SUSTAINABLE AGRICULTURE AND WATER MANAGEMENT IN SEMI ARID REGIONS

Jörg Schulla, Kai Zoellmann, Wolfgang Kinzelbach

ETH-Zürich, Institute of Hydromechanics and Water Resources Management

Abstract:

Water resources are often a limiting factor for food production. Although global fresh water resources are sufficient for the current world population, problems arise locally where a growing population meets water shortages in arid and semi arid regions.

The excessive use of the natural resources soil and water raises the question whether the current way of agricultural production in those regions is sustainable and - if not - whether changes in cropping patterns or improved agricultural technologies may lead to a more sustainable way of using soil and water resources.

The sustainability of irrigated agriculture depends on hydrologic constraints, economic forces, and the prospects for technological innovation. The effects of these diverse factors can be examined in an integrated way with models that simulate the impact of different behaviour of agricultural producers on the natural system (i.e. groundwater levels, salinity levels) over long time periods.

We developed a model consisting of a detailed hydrologic surface water module and a groundwater module coupled by an unsaturated zone module. We applied the model to the Murrumbidgee watershed in southern Australia, a semi arid region with great economic importance for the Australian rice production. The arable land in this area is threatened by increased salinization due to water table rise induced by the rice paddies.

The model works on a daily time base with 2.5 x 2.5 km^2 grid cells. It allows the simulation of water flow and transport of substances dissolved in the water. We compared different cropping strategies and groundwater pumping scenarios focussing on sustainability criteria. Results propose a change in cropping pattern with a reduced amount of rice fields (compared to today's situation) accompanied by groundwater pumping in places with suitable water quality to keep the groundwater levels down and thus prevent salinization.

INTRODUCTION

The modeled site, the lower Murrumbidgee catchment is located in southern Australia, some 200 km west of Canberra. The (lower) catchment is about 41.000 km^2 in extent. It is bounded by the Laughlan River to the north-west and the Murray River to the south-west. The eastern boundary is formed by a line with a relatively constant head in the first layer. Within the 41.000 km^2 there are some 7000 km^2 of irrigation districts the largest of which - the Murrumbidgee Irrigation Area (MIA) – has an area of some 5000 km^^{2}. Agriculture is mostly rice, irrigated pasture and irrigated crops such as wheat. The irrigation water demands of these differ substantially with rice requiring about 15 ML/ha per season compared to pasture (4,5 ML/ha) and other crops (3 ML/ha).

The largest benefit is obtained for rice, resulting in a monotonous increase of the area being grown with rice.

Rice is grown in ponded paddies out of which some 1000 mm of water evapo-transpirate during the growing season of 150 days. The rest becomes recharge (roughly 150 mm) or is drained away. The salt concentration of the underlaying first groundwater layer itself shows relatively high salt concentrations (7000 mg/l). So even if direct salinization in neighboring fields of the rice paddies may not be a threat due to sufficient leaching, the question arises whether the leaching water may lead to rising groundwater tables resulting in swamping and secondary salinization.

This question can only be answered by a model that simulates water and salt flow and transport for the surface hydrology (Rainfall, ET, runoff) including land use as well as the leaching process through the unsaturated zone and the saturated zone.

DESCRIPTION OF THE WASIM-ETH MODEL

The Water Balance Simulation Model of the Swiss Federal Institute of Technology (ETH) is a distributed, physically based combined hydrologic surface-, subsurface and groundwater model including also a simplified solute transport model for all of these three model domains. It is designed for applications in mesoscale and large scale basins using an appropriate spatial resolution between some meters and some kilometers and a temporal resolution between some minutes and some days, with the exact values depending on the actual size and morphology of the basin and the goals of the application. The model can be used for flood modeling as well as for long term water balance simulations. It also includes flow routing and water management functions for irrigation scheduling.

The model domain can be subdivided into subbasins which can be extracted automatically using a digital terrain analysis tool. Apart from this, it is also possible to subdivide the model domain into other zones of interest, e.g. into different irrigation regions, like it was done in the application to the Murrumbidgee basin. In either case, the basic subdivision is given by a rectangular grid which may contain variably sized cells in the way they are used in climate models, i.e. the grid cells show only a small change in their width from row to row. However, the application to the Murrumbidgee river basin was done using a regular spatial resolution of 2.5 km by 2.5 km and a temporal resolution of 1 day.

WaSiM-ETH needs meteorological input data like precipitation, air temperature, global or net radiation, sunshine duration, air humidity resp. vapor pressure and wind speed, of which at least precipitation and temperature has to be delivered. These data may be given either as station data of as many stations as available or as pre calculated altitudinal gradients (e.g. for temperatures) for each region. Besides the basic grid cells and the subbasins resp. zones, regions are a third type of subdivision only used for applying interpolation methods using altitudinal gradients. All meteorological data are interpolated to each grid cell using one of several possible interpolation methods like inverse distance weighted interpolation, altitude dependent regression, bilinear interpolation, or Thiessen polygons.

For calculating the evaporation, the interpolated meteorological data as well as the temporally variable plant behavior is considered. The most important plant properties used in WaSiM-ETH are the stomata resistances, the root density distribution and depth, the leaf area index, the vegetation height, the vegetation coverage degree and the critical soil water pressure at which transpiration starts to diminish. All these parameters are time dependent and specific for each crop type. This offers the possibility to simulate scenarios assuming different crop distributions or different irrigation strategies. It should be noted that all of these properties can be used only when calculating the evaporation by the Penman-Monteith approach, which is the standard evaporation calculation scheme for WaSiM-ETH. Other approaches should be used only when the input data are restricted, e.g. if only precipitation and temperature are available. Within bucket-interception module, the interception evaporation is modeled.

The soil water movement is calculated using the spatially and temporally discretized one dimensional vertical Richards-Equation for each grid cell. By using a second order differential equation it is possible to model vertical moisture profiles and flux profiles for both, water fluxes and salt fluxes which consider not only percolation but also capillary rise, which is of great importance in flat semi arid regions. By assigning a recession in the vertical hydraulic conductivity with increasing depth, it is possible to generate subsurface runoff, or interflow. This runoff component as well as the surface runoff are routed directly into the surface water drainage system. Only the remaining fraction of vertical percolation is considered to become groundwater recharge. Once the water has reached the groundwater, the solute concentration for salts and other tracers like tritium or ^{18}O are updated by mixing the recharge with the first aquifer. This is a compromise which may be acceptable because downward salt fluxes from rural regions are long term, diffuse processes and because the uppermost aquifer in the Murrumbidgee region is only some tens of meters thick. Within the groundwater, the lateral fluxes are modeled for each of the aquifers by a two dimensional finite difference approach. Connections between the aquifers are considered by the leakage principle. Pumping of water or solutes can be considered by boundary conditions such as constant fluxes, which can also be used for boundary in- and outflows, or by constant heads and concentrations repectively. Baseflow generation is modeled by the leakage principle for the interaction between surface and subsurface water, i.e., baseflow can be generated only where the groundwater rises above a river bed or lake bottom water level or where the groundwater reaches the soil surface. However, it is also possible for surface water to reinfiltrate into the groundwater if the groundwater level drops below the river water level, which may also be very important for modeling ephemerical rivers.

Surface runoff, interflow and baseflow are superimposed to the subbasin’s total runoff and routed to the subbasin’s outlet considering the distance to the outlet. The flow routing algorithms for superimposing and routing these runoffs through the basin are based on the kinematic wave approach. It is possible to consider regulated reservoirs, river branchings or artificial abstractions resp. inflows. The model can also consider various irrigation control techniques including moisture controlled irrigation and irrigation using a crop specific irrigation schedule. The irrigation water supply is balanced with the available surface water or, in the case of pumping of groundwater, taken from the groundwater reservoir.

The model efficiency can be estimated using a set of efficiency criteria like the so called Nash criterion (a kind of squared correlation coefficient R^2) or the explained variance *EV* for both, the linear and the logarithmic results compared to the respective observed results. As the model provides a considerably large set of internal states for selected variables and time steps it is possible to calibrate the model by comparing these with observed values e.g. modeled versus observed groundwater heads.

Some features like the integrated snow accumulation and melt model, the glacier model, the possibilities of considering shading and terrain effects on the radiation budget as well as the possibilities for using monthly scenarios or for coupling the model to general circulation models (GCMs) were not used in this project. There exists also a model version using a rather conceptual soil model based on the variable saturation area approach after the TOPMODEL [1]. A detailed description of the model is given in [2].

MODELING APPROACH AND CALIBRATION

The calibration of the model requires a series of daily rainfalls and the associated sequence of daily runoff volumes for comparison of the modeled data with the observed data. Furthermore the modeled groundwater heads as well as the salt concentrations of the river and the groundwater have to be compared with observed data.

The stream flow data were taken from the Murrumbidgee River Report [3], the salt concentrations from the Murray Basin Hydrogeological Map Series [4](AGSO). The groundwater heads were compared with the heads obtained from a calibrated Modflow model of that particular area which was done by the CSIRO in 1994. The meteorological data were interpolated from six gauging (rainfall) stations.

The calibration was carried out for daily discharges at the catchment outflow. Then catchment characteristics and the initial values were adjusted as usual for hydrologic modeling until a satisfactory calibration was achieved. (See Fig. 1)

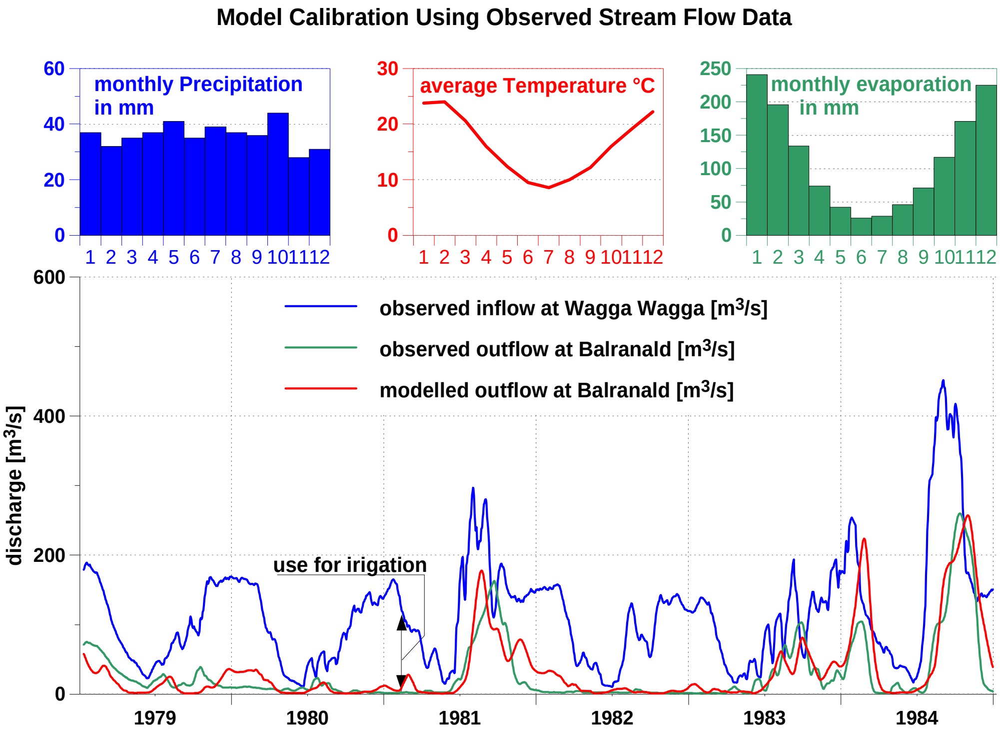

Fig 1: Model Calibration

Results

In a first model run (Scenario 1) the current land use was simulated and assumed to be constant apart from rotating cropping patterns for each farm. This calculation was done in order to answer the question how water tables may develop under current irrigation practicies.

For this purpose the landuse fractions of rice, irrigated pasture and other crops were held constant and meteorological data of the past 30 years were taken. Actual (legal) regulations claim that not more than 30% of the irrigated area of each single farm must be grown with rice. The irrigation water is mainly taken from the Murrumbidgee River and supplied to the farms through an irrigation canal network. As it can be seen from the outflow hydrograph (Fig. 1), not much more (river-) water is available for further irrigation needs at all so that the current state may be considered as the maximum possible amount of rice anyway if only surface water is used for irrigation.

After a total simulation time of 30 years the groundwater table has risen by up to 18 m in some areas of the MIA and the irrigation district that is located in the southern part (Coleambally Irrigation District).

As it can be seen from Fig. 2 large areas of the MIA are likely to be lost due to salinization if current irrigation and land use practices are continued in the future.

This implies that policies will have to be changed to return to a sustainable way of growing rice in the Murrumbidgee area.

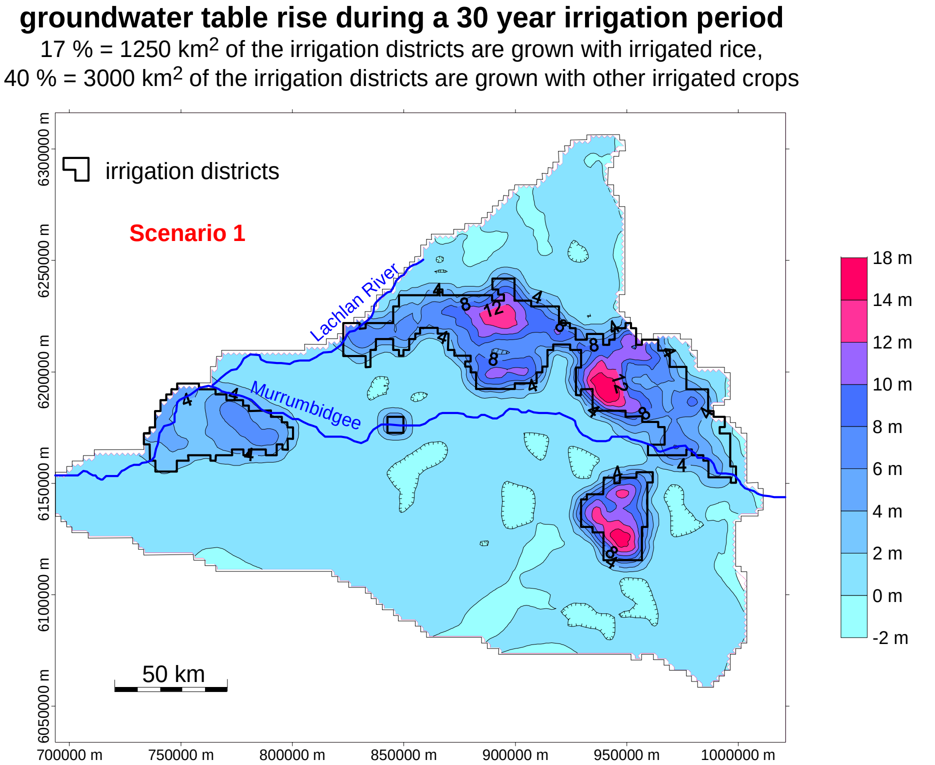

Fig 2: Scenario 1 Groundwater Table rise after 30 years

Scenarios

Although it seems pretty obvious that the areas of rice should be decreased in order to reduce leaching and groundwater table rise, the question remains how such reductions can be achieved and where they are most effective. To answer these questions we simulated two scenarios starting with a simple one which assumes that the overall irrigated area is reduced to one half (Scenario 2). The effect is a radically

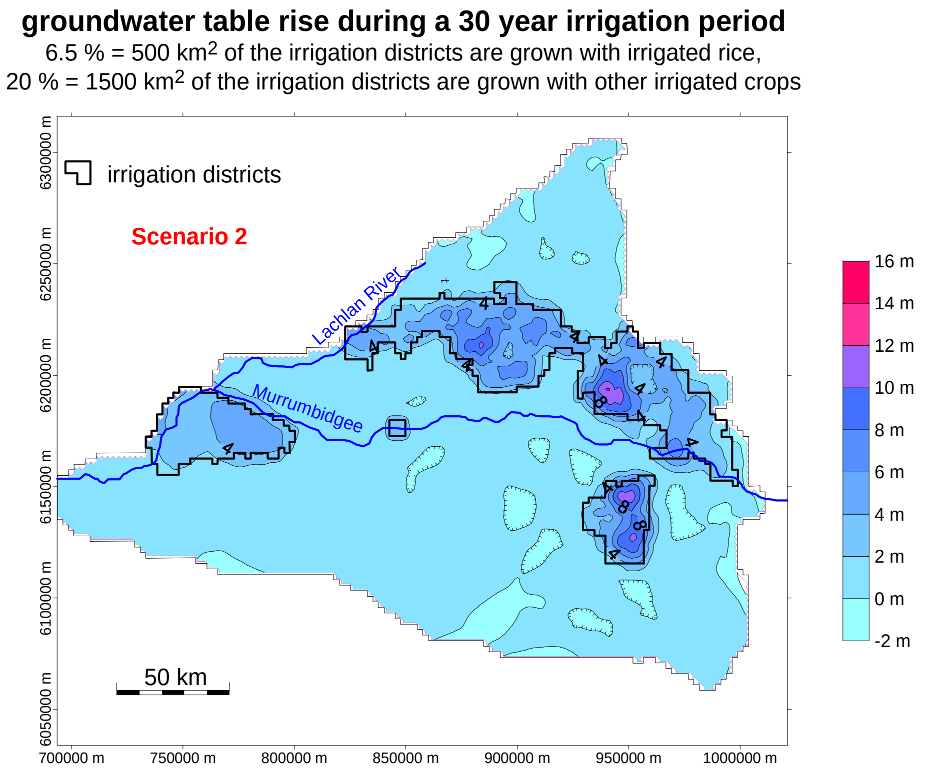

Fig 3: Scenario 2 Groundwater Table rise after 30 years

reduced area with large groundwater table rise.

Scenario 2 shows that it is indeed the irrigation water losses that lead to the rise and that therefore one effective measure can be the reduction of rice fields. Of course this goes along with less profits for the farmers so that alternative strategies have to be found unless compensations or taxes make the farmers act in the desired way.

For scenario 3 we assumed two measures. First groundwater was pumped in the eastern part of the area and added to the irrigation water supply system in order to "relief" the first Groundwater layer from rising due to high recharge from irrigation. Second a dynamic economic optimization model [6](Stubbs, 1999) was coupled on a yearly time base to the hydrologic model in order to reflect the farmers' behavior. The main scope of the economic model was to account for the farmers' concern for future profits. The farmers act in a way which maximizes their profits over 30 years making them sensible for the possible loss of farmland in the future. Furthermore a terminal value for both land and water ensures that the land use at the end of the planing horizon becomes steady state.

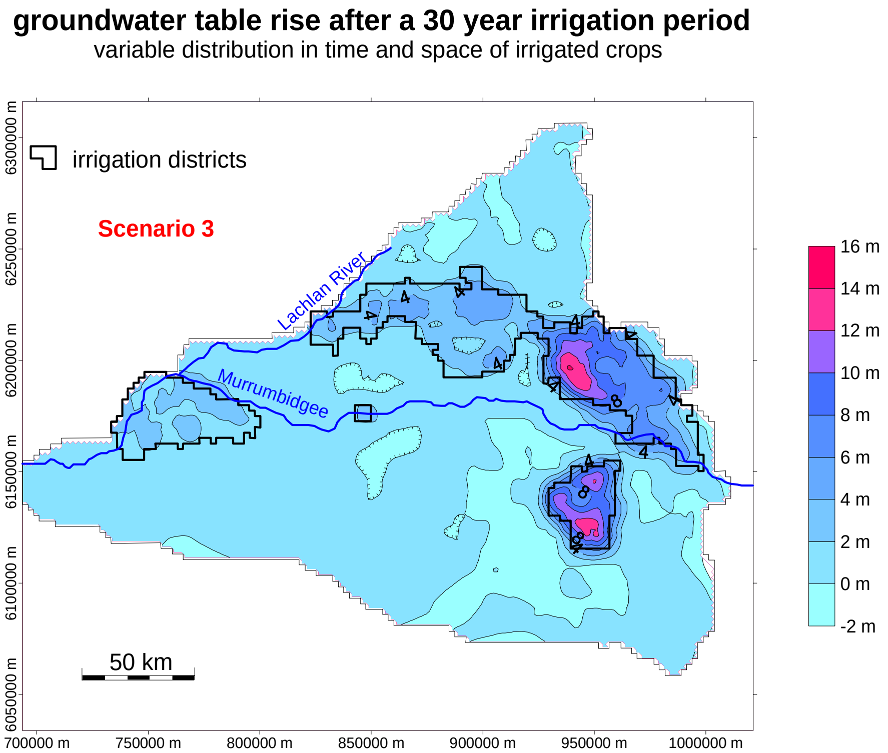

Fig 4: Scenario 3 Groundwater Table rise after 30 years

The groundwater table rise for scenario 3 is much more moderate than for scenario 1 although two areas still show a significant rise. These areas however are much smaller in extent than the areas of scenario 1 (Fig. 4)

The fraction of the irrigated land that is grown with rice now changes due to the dynamical response of the economic model to the environmental impacts. It is reduced with time since the farmers sense the upcoming threat of loosing land due to swamping. But nevertheless the overall fraction remains relatively high at more than 25%

The reason for the low negative impact of this scenario 3 on the environment lies in the pumping of groundwater which at least partially compensates the increased recharge caused by the irrigation losses. Second, the farmers tend to change their cropping patterns according to the situation of the local groundwater table.

Conclusions

It can be concluded from these scenarios that a way towards a sustainable agricultural production consists of the following:

1) The use of groundwater for irrigation instead of surface water only helps keeping the water levels down. The locations that are suited for increased pumping however have to be chosen using long time simulations of the (ground-) water tables in order to ensure best results.

2) The farmers' behavior may be pushed to a more sustainable way by making them sensible for the long term impact of their land use. This can be achieved by "adjusting" the terminal value. A higher terminal value of land and water which means higher prospective benefits in the future leads to less depletion of the resources.

3) Water trading with moderately higher taxed water can result in some farmers selling their water rights and growing crops with lower irrigation demands. Other farmers who buy water rights may even increase their rice fields when their land is not the "high risk" land (land near the river, downstream of the catchment or with sufficient groundwater pumping under the rice paddies)

References

[1] Beven K.J. et. al., 1994: Topmodel and Gridatb, A users Guide to the distribution versions (94.01). *CRES technical report TR1 10/94, Centre for Research on Environmental Systems and Statistics, Institute of Environmental and Biological Sciences, Lancaster University, Lancaster, UK.*

[2] Schulla, J and Jasper, K.: Model Description WaSiM-ETH, available from the authors

[3] Murrumbidgee River Report, Dept. of Land and Water Conservation, Murrumbidgee Region, NSW, Australia

[4] Murray Basin Hydrogeological Map Series, D. Wolley, Dept. of Water Resources, NSW, 1991