Trade-offs between livelihoods and wetland ecosystem services: an integrated dynamic model of Ga-Mampa wetland, South Africa

Morardet, S. (1); Masiyandima, M. (2); Jogo, W. (3) ; Juizo, D. (4)

(1) Cemagref UMR G-EAU, 361, rue J.-F. Breton, BP 5095 F-34196 Montpellier Cedex 05, France, sylvie.morardet@cemagref.fr

(2) International Water Management Institute, Southern Africa office, Private Bag X813 Silverton 0127, Pretoria, South Africa

(3) Department of Agricultural Economics, University of Pretoria, P.O Box 0002, Pretoria, South Africa

(4) Universidade Eduardo Mondhlane, Faculdade de Engenharia, Av. de Mozambique Km 1.5, CP257, Maputo, Moçambique

Abstract: This paper presents an integrated dynamic simulation model that represents wetland functioning and will be used for trade-off analysis. The model was developed using the STELLA platform and comprises five interactive sectors namely: hydrology, crop production, use of natural wetland resources and community well-being. These sectors are inter-linked and changes in one sector impact on other sectors through feedback loops between sectors. Key parameters in the model are demand for food, demand for income, and biophysical drivers (soils, rainfall, groundwater and surface flows). Taking into account these factors, the local community makes choices about uses of different categories of land and water resources available to them (irrigation scheme and wetland). These activities impact on the wetland functioning, which in turn influences economic returns of wetland related activities and ultimately livelihoods. The model will be used to simulate several management options in the valley under various localised scenarios of global changes.

Keywords: dynamic system model; ecological integrity; human well-being; integrated ecological-economic modelling; wetlands

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 provides a means to reduce 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 for wetland systems 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 (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 situations 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 modeling 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; Stoorvogel et al., 2004). 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.

Using a dynamic system modeling approach, disciplinary models are tightly interwoven with strong interactions and feedbacks between model components. The approach 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). This paper presents the dynamic systems approach adopted to analyze the trade-offs between ecosystem services in the case of GaMampa 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. Due to time constraints, it was not possible to perform simulations of alternative wetland management options and the scope of this paper is therefore limited to a detailed presentation of the model. Its major contribution is the development of the linkages between the socio-economic and biophysical factors in a wetland ecosystem.

1. Study site description

The GaMampa 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 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 relief. 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 GaMampa area is part of the 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 (cattle and donkeys) are used for draft power and are considered as assets. 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 was converted to agriculture (Sarron, 2005). These changes have 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 of the population 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. Some external stakeholders have the perception that the wetland plays an important role 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, including grazing. 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, locally and downstream.

2. Model description

2.1. WETSYS model overview

A dynamic simulation model (WETSYS) was developed using the STELLA® platform 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 GaMampa 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 five interactive sectors namely: hydrology, crop production, natural resources, land use and community well-being (Figure 1). A sixth sector controls annual and seasonal cycles of activities. Hydrological processes in the wetland impact on the provisioning services (crop production and natural resources), mainly through supply of water. Provisioning services generate food and income and ultimately determine the level of community well-being together with external sources of income. Human use and management of the wetland for provisioning services impact on the processes that provide the benefits. The model starts in October, at the beginning of a rainy season and runs at monthly time step. The model sectors and their linkages are described in detail in the following sections.

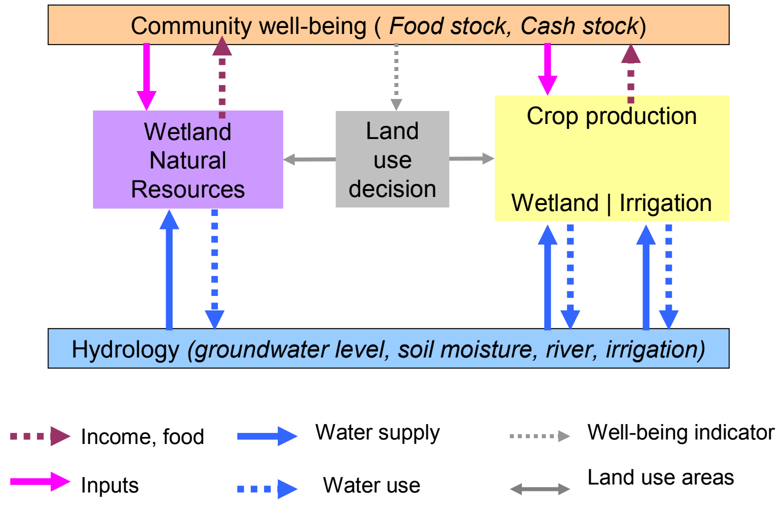


Figure 1: Model sectors and their linkages

2.2. Model sectors and key assumptions

2.2.1. Hydrology sector

This sector describes the hydrology of the wetland. The objective of the sector is to model the impact of loss of water from the wetland through crop water use on water retention in the wetland and wetland contribution to river flow. The GaMampa wetland system comprises six hydrological units inter-linked by water transfers: the upper Mohlapitsi River catchment, the 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 Mohlapitsi catchment that is predominantly under natural vegetation. As most of the area in the upper catchment is classified as a Nature Reserve, no land use change is expected to occur, and the river inflow is considered to depend only on rainfall in the upper catchment.

Water storage in the wetland is influenced by:

- Rainfall (P) and runoff (SWi) in the valley bottom and the upper catchment.
- Soil moisture fluxes (R, CR, E) in the wetland and recharge to the shallow groundwater (see below).
- Natural (LF) and artificial drainage 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 rainfall 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. Many of these channels do not have an outlet; they act as open water areas.
- 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 GaMampa wetland as evidenced 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 channeled 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.
- Surface overflow between the wetland and the river (OF).

The soil water content in the root zone, in the cultivated wetland was computed as:

$$MC_{t+1}^{w} = MC_{t}^{w} + P_{eff} + CR^{w} - ET_{a}^{w} - E_{bs}^{w} - R^{w}$$

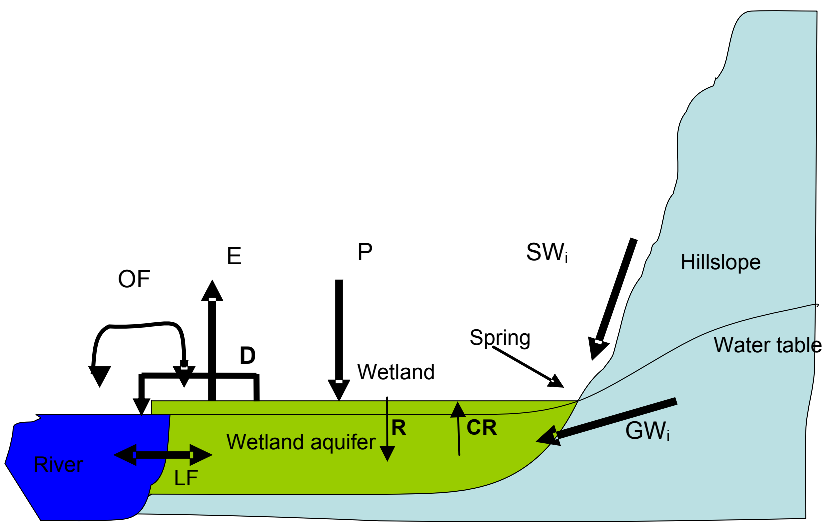
where MC is soil water content, P_{eff} is effective rainfall, CR is capillary rise from the shallow groundwater, R is recharge from root zone to groundwater, ET_a is crop actual evapotranspiration, and E_{bs} is evaporation from bare soil. W superscripts stand for wetland cultivated area. In the natural wetland area, the water dynamics is similar except for Ebs as the soil is always covered by natural vegetation. In the irrigation scheme, diverted irrigation water constitutes an additional inflow into the soil moisture and there is no capillarity rise from groundwater.

Crop and natural vegetation evapotranspiration are by far the largest water losses from the GaMampa wetland. FAO guidelines were used for computing crop and natural vegetation evapotranspiration. For the wetland cropped area and the area under natural wetland vegetation, we considered that recharge to the shallow groundwater takes place when soil moisture in the root zone exceeds the soil water holding capacity.

Following the above, the water balance of the GaMampa wetland and aquifer can be presented as follows:

$$\Delta S_w = R + GW_i - LF + IL - CR$$

where ΔS_w is change in storage in the wetland, GW_i is groundwater inflow from the hill slopes, LF is lateral flow or groundwater outflow from the wetland to the river, IL is losses from irrigation scheme, and CR is capillarity rise. Considering that surface water inflow from the hills to the wetland (SW_i) and overland flow (OF) between the wetland and the river are negligible, they were omitted in the model. The main groundwater outflow from the wetland is subsurface flow (LF) or seepage at the edge of the wetland to the river, which occurs along the entire length of the wetland and was estimated using Darcy's law.



P: rainfall
E: evaporation + evapotranspiration
LF: seepage from wetland to river
OF: overland flow from wetland to river
SW_i: surface water inflow to wetland
GW_i: groundwater inflow to wetland
R: recharge
CR: Capillary rise
D: Drainage

Figure 2. The GaMampa wetland flow generation conceptual model (Modified from McCartney, 2005)

2.2.2. Crop production sector

The crop production sector distinguishes the wetland cultivated area and the irrigated area, the dynamics of which are very similar except for the linkages with the wetland biophysical system. Wetland cultivated area is the difference between the total wetland area (fixed at 120 hectares according to Kotze, 2005) and natural wetland area. However, the wetland cultivated area changes annually due to conversion of the natural wetland area and abandonment of cultivated area to natural vegetation. Maize is the only crop considered in the model, and crop production only occurs once a year. Crop yields are modeled as a function of evapotranspiration using the crop yield response to water function described by Doorenbos and Kassam, 1986.

$$Y_a^i = Y_m^i \left[1 - k_y * \left(1 - ET_a / ET_m\right)\right]$$

where i, represents wetland or irrigation scheme, Y_a is actual yield (ton/ha), Y_m is maximum yield (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: $Et_a= k_s * ET_m$, where k_s depends on soil water content. Et_a is also computed on a monthly basis and summed over the cropping season. In the irrigation scheme ET_a is impacted by rainfall and irrigation water, and in the wetland by rainfall and groundwater level.

Values for k_c, k_y and k_s are derived from the literature. 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 with constant input costs, different for the wetland and the irrigation scheme. From farm surveys and field observations maize production provides higher yields in the wetland than in the irrigation scheme while requiring less labour and inputs (Chiron, 2005).

Total crop production depends on crop yields and cultivated wetland and irrigated areas. It is assumed that local production is too small to influence market prices therefore crop output and input prices are considered exogenous. Maize producer prices are derived from national series (Statistics South Africa, 2009).

2.2.3. Land use sector

This sector describes the processes that lead to conversion of the wetland to agriculture. Two land use classes are considered in the wetland: the wetland cultivated area and the 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 (see natural resources sector). Information from focus group discussions shows that wetland conversion to agriculture is primarily driven by poor production in the irrigation scheme due to water shortages related to degradation of irrigation infrastructure and droughts.

Therefore, we linked wetland conversion to variability in annual rainfall and the need to seek for extra food to meet population grain requirement.

We assumed that the decision to clear natural wetland for cropping occurs in September, so that farmers have time to clear the land before it is time to sow (in December). We assumed three possible situations for conversion of the wetland to cultivation. When rainfall of the previous cropping season is below a given threshold new wetland farmers are attracted in the wetland by the higher yields in the wetland compared to the irrigation schemes such that they convert part of the natural wetland to agricultural land. Based on discussions with farmers, we linked the number of new farmers with the annual food security index (annual food security is the ratio of annual food consumption over annual food needs – see community well-being sector below) and the current number of wetland farmers. The equation of wetland conversion was calibrated on past observed evolution of wetland cultivated area (1994-2006) Based on the household survey, we assumed a fixed area converted per new wetland farmer, set at 0.7ha, which is the average wetland plot size per wetland farming household.

Wetland cultivated area can be abandoned when the rainfall is very high and saturated soils in the wetland cause crop losses. This situation was never observed in GaMampa wetland in the recent past, therefore we could not calibrate the equation of wetland abandonment on observed data. We assumed that wetland abandonment occurs when rainfall is above a second threshold and that the area abandoned is proportional to the current wetland cultivated area. In any situation where rainfall is comprised between the two thresholds, wetland cultivated area and number of wetland farmers remain stable.

2.2.4. 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 review. 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). Following Woodwell, 1998 and Hellden, 2008, we assumed that wetland biomass growth 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 70tons 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. We used an intrinsic growth rate of wetland biomass of 0.3 as a first and 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.

Harvest of natural wetland plants occurs once a year in July. Harvest per hectare is the product of number of harvesters times quantity harvested per harvester over the natural wetland area. Adekola's survey 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).

2.2.5. Community well-being sector

In this sector the local community is considered as homogenous and represented as a whole. 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 depends on natural growth rate (birth and death rate) and migration rates. Population natural growth rate and emigration rate are held constant over the simulation, respectively at the district average estimated at 1.7% per year and at 1% per year (Limpopo Provincial Government, 2004). From focus group discussions conducted in the study area, we assumed that there is no immigration in the area.

Cash stock dynamics

Initial cash stock is set at one month of non farm income. Cash inflow is composed of: net income of 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 a function of the proportion of households engaged in wage work and of the average income earned from wage 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 category were derived from household survey and assumed to be constant over time, to avoid complexity in the model. Both off-farm wage income and social transfers occur at monthly time step, whereas income from harvested wetland natural products only occurs once a year at time of harvest.

Cash outflow is the sum of non-food expenditure and food purchase. Non food expenditure is the sum of 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, cash available for food purchase is equal to cash stock less minimum basic non-food expenditures and crop input costs. An income index is computed from cash stock:

Income index = (Cash /Population_Number - poverty_line)/poverty_line

with poverty line set at R150 per month (StatsSA 2007) to cover the non food basic expenditures.

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 households' consumption; therefore there is no food sale. The population uses this stock to cover its monthly food needs (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.

The 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.

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).

The well-being of the community is assessed each month based on three dimensions: the satisfaction of food requirements (measured through the food security index), the capacity of meeting basic non food expenditures (assessed via the income index) and the status of the natural wetland (measured by wetland index, equal to the ratio of actual natural wetland area over the maximum wetland natural area). The community well-being index is an output of the model on the basis of which scenarios are evaluated.

Conclusions

The WETSYS model was developed to integrate existing knowledge on small-scale wetlands such as the GaMampa wetland in South Africa and support the analysis of trade-off 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 so that it reproduces past observed evolution from 1990 to 2006. 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: 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. Localised global change scenarios will include changes in climate (rainfall and potential evapotranspiration), population dynamics (changes in natural growth and emigration rate) and economic policies (affecting among others social transfer and level of wage rate). Wetland management options, which will be simulated, 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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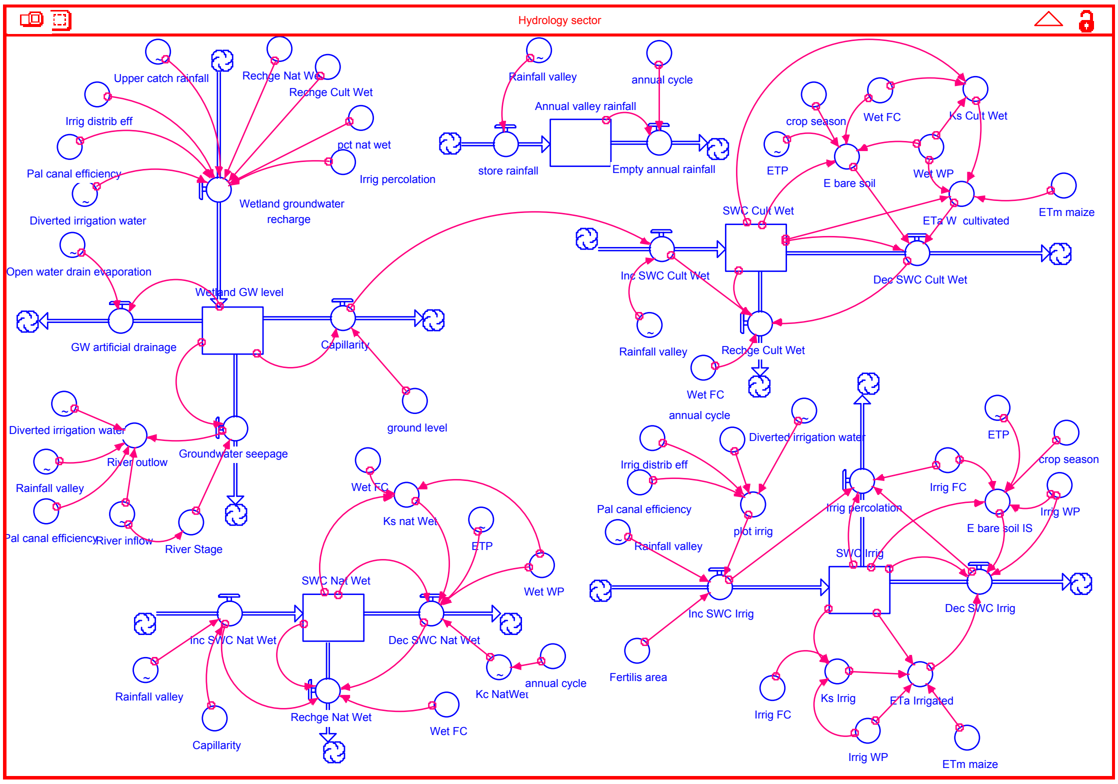
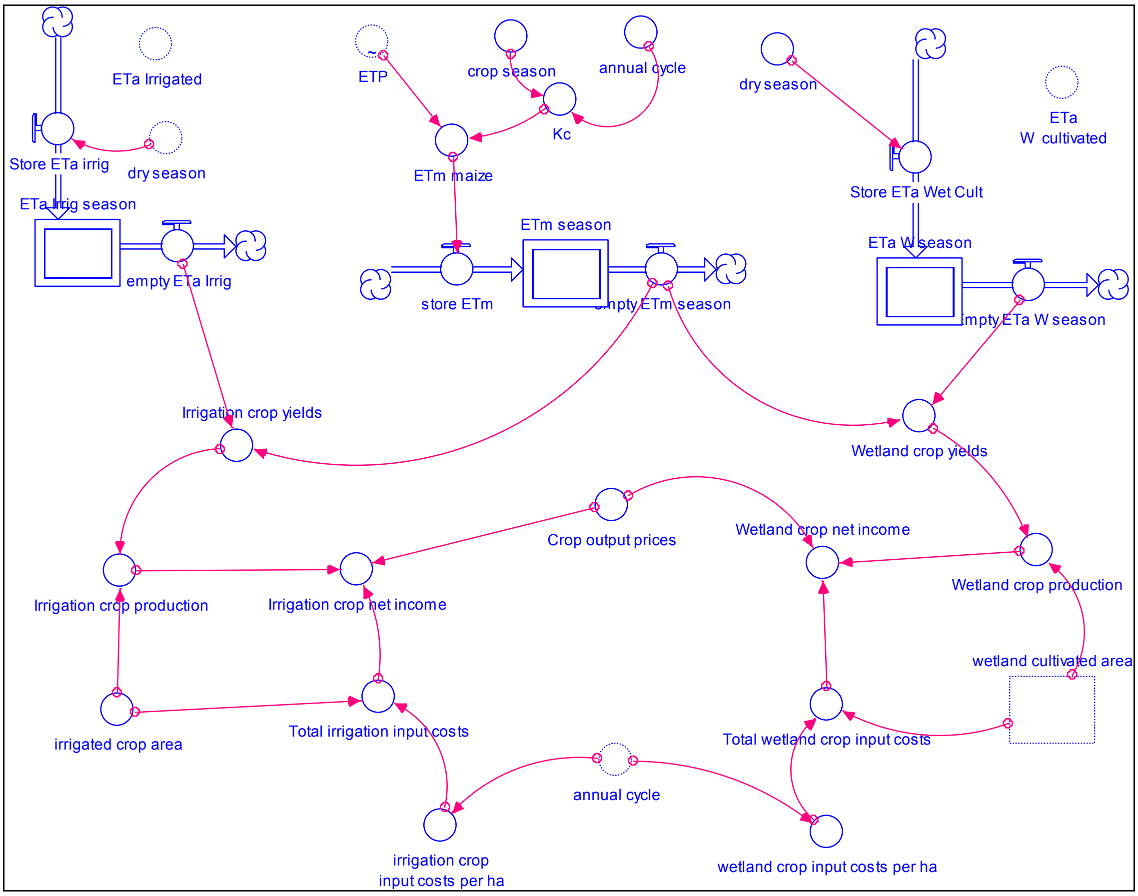
Appendix: Structure of the STELLA model

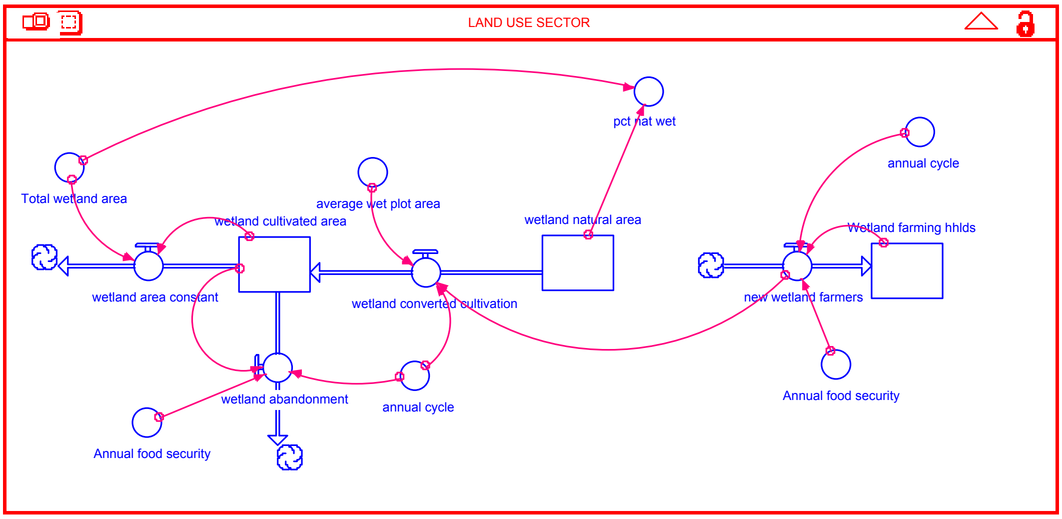
Hydrology sector



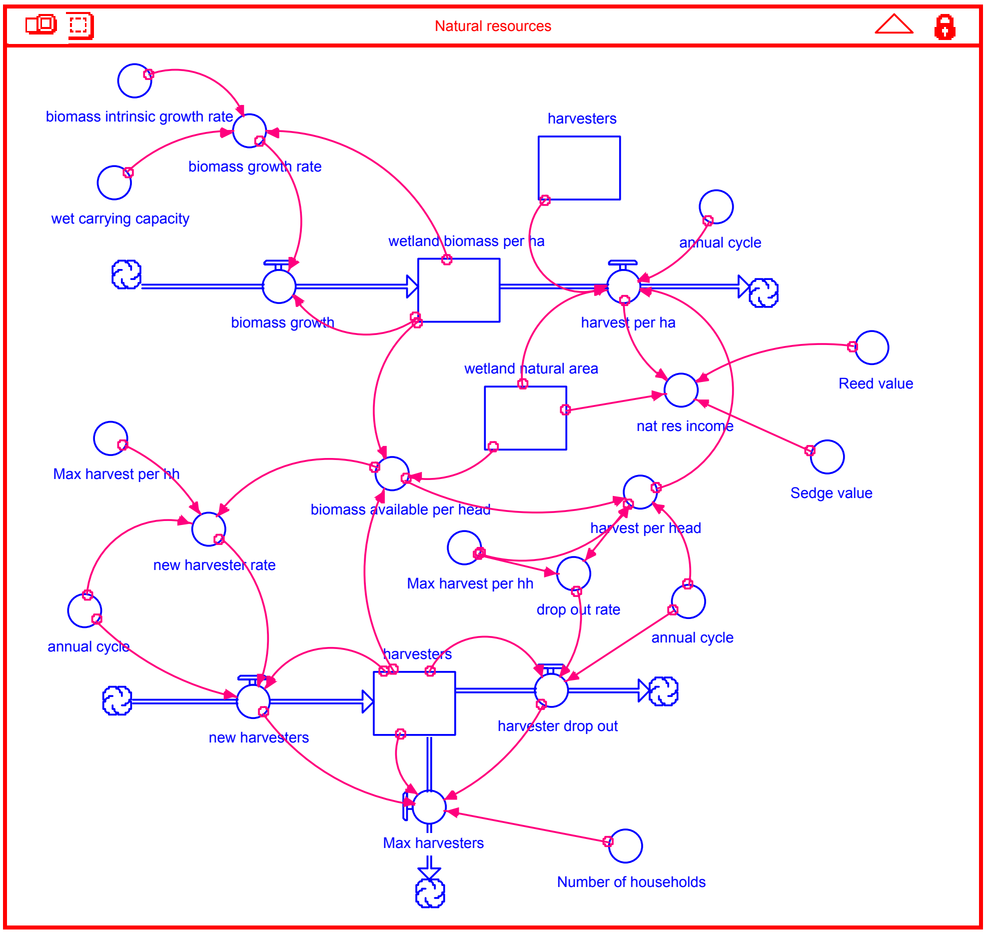
Crop production sector



Land use sector



Natural resources sector



Community well-being sector