Output control commands above vary the output's appearance

EOLCOM > tells GAMS to ignore anything in the line's text after the symbol >
OFFLISTING deletes all program lines and just includes GAMS listing
Setting LIMROW = 0 eliminates equations' all equations in the GAMS listing
It saves space, but is usually a bad idea till the model is known bullet proof.

Colors: We suggest going to 'file' then to 'options,`
then choose as many colors as possible for varying kinds of GAMS syntax
It greatly simplifies error trapping.

* ---------------------------------------------------------------------------------------
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 November 4 2005

Rio Grande Basin Model: Expandable Prototype
Contains essential elements of full Upper Rio Grande Basin Model.

* ---------------------------------------------------------------------------------------
Sponsored by US Geological Survey,
Water Resources Research Institutes and Agricultural Experiment Stations
of Colorado, New Mexico, and Texas
* ---------------------------------------------------------------------------------------

Model has these flow nodes:
6 river nodes
2 inflow nodes
4 diversion nodes
4 consumptive use nodes
4 surface water return flow nodes
2 groundwater return flow nodes
1 reservoir release node

and these stock nodes:
1 reservoir node
1 aquifer node

* ---------------------------------------------------------------------------------------
FLOWS: Spatial unit for FLOWS is set (index) i.
Each element in the set \( i \) is assigned to one water use subset (category). Subset categories include:

1. Inflow nodes to the system, \( \text{inflow}(i) \);
2. Nodes on a river or tributary \( \text{river}(i) \);
3. Diversion nodes \( \text{divert}(i) \);
4. Consumptive uses \( \text{use}(i) \);
5. Return flow nodes directly to the river, \( \text{return}(i) \);
6. Inflows to river from groundwater, pumping/seepage, \( \text{gwflow1}(i) \);
7. Inflows to river from other groundwater \( \text{gwflow2}(i) \);
8. NET reservoir releases from storage, outflow - inflow \( \text{rel}(i) \);

STOCKS: Spatial unit for STOCKS is the set index \( u \). Each element of the set \( u \) is assigned to one water use subset (category). Subset categories are:

1. Groundwater stock nodes, \( \text{gw}(u) \);
2. Reservoir nodes, \( \text{res}(u) \).

TABLE OF CONTENTS

Section 1. Sets
Section 2. Data
Section 3. Variables
Section 4. Equations
Section 5. Models
Section 6. Solves
Section 7. Displays

SETS

Sets -- location of important nodes in RG Basin -- CO to MX

\[ / \text{RG}_h_f \text{Headwater flow nodes} \text{inflow}(i) \]
\[ / \text{Chama}_h_f \text{Headwater flow nodes} \text{inflow}(i) \]
Lobatos_v_f  River gage measurement nodes  river(i)
Embudo_v_f
Chamita_v_f
Otwi_v_f
Acacia_v_f
MX_v_f

SLV_d_f  Diversion nodes  divert(i)
MRGCD_d_f
EBID_d_f
TX_d_f

SLV_u_f  Consumptive use flow nodes  use(i)
MRGCD_u_f
EBID_u_f
TX_u_f

SLV_r_f  Surface water return flow nodes  return(i)
MRGCD_r_f
EBID_r_f
TX_r_f

Abq_gwl_f  GW return flow nodes -- seep or pump  gwflow1(i)
Abq_gw2_f  GW return flow nodes -- other  gwflow2(i)
EB_rel_f  Reservoir-to-river release flow nodes  rel(i)

******************************************************************************
* Subsets of all Flow nodes above by class (function) ******************************************************************************

inflow(i)  Headwater flow nodes  inflow(i)
/  RG_h_f  Rio Grande headwaters CO
    Chama_h_f  Rio Chama headwaters near CO-NM state line
/

river(i)  River gage measurement nodes  river(i)
/  Lobatos_v_f  Lobatos gauge on RG at CO-NM state line
    Embudo_v_f  Embudo gauge on RG northern NM
    Chamita_v_f  Chamita gauge on Rio Chama northern NM
    Otwi_v_f  Otowi gauge on RG downstream of Chama RG confluence
    Acacia_v_f  San Acacia gauge central NM downstream of MRGCD ag
    MX_v_f  RG at Mexico near El Paso TX
/

divert(i)  Diversion nodes  divert(i)
/  SLV_d_f  Rio Grande Conservancy ag in SL Valley CO
    MRGCD_d_f  Middle RG Conservancy District ag near Albuq NM
    EBID_d_f  Elephant Butte Irr Dist ag near Las Cruces NM
    TX_d_f  West TX irrigated Ag near El Paso TX
/

use(i)  Consumptive use flow nodes = div nodes  use(i)
/  SLV_u_f  same as divert(i)
    MRGCD_u_f
Surf wat return flow nodes = div nodes

return(i)

SLV_r_f
same as divert(i)

MRGCD_r_f

EBID_r_f

TX_r_f

gwflow1(i)
Grndwat return flow--seep or pump

Abq_gw1_f
Return from aquifer pumping to RG at Alb NM

gwflow2(i)
Grndwat return flow nodes--other

Abq_gw2_f
Return from aquifer to RG other at Alb NM

rel(i)
Reservoir to river release flow nodes

EB_rel_f
Elephant Butte reservoir releases to RG

*****************************************************************************************
Stocks--location of important nodes on Rio Grande CO to MX
*****************************************************************************************

Abq_gw_s
aquifer stock node

EB_res_s
reservoir stock node

*****************************************************************************************
Stock subsets
*****************************************************************************************

gw(u)
Groundwater stock nodes

Abq_gw_s
Albuquerque NM gw aquifer vol

res(u)
Reservoir stock nodes

EB_res_s
Elephant Butte reservoir vol on RG

*****************************************************************************************
time
*****************************************************************************************

1*2
Two time periods - expandable

terminal period among all periods above
\begin{verbatim}

tlast(t) = yes (ord(t) eq card(t)); > GAMS language -- picks last pd

ALIAS (i,ip);
ALIAS (river, riverp);
ALIAS (divert, divertp);
* lets some tables' nodes be rows or columns

************* Section 2 *********************************************
* This section defines all data in 3 formats
* 1. Scalars (single numbers),
* 2. Parameters (columns of numbers) or
* 3. Tables (data in rows and columns)

* Below are several maps summarizing a basin's geometry
* By geometry we mean location of mainstems, tributaries, confluence,
* source nodes, use nodes, return flow nodes, reservoir nodes, etc.
* Basin geometry is summarized through judicious use of numbers 1, -1, and 0 (blank)

* Map #1:
* Each column below is a streamgage. Each row is a source or use of water.
* Flow at ea gage (column) is directly influenced by at least 1 upstream row.
* SOURCE adds to columns flow (+1)
* USE deplete from col flow (-1)
* BLANK has no effect on col flow ( )
* Geometry accounts for all sources (supplies) and uses (demands) in basin
* Map is used to produce coefficients in equations below to define:
* X(river) = Bhv * X(inflow) + Bvv * X(river) + Bdv * X(divert)
* + Brv * X(return) + Bgv * X(gwflows) + BLv * X(rel)
* These B coeff vectors are stacked below as a single matrix, Bv

TABLE Bv(i,river) Hydrologic Balance Table

*********** Column Heads are River Gauges ***********

<table>
<thead>
<tr>
<th>Lobatos_v_f</th>
<th>Embudo_v_f</th>
<th>Chamita_v_f</th>
<th>Otowi_v_f</th>
<th>Acacia_v_f</th>
<th>MX_v_f</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG_h_f</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chama_h_f</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobatos_v_f</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acacia_v_f</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MX_v_f</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* ------------ headwater inflow node rows (+) -------------------------------
* ------------ river gage node rows (+) -------------------------------------
* ------------ diversion nodes (-) -------------------------------------------
\end{verbatim}
TABLE Bd(i, divert)  Wet river table

* Enforces nonnegative flows at each use node (wet river)
* water sources are rows. Diversion nodes are columns.
* For any column, diversion < summed flows from upstream sources (rows)
  * e.g. SLV Colorado ag use < flows from RG and Conejos headwater sources
  * X(divert) < Bhd * X(inflow) + Brd * X(river) + Bdd * X(divert) +
    * Brd * X(return) + Bgd * X(gwflow) + BLd * X(rel)
* These B coeff vectors are stacked below as the matrix, Bd

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    * Brd * X(return) + Bgd * X(gwflow) + BLd * X(rel)
* These B coeff vectors are stacked below as the matrix, Bd
* ---------------------- groundwater inflow nodes (+) -----------------------------------
Abq_gw1_f 1
Abq_gw2_f 1
* ------------------- reservoir outflow stock-to-flow node row (+)-----------------------
EB_rel_f 1 1
* -------------------------------------------------------------------------------------

*****************************************************************************************
* Map #3:
* Defines use (simplistically) as diversions minus return flows -- ignores seep, pump
* X(use) = Bdu * X(divert) + Bru * X(return)
* These B coeff vectors are stacked below as the matrix, Bu
*****************************************************************************************

TABLE Bu(i, use)  Defines consumptive use
* -------------------------- Use nodes -----------------------------------------------
  SLV_u_f  MRGCD_u_f  EBID_u_f  TX_u_f
* ------------------------ divert nodes (+) ---------------------------------------------
  SLV_d_f  1
  MRGCD_d_f                      1
  EBID_d_f                                       1
  TX_d_f                                                        1
* ---------------------- return flow nodes (-) ------------------------------------------
  SLV_r_f         -1
  MRGCD_r_f                       -1
  EBID_r_f                                      -1
  TX_r_f                                                       -1
*----------------------------------------------------------------------------------------

*****************************************************************************************
* Map #4:
* Table defines relation between diversions and return flow nodes
* Tabled entries = proportion return flow by diversion column nodes
* (+) means the row diversion contributes to column's ret flow
* ( ) means the column diversion makes no cont to row's ret flow
*X(return) = Bdr * X(divert)
*****************************************************************************************

TABLE Bdr(divert, return)  Links return flows to diversions
* --------------------------------- Column Heads are Return Flow Nodes ---------------------
  SLV_d_f  MRGCD_d_f  EBID_d_f  TX_d_f
  SLV_r_f  0.5
  MRGCD_r_f                      0.5
  EBID_r_f                                       0.5
  TX_r_f                                                        0.5
Table relates reservoir stocks in a period to its prev periods' stocks minus releases.

For any reservoir stock node at the column head

(+1) : added water at flow node -- thru releases -- takes from column's res stock (-)

(-1) : added water at flow node adds to column's reservoir stock

(  ) : added water at flow node has no effect on column's reservoir stock

\[ Z(\text{res}(t)) = Z(\text{res}(t-1)) + BLv \times X(\text{rel}(t)) \]

---

### TABLE

<table>
<thead>
<tr>
<th>BLv(rel, u)</th>
<th>Links reservoir releases to downstream flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB_res_s</td>
<td>EB_rel_f</td>
</tr>
</tbody>
</table>

---

### END OF BASIN GEOMETRY MAPS

---

### NEXT APPEAR BASIN INFLOWS, OTHER FLOWS, FLOW RELATIONSHIPS, AND RESERVOIR STARTING VOLUMES, SIMPLE ECONOMIC VALUES PER AC FT WATER USE

---

All water flows are measured in 1000s acre feet per yer

All water stocks are measured in 1000s acre feet instantaneous volume

### TABLE

<table>
<thead>
<tr>
<th>source(inflow,t)</th>
<th>annual basin inflows at headwaters -- snowpack or rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>*****</td>
<td>Data are from historical or forecast headwater node flows</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG_h_f</td>
<td>500</td>
</tr>
<tr>
<td>Chama_h_f</td>
<td>200</td>
</tr>
</tbody>
</table>

### PARAMETERS

- **z0(res)**: initial reservoir levels at stock nodes
- **Gwflows1_0(gwflow1,t)**: groundwater flow from seep or pumping
- **Gwflows2_0(gwflow2,t)**: groundwater flows from other recharge to river

<table>
<thead>
<tr>
<th>1000;</th>
<th>Elephant Butte Reservoir starting vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>0;</td>
<td>Albuq area aquifer seep-pump impacts to river</td>
</tr>
<tr>
<td>-50;</td>
<td>Albuq area aquifer net recharge to river</td>
</tr>
</tbody>
</table>

### PARAMETERS

- **BBu(use)**: marginal benefits from one additional acre foot used
BBu(use) = 1;  > equal marginal benefits = 1 -- every use

**************** Section 3 *******************************************************
* These endogenous (unknown) variables are defined                        *
* Their numerical values are not known till GAMS finds optimal soln *
******************************************************************************

FREE VARIABLES

X(i,t)                water flows -- diversion-use-return - etc.
XUSE                  tot use-benefits-flows summed over node and time (aka obj fn)

POSITIVE VARIABLES

Z(u,t)                water stocks -- reservoirs and groundwater

**************** Section 4 *******************************************************
* The following equations state relationships among a basin's              *
* hydrology, institutions, and economics                                  *
******************************************************************************

EQUATIONS

******************************************
* Equations named
******************************************

* Hydrology Block

Inflows(inflow,t)      Flows: set source nodes
Rivers(i,t)            Flows: hydrologic mass balance for each flow node: sources = uses
Divs(divert,t)         Flows: set divert nodes
Returns(return,t)       Flows: set return flows
Uses(use,t)             Flows: define use = diversions - return flows
gwflows1(gwflow1,t)    Flows: set river flows from seepage or pumping
gwflows2(gwflow2,t)    Flows: set river flows from aquifers
reservoirs(res,t)      Stock: reservoir mass balance accounting

* Institutions Block (empty)

*

* Economics Block

OBJtotuse               Objective: economic value over all nodes and periods

******************************************
* Equations defined algebraically using equation names
******************************************

* Hydrology Block
Inflows\(\text{inflow,t}\) .. \(X(\text{inflow,t}) = \sum \text{source}(\text{inflow,t})\);

Rivers\(\text{river,t}\) .. \(X(\text{river,t}) = \sum \text{Bv}(\text{inflow, river}) \times X(\text{inflow,t}) + \sum \text{Bv}(\text{riverp, river}) \times X(\text{riverp,t}) + \sum \text{Bv}(\text{divert, river}) \times X(\text{divert,t}) + \sum \text{Bv}(\text{return, river}) \times X(\text{return,t}) + \sum \text{Bv}(\text{gwflow1, river}) \times X(\text{gwflow1,t}) + \sum \text{Bv}(\text{gwflow2, river}) \times X(\text{gwflow2,t}) + \sum \text{Bv}(\text{rel, river}) \times X(\text{rel,t})\);

Divs\(\text{divert,t}\) .. \(X(\text{divert,t}) = \sum \text{Bd}(\text{inflow, divert}) \times X(\text{inflow,t}) + \sum \text{Bd}(\text{river, divert}) \times X(\text{river,t}) + \sum \text{Bd}(\text{divertp, divert}) \times X(\text{divertp,t}) + \sum \text{Bd}(\text{return, divert}) \times X(\text{return,t}) + \sum \text{Bd}(\text{gwflow1, divert}) \times X(\text{gwflow1,t}) + \sum \text{Bd}(\text{gwflow2, divert}) \times X(\text{gwflow2,t}) + \sum \text{Bd}(\text{rel, divert}) \times X(\text{rel,t})\);

Uses\(\text{use,t}\) .. \(X(\text{use,t}) = \sum \text{Bu}(\text{divert, use}) \times X(\text{divert,t}) + \sum \text{Bu}(\text{return, use}) \times X(\text{return,t})\);

Returns\(\text{return,t}\) .. \(X(\text{return,t}) = \sum \text{Bdr}(\text{divert, return}) \times X(\text{divert,t})\);

Gwflows1\(\text{gwflow1,t}\) .. \(X(\text{gwflow1,t}) = \text{Gwflows1}_0(\text{gwflow1,t})\);

Gwflows2\(\text{gwflow2,t}\) .. \(X(\text{gwflow2,t}) = \text{Gwflows2}_0(\text{gwflow2,t})\);

reservoirs\(\text{res,t}\) .. \(Z(\text{res,t}) = \sum \text{z0}(\text{ORD(t) EQ 1}) + Z(\text{res,t-1}) - \sum \text{BLv}(\text{rel, res}) \times X(\text{rel,t})\);

* Institutions Block --water laws, compacts, treaties, etc constrains use (Empty for now)

* Economics Block

* Max tot consumptive use over nodes and periods -- no discounting -- all prices = 1.

OBJtotuse.. \(XUSE = \sum (t, \sum \text{BBu}(\text{use}) \times X(\text{use,t}))\);

***************************  End of equations ****************************
MODEL RIO_PROTOTYPE /ALL/;

************************** Section 6 *****************************************************
* The following section defines all solves requested,
* Each solve states a single model for which an optimum is requested.
* Upper, lower and fixed bounds on certain variables can also be included here
* Bounding variables here gives that variable a non-zero shadow price where the optimal
* solution appears at that boundary. If the bound doesn't constrain the model
* the variable's shadow price is zero (complementary slackness)
******************************************************************************************

* Non-negative flows at nodes below
X.lo(inflow,t) = 0;
X.lo(river,t) = 0;
X.lo(divert,t) = 0;
X.lo(use,t) = 0;
X.lo(return,t) = 0;

* Sustainability terminal condition -- each water stock (reservoir, aquifer) ends with
* terminal volume > starting volume.
* It avoids depleting stocks in last period -- saves water for future generations
Z.lo(res, tlast) = Z0(res); > elephant butte reservoir vol > starting value

* Everything including the obj fn is linear in this simple prototype model
* Any nonlinearity in the model requires solving with NLP.

SOLVE RIO_PROTOTYPE USING LP MAXIMIZING XUSE;

************************** Section 7 *****************************************************
* The following section displays post-optimality output
*******************************************************************************

OPTION X:2:1:1; DISPLAY X.L;
OPTION Z:2:1:1; DISPLAY Z.L;

PARAMETER PRIVER RIVER NODES (FLOW)
PARAMETER PINFLOW INFLOW NODES (FLOW)
PARAMETER PUSE USE NODES (FLOW)
PARAMETER PRETURN RETURN FLOW NODES (FLOW)
PARAMETER PGWFLOW1 SHRT TRM RIVER RECHARGE FROM SEEP OR PUMP (FLOW)
PARAMETER PGWFLOW2 LNG TRM OTHER RIVER RECHARGE OR DEPLETION AQUIF (FLOW)
PARAMETER PREL RESERVOIR RELEASE FLOW NODES (FLOW)
PARAMETER PGW GROUNDWATER LEVEL NODES (STOCK)
PARAMETER PRES RESERVOIR LEVEL NODES (STOCK)
;
PRIVER(RIVER,T) = X.L(RIVER,T);
PINFLOW(INFLOW,T) = X.L(INFLOW,T);
PUSE(USE,T) = X.L(USE,T);
PRETURN(RETURN,T) = X.L(RETURN,T);
PGWFLOW1(GWFLOW1,T) = X.L(GWFLOW1,T);
PGWFLOW2 (GWFLOW2, T) = X.L(GWFLOW2, T);
PREL (REL, T) = X.L(REL, T);
PGW (GW, T) = Z.L(GW, T);
PRES (RES, T) = Z.L(RES, T);

DISPLAY PRIVER, PINFLOW, PUSE, PRETURN, PGWFLOW1, PGWFLOW2, PREL, PGW, PRES;

******************************************************************************
* THE END******************************************************************************