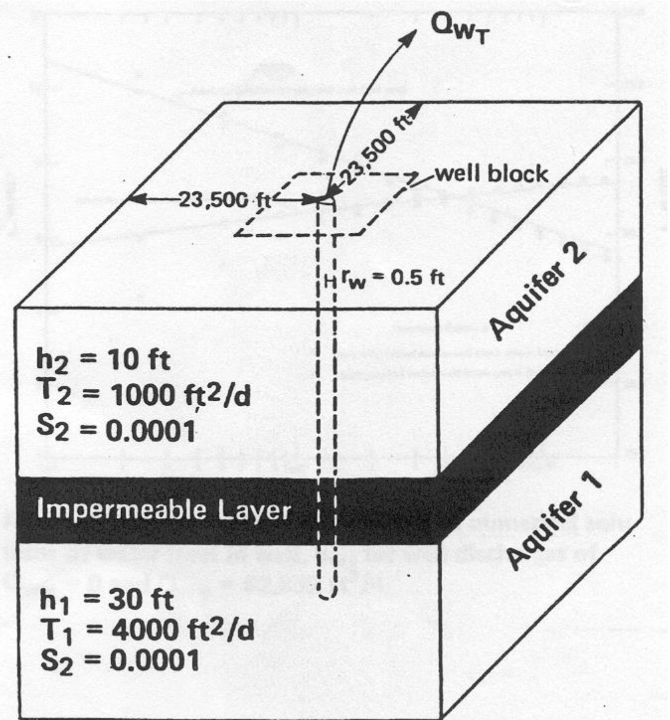


http://www.valutazioniambientali.it

MODFLOW WEL Package/2

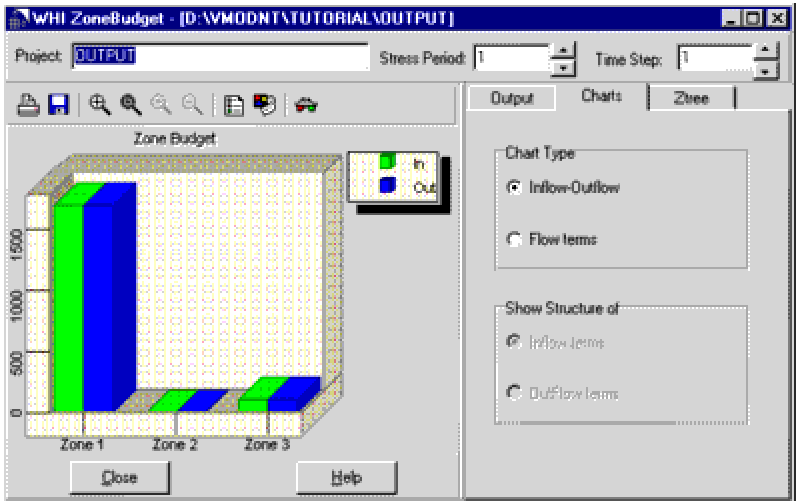
Pumping wells

- List input: layer, row , column, rate (negative means flow out of the ground-water system)
- Rate can be defined using parameters
- Problem to be considered: If a well intersects many model layers, how much water comes from each layer?



Zone Budget

- Not a package, but a separate program
- Specify groups of cells as “zones” and zonebudget calculates water balance on each zone



Flow model creation: Observations (HOB package)

MODFLOW's Observation Process allows simulated values to be compared to observations.

- For example we can use the following observations
  - Head observations
    - At a cell
    - Changes in head over time
  - Flow observations
    - Over the reach of a feature represented by the RIV Package

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Observations (HOB), ctd.

- Heads (HOB in name file)

```
 10    0    0   50   1.E+30 NH,MOBS,MAXM,IUHOBSV,HOBDRY
  1.     TOMULTH     (below, lay,r,c,ts,roff,coff,toff,obs)
hd01.ss    1     3     1     1   0.0   0.0   0.0   101.80
hd02.ss    1     4     4     1   0.0   0.0   0.0   128.12
hd03.ss    1    10     9     1   0.0   0.0   0.0   156.68
. . .
hd10.ss    2    18     6     1   0.0   0.0   0.0   142.02
```

- River Gain (RVOB in name file)

```
 1   18     1    50          NQxx,NQCxx,NQTx
  1.00000E+00                TOMULTxx
         1         18        NQOBxx,NQCLxx
flow01.ss  1  0.0 -4.4       ts,toff,obs
 1  1  1    1.00             lay,r,c,factor
 . . .
 1 18  1    1.00
```

- Output file (“data_50_ex8_.os” in name file)

```
"SIMULATED EQUIVALENT"    "OBSERVED VALUE"      "OBSERVATION NAME"
  100.209701538086         101.800003051758       hd01.ss
  126.954444885254         128.119995117188       hd02.ss
  . . .
 -4.41627883911133        -4.40000009536743       flow01.ss
```

Execute MODFLOW

- If you run MODFLOW from FREEWAT, you do not really need to know this detail, but in case you have to rerun MODFLOW without going through the development in FREEWAT…

- Basically, need to provide the name file filename on the same line (this is often done in a batch file)

  MODFLOW_2005.exe test.nam

Model results

- Possible results:
  - Heads at each active cell in the grid at each time step
  - Global budget (check for overall solution accuracy)
  - Flows at each cell face
  - Simulated equivalents to observations

- Use FREEWAT to visualize the results!

- GW_CHART can help as well in the visualization of the overall water budget.

If you need any assistance, please contact

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FREEWAT Development has received funding from the following projects:

1. Hydrological part has been developed starting from a former project, named SID&GRID, funded by Regione Toscana through EU POR-FSE 2007-2013 (sidgrid.isti.cnr.it).

2. Porting of SID&GRID under QGis has been performed through funds provided by Regione Toscana to Scuola Superiore S.Anna - Project Evoluzione del sistema open source SID&GRID di elaborazione dei dati geografici vettoriali e raster per il porting negli ambienti QGis e Spatialite in uso presso la Regione Toscana (CIG: ZA50E4058A)

3. Latest Version of FREEWAT is under development within EU H2020 project FREEWAT - Free and Open Source Software Tools for Water Resource Management. FREEWAT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 642224 (www.freewat.eu)

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