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Technical Paper on

MODFLOW2000 constraints for preparing/ modifying a groundwater flow model to be linked to WEAP

by

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CONTENT

MODFLOW2000 constraints for preparing/ modifying a groundwater flow model to be linked to WEAP (initial model design or redesign)

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Any existing MODFLOW2000 model can be linked to WEAP, however there are different concepts regarding data assignments in MODFLOW2000 as stand alone model compared to a MODFLOW2000 model, which is linked to WEAP. If a MODFLOW2000 model is already existing and calibrated, minor changes or "translations" have to be done in the linkage procedure and possible recalibrations have to be done inside MODFLOW.

If a MODFLOW2000 model is built or redesigned for the linkage to WEAP, it is important to consider the respective constraints for the linkage already in the modelling process, so that the linkage can be done later on easily without any recalibrations or input data "translations". The following sections describe these constraints.

Overview on requirements for a groundwater model to be linked to WEAP:

GW-MODEL INFORMATION AND CONDITIONS NEEDED, BEFORE LINKED TO WEAP

groundwater model must be calibrated in transient state
a short reference (tables - incl. row and column adresses or gis-shape files) must be prepared on:
recharge (.rch-file) components for the transient model period with respective zone time series values
recharge from rainfall (what assumption have been used - coeffitients/ regionalization)
recharge from irrigation return flow
recharge from river infiltratons
negative recharge (abstractions)
abstraction (.wel-file)
abstraction values for respective wells/ demand sites
which wells are associated for which demand site (domestic, irrigation,...)
boundary conditions
only NO FLOW and CONSTANT HEAD are accepted by WEAP directly
CONSTANT FLOW can be modelled by wells (like artificial recharge) in WEAP
if possible time variant boundary conditions should be avoided as the WEAP-pholosophy is to calculate based on a reference year scenarios. Otherwise it must be clear why and by which natural conditions the time-variant boundaries have been assigned.

1 Zoning of the model area

Before building or redesigning a groundwater flow model by MODFLOW the modeller has to be aware about the „WEAP philosophy“. In MODFLOW all data are assigned to individual cells, whereas in WEAP the spatial units are sub-catchments and if assigned land use classes within the sub-catchments.

Therefore the initial step for building or redesigning a MODFLOW model is to define the outlines of the sub-catchments and land use classes within the model area as a GIS shape-file with the respective attributes (figure 1 & table 1). In WEAP these units are also the result aggregation constraints. That means for these spatial units a detailed water balance can be calculated and visualized for individual land use classes inside a sub-catchment, the whole sub-catchment or the whole model area respectively. If surface runoff plays an important role in the area the sub-catchment boundaries should follow the hydrological basin boundaries to enable correct surface water balance calculations (watershed boundary). The hydrological sub-catchments can be then further subdivided directly into more sub-catchments or can be divided internally into different land use classes regarding:

- Administrative boundaries
- Geology
- Soil type
- Land use
- Crop type
- Irrigation technique
- Slope
- Areas of special interest (problem zones, future development project areas
- General planning units

To keep the WEAP model manageable and its layout clearly arranged and appealing, the number of sub-catchment should not exceed 20 by rule of thumb.

Sub-catchments Land use classes

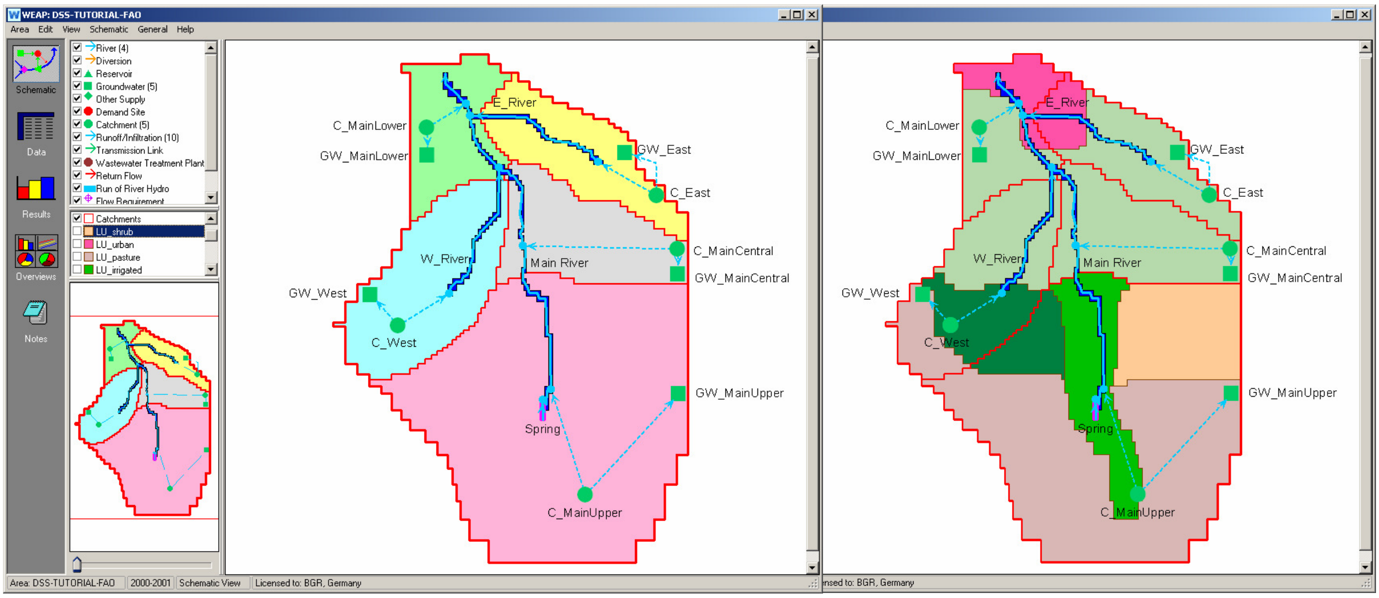


Figure 1: Example for sub–catchment (red outline) and land use class delimitations, resulting in 5 sub-catchments, 6 land use classes and 12 combined sub-catchment-land use classes.

Table 1: Shape-file attribute table.

Polygon ID	Sub-catchment	Land use class	Area [ha]
1	C_East	Unirrigated	6585
2	C_East	Urban	1823
3	C_MainCentral	Unirrigated	9518
4	C_MainLower	Unirrigated	4667
5	C_MainLower	Urban	2694
6	C_MainUpper	Forest	2623
7	C_MainUpper	Irrigated	7121
8	C_MainUpper	Pasture	23567
9	C_MainUpper	Shrub	7388
10	C_West	Forest	3950
11	C_West	Pasture	2390
12	C_West	Unirrigated	6113

2 MODFLOW input data constraints

The table below shows the key data input constraints of MODFLOW and WEAP respectively.

DATA INPUT CONCEPTS	
MODFLOW GW-FLOW-MODEL Modflow 2000	**WEAP – MODEL** (WEAP21)
All data input either to individual cells or to zones (MODFLOW ZONE or GMS "Map to Model")	
Recharge from rain (.rch) - entered to cells or zones	- in WEAP calculated for each catchment/ land use class (WEAP internal models) - or entered as hard data to the GW-node as "Natural Recharge"
Abstractions (.wel or .rch): - entered to cells or zones	- entered as demand sites (filling the attribute "Demand Site 1" in the link-shape file). - if irrigation is modelled by WEAP abstraction is evenly distributed among the land use class cells PumpLayer 1 = .wel, PumpLayer 0 = .rch
Rivers/ Springs (.riv .drn) - entered to cells or cell groups - river interaction - discharge at springs	- one or multiple RIV/ DRN cells are linked to a river reach (linkshape file attribute "RIVER" automatically filled by "guess river/ drain linkage") - in the WEAP schematic a River need to be digitized on top of the RIV / DRN cells

2.1 Recharge (.rch – file)

The following input parameters (if assigned in MODFLOW) must be uniform for the respective Polygon ID (sub-catchment's land use class) area:

- Recharge from precipitation (precipitation regionalisation from respective meteorological stations)
- Recharge from irrigation return flow
- Recharge from river infiltration (only if there is NO exfiltration from the groundwater to the river)
- Negative recharge for irrigation abstraction

Irrigation abstraction and groundwater recharge can be calculated either through WEAP (FAO-method, soil moisture method) or can be calculated externally by using climate and crop data (FAO Irrigation and Drainage Paper No. 56) or climate, soil and crop data (CropWAT, www.fao.org), if the surface runoff fraction is known (river gauges) by the simple formula:

groundwater recharge = precipitation – actual evapotranspiration – surface runoff

If local recharge calculation models or estimations exist these can be also applied, however they should be based on climate, better also on crop data (and if available on soil data). All components are assigned to the .rch-file as the resulting net-value for each cell in the respective polygon. To ensure spatial integrity this is done best by adding respective values as attribute to the shape file and using this shape file as input data to MODFLOW for example by the Map to MODFLOW module in GMS or by using MODFLOW's ZONE function.

2.2 Domestic abstractions (.wel – file)

In MODFLOW an unlimited number of wells with individual abstraction rates from the respective model layer(s) can be assigned. In WEAP in principle the same approach is possible, however in WEAP one demand site corresponds to one or many MODFLOW .wel-cells and distributes the assigned abstraction rate evenly among them and the assigned layer(s). Therefore it is reasonable to group the wells with somehow similar abstraction rates and abstraction layer(s) to the respective demand site. To keep the WEAP model manageable and its layout clearly arranged and appealing, the number of demand sites should be kept on a reasonable level (how many red dots can be on the WEAP schematic view?).

2.3 Rivers/ Springs/ Drains (.riv/ .drn-files)

If the model area is characterized by river-groundwater infiltration and exfiltration this process should be modelled by MODFLOW's RIVER package. If there is only flow from the groundwater to the river the DRAIN package is suitable (also used to model springs). If there is only infiltration from the river to the groundwater this can be assigned as additional recharge component.

2.4 Boundary conditions

No flow and constant head boundaries are the only ones accepted directly by WEAP.

Constant flow boundaries can be modelled in WEAP like artificial recharge or by specifiying an extra catchment along the respective boundary segment where the respective flow values are entered then as "Natural Recharge".

Other boundary conditions should be avoided as the WEAP-philosophy is to calculate future scenarios, based on a reference year. The question is how time-variant boundary conditions will change in the respective scenario.

If time variant boundaries are used by MODFLOW, they can be translated to WEAP, however one have to understand well why they are used and what are the natural constraints.

2.5 MODFLOW Link Technical Details (s. WEAP-Help-File)

When properly linked, data and results flow back and forth between WEAP and MODFLOW for each calculation timestep. The following description provides details of exactly what information is passed between WEAP and MODFLOW, and how the process happens.

WEAP reads information from the MODFLOW packages before calculations begin, along with the linkage information that links MODFLOW cells to WEAP objects. Thereafter, at each calculation timestep, WEAP will write out a new set of MODFLOW package files, run MODFLOW, then read the results from the MODFLOW output files. (If you select the option to save all MODFLOW input and output files, the new MODFLOW package files created will be named with !MF! as a prefix and a suffix unique for each scenario, year and timestep. For example, if the original Recharge filename is Zabadani.rch, the new Recharge file written for the Current Accounts (scenario number 1) for March 2000 would be !MF!Zabadani_S01_2000_03.rch. This allows you to inspect or modify the input files and rerun MODFLOW yourself, outside of WEAP. This could be an aid in debugging. However, keep in mind that all these files will be deleted and recreated the next time WEAP calculates results.)

A MODFLOW model consists of many different "packages," most of which are optional. However, not all packages are used or allowed by WEAP.

- **Used by WEAP**: BAS6 (Basic), BCF6 (Block-Centered Flow), CHD (Constant-Head), DIS (Discretization), DRN (Drain), HUF2 (Hydrogeologic Unit Flow), LPF (Layer Property Flow), NAM (Name), OC (Output Control), RCH (Recharge), RIV (River), WEL (Well). WEAP reads information from each of these, and will write new versions of each with changes, as explained below. (The original files will not be changed.) WEAP only requires NAM, DIS, BAS6 and one of BCF6/HUF2/LPF--all other packages are optional.

- **Allowed but not used by WEAP**: ADV2 (Advective-Transport Observation), DE4 (Direct Solution), DRT (Drain Return), ETS (Evapotranspiration Segments), GAGE, GHB (Ground-Water Flow Process General-Head Boundary), HFB6 (Ground-Water Flow Process Horizontal Flow Barrier), HYD (HYDMOD), IBS (Interbed-Storage), KDEP (Hydraulic-Conductivity Depth-Dependence Capability of the HUF2), LMG (Link-AMG), LVDA (Model-Layer Variable-Direction Horizontal Anisotropy capability of the HUF2), MNW1 (Multi-Node, Drawdown-Limited Well), MULT (multiplier), PCG (Preconditioned Conjugate-Gradient), RES (Reservoir), SIP (Strongly Implicit Procedure), SOR (Slice-Successive Over-Relaxation), SUB (Subsidence and Aquifer-System Compaction), ZONE.

- **Commented out in new name file**: (Observation files might reference stress periods after the first, which no longer exist) CHOB (Constant-Head Flow Observation), DROB (Drain Observation), DTOB Drain Return Observation), GBOB (General-Head-Boundary Observation), HOB (Head-Observation), OBS (Observation Process), RVOB (River Observation), STOB (Streamflow-Routing Observation), LMT6 (Link-MT3DMS)

- **Not allowed**: ASP, DAF (DAFLOW surface-water), DAFG (DAFLOW ground-water), LAK (Lake), EVT (Evapotranspiration). FHB (Flow and Head Boundary), PES (Parameter Estimation), SEN (Sensitivity Process), STR (Streamflow-Routing).

The following describes how WEAP interacts with the MODFLOW packages from the "Used by WEAP" group:

Name (NAM):

The Name File specifies the names of the input and output files, associates each file name with a unit number and identifies the packages that will be used in the model. WEAP reads the name file first to know which packages are used and which file each one is in. WEAP will write a new NAM file for each timestep it calculates, and include in it new entries for an initial head file, output head file, and a cell-to-cell-flow (CCF) file.

Discretization (DIS):

WEAP reads the following information from the Discretization file:

Number of rows, columns and layers

Row and column widths

Time and length units

Number and length of stress periods. Models with more than one stress period are allowed, but only data from the first stress period will be used by WEAP. Time-varying parameters and multiple stress periods are fundamentally opposed to the WEAP-MODFLOW linkage approach, which is that MODFLOW will be run for one stress period, then the results will go back to WEAP, which will write new MODFLOW input files, and then run MODFLOW for the next stress period. When WEAP writes the new DIS package, the length of the stress period will be changed to match the length of the WEAP timestep being calculated. The number of MODFLOW timesteps is not changed.

Which layers have Quasi-3d confining beds below. This information is only used to initially establish individual aquifers in a multi-aquifer system. However, it is up to the user to decide how many aquifers exist and which layers are in which aquifers.

Basis (BAS6):

WEAP reads from the Basic package the locations of active, inactive, and specified head cells and the initial heads in all cells. In addition, BAS specifies if FREE or FIXED formats are used in other packages, and the numeric code to use for no-flow cells (e.g., -999). WEAP writes the initial cell heads to a new binary file, for use in the first WEAP timestep as the initial head for the simulation, and changes the BAS file to refer to this EXTERNAL file. Thereafter, the head results from one WEAP timestep will be used in the next timestep as the initial heads, and the BAS file will be changed to refer to the newly created head file.

The XSECTION tag is not allowed.

Well (WEL):

The Well package is used to simulate a specified flux to individual cells and specified in units of volume/time. WEAP reads from the Well package the number and location of well cells, to which it adds any other cells that are linked to land use or demand site pumping in WEAP but not already included in the Well file. You may choose to model some or all pumping, such as pumping for irrigation, as negative recharge in the Recharge package instead of as pumping in the Well package. When writing the pumping flows in the new Well file for each WEAP timestep, cells that are linked to land use or demand site pumping will have pumping rates calculated by WEAP, whereas cells that are not linked will have the flow rate as specified in the original Well file. The Well package is also modified so that cell-by-cell flow terms will be written to the new CCF file. It is OK if the Well package does not exist in the original MODFLOW model--WEAP will create a new one.

Recharge (RCH):

The Recharge package is used to simulate a specified flux distributed over the top of the model and specified in units of length/time. Within MODFLOW, these rates are multiplied by the horizontal area of the cells to which they are applied to calculate the volumetric flux rates. You may choose to model some or all pumping, such as pumping for irrigation, as negative recharge in the Recharge package instead of as pumping in the Well package. Initial values of recharge from the Recharge package are ignored, to be replaced by recharge values calculated by WEAP. The Recharge package is also modified so that cell-by-cell flow terms will be written to the new CCF file. It is OK if the Recharge package does not exist in the original MODFLOW model--WEAP will create a new one. In this case, the recharge will be applied to the highest active cell in each vertical column.

Drain (DRN):

The Drain package is used to simulate head-dependent flux boundaries. In the Drain package if the head in the cell falls below a certain threshold, the flux from the drain to the model cell drops to zero. WEAP reads from the Drain package the number and location of drain cells. The only change made to the Drain package is to specify the new CCF file that cell-by-cell flow terms will be written to.

River (RIV):

The River package is used to simulate head-dependent flux boundaries. In the River package if the head in the cell falls below a certain threshold, the flux from the river to the model cell is set to a specified lower bound. The River package includes stage height and river bottom elevation, which are used by MODFLOW to calculate fluxes. In each timestep, WEAP will calculate the stage in the river at each reach linked to a river cell and write a new River file with this new stage value. WEAP's flow-stage-width curve can either specify the stage in relative (where 0 is the river bottom) or absolute terms. If in relative terms, WEAP will add the elevation of the river bottom (RBOT) from the original River file to the calculated stage to derive the absolute stage level. River cells that are not linked to WEAP reaches are written back out unchanged. The River package is also modified so that cell-by-cell flow terms will be written to the new CCF file.

Block-Centered Flow (BCF6), Hydrogeologic Unit Flow (HUF2) and Layer Property Flow (LPF):

One and only one of these packages may be used. The only information that WEAP needs from these files is the numeric code for dry cells, e.g., -888. The only change made is to specify the new CCF file that cell-by-cell flow terms will be written to.

Constant Head (CHD):

WEAP does not read from or write to the Constant Head package, but its presence indicates that WEAP should read constant head results from the CCF file, which will be added to the WEAP groundwater mass balance results.

Output Control (OC):

WEAP ignores the original Output Control package (if it exists) and instead creates a new Output Control file, specifying that head and budget results should be saved (for the final MODFLOW timestep), and the file unit to which they are saved.

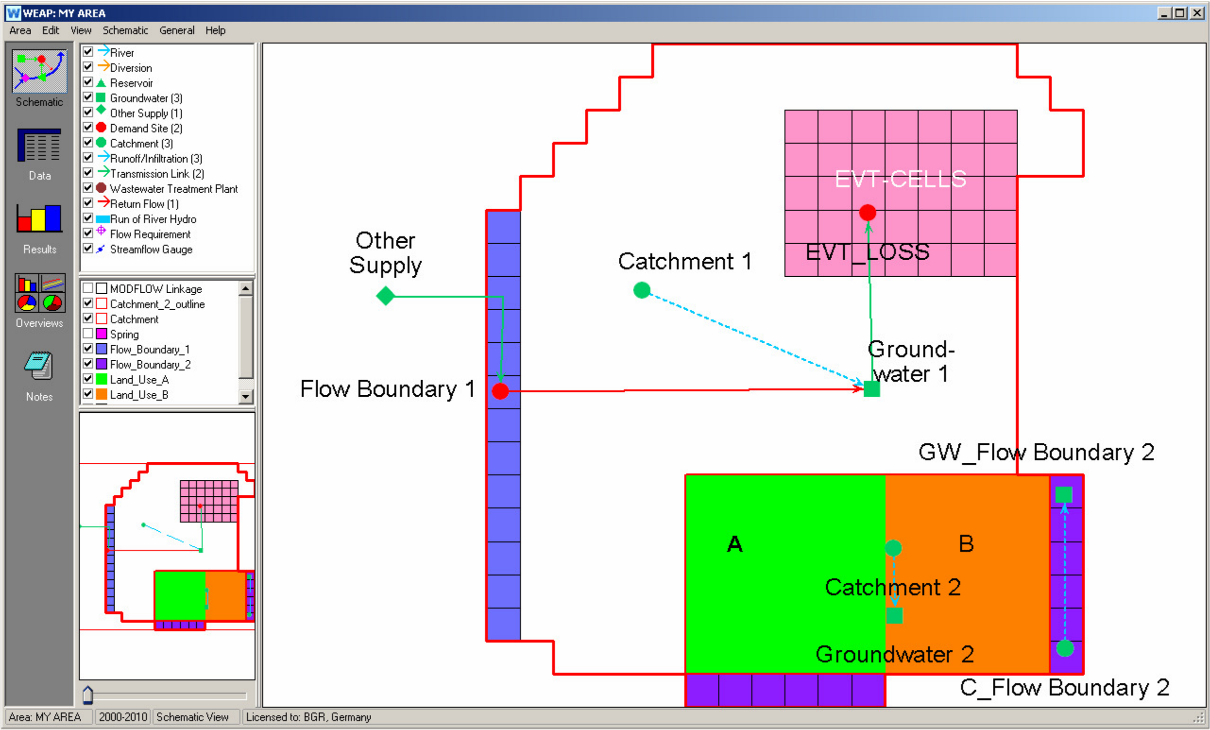
General Notes on Packages

Parameter are handled in all packages, but will not be written to the new package files. This is because time-varying parameters and multiple stress periods are fundamentally opposed to the WEAP-MODFLOW linkage approach, which is that MODFLOW will be run for one stress period, then the results will go back to WEAP, which will write new MODFLOW input files, and then run MODFLOW for the next stress period.

All MODFLOW format options are supported: FREE and FIXED formats, as well as CONSTANT, INTERNAL, EXTERNAL, LOCAT (fixed) and OPEN/CLOSE.

2.6 Options for translating MODFLOW packages which are not supported by WEAP directly

Schematic WEAP model Example:



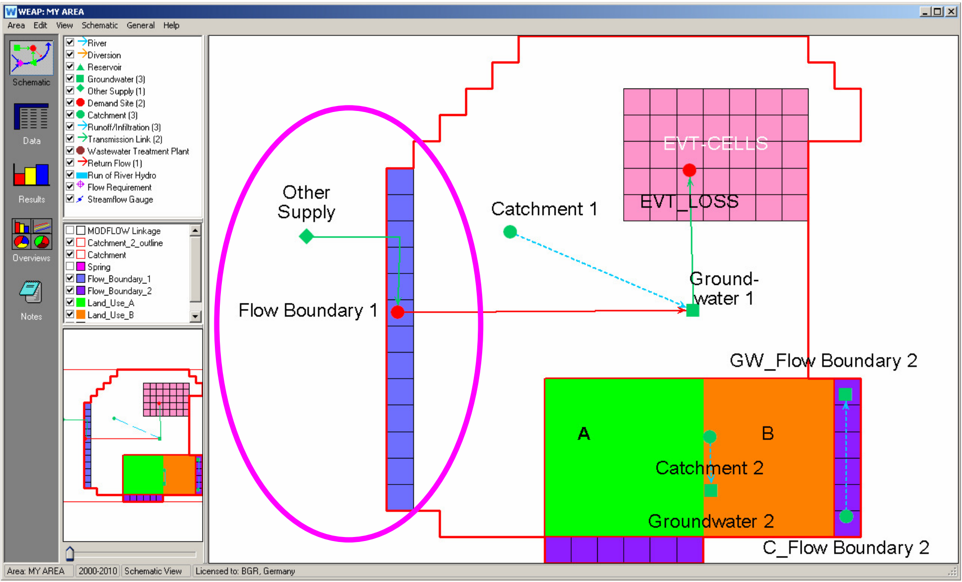
3 Catchments and 3 Groundwater Nodes

Catchment Name	Groundwater Name
Catchment 1	Groundwater 1
Catchment 2	Groundwater 2
C_Flow Boundary 2	GW_Flow Boundary 2

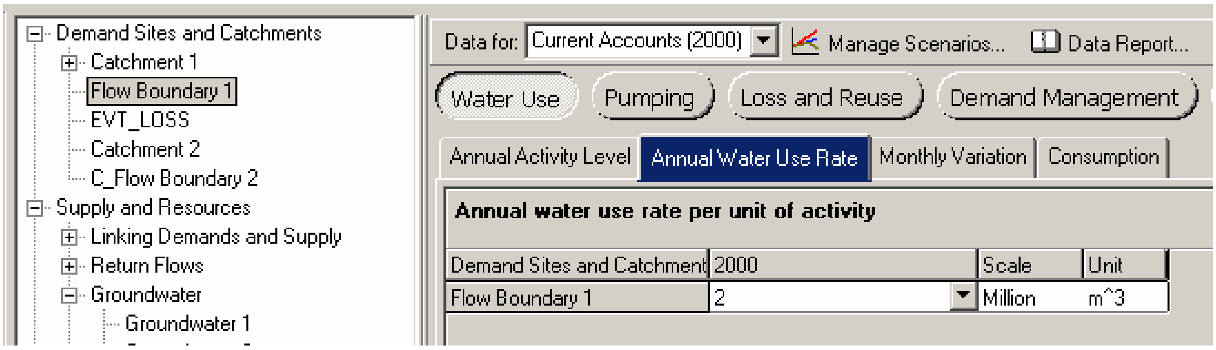
2.6.1 Flow Boundary conditions

Only constant head boundary conditions are supported by WEAP directly. Other boundary conditions (time variant head, time variant flow and general head) have to be translated accordingly. There are two options to do this:

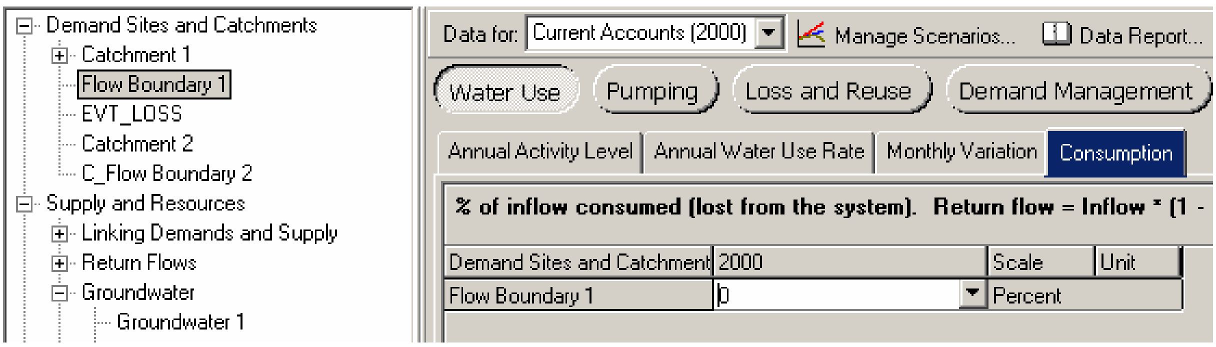
A) Translation to Injection Wells:



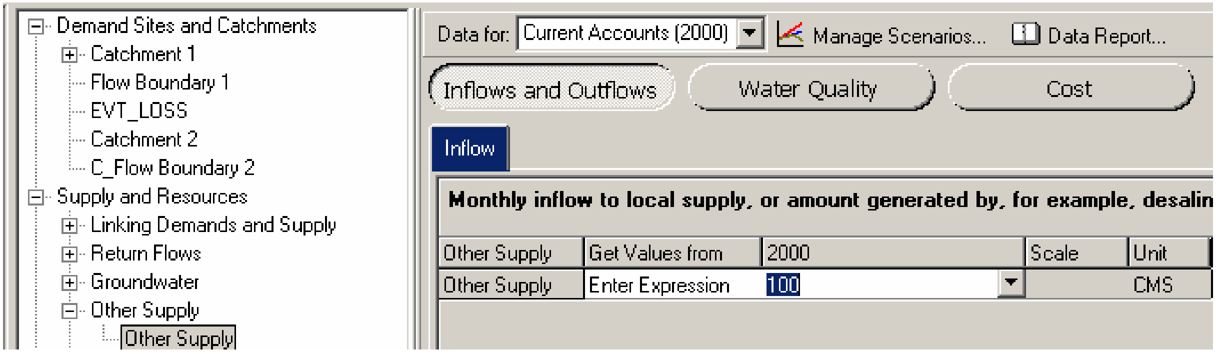
A new demand site is added to the schematic (here Flow Boundary 1), the time variant flow value is entered as Water Use Rate (here 2 Million m³/year)



Consumption is set to 0%:

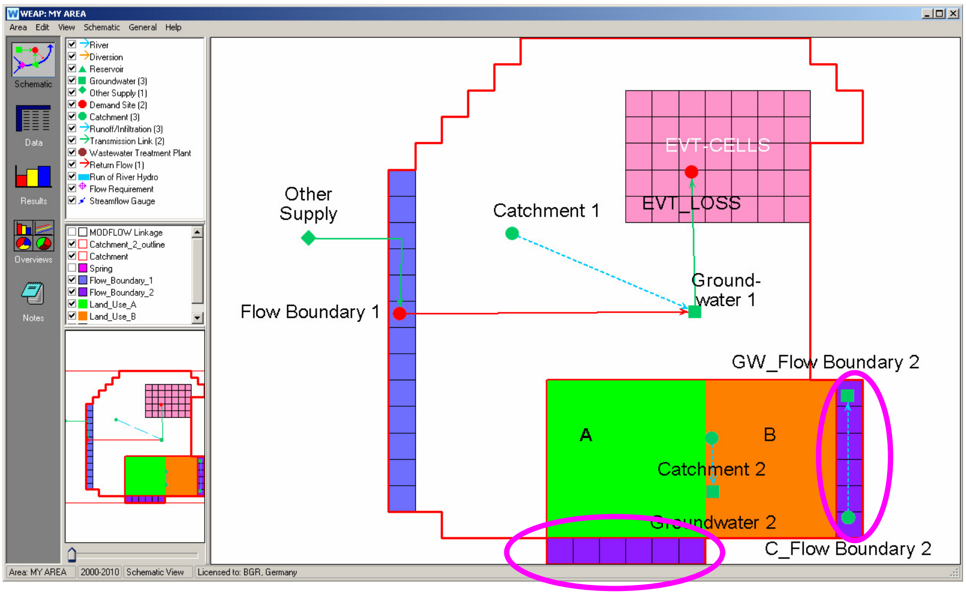


and the Supply is coming from outside (Here „other supply“, there must be sufficient Inflow assigned to satisfy the demand – here 100 CMS) and the whole volume is transfered via a return flow link to the groundwater node.

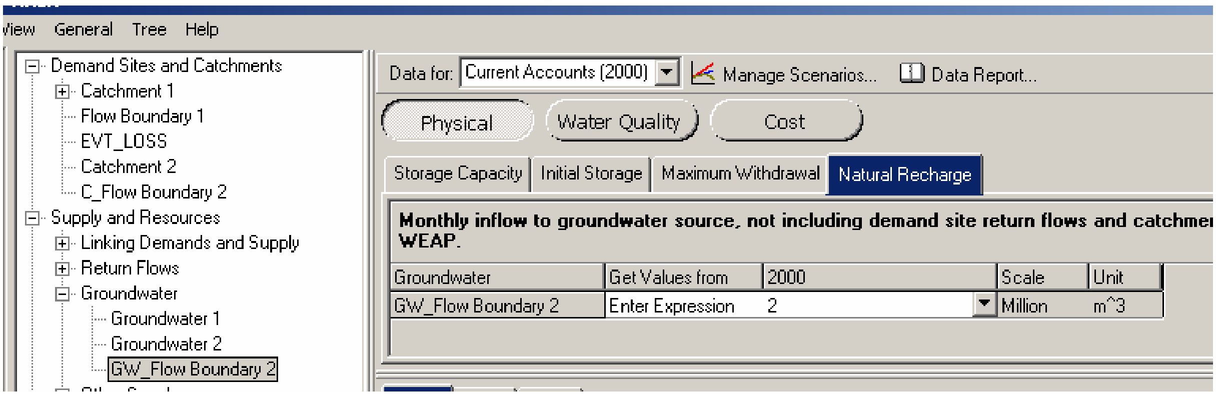


In the linkage – shape – file for the respective boundary cells (blue) the DemandSite attribute is filled by the Demand Site name (here: Flow Boundary 1).

B) Enter flow boundary as “Natural Recharge”.

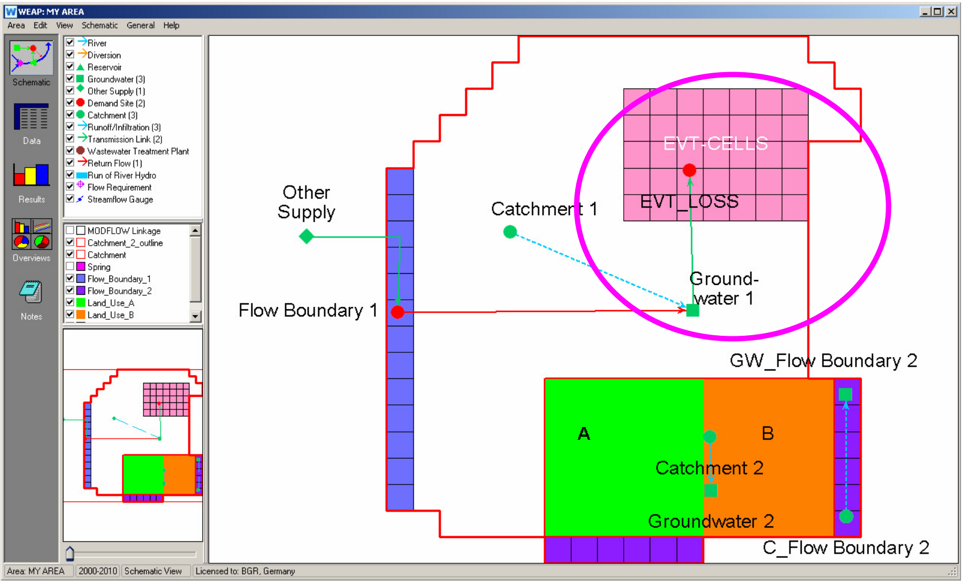


By this approach a new catchment (here C_Flow Boundary 2) and a new groundwater node (here: GW_flow boundary 2) is added for the respective boundary cells (in purple) and the flow rates are entered a “Natural Recharge:

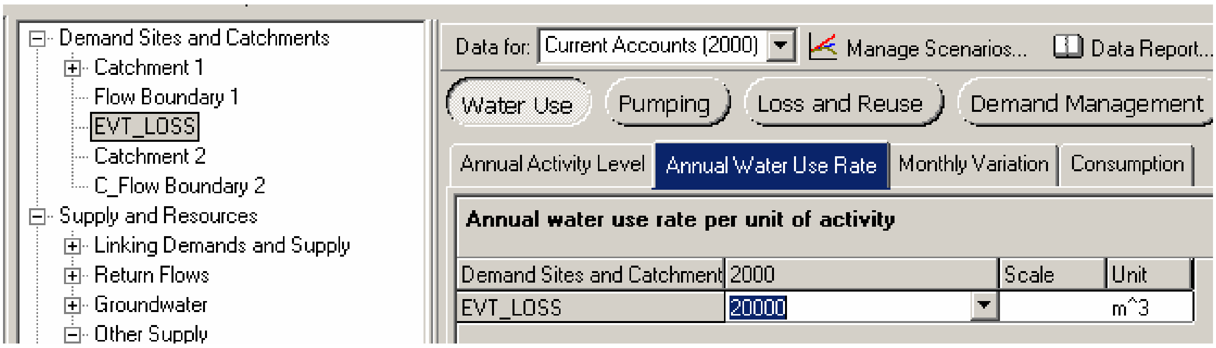


This amount will then be spread evenly among the cells of the catchment C_Flow Boundary 2 (note: you need also to enter the catchment and groundwater attributes into the link-shape-file table).

2.6.2 Evapotranspiration package (EVT)



EVT is not allowed by WEAP, therefore respective evapotranspiration-flows like calculated by MODFLOW must be translated to a new Demand Site (here: EVT-Loss). The flows are entered as Water Use Rate (here 20 000m³/year):

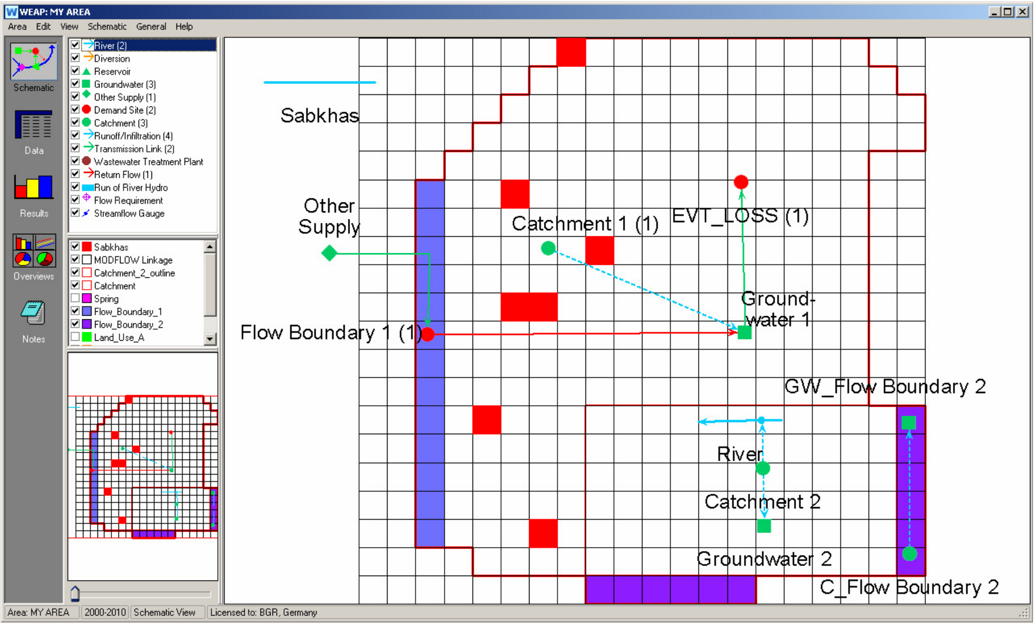


Of course the new Demand Site have to be also entered in the link-shapefile attribute table to the respective cells (EVT-cells). In the Modflow Name File (.mfn or .nam) EVT is then switched off by putting simpy a “#” before the EVT variable.

2.6.3 Drain-Package used to model Sabkhas or other “non-river” features

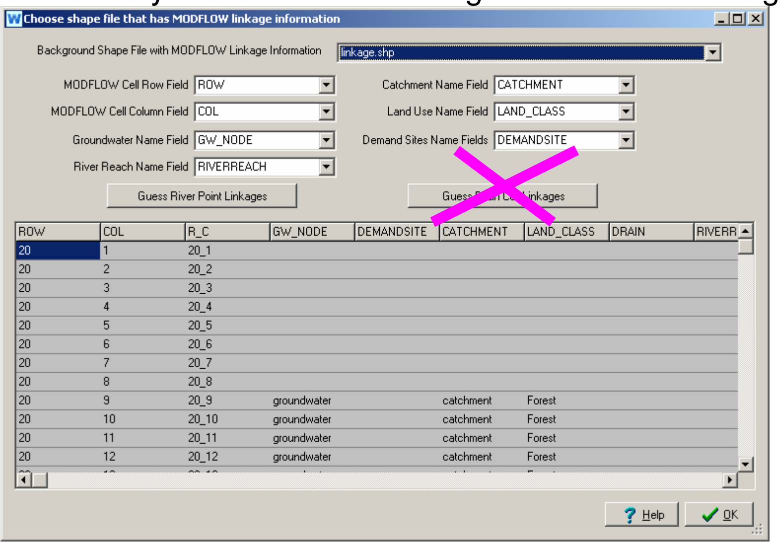
In WEAP each MODFLOW drain cell must correlate to a WEAP river reach. Sometimes sabkhas, small local springs, etc. are modelled by Drains in MODFLOW. If the balance of each of this cells is not important all or groups of drain cells can be associated with one WEAP river.

Here we have many local sabkahs (red cells), which are modelled as Drain



We want to see the water budget in WEAP and therefore we need to link the Drain Cells to one WEAP river (here the River Name is Sabkha)

To do this you will NOT use the “guess drain cell linkage option”,



but enter the River reach name manually in GIS to the respective drain cells in the “RIVER” attribute column. The river reach name syntax can be read out of WEAP:

The complete Synthax to enter in the attribute table is always:

RiverName, RiverReachName

Here: “Sabkhas, Below Sabkhas Headflow”