A Regional Hydrologic Economic Framework for Investigating Sustainable Irrigated Landscape Futures

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Abstract: Waterlogging and salinity problems in irrigation areas demand development of policies aimed at better management of land and water resources. This process can be facilitated through regional scale spatially distributed hydrologic economic models, which can capture and integrate point scale processes at paddock, farm and irrigation area levels. The inputs and outputs of economic significance need to be defined over larger scales than those appropriate for modelling hydrologic responses. This paper describes application of an integrated hydrologic economic model in the Coleambally Irrigation Area, Australia, which can capture and integrate hydrologic and economic variables. The groundwater flow system is initially represented using a calibrated finite difference groundwater model and then the number of groundwater states is significantly reduced using a balanced state truncation technique developed for systems engineering. Crop production and the unsaturated zone hydrology are simulated for different soid and land uses and are incorporated into the hydrologic economic framework as non-linear functions of net recharge, relative yield and irrigation water use using a crop water model. The hydrologic representation of groundwater flow and soil salinisation is incorporated into an economic optimisation model which simulates different policy options such as crop area restrictions and water trading over 15 and 30 year periods using non-linear optimisation solvers. This model has been applied to investigate the impact of rice area restriction and water trading policies on the watertables and associated economics of irrigation areas using common pool and social optimum options.

Keywords: Integrated, Hydrologic, Economic, Water, Policy, Irrigation, Groundwater

1. INTRODUCTION

In semi arid climates rainfall has to be supplemented by irrigation to grow crops as the magnitude and distribution of rainfall do not match crop water requirements. The long term sustainability of irrigated agriculture depends on a balance between irrigation levels, consumptive use, leaching requirements and the ability of groundwater systems to dissipate the irrigation excess reaching the watertable. If excess irrigation is applied for long periods it can result in shallow watertables and secondary salinisation of soils, since under such conditions saline groundwater moves upwards and evaporates leaving behind salts in the soil profile. Waterlogging and soil salinity reduce crop production and increase salinity of surface water features. This poses a serious threat to the economic and environmental viability of irrigated agriculture.

In the southern Murray Darling Basin, Australia, it is estimated that all irrigated soils will have watertables within 2 meters of the soil surface by the year 2010 without new interventions [Murray Darling Basin Ministerial Council, 1999]. Privatisation of irrigation infrastructure and introduction of Land and Water Management Plans have introduced community based actions to secure the long term economic and environmental sustainability of irrigation areas. However, community actions need to be underpinned by appropriate hydrologic and economic decision support systems, which must capture the heterogeneity of soils, aquifers and cropping patterns, and provide quantitative estimates of environmental and economic consequences of management options. Crop-water models and regional surface-groundwater interaction models provide insights into the environmental consequences of land and water management scenarios. Farm level hydrologic economic tools have been developed and used for education and policy development [Khan et al, 2000b]. Efforts to integrate regional hydrologic aspects with economics include those by Fordham [1998]. However, this methodology is not readily adoptable due to the requirement for complex UNIX based hardware and the software platforms used. This paper provides details of a hydrologic economic model which can be implemented in a Windows environment and can dynamically link crop, soil, water and salinity dynamics with surface-groundwater interaction models and irrigation area economics. This integrated approach allows exploration of environmental management options, such as changed cropping patterns, drainage and infrastructure upgrades to reduce seepage losses.

2. MATHEMATICAL FORMULATION

The irrigation area is modelled by dividing it into a number of economic units each containing a number of hydrogeologic cells, unsaturated soil profile and cropping patterns. The integrated hydrologic economic model has three components:

- Hydrogeologic System Module
- Unsaturated Soil Module
- Hydrologic Economic Integration Module

Stubbs [2000] provides a detailed mathematical description of each component. A brief overview of the various model components is provided here.

2.1 Hydrogeological System Module

The groundwater system is initially represented using a finite difference approach. It solves a 2D partial differential equation describing leaky aquifers as given below [de Marsily, 1986].

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}-r+q_L \qquad (1)$$

Where $h=h(x,y,t)$ is the horizontal head distribution (L), T is aquifer transmissivity (L^2T^{-1}), $r=r(x,y,t)$ is a source or a sink term ($L\ T^{-1}$), q_L is leakage ($L\ T^{-1}$) to or from one aquifer to another aquifer depending on the head difference and leakage conductance. S is a dimensionless storage coefficient. For unconfined aquifers Equ. 1 is modified by representing T as a product of hydraulic conductivity K and head h and replacing S with specific yield S_y.

Equ. 1 is discretised in space (not in time) using a finite difference approximation as given in Equ. 2.

$$Mh(t)=S\frac{\partial h}{\partial t}-r(t)+L\left(h(t)-h_{ref}\right) \qquad (2)$$

Where M is the N x N finite difference transmissivity matrix, S is a N x N diagonal matrix of storage coefficients, r(t) is N x 1 nodal recharge matrix, and h_{ref} is a N x 1 vector of nodal recharges.

Rearranging Equ. 2, we get a spatially discrete, continuous time state equation for groundwater head, which is capable of considering leakage from rivers and boundaries of the model area. The state space equations for different aquifers are connected through the leakage term. This formulation of state space equations allows linking of inputs at a finer scale (groundwater cells) with the outputs at the economic area scales.

2.1.1 Input/Output scaling

A number of larger economic units can be associated with each of smaller hydrologic cells. The state space formulation allows the inputs (e.g. nodal recharges) and outputs (heads and leakages) to be defined at different scales. The inputs and outputs are defined for the larger economic units while the groundwater states are defined at the hydrologic scale. The inputs are downscaled (to the hydrologic cells) and outputs are upscaled (to economic units). The upscaling is done using the weighted average of the hydrologic cells in each economic unit depending upon the arable area in each cell as shown in Equ. 3.

$$u=Du^e \qquad (3)$$

Where u is a vector of inputs at the hydrologic cell scale, u^e is a vector of inputs at the economic unit scale and D is a transformation matrix. The downscaling is performed using a reverse operation as given by Equ. 4.

$$y^e=Uy \qquad (4)$$

Where y^e is a vector of outputs at the economic unit scale, y is a vector of outputs at the hydrologic cell scale and U is a transformation matrix.

2.1.2 Model reduction

The standard model reduction method available in Matlab, Robust Control Toolbox [Chiang and

Safonov, 1998] is used to reduce the number of states of the model without significantly changing the input-output response. The number of states of the groundwater model is reduced by choosing new states which are linear combinations of the most important states and deleting other states which are not significantly affected by inputs and outputs.

This model reduction process results in a linearised continuous state-space model which is discretised in time using an analytical solution. The coefficient matrix of the analytical solution is embedded in a hydrologic economic optimisation model described in 2.3.

2.2 Unsaturated Soil Module

The unsaturated zone associated with each hydrologic cell is defined using a finite element solution (Hydrus 1-D) of Richard's Equation (Equ. 5) [de Marsily, 1986]

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(h,c,z) \qquad (5)$$

Where $\theta(h)$ (L^3 L^{-3}) is the volumetric water content, h is the pressure head (L), S is root water uptake (T^{-1}), c is salinity concentration (M L^{-3}) , z is the depth of soil (L) and K(h) (L T^{-1}) is saturated hydraulic conductivity defined using van Genuchten relationships [Vogel and Cislervoa, 1988]. The initial conditions for solving Equ. 5 are described in terms of equilibrium solution pressure distribution in the soil profile. The atmospheric condition with known flux (precipitation, evapotranspiration) is specified as the top boundary condition and the watertable position is used as the bottom boundary condition. Solute transport is described using a standard convection-dispersion equation Equ. 6.

$$\frac{\theta c}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z}\right) - \frac{\partial qc}{\partial z} - SC_S \qquad (6)$$

Where c is the solute concentration (M L^{-3}), D is dispersion coefficient (L^2 T^{-1}), q is fluid flux (L T^{-1}) depending on the pressure head distribution obtained by solving Equ. 5, θ and S are the same as in Equ. 5 and C_S is the solute concentration of water extracted by roots (M L^{-3}). To solve Equ. 6 a specified concentration of infiltrating water at the top of the soil profile and a zero concentration gradient with known salinity at the watertable are used.

The unsaturated zone model (Hydrus) was run for 40 years to simulate root zone salinity dynamics for varying meteorological conditions for a range of soil types and water table depths. The last 20 years simulation results were used to develop transfer functions for recharge, relative yield and irrigation requirements of the form:

$$z_s = \left(\beta_1 + \beta_4 c^{\beta 5}\right)\exp(\beta_2 D) + \beta_3 \qquad (7)$$

Where z_s is the dependent variable (recharge, relative yield or irrigation) for soil type s, β_1, β_2, β_3, β_4, β_5 are the regression parameters and D is depth to groundwater from the soil surface, and c is groundwater salinity. The average recharge transfer function for a medium clay soil for different watertable depths is given in Fig-1. The positive recharge values represent capillary upflow from the watertable to the root zone while negative recharge values represent excess flow to the watertable.

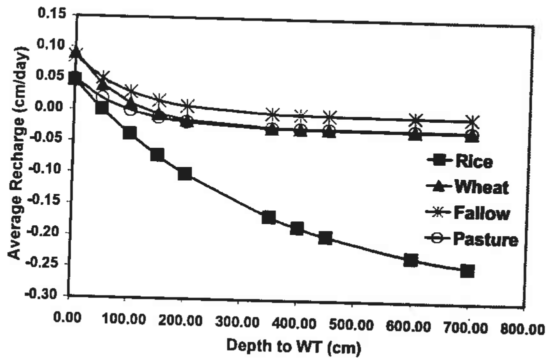

Figure 1. Transfer Function for Recharge.

2.3 Integrated Hydrologic Economic Module

The hydrogeologic and unsaturated zone modules are linked with an economic optimisation module written in GAMS [GAMS, 1999].

2.3.1 Model constraints

The integrated hydrologic economic model is subject to following constraints.

Irrigable Land Constraint: The land cropped in each economic unit is >0 and less than the maximum suitable area.

Rice Area Constraint: An account of current environmental policies for rice growing in southern NSW is given by Khan et al. (2001). For certain scenarios environmental constraints on rice are also simulated e.g. maximum area of rice is less than 30% of the rice approved land.

Water Availability Constraint: The total water used to grow crops is less than or equal to the surface and groundwater water allocation for that economic unit. This constraint is relaxed in the case of water trading between the economic units.

Water Trading Constraint: The model is capable of simulating water trading between economic units. The total water available to all units is less than or equal to the water allocation for the irrigation area.

2.3.2 Economic simulation

The net revenues for each economic unit *i* at each time step t is simulated using Equ. 8. given below:

$$\pi_t^i\left(X_t, U_t^i\right) = \left[P_c Y^i\left(X_t, U_t^i\right) - P_w W^i\left(X_t\right) - P_v\right] U_t^i \tag{8}$$

where π_t^i is a scalar value representing revenue per unit area from unit U_i at time t, X_t is groundwater state vector, P_c, P_w, P_v are the crop prices, water price and variable cost vectors respectively. Y^i and W^i are diagonal matrices of crop yield and irrigation requirement per unit area.

2.3.3 Objective functions

Two objective functions are defined to maximise economic return taking into account system dynamics and externalities and subject to constraints defined in section 2.3.1.

Social Optimum: In this scenario, the economic returns are maximized for the entire area considering both the groundwater state and resource constraints by internalising any externalities, i.e. the total revenue over all economic regions is maximised from society's point of view.

Common Pool: In this scenario, the groundwater system is treated as a common pool resource whereby each unit maximises its economic return without considering optimisation of the groundwater system as a whole. This scenario is close to the current farming practices in the study area.

3. APPLICATIONS IN AUSTRALIA

Stubbs [2000] described application of this model to the Murrumbidgee Irrigation Area, this paper describes its application to the Coleambally Irrigation Area also situated in southern NSW.

3.1 Description of the Study Area

The Coleambally Irrigation Area (CIA) is located in the south eastern part of the Murray Darling Basin. The total average rainfall in the CIA lies between 400–450 mm/year. Prior to irrigation, watertable levels were at depths of 15-20 m. During the 1960's, 333 farms were allocated on 79,000 ha of land with irrigation water diverted from the Murrumbidgee River. Rice is the predominant land use, and average irrigation water use is between 11 to 16 ML/ha (1100 to 1600 mm). Irrigation accessions to the groundwater led to dramatic increases in the shallow watertable areas. At present 54% of the CIA has groundwater within 4m of the ground surface.

The CIA is a part of the Riverine Plain alluvial fan. On the basis of age and type of deposition the sediments of the alluvial sediments are classified into three main groups: Renmark, Calivil and Shepparton formations. The Renmark group is the oldest stratigraphic unit lying above the pre-Cainozoic bedrock and was deposited between the Paleocene to middle Miocene ages. The Renmark formation consist of 30-50% sand and its mean hydraulic conductivity is greater than 12 m/day. The Calivil formation was deposited between the late Miocene to Pliocene ages and consists of 50% -70% sand with an average hydraulic conductivity of around 7 m/day. The Shepparton formation was deposited from the Paleocene age and consists of variable proportions of sand, silt and clay with an average hydraulic conductivity of 1.4 to 1.8 m/day. The general groundwater flow is from east towards west.

3.2 Description of Mathematical Model

A 4 layer, 60 by 66 mesh, 1.25 km square cell size calibrated MODFLOW model of the CIA [Khan et al. 2000a] was converted into an equivalent two layer 30x33 mesh model. The transformed groundwater model was run using a Matlab based solution of Equ. 2. The groundwater pressures for 1985 in the shallow and deeper aquifers were used as the starting heads in the model. Pumping from the Renmark and Calivil formations, general head boundaries and calibrated recharge rates were also incorporated in the Matlab model. Four areas with similar hydrogeologic conditions were defined, and these areas were further subdivided to produce the 11 economic units shown in Fig. 5.

The original 1980 states of the hydrologic model were reduced to 110 states using Matlab, Robust Control Toolbox. Soils in the area were classified into five soil types depending on their physical characteristics i.e. non-self-mulching clays, self-mulching clays, transitional red brown earths, red brown earths and sandier soils. Using soil hydraulic properties (available from previous studies) and Griffith daily weather data, transfer functions for the unsaturated zone were developed for rice, wheat, pasture and fallow land uses for each soil type using the procedures described in section 2.2. The state reduced groundwater model and the unsaturated zone transfer functions were integrated in a GAMS code. The 1999-2000 gross margins for rice, wheat and pastures were used to simulate economic returns. The non-linear optimisation solver CONOPT2 [Drud, 1996] available in GAMS was used to solve the integrated hydrologic economic model.

3.3 Details of Modelling Scenarios

The following social optimum scenarios were simulated:

S1) No rice restriction, water markets

S2) No rice restriction, no water markets

The following common pool scenarios were simulated:

C1) No rice restriction, water markets

C2) No rice restriction, no water markets

C3) 30% Rice restriction, water markets

C4) 30% Rice restriction, no water markets

3.4 Sample Scenario Results

In this section, results for scenario S1 (no rice restriction and water markets under a social optimum situation) are provided to illustrate the capabilities of the integrated hydrologic economic modelling framework. Figure 2 shows the groundwater response under economic units 1 to 11 under the rice, wheat, pasture and fallow land uses. It is important to note that watertables predicted by model are yearly average quasi-equilibrium levels based on implicit dynamic fluctuations around the predicted mean level taking into account 40 years of climatic variability through unsaturated simulations (Section 2.2) incorporated in recharge, water use and crop yield functions. The mean watertables rise to within 2 meters from the surface in the southern economic units (8-11) within 5 years, while for units 1 and 2 in the northern part of the irrigation area it takes more than 15 years before the mean watertables rise to within 2 m from the soil surface. This is explained by heavy groundwater pumping [Khan et al. 2000a] around the northern CIA which causes enhanced vertical and lateral flows from the region and keeps the watertables deeper than the rest of the irrigation area. The economic units in the central and western parts of the irrigation area take around 10 to 15 years before the watertables rise close to the surface.

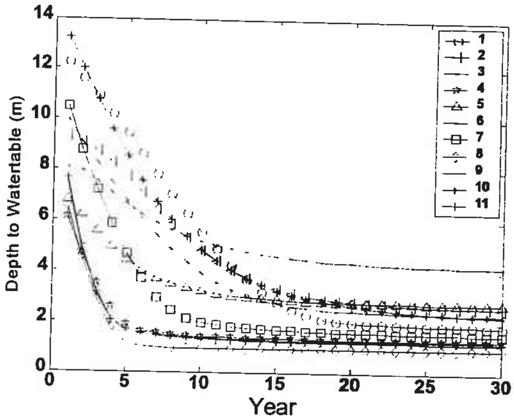

Figure 2. Groundwater response for economic units 1 to 11, scenario S1.

Figure 3 shows the increasing fractions of rice for different economic units with time due to rising watertable depths and shifting of water to more water use efficient regions. Since water trading is allowed between the economic units the water tends to shifts to the shallower watertable areas (southern economic units 8, 9 and 11) from the deeper watertable areas in the north, since it is more water efficient to grow rice under shallow watertable conditions.

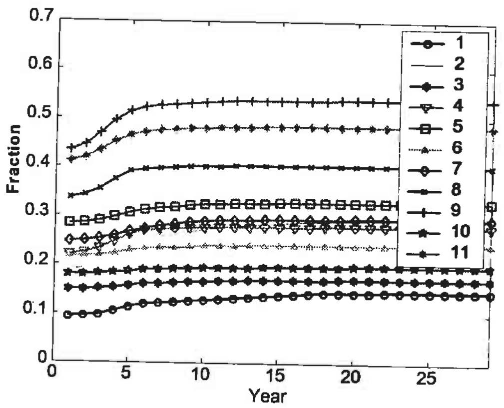

Figure 3. Optimum rice growing area fractions, scenario S1.

Figure 4 shows annual net revenue for the 30 years. A comparison with other scenario results (not presented here) shows that the overall economic returns for all scenarios are quite similar. Figure 5 shows the spatial distribution of rice area fractions, showing that the optimum economic locations for growing rice are located in the southern part of the irrigation area.

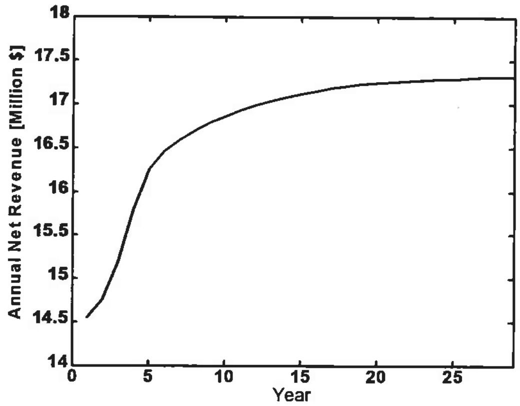

Figure 4. Social optimum economic returns.

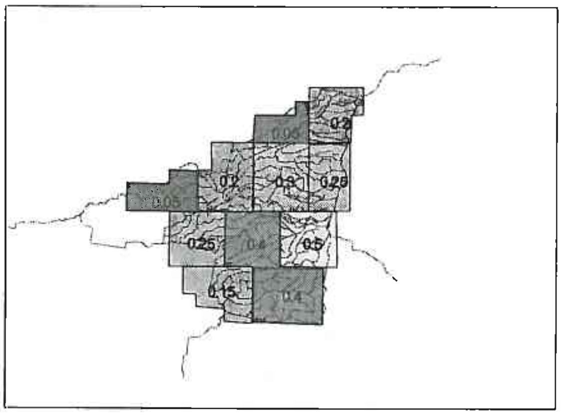

Figure 5. Spatial distribution of optimum rice growing area fractions.

4. CONCLUSIONS

This paper presents a new approach for integrating hydrogeological variability with the unsaturated zone, crop production considerations and economic optimisation. The current applications of this framework in the rice growing areas show the importance of considering regional groundwater dynamics in deciding rice growing policies. Sites with heavier soils and shallow watertables with minimum lateral and vertical flows are the best economic locations for growing rice as water requirements are minimised. The current rice growing policies are mainly based on the clay content of soils and rice water use limits. This work has highlighted the importance of incorporating groundwater dynamics in deciding environmental policies for growing rice.

5. ACKNOWLEDGEMENTS

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