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Integrated Biophysical and Economic Modelling Framework to Assess Impacts of Alternative Groundwater Management Options

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Abstract We developed an integrated biophysical and economic modeling framework to assess impact of various groundwater management options on seawater intrusion and waterlogging and ultimate impact on sugarcane profitability in a coastal region of North Queensland, Australia. The modelling framework used the output of a groundwater management flow model (waterlogged and seawater intruded areas) and a crop simulation model (simulated crop yield) and maximised the net revenue in a mathematical programming (optimisation) model. The framework determined the economically optimal level of water use on different soil types and in different management regimes and estimated impact of seawater intrusion and waterlogging on net revenue of growing sugarcane in two neighbouring water board areas (North Burdekin Water Board – NBWB and South Burdekin Water Board – SBWB). In NBWB, the predicted aggregate net revenue was highest ($19.95 million) when groundwater use was also highest (70%) while predicted aggregate net revenue was lowest when groundwater use was also lowest. In SBWB, the predicted aggregate net revenue was highest ($23 million) when groundwater use was relatively low (61%). The predicted aggregate net revenues of all the management options were higher in SBWB than NBWB.

Keywords Groundwater · Hydrologic · Agronomic · Economic · Simulation
Mathematical modelling · Optimisation

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1 Introduction

Water is becoming an increasingly scarce resource and therefore limiting agricultural development in many regions and countries of the world, including Australia. In the past, building new physical systems to harness water resources was the common policy. However, with increase in demand by other than agricultural users as well as harmful externalities of irrigation becoming apparent, emphasis is now being placed on demand management and improving the performance of existing irrigation systems. In the case of groundwater dependent irrigation, excessive use of groundwater can lead to higher concentrations of salts in the soil and thus to salinity. In some parts of the world, fertile irrigation lands have had to be abandoned due to salt concentration (Bonnis and Steenblik 1998). In coastal areas the lowering of watertables (aquifer levels) can lead to saltwater intrusion (Murphy and Sorensen 2001) and can degrade groundwater quality, rendering it unsuitable for irrigation. The lower watertables also increase pumping costs, and the depletion of aquifers by irrigation raises questions about the sustainability of farming systems. Continued use of groundwater demands a better regional irrigation management strategy which can reduce overexploitation of the aquifer.

Globally, efficient and sustainable management of water resources is increasingly becoming a policy objective. However, the complexity of water resources management requires an integrated biophysical and economic modelling framework that allows for the development of efficient and sustainable use of water use strategies. Conjunctive use of surface and groundwater, which adds operational flexibility, is a common element for integrated management of water resources. The first application of systems analysis to conjunctive use was proposed in 1961 (Castle and Lindeborg 1961). Coe (1990) defined the conjunctive use as the planned, coordinated combined use of different sources such as land and different sources of water over a period of time. Mohan and Jothiprakash (2003) described that conjunctive water use may comprise: (a) the entire area receiving the surface and groundwater throughout the season; (b) the entire area receiving surface water in one period while groundwater in other periods of the irrigation season; (c) part of the area receiving surface water while part of area receiving groundwater in a same season; and (d) mixing of good quality surface water with poor quality groundwater for irrigation or vice versa. However, despite the significant advantages of conjunctive use, its potential has not been fully developed and implemented in many real world water (irrigation) systems (Pulido-Velaquez et al. 2006).

Several conjunctive use optimisation models have been developed. In some studies, emphasis is given on economic theory by simulating the aquifer represented as a simple single tank or a bathtub (e.g., Provencher and Burt 1994). Some conjunctive use optimisation models incorporate stream–aquifer interaction either with lumped-parameter aquifer simulation or using more detailed aquifer simulation through distributed-parameter models, generally employing influence functions as groundwater response equations (e.g., Maddock 1974; Basagaoglu et al. 1999). Azaiez (2002) developed a multistage decision model for the conjunctive use of surface and groundwater with an artificial recharge. By assuming a certain supply and random demand, Azaiez integrated opportunity costs for the unsatisfied demand and incorporated the importance of the weight attributed by the decision-makers to the final groundwater aquifer level at the end of the planning horizon. Mohan and Jothiprakash (2003) used a combined optimisation–simulation approach to develop and evaluate the alternate priority-based policies for operation of surface and groundwater systems. Qureshi et al. (2006) developed an integrated analytical framework including hydrologic, agronomic and economic components, and investigated the costs imposed on irrigators by restricting groundwater use and the potential for more flexible annual extraction rules that account for seasonal variations in rainfall to reduce these costs. Pulido-Velaquez et al. (2006) presented an integrated hydrologic–economic modelling framework for optimising conjunctive use of surface and groundwater at a river basin scale in Spain.

All these studies mentioned above made significant progress in conjunctive use of surface and groundwater along with estimating costs of groundwater restrictions. However, these studies did not account for environmental issues and estimated costs and benefits in monetary terms for alternative groundwater management options, such as issues of seawater intrusion and waterlogging. Therefore, there is a need to identify and link impacts of excessive surface and groundwater use through an approach that not only accounts for benefits and costs of water use in the form of agricultural production but also accounts for waterlogging, salinity and as a result impact on crop yield along with accounting for seawater intrusion and its impact on groundwater quality.

The aim of the current study was to estimate net benefits of conjunctive surface and groundwater use along with investigating the potential impact of waterlogging and seawater intrusion in a coastal region of sugarcane production. An integrated biophysical and economic modeling framework was used to determine the economically optimal level of water application on different soil types for alternative groundwater management option. The framework was also used to estimate the impact of these management options on sugarcane profitability in two areas of the Burdekin delta which are administered by the two water boards with different irrigation water management practices.

2 Burdekin Delta Irrigation Area and Groundwater Management System

2.1 Location and Economic Importance of Burdekin Delta

The Burdekin delta region is located on the northeast coast of Australia with an area of about 850 km^2. The region has a tropical climate and seasonal rainfall, with annual total rainfall ranging between 250 and 2,500 mm, and averaging about 1,000 mm. Evaporation varies from 10 mm/day in November to 2.8 mm/day in June (Arunakumaren et al. 2000). Water flows in the Burdekin River vary enormously within and between years.

The Burdekin delta is one of the most important regions of sugarcane production in Australia. It is one of the few regions in Queensland where sugarcane is grown under full irrigation and conjunctive use of groundwater and surface water is common (Qureshi et al. 2001a). The region is predominately used for sugarcane production because of excellent climatic conditions and the suitability of the soils for the crop (Charlesworth et al. 2002). As a result, sugarcane yield in this region is the highest in Australia. Some small areas are used for tropical fruits and vegetables while the remaining areas where groundwater or soil quality is not suitable are used for cattle grazing. Though the financial returns from fruits and vegetables are much higher than sugarcane, the sugarcane growers who are generally risk averse are loath to shift out of sugarcane production due to uncertain future demand and price prospects for these products if production expands. In addition, sugar is a vertically integrated industry, which requires significant investment in transport and milling infrastructure and a reduction in sugar production would therefore have a significant impact on the whole industry and on the local economy with ripple effects flowing on to other sectors. Also, there is considerable personal preference among growers to continue sugarcane production due to contract farming system.

The Burdekin region produces more than eight million tonnes of cane each year. The sugarcane is crushed and processed into more than one million tonnes of sugar. Sugarcane production injects millions of dollars into the local economy each year, making the Burdekin one of the wealthiest primary production districts in Queensland. Farmers credit the high yield to a combination of rich soils, abundant underground water supplies and year-round sunshine. The region is served by four sugar mills. In 2000–2001, the gross value of sugar production in the region was $177 million which was 28% of Queensland's sugar production by value. A further $92 million in value was added at the farm level and another $44 million through sugar processing (Beare et al. 2003).

2.2 Burdekin Delta Groundwater Management System

The production of irrigated sugarcane in the Burdekin delta region commenced in 1887. The demand on the shallow groundwater supplies increased rapidly as the area under sugarcane expanded. This resulted in a decline in groundwater levels in some parts of the region. Investigations into the problem of groundwater decline revealed an extensive aquifer system which when full represented a significant reservoir of water and one of the largest alluvial aquifer systems in Australia. Further investigation of the aquifer system indicated that it is possible to replenish this aquifer system artificially. As a result, an artificial groundwater recharge scheme was implemented by the Queensland Department of Natural Resources and Mines (formerly Irrigation and Water Supply Commission). It involved setting up the North and South Burdekin Water Boards in 1965 and 1966 respectively to pump water from the Burdekin river into creeks and lagoons some distance away from the river channel in order to replenish the underground aquifers. A study in the mid-1990s identified a number of issues including rising watertable levels in some areas, and an increase in groundwater salinity in other areas of the delta caused by seawater intrusion into the aquifer (SK&M 1997). This study argued that seawater intrusion was a significant threat and a potential limiting factor on the sustainable level of groundwater extraction for sugarcane production in the long term. The study also recognised emerging issue of salinity as a result of rise in watertable levels caused by excessive use of surface water.

The Water Boards use a number of strategies to manage groundwater replenishment, including the use of sand dams in the Burdekin River and a series of distribution channels and natural waterways together with large recharge pits. The sand dams are constructed and maintained in the Burdekin River and are used to contain releases from upstream storages and to help maintain practical operating levels at river pump stations. Farm water practices such as "recycling", "water spreading", and more recently direct pumping from recharge channels to farms in some distal aquifer zones have also evolved to play an integral role in the management of the groundwater systems (Bristow et al. 2000). A schematic representation of key factors in the Burdekin delta irrigation area is shown in Fig. 1.

Several studies have examined the recharging scheme analysing siltation and clogging of artificial recharge channels and pits, for example O'Shea (1985), who concluded that the recharge scheme had been operated successfully since its inception in 1965. While artificial recharge is still occurring in the delta, the water management boards have now shifted their emphasis from groundwater recharge to achieve more efficient and more sustainable use of water by encouraging the farmers in the area to adopt better irrigation management practices. Irrigators in the delta now use a combination of surface water and groundwater. They purchase surface water from the public authority which is relatively more expensive than the groundwater pumped by irrigators on their own farms. The low groundwater charges could cause overpumping of the groundwater resources.

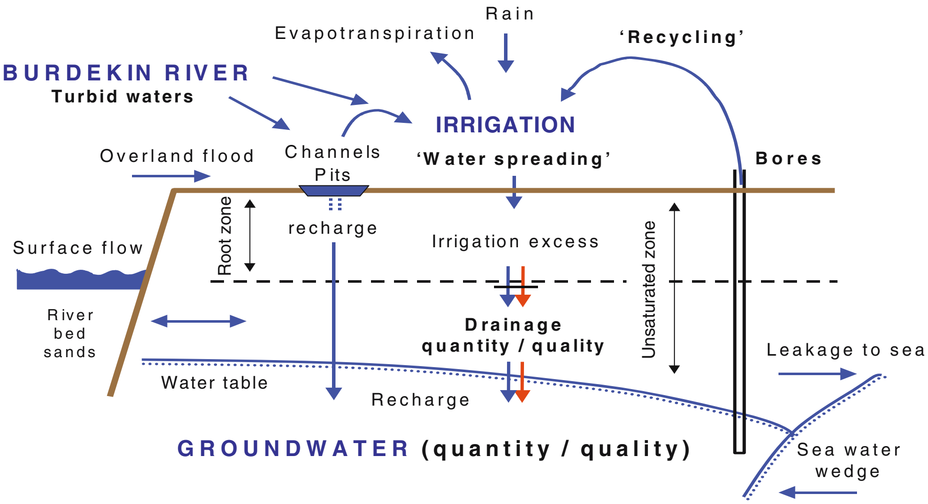

Fig. 1 Schematic representation of key factors in the Burdekin delta irrigation area, source: Bristow et al. (2000)

The appropriate management of the aquifer in the Burdekin delta is not only essential for continued production of sugarcane and other agricultural activities but also critical because the area is situated close to environmentally sensitive wetlands, waterways, estuaries, and the Great Barrier Reef (World Heritage Listed Area) (Bristow et al. 2003). Some sugarcane farms are located within 1 km of the coast and the impact of irrigation management practices on the coastal environment can be significant. If groundwater extraction were to cease and only surface water is used for irrigation, then there is a risk of waterlogging and salinity problems in the area. On the other hand, if the extraction of groundwater continues at the present rate, seawater intrusion may affect groundwater quality, rendering it unsuitable for irrigation.

A delicate balance between the use of groundwater and surface water is required through appropriate design and implementation of management practices for the long-term viability of irrigated agriculture in the delta area while achieving acceptable environmental impact (Bristow et al. 2003). An understanding of the hydrology of the local aquifer system, along with the financial and/or economic consequences of groundwater management practices, is essential for sustainable long term agricultural production while maintaining the value of tourism and recreational assets in the region.

3 Integrated Modelling Framework and Data Collection

The integrated approach used in this analysis included three principal components, as shown in Fig. 2:

(a) an existing groundwater management model to examine the extent of areas associated with salt water intrusion and waterlogging by simulating the behaviour of the aquifer in response to various management strategies;
(b) a crop yield model to estimate yield of sugarcane in the area on different soil types under a range of different irrigation levels and application methods; and

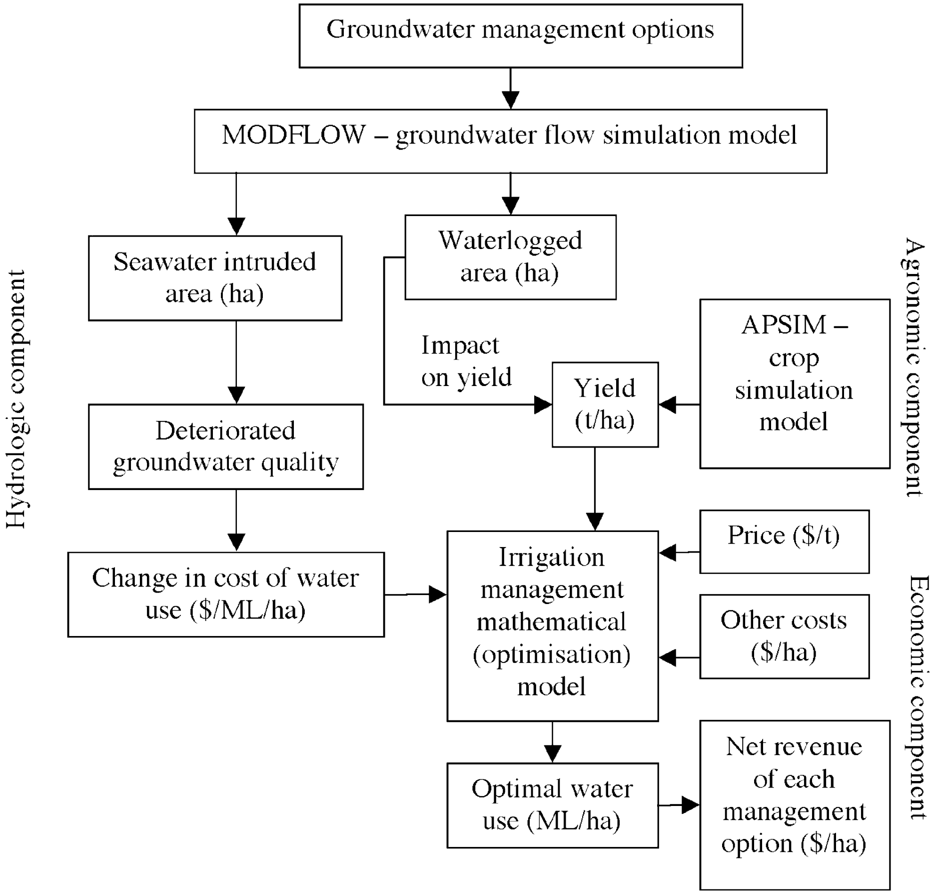

Fig. 2 A schematic presentation of integrated biophysical and economic modelling framework

(c) a regional mathematical programming model to examine change in surface and groundwater use proportions and to assess aggregate net revenue from growing sugarcane in the delta area under a range of management options.

3.1 Hydrologic Component – Estimation of Areas Lost to Waterlogging and Seawater Intrusion

The objective of the hydrologic component was to simulate the behaviour of the groundwater system underlying the Burdekin delta area and estimate areas subject to seawater intrusion and waterlogging in the region.

Since no historical groundwater extraction records were available, the groundwater extraction for the period from 1981 to 2000 was estimated by Arunakumaren et al. (2000) utilising their SPLASH model. SPLASH (Soil, PLAnt Salinity and recHarge) is a lumped parameter model for simulating the temporal behaviour of moisture in the plant root zone and in the unsaturated zone below the root zone. The model produced simulated time series of consumptive use, irrigation demand, run off from the soil surface, recharge to the aquifer,

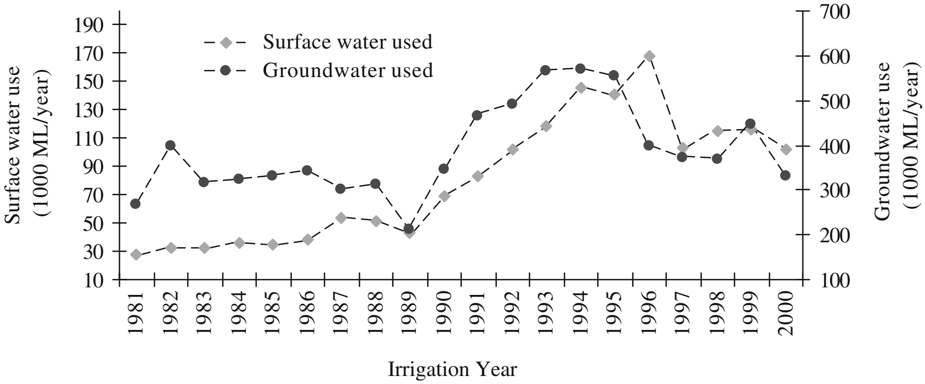

Fig. 3 Use of groundwater and surface water for irrigation – 1981 to 2000

salinity concentration of the root zone water and salinity of the recharge water. In the model, the area was divided into three zones based on the average crop water usage and the farm efficiency factors. The model was calibrated so that the SPLASH-simulated irrigation matched the average irrigation in the respective zones. The SPLASH model was used to determine recharge and extraction rates in the model (Arunakumaren et al. 2000). The simulated annual historical pumping between 1981 and 2000 varied between 211,000 and 568,000 ml/year, as shown in Fig. 3. Thus, despite improvements in irrigation practices, groundwater extraction has increased due to expansion of land for sugarcane production in the delta area. The use of surface water has also increased but the groundwater usage is much higher. The maximum groundwater use in 1994 was about 550,000 ml compared to about 140,000 ml of surface water use.

3.1.1 Groundwater Flow Model

An existing numerical model of the Burdekin Delta aquifer in MODFLOW (McDonald and Harbaugh 1988) based on conceptualisation of hydrological and hydro geological features of the Burdekin Delta system (Arunakumaren et al. 2000, 2001) was adapted. Published guidelines (e.g., Anderson and Woessner 1991) were used in its development. MODFLOW is a three-dimensional finite difference flow code that simulates groundwater levels in space and time subject to aquifer stresses such as groundwater pumping and recharge along with the boundary conditions.

3.1.2 Alternative Groundwater Management Options

The groundwater flow model was used to simulate six irrigation water management options including a baseline case to explore two potential impacts, the extent of waterlogging and potential seawater intrusion. The baseline simulation of groundwater levels in the delta was run for a 50-year period using 1981 initial conditions (e.g., water levels) and 1998 land use data. The other groundwater management options consisted of different groundwater extraction rates from this base case. The five irrigation management options considered for economic analyses were:

Option 1: Reduce groundwater use by 20%;
Option 2: Reduce surface water use by 10%;

Option 3: Increase surface water use by 30%;
Option 4: Cease pumping from all bores in areas where seawater intrusion has occurred; and
Option 5: Reduce surface water use by 50% in areas that are not subject to seawater intrusion.

These options were selected arbitrarily. They represent potential future irrigation water management policies by the Water Boards in the area to address water quantity and quality issues as well as sustainable sugarcane production objectives and regional economic development. The maximum water used by sugarcane crop on each soil type was held constant irrespective of a reduction in one source of water. Thus, when groundwater was not used for sugarcane irrigation due to its poor quality as a result of seawater intrusion, surface water substituted it.

3.1.3 Waterlogged Areas

The numerical groundwater management model resulted in groundwater levels at each grid point for each time step. The areas where the groundwater levels were predicted to be above some pre defined critical depth from the natural surface for a certain number of days was used to indicate the impact of waterlogging on the sugarcane crop. The areas with the potential threat from waterlogging were assessed for three major soil types (clay – low permeability, silt – medium permeability, and sand – high permeability) of the region. The areas where the watertable was predicted to be less than 2, 1, and 0.5 m from the natural surface for a set number of days were calculated for each soil type. Waterlogged areas for these three cases under each management option were estimated for each soil type. Since the focus of economic analysis is on sugarcane which is the major irrigated cropping activity in the delta, only those areas where sugarcane is grown were included in the economic analysis. Total waterlogged areas, estimated for the base case and the five management options, are presented in Table 1.

3.1.4 Seawater Intruded Areas

In a similar way to the waterlogged area estimation, the areas near the coast where groundwater levels were predicted to be below mean sea level (0 m AHD – Australian Height Datum) for a certain number of days (the period of concern) were delineated using the simulated water levels. The coastal areas with groundwater levels below 0 m AHD

Table 1 Waterlogged areas (in hectares) in Burdekin delta for various management options (assessed as rise in watertable relative to the natural surface)

Depth (m)	Base case	20% decrease in GW* use Option 1	10% decrease in SW* use Option 2	30% increase in SW use Option 3	Cease GW use in sea water affected areas Option 4	50% decrease in SW use in sea water exempt areas Option 5
2 m	50,066	52,038	48,314	53,410	54,304	46,526
1 m	44,602	47,836	42,961	49,245	50,384	40,952
0.5 m	41,552	45,680	39,972	47,469	48,743	38,379

*GW** = Groundwater, *SW** = surface water

indicated the risk of seawater intrusion. The distribution of areas in the delta with this potential threat was assessed for the three major soil types. The total areas and sugarcane areas subject to seawater intrusion under each management option in the Burdekin delta are given in Table 2.

3.2 Agronomic Component – Simulation of Sugarcane Crop Yield

The APSIM (Agricultural Production Systems Simulator) cropping systems model (McCown et al. 1996) was used to simulate sugarcane yield. The APSIM model comprises a soil water module, a soil nitrogen cycling module, and a surface residue module linked to a sugarcane growth module. The model operates on a daily time step, grows a leaf canopy, uses intercepted radiation to produce assimilate, and partitions this assimilate into leaf, structural stalk, and sugar. The crop physiological processes represented in the model respond to the radiation and temperature environment and are sensitive to water and nitrogen supply (Keating et al. 1999). APSIM-Sugarcane has been tested and used extensively under Australian conditions, including the Burdekin region (Muchow and Robertson 1994; Connolly et al. 2002; Charlesworth and Bristow 2004).

Long-term climate files for the study area consisting of daily rainfall, minimum and maximum temperatures, and solar radiation data from 1975 to 1994 were used as inputs (along with a crop cycle consisting of one plant crop followed by three ratoon crops) for the simulation runs. These files included a combination of recorded weather station data and data from generated meteorological sequences, obtained from the Bureau of Meteorology and the Queensland Centre for Climate Applications.

To represent profiles with sharply contrasting levels of plant-extractable soil water, crop simulations were performed to estimate response to applied irrigation for the three soil types. Water application rates from zero to 35 ml/ha (in 1-ml increments) and application efficiencies ranging from 30% (for the existing furrow irrigation system) to 90% (for alternative application methods including centre pivot irrigators and trickle irrigation) were simulated. The yield response function of less efficient but most common furrow irrigation system used for the three soil types in the economic analysis is shown in Fig. 4. Simulated yields were about 20% higher than the average sugar yield for each soil type in the region because the model did not account for losses associated with pests, disease, weed competition, or unusual climatic events and results are based on uniform soil characteristics. Therefore, the yield estimates for the various irrigation options were reduced by 20% to give a realistic assessment of the sugarcane profitability in the region (Qureshi et al. 2001b).

Table 2 Area (hectares) affected by sea water intrusion under different management options

	Base case	20% decrease in GW* use Option 1	10% decrease in SW* use Option 2	30% increase in SW use Option 3	Cease GW use in sea water affected areas Option 4	50% decrease in SW use in sea water exempt areas Option 5
Modelled area	20,029	6,468	26,264	3,283	3,185	36,285
Sugarcane area	8,012	2,587	10,506	1,313	1,274	14,514

*GW** = Groundwater, *SW** = surface water

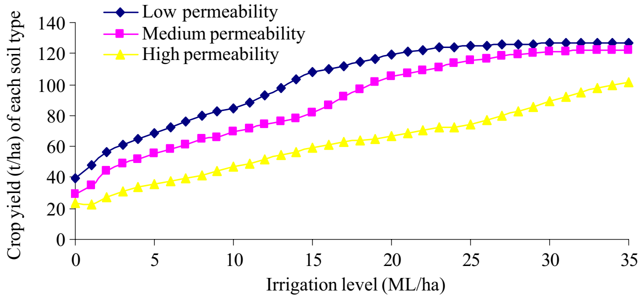

Fig. 4 Crop yield response function of three soil types for low efficient furrow irrigation system

3.3 Economic Model – Estimation of Costs And Benefits of Management Options

An economic model of sugarcane farm profitability was developed using the GAMS (General Algebraic Modelling System) software (Brooke et al. 1998). This model was used to assess impact of a base case and five groundwater management options analysed in the groundwater flow model (discussed above in section 3.1). The objective function of the model was to maximise aggregate annual net revenue from farms growing sugarcane in the delta region. It was assumed that farmers are risk neutral and their objective is maximisation of annual net revenue from their income generating activities. For each groundwater management option, the irrigation management model determined the optimal level of irrigation *l*, for each soil type *s*, area of land available for sugarcane cropping *c* (plant and ratoon crops). The model was also used to calculate the aggregate net revenue for each management option by deducting sugarcane growing costs from sugarcane revenue. Thus the objective function in the model represented the aggregate result of profit maximising decisions by individual farmers under the assumption that they all face a similar decision-making environment. This is an acceptable assumption in the sugar industry where all producers in a mill area receive the same price for their product adjusted for quality parameters.

3.3.1 Objective Function

The model maximised aggregate net revenue under each management option according to the objective:

$$\max\ R = \sum_s \sum_l X_{sl} \times [Y_{sl}(1-\delta_s) \times (P(0.009(\mathrm{CCS}-4)+K))]$$
$$-\sum_s \sum_l X_{sl} \times (\mathrm{IC}_{sl} + \mathrm{OPC}_{sl} + \mathrm{FC}_{sl} + \mathrm{SWP}(\lambda_s)(\mathrm{TWU}_{sl})$$

where:

s	aggregate level of soil resources (identified by soil series/types)
l	irrigation water application level/rate (0–35 ml/ha with an increment of 1 ml)
R	net revenue (\$)
X_{sl}	land area (ha)
Y_{sl}	yield (t/ha)

δ_s penalty factor which reduces cane yield (proportion) in waterlogged areas
P price of raw sugar used as a variable in the standard sugarcane price formula ($/tonne)
CCS-4 commercial cane sugar – commercially recoverable sugar content in sugarcane (%) – a factor originally designed to allocate proceeds two-thirds to growers and one-third to millers when the CCS was 12% and the mill coefficient of work was 90, and the amount of sugar the mill extracts is about 90%, and K is a constant with a value of 0.578 (Wegener 1990; Qureshi and Harrison 2001)
IC_{sl} irrigation related costs ($/ha)
OPC_{sl} other operating costs ($/ha)
FC_{sl} fixed costs ($/ha)
SWP seawater penalty in seawater intruded area ($/ml)
λ_s seawater intruded area (proportion)
TWU_{sl} total water use (ml/ha)

The penalty factor δ_s reduced the proportionate cane yield in all those areas which are subject to waterlogging by a factor WL_s depending on the soil type, and is defined by:

$$\delta_s = \begin{cases} \mathrm{WL}_s & \text{if waterlogged} \\ 0 & \text{otherwise} \end{cases}$$

It is to be noted that fixed and operating costs were the same for all the management options with the exception of irrigation related costs which varied from option to option. Irrigation related costs were divided into five parts: irrigation operating costs (IOC_{sl}), electricity costs for groundwater pumping (GWEC_{sl}), electricity costs for surface water pumping (SWEC_{sl}), groundwater cost (GWC_{sl}), and surface water cost (SWC_{sl}). A breakdown of these costs is:

$$\mathrm{IC}_{sl} = \mathrm{IOC}_{sl} + \mathrm{GWEC}_{sl} + \mathrm{SWEC}_{sl} + \mathrm{GWC}_{sl} + \mathrm{SWC}_{sl}$$

where:

$$\mathrm{GWEC}_{sl} = \mathrm{GWU}_{sl} \times \mathrm{ECGW}$$
$$\mathrm{SWEC}_{sl} = \mathrm{SWU}_{sl} \times \mathrm{ECSW}$$
$$\mathrm{GWC}_{sl} = \begin{cases} \mathrm{WC} & \text{if } \mathrm{GWU}_{sl} > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{SWC}_{sl} = \begin{cases} \mathrm{SWU}_{sl} \times \mathrm{SWP}_a & \text{if} \quad \mathrm{SWU}_{sl} \leq \alpha \\ \alpha \times \mathrm{SWP}_a + (\mathrm{SWU}_{sl} - \alpha) \times \mathrm{SWP}_b & \text{if} \quad \mathrm{SWU}_{sl} > \alpha \end{cases}$$

$$\mathrm{SWU}_{sl} = \mathrm{TWU}_{sl} \times \beta, \quad \mathrm{GWU}_{sl} = \mathrm{TWU}_{sl} \times \gamma \quad \text{and} \quad \beta + \gamma = 1$$

GWU_{sl} groundwater use (ml/ha)
ECGW electricity cost for pumping groundwater ($/ml)
SWU_{sl} surface water use (ml/ha)
ECSW electricity cost for pumping surface water ($/ml)

WC	groundwater charges (\$/ha)
SWP_a	low rate charge for surface water (\$/ml)
SWP_b	high rate charge for surface water (\$/ml)
α	low surface water charges threshold level (beyond the threshold, surface water charges are higher)
β	surface water use (proportion), and
γ	groundwater use (proportion)

The proportions of surface (β) and groundwater (γ) use depended on the area of sugarcane affected by seawater intrusion under each management option. For all of the affected areas with each management option, groundwater use was reduced and surface water substituted it. Each management option attracted a penalty factor as a result of seawater intrusion. A constant penalty value (λ) was imposed across the management options depending on their areas subject to seawater intrusion and optimal usage of water (ml/ha) on each soil type. For example, if optimal water was 25 ml and 100 ha were subject to seawater intrusion then this penalty (say, \$15/ml) was multiplied by total water usage (ml/ha). This value is imposed due to shift in surface water use which is relatively more expensive than groundwater use charges.

3.3.2 Land and Water Constraints

The land and water constraints were:

$$\sum_{s}\sum_{l} X_{sl} \leq A$$

$$\sum_{l} X_{sl} \leq A \times \Pr_{s}$$

$$\sum_{s}\sum_{l} X_{sl} \times (\mathrm{PSW}_{sl} + \mathrm{PGW}_{sl}) \leq W$$

where:

A	total area available (ha)
$\Pr_s$	soil type s area (proportion)
PSW_{sl}	surface water use (proportion)
PGW_{sl}	groundwater use (proportion)
W	total water available for irrigation from two sources (ml/ha)

3.4 Case Study Area Data Collection Procedure

In the irrigation management model, the areas controlled by the North and South Burdekin Water Boards were regarded as one integrated unit and the total areas subject to seawater intrusion and potentially affected by waterlogging were estimated. The model was used to evaluate and compare the management strategies used in the North and South Burdekin Water Board Areas to reduce dependence on groundwater resources in the Burdekin delta. There are differences in the structure of groundwater charges between the two boards and in the threshold volume of water above which the high-rate charges for surface water apply. Also, the proportions of groundwater and surface water used are different, due to differences in quality of groundwater and the rate at which the aquifer is being recharged. In the area controlled by North Burdekin Water Board, the proportions of groundwater and surface water are 40% and 60% respectively, while in the South Burdekin Water Board area, these proportions are 70% and 30%, respectively. The average cane farm in the area serviced by NBWB uses less groundwater and more surface water than an average cane farm in the SBWB area. Based on estimates of a previous study (Arunakumaren et al. 2000), the proportion of the three soil types in the study area were low permeability 33%, medium permeability 56%, and high permeability 11%.

Information on technical and economic systems of cane farming in the study area which affects model parameters was obtained from published literature, various public departments and organizations, the water supply authorities, farmers and their organisations, as well as from various irrigation and other business organizations, such as banks. Information from these sources was cross-checked through informal discussion with local farmers and representatives of relevant organisations.

Sugar production cost data were obtained from a survey report (Small 2000) and from the office of CANEGROWERS. Fixed costs were estimated by the ABARE Farm Survey (ABARE 1996). The information about permanent (family) labour hours used and labour costs were estimated after discussions with growers and from the office of the CANEGROWERS. Electricity charges were estimated on the basis of the appropriate electricity tariff and pumping rates for groundwater as well as surface water. Some costs were area based while others were based on water usage. Water charges and the threshold payment structure were obtained from material published by the water supply authorities.

The basis for minimum threshold water charges for low and high surface water usage was different for the two authorities. For example, groundwater charges by NBWB were AU$68.50/ha while SBWB charges AU$48.50/ha. As a whole, the water charges imposed by the NBWB were higher than the SBWB. The proportions of groundwater and surface water used in each of the two board areas also differed and this resulted in different cost structures for irrigators in each water board area. The model reflected these differences. The areas available for sugarcane production in NBWB and SBWB were different. However, total area under sugarcane in the whole delta region was about 35000 ha. For simplicity, this area was used for economic analysis in both NBWB and SBWB regions for comparison.

3.4.1 Seawater Intruded Areas

The area where the fresh water level might fall below mean sea level and affect groundwater quality estimated (in the section 3.1 above) for each soil type under each management option was used to estimate economic impacts. It was assumed in the analysis that all the areas which faced seawater intrusion would no longer use groundwater (because of poor quality water) in the affected areas and would rely on alternative sources of water (either pumping groundwater from other areas or on surface water) for sugarcane production. The proportion of area depended on groundwater and surface water for sugarcane production under each management option was therefore estimated. For example, in the NBWB area, irrigators were required by the NBWB to use 40% groundwater and

60% surface water on their sugarcane land. It was assumed in the analysis that out of 100 ha (for example), 40 ha will be irrigated by groundwater and 60 ha by surface water. In the base case, the hydrology model estimated that 28% of the groundwater area which is 40% of the total land would be subject to seawater intrusion and have impact on groundwater quality (i.e. 40×28%=11 ha). As a result, this area (11 ha) would attract the penalty factor which would increase total cost of production and have impact on profitability of sugarcane production. The model has been modified appropriately to estimate impact of seawater intrusion and to account for increase in cost of water charges on each management option.

3.4.2 Waterlogged Areas and Impact on Crop Yield

Waterlogging can be the consequence of accumulated precipitation over an extended period, shallow groundwater tables, irrigation, or a combination of these factors (White 2001). The impact of waterlogging on crop yield also depends on a number of factors including soil type, depth of water table from the soil surface along with the local environmental conditions. Kahlown and Azam (2002) evaluated the impact of waterlogging on the yields of major agricultural crops including sugarcane. They found up to 33% loss in the yield of sugarcane when the water table was less than 1 m from the soil surface. No scientific study was found in the Burdekin region which describes the impact of waterlogging and/or salinity on cane yield. However, the local sugarcane research centre reported that each day the watertable remained within 0.5 m of the soil surface could result in a reduction in potential cane yield of 0.5 tonnes per ha. If the soil remains waterlogged for 100 days, sugarcane crop can reduce up to 50 tonnes per ha (BSES 1998, p. 47).

The hydrology model (discussed above) simulated areas where watertable was less than 0.5, 1 and 1.5 m from the soil surface. In the current analysis only those areas where the groundwater is less than 0.5 m below the soil surface were used to estimate impact of each management option. The total areas estimated to be subject to waterlogging in the region and the areas of sugarcane affected (40% of the region) when watertable level was less than 0.5 m from the natural surface are presented in Table 3.

After discussions with agronomists and irrigation scientists involved in the sugar industry research projects about impact of waterlogging on sugarcane yield, it was assumed that the impact on cane production from waterlogging and salinity would differ between soil types and the low permeability soil would be affected more than the highly permeable soil. Over two thirds of the annual rainfall in this area occurs during the months of January to March and for the current analysis, it was assumed that there will be yield reductions of

Table 3 Water logged areas (in hectares) where water table rises to less than 0.5 m from the natural surface

	Base option	20% decrease in GW* use Option 1	10% decrease in SW* use Option 2	30% increase in SW* use Option 3	Cease GW* use in sea water affected areas Option 4	50% decrease in SW* use in sea water exempt areas Option 5
Modelled area	41,552	45,680	39,972	47,469	48,743	38,379
Sugarcane area	16,621	18,272	15,989	18,988	19,497	15,352

*GW** = Groundwater, *SW** = surface water

20%, 16%, and 12% respectively in cane growing on low permeability, medium permeability, and high permeability soil types. The coefficients in the model were adjusted accordingly for each management option.

The average yield from each soil type for cane grown with most common furrow irrigation system were obtained using the APSIM crop yield simulation model and were adjusted as described previously. Sugar content data were obtained from the local sugar mill and an average of the past 10 years data was used in the analysis. Similarly, the average pool price ($325 per tonne sugar) of sugar in Queensland was used and the price paid to growers for cane was estimated using the standard cane price formula (Wegener 1990; Qureshi and Harrison 2001).

4 Results and Discussion

Figure 5 presents impact of groundwater use on seawater intruded and waterlogged areas in both NBWB and SBWB. There is positive relationship between groundwater use and seawater-intruded area and negative relationship between groundwater use and waterlogged area. These functional relationships and their impacts were critical for estimating net revenue of alternative groundwater management option.

In NBWB, the optimal levels of water application for the three soil types were the same for the base case and four management options, i.e. 23, 28 and 35 ml/ha, for low, medium, and high permeability soil types, respectively while in fifth management option, the optimal levels of water application for these soil types were 27, 31 and 35 Ml/ha, respectively. In SBWB, the optimal irrigation levels for low, medium and high permeability soil types remained the same for all the management options (i.e. 27, 31 and 35 ml/ha), except the management option 4 in its low permeability soil type (i.e. 23 ml/ha). The slightly higher irrigation application rates in SBWB were due to its the greater reliance on groundwater in

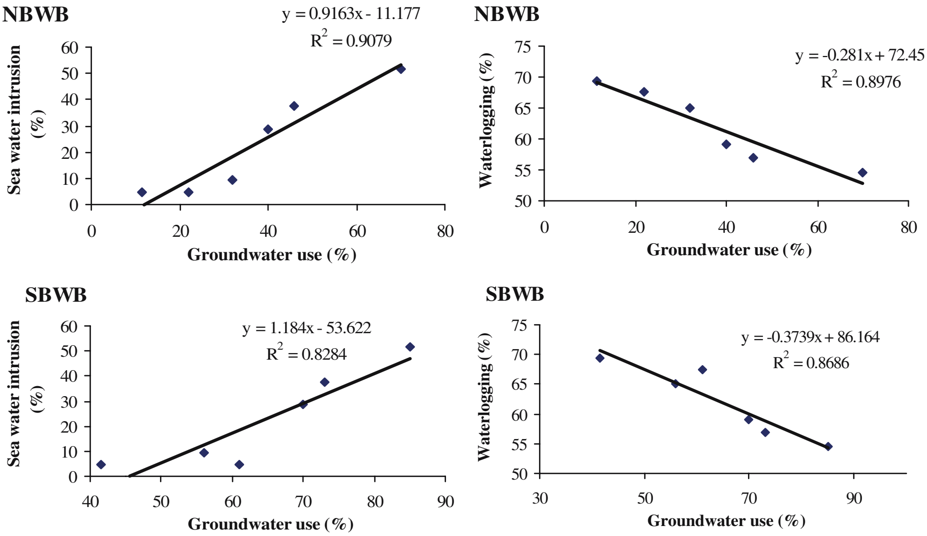

Fig. 5 Relationship between groundwater use and seawater intruded and waterlogged areas in NBWB and SBWB

the SBWB area which was less expensive than surface water and due to relatively less surface water charges compared to NBWB. It is to be noted that this level of irrigation water application may seem large compared to other agricultural activities and/or in other regions but it is a common practice due to the aquifer recharging and low efficiency furrow irrigation system in the region.

The net revenue per ha of each management option is presented in Table 4. In NBWB, the net revenue was highest ($764) for low permeability soil types in option 2 while the net revenues for medium and high permeability soil types were highest (i.e., $655 and $398, respectively) in option 1. The net revenues were lowest for option 4 in low permeability soil type ($716/ha), for the base case in medium permeability soil type ($621/ha) and for option 5 in high permeability soil type ($341/ha). In SBWB, the net revenues from option 2 were highest for low ($862 per ha), from option 1 for medium permeability soil type ($796 per ha) and from option 1 for high permeability soil type ($584/ha) while the net revenues were lowest for low permeability soil type from option 4, for medium permeability soil type from the base case ($757/ha) and for high permeability soil type from option 5 ($539/ha).

Figure 6 (a) indicates that in NBWB, aggregate net revenue was highest ($19.95 million) for option 5 where increase in groundwater use though increased seawater intruded area but resulted in less waterlogged area compared to the base case who is ranked fourth on the basis of aggregate net revenue ($18.64 million). In option 4, least groundwater use resulted in minimum seawater intruded area but increased waterlogged area significantly. Aggregate net revenue of this option is least ($16.17 million) as a result of impact on crop yield of waterlogged area. The situation in SBWB, as shown in Fig. 6 (b) is different. The aggregate net revenue is highest ($23 million) in a relatively less groundwater use option 3. Seawater intruded area in this option was second least while waterlogged area was second most among all the management options.

Figure 7 shows relationship between groundwater use and net revenue in both NBWB and SBWB. Figure 7 (a) indicates that in NBWB, there is always positive correlation between groundwater use and aggregate net revenue while Fig. 7 (b) indicates that in SBWB, this relationship is not always positive. In the later case, after 61% of groundwater use, there is a negative correlation between groundwater use and the aggregate net revenue.

Table 4 Net revenue per ha for each management option for each soil type ($AU=$US0.77, 8 February 2007)

Management option	Base case ($/ha)	Option 1 ($/ha)	Option 2 ($/ha)	Option 3 ($/ha)	Option 4 ($/ha)	Option 5 ($/ha)
NBWB area						
Low permeability soil	722	744	764	731	716	760
Medium permeability soil	621	655	650	648	637	638
Highly permeable soil	358	398	366	398	391	341
SBWB area						
Low permeability soil	814	832	862	819	804	861
Medium permeability soil	757	796	795	788	777	782
Highly permeable soil	541	584	560	582	575	539

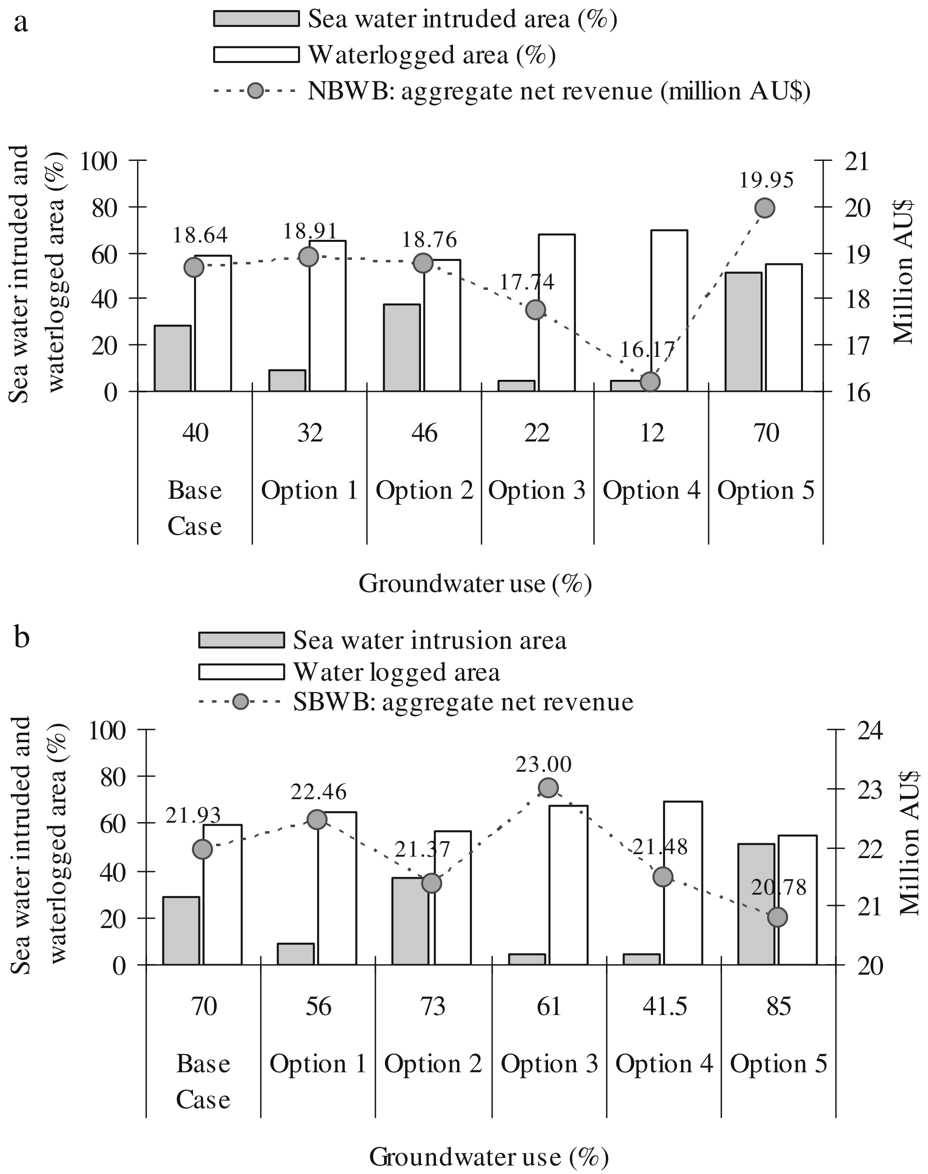

Fig. 6 Waterlogged and seawater intruded areas (%) along with aggregate net revenue of alternative management options in **a** NBWB and **b** SBWB

Further increase in groundwater use beyond this level resulted in less aggregate net revenue. Key parameters used which are different in the two areas are proportions of groundwater and surface water use along with surface and groundwater charges. Further analysis revealed that high surface water charges caused greater impact on the aggregate net revenues. A decline in surface water charges resulted in the similar trend in NBWB which appeared in SBWB. Further increase in groundwater use beyond a certain point in each management case resulted in less aggregate net revenue. It is clear from these figures that

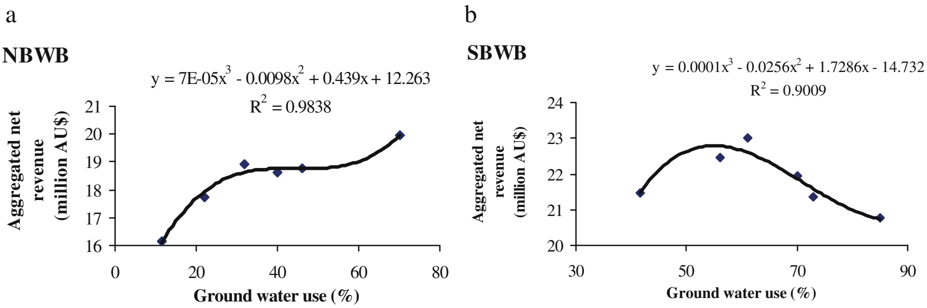

Fig. 7 Predicted groundwater use and predicted aggregate net revenue for NBWB and SBWB

the net revenues for all management options in the SBWB are higher than the net revenues for the NBWB because the proportion of groundwater usage in the SBWB area is higher, and groundwater costs are less.

Figure 8 presents relationship between groundwater use and aggregate net revenues for three soil types. In NBWB, the relationship in low permeability soil type is always positive while in medium and high permeability soil types, the relationship is positive at the beginning, negative at the middle and positive at the end of groundwater use. In SBWB, shape of the relationship between groundwater use and net revenue is similar across three soil types. There is only one peak in the net revenue of each management option and further increase in groundwater use resulted in less net revenue.

5 Conclusions and Policy Implications

The integrated approach adopted in this paper captured hydrologic, agronomic, and economic impacts of alternative groundwater management policies when irrigated sugarcane is a dominant crop in the region. The Burdekin groundwater irrigation management model links information about areas subject to seawater intrusion and at risk

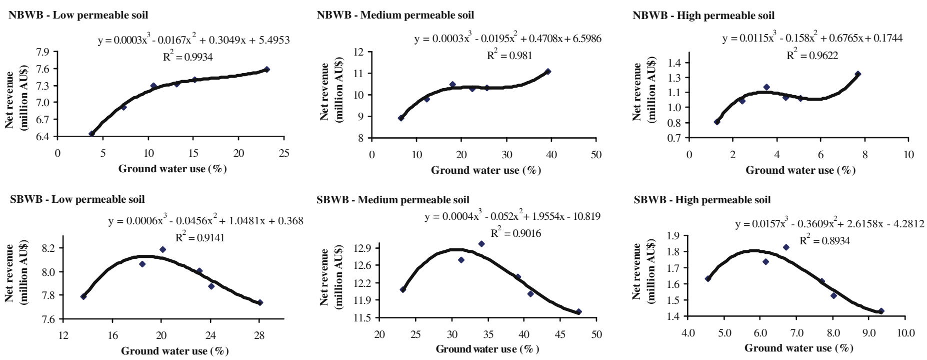

Fig. 8 Relationship between groundwater use and net revenues of three soil types in NBBW and SBWB

of groundwater contamination as well as areas subject to waterlogging into a management optimisation model.

The mathematical programming model determined the economically optimal level of water use and estimated impact of seawater intrusion and waterlogging on net revenues of each management option. The model could be useful to inform water board managers and policy makers about the likely impact of changing their pricing structure and delivery conditions for water. The incorporation of soil types currently growing sugarcane in the Burdekin delta into the model represented the real situation in the delta area by determining optimal water use on each soil type and by estimating impact on sugarcane farm profitability under each management option in both NBWB and SBWB. At a policy level, the framework provided a useful means to examine various options and test policy options that affected either input costs or output prices relevant to growers or to impose restriction on water use.

The aggregate net revenue in NBWB was highest for option 5 which used maximum proportion of groundwater use. The results indicate that though increased groundwater use increased seawater intruded area it resulted in less waterlogged area compared to the base case. The option 5 which used least groundwater resulted in minimum seawater intruded area but increased waterlogged area significantly and reduction in crop sugarcane yield resulted in minimum aggregate net revenue among all the management options. The situation in SBWB was different. The aggregate net revenue was highest in a relatively less groundwater use option 4. Seawater intruded area in this option was second least while waterlogged area was second most among all the management options. It is clear from these results that the net revenues for all management options in the SBWB are higher than the net revenues for the NBWB because the proportion of groundwater usage in the SBWB area is higher, and groundwater and surface costs are lower than NBWB.

In NBWB, there is always a positive correlation between groundwater use and aggregate net revenue while this relationship is not always positive in SBWB because increase in groundwater use beyond a point resulted in reduced aggregate net revenue. However, when one of the key parameters (surface water charges) was altered in NBWB, the shape of the relationship was similar to the SBWB.

The groundwater charges do not relate to the principle of ‘efficiency’ which requires highly productive use of water. Rather, the groundwater charges in both these areas are currently based on area of production and have no impact on the optimal irrigation level but they do affect overall farm profitability. Economically optimal level of water application will depend on marginal value product of the resource on each soil type.

The net revenues for all management options in the SBWB were higher than the corresponding values for the NBWB because the proportion of groundwater use in the SBWB area was higher which is relatively cheaper than surface water charges. Any change in water pricing in future will change the impact of these management options. Further, surface water charges were also lower in SBWB which means less cost of irrigation and greater net revenue. These results indicate that the overall impact of these management options varies in different soil types in two board areas and requires an area specific strategic action by the water boards to minimise impact on sugarcane profitability in each board area/region of specific soil type.

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