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WETSYS, a dynamic system model to assess trade-off between wetland ecosystem services at local level

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WETSYS, a dynamic system model to assess trade-off between wetland ecosystem services at local level

SEVENTH FRAMEWORK PROGRAMME

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1 Introduction

In southern Africa, as in other regions in Africa, many communities depend on wetlands for multiple benefits, including social, economic, ecological and aesthetic values (Taylor *et al.* 1995; Breen *et al.* 1997). In such semi-arid to arid conditions, wetland agriculture provide a means to reduce the variability of crop yield losses associated with low and unreliable rainfall and frequent droughts and thus enhances food security and incomes of poor agriculture-dependent communities (Frenken and Mharapara 2002; Breen *et al.,* 1997).

Besides agriculture, wetlands provide other provisioning services which are important for supporting the livelihoods of most poor people in the region. These include dry season livestock grazing and watering, fisheries, wildlife, wetland plants used for building, crafting, cooking and healing, fuel wood, clay for pottery, water supply for domestic use, irrigation and industrial use (Breen *et al.,* 1997).

Whilst wetlands play a key role in supporting the livelihoods of many communities in the region, their continuous use for cultivation and grazing has potential to degrade their fragile ecosystems and undermine their capacity to provide services in future. Assessing the trade-offs between use of wetlands for human well-being and their ecological integrity involves quantifying the impacts of alternative wetland uses on wetland systems, the services they provide and human well-being. Very limited work in this area has been done particularly in southern Africa.

The main empirical approaches used for assessing ecological-economic trade-offs in the literature are: (i) economic valuation of ecosystem services and economic activities (ii) multi-criteria analysis and (iii) integrated ecological-economic models.

In the first approach the values of ecosystem services and economic activities such as agricultural production are expressed in monetary terms through economic valuation. Trade-offs are analysed through plotting curves for ecosystem services and agricultural values computed for increasing levels of human intervention (see for example Viglizzo and Frank 2006). Multi-criteria analysis represents trade-offs through pay-off matrices representing values of several economic and environmental indicators computed for various scenarios (Brown *et al.* 2001; Tiwari *et al.* 1999). In the multi-attribute approach proposed by McDaniels 1999, adapted to situation where little quantitative information is available, trade-offs are based on preferences expressed by stakeholders or experts through multi-attribute rating techniques.

Integrated ecological–economic models provide a useful approach for quantifying the trade-offs in ecosystem services in complex dynamic systems (Farber *et al.* 2006). Two forms of integrated modelling approaches are used in the literature: (i) modular or heuristically integrated models and (ii) dynamic systems models.

In the modular approach loose connections are built between the disciplinary models and output from one model provides the necessary input for the other (see for example Bouman *et al.* 1998; Lu and van Ittersum 2003; Ringler and Cai 2003; Stoorvogel *et al.* 2004; Turner *et al.* 2000). Trade-offs are represented either by trade-off curves between indicators or by matrices of indicators for discrete scenarios. Although, the approach allows for detailed analysis of each of the model components, it does not take into account the interactions and feedback loops between the disciplinary models (Wätzold *et al.* 2006).

The dynamic systems modelling approach has become increasingly popular in modelling human-ecosystem interactions. In contrast to the modular approach, in this approach the disciplinary models are tightly interwoven with strong interactions and feedbacks between model components. It has the ability to capture the complex non-linear interactions and feedback loops which characterize ecological-economic systems (Wiegert 1975; Cleveland *et al.* 1996; Costanza *et al.* 1993; Costanza 1996; Bockstael *et al.* 1995).

Dynamic system modelling has been widely used to study land use dynamics, especially in developing countries. Several approaches can be identified in the formalization of land use changes. In models operating at micro or meso scales, land use changes are often based on the comparison of economic returns of resources invested in each land use (e.g. Luckert *et al.* 2000; Evans *et al.* 2001; Saysel *et al.* 2002). In Stephenne and Lambin 2001, land area used for crop production, livestock grazing and fuel wood collection at national level is directly derived from population needs and land productivity. In a model representing the economy of the Dominic island, Patterson *et al.* 2004 used both approaches. In CLUE, a spatially explicit dynamic model (Verburg *et al.* 2002; de Koning *et al.* 1999), local land use changes are driven by global population demand for agricultural products at regional or national level. Allocation of land use changes across space is based on empirically quantified relations between land use types and their driving factors.

In this paper, we adopted the dynamic systems approach to analyze the trade-offs between the provision of ecosystem services and ecosystem integrity and resulting land use changes in the Ga-Mampa wetland in the Limpopo basin in South Africa. The purpose of the analysis is to generate knowledge that can assist decision-makers and local communities in managing wetland ecosystems in a sustainable manner.

2 Study site description

The Ga-Mampa wetland is a riverine wetland of about 120 ha that lies on the valley bottom of the Mohlapitsi River, a tributary of the Olifants River in the middle part of the Limpopo River basin in South Africa. The Mohlapitsi catchment is characterized by seasonal rainfall that largely occurs during the summer months, from October to April. Mean annual rainfall for the catchment is 771 mm, but varies significantly with altitude and aspect. Mean annual rainfall in the valley bottom, where the wetland is located, is typically 500 – 600 mm. Within the boundaries of the wetland, the valley floor consists of reasonably well-drained sandy soils upstream and poorly drained sand-loamy soils downstream.

The Ga-Mampa area is part of Lepelle-Nkumpi local municipality and is located in the former homeland area of Lebowa in the Limpopo province. It is predominantly rural with low population density. The main source of livelihood is small-scale agriculture (Ferrand 2004), complemented by social grants and pensions. Livestock farming is dominated by cattle and donkeys which are used for draft power and as a way of saving. Crop production is divided into wetland and irrigation crop production. Maize (the staple crop) is the main crop grown under irrigation and in the wetland. It is estimated that 394 households (2758 people) reside in the 5 villages situated around the wetland (Adekola 2007). More than 80% of the households in the area are poor and vulnerable (Tinguery 2006).

The main provisioning services provided by the wetland include crop production, livestock grazing, edible plants collection, reeds collection, sedge collection, and water supply (Darradi 2005; Adekola 2007). Between 1996 and 2004 more than half of the wetland had been converted to agriculture (Sarron 2005). Conversion of the wetland to agriculture has been driven by three main factors: (i) collapse of the small-scale irrigation schemes in the area following the withdrawal of government support in the early nineties and the destruction of the remaining irrigation infrastructure by floods in 2000; (ii) frequent droughts experienced since 2000; and (iii) high dependence on the wetland for crop production and natural products due to limited access to fertile lands and other livelihood alternatives.

The wetland activities have an impact on the hydrological and ecological functioning of the wetland (Kotze 2005). However, the magnitude of these impacts is not well understood. Because the Mohlapitsi River contributes up to 16% of the dry season flow in the Olifants River (McCartney 2005), some external stakeholders have the perception that the wetland, regardless of its small size, provides an important regulating ecosystem services, in maintaining dry season flows downstream (Darradi 2005).

Initial analysis showed that trade-offs between wetland services occur locally and in the short term between crop production and other local uses of the wetland. At catchment scale, there is a potential trade-off between crop production on one hand and the Mohlapitsi river flow regulation and water supply downstream on the other hand. Finally, in a longer term, continuous use of wetland for agriculture without mitigating management practices may result in irreversible loss of wetland functioning (depletion of organic matter, soil erosion, lowering of shallow water table and reduced contribution to base flow), thus impacting on the wetland ability to provide ecosystem services, including crop production.

3 Model description

3.1 WETSYS model overview

A dynamic system simulation model (WETSYS) was developed using the STELLA® platform (Costanza *et al.* 1998) to simulate the impacts of alternative wetland management strategies and external pressures on wetland ecosystem functioning, ecosystem services and ultimately on community well-being in Ga-Mampa area.

In order to reduce complexity of the model, allow for in-depth understanding of the system processes and their interactions and make calibration of the model less difficult (Voinov *et al.* 2004), the model is divided into seven interactive sectors namely: hydrology (itself sub-divided into three sub-sectors: natural wetland, cultivated wetland and irrigation scheme), crop production, crop economics, irrigation management, natural resources use, land use change decision, and community well-being (Figure 1).

On one hand, the hydrological processes of the wetland impact on the provisioning services (crop production and natural resources), mainly through supply of water. Provisioning services generate income and food and ultimately determine the level of community well-being together with external sources of income (social transfer, paid jobs). On the other hand, human use of the wetland for provisioning services (e.g., crop management practices) impact on the hydrological processes of the wetland. The provisioning sectors in the model are also inter-linked through competition for land. Expansion of the wetland cultivated area (crop production) leads to reduction in the natural wetland area and natural wetland biomass. Land use change decisions are based on the respective contribution of the provisioning activities to the total well-being of the community and on the physical capacity of the available land and water resources to produce expected average yields.

Based on the same conceptual framework and case-study as the model proposed by Jogo and Hassan 2010, WETSYS is an attempt to overcome some of its limitations, and thus differs from it on a number of aspects:

- The model runs at a monthly time step (instead of yearly), which enables it to reproduce the seasonal variations of the water dynamics in the wetland. To allow for differences in time scale between biophysical processes and socio-economic decisions, a specific sector controls annual and seasonal cycles of activities.
- Contrary to the model of Jogo and Hassan, where crop evapotranspiration is derived from yield through a yield-to-water response function, crop water use is directly computed from soil water content thanks to a more realistic representation of hydrological processes occurring in the wetland and the irrigation scheme.
- Land use change decisions are formalized as logical rules reflecting the main drivers of farming households' behaviour in the area, and not as econometrically estimated functions. This choice was motivated by the objective to use the model as a tool for supporting stakeholder dialogue around wetland management, which requires transparent and easy to understand formalizations.
- Finally the estimation of supply and demand functions used by Jogo and Hassan are based on the major assumption that labour is a bidding constraint for farming households in the area. This assumption was contradicted by several focus group discussions conducted in the villages and the observed high level of unemployment. This is compounded by the limited information existing on household labour allocation between various on-farm and off-farm activities in the area.

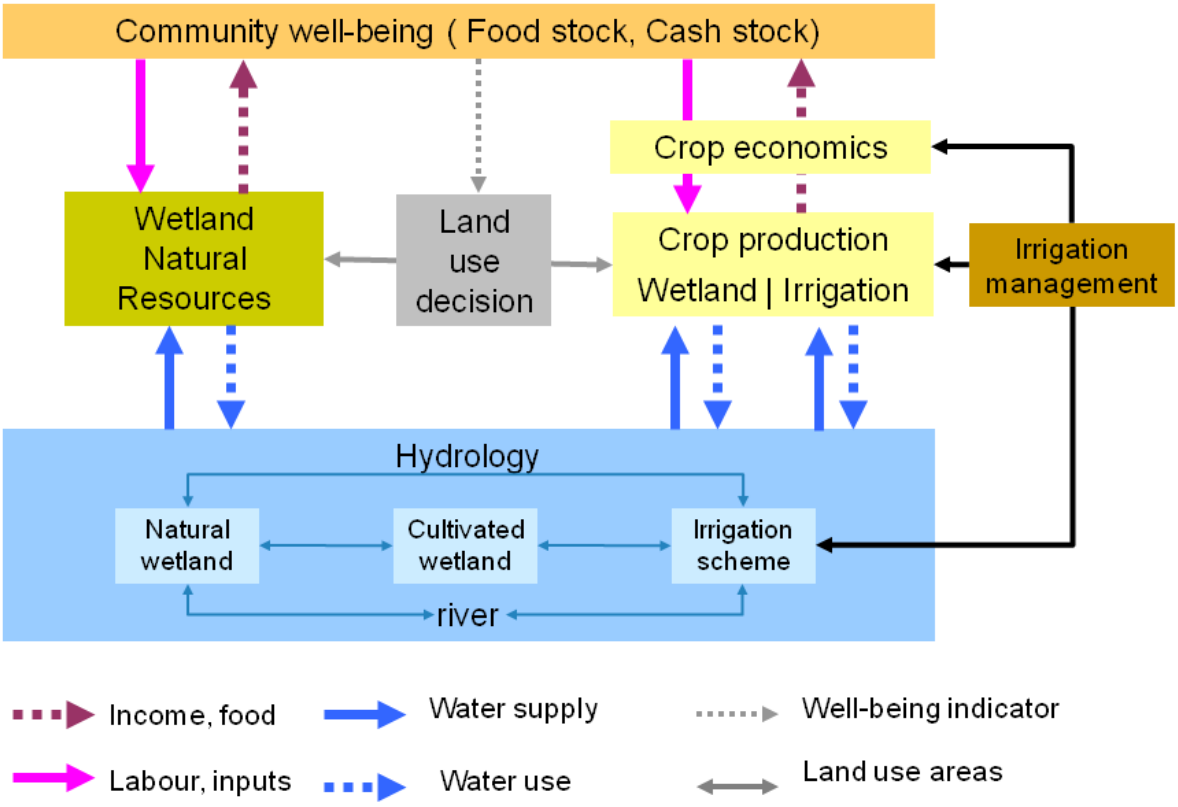


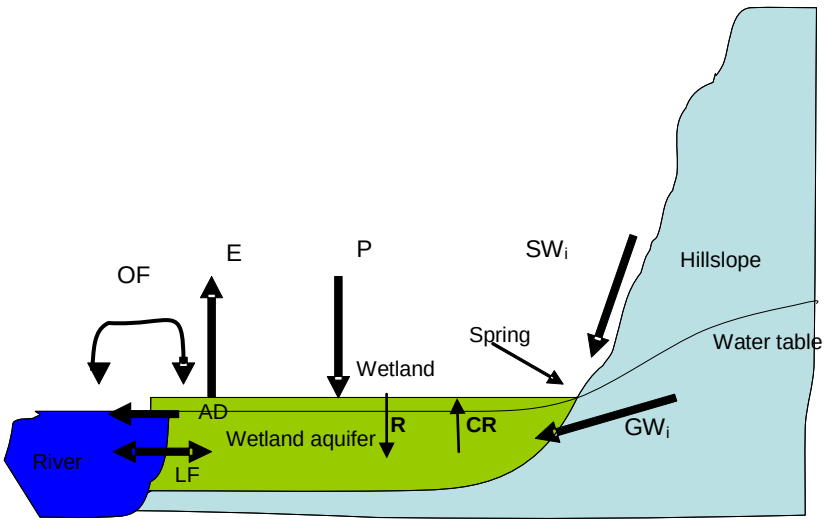
Figure 1: WETSYS model sectors and their linkages

3.2 Hydrology sector

3.2.1 Hydrology sector description

This sector describes the hydrology of the wetland. The objective of the sector is to model the impact of various wetland uses on water dynamics in the wetland and wetland contribution to river flow. The Ga-Mampa wetland system comprises six hydrological units inter-linked by water transfers: the upper Mohlapitsi River catchment (hill slopes), the irrigated scheme on the perimeter of the wetland, the root zone in the cultivated and natural wetland, the shallow aquifer below the wetland, and the river (Figure 2).

The flow of the river upstream of the wetland is mostly generated from the upstream part of the catchment that is predominantly under natural vegetation. As most of the area in the upper catchment is classified as a nature reserve for several decades, no land use change has happened in the recent past and is expected to occur. Therefore the river inflow is considered to depend only on rainfall in the upper catchment.



P: rainfall

E: evaporation + evapotranspiration (crop and wetland vegetation)

AD: artificial drainage

LF: seepage from wetland to river called GW_o, groundwater fow to the river by MMcC

OF: overland flow from wetland to river called SW_o , overland flow to the river by MMcC

SW_i: surface water inflow to wetland from the hill slopes

GW_i: groundwater inflow to wetland from the surrounding catchment

R: recharge

CR: Capillary rise

Figure 2: The Ga-Mampa wetland flow generation conceptual model

Water storage in the wetland is influenced by:

- Rainfall (P) and runoff (SW_i) in the valley bottom and the upper catchment.
- Soil moisture fluxes (Recharge to groundwater R, capillarity rise CR, and evapotranspiration E) in the wetland.
- Natural (LF or GW_o) and artificial drainage (AD) of the wetland: because the shallow groundwater level in the wetland is close to the surface for most of the year and particularly in the rainy season when most agricultural production is carried out, farmers dig open drainage canals to lower the water levels so that the root zone is aerated. Although many of these channels do not have an outlet into the river and act as open water areas, they also effectively drain water out of the wetland into the river.
- Groundwater inflow from the surrounding catchment (GW_i): Much of the upper catchment consists of dolomite and a significant groundwater recharge to the regional aquifer takes place in the upper catchment. This regional groundwater flows into the shallow aquifer of the Ga-Mampa wetland, as shown by the many springs observed at the foot of the hills.

- Irrigation diversion for the irrigation scheme above the wetland: Immediately upstream of the wetland is a water diversion for the irrigation scheme on the perimeter of the wetland. The main and primary irrigation canals are lined but are broken in many places, resulting in loss of water due to leakage. Irrigation water is then channelled to the plots via secondary earthen canals that also leak severely. It is assumed that some water seepage from the irrigation scheme into the wetland groundwater storage occurs, recharging the wetland. The irrigation seepage volume is a function of the efficiency of the distribution system (Chiron 2005). Leakages from the main canal are assumed to flow back to the river without recharging the wetland groundwater, as the canal is very close to the river bed. Leakages occurring in the primary and secondary canals are assumed to recharge the groundwater.
- Surface overflow between the wetland and the river (OF or SW_o): In most years the Mohlapitsi River acts as drainage for the wetland with no contribution to the wetland through lateral flows. Local communities have indicated that over bank flow is relatively uncommon, only occurring during extreme events such as the floods in 2000.

Domestic and livestock groundwater abstraction from the wetland aquifer was considered negligible based on focus group discussion at Ga-Mampa in 2007. Most households use tap water from the municipal water supply network in the villages and water uptake is very limited.

Following Voinov *et al.* 2004[1], the Ga-Mampa valley hydrological system is modelled in three sectors following a similar structure (cultivated wetland hydrology, natural wetland hydrology, irrigation hydrology). Each sector is composed of three interlinked stocks: surface water (water stored above the soil surface), unsaturated water (water stored in the unsaturated zone of the soil), and saturated water (water held in the saturated zone of the soil, or in other words, wetland shallow aquifer), as shown on Figure 3. Inflows and outflows from these stocks are summarized in Table 1 for cultivated wetland. Dynamics of each stock is further detailed below.

In the natural wetland area, the water dynamics is similar as in the cultivated wetland except that the soil is always covered by natural vegetation (no bare soil evaporation) and evapotranspiration is from natural vegetation rather than from crops. In the irrigation scheme, diverted irrigation water constitutes an additional inflow into the soil moisture.

In cultivated wetland and irrigation schemes the water dynamics is described for each succession of summer crops and winter crops as evapotranspiration varies with crops. We assume that there are no lateral flows between land units covered by different successions. In natural wetland the vegetation is considered as homogenous and the water dynamics is represented by only one set of equations.

[1] See http://giee.uvm.edu/LHEM for detailed description

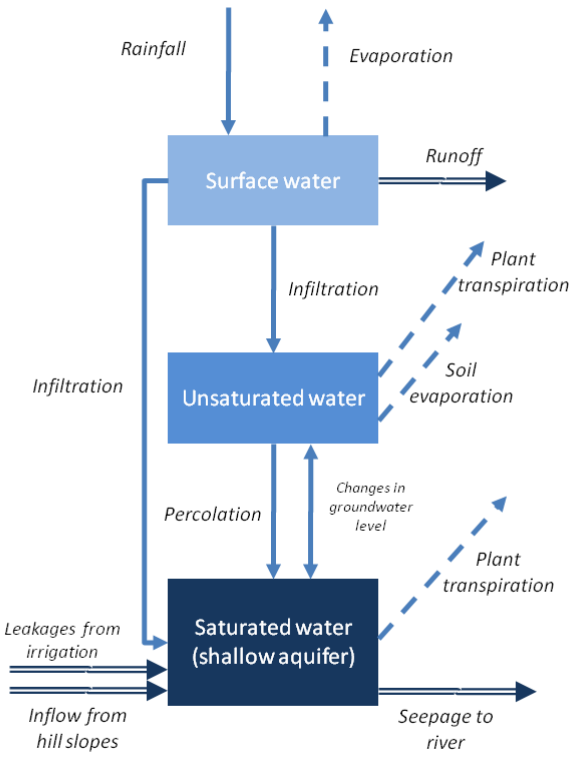


Figure 3 : Cultivated wetland hydrological sub-system represented as 3 interlinked stocks

Table 1: State variables in the hydrological sub-systems and control variables impacting on them (example of cultivated wetland)

Description	Inflows	Outflows
Cultivated wetland surface water (CW_SurfW)	- Rainfall (CW_SW_in) - Inflow from saturated layer when water table reaches the surface (CW_SatW_to_SW)	- Horizontal runoff towards the river (CW_SW_out) - Evaporation (CW_SW_Evap) - Infiltration when the unsaturated layer becomes saturated (CW_SW_to_SatW)
Cultivated wetland unsaturated water (CW_UW)	- Part of the rainfall that infiltrates into the unsaturated storage (CW_UW_from_precip) - Drop of water table (CW_SatW_to_UW)	- Percolation to groundwater (CW_UW_to_SatW) - Evaporation from bare soil and evapotranspiration from crops (CW_UW_eTransp)

Description	Inflows	Outflows
Cultivated wetland saturated water (CW_SatW)	- Percolation from unsaturated zone to groundwater and rise of water table (CW_UW_to_SatW) - Part of the rainfall that infiltrates into the saturated storage (CW_SatW_from_precip) - Infiltration when the unsaturated layer becomes saturated (CW_SW_to_SatW) - Groundwater inflow from hill slopes and leakages from irrigation scheme (CW_GW_inflow)	- Evapotranspiration from the saturated storage (CW_SatW_Transp) - Seepage to river (CW_Seepage_to_river) - Drop of water table (CW_SatW_to_UW)

Surface water flows

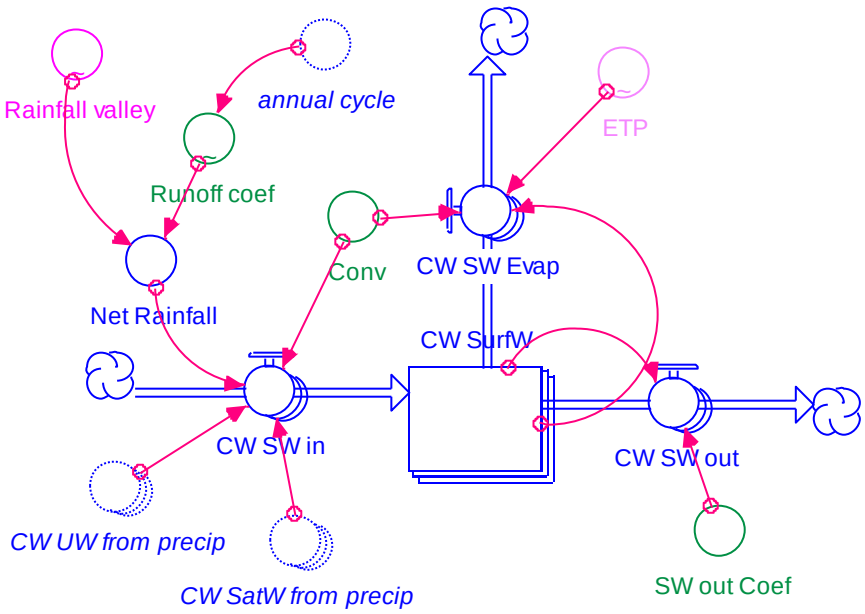


Figure 4: Map describing the surface water flows

Surface water inflow from hill slopes

The bare soil in the valley bottom can generate significant runoff. However, this runoff infiltrates into the wetland before reaching the river. The peat soils in the wetland suggest that direct runoff from the wetland to the river does not occur. Therefore surface water inflow from hill slopes is assumed to be negligible.

Runoff

Runoff depends on a number of factors, including the antecedent conditions of the soil and rainfall intensity, slope etc. Because the model is working at a monthly time step and topography is not really modelled, it is not possible to compute runoff as remaining water after infiltration since this may occur for just a few days in a month during the wet season. As an approximation, runoff was thus estimated as a fraction of rainfall during the wettest months (20% of rainfall from December to February) (McCartney, personal communication) and as null the rest of the year.

$RO = g \times P$ with $g = 0.2$ ***(Equation 1)***

Surface water flow between wetland and river (SW_o)

Based on observations and community members interviews, surface water flow from the wetland to the river can be assumed negligible, except during major flooding events. Overflow of the river onto the wetland is only observed during extreme rainfall events, and is not considered in the model.

Infiltration

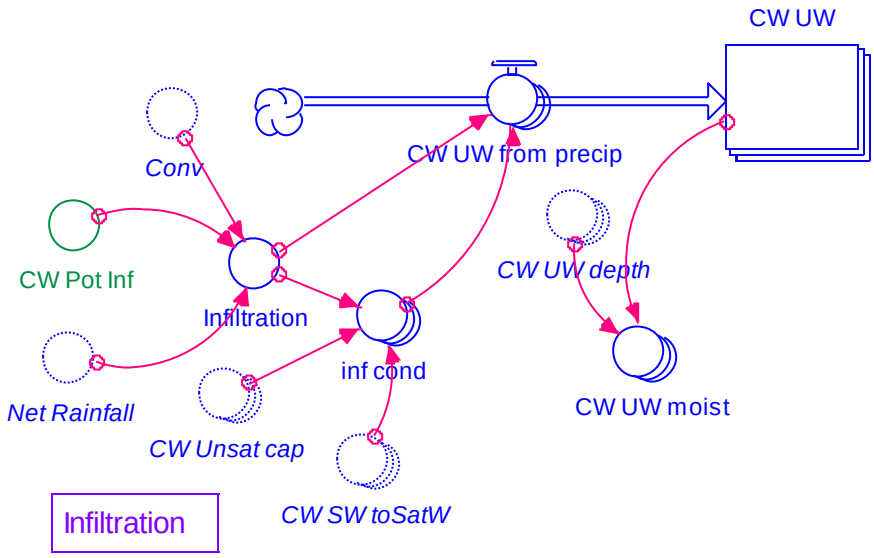


Figure 5: Map describing the infiltration process to unsaturated layer

We assume that net rainfall (after runoff) infiltrates immediately to the unsaturated layer and only accumulates as surface water if the unsaturated layer becomes saturated or if the infiltration rate is exceeded. Therefore, infiltration is defined by the potential infiltration (*CW_Pot_Inf*), which is a feature of soil type and vegetation cover[2], and by the unsaturated storage that is currently available (unsaturated capacity). The unsaturated capacity is the total volume of pores in the soil that is not yet filled by water:

$$Unsat_Cap = UW_depth \cdot (Porosity - Moist)$$ ***(Equation 2)***

[2] Theoretically it also depends on the slope, but we did not consider the influence of slope in this model, because of the spatial resolution of the model (landscape unit) and because the wetland area is rather flat

Where *Porosity* is the soil porosity (m/m of soil)
Moist is the soil moisture (m/m of soil)
and *UW_depth* is the depth of the unsaturated layer (in meters).

If the infiltration is less than the unsaturated capacity, all water available for infiltration is added to the unsaturated water storage (*UW_from precip*). If the volume of water to be infiltrated is greater than the unsaturated capacity, then the incoming water will fill up all the pores in the unsaturated layer, saturating the soil and eliminating the unsaturated zone. In this case all the infiltrated flow is channelled to the saturated storage (*SatW_from_precip*), the available unsaturated water is added to it and the unsaturated storage is set to zero. In the model this dynamics is controlled by the variable *inf_cond*, which distributes the volume of potential infiltration between the unsaturated storage (*UW_from_precip*), the saturated storage (*SatW_from_precip*) and the surface water.

*inf_cond = IF SW_to_SatW*DT = Unsat_cap THEN 0 ELSE MAX (Unsat_cap - Infiltration, 0)* **(Equation 3)**

inf_cond is equal to zero when the groundwater table reaches the ground surface and all the water available for infiltration is channelled to the saturated layer.

UW_from_precip = IF inf_cond>0 THEN Infiltration ELSE 0 ***(Equation 4)***

SatW_from_precip = IF inf_cond=0 THEN Unsat_cap/DT - SW_to_SatW ELSE 0 ***(Equation 5)***

The volume of water left after infiltration is surface water that is available for horizontal runoff towards the river (*SW_out*) at a certain rate (*SW_out_Coef*).

Evaporation and transpiration

Surface water left after infiltration evaporates (*SW_Evap*) according to climatic conditions (potential evapotranspiration, ETP).

Evapotranspiration from the soil (*UW_eTransp*) includes two components:

- Evaporation from bare soil (E_{bs}) which occurs when there is no crop (most often during the winter), and
- Evapotranspiration from the crops, which is further sub-divided into evapotranspiration from the unsaturated storage (*Transp*UW_Trans_pr*) and from the saturated storage (*SatW_Transp*).

$UW_eTransp = Transp*UW_Trans_pr + E_{bs}$ ***(Equation 6)***

Evaporation from bare soil (E_{bs})

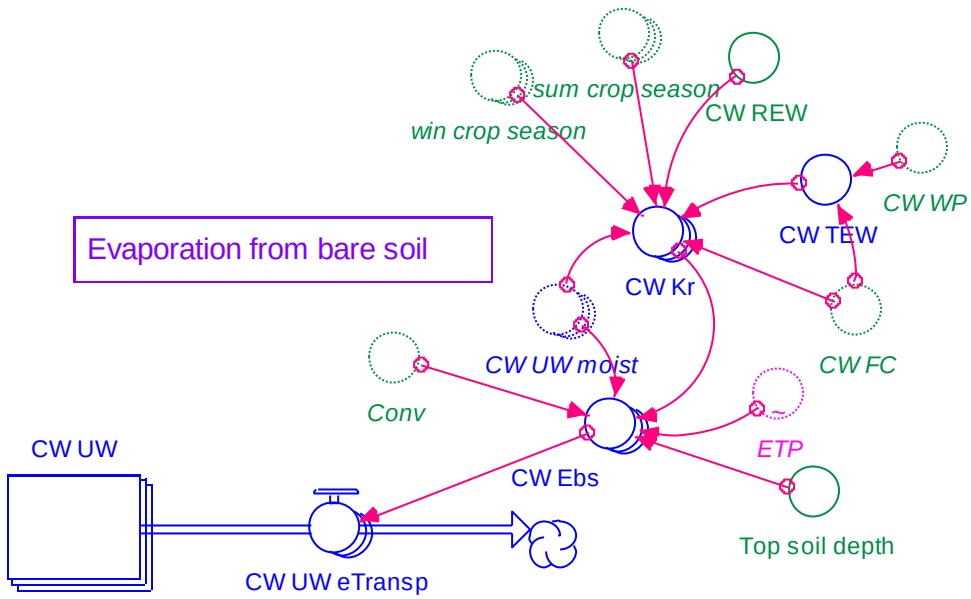


Figure 6: Map describing the evaporation from bare soil process

Outside the cropping season, when the soil is not covered by any crop, evapotranspiration is limited to evaporation from bare soil (E_{bs}), which is assumed to only occur in the 10 first centimetres of the soil layer. Its value depends on the soil water content in the top soil layer and on the climatic demand. The Total Evaporable Water (TEW) is the maximum depth of water that can be evaporated from the soil when the top soil has been initially completely wetted. Readily Evaporable Water (REW) is the depth of water that can be evaporated from the top soil at maximum rate (only limited by energy) (Allen *et al.* 1998). REW and TEW depend on soil characteristics.

$TEW = (FC - 0.5*WP)$ where FC is the field capacity, and WP is the wilting point

When soil moisture is above FC – REW, evaporation occurs at maximum rate (and is equal to the minimum between ETP and TEW) and the soil evaporation reduction coefficient K_r is equal to 1. If soil moisture is between $FC\text{-}REW$ and $FC\text{-}TEW$, K_r decreases linearly. When soil moisture is below 0.5*WP, K_r and then E_{bs} are null; (Figure 7). In any case E_{bs} is capped by the available water in the top soil layer.

$E_{bs} = MIN(1.15*Kr*ETP, UW_moist*0.1)$ ***(Equation 7)***[3]

where UW_moist is the soil moisture expressed in water depth per meter of soil.

In the natural wetland, as the ground is covered all year long by natural vegetation, evaporation from bare soil is omitted.

[3] The 0.1 coefficient caters for the fact that evaporation only occurs in the first 10 cm of soil.

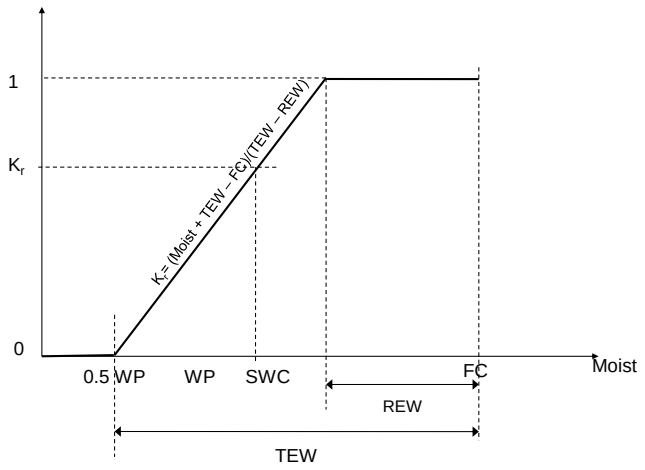


Figure 7: Variation of the soil evaporation reduction coefficient K_r with soil moisture

Evapotranspiration from crop or natural vegetation

Following FAO guidelines, actual evapotranspiration ET_a depends on meteorological factors (radiation, temperature, wind speed, humidity), the water stored in the soil, the nature of the crop (or natural vegetation) and its development stage.

Total available water (TAW) is the quantity of water that can be stored in the soil and absorbed by plants (expressed in m/m of soil depth), and is computed as the difference between field capacity and wilting point (see Table 4). A certain fraction of TAW is easily accessible by plants ($RAW = p \ x \ TAW$, where p is the depletion coefficient, a crop characteristics). The fraction p of soil water content that is easily accessible by the plant depends on crop, ET_m and soil. For sake of simplicity p is assumed to be only dependent on crop. Values for local crops are given in Table 8. Between field capacity and field capacity less than RAW (i.e. when water is not a limiting factor), the actual evapotranspiration ET_a equals the maximal evapotranspiration ET_m. Below this threshold, water stress applies (K_s) and ET_a decreases proportionally to water content.

Crop transpiration is also hampered when the root zone is water logged, resulting in deficient soil aeration. If the soil water content is above the anaerobiosis point, the transpiration decreases linearly up to 0 when the soil water content is at saturation.

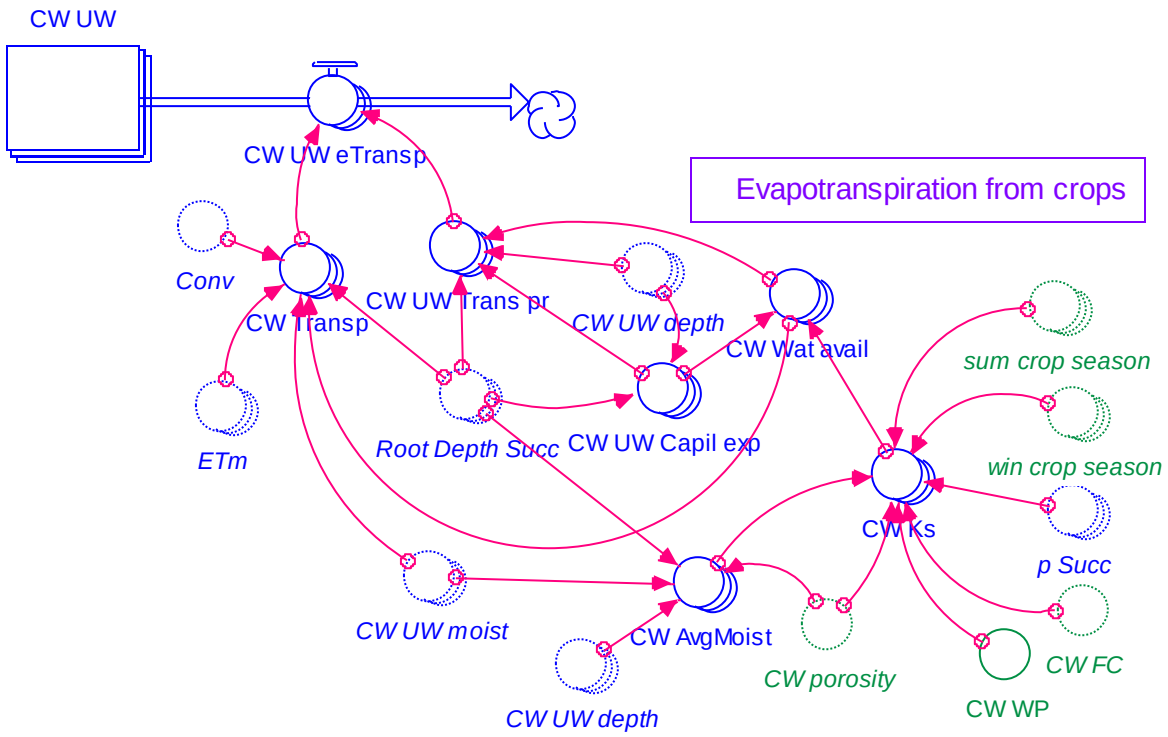


Figure 8: Map describing the evapotranspiration process

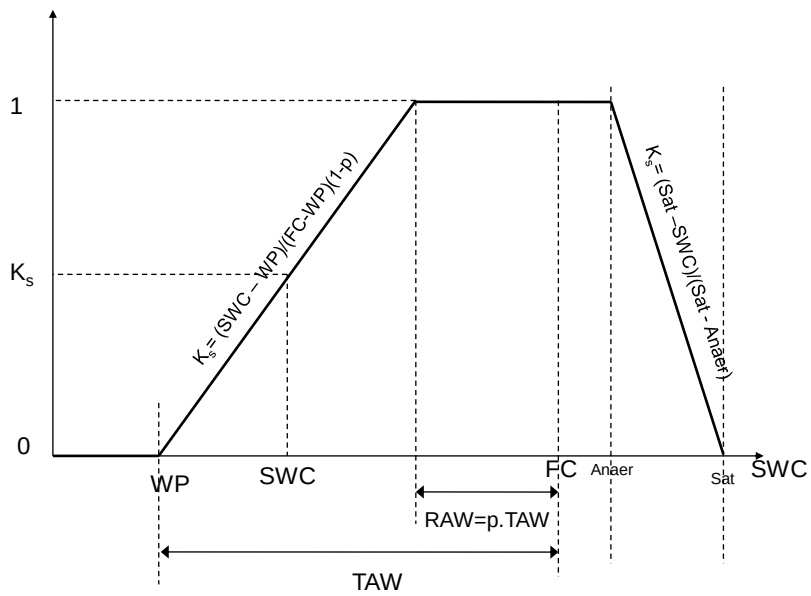


Figure 9 : Variation of water stress factor K_s with soil water content (adapted from Raes et al. 2006)

This is computed in the model as follows:

$Transp = Wat_avail \times ET_m$ ***(Equation 8)***

With Wat_avail the water availability factor, evolving with soil moisture and root depth

ET_m is the crop water demand when there is not restriction on water availability.

The water availability factor depends mainly on the soil moisture, through K_s, water stress factor defined by Allen et al. 1998, which evolves with soil moisture as shown on Figure 9. In addition, when roots come close to the saturated layer, water availability for transpiration is increased by capillarity rise.

$Wat_avail = MIN(1.0, UW_Capil_exp + K_s)$ ***(Equation 9)***

Capillary rise can be significant in the wetland due to the presence of the shallow water table. Following Voinov *et al.* (2004), we assumed that capillary rise decreases exponentially when the distance between root zone and groundwater table increases (Equation 9)[4].

$UW_Capil_exp = EXP(-10*MAX(UW_depth-Root_Depth, 0))$ ***(Equation 10)***

With UW_depth, depth of unsaturated layer and $Root_depth$ depth of crop or natural vegetation roots

As mentioned above, transpiration fluxes are supplied both by the unsaturated and saturated layers. The proportion of transpiration from the unsaturated layer (UW_Trans_pr) depends on the root depth and the depth of unsaturated layer. When the root depth is largely smaller than the depth of unsaturated layer, transpiration comes entirely from the unsaturated layer. When the roots come closer to the saturated layer, the available water is increased by capillarity rise. When root depth is greater than the depth of unsaturated layer or when the soil is saturated (unsaturated layer depth is equal to zero), then transpiration is supposed to come entirely from the saturated layer (Table 2).

Table 2: Variation of the proportion of transpiration from the unsaturated layer with root depth

Conditions	UW_Trans_pr
Root_depth> UW_depth – z	Wat_avail*UW_depth/(Root_Depth_Succ+UW_Capil_exp)
Root_depth < UW_depth – z	1
UW_depth = 0	0

With z distance to the saturated layer at which the capillarity effect becomes pronounced (here z=0.2m)

Maximum evapotranspiration ET_m depends on meteorological conditions summarized in potential evapotranspiration ETP and on the crop nature through the crop coefficient K_c. K_c varies along the cropping season as typically shown on Figure 10**Hiba! A hivatkozási forrás nem található.**.

$ETm = Kc \times ETp$ ***(Equation 11)***

[4] This specification of capillarity leads to a value sensibly smaller than those found by Raes and Deproost 2003 for different soil textures.

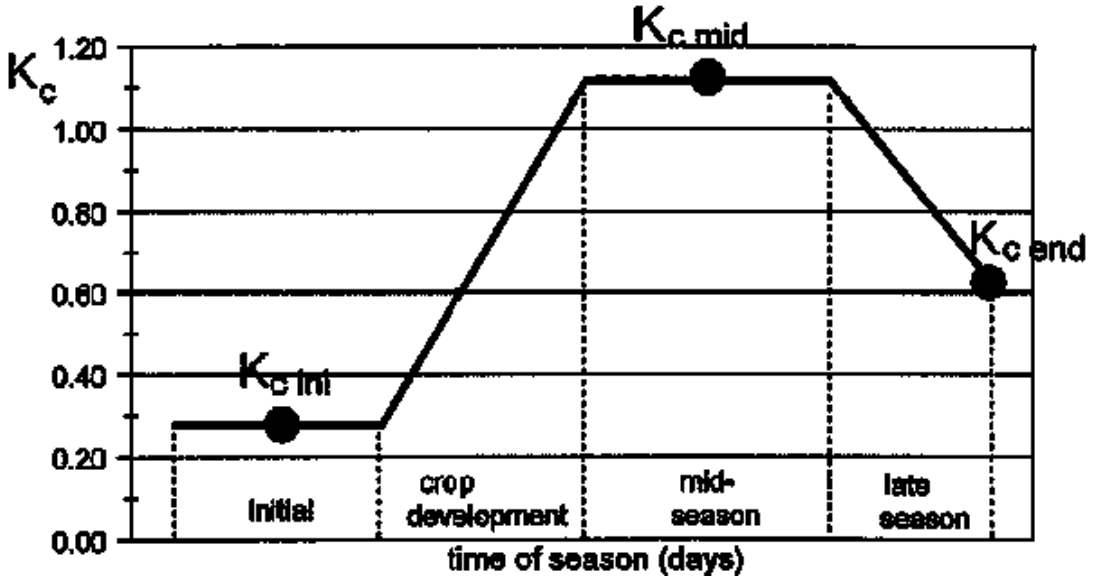


Figure 10 : Variation of crop factor K_c along the growing season (Source : Allen et al. 1998)

At each period t and over the growing season, the values of evapotranspiration ET_a (t) are stored for yield computation (see crop production sector).

Percolation

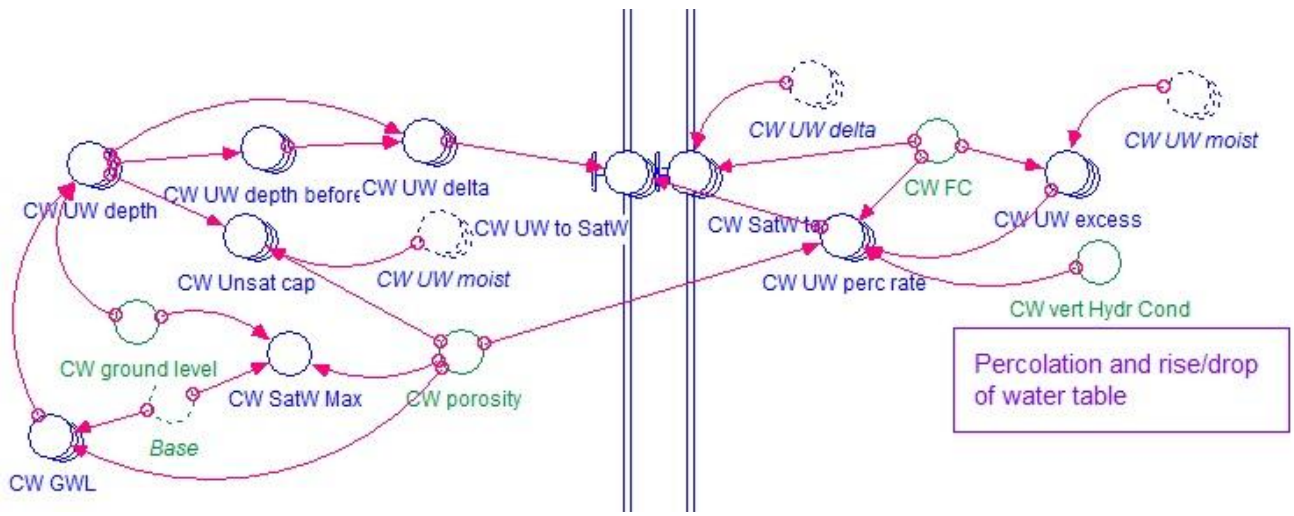


Figure 11: Map describing the percolation process from unsaturated to saturated soil layer

By gravity a certain quantity of water percolates from the unsaturated storage down to the saturated layer. Only the water in excess of field capacity in the unsaturated layer is available for percolation.

UW_excess= MAX(0, UW_moist - FC) ***(Equation 12)***

The percolation rate is defined by Equation 12 as in Voinov et al. 2004:

*UW_perc_rate = 2*vert_Hydr_Cond*porosity*(UW_excess^0.4)/((porosity - FC)^0.4 + (UW_excess^0.4))* **(Equation 13)**

where *vert_Hydr_Cond* is the soil dependent vertical hydraulic conductivity parameter

In addition to the percolation process, additional water is transferred from the unsaturated layer to the saturated layer whenever the water table is moving up. In this case water contained in the pores of the unsaturated layer is added to the water coming up from the saturated layer. This amount is equal to:

UW_to_SatW = IF (inf_cond=0) THEN UW/DT ELSE
*MIN(UW/DT, MAX(0, UW_delta*UW_moist/DT + UW_perc_rate))* **(Equation 14)**

where *UW_delta* is the variation of groundwater table over one time step

Conversely, if the water table is going down, the moisture at field capacity stays in the soil and is added to the unsaturated storage

*SatW_to_UW = MAX(0, MIN(-UW_delta*FC, SatW/DT))* **(Equation 15)**

Similarly, exchanges of water occur between the surface storage and the saturated storage when the water table drops (respectively rises) from (respectively towards) a situation where the water table is at or above ground level:

SW_to_SatW = IF (UW_depth_before=0 AND Unsat_cap>0)
THEN MIN(Unsat_cap/DT, SurfW/DT) ELSE 0 **(Equation 16)**

SatW_to_SW = IF SatW>SatW_Max THEN SatW - SatW_Max ELSE 0 **(Equation 17)**

where *UW_depth_before* is the water table depth at the previous time step

SurfW is the water content in the surface storage

SatW_Max is the maximum content of water at saturation. It depends of the maximal depth of the shallow aquifer and of the average porosity of the soil (*SatW_Max = (ground level – base)*porosity*)

Groundwater inflow from hill slopes and irrigation leakages

In absence of measurement, groundwater inflow from upper catchment is assumed to be a fraction of upper catchment rainfall.

*GW_inflow = Upper_catch_rainfall*Up_Catch_Coef/Conv* (***Equation 18***)

where *Upper_catch_rainfall* is the rainfall over the upper catchment, and *Up_catch_Coef* is a parameter whose value was set as part of the calibration process.

Water losses from the irrigation schemes (mainly Fertilis scheme which is located directly upstream of the right edge of the wetland) to the wetland were estimated based on measurement of water flows in the canal network in 2004 by Chiron (Chiron 2005) and confirmed by measurements made by Murgue in 2010. From observations it appears that losses from the main canal flow directly to the river, as the canal is following the river bed. On the opposite, losses from the primary and secondary

canals as well as losses occurring in the fields can be assumed to recharge the irrigation scheme groundwater.

Seepage from IS groundwater to wetland groundwater is supposed to occur whenever the groundwater table in the irrigation scheme is greater than in the wetland. Seepage per unit area of wetland and unit of transactional area (*CW_GW_from_IS*) is estimated using Darcy's law:

*CW_GW_from_IS = IS_CW_HydrGrad * IS_Hydr_Cond* ***(Equation 19)***

Where *IS_Hydr_Cond* is the saturated hydraulic conductivity of soil in the irrigation scheme

IS_CW_HydrGrad is the hydraulic gradient between the saturated layer in the irrigation scheme and the same layer in the cultivated wetland

IS_CW_HydrGrad = (Avg_IS_GWL – Avg_CW_GWL)/IS width (***Equation 20***)

Where *Avg_IS_GWL* (respectively *Avg_CW_GWL*) is the average level of groundwater in IS (respectively in cultivated wetland) and *IS_width* is the average width of Fertilis irrigation scheme.

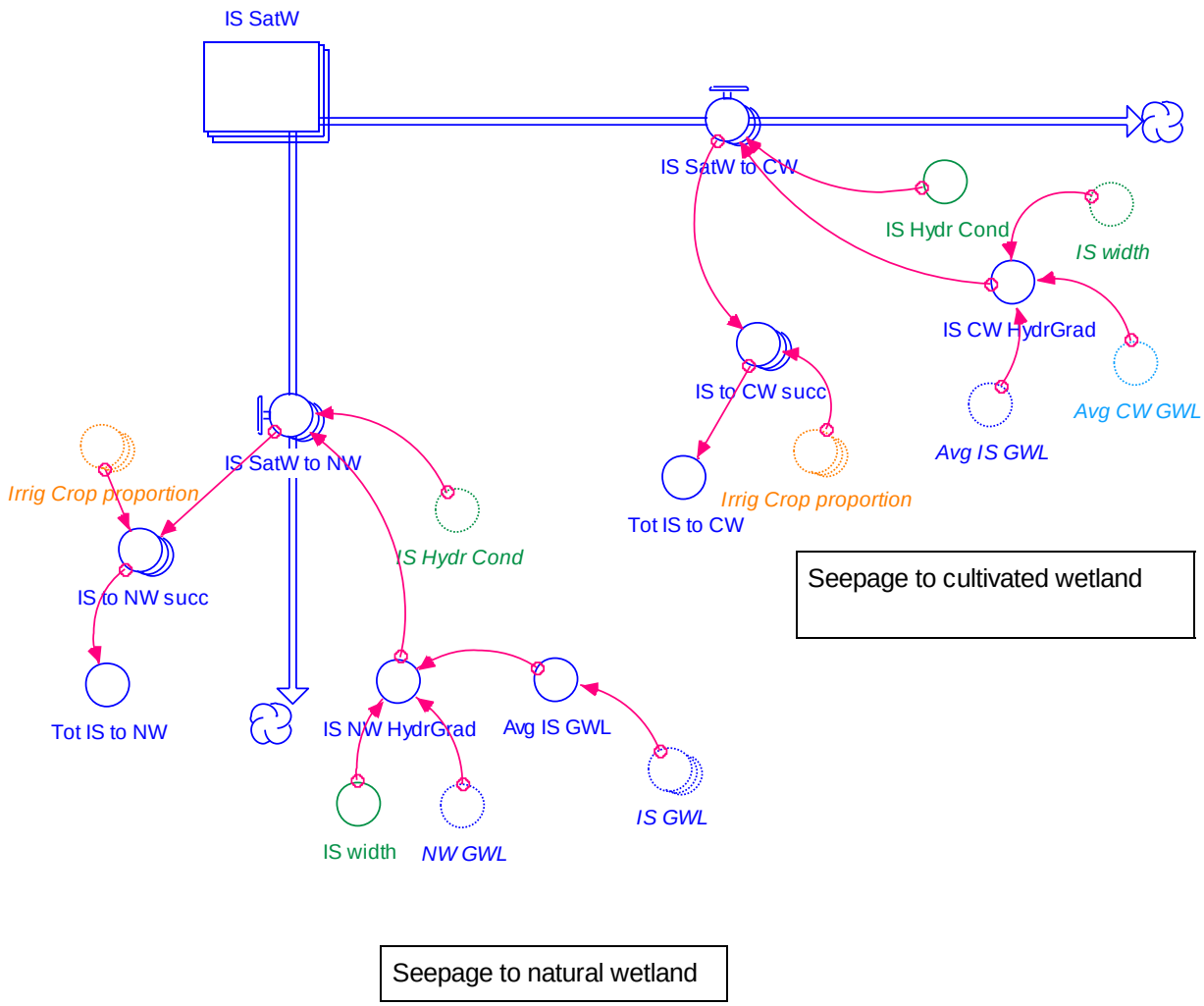


Figure 12: Map of the seepage from IS to cultivated and natural wetland

Groundwater seepage to the river (GW_o)

Subsurface flow (GW_o) or seepage at the edge of the wetland to the river occurs along the entire length of the wetland when groundwater level is above the level of water in the river. GW_o was estimated using Darcy's law as in Equation 20:

$$GW_o = K \cdot d \cdot W \cdot \frac{dh}{dl} \qquad \textbf{(Equation 21)}$$

Where

GW_o is the total volume of water (in m3) moving through the cross sectional area A= d.W

K (m/ month) is the saturated hydraulic conductivity of the aquifer soil layer (see Table 4

d (in m) is the thickness of the aquifer

W (in m) is the length of wetland along which seepage occurs

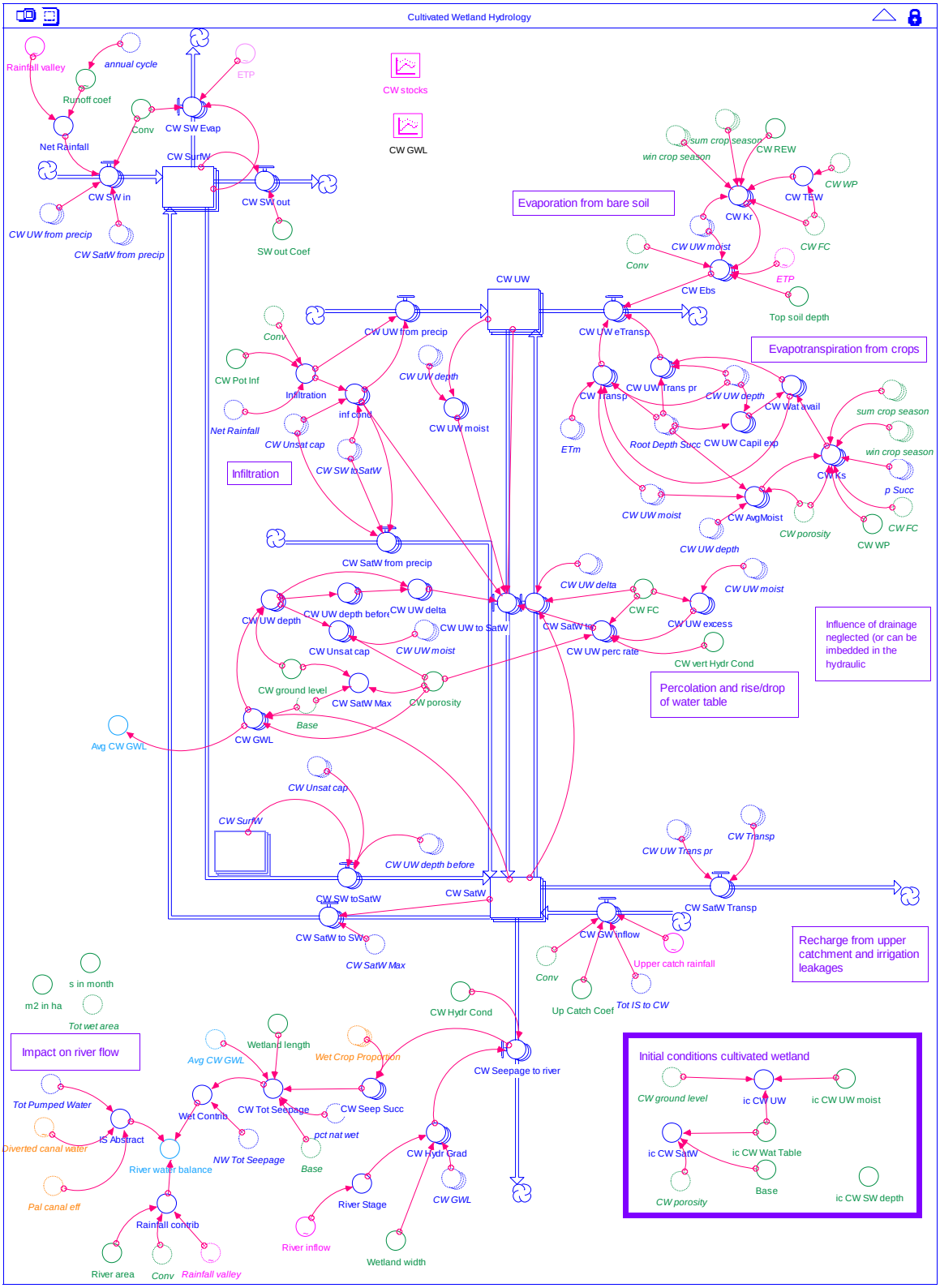
dh/dl is the hydraulic gradient between the wetland groundwater and the river

In the model, seepage is expressed as a variation of depth of water per unit area of wetland across a unit of cross sectional area, and then aggregated over the whole wetland area and the whole sectional area A. The hydraulic gradient is computed as the difference between groundwater level in the wetland and the river level divided by the average wetland width. River level and river flow were measured upstream of the wetland during the period July-August 2006. An equation of river level as a third degree polynomial function of river inflow was then estimated from these measurements. Parameters values used for modelling seepage to river are reported in Table 5.

Artificial drainage

The wetland is intersected by a number of drainage canals intended to create an environment suitable for the production of maize. The drains accelerate outflow from the wetland, resulting in lower groundwater levels in the wetland. In the model water outflow from artificial drainage is not explicitly represented as an out flow from unsaturated storage. Rather hydraulic conductivity is increased compared to values derived from soil textures.

Global map of cultivated wetland sector is given in Figure 13 and equations of the sector model in Stella are presented in Annex 1.



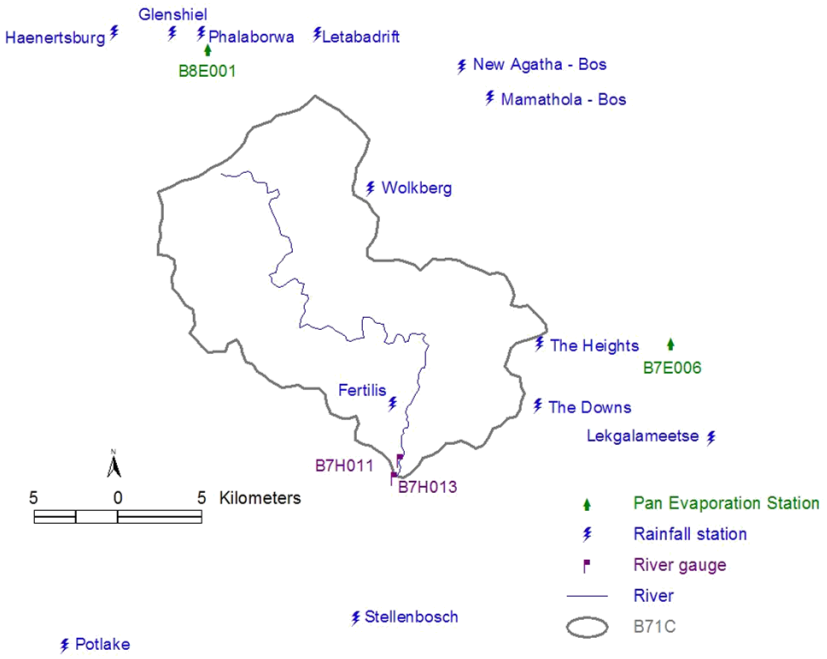
(in green constant parameters, in pink variables affected by scenarios of global change, in orange variables affected by management options)

Figure 13: Map describing relationships in the cultivated wetland hydrology sector

3.2.2 Hydrology sector input data

Rainfall, runoff and potential evapotranspiration

Rainfall series were obtained from two sources: South African Weather Service (SAWS) and Department of Water Affairs (DWA). The location of weather stations is shown on Figure 14 (rainfall station from SAWS in blue and DWA stations in green).



Location	Station name	Latitude (deg mn s)	Longitude (deg mn s)	Altitude (m)	Length of record
Valley	Fertilis	-24 13	30 10	1143	April 1959 - Nov. 1989
Upper catchment	Wolkberg	-24 02	30 08	1524	Jan. 1972 - May 2005
	B7E006	-24 05 56	30 15 30		Aug. 1992- Dec. 2009

Figure 14: Location of weather stations relative to catchment B71C (Source: Mwenge-Kahinda and Kileshye Onema 2009)

Fertilis was the most appropriate rainfall station for the Ga-Mampa valley but unfortunately records stopped after 1989, although data from 1994 to 2007 were necessary for model calibration. Thus, data from 1972 to 1989 were used to express rainfall in Fertilis as a function of rainfall in Wolkberg. Then the equation was used to generate a rainfall data series for the valley from 1990 to 2007. For the upper catchment, the B7E006 station was used. Potential evapotranspiration was available only for B7E006 station.

Soils parameters

Values of soil parameters (FC, WP, hydraulic conductivity, porosity) in the three soil compartments are reported in Table 4 below. These values were derived from soil texture obtained from soil analysis in the irrigation scheme (Nell and Dreyer 2005) (see Table 3) through pedo-transfer functions implemented in the Texture Triangle calculator of the SPAW model (Saxton and Rawls 2006).

Vertical hydraulic conductivity was calibrated at 1.8 m/month, using the value proposed by Voinov et al. 2004 for loamy soil as a starting point (0.09 m/day).

Table 3: Texture and depth of soil layers in Ga-Mampa valley

Location	Soil form	area (ha)	horizon	depth (mm)	% of Sand	% of Silt	% of Clay
Irrigation scheme	Hutton 3100	22.37	A1	290	50.1	36.2	11.3
			B21	1250	54.4	31.2	13.2
			avge	**1540**	**53.6**	**32.1**	**12.8**
	Oakleaf 1220	57.48	A	320	40.2	45.3	12.6
			B21	1200	34.6	42.5	20.8
			avge	**1520**	**35.8**	**43.1**	**19.1**
	Valsrivier	5.9	A	200	28.7	45.9	24.1
			B1	700	31.6	34.2	32.4
			B2	1200	61.1	17.2	20.4
			avge	2100	48.2	25.6	24.8
			avge A-B1	**900**	**31.0**	**36.8**	**30.6**
	Avge IS	85.75			40.1	39.8	18.2
Wetland edge	Katspruit 1000	5.34	A	280	36.8	37.8	23.9
			G	1100	27.1	40.8	30
			avge	**1380**	**29.1**	**40.2**	**28.8**
	Kroonstad 1000		A	380	42.8	42.3	12.9
			E	580	37.2	40.2	19.6
			G	1200	49.3	38.3	10.1
			avge	**2160**	**44.9**	**39.5**	**13.1**
			Avge A-E	**960**	**39.4**	**41.0**	**16.9**

(Source: Nell & Dreyer 2005)

Table 4: Values of soils parameters used in WETSYS model for the different landscape units

Soil compartment	% sand	% clay	% organic matter	Field Capacity (FC) (% of volume)	Wilting Point (WP) (% of volume)	Total Available Water (mm/m of soil)	Porosity (% of volume)	Saturated hydraulic conductivity (mm/h)	TEW (total evaporable water) (% of volume)	REW (readily evaporable water) (mm/m of soil
natural wetland	45	13	7.5	31	14	170	61.2	69.73	0.24	8-10
cultivated wetland	45	13	5%	27	12	160	53.4	46.22	0.21	8-10
irrigation scheme	40	18	2%	26	12	140	44.6	16.04	0.20	8-11

(Source: Nell and Dreyer 2005 for soil texture; Saxton and Rawls 2006 for FC, WP and AW)

Table 5: Parameter values for groundwater inflow and outflow computation

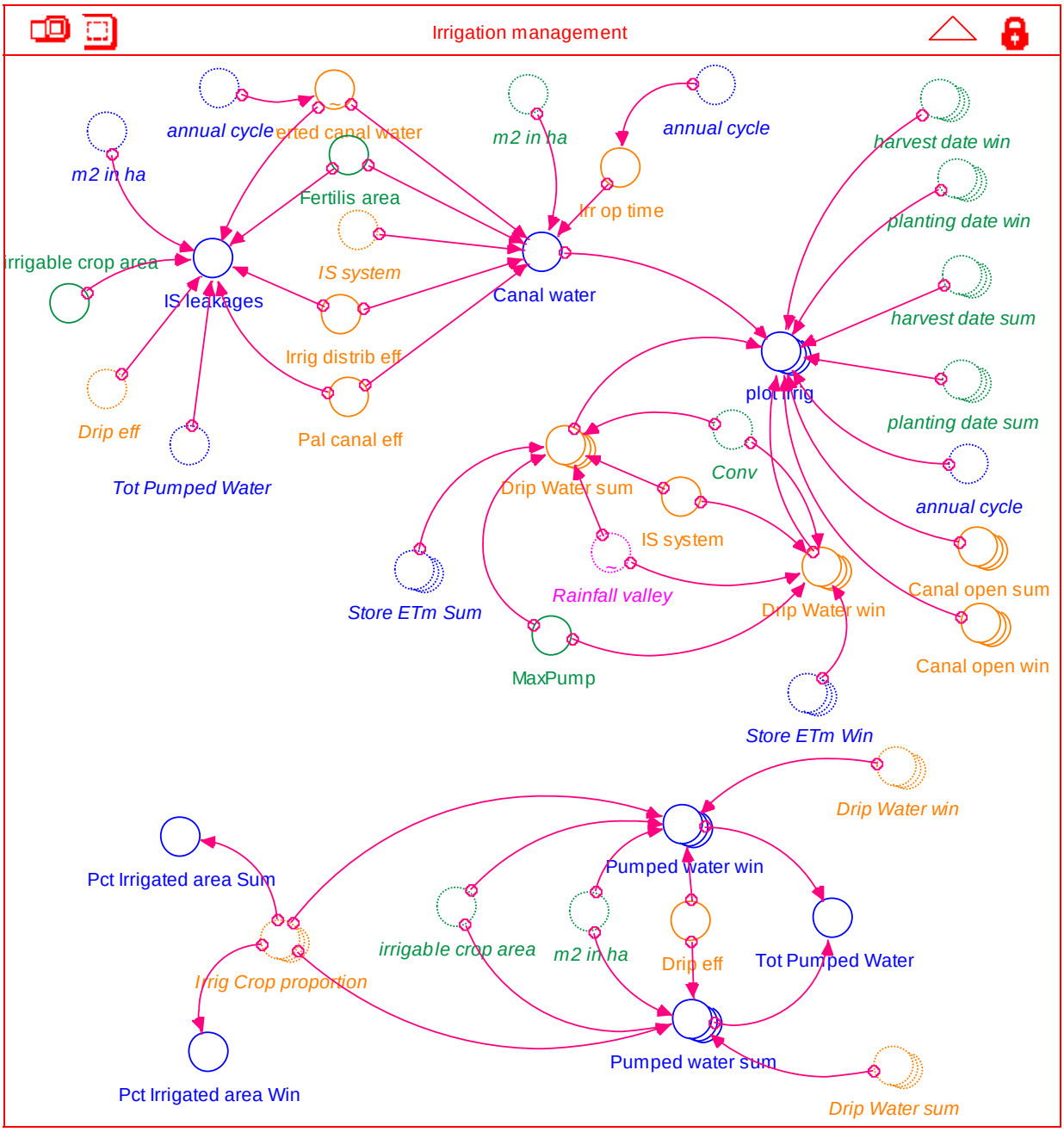
Parameter	Value	Source
Length of wetland W	5000 m	Calculated from map
Wetland width	400 m	Calculated from map
Up_catch_Coef	0.05	From calibration

3.2.3 Irrigation management sector

This sector models the characteristics of the irrigation scheme that impact on the hydrology sectors: amount of water available at plot level (which affects evapotranspiration and then crop yields) and irrigation leakages (which affects groundwater inflows to wetland aquifer and river outflow).

Table 6: Irrigation management input data

Variables	Description	Value in baseline	Source
Fertilis_area	Area of the Fertilis irrigation scheme	88 ha	Chiron, 2005
Irrig_contribution_coef	Coefficient controlling the contribution of irrigation leakages to groundwater	1	
Pal_canal_efficiency	Head canal efficiency	0.5	Average between Chiron, 2005 (0.42) and Murgue, 2010 (0.6)
Irrig_distrib_efficiency	Efficiency of the canal distribution system	0.7*0.7*0.6	Murgue, 2010
Irr_op_time	Operating time of the gravity system	8h/day, 6 days/week in winter 12h/day, 6 days/week in summer	Chiron, 2005 Murgue, 2010
Diverted_canal_water	Amount of water diverted from river per month	Maximum of 130 l/s from December to March, minimum of 55 l/s in September	Chiron, 2005
Drip_eff	Distribution efficiency of drip irrigation system	0.85	Murgue, 2010
Canal_open_win	Calendar of operation of irrigation canal in winter	1 when there is a crop, 0 otherwise	Murgue, 2010
Canal_open_sum	Calendar of operation of irrigation canal in summer	1 when there is a crop, 0 otherwise	Murgue, 2010
IS_system	Indicator of the irrigation system	0 for gravity system, 1 for drip system, 2 for mix system	
MaxPump	Maximum depth of water supplied by drip irrigation system per unit area at plot level	0.85*109*4*20*30/(10000*88) LADC plan makes use of 4 pumps with a flow rate of 109m3/h and efficiency of 0.85 running 20h per day in the simulation the drip system is extended beyond Fertilis (88ha) to the whole irrigation area (171 ha), assuming that the same type of pumping system will be applied	Murgue, 2010



(in green constant parameters, in pink variables affected by scenarios of global change, in orange variables affected by management options)

Figure 15: Map of the relationships in the irrigation management sector

3.3 Crop production sector

3.3.1 Description

The crop production sector distinguishes the wetland cultivated area and the irrigated area, the dynamics of which is very similar except for the linkages with the wetland biophysical system. The wetland cultivated area changes annually due to conversion of the natural wetland area or abandonment of cultivated area to natural vegetation. The main crop grown in the wetland and irrigation scheme is maize. Although the model allows for diversified crops both during the rainy and

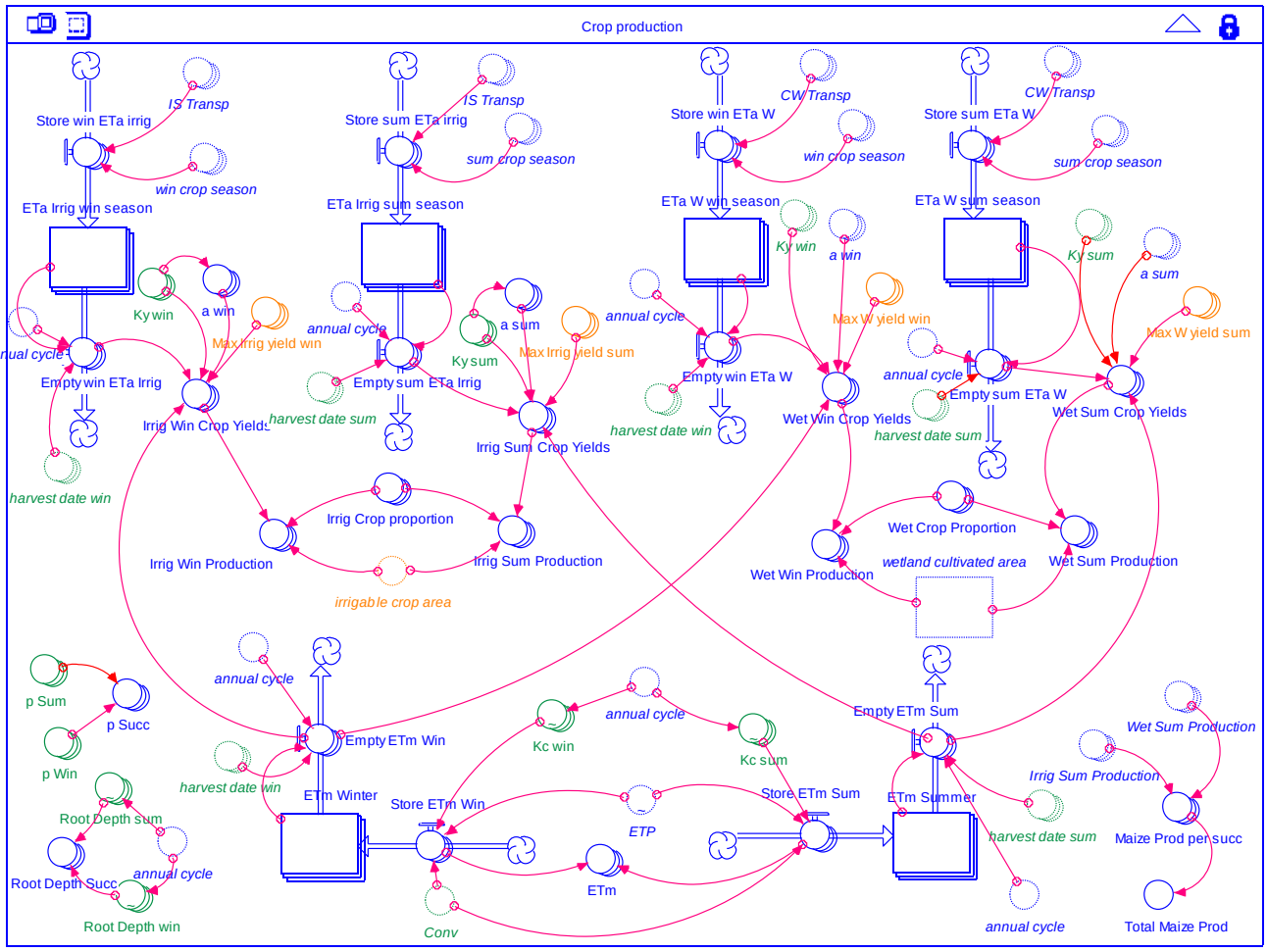
dry seasons, maize is the only crop considered in the baseline version of the model and crop production only occurs once a year. Crop yields are modelled as a function of evapotranspiration using the crop yield response to water function described by Doorenbos and Kassam 1986:

$$Y_a^i = Y_m^i \left(1 - k_y * \left(1 - ET_a^i / ET_m^i\right)\right) \qquad \textbf{\textit{(Equation 22)}}$$

where i, represents wetland or irrigation scheme,
Y_a is actual yield (ton/ha)
Y_m is the maximum yield that can be reached with the present technology and unconstrained supply of water (ton/ha)
ET_a is actual crop evapotranspiration over the cropping season (mm),
ET_m is maximum crop evapotranspiration over the cropping season (mm),
and k_y is crop yield response to water stress factor.

Maximal evapotranspiration, ET_m, is computed on a monthly basis, from potential evapotranspiration *ETP* using crop coefficients K_c ($ET_m = K_c*ETP$), and then summed over the cropping season. Actual evapotranspiration is computed from ET_m: $Et_a = Wat_avail * ET_m$, where *Wat_avail* depends on soil water content (see description of hydrology sector). Et_a is also computed on a monthly basis and summed over the cropping season. In the irrigation scheme ET_a is thus impacted by rainfall and irrigation water, and in the wetland by rainfall and groundwater level through capillarity rise.

Values for K_c, K_y *and* K_s are derived from the literature and Y_m values are derived from household surveys in the study area (Adekola 2007; Jogo *et al.* 2008) and cross-checked with previous research results (Chiron 2005). We assume a fixed technology, different for the wetland and the irrigation scheme, and therefore crop input quantities and costs are fixed and yields do not vary with input quantities. From farm surveys and field observations maize cropping provides higher yields in the wetland than in the irrigation scheme while requiring less labour and inputs (Chiron 2005).



(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)

Figure 16: Crop production sector

3.3.2 Input data

For maize, typical values for K_c are given in **Table 7** below. Table 8 and Figure 17 summarize the crop characteristics used for the crops considered in the model.

Table 7: Values of K_c for maize

Growing stages	Dates	Duration		K_c			
		(1)	(3)	(1)	(2)	(3)	(4)
initial stage	01/12 – 01/01	20-30	30	0.4	0.3-0.5		0.3
crop development	01/01 – 01/02	35-50	30	0.8	0.7-0.85		
mid-season	01/02 – 05/04	40-60	60-70	1.15	1.05-1.2	1.15	1.2
late season	05/04 – 15/04	30-40	10	0.7	0.8-0.95		0.5
at harvest					0.55-0.6		
total growing period			130-140		0.75-0.9		

Source : (1) Brouwer and Heibloem 1986 - (2) Doorenbos and Kassam 1986
(3) Sapwat, Highveld, http://www.sapwat.org.za/ - (4) http://www.fao.org/ag/agl/aglw/cropwater/maize.stm

Table 8: Crop characteristics

Crop	Planting date (1)	Harvesting date (1)	Depletion coefficient (2)	Maximum root depth (m) (2)	Maximum yield in irrigation scheme (T/ha) (3)	Maximum yield in wetland (T/ha) (3)	Yield reduction coefficient (2)
Maize	1st December	1st April	0.55	1	2.5	4	1.25
Groundnut	1st November	1st April	0.5	0.75	1.8	2.2	0.7
Sweet potato	1st December	1st July	0.65	1	3	3	1.1
Onion	1st May	1st October	0.25	0.4	1.5	1.5	1.1
Tomato	1st April	1st August	0.4	1	2.5	2.5	1.05
Cabbage	1st May	1st September	0.35	0.45	2	2	0.95
Dry bean	1st March	1st July	0.45	0.6	0.6	0.6	1.15

(Sources: (1) Chiron 2005 and own surveys; (2) Allen et al. 1998 and FAO website http://www.fao.org/landandwater/aglw/cropwater/); (3) Chiron 2005 and farmers group discussion

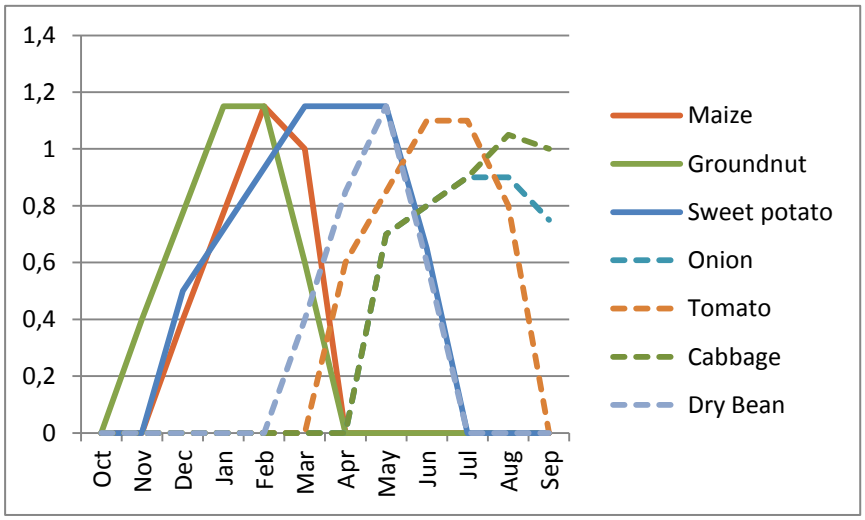


Figure 17: Variation of K_c for various crops over the cropping seasons

(Source: SAPWAT, 2003 (http://www.sapwat.org.za/, visited on 20/06/2011, Allen et al. 1998, http://www.fao.org/landandwater/aglw/cropwater/)

3.4 Crop economics sector

This sector computes the total economic value of crop production for each crop, based on crop yields calculated in the crop production sector, allocation of cultivated land to various crops, input costs and market output prices (*(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)*

Figure 18). The total volume of production is valued at market price regardless of the destination of production (self-consumption or market). Cropping patterns are exogenous and specified as management options. It is assumed that local production is too small to influence market prices therefore crop output and input prices are considered exogenous. Input costs were estimated based on household survey. They are spread over the cropping season following observed agricultural practices: land preparation costs one month before the planting date, (November in the case of maize), seeds and fertilizers in the first month of cropping season (December for maize) and

transport to market in the harvest month (April for maize). Crop producer prices are derived from local observations in 2006 and national series (Statistics South Africa, interactive time series data base[5]).

Crop net values are then aggregated for each cultivated land type (irrigation scheme and wetland) and at community level and are used in the land-use decision sector to trigger natural wetland conversion.

The sector also calculates the financial value of crop sales and crop input costs which contribute to the cash dynamics modelled in the community well-being sector. In this case, only the fraction of the production that is sold on the market is considered. To avoid complexity of the model, each type of crop is assigned to a destination: maize is the only crop considered for self-consumption, all the other crops are considered as cash crops.

Table 9: Crop output prices per ton

Crop	Selling price (ZAR/Ton)
Maize	2500
Groundnut	4400
Sweet Potato	3800
Tomato	5000
Onion	1500
Cabbage	4300
Bean	10000

(Source: household surveys 2006 and 2010, focus group discussions 2010)

Table 10: Crop input costs per hectare and per month in irrigation scheme and cultivated wetland (ZAR/ha)

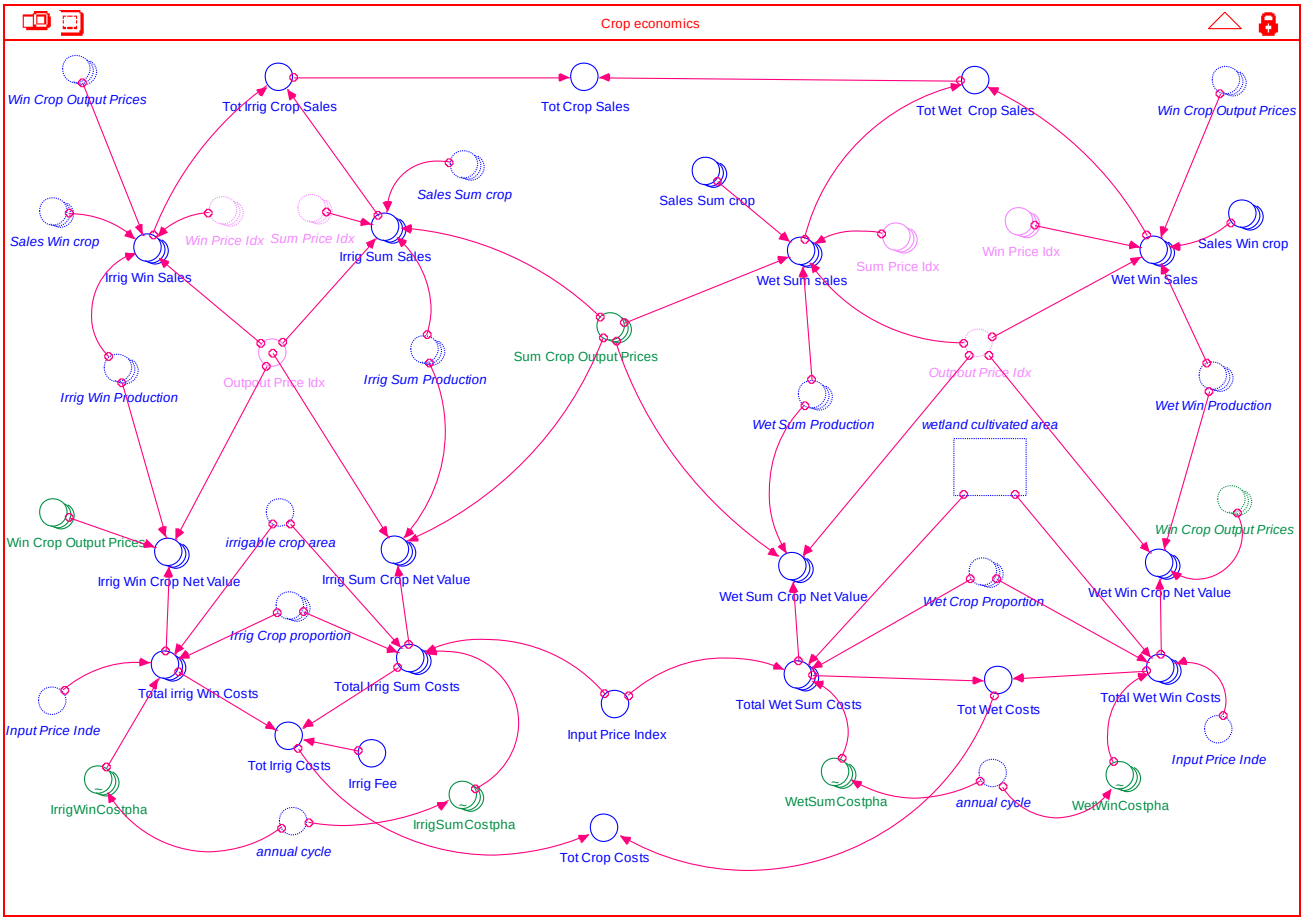
Summer crops

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Irrigation scheme												
Maize	720	800	0	0	0	0	0	0	0	130	0	800
Groundnut	175	600	0	0	0	0	0	0	0	0	0	800
Sweet Potato	0	1800	0	0	0	0	0	0	0	0	0	0
Tomato	0	0	950	800	1800	6550	0	0	0	0	0	0
Cultivated wetland												
Maize	220	600	0	0	0	0	0	0	0	250	0	600
Groundnut	175	600	0	0	0	0	0	0	0	0	0	600
Sweet Potato	0	1800	0	0	0	0	0	0	0	0	0	0
Tomato	0	0	750	600	1800	6550	0	0	0	0	0	0

[5] http://www.statssa.gov.za/

Winter crops

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Irrigation scheme												
Onion	0	0	0	0	0	0	950	800	1800	0	0	0
Tomato	0	0	0	0	0	950	800	1800	6550	0	0	0
Cabbage	0	0	0	0	0	0	950	800	1850	0	0	0
Bean	0	0	0	0	800	900	0	0	0	0	0	0
Cultivated wetland												
Onion	0	0	0	0	0	0	750	600	1800	0	0	0
Tomato	0	0	0	0	0	750	600	1800	6550	0	0	0
Cabbage	0	0	0	0	0	0	750	600	1850	0	0	0
Bean	0	0	0	0	600	0	0	0	0	0	0	0



(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)

Figure 18: Crop economics sector

3.5 Land use sector

This sector describes the processes that lead to conversion of the wetland to agriculture. Four state variables (stocks) are represented, three land use classes and the number of farming households (*(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)*

Figure 19). The total area of wetland is distributed among three land use classes: wetland cultivated area, fallow land and natural wetland area.

The wetland natural area is covered by natural vegetation, which includes sedges, reeds, and other natural products that are used by the local community. Information from focus group discussions in Ga-Mampa villages shows that wetland conversion to agriculture was primarily driven by poor production in the irrigation scheme due to water shortages related to degradation of irrigation infrastructures and droughts. Therefore, in the model, clearing of natural wetland to cultivated wetland is controlled by annual food security index, computed in the community well-being sector, as the ratio between annual maize consumption and annual maize needs. If this index is below 1, new cropping land is needed to produce maize (*Wet_area_needed*), which is computed from deficit in maize production and expected maize yield. Expected maize yield is a parameter but could be derived from calculated yields of previous years. This new area can come either from fallow land (through *Cropping*), or from natural wetland area (through *Clearing*). It appeared from household surveys conducted in 2006 and 2010, that the average wetland plot area is quite stable across households. The number of new wetland farmers is thus computed from the newly cleared wetland area and the average wetland plot area. Two other control variables, *Clearing_poss*, which takes the value 0 when clearing is forbidden and 1 when it is authorized, and *Min_pct_Nat_Wet* (minimum percentage of natural wetland) have been added to allow simulation of land use management options.

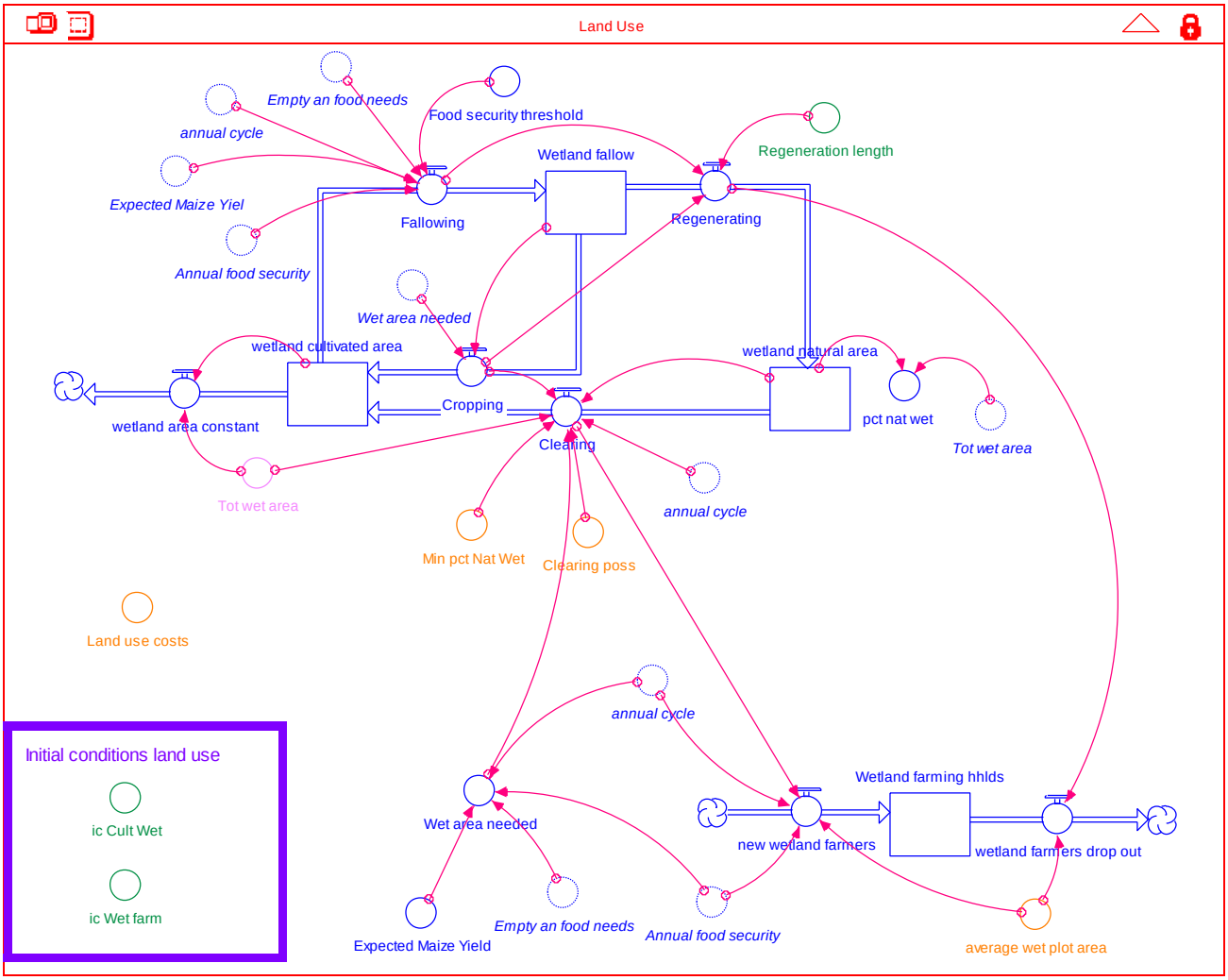
Conversely, if annual food security index is above a certain threshold (*Food_security_threshold*) that is set to account for risk aversion, previously cultivated wetland can be put to fallow (*Fallowing*). The area fallowed depends on annual food security index and expected maize yield. After a certain period of time (*Regeneration_length*), natural vegetation can regenerate in a fallowed plot (*Regenerating*). The regeneration length has been estimated at three years based on discussions with local wetland farmers. The number of wetland farmers decreases proportionally to the wetland average plot area, when fallow land regenerates into natural wetland.

Decisions regarding land use in the wetland occur in September so that farmers have time to clear the land before sowing time (in December). Parameters for the equation of wetland conversion were calibrated on past observed evolution of wetland cultivated area (1994-2006) (Table 11).

Table 11: Land use parameters

Variables	Description	Value in baseline	Source
Average_wet_plot_area	Average wetland plot area	0.7 ha	Household survey 2006, 2010
Expected _Maize_Yield	Expected maize yield	2 T/ha	average of observed yields (Adekola, 2007)
Food_security_threshold	Food security threshold	1.2	Calibrated
Regeneration_length	Time necessary to regenerate natural vegetation after cropping	36 months	Farmers' interviews
Tot_wet_area	Total area of wetland	110 ha	Average between Kotze, 2005 and Sarron, 2005
Land_use_costs	Land use costs	0	Household survey
Min_pct_Nat_Wet	Minimum percentage of natural wetland	0	Interview of key informants

Clearing_poss	Clearing possibility	1	



(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)

Figure 19: Land use sector

3.6 Natural resources sector

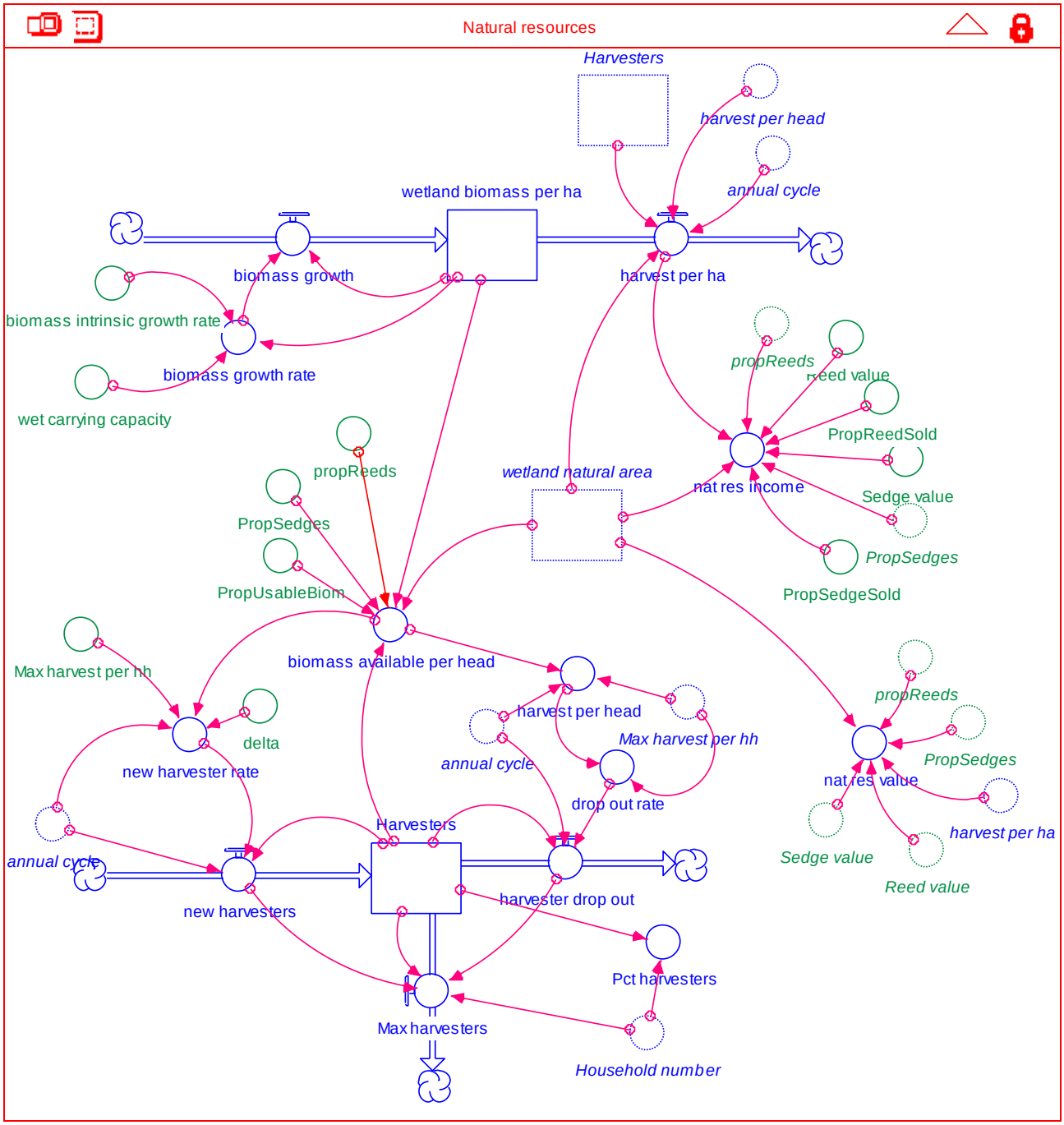
This sector models the dynamics of wetland natural biomass. Due to limited data on the study site, its formulation relied mainly on literature. Reeds (*Phragmites australis* and *Phragmites mauritanus)* and sedges *(Cyperus latifolis* and *Cyperus sexangularis)* are the main species used by the local community in the wetland. They cover respectively 20% and 2.5% of the natural wetland area (Kotze, 2005). We assumed a homogeneous distribution of reeds and sedges over the natural wetland area and similarly a homogenous distribution of biomass harvesting. Following Woodwell 1998 and Helldén 2008, we assumed that wetland biomass follows a logistic growth function, where the actual growth rate varies negatively with the ratio of actual biomass to carrying capacity of the wetland (i.e., the maximum quantity of biomass per unit area). The carrying capacity was set to a maximum of 70 tons per hectare per annum. This corresponds to the maximum annual productivity of reeds (Finlayson and Moser 1991 cited in Turpie *et al.* 1999), considering that in the case of reeds, maximum annual productivity is equal to carrying capacity. The initial value of total biomass was computed by multiplying the biomass productivity by the wetland natural area.

Thenya 2006 reported growth rate of *Phragmites* species up to be 300% just after harvest in Yala swamp, Kenya. In the absence of local measurement, we used an intrinsic growth rate of wetland biomass of 0.3 as a very conservative approximation. Reeds are deemed to be resistant to drought and variation of water levels, and little is known on the effects of water regime on its production level (Roberts and Marston 2000), therefore we assumed that intrinsic growth rate is independent of groundwater level. The intrinsic growth rate is multiplied by a density dependent factor ($1 - X_t / k_x$), which captures the changes in actual growth rate as biomass stock changes. As biomass increases the actual growth rate decreases due to competition for limited resources of e.g. light, water, nutrients and space. On the other hand, when biomass is removed from the wetland (e.g. through biomass harvesting) the actual growth rate will increase.

Harvest of natural wetland plants occur once a year in July. Harvest per hectare is the product of the number of harvesters and of the quantity harvested per harvester over the natural wetland area. Adekola's survey (2006) showed that the number of harvesters has decreased in the recent past in relation with the availability of wetland natural products. We therefore assumed that the community assesses the biomass available per head (computed from natural wetland area, biomass per hectare and the present number of harvesters) each year before harvest. When the available biomass per head is above the maximum harvest per head new harvesters are attracted in the wetland and their number is proportional to the relative difference between available biomass per head and the maximum harvest per head (set at 0.6T/ha according to household survey, Adekola 2007). Similarly, harvester drop-out rate varies negatively with the harvest per head. The fraction of harvested biomass which is sold on the market is valued at market prices (obtained from household survey) and feeds into the cash stock (community well-being sector). The total value of harvested biomass and natural wetland productivity are computed in the economic valuation sector.

Table 12: Natural resources parameters

Variables	Description	Value in baseline	Source
Biomass_intrinsic_growth_rate	Biomass intrinsic growth rate for wetland vegetation	0.3	Calibration
Wet_carrying_capacity	Maximum amount of biomass per unit area	60 T/ha	Turpie *et al.* 1999: 70T/ha in Zambia Hocking *et al.* 1983: 30-40 T/ha in Australia
Max_harvest_per_hh	Maximum harvest per household	0.6	Adekola, 2007
delta	Parameter in the equation of new harvester rate	0.2	Calibration
propReeds	Proportion of reed cover in the natural wetland	0.2	Kotze, 2005
PropSedges	Proportion of sedge cover in the natural wetland	0.025	Kotze, 2005
PropUsableBiom	Proportion of biomass that is usable for crafting and roofing	0.15	McKean 2001
Reeds_value	Economic value of reeds	ZAR 2000/Ton	Adekola, 2007
Sedge_value	Economic value of sedges	ZAR 8500/Ton	Adekola, 2007
PropReedSold	Proportion of reeds which is sold	0.19	Adekola, 2007
PropSedgeSold	Proportion of sedges which is sold	0.8	Adekola, 2007
Harvesters	Number of harvesters	24% of households in 2006	Adekola, 2007



(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options)

Figure 20: Natural resources sector

3.7 Community well-being sector

This sector models the dynamics of three interrelated stocks: human population, food stock and cash stock. The local community is considered as homogenous. Cash and food stocks dynamics are computed at community level based on observations made at household level (Adekola 2007; Jogo *et al.* 2008) and aggregated across the total number of households.

Population dynamics

The dynamics of human population in the study area influences the demand for wetland and other resources through the food and cash stocks dynamics. An exponential population growth function is used following other studies (Woodwell, 1998; Hellden, 2008). Population growth rate, held constant over the simulation, includes both natural growth rate (birth and death rate) and migration rates. From focus group discussions conducted in the study area, we assumed that there is no immigration. The population structure in terms of age classes is supposed to remain stable over the simulation period to avoid the complexity of modelling age class dynamics. Initial population in 1994 was estimated based on the observed population in 2006 and the assumed annual population growth.

Cash stock dynamics

Initial cash stock is set at one month of non farm income. Cash inflow is composed of: net income from wetland harvested natural biomass, which is computed in the natural resource sector; off-farm wage income and social transfers from the government. Off-farm wage income is assumed to be the product of the proportion of households engaged in off-farm work and of the average income earned from off-farm work. Similarly, exogenous income from social grants is a function of the proportion of the population entitled to receiving social grants (children under the age of 14 and adults aged 64 and over). Proportions of the population in each categories were derived from household survey and assumed to be constant over time. Both off-farm wage income and social transfers occur at monthly time step, whereas income from harvested wetland natural products or from crop production only occurs once a year at time of harvest.

Cash outflow is the sum of non-food expenditure and food purchase. Non food expenditure includes domestic expenditure, and crop inputs expenditures (see crop production sector). The level of cash stock at each time period determines the maximum quantity of food that the community can buy. At any point in time, priority is given to food purchase over other expenditure, thus cash available for food purchase is equal to cash stock. Alternative decision rules can be implemented in the model (e.g., priority given to basic non-food expenditures and crop input costs). Cash stock can be compared to poverty line, set at ZAR150 per person per month (Statistics South Africa 2007) to cover the non-food basic expenditures[6].

Food stock dynamics

At the beginning of the simulation, the food stock is assumed to be at a mid-level, with the harvest from the last cropping season partly consumed by the needs of the total population over the dry season. Based on the household survey, it was assumed that maize is not sold on the market and only used for household consumption. The population uses this stock to cover its monthly food need (estimated at 95kg/household/month, according to Adekola 2007). When the food stock is empty, the community starts to buy maize to meet their food needs if the cash stock allows it (food purchase). Buying price of maize is assumed to be 15% higher than farm gate price.

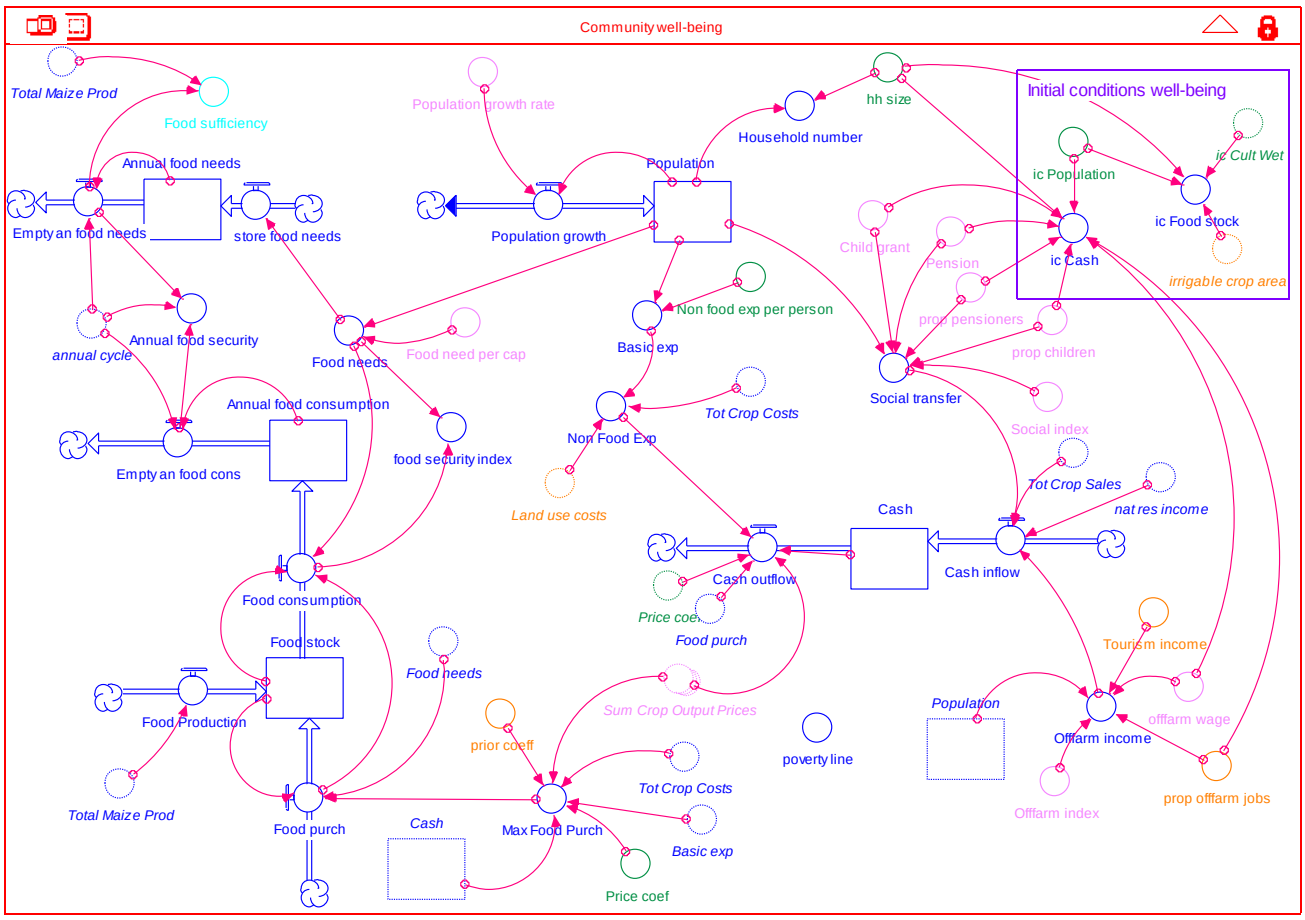
Food stock increases once a year in April with maize production from wetland and irrigation scheme. It decreases every month with food consumption, which ideally depends on food needs per person and total population, but is limited to food stock at any point in time. So it may happen that food consumption is less than food needs.

[6] StatsSA calculated a poverty line of R 431 per person per month in 2006 prices. Around one third of this amount corresponds to the basic expenditures for non food items. Considering that a large part of the food requirements are covered by food production, we only consider the portion of poverty line meant to cover non food expenditures.

The food security index is defined at any point in time as the ratio of food consumption over food need. Similarly, an annual food security index is computed once a year in September from annual food consumption and annual food needs to make decision over natural wetland conversion to agricultural land (see land use sector).

Table 13: Community well-being parameters

Variables	Description	Value in baseline	Source
Ic_Population	Initial population	2519 in 1994	Estimated from observed population in 2006 (Adekola, 2007) and application of annual growth rate
Population_growth_rate	Monthly growth rate of population, includes both natural and migration rates	0.0011	Statistics South Africa 2004
Hh_size	Number of persons per household	7	Adekola, 2007
Food_need_per_cap	Maize need per person per year	95/ (1000*7) Ton/person	Adekola, 2007 (one bag of maize grain per household per month)
Non_food_exp_per_person	Non food basic expenditure per person per year	ZAR 1750/12	Adekola, 2007, focus group discussion
Child_grant	Monthly value of child grant	ZAR 200 in 2007	
Pension	Monthly value of pension	ZAR 800 in 2007	
prop_children	Proportion of children in total population	0.28	Statistics South Africa Census 2001 at ward level
Prop_pensioners	Proportion of pensioners in total population	0.06	Statistics South Africa Census 2001 at ward level
Social_index	Index allowing variation of social grant over time	1 in baseline	
Tourism_income	Monthly value of income from tourism	0 in baseline	
Offfarm_wage	Monthly value of average off farm wage	ZAR 1000	Household survey 2006, focus group discussion
Offfarm_index	Index allowing variation of off farm wage over time	1 in baseline	
Prop_offfarm_job	Proportion of household with member working off farm	0.24	Household survey 2006
Price_coef	Ratio of maize buying price to maize selling price	1.15	Extension officer and farmers' interviews
Prior_coef	Coefficient giving priority to food purchase over other expenditures when 0	0 in baseline	Focus group discussions



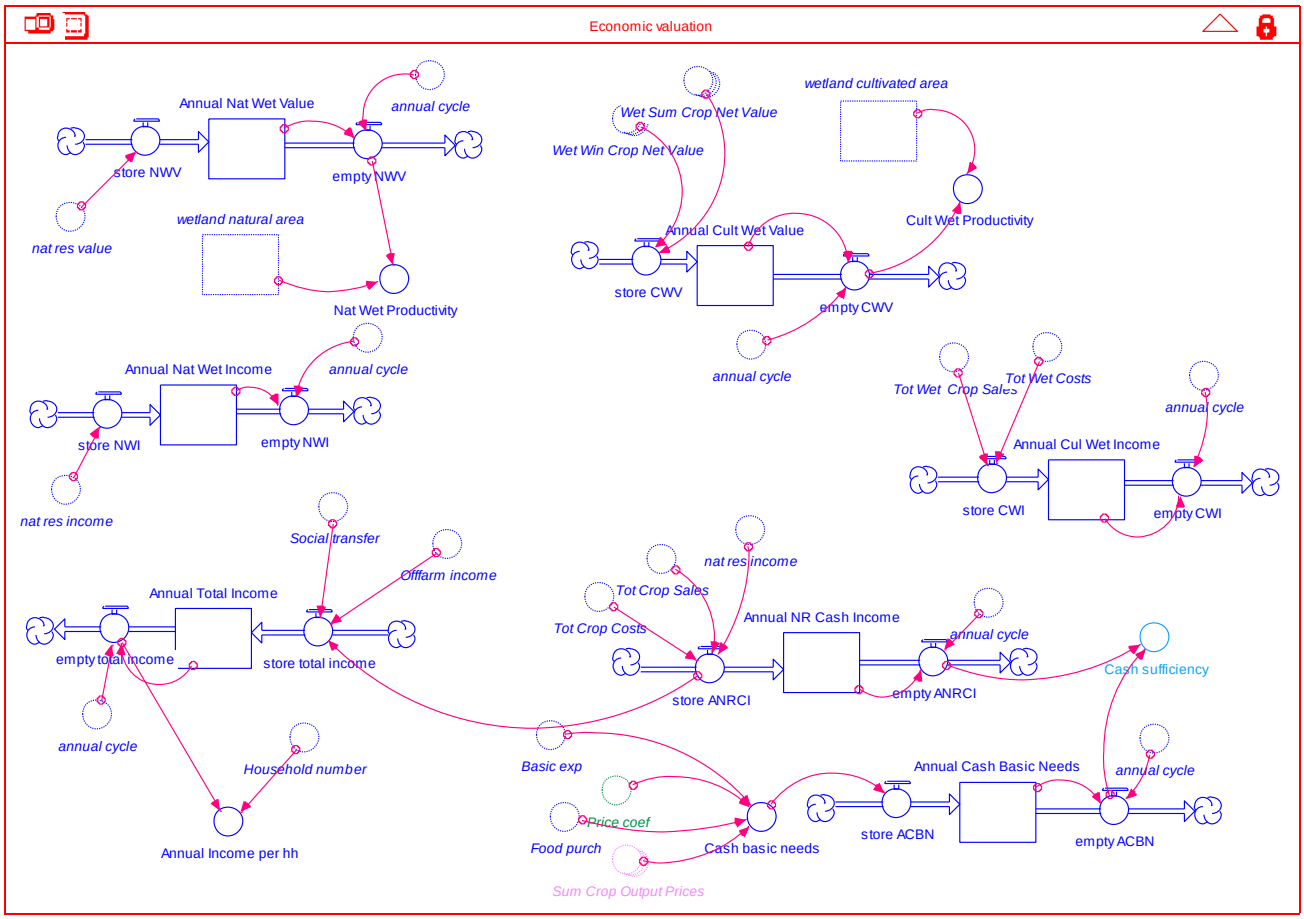
(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options, in light blue indicator used in MCA)

Figure 21: Community well-being sector

3.8 Economic valuation sector

This sector is used to compute some economic indicators, some of which are used in multi-criteria analysis of the management solutions:

- Annual economic value of the flow of provisioning services from natural wetland area (*empty_NWV*) and natural wetland productivity (annual value per unit area)
- Annual economic value of the flow of provisioning services from cultivated wetland area (*empty_CWV*) and cultivated wetland productivity (annual value per unit area)
- Annual cash value of the flow of marketed provisioning services from natural wetland area (*empty_NWI*)
- Annual cash value of the flow of marketed provisioning services from cultivated wetland area (*empty_CWI*)
- Annual total income from all sources (*empty_total_income*) and annual income per household
- Annual cash income from natural resources (including natural wetland, cultivated wetland, irrigation schemes and tourism income) (*empty_ANRCI*)
- Annual cash basic needs (*empty_ACBN*)
- Cash sufficiency: ratio of annual cash basic needs to annual cash income from natural resources, which is an indicator in the MCA for Ga-Mampa



(in green constant parameters, in pink variables affected by scenarios of external drivers, in orange variables affected by management options, in light blue indicator used in MCA)

Figure 22: Economic valuation sector

3.9 Time control

This sector allows controlling annual and seasonal cycles of activities. The *annual_cycle* variable takes increasing values from 1 to 12 starting in October and then starts again. Planting and harvesting dates for the different crops define the cropping seasons in winter and summer.

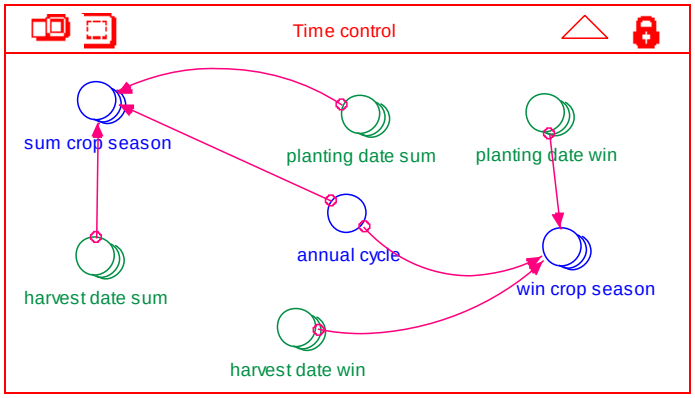


Figure 23: Time control sector

4 Model calibration

4.1 Hydrology sector calibration

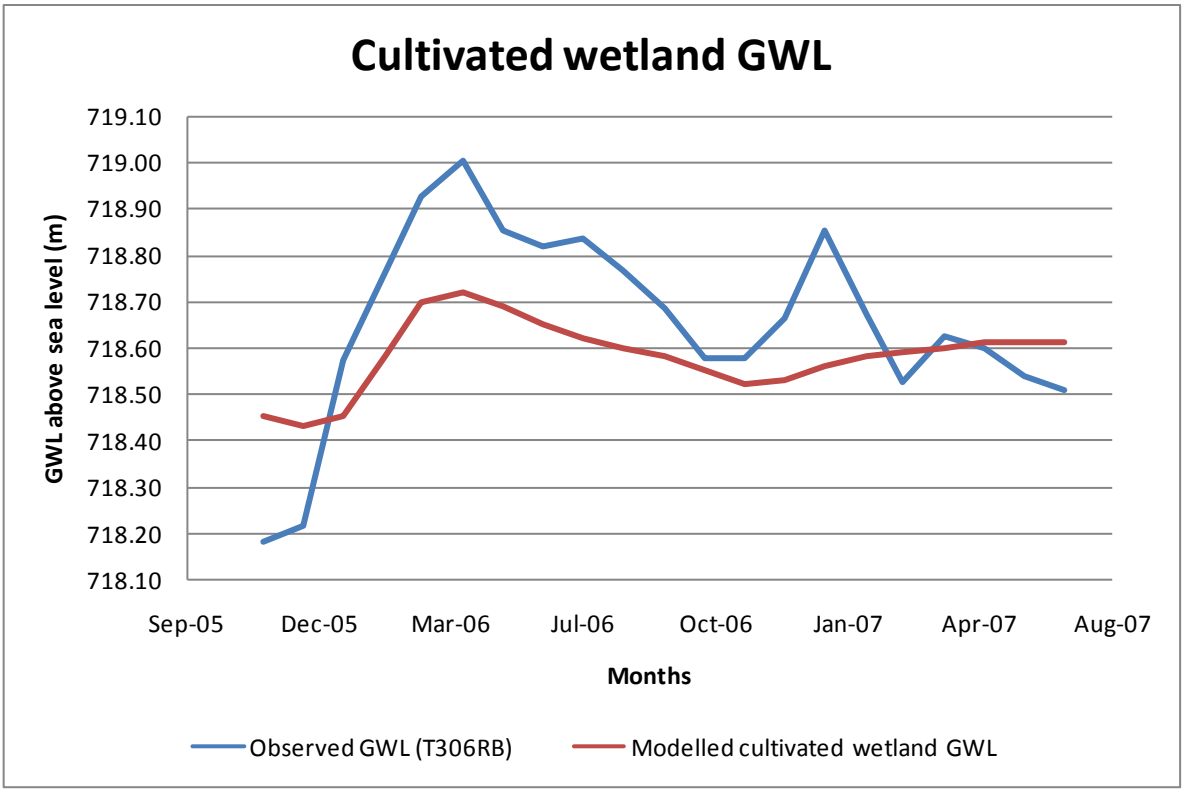
Calibration of the whole model was done for the period 1994-2006. A specific calibration of the hydrology module was conducted for the period 2005-2007 for which field measurements of some variables were available.

The dynamics of groundwater level modelled by WETSYS (value at beginning of the month) was compared with observations from piezometer measurements (average value over the month) ((model used for simulations: WETSYS_20111201_Calibration_1994-2007.STM)

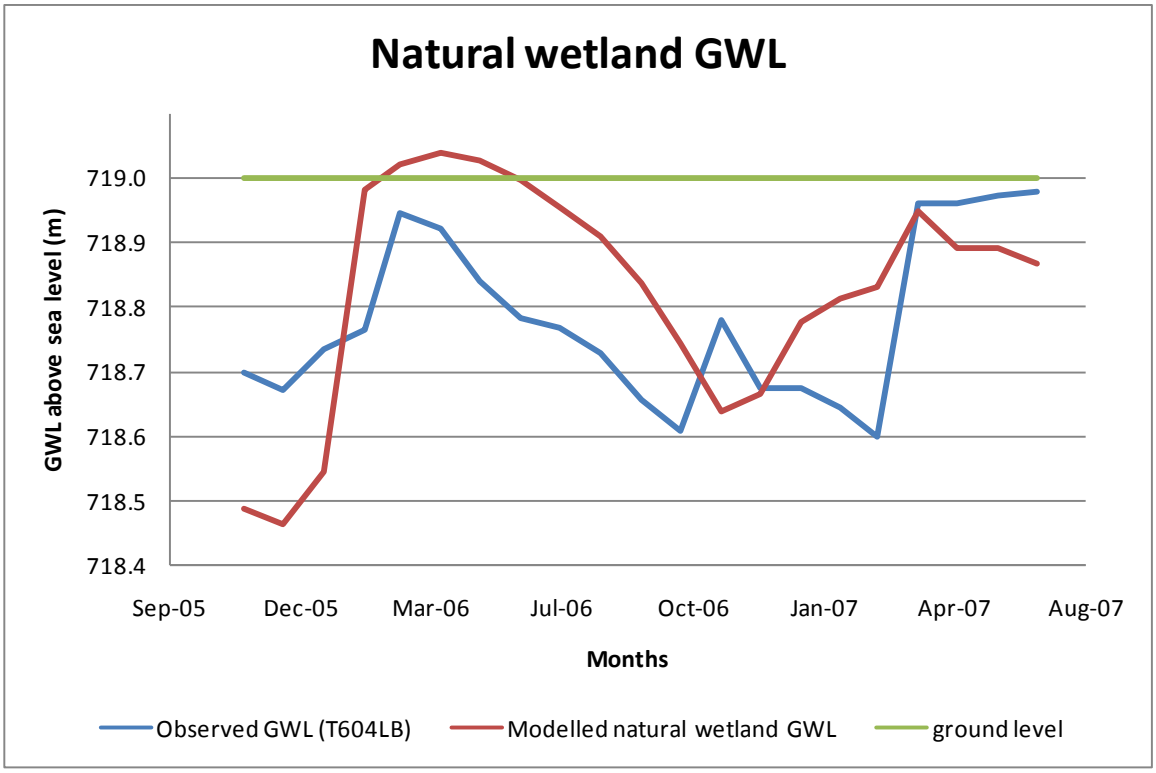
Figure 24[7]). Piezometer T306RB was chosen as a reference for cultivated wetland and piezometer T604LB as a reference for the natural wetland (see Kogelbauer 2010 for location of the piezometers).

Comparison of modelled and observed groundwater levels show that:

- Although during the first year modelled groundwater peaks at the same time as observed groundwater, it is not the case in the second year. However it should be noticed that the various piezometers have very different behaviour depending on their location.
- Observed groundwater level is generally higher (respectively lower) than modelled groundwater for cultivated wetland (respectively natural wetland). Adjusting for the initial value of groundwater stock could probably reduce the difference, but the influence of initial values tends to decrease over the simulation length.
- Amplitude of modelled groundwater seasonal variation is less important than for observed data.

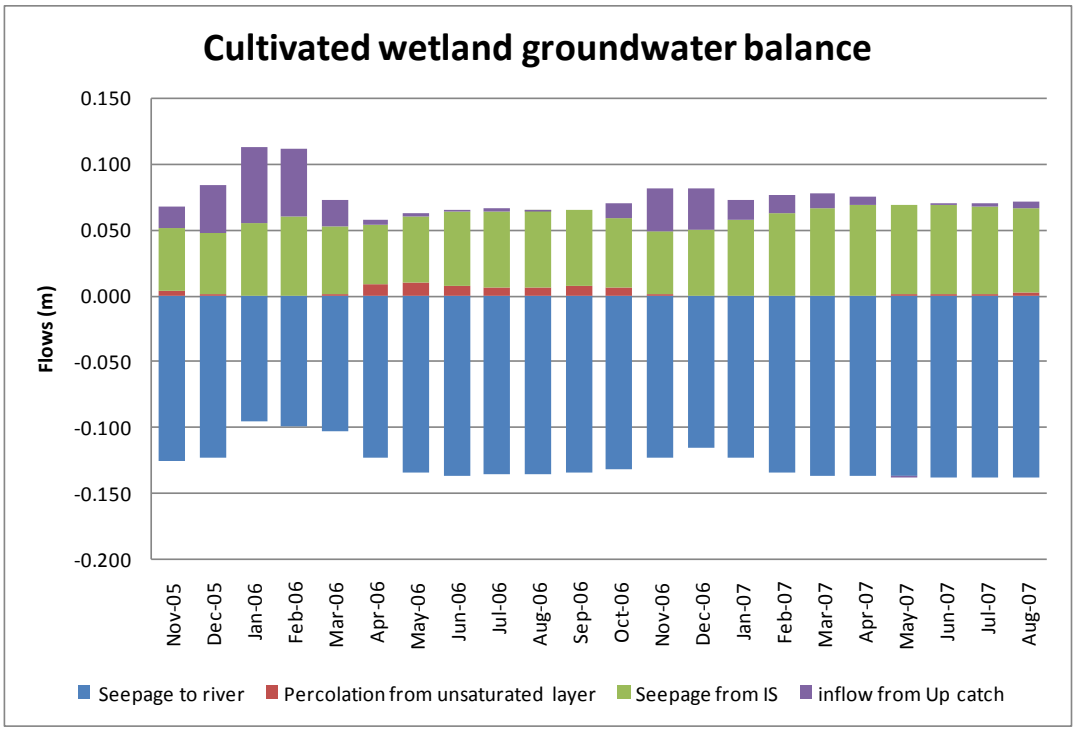


[7] Modelled values were obtained by running the model over the period October 1994 to September 2007.



(model used for simulations: WETSYS_20111201_Calibration_1994-2007.STM)

Figure 24: Observed and modelled groundwater level in cultivated and natural wetland



(model used for simulations: WETSYS_20111201_Calibration_1994-2007.STM)

Figure 25: Contribution of the flows to the groundwater level dynamics for a simulation period of 50 months

In addition the contribution of each inflow and outflow to this dynamics was analysed and is shown on **Hiba! A hivatkozási forrás nem található.**. The analysis of contribution of each variable to the state f ground water level showed that:

- Among inflows the biggest contribution comes from the irrigation scheme losses (diverted irrigation). Recharge of ground water from upper catchment rainfall is limited to the highest rainfall months, and less important with the current values of parameters used in the model. Percolation from unsaturated layer in the cultivated wetland is very small.
- Seepage to the river is the only outflow from unsaturated stock in the cultivated wetland.

To get an idea of the order of magnitude of the two unknown components of the water balance, groundwater inflow and outflow, flows modelled by WETSYS were compared to the studies from Kogelbauer and McCartney (Kogelbauer 2010; McCartney *et al.* 2011). Using the same water balance approach they found very different values for these two components.

- *Groundwater inflow from hill slopes*

Using a water balance approach Kogelbauer estimated that groundwater inflow from hill slopes varies between 0.074m/month during drying out period (April to June) and 0.071m/month in dry season, with a negative value during the rainy season.

Using the same kind of water balance approach, McCartney et al. estimated that for the months of July and August 2006 the groundwater inflow from hill slopes was between 1.12 and 1.349 Mm3 for the whole wetland area (1 km^2). Expressed as a water depth, this is equivalent to 1.12 to 1.349 m for two months or 0.56 m to 0.67 m/month (8 times Kogelbauer's estimation).

WETSYS estimation is the range of Kogelbauer's results (average of 0.072m/month between December 2005 and September 2007).

- *Groundwater outflow (GW_o)*

In her study of Ga-Mampa wetland groundwater, based on groundwater level measurements, Kogelbauer found an hydraulic gradient ranging from 0.007 in wet season to 0.008 during drying out (April-June) and dry season (July-September) (Kogelbauer 2010).

With this value of hydraulic gradient GW_o is about 2000 m3 for the whole wetland area (1km2), or 0.002 m if expressed in terms of water depth.

On the opposite, McCartney *et al.* estimated a groundwater outflow of 1.178 10^6 m3 for the months of July and August 2006, equivalent to a water depth of 0.589 m/month (almost 300 times higher !!!).

The values for groundwater outflow simulated by WETSYS range from 0.096 to 0.138 m/month, which stays between the two extreme estimated above.

Given the high uncertainties about the components of the water balance in the Ga-Mampa system, we can consider that WETSYS provides an acceptable representation of the water dynamics. To improve the hydrology sector more information would be needed on:

- Inflows to the wetland shallow aquifer from the regional (upper catchment) aquifer
- Leakages from the irrigation schemes (especially Fertilis)
- Importance of water losses from artificial drainage: do they affect the soil layer used by the crops (first 20cm or more) or even the shallow groundwater? In the current version of WETSYS drainage is not considered or can be incorporated into the vertical hydraulic conductivity coefficient.

- Groundwater seepage to the river.

4.2 Land use and crop production sector calibration

With the current value of parameters, the wetland cultivated area modelled by WETSYS is above the observed area but remains in an acceptable range (Figure 26). With these values and modelled crop yields it is possible to compare modelled maize production in the wetland and irrigation scheme to observed values (known from 2000 to 2010[8]) (Figure 27). It appears that, with a constant irrigated area of 171 ha and an increasing cultivated wetland area from 15 to 91 ha (calculated by the model), the maize production modelled by WETSYS is above observation for the irrigation scheme and below observation in the wetland. The total average production computed by WETSYS is about 15% less than observed. With irrigated area adjusted to observation (130 ha in 2001 and 50 ha thereafter) and yields calculated by the model, the modelled production in the irrigation scheme (blue line in Figure 27) is very close to observed production. Further adjustments of the food security threshold or of the average wetland plot area, that trigger wetland conversion, would be necessary to ensure a better calibration of wetland cultivated area and food production. Maize yields in the wetland appear to be very sensitive to climatic events.

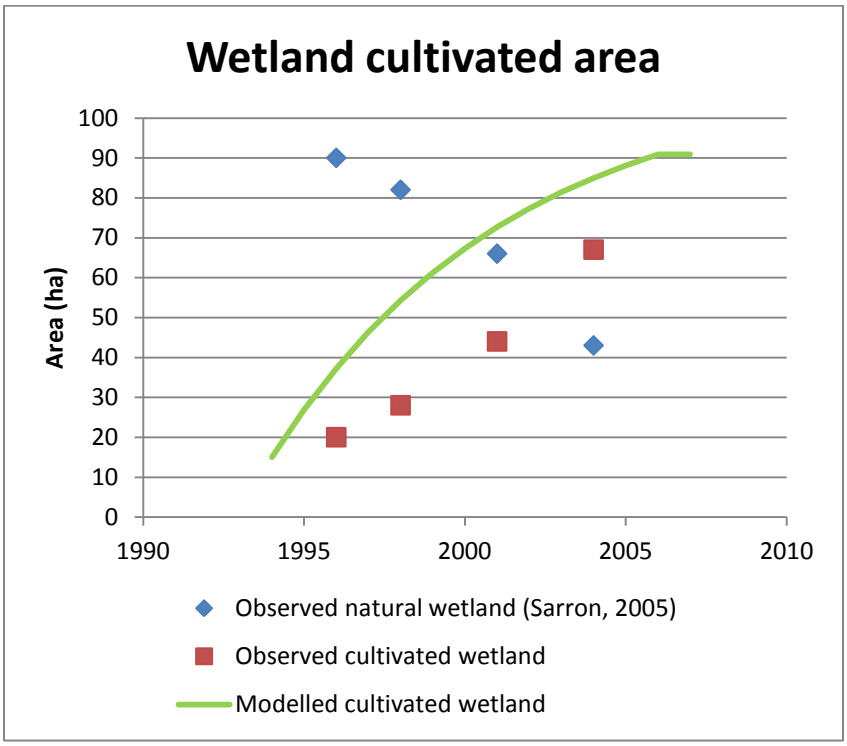


Figure 26: Comparison of observed and modelled cultivated wetland area between 1994 and 2007

[8] Phillip Mosima, extension officer, personal communication

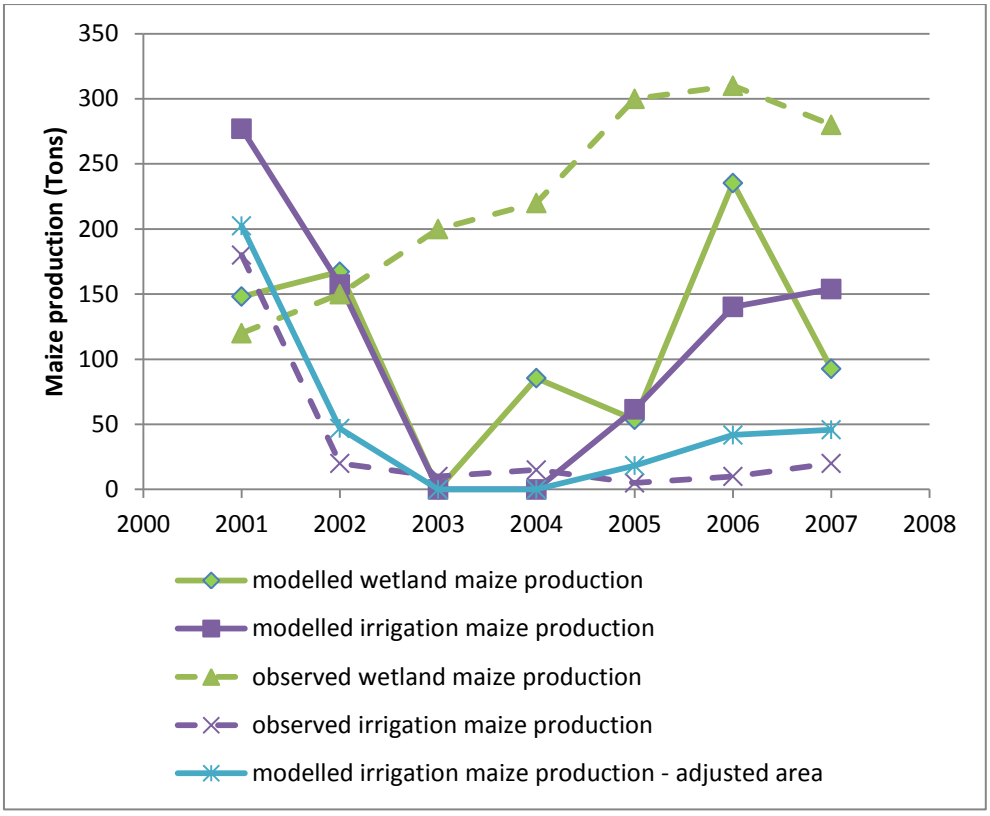


Figure 27: Comparison of modelled and observed maize production in the wetland and irrigation scheme

5 Conclusion

The WETSYS model was developed to integrate existing knowledge on small-scale wetlands such as the Ga-Mampa wetland in South Africa and support the analysis of trade-offs between supply of ecosystem services by the wetland and its ecological integrity. The modelling process proved to be instrumental in fostering inter-disciplinary dialogue and identifying knowledge gaps. The model was calibrated such as it reproduces past observed evolution from 1994 to 2007. The main challenges in the development of the model were the limitation in available time series data to calibrate it, especially regarding the socio-economic information, and the difficulty to translate narratives about past land use changes into quantitative decision rules.

Possible improvements and developments of WETSYS include: a better calibration, improved land use decision rules, through the incorporation of stakeholders' knowledge, feedback from well-being to population dynamics through emigration rate, linking biomass production to wetland groundwater level, adding a sector on organic matter dynamics in the wetland soils. Due to its modularity, WETSYS can easily be adapted to similar small-scale wetlands in Southern Africa.

It is planned to use WETSYS model to simulate different management interventions under various global change scenarios. Localized global change scenarios will include changes in climate (rainfall and potential evapotranspiration), population dynamics (changes in natural growth and emigration rates) and economic policies (affecting among others social transfer and level of wage rate). Wetland management options to be simulated were discussed with stakeholders at local and provincial levels (see WETwin project report D7.2, D8.1 by Johnston and Mahieu 2012). They include (1) rehabilitation of the irrigation scheme, (2) introduction of crops more adapted to wetland environment and reduction of artificial drainage; (3) development of ecotourism with the launch of a recently built tourism facility; and (4) imposing controls on resource use in the wetland. The choice of management options is informed by discussions with the community as well as field surveys that took place between 2004 and 2008. This process conducted with the involvement of local and external stakeholders will support the development of a wetland management plan.

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Annex 1: Model equations in WETSYS_20111201_Calibration_1994-2007.STM

Community well-being

```
Annual_food_consumption(t) = Annual_food_consumption(t - dt) + (Food_consumption - Empty_an_food_cons) * dt
INIT Annual_food_consumption = 0
INFLOWS:
Food_consumption = IF(Food_stock/DT>Food_needs) THEN Food_needs ELSE (Food_stock/DT+Food_purch)
OUTFLOWS:
Empty_an_food_cons = IF(annual_cycle=12) THEN Annual_food_consumption/DT ELSE 0
Annual_food_needs(t) = Annual_food_needs(t - dt) + (store_food_needs - Empty_an_food_needs) * dt
INIT Annual_food_needs = 0
INFLOWS:
store_food_needs = Food_needs
OUTFLOWS:
Empty_an_food_needs = IF(annual_cycle=12) THEN Annual_food_needs/DT ELSE 0
Cash(t) = Cash(t - dt) + (Cash_inflow - Cash_outflow) * dt
INIT Cash = ic_Cash
INFLOWS:
Cash_inflow = nat_res_income + Tot_Crop_Sales + Offfarm_income + Social_transfer
OUTFLOWS:
Cash_outflow = MIN(Cash/DT, (Food_purch*Sum_Crop_Output_Prices[Maize]*Price_coef + Non_Food_Exp))
Food_stock(t) = Food_stock(t - dt) + (Food_Production + Food_purch - Food_consumption) * dt
INIT Food_stock = ic_Food_stock
INFLOWS:
Food_Production = Total_Maize_Prod
Food_purch = IF(Food_needs>Food_stock/DT) THEN MIN (Food_needs-Food_stock/DT,Max_Food_Purch) ELSE 0
OUTFLOWS:
Food_consumption = IF(Food_stock/DT>Food_needs) THEN Food_needs ELSE (Food_stock/DT+Food_purch)
Population(t) = Population(t - dt) + (Population_growth) * dt
INIT Population = ic_Population
INFLOWS:
Population_growth = Population_growth_rate*Population
Annual_food_security = IF(annual_cycle=12) THEN Empty_an_food_cons/Empty_an_food_needs ELSE 0
Basic_exp = (Population*Non_food_exp_per_person)
Child_grant = 200
Food_needs = Population * Food_need_per_cap/DT
Food_need_per_cap = 95/(1000*7)
food_security_index = Food_consumption/Food_needs
Food_sufficiency = IF Empty_an_food_needs=0 THEN 0 ELSE Total_Maize_Prod / Empty_an_food_needs
hh_size = 7
Household_number = Population/hh_size
ic_Cash = ic_Population*((prop_pensioners*Pension) + (prop_children*Child_grant) +
(prop_offfarm_jobs*offfarm_wage)/hh_size)
ic_Food_stock = (irrigable_crop_area*2)+(ic_Cult_Wet*2.5) - (ic_Population*95*6)/(hh_size*1000)
ic_Population = 2323
Max_Food_Purch = IF (Cash >(Tot_Crop_Costs+prior_coeff*Basic_exp)*DT) THEN (Cash-Tot_Crop_Costs*DT-
prior_coeff*Basic_exp*DT) /(Price_coef*Sum_Crop_Output_Prices[Maize]) ELSE 0
Non_Food_Exp = Tot_Crop_Costs+ Basic_exp + Land_use_costs
Non_food_exp_per_person = 1750/12
Offfarm_income =  (prop_offfarm_jobs*offfarm_wage)*Population*Offfarm_index + Tourism_income
Offfarm_index = 1
offfarm_wage = 1000
Pension = 800
Population_growth_rate = CGROWTH(0.0011*100)
poverty_line = 150
Price_coef = 1.15
prior_coeff = 0
prop_children = 0.28
prop_offfarm_jobs = 0.24/7
prop_pensioners = 0.06
Social_index = 1
Social_transfer = ((prop_pensioners*Pension) + (prop_children*Child_grant))*Population*Social_index
Tourism_income = 0
```

Crop economics
Input_Price_Index = 1
Irrig_Fee = 0
Irrig_Sum_Crop_Net_Value[Sum_crops] =
Outpout_Price_Idx*Sum_Crop_Output_Prices[Sum_crops]*ARRAYSUM(Irrig_Sum_Production[Sum_crops,*])-
Total_Irrig_Sum_Costs[Sum_crops]
Irrig_Sum_Sales[Sum_crops] =
ARRAYSUM(Irrig_Sum_Production[Sum_crops,*])*Sales_Sum_crop[Sum_crops]*Sum_Crop_Output_Prices[Sum_crops]*Sum_Price_Idx[Sum_crops]*Outpout_Price_Idx
Irrig_Win_Crop_Net_Value[Win_crops] =
Outpout_Price_Idx*Win_Crop_Output_Prices[Win_crops]*ARRAYSUM(Irrig_Win_Production[*,Win_crops])-
Total_irrig_Win_Costs[Win_crops]
Irrig_Win_Sales[Win_crops] =
Sales_Win_crop[Win_crops]*Win_Crop_Output_Prices[Win_crops]*ARRAYSUM(Irrig_Win_Production[*,Win_crops])*Win_Price_Idx[Win_crops]*Outpout_Price_Idx
Outpout_Price_Idx = 1
Sales_Sum_crop[Maize] = 0
Sales_Sum_crop[Groundnut] = 1
Sales_Sum_crop[eMaize] = 0
Sales_Sum_crop[SwPot] = 1
Sales_Sum_crop[FallSum] = 0
Sales_Sum_crop[TomSum] = 1
Sales_Win_crop[Onion] = 1
Sales_Win_crop[Tomato] = 1
Sales_Win_crop[No_crop] = 0
Sales_Win_crop[Cabb] = 1
Sales_Win_crop[Bean] = 1
Sum_Crop_Output_Prices[Sum_crops] = [2500,4400,2500,3800,0,5000]
Sum_Price_Idx[Sum_crops] = 1
Total_Irrig_Sum_Costs[Sum_crops] =
ARRAYSUM(Irrig_Crop_proportion[Sum_crops,*])*irrigable_crop_area*IrrigSumCostpha[Sum_crops]*Input_Price_Index
Total_irrig_Win_Costs[Win_crops] =
ARRAYSUM(Irrig_Crop_proportion[*,Win_crops])*irrigable_crop_area*IrrigWinCostpha[Win_crops]*Input_Price_Index
Total_Wet_Sum_Costs[Sum_crops] =
wetland_cultivated_area*ARRAYSUM(Wet_Crop_Proportion[Sum_crops,*])*WetSumCostpha[Sum_crops]*Input_Price_Index
Total_Wet_Win_Costs[Win_crops] =
wetland_cultivated_area*ARRAYSUM(Wet_Crop_Proportion[*,Win_crops])*WetWinCostpha[Win_crops]*Input_Price_Index
Tot_Crop_Costs = Tot_Irrig_Costs+Tot_Wet_Costs
Tot_Crop_Sales = Tot_Irrig_Crop_Sales + Tot_Wet__Crop_Sales
Tot_Irrig_Costs = ARRAYSUM(Total_Irrig_Sum_Costs[*])+ARRAYSUM(Total_irrig_Win_Costs[*]) + Irrig_Fee
Tot_Irrig_Crop_Sales = ARRAYSUM(Irrig_Sum_Sales[*]) + ARRAYSUM(Irrig_Win_Sales[*])
Tot_Wet_Costs = ARRAYSUM(Total_Wet_Sum_Costs[*]) + ARRAYSUM(Total_Wet_Win_Costs[*])
Tot_Wet__Crop_Sales = ARRAYSUM(Wet_Sum_sales[*]) + ARRAYSUM(Wet_Win_Sales[*])
Wet_Sum_Crop_Net_Value[Sum_crops] =
Outpout_Price_Idx*Sum_Crop_Output_Prices[Sum_crops]*ARRAYSUM(Wet_Sum_Production[Sum_crops,*])-
Total_Wet_Sum_Costs[Sum_crops]
Wet_Sum_sales[Sum_crops] = ARRAYSUM(Wet_Sum_Production[Sum_crops,*])*
Sales_Sum_crop[Sum_crops]*Sum_Crop_Output_Prices[Sum_crops]*Sum_Price_Idx[Sum_crops]*Outpout_Price_Idx
Wet_Win_Crop_Net_Value[Win_crops] =
Outpout_Price_Idx*Win_Crop_Output_Prices[Win_crops]*ARRAYSUM(Wet_Win_Production[*,Win_crops])-
Total_Wet_Win_Costs[Win_crops]
Wet_Win_Sales[Win_crops] = Sales_Win_crop[Win_crops] *
Win_Crop_Output_Prices[Win_crops]*ARRAYSUM(Wet_Win_Production[*,Win_crops])*Win_Price_Idx[Win_crops]*Outpout_Price_Idx
Win_Crop_Output_Prices[Win_crops] = [1500,5000,0,4300,10000]
Win_Price_Idx[Win_crops] = 1
IrrigSumCostpha[Maize] = GRAPH(annual_cycle)
(1.00, 720), (2.00, 800), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 130), (11.0, 0.00), (12.0, 800)
IrrigSumCostpha[Groundnut] = GRAPH(annual_cycle)
(1.00, 175), (2.00, 600), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 800)
IrrigSumCostpha[eMaize] = GRAPH(annual_cycle)

(0.00, 800), (20.0, 0.00), (40.0, 0.00), (60.0, 0.00), (80.0, 0.00), (100, 0.00)
IrrigSumCostpha[SwPot] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 1800), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
IrrigSumCostpha[FallSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
IrrigSumCostpha[TomSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 950), (27.3, 800), (36.4, 1800), (45.5, 6550), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
IrrigWinCostpha[Onion] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 950), (8.00, 800), (9.00, 1800), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
IrrigWinCostpha[Tomato] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 950), (7.00, 800), (8.00, 1800), (9.00, 6550), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
IrrigWinCostpha[No_crop] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
IrrigWinCostpha[Cabb] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 950), (63.6, 800), (72.7, 1850), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
IrrigWinCostpha[Bean] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 800), (45.5, 900), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
WetSumCostpha[Maize] = GRAPH(annual_cycle)
(1.00, 220), (2.00, 600), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 250), (11.0, 0.00), (12.0, 600)
WetSumCostpha[Groundnut] = GRAPH(annual_cycle)
(1.00, 175), (2.00, 600), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 600)
WetSumCostpha[eMaize] = GRAPH(annual_cycle)
(0.00, 600), (20.0, 0.00), (40.0, 0.00), (60.0, 0.00), (80.0, 0.00), (100, 0.00)
WetSumCostpha[SwPot] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 1800), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
WetSumCostpha[FallSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
WetSumCostpha[TomSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 750), (27.3, 600), (36.4, 1800), (45.5, 6550), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
WetWinCostpha[Onion] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 750), (8.00, 600), (9.00, 1800), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
WetWinCostpha[Tomato] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 750), (7.00, 600), (8.00, 1800), (9.00, 6550), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
WetWinCostpha[No_crop] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
WetWinCostpha[Cabb] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 750), (63.6, 600), (72.7, 1850), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
WetWinCostpha[Bean] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 600), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)

Crop production
ETa_Irrig_sum_season[Sum_crops,Win_crops](t) = ETa_Irrig_sum_season[Sum_crops,Win_crops](t - dt) + (Store_sum_ETa_irrig[Sum_crops,Win_crops] - Empty_sum_ETa_Irrig[Sum_crops,Win_crops]) * dt
INIT ETa_Irrig_sum_season[Sum_crops,Win_crops] = 0
INFLOWS:
Store_sum_ETa_irrig[Sum_crops,Win_crops] = IS_Transp[Sum_crops,Win_crops]*sum_crop_season[Sum_crops]

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OUTFLOWS:
Empty_sum_ETa_Irrig[Sum_crops,Win_crops] = IF annual_cycle=harvest_date_sum[Sum_crops] THEN
ETa_Irrig_sum_season[Sum_crops,Win_crops]/DT ELSE 0
ETa_Irrig_win_season[Sum_crops,Win_crops](t) = ETa_Irrig_win_season[Sum_crops,Win_crops](t - dt) +
(Store_win_ETa_irrig[Sum_crops,Win_crops] - Empty_win_ETa_Irrig[Sum_crops,Win_crops]) * dt
INIT ETa_Irrig_win_season[Sum_crops,Win_crops] = 0
INFLOWS:
Store_win_ETa_irrig[Sum_crops,Win_crops] = IS_Transp[Sum_crops,Win_crops]*win_crop_season[Win_crops]
OUTFLOWS:
Empty_win_ETa_Irrig[Sum_crops,Win_crops] = IF annual_cycle = harvest_date_win[Win_crops] THEN
ETa_Irrig_win_season[Sum_crops,Win_crops]/DT ELSE 0
ETa_W_sum_season[Sum_crops,Win_crops](t) = ETa_W_sum_season[Sum_crops,Win_crops](t - dt) +
(Store_sum_ETa_W[Sum_crops,Win_crops] - Empty_sum_ETa_W[Sum_crops,Win_crops]) * dt
INIT ETa_W_sum_season[Sum_crops,Win_crops] = 0
INFLOWS:
Store_sum_ETa_W[Sum_crops,Win_crops] = CW_Transp[Sum_crops,Win_crops]*sum_crop_season[Sum_crops]
OUTFLOWS:
Empty_sum_ETa_W[Sum_crops,Win_crops] = IF annual_cycle=harvest_date_sum[Sum_crops] THEN
ETa_W_sum_season[Sum_crops,Win_crops]/DT ELSE 0
ETa_W_win_season[Sum_crops,Win_crops](t) = ETa_W_win_season[Sum_crops,Win_crops](t - dt) +
(Store_win_ETa_W[Sum_crops,Win_crops] - Empty_win_ETa_W[Sum_crops,Win_crops]) * dt
INIT ETa_W_win_season[Sum_crops,Win_crops] = 0
INFLOWS:
Store_win_ETa_W[Sum_crops,Win_crops] = CW_Transp[Sum_crops,Win_crops]*win_crop_season[Win_crops]
OUTFLOWS:
Empty_win_ETa_W[Sum_crops,Win_crops] = IF annual_cycle = harvest_date_win[Win_crops] THEN
ETa_W_win_season[Sum_crops,Win_crops]/DT ELSE 0
ETm_Summer[Sum_crops](t) = ETm_Summer[Sum_crops](t - dt) + (Store_ETm_Sum[Sum_crops] -
Empty_ETm_Sum[Sum_crops]) * dt
INIT ETm_Summer[Sum_crops] = 0
INFLOWS:
Store_ETm_Sum[Sum_crops] = ETP*Kc_sum[Sum_crops]/Conv
OUTFLOWS:
Empty_ETm_Sum[Sum_crops] = IF annual_cycle=harvest_date_sum[Sum_crops] THEN ETm_Summer[Sum_crops]/DT
ELSE 0
ETm_Winter[Win_crops](t) = ETm_Winter[Win_crops](t - dt) + (Store_ETm_Win[Win_crops] -
Empty_ETm_Win[Win_crops]) * dt
INIT ETm_Winter[Win_crops] = 0
INFLOWS:
Store_ETm_Win[Win_crops] = ETP*Kc_win[Win_crops]/Conv
OUTFLOWS:
Empty_ETm_Win[Win_crops] = IF annual_cycle=harvest_date_win[Win_crops] THEN ETm_Winter[Win_crops]/DT ELSE 0
a_sum[Sum_crops] = (Ky_sum[Sum_crops]-1)/Ky_sum[Sum_crops]
a_win[Win_crops] = (Ky_win[Win_crops]-1)/Ky_win[Win_crops]
ETm[Sum_crops,Win_crops] = Store_ETm_Sum[Sum_crops]+Store_ETm_Win[Win_crops]
Irrig_Crop_proportion[Maize,Onion] = 0
Irrig_Crop_proportion[Maize,Tomato] = 0
Irrig_Crop_proportion[Maize,No_crop] = 1
Irrig_Crop_proportion[Maize,Cabb] = 0
Irrig_Crop_proportion[Maize,Bean] = 0
Irrig_Crop_proportion[Groundnut,Onion] = 0
Irrig_Crop_proportion[Groundnut,Tomato] = 0
Irrig_Crop_proportion[Groundnut,No_crop] = 0
Irrig_Crop_proportion[Groundnut,Cabb] = 0
Irrig_Crop_proportion[Groundnut,Bean] = 0
Irrig_Crop_proportion[eMaize,Onion] = 0
Irrig_Crop_proportion[eMaize,Tomato] = 0
Irrig_Crop_proportion[eMaize,No_crop] = 0
Irrig_Crop_proportion[eMaize,Cabb] = 0
Irrig_Crop_proportion[eMaize,Bean] = 0
Irrig_Crop_proportion[SwPot,Onion] = 0
Irrig_Crop_proportion[SwPot,Tomato] = 0
Irrig_Crop_proportion[SwPot,No_crop] = 0
Irrig_Crop_proportion[SwPot,Cabb] = 0
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Irrig_Crop_proportion[SwPot,Bean] = 0
Irrig_Crop_proportion[FallSum,Onion] = 0
Irrig_Crop_proportion[FallSum,Tomato] = 0
Irrig_Crop_proportion[FallSum,No_crop] = 0
Irrig_Crop_proportion[FallSum,Cabb] = 0
Irrig_Crop_proportion[FallSum,Bean] = 0
Irrig_Crop_proportion[TomSum,Onion] = 0
Irrig_Crop_proportion[TomSum,Tomato] = 0
Irrig_Crop_proportion[TomSum,No_crop] = 0
Irrig_Crop_proportion[TomSum,Cabb] = 0
Irrig_Crop_proportion[TomSum,Bean] = 0
Irrig_Sum_Crop_Yields[Sum_crops,Win_crops] = IF
(Empty_sum_ETa_Irrig[Sum_crops,Win_crops]<=a_sum[Sum_crops]*Empty_ETm_Sum[Sum_crops] OR
Empty_ETm_Sum[Sum_crops]=0) THEN 0 ELSE Max_Irrig_yield_sum[Sum_crops]* (1-Ky_sum[Sum_crops]*(1-
Empty_sum_ETa_Irrig[Sum_crops,Win_crops]/Empty_ETm_Sum[Sum_crops]))
Irrig_Sum_Production[Sum_crops,Win_crops] = irrigable_crop_area * Irrig_Crop_proportion[Sum_crops,Win_crops] *
Irrig_Sum_Crop_Yields[Sum_crops,Win_crops]
Irrig_Win_Crop_Yields[Sum_crops,Win_crops] = IF
(Empty_win_ETa_Irrig[Sum_crops,Win_crops]<a_win[Win_crops]*Empty_ETm_Win[Win_crops] OR
Empty_ETm_Win[Win_crops]=0) THEN 0 ELSE Max_Irrig_yield_win[Win_crops]*(1-Ky_win[Win_crops]*(1-
Empty_win_ETa_Irrig[Sum_crops,Win_crops]/Empty_ETm_Win[Win_crops]))
Irrig_Win_Production[Sum_crops,Win_crops] =
irrigable_crop_area*Irrig_Crop_proportion[Sum_crops,Win_crops]*Irrig_Win_Crop_Yields[Sum_crops,Win_crops]
Ky_sum[Sum_crops] = [1.25,0.7,1.25,1.1,1,1.05]
Ky_win[Win_crops] = [1.1,1.05,1,0.95,1.15]
Maize_Prod_per_succ[Sum_crops,Win_crops] =
Irrig_Sum_Production[Maize,Win_crops]+Wet_Sum_Production[Maize,Win_crops]
Max_Irrig_yield_sum[Sum_crops] = [4,2.2,4,3,0,2.5]
Max_Irrig_yield_win[Win_crops] = [1.5,2.5,0,2,0.6]
Max_W_yield_sum[Sum_crops] = [4,2.2,4,3,0,2.5]
Max_W_yield_win[Win_crops] = [1.5,2.5,0,2,0.6]
p_Succ[Sum_crops,Win_crops] = p_Sum[Sum_crops] + p_Win[Win_crops]
p_Sum[Sum_crops] = [0.55,0.5,0.55,0.65,0,0.4]
p_Win[Win_crops] = [0.25,0.4,0,0.35,0.45]
Root_Depth_Succ[Sum_crops,Win_crops] = Root_Depth_sum[Sum_crops] + Root_Depth_win[Win_crops]
Total_Maize_Prod = ARRAYSUM(Maize_Prod_per_succ[*,*])
Wet_Crop_Proportion[Maize,Onion] = 0
Wet_Crop_Proportion[Maize,Tomato] = 0
Wet_Crop_Proportion[Maize,No_crop] = 1
Wet_Crop_Proportion[Maize,Cabb] = 0
Wet_Crop_Proportion[Maize,Bean] = 0
Wet_Crop_Proportion[Groundnut,Onion] = 0
Wet_Crop_Proportion[Groundnut,Tomato] = 0
Wet_Crop_Proportion[Groundnut,No_crop] = 0
Wet_Crop_Proportion[Groundnut,Cabb] = 0
Wet_Crop_Proportion[Groundnut,Bean] = 0
Wet_Crop_Proportion[eMaize,Onion] = 0
Wet_Crop_Proportion[eMaize,Tomato] = 0
Wet_Crop_Proportion[eMaize,No_crop] = 0
Wet_Crop_Proportion[eMaize,Cabb] = 0
Wet_Crop_Proportion[eMaize,Bean] = 0
Wet_Crop_Proportion[SwPot,Onion] = 0
Wet_Crop_Proportion[SwPot,Tomato] = 0
Wet_Crop_Proportion[SwPot,No_crop] = 0
Wet_Crop_Proportion[SwPot,Cabb] = 0
Wet_Crop_Proportion[SwPot,Bean] = 0
Wet_Crop_Proportion[FallSum,Onion] = 0
Wet_Crop_Proportion[FallSum,Tomato] = 0
Wet_Crop_Proportion[FallSum,No_crop] = 0
Wet_Crop_Proportion[FallSum,Cabb] = 0
Wet_Crop_Proportion[FallSum,Bean] = 0
Wet_Crop_Proportion[TomSum,Onion] = 0
Wet_Crop_Proportion[TomSum,Tomato] = 0
Wet_Crop_Proportion[TomSum,No_crop] = 0
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Wet_Crop_Proportion[TomSum,Cabb] = 0
Wet_Crop_Proportion[TomSum,Bean] = 0
Wet_Sum_Crop_Yields[Sum_crops,Win_crops] = IF
(Empty_sum_ETa_W[Sum_crops,Win_crops]<=a_sum[Sum_crops]*Empty_ETm_Sum[Sum_crops] OR
Empty_ETm_Sum[Sum_crops]=0) THEN 0 ELSE Max_W_yield_sum[Sum_crops]*(1-Ky_sum[Sum_crops]*(1-
Empty_sum_ETa_W[Sum_crops,Win_crops]/Empty_ETm_Sum[Sum_crops]))
Wet_Sum_Production[Sum_crops,Win_crops] = wetland_cultivated_area * Wet_Crop_Proportion[Sum_crops,Win_crops] *
Wet_Sum_Crop_Yields[Sum_crops,Win_crops]
Wet_Win_Crop_Yields[Sum_crops,Win_crops] = IF
(Empty_win_ETa_W[Sum_crops,Win_crops]<=a_win[Win_crops]*Empty_ETm_Win[Win_crops] OR
Empty_ETm_Win[Win_crops]=0) THEN 0 ELSE Max_W_yield_win[Win_crops]*(1-Ky_win[Win_crops]*(1-
Empty_win_ETa_W[Sum_crops,Win_crops]/Empty_ETm_Win[Win_crops]))
Wet_Win_Production[Sum_crops,Win_crops] =
wetland_cultivated_area*Wet_Crop_Proportion[Sum_crops,Win_crops]*Wet_Win_Crop_Yields[Sum_crops,Win_crops]
Kc_sum[Maize] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.4), (4.00, 0.775), (5.00, 1.15), (6.00, 1.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Kc_sum[Groundnut] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.4), (3.00, 0.775), (4.00, 1.15), (5.00, 1.15), (6.00, 0.6), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Kc_sum[eMaize] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.4), (18.2, 0.775), (27.3, 1.15), (36.4, 1.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Kc_sum[SwPot] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.5), (27.3, 0.717), (36.4, 0.933), (45.5, 1.15), (54.5, 1.15), (63.6, 1.15), (72.7, 0.65), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Kc_sum[FallSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Kc_sum[TomSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.6), (36.4, 0.85), (45.5, 1.10), (54.5, 0.8), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Kc_win[Onion] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.7), (9.00, 0.8), (10.0, 0.9), (11.0, 0.9), (12.0, 0.75)
Kc_win[Tomato] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.6), (8.00, 0.85), (9.00, 1.10), (10.0, 0.8), (11.0, 0.00), (12.0, 0.00)
Kc_win[No_crop] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Kc_win[Cabb] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.7), (72.7, 0.8), (81.8, 0.9), (90.9, 1.05), (100, 1.00)
Kc_win[Bean] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.4), (54.5, 0.85), (63.6, 1.15), (72.7, 0.6), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Root_Depth_sum[Maize] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.3), (4.00, 0.53), (5.00, 0.77), (6.00, 1.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Root_Depth_sum[Groundnut] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.25), (3.00, 0.33), (4.00, 0.42), (5.00, 0.5), (6.00, 0.5), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Root_Depth_sum[eMaize] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.3), (18.2, 0.53), (27.3, 0.77), (36.4, 1.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Root_Depth_sum[SwPot] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.3), (27.3, 0.4), (36.4, 0.5), (45.5, 0.6), (54.5, 0.6), (63.6, 0.6), (72.7, 0.6), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Root_Depth_sum[FallSum] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Root_Depth_sum[TomSum] = GRAPH(annual_cycle)

(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.25), (36.4, 0.5), (45.5, 0.75), (54.5, 1.00), (63.6, 0.00), (72.7, 0.00), (81.8, 0.00), (90.9, 0.00), (100, 0.00)
Root_Depth_win[Onion] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.2), (9.00, 0.4), (10.0, 0.6), (11.0, 0.6), (12.0, 0.6)
Root_Depth_win[Tomato] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.25), (8.00, 0.5), (9.00, 0.75), (10.0, 1.00), (11.0, 0.00), (12.0, 0.00)
Root_Depth_win[No_crop] = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Root_Depth_win[Cabb] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.00), (54.5, 0.00), (63.6, 0.25), (72.7, 0.33), (81.8, 0.41), (90.9, 0.5), (100, 0.00)
Root_Depth_win[Bean] = GRAPH(annual_cycle)
(0.00, 0.00), (9.09, 0.00), (18.2, 0.00), (27.3, 0.00), (36.4, 0.00), (45.5, 0.3), (54.5, 0.65), (63.6, 1.00), (72.7, 1.00), (81.8, 1.00), (90.9, 0.00), (100, 0.00)

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CW_SatW[Sum_crops,Win_crops](t) = CW_SatW[Sum_crops,Win_crops](t - dt) +
(CW_UW_to_SatW[Sum_crops,Win_crops] + CW_SW_toSatW[Sum_crops,Win_crops] +
CW_SatW_from_precip[Sum_crops,Win_crops] + CW_GW_inflow[Sum_crops,Win_crops] -
CW_SatW_to_SW[Sum_crops,Win_crops] - CW_SatW_to_UW[Sum_crops,Win_crops] -
CW_SatW_Transp[Sum_crops,Win_crops] - CW_Seepage_to_river[Sum_crops,Win_crops]) * dt
INIT CW_SatW[Sum_crops,Win_crops] = ic_CW_SatW
INFLOWS:
CW_UW_to_SatW[Sum_crops,Win_crops] = IF (inf_cond[Sum_crops,Win_crops]=0)  THEN
CW_UW[Sum_crops,Win_crops]/DT ELSE
MIN (CW_UW[Sum_crops,Win_crops]/DT, MAX(0,
CW_UW_delta[Sum_crops,Win_crops]*CW_UW_moist[Sum_crops,Win_crops]/DT +
CW_UW_perc_rate[Sum_crops,Win_crops]))
CW_SW_toSatW[Sum_crops,Win_crops] = IF (CW_UW_depth_before[Sum_crops,Win_crops]=0 AND
CW_Unsat_cap[Sum_crops,Win_crops]>0)
 THEN  MIN (CW_Unsat_cap[Sum_crops,Win_crops]/DT, CW_SurfW[Sum_crops,Win_crops]/DT)
ELSE 0
CW_SatW_from_precip[Sum_crops,Win_crops] = IF inf_cond[Sum_crops,Win_crops]=0
THEN CW_Unsat_cap[Sum_crops,Win_crops]/DT - CW_SW_toSatW[Sum_crops,Win_crops]
ELSE 0
CW_GW_inflow[Sum_crops,Win_crops] = Upper_catch_rainfall*Up_Catch_Coef/Conv + Tot_IS_to_CW
OUTFLOWS:
CW_SatW_to_SW[Sum_crops,Win_crops] = IF CW_SatW[Sum_crops,Win_crops]>CW_SatW_Max THEN
(CW_SatW[Sum_crops,Win_crops] - CW_SatW_Max)/DT ELSE 0
CW_SatW_to_UW[Sum_crops,Win_crops] = MAX( 0, MIN(-CW_UW_delta[Sum_crops,Win_crops]*CW_FC,
CW_SatW[Sum_crops,Win_crops]/DT))
CW_SatW_Transp[Sum_crops,Win_crops] = CW_Transp[Sum_crops,Win_crops]*(1-
CW_UW_Trans_pr[Sum_crops,Win_crops])
CW_Seepage_to_river[Sum_crops,Win_crops] = CW_Hydr_Grad[Sum_crops,Win_crops]*CW_Hydr_Cond
CW_SurfW[Sum_crops,Win_crops](t) = CW_SurfW[Sum_crops,Win_crops](t - dt) + (CW_SW_in[Sum_crops,Win_crops] +
CW_SatW_to_SW[Sum_crops,Win_crops] - CW_SW_toSatW[Sum_crops,Win_crops] -
CW_SW_Evap[Sum_crops,Win_crops] - CW_SW_out[Sum_crops,Win_crops]) * dt
INIT CW_SurfW[Sum_crops,Win_crops] = ic_CW_SW_depth
INFLOWS:
CW_SW_in[Sum_crops,Win_crops] = Net_Rainfall/Conv - CW_UW_from_precip[Sum_crops,Win_crops] -
CW_SatW_from_precip[Sum_crops,Win_crops]
CW_SatW_to_SW[Sum_crops,Win_crops] = IF CW_SatW[Sum_crops,Win_crops]>CW_SatW_Max THEN
(CW_SatW[Sum_crops,Win_crops] - CW_SatW_Max)/DT ELSE 0
OUTFLOWS:
CW_SW_toSatW[Sum_crops,Win_crops] = IF (CW_UW_depth_before[Sum_crops,Win_crops]=0 AND
CW_Unsat_cap[Sum_crops,Win_crops]>0)
 THEN  MIN (CW_Unsat_cap[Sum_crops,Win_crops]/DT, CW_SurfW[Sum_crops,Win_crops]/DT)
ELSE 0
CW_SW_Evap[Sum_crops,Win_crops] = MIN (MAX (ETP/Conv,0), CW_SurfW[Sum_crops,Win_crops]/DT)
CW_SW_out[Sum_crops,Win_crops] = SW_out_Coef*CW_SurfW[Sum_crops,Win_crops]/DT
```

```
CW_UW[Sum_crops,Win_crops](t) = CW_UW[Sum_crops,Win_crops](t - dt) +
(CW_UW_from_precip[Sum_crops,Win_crops] + CW_SatW_to_UW[Sum_crops,Win_crops] -
CW_UW_eTransp[Sum_crops,Win_crops] - CW_UW_to_SatW[Sum_crops,Win_crops]) * dt
INIT CW_UW[Sum_crops,Win_crops] = ic_CW_UW
INFLOWS:
CW_UW_from_precip[Sum_crops,Win_crops] = IF inf_cond[Sum_crops,Win_crops]>0 THEN Infiltration ELSE 0
CW_SatW_to_UW[Sum_crops,Win_crops] = MAX( 0, MIN(-CW_UW_delta[Sum_crops,Win_crops]*CW_FC,
CW_SatW[Sum_crops,Win_crops]/DT))
OUTFLOWS:
CW_UW_eTransp[Sum_crops,Win_crops] =
CW_Transp[Sum_crops,Win_crops]*CW_UW_Trans_pr[Sum_crops,Win_crops]  +CW_Ebs[Sum_crops,Win_crops]
CW_UW_to_SatW[Sum_crops,Win_crops] = IF (inf_cond[Sum_crops,Win_crops]=0)  THEN
CW_UW[Sum_crops,Win_crops]/DT ELSE
MIN (CW_UW[Sum_crops,Win_crops]/DT, MAX(0,
CW_UW_delta[Sum_crops,Win_crops]*CW_UW_moist[Sum_crops,Win_crops]/DT +
CW_UW_perc_rate[Sum_crops,Win_crops]))
Avg_CW_GWL = ARRAYMEAN(CW_GWL[*,*])
Base = 716.5
Conv = 1000
CW_AvgMoist[Sum_crops,Win_crops] = IF CW_UW_depth[Sum_crops,Win_crops]=0 THEN CW_porosity ELSE
IF Root_Depth_Succ[Sum_crops,Win_crops]>=CW_UW_depth[Sum_crops,Win_crops] THEN
((CW_UW_depth[Sum_crops,Win_crops]*CW_UW_moist[Sum_crops,Win_crops]) +
CW_porosity*(Root_Depth_Succ[Sum_crops,Win_crops] -
CW_UW_depth[Sum_crops,Win_crops]))/Root_Depth_Succ[Sum_crops,Win_crops]
ELSE CW_UW_moist[Sum_crops,Win_crops]
CW_Ebs[Sum_crops,Win_crops] = MIN(1.15*CW_Kr[Sum_crops,Win_crops]*ETP/Conv,
CW_UW_moist[Sum_crops,Win_crops]*Top_soil_depth/DT)
CW_FC = 0.3
CW_ground_level = 720.6
CW_GWL[Sum_crops,Win_crops] = Base+CW_SatW[Sum_crops,Win_crops]/CW_porosity
CW_Hydr_Cond = 36
CW_Hydr_Grad[Sum_crops,Win_crops] = IF CW_GWL[Sum_crops,Win_crops]>River_Stage
THEN (CW_GWL[Sum_crops,Win_crops]-River_Stage)/Wetland_width
ELSE 0
CW_Kr[Sum_crops,Win_crops] = IF sum_crop_season[Sum_crops] = 1 OR win_crop_season[Win_crops] = 1 THEN 0
ELSE
IF CW_UW_moist[Sum_crops,Win_crops]>=CW_FC - CW_REW THEN 1 ELSE
IF CW_UW_moist[Sum_crops,Win_crops]>=CW_FC - CW_TEW
THEN (CW_UW_moist[Sum_crops,Win_crops] + CW_TEW- CW_FC)/(CW_TEW - CW_REW)
ELSE 0
CW_Ks[Sum_crops,Win_crops] = IF sum_crop_season[Sum_crops]=0 AND win_crop_season[Win_crops]=0 THEN 0
ELSE
IF CW_AvgMoist[Sum_crops,Win_crops]>= 0.9*CW_porosity
THEN (CW_porosity - CW_AvgMoist[Sum_crops,Win_crops])/(0.1*CW_porosity) ELSE
IF CW_AvgMoist[Sum_crops,Win_crops]>=CW_FC - (CW_FC-CW_WP)*p_Succ[Sum_crops,Win_crops] THEN 1 ELSE
IF CW_AvgMoist[Sum_crops,Win_crops]>=CW_WP
THEN (CW_AvgMoist[Sum_crops,Win_crops] - CW_WP)/((CW_FC -CW_WP)*(1 - p_Succ[Sum_crops,Win_crops]))
ELSE 0
CW_porosity = 0.53
CW_Pot_Inf = 3.66
CW_REW = 0.01
CW_SatW_Max = (CW_ground_level - Base)*CW_porosity
CW_Seep_Succ[Sum_crops,Win_crops] =
CW_Seepage_to_river[Sum_crops,Win_crops]*Wet_Crop_Proportion[Sum_crops,Win_crops]
CW_TEW = (CW_FC-0.5*CW_WP)
CW_Tot_Seepage = ARRAYSUM(CW_Seep_Succ[*,*])*(1-pct_nat_wet)*Wetland_length*(Avg_CW_GWL - Base)
CW_Transp[Sum_crops,Win_crops] = IF
Root_Depth_Succ[Sum_crops,Win_crops]>CW_UW_depth[Sum_crops,Win_crops]
THEN ETm[Sum_crops,Win_crops]*CW_Wat_avail[Sum_crops,Win_crops] ELSE
Min(ETm[Sum_crops,Win_crops]*CW_Wat_avail[Sum_crops,Win_crops],
CW_UW_moist[Sum_crops,Win_crops]*Root_Depth_Succ[Sum_crops,Win_crops]/DT)
CW_Unsat_cap[Sum_crops,Win_crops] = MAX (CW_UW_depth[Sum_crops,Win_crops]*(CW_porosity -
CW_UW_moist[Sum_crops,Win_crops]), 0 )
```

CW_UW_Capil_exp[Sum_crops,Win_crops] = EXP(-10*MAX(CW_UW_depth[Sum_crops,Win_crops]-
Root_Depth_Succ[Sum_crops,Win_crops], 0))
CW_UW_delta[Sum_crops,Win_crops] = CW_UW_depth[Sum_crops,Win_crops] -
CW_UW_depth_before[Sum_crops,Win_crops]
CW_UW_depth[Sum_crops,Win_crops] = MAX (CW_ground_level - CW_GWL[Sum_crops,Win_crops], 0)
CW_UW_depth_before[Sum_crops,Win_crops] = DELAY(CW_UW_depth[Sum_crops,Win_crops], DT)
CW_UW_excess[Sum_crops,Win_crops] = MAX(0, CW_UW_moist[Sum_crops,Win_crops]-CW_FC)
CW_UW_moist[Sum_crops,Win_crops] = IF (CW_UW_depth[Sum_crops,Win_crops]>0) THEN
CW_UW[Sum_crops,Win_crops]/CW_UW_depth[Sum_crops,Win_crops] ELSE 0
CW_UW_perc_rate[Sum_crops,Win_crops] =
2*CW_vert_Hydr_Cond*CW_porosity*(CW_UW_excess[Sum_crops,Win_crops]^0.4)/((CW_porosity-CW_FC)^0.4 +
(CW_UW_excess[Sum_crops,Win_crops]^0.4))
CW_UW_Trans_pr[Sum_crops,Win_crops] = IF Root_Depth_Succ[Sum_crops,Win_crops]=0 THEN 0 ELSE
IF Root_Depth_Succ[Sum_crops,Win_crops]+0.2<CW_UW_depth[Sum_crops,Win_crops] THEN 1 ELSE
IF CW_UW_depth[Sum_crops,Win_crops]>0 THEN
CW_Wat_avail[Sum_crops,Win_crops]*CW_UW_depth[Sum_crops,Win_crops]/(Root_Depth_Succ[Sum_crops,Win_crops]
)
ELSE 0
CW_vert_Hydr_Cond = 0.06*30
CW_Wat_avail[Sum_crops,Win_crops] = MIN(1.0,
CW_UW_Capil_exp[Sum_crops,Win_crops]+CW_Ks[Sum_crops,Win_crops])
CW_WP = 0.14
ic_CW_SatW = (ic_CW_Wat_Table-Base)*CW_porosity
ic_CW_SW_depth = 0
ic_CW_UW = IF CW_ground_level>ic_CW_Wat_Table THEN (CW_ground_level-ic_CW_Wat_Table)*ic_CW_UW_moist
ELSE 0
ic_CW_UW_moist = 0.3
ic_CW_Wat_Table = 718.3
Infiltration = MIN(CW_Pot_Inf,Net_Rainfall/Conv)
inf_cond[Sum_crops,Win_crops] = IF CW_SW_toSatW[Sum_crops,Win_crops]*DT =
CW_Unsat_cap[Sum_crops,Win_crops] THEN 0
ELSE MAX (CW_Unsat_cap[Sum_crops,Win_crops] - Infiltration*DT,0)
IS_Abstract = (Pal_canal_eff*Diverted_canal_water) + Tot_Pumped_Water
m2_in_ha = 10000
Net_Rainfall = Rainfall_valley*(1-Runoff_coef)
Rainfall_contrib = (Rainfall_valley*River_area/Conv)
River_area = 4000*4
River_Stage = 8E-5*River_inflow^3-0.0095*River_inflow^2+0.170*River_inflow+717
River_water_balance = Wet_Contrib + Rainfall_contrib - IS_Abstract
SW_out_Coef = 0
s_in_month = 3600*24*30
Top_soil_depth = 0.1
Up_Catch_Coef = 0.175
Wetland_length = 5000
Wetland_width = 400
Wet_Contrib = (CW_Tot_Seepage+NW_Tot_Seepage)
ETP = GRAPH(TIME)
(1.00, 176), (2.00, 183), (3.00, 220), (4.00, 193), (5.00, 174), (6.00, 183), (7.00, 147), (8.00, 95.0), (9.00, 141), (10.0, 156), (11.0, 184), (12.0, 217), (13.0, 223), (14.0, 201), (15.0, 139), (16.0, 154), (17.0, 144), (18.0, 128), (19.0, 89.5), (20.0, 99.2), (21.0, 116), (22.0, 98.2), (23.0, 142), (24.0, 177), (25.0, 185), (26.0, 169), (27.0, 169), (28.0, 163), (29.0, 115), (30.0, 120), (31.0, 104), (32.0, 112), (33.0, 158), (34.0, 103), (35.0, 149), (36.0, 90.3), (37.0, 181), (38.0, 173), (39.0, 158), (40.0, 174), (41.0, 148), (42.0, 143), (43.0, 117), (44.0, 117), (45.0, 23.5), (46.0, 41.8), (47.0, 52.0), (48.0, 137), (49.0, 125), (50.0, 134), (51.0, 124), (52.0, 166), (53.0, 138), (54.0, 136), (55.0, 113), (56.0, 106), (57.0, 107), (58.0, 96.0), (59.0, 126), (60.0, 150), (61.0, 166), (62.0, 146), (63.0, 166), (64.0, 144), (65.0, 108), (66.0, 135), (67.0, 98.3), (68.0, 98.5), (69.0, 94.8), (70.0, 106), (71.0, 116), (72.0, 140), (73.0, 152), (74.0, 148), (75.0, 141), (76.0, 159), (77.0, 98.7), (78.0, 128), (79.0, 108), (80.0, 107), (81.0, 96.0), (82.0, 113), (83.0, 112), (84.0, 178), (85.0, 159), (86.0, 109), (87.0, 123), (88.0, 161), (89.0, 110), (90.0, 154), (91.0, 122), (92.0, 130), (93.0, 107), (94.0, 137), (95.0, 124), (96.0, 181), (97.0, 187), (98.0, 184), (99.0, 165), (100, 162), (101, 162), (102, 166), (103, 129), (104, 129), (105, 84.8), (106, 140), (107, 179), (108, 186), (109, 182), (110, 188), (111, 166), (112, 206), (113, 156), (114, 109), (115, 120), (116, 119), (117, 102), (118, 140), (119, 154), (120, 174), (121, 202), (122, 173), (123, 158), (124, 188), (125, 181), (126, 160), (127, 110), (128, 125), (129, 114), (130, 136), (131, 135), (132, 208), (133, 217), (134, 180), (135, 151), (136, 156), (137, 154), (138, 98.5), (139, 86.6), (140, 27.0), (141, 120), (142, 131), (143, 178), (144, 202), (145, 194), (146, 228), (147, 161), (148, 196), (149, 206), (150, 192), (151, 131), (152, 148), (153, 73.6), (154, 124), (155, 163), (156, 212)

Rainfall_valley = GRAPH(TIME)
(1.00, 69.5), (2.00, 41.2), (3.00, 87.1), (4.00, 79.0), (5.00, 70.8), (6.00, 66.4), (7.00, 43.1), (8.00, 4.90), (9.00, 0.2), (10.0, 0.2), (11.0, 0.8), (12.0, 6.70), (13.0, 29.6), (14.0, 122), (15.0, 134), (16.0, 151), (17.0, 429), (18.0, 40.9), (19.0, 48.9), (20.0, 51.2), (21.0, 9.40), (22.0, 33.1), (23.0, 7.80), (24.0, 4.80), (25.0, 80.5), (26.0, 70.2), (27.0, 141), (28.0, 230), (29.0, 54.6), (30.0, 274), (31.0, 34.1), (32.0, 19.2), (33.0, 0.2), (34.0, 5.30), (35.0, 0.7), (36.0, 42.8), (37.0, 62.6), (38.0, 70.6), (39.0, 35.6), (40.0, 131), (41.0, 11.6), (42.0, 18.5), (43.0, 40.2), (44.0, 0.2), (45.0, 0.2), (46.0, 10.5), (47.0, 0.2), (48.0, 11.6), (49.0, 69.6), (50.0, 80.5), (51.0, 162), (52.0, 137), (53.0, 66.7), (54.0, 84.0), (55.0, 18.6), (56.0, 15.3), (57.0, 6.30), (58.0, 22.4), (59.0, 2.10), (60.0, 1.80), (61.0, 33.9), (62.0, 204), (63.0, 142), (64.0, 159), (65.0, 571), (66.0, 130), (67.0, 84.1), (68.0, 13.4), (69.0, 52.0), (70.0, 12.9), (71.0, 0.2), (72.0, 13.3), (73.0, 51.8), (74.0, 88.0), (75.0, 181), (76.0, 5.30), (77.0, 211), (78.0, 81.2), (79.0, 22.9), (80.0, 16.0), (81.0, 1.20), (82.0, 9.20), (83.0, 0.2), (84.0, 2.60), (85.0, 57.4), (86.0, 206), (87.0, 68.3), (88.0, 157), (89.0, 17.0), (90.0, 21.1), (91.0, 37.1), (92.0, 21.4), (93.0, 6.30), (94.0, 3.00), (95.0, 12.2), (96.0, 12.2), (97.0, 25.9), (98.0, 4.70), (99.0, 51.3), (100, 74.8), (101, 44.4), (102, 27.1), (103, 0.2), (104, 0.2), (105, 45.0), (106, 0.2), (107, 0.2), (108, 7.40), (109, 31.2), (110, 113), (111, 62.2), (112, 63.5), (113, 89.4), (114, 189), (115, 41.5), (116, 0.2), (117, 6.80), (118, 2.50), (119, 1.90), (120, 5.90), (121, 27.7), (122, 103), (123, 80.5), (124, 54.9), (125, 23.0), (126, 50.4), (127, 32.9), (128, 10.2), (129, 9.80), (130, 9.80), (131, 10.4), (132, 9.80), (133, 12.4), (134, 58.0), (135, 74.9), (136, 173), (137, 207), (138, 152), (139, 13.6), (140, 9.80), (141, 9.80), (142, 10.9), (143, 15.0), (144, 10.3), (145, 16.1), (146, 101), (147, 139), (148, 49.8), (149, 53.9), (150, 37.3), (151, 44.9), (152, 9.80), (153, 10.1), (154, 25.3), (155, 12.4), (156, 56.5)
River_inflow = GRAPH(TIME)
(1.00, 0.164), (2.00, 0.143), (3.00, 0.148), (4.00, 0.265), (5.00, 0.295), (6.00, 0.482), (7.00, 0.631), (8.00, 0.526), (9.00, 0.418), (10.0, 0.335), (11.0, 0.263), (12.0, 0.213), (13.0, 0.167), (14.0, 0.933), (15.0, 1.72), (16.0, 3.12), (17.0, 8.33), (18.0, 1.44), (19.0, 0.00), (20.0, 1.29), (21.0, 1.53), (22.0, 1.28), (23.0, 1.22), (24.0, 0.777), (25.0, 0.75), (26.0, 1.05), (27.0, 1.84), (28.0, 4.00), (29.0, 3.85), (30.0, 0.485), (31.0, 0.183), (32.0, 0.071), (33.0, 0.00), (34.0, 0.034), (35.0, 0.001), (36.0, 0.2), (37.0, 0.48), (38.0, 0.526), (39.0, 0.268), (40.0, 0.934), (41.0, 0.354), (42.0, 0.825), (43.0, 0.437), (44.0, 0.00), (45.0, 0.00), (46.0, 0.035), (47.0, 0.00), (48.0, 0.333), (49.0, 0.604), (50.0, 1.18), (51.0, 2.25), (52.0, 3.64), (53.0, 1.33), (54.0, 2.32), (55.0, 0.526), (56.0, 0.18), (57.0, 0.00), (58.0, 0.372), (59.0, 0.616), (60.0, 0.504), (61.0, 0.448), (62.0, 0.676), (63.0, 1.83), (64.0, 4.26), (65.0, 9.67), (66.0, 11.8), (67.0, 7.54), (68.0, 3.81), (69.0, 2.94), (70.0, 2.34), (71.0, 1.80), (72.0, 1.43), (73.0, 1.27), (74.0, 1.38), (75.0, 2.00), (76.0, 1.69), (77.0, 2.82), (78.0, 5.04), (79.0, 2.18), (80.0, 1.64), (81.0, 1.23), (82.0, 1.11), (83.0, 0.96), (84.0, 0.81), (85.0, 0.788), (86.0, 2.89), (87.0, 3.81), (88.0, 2.18), (89.0, 2.27), (90.0, 1.39), (91.0, 1.02), (92.0, 0.963), (93.0, 0.84), (94.0, 0.784), (95.0, 0.736), (96.0, 0.65), (97.0, 0.62), (98.0, 0.534), (99.0, 0.53), (100, 0.638), (101, 0.534), (102, 0.534), (103, 0.455), (104, 0.437), (105, 0.426), (106, 0.433), (107, 0.388), (108, 0.346), (109, 0.357), (110, 0.33), (111, 0.358), (112, 0.407), (113, 0.881), (114, 2.92), (115, 1.87), (116, 0.818), (117, 0.687), (118, 0.676), (119, 0.612), (120, 0.594), (121, 0.65), (122, 0.549), (123, 0.489), (124, 0.429), (125, 0.139), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.189), (131, 0.301), (132, 0.27), (133, 0.244), (134, 0.27), (135, 0.332), (136, 3.13), (137, 3.92), (138, 4.37), (139, 2.29), (140, 1.12), (141, 0.724), (142, 0.624), (143, 0.519), (144, 0.459), (145, 0.399), (146, 0.948), (147, 1.69), (148, 1.25), (149, 0.489), (150, 0.418), (151, 0.534), (152, 0.556), (153, 0.448), (154, 0.448), (155, 0.381), (156, 0.381)
Runoff_coef = GRAPH(annual_cycle)
(1.00, 0.00), (2.00, 0.00), (3.00, 0.2), (4.00, 0.2), (5.00, 0.2), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)
Upper_catch_rainfall = GRAPH(TIME)
(1.00, 55.0), (2.00, 42.2), (3.00, 125), (4.00, 188), (5.00, 69.4), (6.00, 144), (7.00, 61.2), (8.00, 20.0), (9.00, 0.00), (10.0, 0.00), (11.0, 2.00), (12.0, 7.00), (13.0, 45.0), (14.0, 246), (15.0, 192), (16.0, 339), (17.0, 586), (18.0, 91.0), (19.0, 49.0), (20.0, 118), (21.0, 7.00), (22.0, 35.0), (23.0, 17.0), (24.0, 11.0), (25.0, 105), (26.0, 178), (27.0, 90.0), (28.0, 201), (29.0, 145), (30.0, 215), (31.0, 39.0), (32.0, 15.0), (33.0, 0.00), (34.0, 7.00), (35.0, 0.2), (36.0, 41.2), (37.0, 94.8), (38.0, 98.2), (39.0, 48.1), (40.0, 158), (41.0, 56.8), (42.0, 126), (43.0, 63.7), (44.0, 0.00), (45.0, 0.00), (46.0, 5.00), (47.0, 0.00), (48.0, 47.2), (49.0, 83.0), (50.0, 153), (51.0, 267), (52.0, 377), (53.0, 125), (54.0, 205), (55.0, 44.4), (56.0, 15.0), (57.0, 0.00), (58.0, 5.00), (59.0, 9.40), (60.0, 2.00), (61.0, 45.9), (62.0, 149), (63.0, 215), (64.0, 196), (65.0, 972), (66.0, 458), (67.0, 113), (68.0, 10.0), (69.0, 60.0), (70.0, 2.00), (71.0, 4.00), (72.0, 11.0), (73.0, 57.0), (74.0, 110), (75.0, 287), (76.0, 40.0), (77.0, 284), (78.0, 60.0), (79.0, 61.0), (80.0, 14.0), (81.0, 2.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.00), (85.0, 62.0), (86.0, 280), (87.0, 148), (88.0, 127), (89.0, 40.0), (90.0, 17.0), (91.0, 42.0), (92.0, 7.30), (93.0, 6.30), (94.0, 6.00), (95.0, 6.30), (96.0, 16.3), (97.0, 35.4), (98.0, 16.7), (99.0, 45.3), (100, 117), (101, 60.8), (102, 43.7), (103, 6.70), (104, 0.00), (105, 30.6), (106, 0.00), (107, 0.00), (108, 10.0), (109, 38.7), (110, 68.7), (111, 56.0), (112, 37.0), (113, 324), (114, 241), (115, 130), (116, 0.00), (117, 2.80), (118, 5.30), (119, 0.00), (120, 14.3), (121, 26.9), (122, 0.00), (123, 64.0), (124, 102), (125, 103), (126, 17.0), (127, 57.4), (128, 21.7), (129, 0.00), (130, 0.00), (131, 1.10), (132, 0.00), (133, 4.60), (134, 85.8), (135, 116), (136, 290), (137, 350), (138, 253), (139, 6.80), (140, 0.00), (141, 0.00), (142, 2.00), (143, 9.20), (144, 1.00), (145, 11.2), (146, 161), (147, 230), (148, 71.0), (149, 78.4), (150, 48.8), (151, 62.4), (152, 0.00), (153, 0.6), (154, 27.6), (155, 4.60), (156, 83.0)

Economic valuation
Annual_Cash_Basic_Needs(t) = Annual_Cash_Basic_Needs(t - dt) + (store_ACBN - empty_ACBN) * dt
INIT Annual_Cash_Basic_Needs = 0
INFLOWS:
store_ACBN = Cash_basic_needs
OUTFLOWS:
empty_ACBN = IF annual_cycle=12 THEN Annual_Cash_Basic_Needs/DT ELSE 0

```
Annual_Cult_Wet_Value(t) = Annual_Cult_Wet_Value(t - dt) + (store_CWV - empty_CWV) * dt
INIT Annual_Cult_Wet_Value = 0
INFLOWS:
store_CWV = ARRAYSUM(Wet_Win_Crop_Net_Value[*]) + ARRAYSUM(Wet_Sum_Crop_Net_Value[*])
OUTFLOWS:
empty_CWV = IF annual_cycle=12 THEN Annual_Cult_Wet_Value/DT ELSE 0
Annual_Cul_Wet_Income(t) = Annual_Cul_Wet_Income(t - dt) + (store_CWI - empty_CWI) * dt
INIT Annual_Cul_Wet_Income = 0
INFLOWS:
store_CWI = Tot_Wet__Crop_Sales - Tot_Wet_Costs
OUTFLOWS:
empty_CWI = IF annual_cycle=12 THEN Annual_Cul_Wet_Income/DT ELSE 0
Annual_Nat_Wet_Income(t) = Annual_Nat_Wet_Income(t - dt) + (store_NWI - empty_NWI) * dt
INIT Annual_Nat_Wet_Income = 0
INFLOWS:
store_NWI = nat_res_income
OUTFLOWS:
empty_NWI = IF (annual_cycle=12) THEN Annual_Nat_Wet_Income/DT ELSE 0
Annual_Nat_Wet_Value(t) = Annual_Nat_Wet_Value(t - dt) + (store_NWV - empty_NWV) * dt
INIT Annual_Nat_Wet_Value = 0
INFLOWS:
store_NWV = nat_res_value
OUTFLOWS:
empty_NWV = IF (annual_cycle=12) THEN Annual_Nat_Wet_Value/DT ELSE 0
Annual_NR_Cash_Income(t) = Annual_NR_Cash_Income(t - dt) + (store_ANRCI - empty_ANRCI) * dt
INIT Annual_NR_Cash_Income = 0
INFLOWS:
store_ANRCI = Tot_Crop_Sales-Tot_Crop_Costs+nat_res_income
OUTFLOWS:
empty_ANRCI = IF annual_cycle=12 THEN Annual_NR_Cash_Income/DT ELSE 0
Annual_Total_Income(t) = Annual_Total_Income(t - dt) + (store_total_income - empty_total_income) * dt
INIT Annual_Total_Income = 0
INFLOWS:
store_total_income = store_ANRCI + Offfarm_income + Social_transfer
OUTFLOWS:
empty_total_income = IF annual_cycle=12 THEN Annual_Total_Income/DT ELSE 0
Annual_Income_per_hh = empty_total_income/Household_number
Cash_basic_needs = Basic_exp + Food_purch*Sum_Crop_Output_Prices[Maize]*Price_coef
Cash_sufficiency = IF empty_ANRCI=0 THEN 0 ELSE empty_ACBN/empty_ANRCI
Cult_Wet_Productivity = empty_CWV/wetland_cultivated_area
Nat_Wet_Productivity = IF wetland_natural_area=0 THEN 0 ELSE empty_NWV/wetland_natural_area
```

Irrigation Hydrology

```
IS_SatW[Sum_crops,Win_crops](t) = IS_SatW[Sum_crops,Win_crops](t - dt) + (IS_UW_to_SatW[Sum_crops,Win_crops] +
IS_SW_toSatW[Sum_crops,Win_crops] + IS_SatW_from_precip[Sum_crops,Win_crops] +
IS_GW_inflow[Sum_crops,Win_crops] - IS_SatW_to_SW[Sum_crops,Win_crops] -
IS_SatW_to_UW[Sum_crops,Win_crops] - IS_SatW_Transp[Sum_crops,Win_crops] -
IS_SatW_to_NW[Sum_crops,Win_crops] - IS_SatW_to_CW[Sum_crops,Win_crops]) * dt
INIT IS_SatW[Sum_crops,Win_crops] = ic_IS_SatW
INFLOWS:
IS_UW_to_SatW[Sum_crops,Win_crops] = IF (IS_inf_cond[Sum_crops,Win_crops]=0)  THEN
IS_UW[Sum_crops,Win_crops]/DT ELSE
MIN (IS_UW[Sum_crops,Win_crops]/DT, MAX(0,
IS_UW_delta[Sum_crops,Win_crops]*IS_UW_moist[Sum_crops,Win_crops]/DT +
IS_UW_perc_rate[Sum_crops,Win_crops]))
IS_SW_toSatW[Sum_crops,Win_crops] = IF (IS_UW_depth_before[Sum_crops,Win_crops]=0 AND
IS_Unsat_cap[Sum_crops,Win_crops]>0)
 THEN  MIN (IS_Unsat_cap[Sum_crops,Win_crops]/DT, IS_SurfW[Sum_crops,Win_crops]/DT)
ELSE 0
IS_SatW_from_precip[Sum_crops,Win_crops] = IF IS_inf_cond[Sum_crops,Win_crops]=0
THEN IS_Unsat_cap[Sum_crops,Win_crops]/DT - IS_SW_toSatW[Sum_crops,Win_crops]
ELSE 0
IS_GW_inflow[Sum_crops,Win_crops] = Upper_catch_rainfall*Up_Catch_Coef/Conv + IS_leakages
```

```
OUTFLOWS:
IS_SatW_to_SW[Sum_crops,Win_crops] = IF IS_SatW[Sum_crops,Win_crops]>IS_SatW_Max THEN
(IS_SatW[Sum_crops,Win_crops] - IS_SatW_Max)/DT ELSE 0
IS_SatW_to_UW[Sum_crops,Win_crops] = MAX( 0, MIN(-IS_UW_delta[Sum_crops,Win_crops]*IS_FC,
IS_SatW[Sum_crops,Win_crops]/DT))
IS_SatW_Transp[Sum_crops,Win_crops] = IS_Transp[Sum_crops,Win_crops]*(1-
IS_UW_Trans_pr[Sum_crops,Win_crops])
IS_SatW_to_NW[Sum_crops,Win_crops] = IS_NW_HydrGrad*IS_Hydr_Cond
IS_SatW_to_CW[Sum_crops,Win_crops] = IS_CW_HydrGrad*IS_Hydr_Cond
IS_SurfW[Sum_crops,Win_crops](t) = IS_SurfW[Sum_crops,Win_crops](t - dt) + (IS_SW_in[Sum_crops,Win_crops] +
IS_SatW_to_SW[Sum_crops,Win_crops] - IS_SW_toSatW[Sum_crops,Win_crops] - IS_SW_Evap[Sum_crops,Win_crops] -
IS_SW_out[Sum_crops,Win_crops]) * dt
INIT IS_SurfW[Sum_crops,Win_crops] = ic_IS_SW_depth
INFLOWS:
IS_SW_in[Sum_crops,Win_crops] = Net_Rainfall/Conv - IS_from_precip[Sum_crops,Win_crops] -
IS_SatW_from_precip[Sum_crops,Win_crops] +
plot_irrig[Sum_crops,Win_crops]
IS_SatW_to_SW[Sum_crops,Win_crops] = IF IS_SatW[Sum_crops,Win_crops]>IS_SatW_Max THEN
(IS_SatW[Sum_crops,Win_crops] - IS_SatW_Max)/DT ELSE 0
OUTFLOWS:
IS_SW_toSatW[Sum_crops,Win_crops] = IF (IS_UW_depth_before[Sum_crops,Win_crops]=0 AND
IS_Unsat_cap[Sum_crops,Win_crops]>0)
 THEN  MIN (IS_Unsat_cap[Sum_crops,Win_crops]/DT, IS_SurfW[Sum_crops,Win_crops]/DT)
ELSE 0
IS_SW_Evap[Sum_crops,Win_crops] = MIN (MAX (ETP/Conv,0), IS_SurfW[Sum_crops,Win_crops]/DT)
IS_SW_out[Sum_crops,Win_crops] = IS_out_Coef*IS_SurfW[Sum_crops,Win_crops]/DT
IS_UW[Sum_crops,Win_crops](t) = IS_UW[Sum_crops,Win_crops](t - dt) + (IS_from_precip[Sum_crops,Win_crops] +
IS_SatW_to_UW[Sum_crops,Win_crops] - IS_UW_eTransp[Sum_crops,Win_crops] -
IS_UW_to_SatW[Sum_crops,Win_crops]) * dt
INIT IS_UW[Sum_crops,Win_crops] = ic_IS_UW
INFLOWS:
IS_from_precip[Sum_crops,Win_crops] = IF IS_inf_cond[Sum_crops,Win_crops]>0 THEN IS_Infilt ELSE 0
IS_SatW_to_UW[Sum_crops,Win_crops] = MAX( 0, MIN(-IS_UW_delta[Sum_crops,Win_crops]*IS_FC,
IS_SatW[Sum_crops,Win_crops]/DT))
OUTFLOWS:
IS_UW_eTransp[Sum_crops,Win_crops] = IS_Transp[Sum_crops,Win_crops]*IS_UW_Trans_pr[Sum_crops,Win_crops]
+IS_Ebs[Sum_crops,Win_crops]
IS_UW_to_SatW[Sum_crops,Win_crops] = IF (IS_inf_cond[Sum_crops,Win_crops]=0)  THEN
IS_UW[Sum_crops,Win_crops]/DT ELSE
MIN (IS_UW[Sum_crops,Win_crops]/DT, MAX(0,
IS_UW_delta[Sum_crops,Win_crops]*IS_UW_moist[Sum_crops,Win_crops]/DT +
IS_UW_perc_rate[Sum_crops,Win_crops]))
Avg_IS_GWL = ARRAYMEAN(IS_GWL[*,*])
ic_IS_SatW = (ic_IS_Wat_Table-IS_Base)*IS_porosity
ic_IS_SW_depth = 0
ic_IS_UW = IF IS_ground_level>ic_IS_Wat_Table THEN  (IS_ground_level-ic_IS_Wat_Table)*ic__IS_UW_moist ELSE 0
ic_IS_Wat_Table = 721.7
ic__IS_UW_moist = 0.2
IS_AvgMoist[Sum_crops,Win_crops] = IF IS_UW_depth[Sum_crops,Win_crops]=0 THEN IS_porosity ELSE
IF Root_Depth_Succ[Sum_crops,Win_crops]>=IS_UW_depth[Sum_crops,Win_crops]
THEN ((IS_UW_depth[Sum_crops,Win_crops]*IS_UW_moist[Sum_crops,Win_crops])
+IS_porosity*(Root_Depth_Succ[Sum_crops,Win_crops] -
IS_UW_depth[Sum_crops,Win_crops]))/Root_Depth_Succ[Sum_crops,Win_crops]
ELSE IS_UW_moist[Sum_crops,Win_crops]
IS_Base = 716.5
IS_CW_HydrGrad = IF Avg_IS_GWL>Avg_CW_GWL THEN (Avg_IS_GWL - Avg_CW_GWL)/IS_width ELSE 0
IS_Ebs[Sum_crops,Win_crops] = MIN(1.15*IS_Kr[Sum_crops,Win_crops]*ETP/Conv,
IS_UW_moist[Sum_crops,Win_crops]*Top_soil_depth/DT)
IS_FC = 0.265
IS_ground_level = 724
IS_GWL[Sum_crops,Win_crops] = IS_Base+IS_SatW[Sum_crops,Win_crops]/IS_porosity
IS_Hydr_Cond = 11.55
IS_Infilt = MIN(IS_Pot_Inf,Net_Rainfall/Conv)
```

```
IS_inf_cond[Sum_crops,Win_crops] = IF IS_SW_toSatW[Sum_crops,Win_crops]*DT =
IS_Unsat_cap[Sum_crops,Win_crops] THEN 0
ELSE MAX (IS_Unsat_cap[Sum_crops,Win_crops] - IS_Infilt*DT,0 )
IS_Kr[Sum_crops,Win_crops] = IF sum_crop_season[Sum_crops] = 1 OR win_crop_season[Win_crops] = 1 THEN 0 ELSE
IF IS_UW_moist[Sum_crops,Win_crops]>=IS_FC - IS_REW THEN 1 ELSE
IF IS_UW_moist[Sum_crops,Win_crops]>=IS_FC - IS_TEW
THEN (IS_UW_moist[Sum_crops,Win_crops] + IS_TEW- IS_FC)/(IS_TEW - IS_REW)
ELSE 0
IS_Ks[Sum_crops,Win_crops] = IF sum_crop_season[Sum_crops]=0 AND win_crop_season[Win_crops]=0 THEN 0 ELSE
IF IS_AvgMoist[Sum_crops,Win_crops]>= 0.9*IS_porosity
THEN (IS_porosity - IS_AvgMoist[Sum_crops,Win_crops])/(0.1*IS_porosity) ELSE
IF IS_AvgMoist[Sum_crops,Win_crops]>=IS_FC - (IS_FC-IS_WP)*p_Succ[Sum_crops,Win_crops] THEN 1 ELSE
IF IS_AvgMoist[Sum_crops,Win_crops]>=IS_WP
THEN (IS_AvgMoist[Sum_crops,Win_crops] - IS_WP)/((IS_FC -IS_WP)*(1 - p_Succ[Sum_crops,Win_crops]))
ELSE 0
IS_NW_HydrGrad = IF Avg_IS_GWL>NW_GWL THEN (Avg_IS_GWL - NW_GWL)/IS_width ELSE 0
IS_out_Coef = 0
IS_porosity = 0.446
IS_Pot_Inf = 3.66
IS_REW = 10
IS_SatW_Max = (IS_ground_level - IS_Base)*IS_porosity
IS_TEW = (IS_FC-0.5*IS_WP)
IS_to_CW_succ[Sum_crops,Win_crops] =
IS_SatW_to_CW[Sum_crops,Win_crops]*Irrig_Crop_proportion[Sum_crops,Win_crops]
IS_to_NW_succ[Sum_crops,Win_crops] =
IS_SatW_to_NW[Sum_crops,Win_crops]*Irrig_Crop_proportion[Sum_crops,Win_crops]
IS_Transp[Sum_crops,Win_crops] = IF Root_Depth_Succ[Sum_crops,Win_crops]>IS_UW_depth[Sum_crops,Win_crops]
THEN ETm[Sum_crops,Win_crops]*IS_Wat_avail[Sum_crops,Win_crops] ELSE
Min(ETm[Sum_crops,Win_crops]*IS_Wat_avail[Sum_crops,Win_crops],
IS_UW_moist[Sum_crops,Win_crops]*Root_Depth_Succ[Sum_crops,Win_crops]/DT)
IS_Unsat_cap[Sum_crops,Win_crops] = MAX (IS_UW_depth[Sum_crops,Win_crops]*(IS_porosity -
IS_UW_moist[Sum_crops,Win_crops]), 0 )
IS_UW_Capil_exp[Sum_crops,Win_crops] = EXP(-10*MAX(IS_UW_depth[Sum_crops,Win_crops]-
Root_Depth_Succ[Sum_crops,Win_crops], 0))
IS_UW_delta[Sum_crops,Win_crops] = IS_UW_depth[Sum_crops,Win_crops] -
IS_UW_depth_before[Sum_crops,Win_crops]
IS_UW_depth[Sum_crops,Win_crops] = MAX (IS_ground_level - IS_GWL[Sum_crops,Win_crops], 0)
IS_UW_depth_before[Sum_crops,Win_crops] = DELAY(IS_UW_depth[Sum_crops,Win_crops], DT)
IS_UW_excess[Sum_crops,Win_crops] = MAX(0, IS_UW_moist[Sum_crops,Win_crops]-IS_FC)
IS_UW_moist[Sum_crops,Win_crops] = IF (IS_UW_depth[Sum_crops,Win_crops]>0)  THEN
IS_UW[Sum_crops,Win_crops]/IS_UW_depth[Sum_crops,Win_crops]   ELSE   0
IS_UW_perc_rate[Sum_crops,Win_crops] =
2*IS_vert_Hydr_Cond*IS_porosity*(IS_UW_excess[Sum_crops,Win_crops]^0.4)/((IS_porosity-IS_FC)^0.4 +
(IS_UW_excess[Sum_crops,Win_crops]^0.4))
IS_UW_Trans_pr[Sum_crops,Win_crops] = IF Root_Depth_Succ[Sum_crops,Win_crops]=0 THEN 0 ELSE
IF Root_Depth_Succ[Sum_crops,Win_crops]+0.2<IS_UW_depth[Sum_crops,Win_crops] THEN 1 ELSE
IF IS_UW_depth[Sum_crops,Win_crops]>0 THEN
IS_Wat_avail[Sum_crops,Win_crops]*IS_UW_depth[Sum_crops,Win_crops]/(Root_Depth_Succ[Sum_crops,Win_crops])
ELSE 0
IS_vert_Hydr_Cond = 0.06*30
IS_Wat_avail[Sum_crops,Win_crops] = MIN(1.0, IS_UW_Capil_exp[Sum_crops,Win_crops]+IS_Ks[Sum_crops,Win_crops])
IS_width = 200
IS_WP = 0.123
Tot_IS_to_CW = ARRAYSUM(IS_to_CW_succ[*,*])
Tot_IS_to_NW = ARRAYSUM(IS_to_NW_succ[*,*])
```

Irrigation management

```
Canal_open_sum[Maize] = 1
Canal_open_sum[Groundnut] = 1
Canal_open_sum[eMaize] = 1
Canal_open_sum[SwPot] = 1
Canal_open_sum[FallSum] = 0
Canal_open_sum[TomSum] = 1
Canal_open_win[Onion] = 1
```

Canal_open_win[Tomato] = 1
Canal_open_win[No_crop] = 0
Canal_open_win[Cabb] = 1
Canal_open_win[Bean] = 1
Canal_water = IF IS_system=1 THEN 0 ELSE
Diverted_canal_water*Irrig_distrib_eff*Pal_canal_eff*Irr_op_time/(Fertilis_area*m2_in_ha)
Drip_eff = 0.85
Drip_Water_sum[Sum_crops] = IF IS_system=0 THEN 0 ELSE MIN(Store_ETm_Sum[Sum_crops] - Rainfall_valley/Conv, MaxPump)
Drip_Water_win[Win_crops] = IF IS_system=0 THEN 0 ELSE MIN(Store_ETm_Win[Win_crops] - Rainfall_valley/Conv,MaxPump)
Fertilis_area = 88
irrigable_crop_area = 171
Irrig_distrib_eff = 0.7*0.7*0.6
Irr_op_time = IF annual_cycle>=8 AND annual_cycle<=12 THEN (8/24)*(6/7) ELSE (12/24)*(6/7)
IS_leakages = (1-Irrig_distrib_eff)*Pal_canal_eff*Diverted_canal_water/(Fertilis_area *m2_in_ha) + Tot_Pumped_Water*(1 - Drip_eff)/(irrigable_crop_area*m2_in_ha)
IS_system = 0
MaxPump = 0.85*109*4*20*30/(10000*88)
Pal_canal_eff = 0.5
Pct_Irrigated_area_Sum = 1 - ARRAYSUM(Irrig_Crop_proportion[FallSum,*])
Pct_Irrigated_area_Win = 1 - ARRAYSUM(Irrig_Crop_proportion[*,No_crop])
plot_irrig[Sum_crops,Win_crops] = IF (annual_cycle>=planting_date_sum[Sum_crops] - 1 AND annual_cycle <harvest_date_sum[Sum_crops])
THEN Canal_water*Canal_open_sum[Sum_crops] + Drip_Water_sum[Sum_crops] ELSE
IF (annual_cycle>=planting_date_win[Win_crops] - 1 AND annual_cycle<harvest_date_win[Win_crops])
THEN Canal_water*Canal_open_win[Win_crops] + Drip_Water_win[Win_crops]
ELSE 0
Pumped_water_sum[Sum_crops] = Drip_Water_sum[Sum_crops]*ARRAYSUM(Irrig_Crop_proportion[Sum_crops,*])*irrigable_crop_area*m2_in_ha/Drip_eff
Pumped_water_win[Win_crops] = Drip_Water_win[Win_crops]*ARRAYSUM(Irrig_Crop_proportion[*,Win_crops])*irrigable_crop_area*m2_in_ha/Drip_eff
Tot_Pumped_Water = ARRAYSUM(Pumped_water_sum[*]) + ARRAYSUM(Pumped_water_win[*])
Diverted_canal_water = GRAPH(annual_cycle)
(1.00, 23328), (2.00, 67392), (3.00, 259200), (4.00, 336960), (5.00, 336960), (6.00, 336960), (7.00, 336960), (8.00, 282528), (9.00, 269568), (10.0, 246240), (11.0, 199584), (12.0, 101088), (13.0, 23328), (14.0, 67392), (15.0, 259200), (16.0, 336960), (17.0, 336960), (18.0, 336960), (19.0, 336960), (20.0, 282528), (21.0, 269568), (22.0, 246240), (23.0, 199584), (24.0, 101088), (25.0, 23328), (26.0, 67392), (27.0, 259200), (28.0, 336960), (29.0, 336960), (30.0, 336960), (31.0, 336960), (32.0, 282528), (33.0, 269568), (34.0, 246240), (35.0, 199584), (36.0, 101088), (37.0, 23328), (38.0, 67392), (39.0, 259200), (40.0, 336960), (41.0, 336960), (42.0, 336960), (43.0, 336960), (44.0, 282528), (45.0, 269568), (46.0, 246240), (47.0, 199584), (48.0, 101088), (49.0, 23328), (50.0, 67392), (51.0, 259200), (52.0, 336960), (53.0, 336960), (54.0, 336960), (55.0, 336960), (56.0, 282528), (57.0, 269568), (58.0, 246240), (59.0, 199584), (60.0, 101088), (61.0, 23328), (62.0, 67392), (63.0, 259200), (64.0, 336960), (65.0, 336960), (66.0, 336960), (67.0, 336960), (68.0, 282528), (69.0, 269568), (70.0, 246240), (71.0, 199584), (72.0, 101088), (73.0, 23328), (74.0, 67392), (75.0, 259200), (76.0, 336960), (77.0, 336960), (78.0, 336960), (79.0, 336960), (80.0, 282528), (81.0, 269568), (82.0, 246240), (83.0, 199584), (84.0, 101088), (85.0, 23328), (86.0, 67392), (87.0, 259200), (88.0, 336960), (89.0, 336960), (90.0, 336960), (91.0, 336960), (92.0, 282528), (93.0, 269568), (94.0, 246240), (95.0, 199584), (96.0, 101088), (97.0, 23328), (98.0, 67392), (99.0, 259200), (100, 336960), (101, 336960), (102, 336960), (103, 336960), (104, 282528), (105, 269568), (106, 246240), (107, 199584), (108, 101088), (109, 23328), (110, 67392), (111, 259200), (112, 336960), (113, 336960), (114, 336960), (115, 336960), (116, 282528), (117, 269568), (118, 246240), (119, 199584), (120, 101088), (121, 23328), (122, 67392), (123, 259200), (124, 336960), (125, 336960), (126, 336960), (127, 336960), (128, 282528), (129, 269568), (130, 246240), (131, 199584), (132, 101088), (133, 23328), (134, 67392), (135, 259200), (136, 336960), (137, 336960), (138, 336960), (139, 336960), (140, 282528), (141, 269568), (142, 246240), (143, 199584), (144, 101088), (145, 23328), (146, 67392), (147, 259200), (148, 336960), (149, 336960), (150, 336960), (151, 336960), (152, 282528), (153, 269568), (154, 246240), (155, 199584), (156, 101088)

Land Use

wetland_cultivated_area(t) = wetland_cultivated_area(t - dt) + (Clearing + Cropping - wetland_area_constant - Fallowing) * dt
INIT wetland_cultivated_area = ic_Cult_Wet
INFLOWS:
Clearing = IF Clearing_poss=0 THEN 0 ELSE
IF annual_cycle=12 THEN
IF wetland_natural_area - (Wet_area_needed - Cropping*DT) <= Min_pct_Nat_Wet*Tot_wet_area

```
THEN wetland_natural_area - Min_pct_Nat_Wet*Tot_wet_area
ELSE Wet_area_needed - Cropping*DT
ELSE 0
Cropping = MIN(Wet_area_needed,Wetland_fallow)/DT
OUTFLOWS:
wetland_area_constant = IF wetland_cultivated_area>Tot_wet_area
THEN wetland_cultivated_area-Tot_wet_area
ELSE 0
Fallowing = IF annual_cycle=12 THEN
IF Annual_food_security>Food_security_threshold
THEN (Annual_food_security-Food_security_threshold)*Empty_an_food_needs/Expected_Maize_Yield
ELSE 0
ELSE 0
Wetland_fallow(t) = Wetland_fallow(t - dt) + (Fallowing - Regenerating - Cropping) * dt
INIT Wetland_fallow = 0
INFLOWS:
Fallowing = IF annual_cycle=12 THEN
IF Annual_food_security>Food_security_threshold
THEN (Annual_food_security-Food_security_threshold)*Empty_an_food_needs/Expected_Maize_Yield
ELSE 0
ELSE 0
OUTFLOWS:
Regenerating = DELAY(Fallowing-Cropping, Regeneration_length)
Cropping = MIN(Wet_area_needed,Wetland_fallow)/DT
Wetland_farming_hhlds(t) = Wetland_farming_hhlds(t - dt) + (new_wetland_farmers - wetland_farmers_drop_out) * dt
INIT Wetland_farming_hhlds = ic_Wet_farm
INFLOWS:
new_wetland_farmers = IF ((annual_cycle=12) AND (Annual_food_security<1) )
THEN Clearing / average_wet_plot_area
ELSE 0
OUTFLOWS:
wetland_farmers_drop_out = Regenerating / average_wet_plot_area
wetland_natural_area(t) = wetland_natural_area(t - dt) + (Regenerating - Clearing) * dt
INIT wetland_natural_area = Tot_wet_area-INIT(wetland_cultivated_area)-INIT(Wetland_fallow)
INFLOWS:
Regenerating = DELAY(Fallowing-Cropping, Regeneration_length)
OUTFLOWS:
Clearing = IF Clearing_poss=0 THEN 0 ELSE
IF annual_cycle=12 THEN
IF wetland_natural_area - (Wet_area_needed - Cropping*DT) <= Min_pct_Nat_Wet*Tot_wet_area
THEN wetland_natural_area - Min_pct_Nat_Wet*Tot_wet_area
ELSE Wet_area_needed - Cropping*DT
ELSE 0
average_wet_plot_area = 0.7
Clearing_poss = 1
Expected_Maize_Yield = 2
Food_security_threshold = 1.2
ic_Cult_Wet = 15
ic_Wet_farm = 21
Land_use_costs = 0
Min_pct_Nat_Wet = 0
pct_nat_wet = wetland_natural_area/Tot_wet_area
Regeneration_length = 36
Tot_wet_area = 110
Wet_area_needed = IF annual_cycle=12 THEN
IF Annual_food_security>=1 THEN 0
ELSE (1 - Annual_food_security)*Empty_an_food_needs/Expected_Maize_Yield
ELSE 0
```

Natural resources

```
Harvesters(t) = Harvesters(t - dt) + (new_harvesters - harvester_drop_out - Max_harvesters) * dt
INIT Harvesters = 0.24*INIT(Population)/hh_size
INFLOWS:
new_harvesters = IF annual_cycle= 10 THEN Harvesters*new_harvester_rate ELSE 0
```

OUTFLOWS:
harvester_drop_out = IF annual_cycle = 10 THEN Harvesters*drop_out_rate ELSE 0
Max_harvesters = IF Harvesters + new_harvesters*DT- harvester_drop_out *DT>Household_number
THEN Harvesters + new_harvesters*DT - harvester_drop_out*DT - Household_number
ELSE 0
wetland_biomass_per_ha(t) = wetland_biomass_per_ha(t - dt) + (biomass_growth - harvest_per_ha) * dt
INIT wetland_biomass_per_ha = 20
INFLOWS:
biomass_growth = wetland_biomass_per_ha*biomass_growth_rate
OUTFLOWS:
harvest_per_ha = IF wetland_natural_area = 0 THEN 0
ELSE IF annual_cycle = 10 THEN Harvesters*harvest_per_head/wetland_natural_area
ELSE 0
biomass_available_per_head = IF wetland_natural_area = 0 THEN 0 ELSE
wetland_biomass_per_ha*PropUsableBiom*wetland_natural_area*(propReeds+PropSedges)/(Harvesters*DT)
biomass_growth_rate = CGROWTH(100*biomass_intrinsic_growth_rate*(1-
wetland_biomass_per_ha/wet_carrying_capacity))
biomass_intrinsic_growth_rate = 0.3
delta = 0.2
drop_out_rate = CGROWTH(100*(1 - harvest_per_head/Max_harvest_per_hh))
harvest_per_head = IF annual_cycle=10 THEN MIN(biomass_available_per_head, Max_harvest_per_hh) ELSE 0
Max_harvest_per_hh = 0.6
nat_res_income = wetland_natural_area*harvest_per_ha
*(((propReeds/(propReeds+PropSedges))*Reed_value*PropReedSold) +
(PropSedges/(propReeds+PropSedges))*Sedge_value*PropSedgeSold)
nat_res_value = wetland_natural_area*harvest_per_ha*(Reed_value*propReeds/(propReeds+PropSedges) +
Sedge_value*PropSedges/(propReeds+PropSedges))
new_harvester_rate = IF annual_cycle= 10
THEN IF biomass_available_per_head>Max_harvest_per_hh
THEN CGROWTH(100*delta*(biomass_available_per_head-Max_harvest_per_hh)/Max_harvest_per_hh)
ELSE 0
ELSE 0
Pct_harvesters = Harvesters/Household_number
propReeds = 0.2
PropReedSold = 0.19
PropSedges = 0.025
PropSedgeSold = 0.8
PropUsableBiom = 0.15
Reed_value = 2000
Sedge_value = 8500
wet_carrying_capacity = 60

Natural Wetland hydrology
NW_SatW(t) = NW_SatW(t - dt) + (NW_UW_to_SatW + NW_SW_toSatW + NW_SatW_from_precip + NW_GW_inflow +
IS_SatW_to_NW[Maize,Onion] + IS_SatW_to_NW[Maize,Tomato] + IS_SatW_to_NW[Maize,No_crop] +
IS_SatW_to_NW[Maize,Cabb] + IS_SatW_to_NW[Maize,Bean] + IS_SatW_to_NW[Groundnut,Onion] +
IS_SatW_to_NW[Groundnut,Tomato] + IS_SatW_to_NW[Groundnut,No_crop] + IS_SatW_to_NW[Groundnut,Cabb] +
IS_SatW_to_NW[Groundnut,Bean] + IS_SatW_to_NW[eMaize,Onion] + IS_SatW_to_NW[eMaize,Tomato] +
IS_SatW_to_NW[eMaize,No_crop] + IS_SatW_to_NW[eMaize,Cabb] + IS_SatW_to_NW[eMaize,Bean] +
IS_SatW_to_NW[SwPot,Onion] + IS_SatW_to_NW[SwPot,Tomato] + IS_SatW_to_NW[SwPot,No_crop] +
IS_SatW_to_NW[SwPot,Cabb] + IS_SatW_to_NW[SwPot,Bean] + IS_SatW_to_NW[FallSum,Onion] +
IS_SatW_to_NW[FallSum,Tomato] + IS_SatW_to_NW[FallSum,No_crop] + IS_SatW_to_NW[FallSum,Cabb] +
IS_SatW_to_NW[FallSum,Bean] + IS_SatW_to_NW[TomSum,Onion] + IS_SatW_to_NW[TomSum,Tomato] +
IS_SatW_to_NW[TomSum,No_crop] + IS_SatW_to_NW[TomSum,Cabb] + IS_SatW_to_NW[TomSum,Bean] -
NW_SatW_to_SW - NW_SatW_to_UW - NW_SatW_Transp - NW_Seepage_to_river) * dt
INIT NW_SatW = ic_NW_SatW
INFLOWS:
NW_UW_to_SatW = IF (NW_inf_cond=0) THEN NW_UW/DT
ELSE MIN (NW_UW/DT, MAX(0, NW_UW_delta*NW_UW_moist/DT + NW_UW_perc_rate))
NW_SW_toSatW = IF (NW_UW_depth_before=0 AND NW_Unsat_cap>0) THEN MIN (NW_Unsat_cap/DT,
NW_SurfW/DT) ELSE 0
NW_SatW_from_precip = IF NW_inf_cond=0 THEN NW_Unsat_cap/DT - NW_SW_toSatW ELSE 0
NW_GW_inflow = Upper_catch_rainfall*Up_Catch_Coef/Conv +Tot_IS_to_NW
OUTFLOWS:

```
NW_SatW_to_SW = IF NW_SatW>NW_SatW_Max THEN (NW_SatW - NW_SatW_Max)/DT ELSE 0
NW_SatW_to_UW = MAX( 0, MIN(-NW_UW_delta*NW_FC, NW_SatW/DT))
NW_SatW_Transp = NW_Transp*(1-NW_UW_Trans_pr)
NW_Seepage_to_river = NW_Hydr_Grad*NW_Hydr_Cond
NW_SurfW(t) = NW_SurfW(t - dt) + (NW_SW_in + NW_SatW_to_SW - NW_SW_toSatW - NW_SW_Evap - NW_SW_out) *
dt
INIT NW_SurfW = ic_NW_SW_depth
INFLOWS:
NW_SW_in = Rainfall_valley/Conv - NW_UW_from_precip - NW_SatW_from_precip
NW_SatW_to_SW = IF NW_SatW>NW_SatW_Max THEN (NW_SatW - NW_SatW_Max)/DT ELSE 0
OUTFLOWS:
NW_SW_toSatW = IF (NW_UW_depth_before=0 AND NW_Unsat_cap>0)   THEN  MIN (NW_Unsat_cap/DT,
NW_SurfW/DT)  ELSE 0
NW_SW_Evap = MIN (ETP/Conv, NW_SurfW/DT)
NW_SW_out = NW_out_Coef*NW_SurfW/DT
NW_UW(t) = NW_UW(t - dt) + (NW_UW_from_precip + NW_SatW_to_UW - NW_UW_eTransp - NW_UW_to_SatW) * dt
INIT NW_UW = ic_NW_UW
INFLOWS:
NW_UW_from_precip = IF NW_inf_cond>0 THEN NW_Infilt ELSE 0
NW_SatW_to_UW = MAX( 0, MIN(-NW_UW_delta*NW_FC, NW_SatW/DT))
OUTFLOWS:
NW_UW_eTransp = NW_Transp*NW_UW_Trans_pr
NW_UW_to_SatW = IF (NW_inf_cond=0)  THEN NW_UW/DT
ELSE  MIN (NW_UW/DT, MAX(0, NW_UW_delta*NW_UW_moist/DT + NW_UW_perc_rate))
ic_NW_SatW = (ic_NW_Wat_Table-Base)*NW_porosity
ic_NW_SW_depth = 0
ic_NW_UW = IF NW_ground_level>ic_NW_Wat_Table THEN  (NW_ground_level-ic_NW_Wat_Table)*ic_NW_UW_moist
ELSE 0
ic_NW_UW_moist = 0.14
ic_NW_Wat_Table = 718.6
NW_AvgMoist = IF NW_UW_depth=0 THEN NW_porosity ELSE
IF Reed_Root_Depth<NW_UW_depth THEN NW_UW_moist ELSE
((NW_UW_depth*NW_UW_moist) + NW_porosity*(Reed_Root_Depth-NW_UW_depth))/Reed_Root_Depth
NW_dist_to_river = 220
NW_FC = 0.31
NW_ground_level = 719
NW_GWL = Base+NW_SatW/NW_porosity
NW_Hydr_Cond = 200
NW_Hydr_Grad = IF NW_GWL>River_Stage  THEN (NW_GWL-River_Stage)/NW_dist_to_river  ELSE 0
NW_Infilt = MIN(NW_Pot_Inf,Rainfall_valley/Conv)
NW_inf_cond = IF NW_SW_toSatW*DT = NW_Unsat_cap THEN 0 ELSE MAX (NW_Unsat_cap - NW_Infilt*DT,0 )
NW_Ks = IF NW_AvgMoist>= 0.99*NW_porosity THEN (NW_porosity - NW_AvgMoist)/(0.01*NW_porosity) ELSE
IF NW_AvgMoist>=NW_FC - (NW_FC-NW_WP)*p_Reeds THEN 1 ELSE
IF NW_AvgMoist>=NW_WP THEN (NW_AvgMoist - NW_WP)/((NW_FC -NW_WP)*(1 - p_Reeds))
ELSE 0
NW_out_Coef = 1
NW_porosity = 0.53
NW_Pot_Inf = 3.66
NW_SatW_Max = (NW_ground_level - Base)*NW_porosity
NW_Tot_Seepage = NW_Seepage_to_river*pct_nat_wet*Wetland_length*(NW_GWL-Base)
NW_Transp = IF Reed_Root_Depth> NW_UW_depth THEN NW_Wat_avail*NW_Kc*ETP/Conv ELSE
Min(NW_Wat_avail*NW_Kc*ETP/Conv, NW_UW_moist*Reed_Root_Depth/DT)
NW_Unsat_cap = MAX (NW_UW_depth*(NW_porosity - NW_UW_moist), 0 )
NW_UW_Capil_exp = EXP(-10*MAX(NW_UW_depth-Reed_Root_Depth, 0))
NW_UW_delta = NW_UW_depth - NW_UW_depth_before
NW_UW_depth = MAX (NW_ground_level - NW_GWL, 0)
NW_UW_depth_before = DELAY(NW_UW_depth, DT)
NW_UW_excess = MAX(0, NW_UW_moist-NW_FC)
NW_UW_moist = IF (NW_UW_depth>0)  THEN  NW_UW/NW_UW_depth   ELSE   0
NW_UW_perc_rate = 2*NW_vert_Hydr_Cond*NW_porosity*(NW_UW_excess^0.4)/((NW_porosity-NW_FC)^0.4 +
(NW_UW_excess^0.4))
NW_UW_Trans_pr = IF Reed_Root_Depth+0.2<NW_UW_depth THEN 1
 ELSE
IF NW_UW_depth>0 THEN NW_Wat_avail*NW_UW_depth/(Reed_Root_Depth)
```

ELSE 0
NW_vert_Hydr_Cond = 0.06*30
NW_Wat_avail = MIN(1.0, NW_UW_Capil_exp+NW_Ks)
NW_WP = 0.14
p_Reeds = 0.65
Reed_Root_Depth = 1.5
NW_Kc = GRAPH(annual_cycle)
(1.00, 1.00), (2.00, 1.10), (3.00, 1.20), (4.00, 1.20), (5.00, 1.20), (6.00, 1.08), (7.00, 0.95), (8.00, 0.825), (9.00, 0.7), (10.0, 0.7), (11.0, 0.8), (12.0, 0.9)

Time control
annual_cycle = COUNTER(1,13)
harvest_date_sum[Sum_crops] = [7,7,6,10,7,8]
harvest_date_win[Win_crops] = [13,11,13,12,10]
planting_date_sum[Sum_crops] = [3,2,2,3,1,4]
planting_date_win[Win_crops] = [8,7,7,8,6]
sum_crop_season[Sum_crops] = IF annual_cycle>=planting_date_sum[Sum_crops] AND
annual_cycle<harvest_date_sum[Sum_crops] THEN 1 ELSE 0
win_crop_season[Win_crops] = IF annual_cycle>=planting_date_win[Win_crops] AND
annual_cycle<harvest_date_win[Win_crops] THEN 1 ELSE 0