Economic and environmental impacts of groundwater management scenarios in Burdekin Delta[1]

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The Burdekin delta in north Queensland is the most important area for irrigated sugarcane production in Australia. Conjunctive use of groundwater and surface water is a common practice in this area, and requires that the groundwater systems be carefully managed to ensure the long-term economic and environmental well being of the whole region. Management of the system requires that sufficient water be provided to the crops grown in the area while maintaining sufficient pressure in the groundwater system to minimise potential problems associated with salt water intrusion. A groundwater management model is being developed to help address these issues by simulating the behaviour of the groundwater system in response to various management strategies. The output from the groundwater model along with data from a plant growth simulation model has been used as input to a regional mathematical programming model, to examine the economic and environmental impacts of various groundwater management strategies in the delta region.

Keywords: Groundwater, aquifer, hydrologic, economic, simulation, optimisation.

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Introduction

The Burdekin delta in north Queensland is one of the more important areas for irrigated agriculture in Australia. The delta area is predominately used for sugarcane production because of its dry clear climate for much of the year and the availability of water as well as the suitability of deltaic soils for sugarcane. There are also some small areas under tropical fruit and vegetable farms. The production of commercial sugar commenced in 1883 while irrigation practices began in 1887. The demand on the shallow groundwater supplies increased rapidly as the area under sugarcane expanded. In 1962/63, despite excellent rainfall, it was clear that there was a situation of water overdraft in the delta which resulted in a decline in groundwater levels. Investigations into the problem revealed a deficiency of about 108,000 to 150,000 ML to service the level of cane assignment in 1964. Test drilling revealed an extensive aquifer system which when full would represent a storage in excess of 1.23 million ML. A further study of the aquifer system deemed it possible to replenish this underground basin artificially (NBWB, 1998). This situation resulted in the implementation of an artificial groundwater recharge scheme by the Queensland Department of Natural Resources (formerly Irrigation and Water Supply Commission) by establishing the North and South Burdekin Water Boards in 1965 and 1966 respectively. A consultant (SK&M, 1997) engaged by the North and South Burdekin Water Boards identified a number of issues including rise in water table levels in some areas, and increase in groundwater salinity in some sections of the delta due to the presence of saline water inflow, and seawater intrusion into deeper aquifers. The study argued that seawater intrusion was a significant threat and a potential limiting factor on the sustainable level of groundwater extraction in the long term.

The aim of this study is to link the output from both a groundwater management model and a biophysical crop growth simulation model through a regional mathematical programming model to estimate the impact of various groundwater management strategies on sugarcane profitability in the delta area/region. The groundwater management model simulates the behaviour of the groundwater system underlying the Burdekin delta area and the potential impact of two cases of environmental degradation, waterlogging and seawater intrusion, have been explored. The model estimated the areas where the water levels were lower than the natural surface and the areas where the water levels in the underground aquifer dropped below mean sea level. The biophysical simulation model estimated sugarcane crop yield response to irrigation water. In the following section, an overview of Burdekin delta study area is presented and need for an appropriate groundwater management discussed. This is followed by a discussion on analytical framework and data collection. Results and discussion are presented in the following section and concluding remarks are given in the last section.

Burdekin delta irrigation system and groundwater management

The Burdekin River delta is located on the northeast coast of Queensland, approximately 90 km southeast of Townsville, and close to wetlands, waterways, estuaries, and the Great Barrier Reef. It covers an area of about 850 km^2, and together with the Haughton

River – Barratta Creek system, is one of the largest alluvial aquifer[2] systems in Australia. The area has a tropical climate and seasonal rainfall (two thirds falling during January to March each year), with annual totals ranging between 250 mm and 2500 mm, and an average of about 1000 mm. Evaporation varies from 10 mm/day in November to 2.8 mm/day in June. The delta area is predominantly used for sugarcane production, with some smaller areas under tropical fruits and vegetables. There are small areas where groundwater or soil quality is not suitable for the sugarcane crop or horticulture and these are used for cattle grazing. The delta is one of the few areas in Queensland where cane is grown under full irrigation and conjunctive use of groundwater and surface water is a common practice. [3]

A number of studies on the Burdekin Delta area focus on research projects into the siltation and clogging of artificial recharge channels and pits. O'Shea (1985) discussed these studies and concluded that the recharge scheme had been operating successfully since its inception in 1965. This scheme is entirely financed by the local cane growers and the milling company. Currently, sugarcane is the dominant crop grown in the delta with 21,800 ha in the NBWB area and 13,344 ha in the SBWB area in 2001. There were only 1,500 and 84 hectares, respectively, under other crops in the delta area in 2001. Artificial recharge is still practiced in the delta area, although the water management boards have now shifted their emphasis from groundwater recharge to more efficient use of water which incorporates the direct use of more surface water for irrigation.

The management of the aquifer in the Burdekin delta is a critical and challenging exercise because it overlies shallow groundwater supplies which represent the major source of irrigation water in the area and the sugar industry relies heavily on these supplies for its continued well-being. In addition, the area is situated in close proximity to environmentally sensitive wetlands, waterways, estuaries, and the Great Barrier Reef, while water charging and water management practices have evolved in response to local needs (Bristow et al., 2000). Therefore, it is important to design and implement practices which ensure the long-term viability of irrigated agriculture in the area.

Analytical framework and data collection

The integrated approach used in this analysis includes three principal components:

(a) a groundwater management model to examine problems associated with salt water intrusion and water logging by simulating the behaviour of the groundwater pool in response to various management strategies;
(b) a biophysical simulation model to predict crop yields of sugarcane (the only major crop in the region) under different irrigation levels; and
(c) a regional mathematical programming model to assess net benefits of growing sugarcane in the region under these management scenarios.

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[2] Groundwater collects in porous layers of underground geological formations known as aquifers.

[3] Conjunctive use means a certain volume of surface water and of that is groundwater, a practice recommended by the water boards to recharge the aquifer when irrigating.

A detailed description of the analytical framework and its components is presented in this section.

Hydrological model

MODFLOW is a finite difference groundwater flow model developed by the U.S. Geological Survey, which determines the amount of draw-down and water levels in the aquifer (McDonald and Harbaugh, 1988). It was used to simulate six different groundwater flow management scenarios including a baseline scenario. The baseline simulation of groundwater levels in the Delta region were run for a 50-year period (2000-2050) using 1981 initial conditions and 1998 land use data. The numerical simulation comprises 600 time steps each of one-month duration. For details on the assumption of the data used and the numerical model, the reader is referred to Phase 3, Numerical Model Development in Arunakumaren et al. (2001).

The five management scenarios that were evaluated are listed below. The changes in water usage are measured with respect to the baseline simulation.

Scenario 1: Reduce (groundwater) irrigation by 20%.
Scenario 2: Reduce the Burdekin River water allocations (surface water) by 10%.
Scenario 3: Increase the open water (surface water) usage by 30% where open water is accessible.
Scenario 4: Turn off all pumping bores (groundwater) in areas where seawater intrusion has occurred and supply those farms with open water licenses.
Scenario 5: Reduce the open water (surface water) usage by 50% in areas that are not subject to seawater intrusion.

It is assumed in this analysis that all areas are prospective sugarcane growing areas. The soils in the Burdekin Delta region were grouped into three types based on their relative permeability. The areas in the delta under threat of environmental degradation as a result of implementing each of the five water management scenarios described above were then assessed with respect to the three types of soil.

The model simulations explored the potential impact of two cases of environmental degradation: water logging and seawater intrusion.

(a) Waterlogging:
The areas where the water levels were less than 2, 1 and 0.5 m from the natural surface were reported for each of the soil types. In addition, the number of times an area of each of the soil types was waterlogged during the 50-year simulation was calculated.

(b) Seawater intrusion:
The areas where water levels in the aquifer dropped below mean sea level (0 m AHD) were reported for each of the soil types. Also reported is the frequency and extent of the area that dropped below the mean sea level for each of the soil types during the course of the 50-year simulation.

Biophysical model

The APSIM cropping systems model (McCown *et al*. 1996) was used to estimate sugarcane crop yield responses to irrigation water over a 20-year period from 1975 to 1995 with a cycle consisting of one plant crop followed by three ratoon crops. The systems model linked a sugar crop module, a soil water module, a soil nitrogen module and a surface residue module. A series of crop simulations were performed to estimate response to applied irrigation for a range of soil types, water allocation levels and application efficiencies for the widely used furrow irrigation system, as well as alternatives such as centre pivot irrigators and trickle irrigation. The results of these simulation experiments were reported elsewhere (Qureshi *et al*., 2001).

A selection of irrigation options was to investigate a combinations of soil types, water quantities (0 to 35 ML/ha in 1 ML/ha increments) and above-ground application efficiencies of 30% to 60% for three soil types. The three soil types (Clay, Silt and Sand) used in the simulations were selected to represent profiles with sharply contrasting levels of plant-extractable soil water (representative of low, medium, and highly permeable soil types in the study area).

The long-term climate files for the study area from 1975 to 1995, consisting of daily rainfall, minimum and maximum temperature and solar radiation data were used as inputs for the simulation experiments. These files included a combination of recorded weather station data and data from generated meteorological surfaces, obtained from the Bureau of Meteorology and the Queensland Centre for Climate Applications. Simulated yields were about 20% higher than the average sugar yield in the region because the model does not take account of losses associated with pests, disease, weed competition, or unusual climatic events and results are based on uniform soil characteristics. Therefore, the yields for the various irrigation levels have been reduced by 20% for each of the three irrigation methods and three soil types.

Mathematical programming model

Linear programming (LP) has been used to develop a Burdekin delta groundwater irrigation management model (BDGIMM).[4] The BDGIMM model of sugarcane farms in the delta area has been developed in GAMS (General Algebraic Modelling System) (Brooke *et al*., 1998) to analyse responses to five groundwater management options and compare them with the base case scenario. The aim of the model was to maximise net annual profit from growing sugarcane in the delta area.

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[4] Mathematical programming methods are well suited for economic analysis because; (i) many activities and restrictions can be considered at the same time, (ii) an explicit and efficient optimum seeking procedure is provided, (iii) with a once-formulated model, results from changing variables can be calculated easily, (iv) new production techniques can be incorporated easily by means of additional activities in the model (Wossink et al., 1992), and (v) the method does not depend upon time series data which is necessary condition for econometric modelling, thus enables to predict impact due to various prices and under different institutional constraints (Chewings and Pascoe, 1988).

It is assumed that farmers are risk neutral and their objective is maximisation of profit from their income generating activities. The BDGIMM model determines the optimal levels of irrigation for each soil type *s*, amount of land resources allocated across crops *c* (plant cane and ratoons only), irrigation level *l,* water source *w* and groundwater management option *m.*

The aggregate net revenue was calculated by deducting total canegrowing costs from total revenue. Thus the objective function is equivalent to maximisation of total net private economic benefits:

The objective function:

$$\begin{aligned}\max\ \pi^{m} &= \sum_{c=1}^{2}\sum_{s=1}^{3}\sum_{l=1}^{35} X_{csl}^{m}\times[Y_{csl}^{m}\times(1-WL_{s})\times P\times(0.009(CCS-4)+0.578)] \\ &\quad -\sum_{c=1}^{2}\sum_{s=1}^{3}\sum_{l=1}^{35} X_{csl}^{m}\times(IC_{csl}^{m}+OPC_{csl}+FC_{csl})\end{aligned}$$

where:

c	is crop type (plant and ratoon only)
s	is the aggregate level of soil resources (identified by soil series/type)
l	is level of irrigation water potentially applied (0 to 35 ML per hectare)
m	is management scenario (refer to management options for the aquifer)
π^{m}	is profit from the management scenario m
X_{csl}^{m}	are hectares of crop c, soil s and water level *l* under management scenario m
Y_{csl}^{m}	are yields for management scenario m associated with c, s and *l*th activity
WL_{s}	is proportionate reduction in cane yield because of waterlogged areas in soil s
P	is price of raw sugar used as a variable in the standard sugarcane price formula
IC_{csl}^{m}	is irrigation related costs for each management scenario m associated with c, s and *l*th activity
OPC_{csl}	are other operating costs associated with c, s and *l*th activity
FC_{csl}	are fixed costs associated with c, s and *l*th activity

It should be noted that fixed costs and operating costs are the same for all the management scenarios. However, the irrigation related costs vary from scenario to scenario. Irrigation related costs are divided into five parts: irrigation operating costs (IOC_{csl}), electricity cost for groundwater pumping ($GWEC_{csl}^{m}$), electricity costs for pumping surface water ($SWEC_{csl}^{m}$), groundwater cost (GWC_{csl}^{m}) and surface water cost (SWC_{csl}^{m}). These costs are given below:

thus

$$IC_{csl}^{m} = IOC_{csl} + GWEC_{csl}^{m} + SWEC_{csl}^{m} + GWC_{csl}^{m} + SWC_{csl}^{m}$$

where:

$$GWEC_{csl}^{m} = GWU_{csl}^{m} \times ECGW$$

$$SWEC_{csl}^{m} = SWU_{csl}^{m} \times ECSW$$

$$GWC_{csl}^{m} = \begin{cases} WC & if \quad GWU_{csl}^{m} > 0 \\ 0 & otherwise \end{cases}$$

$$SWC_{csl}^{m} = \begin{cases} SWU_{csl}^{m} \times SWP_{a} & if \quad SWU_{csl}^{m} \leq \alpha \\ \alpha \times SWP_{a} + (SWU_{csl}^{m} - \alpha) \times SWP_{b} & if \quad SWU_{csl}^{m} > \alpha \end{cases}$$

$$SWU_{csl}^{m} = TWU_{csl}^{m} \times \beta^{m}, \; GWU_{csl}^{m} = TWU_{csl}^{m} \times \gamma^{m} \quad and \quad \beta^{m} + \gamma^{m} = 1$$

GWU_{csl}^{m}	is groundwater used for c, s and l^{th} activities and management scenario m
ECGW	is electricity cost of using groundwater
SWU_{csl}^{m}	is surface water used for c, s and l^{th} activities and management scenario m
ECSW	is electricity cost of using surface water
WC	are water charges
SWP_a	is the low rate charge for surface water
SWP_b	is the high rate charge for surface water
TWU_{csl}^{m}	is total water used
α	is water threshold for low surface water charges (beyond the threshold surface water charges are higher)
β^m	is proportion of surface water for scenario m, and
γ^m	is proportion of groundwater for scenario m

The proportions for surface water and groundwater vary from scenario to scenario. Adding or subtracting the required proportion of sea water affected sugarcane area depending on each management scenario calculates β^m and γ^m.

Land constraint:

The land constraint is expressed as

$$\sum_{c=1}^{2} \sum_{s=1}^{3} \sum_{l=1}^{35} X_{csl}^{m} \leq A^{m} \times (1 - \delta)$$

where:

A^m	is total area available for management scenario m; and
δ	is the proportion of fallow land

Soil area allocation constraints:

$$\sum_{c=1}^{2}\sum_{l=1}^{35} X_{csl}^{m} \le A^{m} \times (1-\delta) \times \Pr_{s}^{m}$$

where:

$\Pr_s^m$ is proportion of soil type s of area A^m available for management scenario m

Water constraint:

$$\sum_{c=1}^{2}\sum_{s=1}^{3}\sum_{l=1}^{35} (PSW_{csl}^{m} + PGW_{csl}^{m}) \le W^{m}$$

where:

PSW_{csl}^m is proportion of surface water used

PGW_{csl}^m is proportion of groundwater used

W^m is the total available water from both groundwater and surface water sources

The groundwater management hydrological model considers North and South Burdekin Water Board area as one integrated unit and estimated the total area subject to seawater intrusion and the area subject to waterlogging. The BDGIMM model has been used to evaluate and compare the management strategies used in the North and South Burdekin Water Board Areas. There are differences in the structure of groundwater charges between the two boards and in the threshold volume to which the low-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 need to recharge the aquifer. In NBWB, the proportions of groundwater and surface water are 40% and 60% respectively, while in the case of SBWB, 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 SBWB area. Based on recent estimates (Arunakumaren, *et al*., 2000), the proportions of the three soil types in the study area were low permeability 33%, medium permeability 56%, and high permeability 11%.[5]

Area (in hectares) where the fresh water level might fall below mean sea level and areas regarded as waterlogged, which are areas where the watertable is less than 0.5 m from the soil surface, under different management scenarios for the each soil type, were estimated by the hydrological model. These data have been used in the analysis. In the delta, approximately 40% of the area (35 144 ha) is under sugarcane while remaining area is pasture and used for grazing or is under some other small crops or fruit and vegetables. Therefore, only 40% of the area of each soil type (based on their proportion in the region) was subject to seawater intrusion and, out of this area, only 5% is assumed to be area

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[5] The three soil types (Clay, Silt and Sand) represent profiles with sharply contrasting plant extractable soil water contents. These soil types have been considered representative of low, medium and high permeable soil types in the study area.

affected by sea water. The groundwater in this area will become salty and not useful for cane production. Also, a shift towards surface water is considered in the analysis and the model adjusted for each management scenario (i.e. a reduction in groundwater proportion and increase in surface water proportion in the region). It is assumed that currently there is no limit on surface water and growers can access as much water as they need. However, they will face higher surface water charges compared to comparatively little in the way of groundwater charges. A similar approach was adopted in estimating areas (hectares) where the groundwater was less than 0.5 m below the soil surface under different management scenarios and for the each soil type. BSES has reported that each day the watertable remained within 0.5 m of the soil surface can result in a cane yield loss of 0.5 tonnes per ha. Therefore if the soil remains waterlogged for 100 days, yield losses up to 50 tonnes per ha can occur (BSES, 1998, p. 47). To link waterlogging with salinity and its impact on cane production (after discussing with agronomists and irrigation scientists involved in the region) it is assumed that impact on cane production will differ for each soil type and the low permeable soil will be more affected than the high permeable soil. Over two thirds of the annual rainfall occurs during the months of January to March so, for the current analysis, it is assumed that there will be a yield reduction of 20%, 16% and 12% respectively in tonnes cane produced on low permeable, medium permeable, and highly permeable soil types. The coefficients in the model have been adjusted accordingly for each management scenario.

Information on technical and economic systems of cane farming in the study area has been obtained from published literature, various public departments and organizations, water boards, farmers and their organisations, as well as from various irrigation and other business organizations. Information from the various sources was cross- checked through informal discussion with local farmers and representatives of various organisations. Average yields from each soil type and for furrow irrigation system only (the widely used irrigation system in the region) obtained by using the APSIM biophysical simulation model were used in the analysis. Sugar production cost data were obtained from a survey report compiled by the local BSES office (Small, 2000) and from the local office of CANEGROWERS with fixed costs estimated by the ABARE Farm Survey (ABARE, 1996). The information about permanent (family) labour hours used and labour costs were estimated after discussion with growers and from the office of their association. Sugar content data were obtained from the local sugar mill and an average of the past 10 years was used. Similarly, the average pool price of sugar in Queensland was used and the price paid to the grower was estimated by using the standard sugar price formula. Water charges and the threshold payment structure were obtained from material published by the water boards. Electricity charges were estimated on the basis of the appropriate electricity tariff and pumping costs for groundwater as well as surface water. The parameters used in the analysis are set out in Table 1.

Table 1: Parameter values used in the analysis

PARAMETER	VALUE	PARAMETER	VALUE
Farm/Labour Characteristics		*Irrigation Costs*	
Furrow irrigation operating cost	$50/ha	NBWB ground water charge	$68.50/ha
Sugar pool price	$325/t	SBWB ground water charge	$48.50/ha
Fixed costs	$333/ha	NBWB threshold for low priced surf water	8 ML/ha
Permanent labour cost	$20/hour	NBWB surface water (low price)	$4.80/ML
Harvesting contract cost	$5.60/t	NBWB surface water (high price)	$22.20/ML
Tractor cost	$28/hour	SBWB threshold for low priced surf water	4 ML/ha
Planting cost	$375/ha	SBWB surface water (low price)	$5.40/ML
Fertilizer cost (plant cane)	$250/ha	SBWB surface water (high price)	$13.67/ML
Fertilizer cost (ratoon cane)	$275/ha	Groundwater electricity charges	$9.11/ML
Herbicide cost (plant cane)	$133/ha	*Groundwater and surface water proportion in N&SBWB*	
Herbicide cost (ratoon cane)	$75/ha	Surface water electricity charges	$4/ML
Insecticide cost (plant cane)	$0-300/ha	NBWB groundwater proportion	0.40
Insecticide cost (ratoon cane)	$0-300/ha	NBWB surface water proportion	0.60
Labour (plant cane)	40 hours /ha	SBWB groundwater proportion	0.70
Labour (ratoon cane)	20 hours/ha	SBWB groundwater proportion	0.30

Results and discussion

The analysis consists of a baseline and five management scenarios. The base case scenario is designed to represent the current groundwater and surface water proportions used in the North and South Burdekin Water Board areas. It also reflects the expected future in the absence of a specific groundwater management plan or policy. Five groundwater management scenarios have been evaluated. They were:

(a) reduction in groundwater irrigation in the region by 20%;
(b) reduction in surface water use by 10%;
(c) an increase in the surface water used by 30% when surface water is accessible;
(d) a total ban on the use of groundwater in areas where sea water intrusion has occurred and move to reliance on surface water; and
(e) reduction in surface water use by 50% in areas that are not subject to sea water intrusion.

The model was first run for the NBWB and then for the SBWB area by using the appropriate water charges and threshold values for each area. Results from the preliminary analyses for NBWB and SBWB are presented in Tables 2-5. The change in groundwater and surface water proportions for the base case, and for the five groundwater management scenarios in both areas, are presented in Table 2.[6] After deducting 5% of the area where use of groundwater was not permitted, the volume of groundwater used in the base case, Scenarios 1 and 3 has decreased from 40% to 39%, 32% and 22% respectively, and increased to 45% and 60% in Scenarios 2 and 5 respectively, in NBWB area. In SBWB area case, the volume of groundwater used in the

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[6] First, the proportion of groundwater and surface water was estimated on the basis of each management scenario and then re-estimated after deducting 5% sea water affected area. This process further deducts groundwater and increase surface water proportion from the first four management scenarios and the base case scenario. In case of Scenario 5, 95% is considered unaffected by sea water and surface water use is reduced by 50% according to the scenario (i.e. surface water proportion decreased while groundwater proportion increased).

base case, Scenarios 1 and 3 has also decreased from 70% to 69%, 56% and 61% respectively, and increased to 72% and 90% in Scenarios 2 and 5 respectively. The proportion of groundwater to surface water is always higher in SBWB than NBWB area. This is due to recommendation of each board on the basis of groundwater quality in each area and availability of surface water. Groundwater use in Scenario 4 is zero because this option does not permit the use of groundwater

Table 2: Change in groundwater and surface water proportion under each management Scenario for North and South Burdekin Water Board Areas

Management Scenario	NBWB and groundwater-surface proportion (40:60)	SBWB and groundwater-surface proportion (70:30)
Base Case	39:61	69:31
Scenario 1	32:68	56:44
Scenario 2	45:55	72:28
Scenario 3	22:78	61:39
Scenario 4	0:1	0:1
Scenario 5	60:40	90:10

In case of NBWB area, the optimal levels of water application for the three soil types (base case and Scenarios 1, 2 and 5) are the same, i.e. 23, 28 and 35 ML/ha for low, medium and highly permeable soil types, respectively. But the optimal level for the low permeable soil type has decreased by one ML (from 23 to 22 ML/ha) in Scenarios 3. This is due to the reliance on surface water which is relatively more expensive compared to groundwater. In SBWB area, the optimal level of irrigation for the base case and the first three scenarios are similar (i.e. 23, 31 and 35 ML/ha for low, medium and highly permeable soil types) but in Scenario 4, the application rate for medium permeable soil has decreased by three ML (i.e. 28 ML) while in Scenario 5, the application rate increased by 4 ML for low permeable soil type (i.e. from 23 to 27 ML/ha). The increase in water use level is due to the relatively greater use of less expensive groundwater compared to surface water. Similarly, the higher optimal levels in the SBWB area are due to the relatively greater use of less expensive groundwater (only 30% surface water use) compared to the NBWB area (where only 40% groundwater use is permitted)

Table 3:Optimal water application for three soil types for the NBWB and SBWB areas (ML/ha)

Management Scenario	Base case (ML/ha)	S 1 (ML/ha)	S 2 (ML/ha)	S 3 (ML/ha)	S 4 (ML/ha)	S 5 (ML/ha)
NBWB area						
Low permeable	23	23	23	22	22	23
Medium permeable	28	28	28	28	28	28
Highly permeable	35	35	35	35	35	35
SBWB area						
Low permeable	23	23	23	23	23	27
Medium permeable	31	31	31	31	28	31
Highly permeable	35	35	35	35	35	35

The net benefits per ha for the base case and five different management scenarios for NBWB and SBWB areas are presented in Table 4. The discussion of NBWB results only is presented. The net benefits ($ per ha) for Scenario 5 are highest (i.e. $476, $446 and $290 per ha respectively, for low, medium and highly permeable soil types) while the net benefits from Scenario 4 are lowest (i.e. $347, $273 and $59 per ha, for low, medium and highly permeable soil types, respectively).

Table 4: Net benefit per ha of each management for each soil type

Management Scenario	Base case Net benefit ($/ha)	S 1 Net benefit ($/ha)	S 2 Net benefit ($/ha)	S 3 Net benefit ($/ha)	S 4 Net benefit ($/ha)	S 5 Net benefit ($/ha)
NBWB area						
Low permeable	411	388	428	358	347	476
Medium permeable	367	339	388	301	273	446
Highly permeable	191	156	218	109	59	290
SBWB area						
Low permeable	485	464	489	472	415	512
Medium permeable	480	451	485	462	379	518
Highly permeable	340	308	346	320	213	387

The aggregate net revenues (benefits) for five different management scenarios applicable to the NBWB and SBWB areas are presented in Table 5. The net benefit of Scenario 5 in NBWB area is highest (over 15 million dollars) while the net benefit for Scenario 4 is lowest among all of the scenarios including the base case (i.e. over nine million dollars) and there is a difference of about six million dollars between Scenarios 4 and 5. It is reminded that Scenario 4 does not allow groundwater pumping and total reliance is on surface water in areas where seawater intrusion has occurred while Scenario 5 requires 50% reduction in surface water use in areas that are not subject to sea water intrusion. In the analysis, only 5% area is affected, therefore, surface water use on the remaining 95% area has decreased by 50%. As a result, total use of surface water has decreased while groundwater use increased.

Table 5: Aggregate net revenue for each management Scenario for NBWB and SBWB areas

Management Scenario	NBWB ($)	SBWB ($)
Base Case	12,712267	16,373830
Scenario 1	11,770361	15,456953
Scenario 2	13,447880	16,557170
Scenario 3	10,501711	15,816076
Scenario 4	9,619747	13,094748
Scenario 5	15,417004	17,633904

Sensitivity analysis

The major uncertain parameter in the analysis is the sea water affected area under each management scenario. It was assumed that only 5% sea water intruded area is subject to be severely affected where groundwater is not be used and surface water is the only source of irrigation. The value of this parameter was increased to 100% (of the actual sea water intrusion area) estimated for each management scenario. The altered aggregate net benefit of each management scenario is presented in Table 6. The aggregate net benefit of each scenario decreased but the overall attraction for the Scenario 5 and the least attraction for Scenario 4 remains the same (i.e. they still had highest and lowest net benefits). The aggregate net benefit of Scenario 5 reduced from $15417004 to $12,860794.

Table 6: Altered aggregate net revenue for each management Scenario due to increase in sea water affect area

Management Scenario	NBWB ($)	SBWB ($)
Base Case	9,908379	14,872785
Scenario 1	10,865369	14,972212
Scenario 2	9,767195	14,588828
Scenario 3	10,044771	15,570033
Scenario 4	9,619747	13,094748
Scenario 5	12,860794	16,452832

The groundwater charges in SBWB and NBWB areas were based on production (i.e. $48.50 and $68.50/ha, respectively). By assuming around 25 ML/ha water use for irrigation, the water charges on the basis of volume ($/ML) are not more than $2 and $3/ML in SBWB and NBWB areas, respectively. The value of this parameter was increased (in NBWB area, for example) to $250 and $275/ha (i.e. $10 and 15/ML) and aggregate net benefits of each increase have been estimated. The altered aggregate net benefits due to change in these charges for each management scenario are presented in Table 7. When $10/ML for groundwater used, the aggregate net benefit of each scenario decreased. Scenario 5 remains the most attractive scenario and Scenario 4 moves from the least attractive to second most attractive scenario while Scenario 3 becomes the least attractive option. When $15/ML used, Scenario 4 becomes the most attractive scenario while Scenario 5 becomes the second most attractive scenario. Scenario 3 remains least attractive scenario. These results indicate that water charges are key parameter and have altered the original rankings of the management scenario.

Table 7: Altered aggregate net revenue for each management Scenario due to increase in groundwater charges from about $2/ML to $10 and $15/ML

Management Scenario	NBWB ($10/ML)	NBWB ($15/ML)
Base Case	7,609358	6,906478
Scenario 1	6,667452	5,964572
Scenario 2	8,344971	7,642091
Scenario 3	5,398803	4,695923
Scenario 4	9,619747	9,619747
Scenario 5	10,314095	9,611215

Conclusions and policy implications

The integrated approach adopted in this paper captures hydrologic, agronomic and economic impacts of alternative groundwater management scenarios when irrigated sugarcane is a dominant crop in the region. The BDGIMM model links information about areas subject to sea water intrusion and at risk of groundwater contamination as well as areas subject to waterlogging. The model shows how the proportion of groundwater and surface water used for irrigation of sugarcane should change when the response to irrigation on different soil types, level of water use and crop yield, are used in a mathematical programming model to determine the economically optimal level of water use. In addition to soil types, relevant input costs and output prices have been included in the model. The model is useful in informing water board managers and policy makers about the likely impact of changing their pricing structure and delivery conditions for water. Reality is added to the model because the range of soil types currently growing cane in the district has been incorporated into the model. Overall farm profitability under each management scenario has been assessed. At a policy level, the framework provides a useful means for examining various scenarios and testing policy options that affect either input costs or output prices of growers or impose restriction on water use.

The net benefit of Scenario 5 is highest while the net benefit for Scenario 4 was lowest among all of the scenarios including the base case. One of the reasons that Scenario 5 is the most attractive option was due to reduction in surface water and more reliance on groundwater pumping. The charges of groundwater are comparatively lower than surface water (i.e. about 50c per ML). Therefore, cost of production was lower when more reliance was on groundwater. This resulted in higher net benefit for this scenario. When the groundwater charges are increased to \$15/ML, the least attractive scenario (Scenario 4) in the original ranking becomes the most attractive scenario.

The water charges are based on area of production and have no impact on the optimal irrigation level other than their impact on overall farm profitability. These charges do not relate to the efficiency initiatives of the Queensland government or the Commonwealth of Australia's competition policy which puts emphasis on highly productive use of water. In addition, the analysis assumed that there was no limit on surface water and growers can access as much water as they need. However, more demand of water in future for other crops or activities would restrict the available surface water in the region.

The model considers sugarcane as the only crop in the region, without examining any competitive crops or other activities which may require less water but have a higher marginal value product for the resource. While sugar is the dominant crop in the region, some allowance could be made for other crops in estimating the overall demand curve for water. The model does not examine the impact of leaching on groundwater contamination which is likely to add to social cost. These topics require further study.

References

ABARE (1996), *Queensland Sugar Cane Industry 1993-94 to 1995-96: A Report Prepared for the Sugar Research and Development Corporation*, Australian Bureau of Agricultural and Resource Economics, Canberra.

Arunakumaren, N. J., Bajracharya, K. and McMahon, G. A. (2001). Water Management in the Lower Burdekin, The Burdekin Delta Groundwater Model, Water

Assessment and Planning, Resource Science and Knowledge, Queensland Department of Natural Resources, Brisbane.

Arunakumaren, N.J., McMahon, G.A. and Bajracharya, K. (2000), *Water Management in the Lower Burdekin: Groundwater Model Conceptualisation,* Water Assessment and Planning, Resource Science and Knowledge, Queensland Department of Natural Resources, Brisbane.

Brooke, A., Kendrick, D., Meeraus, A., and Raman, R. (1998), *GAMS: A User's Guide, GAMS Development Corporation*, Washington, D.C.

BSES (1998), Irrigation of Sugarcane, Bureau of Sugar Experiment Stations, Brisbane.

Bristow, K. L., Charlesworth, P.B., McMahon, G.A., Arunakumaren, J.K., Bajracharya, K, Ham, G., Sutherland, P., Laidlow, G., Lowis, B., Nielson, G., Qureshi, M.E., Christianos, N., Enderlin, N and Eldridge, S. (2000), Towards a more integrated approach to water management in the Burdekin Delta irrigation area, Australian National Committee of Irrigation and Drainage Conference, Toowoomba, 11-13 September.

Chewings, R.A. and Pascoe, S. (1988), Demand for Water in the Murray Valley, New South Wales: An Application of Linear Programming, *32nd Annual Conference of the Australian Agricultural Economic Society*, La Trobe University, Melbourne, 8-12 February.

McCown R.L., Hammer G.L., Hargreaves J.N.G., Holzworth, D.P. and Freebairn D.M. (1996), 'APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research' *Agricultural Systems*, 50: 255-271.

McDonald, M. G. and Harbaugh, A. W. (1988), MODFLOW: A modular three dimensional finite difference ground water model. Open File Report 83-875, US Geological Survey, Washington.

NBWB (North Burdekin Water Board) 1998, *Profile of the North Burdekin Water Board 1965- 1998*, North Burdekin Water Board, Ayr.

O'shea, J.A. 1985, *A review of the Burdekin Delta recharge scheme, Internal report*, Water Resources Division, Water Resources Commission, Brisbane.

Qureshi, M.E. Wegener, M.K., Bristow, K.L, Mallawaarachchi, T. and Charlesworth, P.B. (2001), Economic evaluation of alternative irrigation practices for sugarcane production in the Burdekin Delta, AARES 2001 (Australian Agricultural and Resource Economics Society) Conference, January 22-25, Adelaide.

Small, F. (2000), Socio-Economic Costs and Benefits of Cane Production in the Burdekin and Proserpine Districts: Growers Survey Report, Bureau of Sugar Experiment Station, Brandon, Qld.

SK&M, (1997), Burdekin River Issues – 1996: Technical Issues, Sinclair Knight Mertz Ptv Ltd, Toowoomba.

Wossink, G.A.A., de Koeijer, T.J. and Renkema, J.A. (1992), 'Environmental-economic policy assessment: a farm economic approach', *Agricultural Systems*, vol. 39, pp. 421-438.