May 13, 2013

* Model 6 Simple Farm Management
* Expands scope and scale of Model 5
* 2 to 13 provinces
* 2 to 3 water supply scenarios
* 2 to 4 water shortage sharing methods
* 2 to 9 crops
* model 6, adds 13 provinces and 9 crops and 4 water sharing arrangements

******************************************* Section 1 *******************************************
* Sets *
SETS

i province

/ 1-Mousil
  2-Kurkuk
  3-Salaheldeen
  4-Deyala
  5-Anbar
  6-Baghdad
  7-Babylon
  8-Karbala
  9-Qadeseeya
  10-Muthana
  11-Thieqar
  12-Meesan
  13-Basra
/

k crop

/ 1-Rice
  2-Wheat
  3-Cotton
  4-Sunflower
  5-Maize
  6-Barley
  7-Tomato
  8-Lettuce
  9-Onion
/

s hydrologic water supply scenario

/ 1-normal
2-dry
3-drought/

j water right priority: water right priority: same number # of elements as # of provinces - 1 priority per province

/ j1*j13 /

set r water allocation rule allows for many water shortage sharing rules to be considered

/l-ds_priority downstream priority // rule 1
2-us_priority upstream priority // rule 2
3-prop_sharing proportional sharing of shortages // rule 3
4-free_market free market - proportional sharing then water moves by market // rule 4
/

*subsets of r

set rwa(r) / l-ds_priority, 2-us_priority, 3-prop_sharing/ // subset of rules = everything except market trading
set rfm(r) / 4-free_market/ // subset of rules = only market trading of water in drought

Set rji(r, j, i) mapping set: assigns priorities to province - separate assignments for each proposed rule

// best (senior) right assigned to canal with j1 priority - worst (junior) priority assigned to canal with j4
// Two canals with equal priority (e.g. two both with j1) share shortages proportionally

/l-ds_priority . (j1.13-Basra, j2.12-Meesan, j3.11-Thieqar, j4.10-Muthana, j5.9-Qadesseya, j6.8-Karbala, j7.7-Babylon, j8.6-
Baghdad, j9.5-Anbar, j10.4-Deyala, j11.3-Salaheldeen, j12.2-Kurkuk, j13.1-Mousil)
2-us_priority . (j1.1-Mousil, j2.2-Kurkuk, j3.3-Salaheldeen, j4.4-Deyala, j5.5-Anbar, j6.6-Baghdad, j7.7-Babylon, j8.8-
3-prop_sharing . j1. (1-Mousil, 2-Kurkuk, 3-Salaheldeen, 4-Deyala, 5-Anbar, 6-Baghdad, 7-Babylon, 8-Karbala, 9-Qadesseya, 10-
Muthana, 11-Thieqar, 12-Meesan, 13-Basra)
4-free_market . j1. (1-Mousil, 2-Kurkuk, 3-Salaheldeen, 4-Deyala, 5-Anbar, 6-Baghdad, 7-Babylon, 8-Karbala, 9-Qadesseya, 10-
Muthana, 11-Thieqar, 12-Meesan, 13-Basra)
/

************************************************************************** Section 2 **************************************************************************

* Data

**************************************************************************
**TABLE**  
Bc(i, k)  
ET - Per hectare crop water demand 10ths of meters depth = 1000s cubic meters per ha.


* ----- Column Heads are Crops -- Row heads are irrigation canals (water use areas) ----- *

<table>
<thead>
<tr>
<th>Rice</th>
<th>Wheat</th>
<th>Cotton</th>
<th>Sunflower</th>
<th>Maize</th>
<th>Barley</th>
<th>Tomato</th>
<th>Lettuce</th>
<th>Onion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Mousil</td>
<td>30.8</td>
<td>11.9</td>
<td>18.0</td>
<td>12.9</td>
<td>7.0</td>
<td>2.8</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>2-Kurkuk</td>
<td>32.4</td>
<td>12.3</td>
<td>19.1</td>
<td>13.4</td>
<td>7.8</td>
<td>2.6</td>
<td>7.9</td>
<td>1.6</td>
</tr>
<tr>
<td>3-Salaheldeen</td>
<td>28.4</td>
<td>9.9</td>
<td>16.6</td>
<td>10.9</td>
<td>6.8</td>
<td>2.5</td>
<td>6.9</td>
<td>1.6</td>
</tr>
<tr>
<td>4-Deyala</td>
<td>29.6</td>
<td>10.8</td>
<td>17.3</td>
<td>11.8</td>
<td>6.6</td>
<td>3.1</td>
<td>6.7</td>
<td>2.4</td>
</tr>
<tr>
<td>5-Anbar</td>
<td>33.8</td>
<td>12.4</td>
<td>19.7</td>
<td>13.6</td>
<td>8.8</td>
<td>3.1</td>
<td>8.8</td>
<td>1.9</td>
</tr>
<tr>
<td>6-Baghdad</td>
<td>32.2</td>
<td>11.8</td>
<td>18.8</td>
<td>13.0</td>
<td>8.2</td>
<td>2.8</td>
<td>8.2</td>
<td>1.7</td>
</tr>
<tr>
<td>7-Babylon</td>
<td>32.5</td>
<td>11.9</td>
<td>18.6</td>
<td>13.0</td>
<td>8.2</td>
<td>3.0</td>
<td>8.2</td>
<td>1.8</td>
</tr>
<tr>
<td>8-Karbala</td>
<td>32.8</td>
<td>11.9</td>
<td>18.8</td>
<td>13.1</td>
<td>8.6</td>
<td>3.1</td>
<td>8.6</td>
<td>1.9</td>
</tr>
<tr>
<td>9-Qadeseeya</td>
<td>34.2</td>
<td>12.3</td>
<td>19.6</td>
<td>13.6</td>
<td>9.2</td>
<td>3.4</td>
<td>9.2</td>
<td>2.0</td>
</tr>
<tr>
<td>10-Muthana</td>
<td>34.4</td>
<td>12.3</td>
<td>19.6</td>
<td>13.5</td>
<td>9.3</td>
<td>3.6</td>
<td>9.3</td>
<td>2.1</td>
</tr>
<tr>
<td>11-Thieqar</td>
<td>35.6</td>
<td>12.8</td>
<td>20.3</td>
<td>14.1</td>
<td>9.0</td>
<td>3.0</td>
<td>9.1</td>
<td>1.9</td>
</tr>
<tr>
<td>12-Meesan</td>
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<td>12.5</td>
<td>20.1</td>
<td>13.8</td>
<td>9.2</td>
<td>3.4</td>
<td>9.2</td>
<td>2.1</td>
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<tr>
<td>13-Basra</td>
<td>37.2</td>
<td>13.4</td>
<td>21.4</td>
<td>14.9</td>
<td>9.7</td>
<td>3.4</td>
<td>9.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

*Bc(k) = 0.5 * Bc(k)*

<table>
<thead>
<tr>
<th>Yield p(i,k)</th>
<th>Crop Yield tons per Ha (proportional to ET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>Wheat</td>
</tr>
<tr>
<td>1-Mousil</td>
<td>2.89</td>
</tr>
<tr>
<td>2-Kurkuk</td>
<td>2.89</td>
</tr>
<tr>
<td>3-Salaheldeen</td>
<td>2.89</td>
</tr>
<tr>
<td>4-Deyala</td>
<td>2.89</td>
</tr>
<tr>
<td>5-Anbar</td>
<td>2.89</td>
</tr>
<tr>
<td>6-Baghdad</td>
<td>2.89</td>
</tr>
<tr>
<td>7-Babylon</td>
<td>2.89</td>
</tr>
<tr>
<td>8-Karbala</td>
<td>2.89</td>
</tr>
<tr>
<td>9-Qadeseeya</td>
<td>2.89</td>
</tr>
<tr>
<td>10-Muthana</td>
<td>2.89</td>
</tr>
</tbody>
</table>
Yield_p(i,k) = yield_p ('6-baghdad',k) * Bc(i, k)/ Bc('6-baghdad', k) ;

* economic data

Parameter Price_p(k)  Crop Prices ($ US per ton)

/1-Rice  985
2-wheat  225
3-cotton  906
4-sunflower  415
5-Maize  180
6- Barley  175
7-tomato  115
8-lettuce  120
9-onion  142
/

Table Cost_p(i,k)  Crop Production Costs Excluding water ($ US per Ha)

1-Mousil  180  200  1300  220  70  100  60  80  70 70
2-Kurkuk  180  200  1300  220  70  100  60  80  70 70
3-Salaheldeen  180  200  1300  220  70  100  60  80  70 70
4-Deyala  180  200  1300  220  70  100  60  80  70 70
5-Anbar  180  200  1300  220  70  100  60  80  70 70
6-Baghdad  180  200  1300  220  70  100  60  80  70 70
7-Babylon  180  200  1300  220  70  100  60  80  70 70
8-Karbala  180  200  1300  220  70  100  60  80  70 70
9-Qadesseeya  180  200  1300  220  70  100  60  80  70 70
10-Muthana          180       200         1300          220         70         100       60         80             70
11-Thieqar          180       200         1300          220         70         100       60         80             70
12-Meesan           180       200         1300          220         70         100       60         80             70
13-Basra            180       200         1300          220         70         100       60         80             70

*----------------------------------------------------------------------------------------------------------------------------*

1/4 of all costs relate to yield, and 3/4 are independent of yield

**parameter** cost_harvest_p(i,k)  production costs per ha related to crop yield

\[
\text{cost}_\text{harvest}_p(i,k) = 0.25 \times \text{cost}_p(i,k); \quad \text{// harvest-related costs approx 25% of all prodn costs - data source needed}
\]

\[
\text{cost}_\text{harvest}_p(i,k) = \text{cost}_\text{harvest}_p(\text{'6-Baghdad'}, k) \times \text{yield}_p(i,k) / \text{yield}_p(\text{'6-baghdad'}, k); \quad \text{// costs related to harvests}
\]

**parameter** cost_n_harvest_p(i,k)  costs not related to (independent of) harvest;

\[
\text{cost}_n\text{harvest}_p(i,k) = 0.75 \times \text{cost}_p(i,k) \quad \text{// higher total prodn costs with higher yields. Baghdad is reference value}
\]

* re assemble cost below. For any given crop we have (1) rising costs with higher yields and (2) constant costs over provinces

**parameter** cost_p(i,k)  total cost per ha;

\[
\text{Cost}_p(i,k) = \text{Cost}_\text{harvest}_p(i,k) + \text{cost}_n\text{harvest}_p(i,k);
\]

**Table** land_p(i, k)  observed land in prodn (1000 Ha)

<table>
<thead>
<tr>
<th></th>
<th>1-Rice</th>
<th>2-wheat</th>
<th>3-cotton</th>
<th>4-sunflower</th>
<th>5-Maize</th>
<th>6-Barley</th>
<th>7-tomato</th>
<th>8-lettuce</th>
<th>9-onion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Mousil</td>
<td>0.0</td>
<td>47.4</td>
<td>0.45</td>
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<td>3-Salaheldeen</td>
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<td>3.0</td>
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<td>4-Deyala</td>
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<td>17.7</td>
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<tr>
<td>5-Anbar</td>
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<td>55.5</td>
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<td>3.4</td>
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<tr>
<td>6-Baghdad</td>
<td>0.0</td>
<td>65.7</td>
<td>2.60</td>
<td>2.6</td>
<td>2.0</td>
<td>25.6</td>
<td>8.2</td>
<td>51.8</td>
<td>27.6</td>
</tr>
<tr>
<td>7-Babylon</td>
<td>1.6</td>
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<td>1.00</td>
<td>1.0</td>
<td>0.6</td>
<td>73.0</td>
<td>44.4</td>
<td>15.6</td>
<td>15.3</td>
</tr>
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<td>8-Karbala</td>
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<td>2.9</td>
<td>0.04</td>
<td>0.0</td>
<td>0.2</td>
<td>3.1</td>
<td>2.9</td>
<td>11.8</td>
<td>7.8</td>
</tr>
<tr>
<td>9-Qadeseyya</td>
<td>32.5</td>
<td>91.8</td>
<td>0.40</td>
<td>0.4</td>
<td>0.05</td>
<td>3.8</td>
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<td>15.2</td>
<td>9.6</td>
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<td>10-Muthana</td>
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<td>12.8</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>29.1</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>11-Thieqar</td>
<td>0.1</td>
<td>61.3</td>
<td>0.05</td>
<td>0.0</td>
<td>0.03</td>
<td>3.4</td>
<td>81.5</td>
<td>16.7</td>
<td>11.1</td>
</tr>
</tbody>
</table>
Parameter Net_revenue_p (i,k)  net revenue per ha observed
   T_net_revenue_p(i  )  total net revenue by province summed over crops
;
Net_revenue_p (i,k) = Price_p(k) * Yield_p(i,k) - Cost_p(i,k) + eps;

parameter Wat_supply_p(s)  total water available (million cubic meters per year) calculated total ag water use (not meas from gauges)
;
Wat_supply_p('1-normal') = sum((i,k), Bc(i,k) * land_p(i,k)); // actual water use in full supply year
Wat_supply_p('2-dry') = 0.50 * Wat_supply_p('1-normal'); // 50% of full supply
Wat_supply_p('3-drought') = 0.20 * Wat_supply_p('1-normal'); // 20% of full supply

parameter right_p(i)  total water assigned by province in full supply conditions (paper water)
;
right_p(i)  =  sum(k, Bc(i,k) * land_p(i,k));

*************** code defines water sharing methods ****************************

* code below loops over each priority (j) then maps each priority to corresponding province i
* code is thanks to Pete Stacy at GAMS Development Corporation Feb 1 2012

parameter tot_assigned(r,s) cumulative assignment at canal i including higher priorities;
tot_assigned(r,s)  = 0; // starts at 0 - prepares to loop

parameter tot_pap_right_by_prior( r,j) total paper rights by jth priority for all canals including ties
remain_supply_by_prior(r,s,j) residual supply by jth priority after supplying higher priorities
wet_wat_use (r,s,i) wet water use assigned to ith limited by total basin supply
;
Loop(r, // loop over sharing rule (r)
   Loop(j, // loop over priority (j)
        tot_pap_right_by_prior(r,j) = sum[i$rji(r, j, i), right_p(i)]; // total paper rights by (j) after protecting higher priorities
        remain_supply_by_prior(r,s,j) = min((Wat_supply_p(s) - tot_assigned(r,s)), tot_pap_right_by_prior(r,j)) + eps; // remaining supply by jth priority after
*supplying higher priorities

Loop (i$rji(r, j, i),
    wet_wat_use(r,s,i) = (right_p(i)/tot_pap_right_by_prior(r,j))
    * remain_supply_by_prior(r,s,j) + eps;          // wet water assigned to (i) province
    tot_assigned(r,s) = tot_assigned(r,s) + wet_wat_use(r,s,i) ;             // cumulative water (check) assigned to last province
*getting water - should match total supply

    );                                           // end province loop
);                                               // end priority loop
);                                                 // end rule loop

parameter tot_wat_use(r,s) total water use;
tot_wat_use (r,s) = sum(i, wet_wat_use(r,s,i)) + eps;

************** end of water allocation system ********************************************

**** begin looping over water sharing rule and water supply scenario below
* rr, ss, are subset of orginal sets... allows fast scenario analysis below

set rr(r);  // water sharing rule
set ss(s);  // water supply scenario

rr(r) = no;  // switch rr subset off -- prepares to turn it on below in equations
ss(s) = no;  // switch ss subset off -- prepares to turn it on below in equations

******************************  SECTION 3 ***********************************************
*                               Variables                                               *
*****************************************************************************************

POSITIVE VARIABLES

hectares_v          (r,s,i,k)   land in production by rule-province-crop-scen   (1000 Ha - marginal is $US per Ha)
T_hectares_v        (r,s,i  )   total land in prodn by rule-province-scen     (1000 Ha - marginal is $US per Ha)
Uses_v              (r,s,i  )   total water use by rule-province-crop-scen       (million m^3 - marginal is $US per 1000 m^3)
Uses_Crop_v         (r,s,i,k)   total water use by rule-province-scen          (million m^3 - marginal is $US per 1000 m^3)
Sum_uses_v          (r,s    )   summed wat uses over provinces by rule-scen      (million m^3 - marginal is $US per 1000 m^3)

variables
Ag_Ben_k_v   (r,s,i,k)  total farm income by rule-scenario-province-crop ($US 1000s - no marginals shown)
Ag_Ben_v     (r,s    )  total farm income by rule-scenario-province ($US 1000s - no marginals shown)

Tot_b_v      total farm income re-calc for each rule-scen (objective) ($US 1000s - no marginals shown)

;*******************************   Section 4  ********************************************
*                                 Equations                                             *
*****************************************************************************************

EQUATIONS

// Equations DECLARED

T_hectares_e   (r,s,i      )       total land in production by province-scen  (1000 Ha - marginal is $US per Ha)
Uses_crop_e   (r,s,i,k    )       total water use by rule-scen-prov-crop     (million m^3 - marginal is $US per 1000 m^3)
Uses_e        (r,s,i      )       total water use by rule-scen-prov          (million m^3 - marginal is $US per 1000 m^3)
Sum_uses_e    (r,s        )       total water use by rule-scen               (million cubic meters per year)
ag_ben_k_e    (r,s,i,   k )       total farm income by rule-scen-prov-crop   ($US 1000)
Ag_ben_e      (r,s        )       total farm income by rule-scen-prov        ($US 1000)

Tot_b_e                                      total farm income by element of loop       ($US 1000)

;                                  // Equations defined (using above names with algebraic formulas)

// Equations below defined over rule (rr) and scenario (ss) using subset rr and ss

T_hectares_e(rr,ss,i  )..  T_hectares_v(rr,ss,i  ) =e=  sum(k, hectares_v(rr,ss,i,k));
Uses_crop_e (rr,ss,i,k)..  Uses_crop_v(rr,ss,i,k)  =e=   Bc(i,k) * hectares_v(rr,ss,i,k) ;
Uses_e      (rr,ss,i  )..       Uses_v(rr,ss,i  )  =e=  sum(k, Uses_crop_v(rr,ss,i,k));
sum_uses_e  (rr,ss    )..   sum_uses_v(rr,ss    )  =e=  sum(i, Uses_v(rr,ss,i  ));
ag_ben_k_e  (rr,ss,i,k)..  Ag_Ben_k_v (rr,ss,i,k)  =e=  Net_revenue_p(i,k) * hectares_v(rr,ss,i,k);
Ag_ben_e    (rr,ss    )..  Ag_Ben_v   (rr,ss    )  =e=  sum((i,k), Ag_Ben_k_v(rr,ss,i,k));
Tot_b_e                ..  Tot_b_v     =e= sum((rr,ss), ag_ben_v(rr,ss    )); //sums total benefits over indices for each rule-scen

MODEL TE_06 /all/;

uses_v.up   (rwa,s, i)  = wet_wat_use(rwa,s,i); // without water trading water use limited to historic by province
sum_uses_v.up(rfm,s  )  = tot_wat_use(rfm,s  ); // with water trading only total (basin) water is bounded
hectares_v.up(r,s,i,k)  = land_p(i,k); // can produce no more crops than observed under full water supply

parameter shad_price_p(r,s,i)  shadow prices calculated below after each optimization
;

* prepare for multiple solves inside the loops

    loop(r,
        loop(s,
            ss(s) = yes;
            rr(r) = yes;
            Solve TE_06 using nlp maximizing Tot_b_v;

            shad_price_p(rwa,s,i ) = uses_v.m(rwa,s,i) + eps; // shad prices for all water allocation rules ex trading
            shad_price_p(rfm,s,i ) = sum_uses_v.m(rfm,s ) + eps; // shad prices for trading - should be = across provinces

        )
    )

* closes loops below over r,s (rule for sharing water shortages, water supply scenario)
\[
rr(r) = \texttt{no}; \\
ss(s) = \texttt{no}; \\
\]

\[
\]

****************************************************************************
* Section 8: DISPLAYS *
****************************************************************************

* Parameters are calculated values from the optimal solution, first defined then found

\textbf{parameter}

\begin{align*}
tot\_use\_p & \quad (r,s,i,k) \quad \text{total water use by rule-scen-prov-crop} \\
uses\_p & \quad (r,s,i) \quad \text{total water use by rule-scen_prov} \\
land\_v\_p & \quad (r,s,i,k) \quad \text{total land in production} \\
ben\_by\_crop\_canal\_p & \quad (r,s,i,k) \quad \text{total benefits by crop and province} \\
ben\_by\_canal\_p & \quad (r,s,i) \quad \text{total economic benefits by province} \\
tot\_ben\_p & \quad (r,s) \quad \text{total economic benefits} \\
\end{align*}

* land in prodn (1000 hectares)

\[
l_{\text{land\_v\_p}}(r,s,i,k) = \text{hectares\_v\_l}(r,s,i,k) + \text{eps}; \\
\]

* water (1000 hectare meters)

\[
l_{\text{tot\_use\_p}}(r,s,i,k) = \text{Uses\_crop\_v\_l}(r,s,i,k) + \text{eps}; \\
l_{\text{uses\_p}}(r,s,i) = \text{Uses\_v\_l}(r,s,i) + \text{eps}; \\
\]

* economic benefits ($1000 US)

\[
l_{\text{ben\_by\_crop\_canal\_p}}(r,s,i,k) = \text{Ag\_ben\_k\_v\_l}(r,s,i,k) + \text{eps}; \\
l_{\text{ben\_by\_canal\_p}}(r,s,i) = \text{sum}(k, \text{ag\_ben\_k\_v\_l}(r,s,i,k)) + \text{eps}; \\
l_{\text{tot\_ben\_p}}(r,s) = \text{ag\_ben\_v\_l}(r,s) + \text{eps}; \\
\]

* GAMS GDX facility writes to external spreadsheet
execute_unload "farm_mgmt_06.gdx"

execute 'gdxxrw.exe @gdxxrwout.txt trace=2';

// THE END