# Modelling trade-offs between livelihoods and wetland ecosystem services: the case of Ga-Mampa wetland, South Africa

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Abstract: This paper presents an integrated dynamic simulation model that represents the functioning of a small South African wetland. The model was developed using the STELLA platform and comprises six interactive sectors namely: hydrology, crop production, crop economics, use of natural wetland resources, land use decision 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 is used to simulate several land management options 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 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 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; 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 modeling approach has become increasingly popular in modeling 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 modeling 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 (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 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.

# 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 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 GaMampa 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.

# 2. Model description

## 2.1. 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 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 six interactive sectors namely: hydrology, crop production, crop economics, 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 In Press, 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.
- Land use change decisions are formalized as logical rules reflecting the main drivers of farming households' behavior 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 formalizations as transparent as possible.
- Finally the estimation of supply and demand functions used by Jogo and Hassan are based on the major assumption that labor 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 labor allocation between various on-farm and off-farm activities in the area.

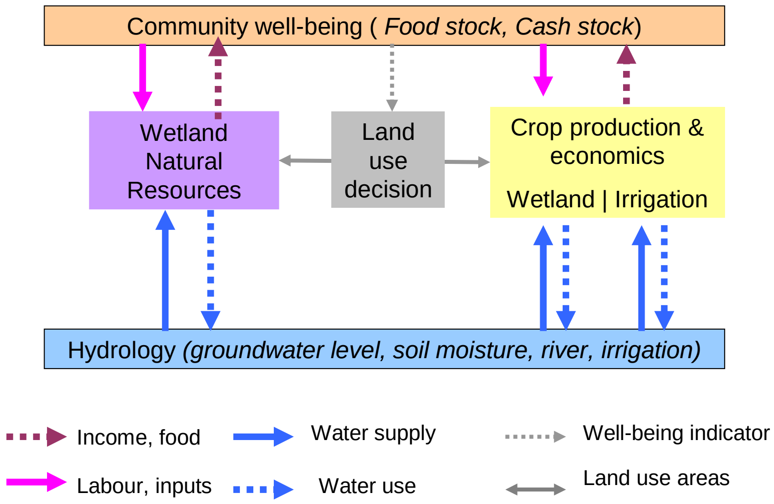

*Figure 1: WETSYS model sectors and their linkages*

## 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 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.

Water storage in the wetland is influenced by:

- Rainfall (P) and runoff (SWi) 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) 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 (GWi): 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 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 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. The irrigation seepage volume is a function of the efficiency of the distribution system (Chiron 2005).

- Surface overflow between the wetland and the river (OF): 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.

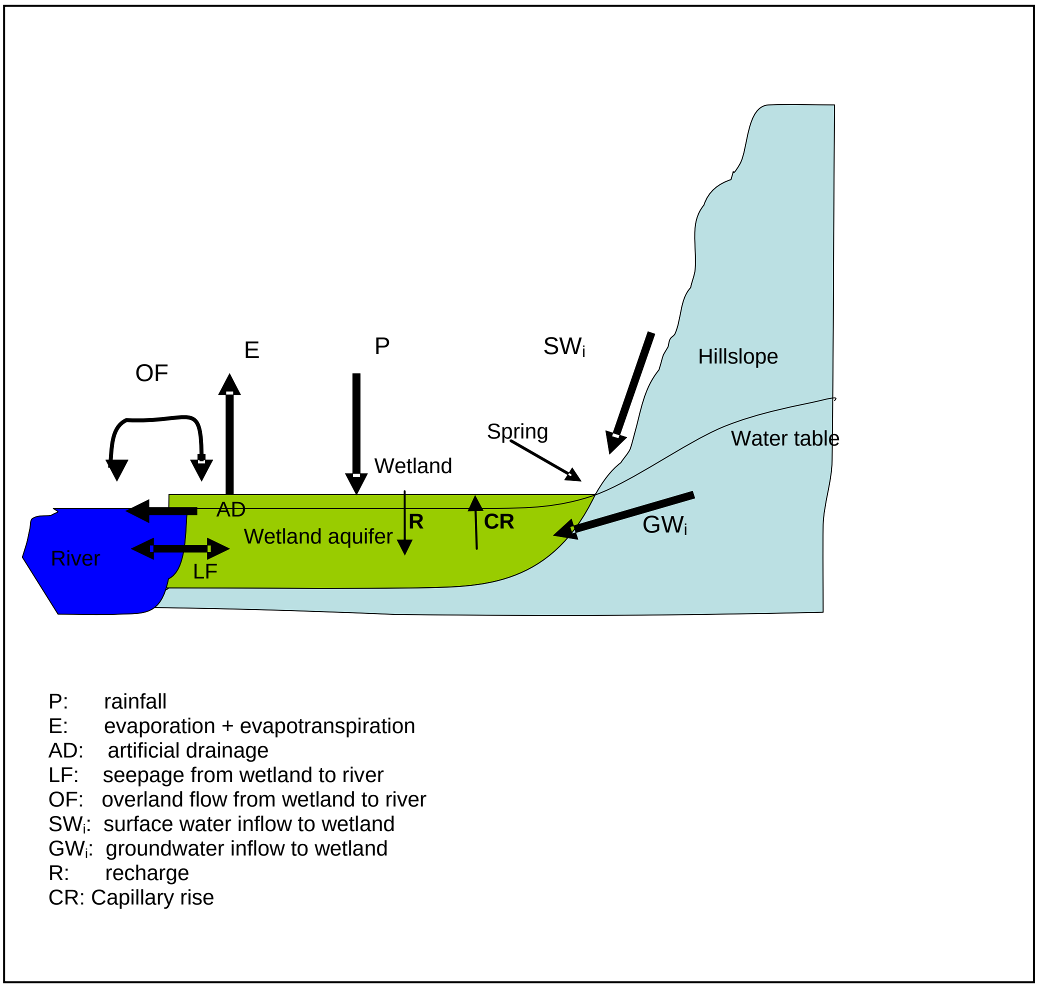

*Figure 2. The GaMampa wetland flow generation conceptual model*

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 efficient 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 subscripts stand for wetland cultivated area. In the natural wetland area, the water dynamics is similar except for $E_{bs}$ 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. Capillary rise can be significant in the loamy wetland soils due to the presence of the shallow water table. Following Raes and Deproost 2003, we assumed that capillary rise is a function of the depth to 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 natural and cultivated wetland we considered that recharge to the shallow groundwater occurs only when moisture in the root zone exceeds water holding capacity. Values for water holding capacity were derived from soil texture measured by Nell and Dreyer 2005, using the Soil Water Characteristics calculator included in the SPAW model (Saxton and Rawls 2006).

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 $\Delta S_w$ is change in storage in the wetland, $GW_i$ is groundwater inflow from the hill slopes, $LF$ is lateral flow 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) 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.

Domestic and livestock groundwater abstraction from the wetland shallow groundwater was considered negligible based on a focus group discussion at GaMampa in 2007. Most households use tap water from the formal water supply system in the villages and water uptake by livestock is very limited.

Changes in river flow downstream of the wetland are mainly due to groundwater outflow from the wetland into the river (LF). We assumed that runoff from bare soils in the valley bottom 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.

### 2.2.2. Crop production sector

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 modeled as a function of evapotranspiration using the crop yield response to water function described by Doorenbos and Kassam 1986:

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

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 $ET_m$: $Et_a = k_s * ET_m$, 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 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 production provides higher yields in the wetland than in the irrigation scheme while requiring less labor and inputs (Chiron 2005).

### 2.2.3. 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. 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[1]).

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 modeled 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.

### *2.2.4. 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. In a given period, the natural wetland area is the difference between the total wetland area (fixed at 120 hectares according to Kotze, 2005) and wetland cultivated area. Information from focus group discussions in the 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.

Two land use decision rules were tested:

- In the first case, wetland conversion was linked to variability in annual rainfall and the need to seek for extra food to meet population grain requirement. We assumed three possible situations for conversion of the natural 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 compared to the irrigation schemes. Based on discussions with farmers, the number of new farmers was linked with the annual food security index (see community well-being sector below) and the current number of wetland farmers. 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. When rainfall is above a second threshold, saturated soils in the wetland cause crop losses and wetland is abandoned at a rate proportional to the present cultivated area[2]. In any situation where rainfall is comprised between the two thresholds, wetland cultivated area and number of wetland farmers remain stable.
- In the second case, decision of wetland conversion was based on the comparison of economic returns from cultivated wetland and natural wetland in the previous year: if the average value of cultivated wetland is higher than the average value of natural wetland then conversion occurs. The area converted is directly linked to the expected gap between food needs and food stock (see community well being sector).

In both cases 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 maize (in December). Parameters for the equation of wetland conversion were calibrated on past observed evolution of wetland cultivated area (1994-2006).

### *2.2.5. 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). 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 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

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

[2] 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.

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. As biomass increases the actual growth rate decreases due to competition for limited resources of e.g. light, water and 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 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 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 land use sector.

### *2.2.6. Community well-being sector*

In this sector 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 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 (Statistics South Africa 2004). From focus group discussions conducted in the study area, we assumed that there is no immigration.

*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 the product of the proportion of households engaged in wage work and of the average income earned from wage work (respectively 24%, and R1000 per month according to our household survey). 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 (respectively at 6% for pensioners and 28% for children under 14), to avoid complexity of the model. 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 (equal to ZAR1750 per person per year according to household survey), 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 is the model (e.g., priority given to basic non-food expenditures and crop input costs). An income index is computed from Cash stock:

$$\text{Income index} = (\text{Cash} / \text{Population\_Number} - \text{poverty\_line})/\text{poverty\_line}$$

with poverty line set at ZAR150 per month (StatsSA 2007) to cover the non-food basic expenditures[3].

*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. 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 then 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.

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). Weights attached to the three dimensions can be adjusted to reflect various preferences of the local community. 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 such as 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. 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 are currently discussed with stakeholders at local and provincial levels. They may 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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[3] 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.

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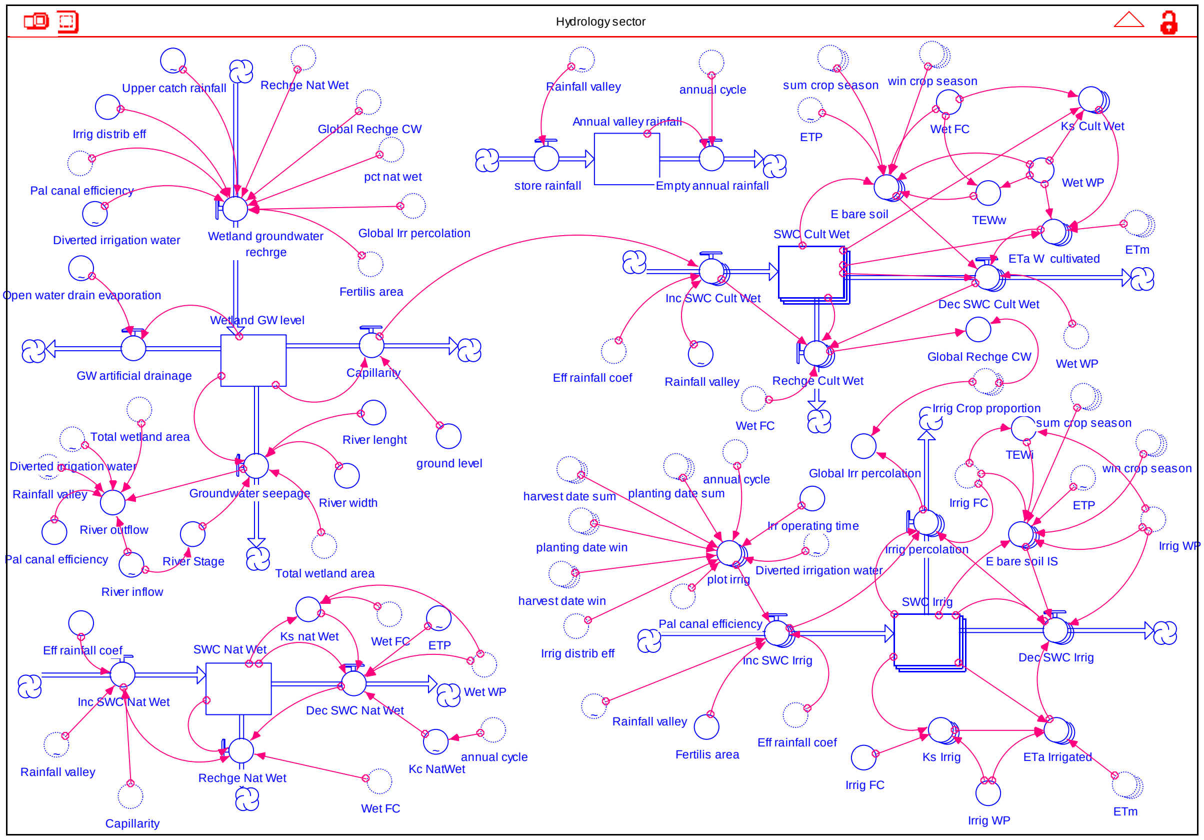
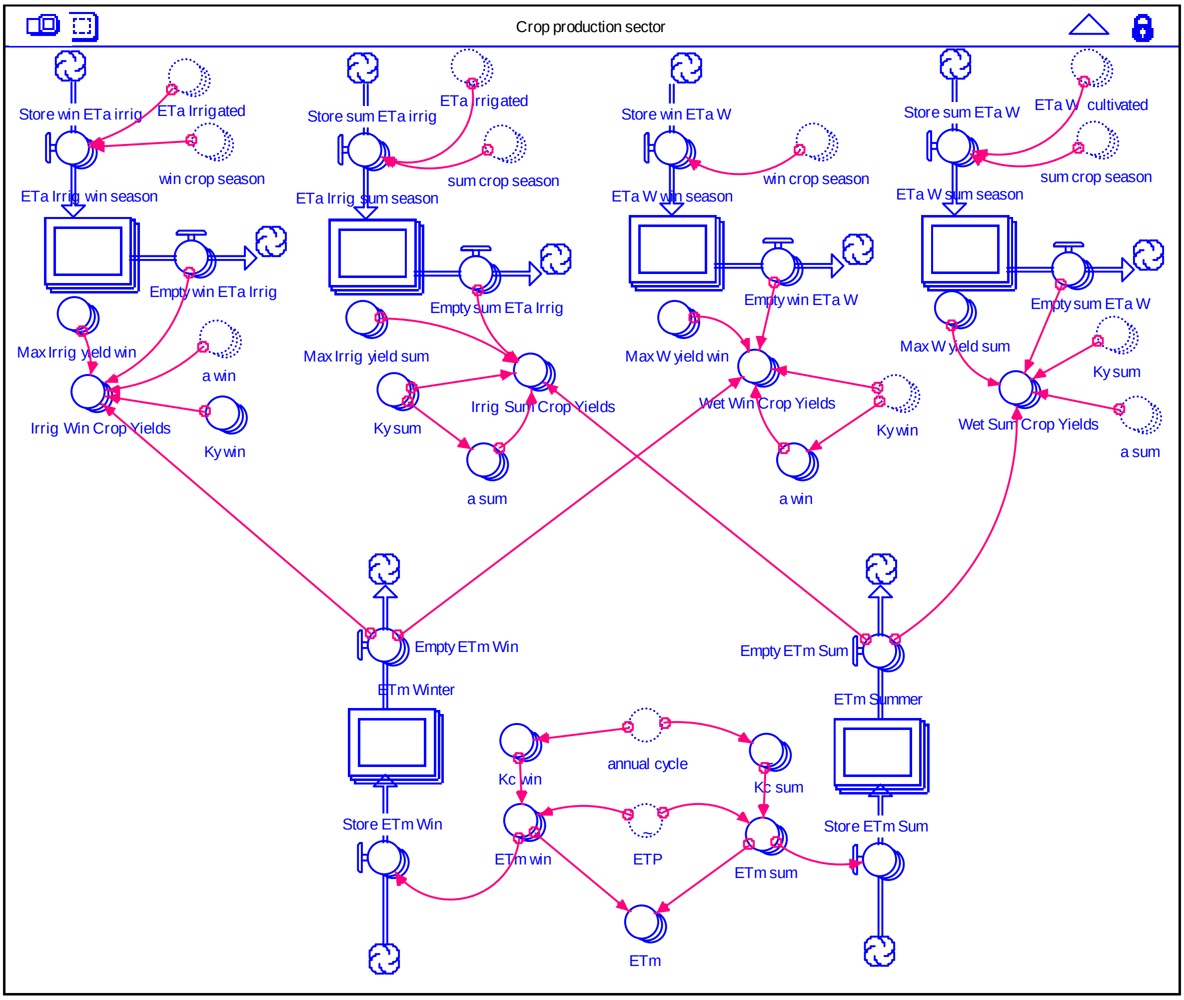
# Appendix: Structure of the STELLA model

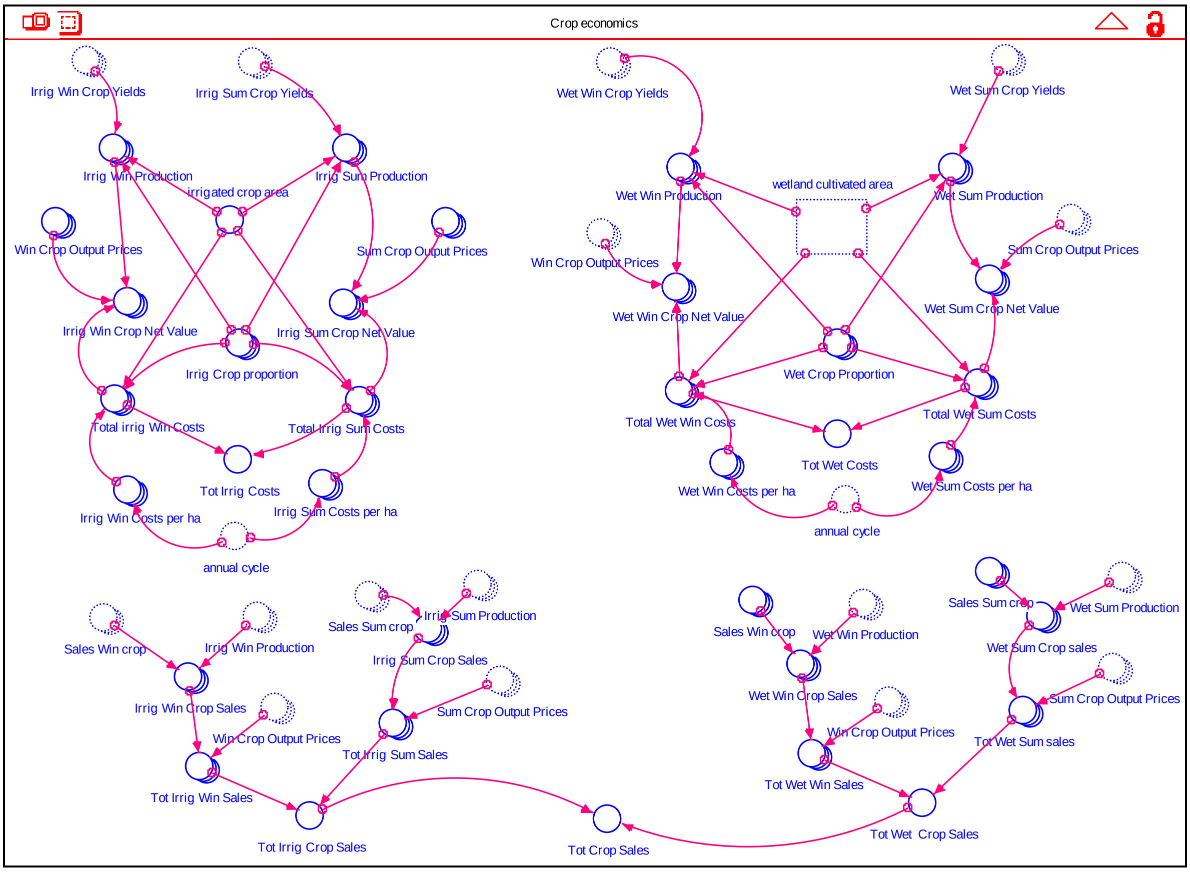
Hydrology sector



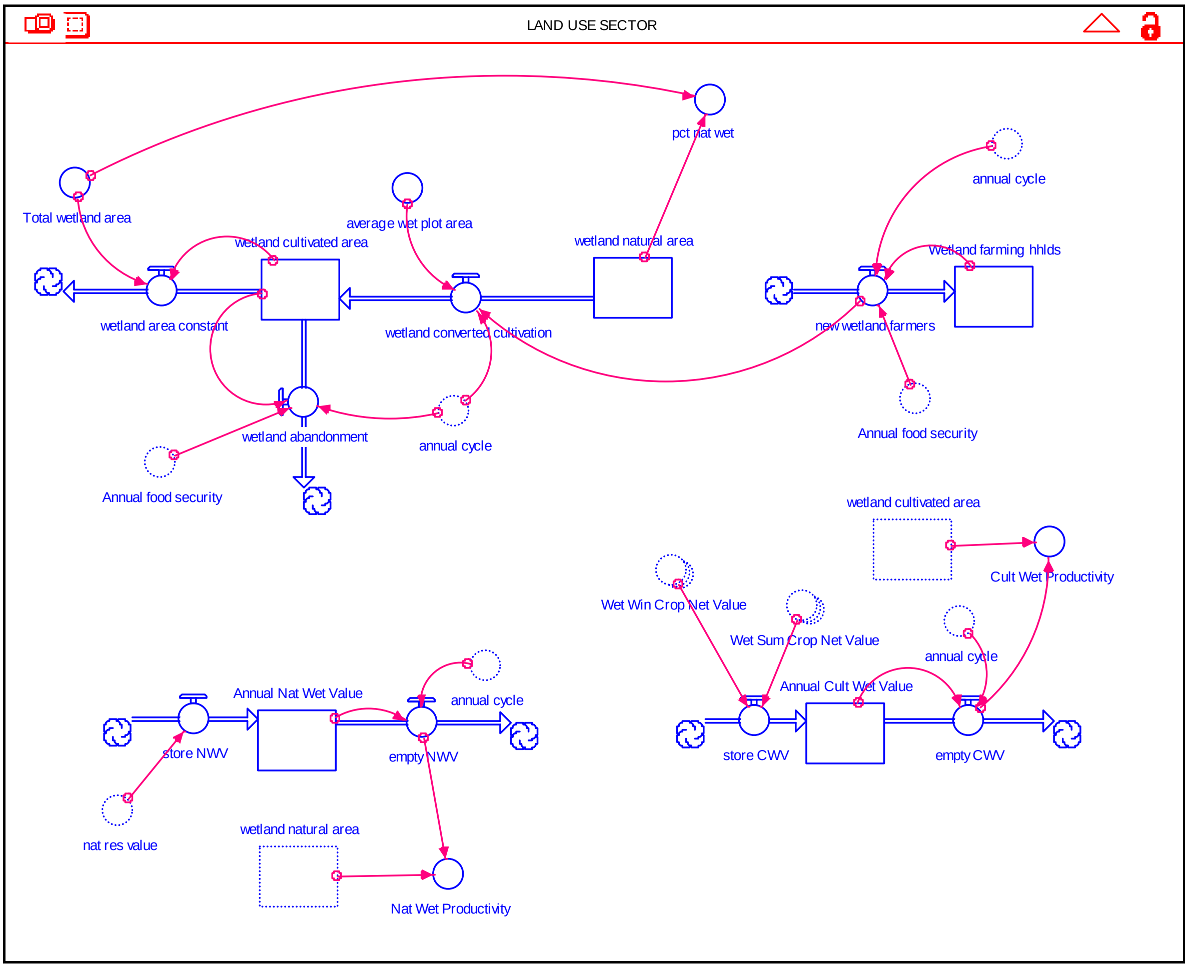
Crop production sector



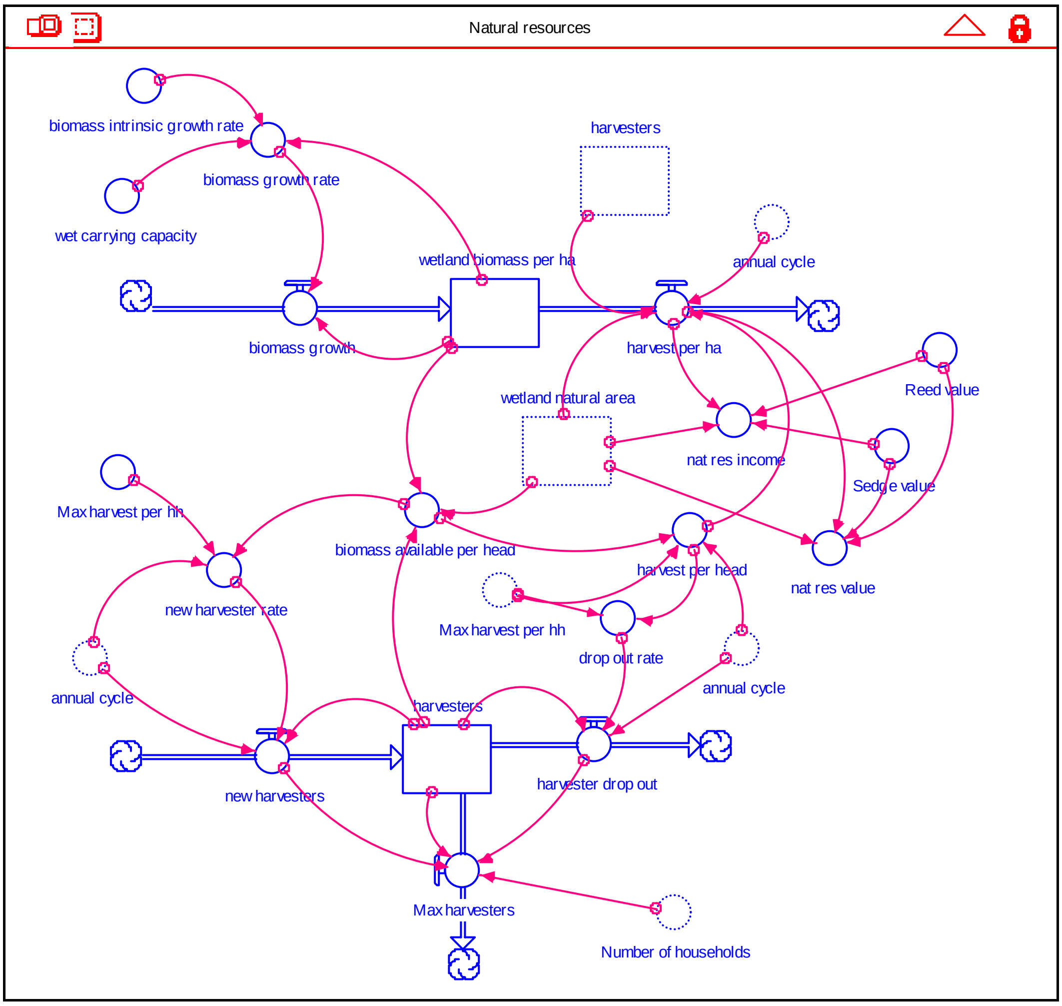
## Crop economics sector



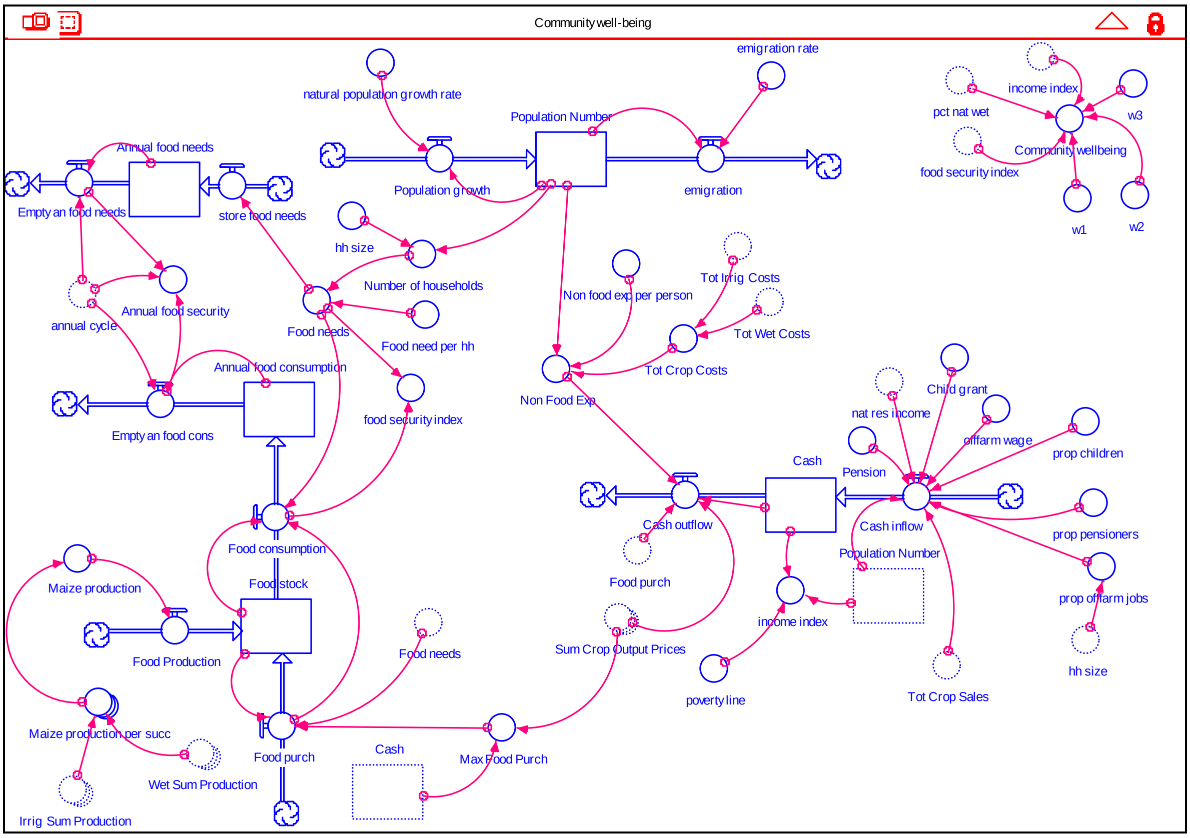
Land use sector (land use change decision based on food security index)



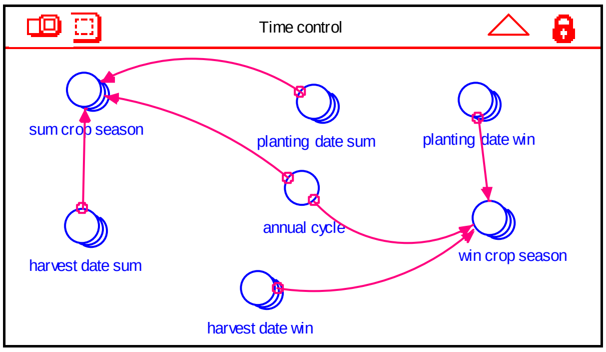
Natural resources sector



## Community well-being sector



## Time control



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