Assessing the Economic and Environmental Benefits and Risks of Investing in Recycled Water for Irrigation on the Darling Downs, Australia

L.E. Brennan[a,c], S.N. Lisson[a,c*], P.L. Poulton[b,c], P.S. Carberry[b,c], K.L. Bristow[c,d] and S. Khan[e]

[a]CSIRO Sustainable Ecosystems, 120 Meiers Rd, Indooroopilly, Queensland 4068, Australia, e-mail: lisa.brennan@csiro.au

[b]CSIRO Sustainable Ecosystems, PO Box 102, Toowoomba, Queensland 4350, Australia

[c]Agricultural Production Systems Research Unit, PO Box 102, Toowoomba, Queensland 4350, Australia

[b]CSIRO Land and Water, PMB, PO Aitkenvale, Queensland 4814, Australia

[e]CSIRO Land and Water, PMB No. 3, Griffith, NSW 2680, Australia

Abstract: Crop production in much of Australia is strongly influenced by the availability of water. Rainfall is highly variable in both amount and distribution and, as a result, so too are supplies of irrigation water from existing sources such as overland flow (catchment runoff), rivers and bores. The search for additional sources of irrigation water, coupled with the need for urban communities to dispose of large quantities of treated recycled water has led to increasing interest from communities in the reticulation of this recycled water to adjacent crop production areas for irrigation purposes. Proposals to use recycled water inevitably lead to a complex range of production, economic and environmental issues. Computer-based simulation models can capture many of the key factors and processes influencing such systems, and hence can play a useful role in exploring these issues. In this paper, we describe an approach that couples farming system and economic models, in a way that enables analysis of the likely benefits and risks of investing in recycled water. The paper includes a case study based on a farm in the Darling Downs, Queensland, which has a mixture of crop and irrigation sources.

Keywords: *Recycled water; farming system; APSIM; economics; model; irrigation.*

1. INTRODUCTION

The agricultural industry in Australia, like many other sectors of the Australian economy, relies heavily on access to good quality water. With ongoing growth in the non-agricultural sectors and increasing volumes allocated to environmental flows, there will be increasing competition for available water resources and an associated increase in water price. As a consequence, farmers will come under even more pressure to maximise the efficiency of irrigation water use and to look for alternative irrigation supplies. With this in mind, farmers are looking to new options such as the use of on-farm water storages and the reticulation of recycled water from urban sewage treatment plants. Farmers or communities considering the risks and benefits of investing in recycled water and the associated infrastructure are confronted with a raft of complex production, economic and environmental questions. Integrated economic and dynamic, process-based farming system simulation models that capture the key biophysical and economic factors and their interactions, can play a useful decision support role when it comes to exploring these types of questions. In this paper we describe and demonstrate an application of a simulation approach that integrates a novel configuration of the comprehensive, computer based farming systems model, Agricultural Production Systems Simulator (APSIM, McCown et al 1996), with a farm scale economic analysis tool in order to address production, economic and environmental issues relating to investment in recycled water.

2. BIOPHYSICAL MODEL

The farming systems model, APSIM (McCown et al. 1996) is the principal biophysical modeling framework used in this study. APSIM simulates agricultural production systems at the paddock scale by combining modules describing specific soil and crop related processes and their responses to management and climate.

2.1. Irrigation infrastructure & sources

The Manager module of APSIM is configured to enable simulation of an irrigated production system using water derived from overland flow, river and bore allocations and recycled water (Figure 1). The configuration includes an on-farm water storage (OFWS) for which a daily water balance is maintained that takes into account the individual inflows and ouflows. Depending on the dam design, overland flow is received into the OFWS either directly or via a sump.

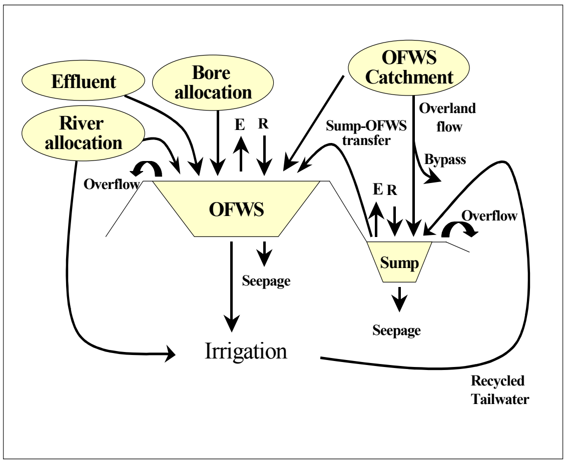

Figure 1. Biophysical model framework.

Bore water. The bore water allocation is defined by an amount (ML/year) and an 'allocation period' over which that amount is potentially available. The operator specifies a 'pumping period' during which water can be pumped from the bore, whether or not carry-over of unused allocation to the following allocation period is allowed, and the pumping rate from the bore to the OFWS (ML/day).

River water. The configuration details for river allocation are similar to those for bore water, but with some key differences. The volume of river water actually pumped each year is determined by a number of user defined factors including: the nominal or maximum amount allowed to be pumped each year, the period over which that amount can be accessed, the threshold river flow rate above which the farmer is allowed to pump and the maximum daily pumping rate. As with bore water, when the farm is receiving recycled water, the model user can specify a threshold OFWS volume, above which river pumping stops to allow sufficient residual OFWS capacity to receive the recycled water inflow.

Recycled water. Recycled water is defined by an annual total amount (ML/year), the frequency of delivery events (days), and the amount received per event (ML). The recycled water must be received and cannot be delayed or postponed. Where the residual volume in the OFWS is less than the incoming volume, the water will be shunted into the sump. Once the sump is full, surplus is recorded as overflow from the OFWS.

Overland flow. Daily overland flow from the OFWS catchment is estimated using the QDPI model, RUSTIC (Runoff, Storage and Irrigation Calculator) (QDPI 1994). The method adopted in RUSTIC for predicting runoff is that developed by the United States Department of Agriculture (USDA 1972). The overland flow is subsequently partitioned into bypass, the volume that is transferred to the OFWS from the sump, and the portion left over in the sump.

On-farm water storage / sump. The volumes of water in the OFWS and sump are calculated daily and take into account the various elements of the storage water balance. In the case of the OFWS, inflows include water sourced from the sump (or directly from the catchment depending on the presence or not of a sump), direct rainfall capture, recycled water, river water and bore water. Outflows are from surface evaporation, irrigation, seepage losses and overflow. In the case of the sump, inflows include recycled tailwater, overland flow and direct rainfall capture. Outflows are from surface evaporation, sump-to-OFWS transfer, seepage losses and overflow. Evaporative loss from the storage is assumed to be 70% of that from a Class A pan (Pratt et al 1975). Seepage losses depend on the depth of water in the storage or sump and the permeability of the soil underlying the storage or sump and are calculated using seepage loss equations from Horton & Jobling (1992). Overflow occurs when the capacity of the storage is exceeded.

2.2. Irrigation rules

For an irrigation event to occur the soil water deficit (drained upper limit – current soil water content) to a specified soil depth must be greater than or equal to a given threshold. The user also specifies the maximum number of irrigation events per crop, the period over which irrigation can occur, and a minimum duration between irrigation events. The amount of irrigation water applied can be a fixed amount or variable depending on the current soil water deficit. The applied irrigation amount is defined as the volume of water pumped from the OFWS less that returned to the OFWS/sump as recycled tailwater. Some of this water will be lost through evaporation and seepage in the head ditches, furrows and recycling channels or will be lost through pipe leakages etc. These losses are collectively referred to as application inefficiencies. What remains, enters the soil profile and is available for crop uptake and is referred to as 'effective' irrigation. The concentration (ppm) of salt in the irrigation water can be specified at the start of a simulation and this is assumed to remain constant with time. In reality, however, the salt concentration will vary as a result of the mixing of water from different sources having different salt concentrations and through evaporative losses.

2.3. Other features of the biophysical model

Within the broader framework of APSIM, it is possible to configure detailed management events relating to the cropping cycle (ie species, planting dates, harvesting dates), tillage practices (ie implement used, depth and timing), crop residue management (ie timing, depth and fraction of residues incorporated) and nitrogen management (ie amount, type, timing, depth). For each farm system, model runs are conducted over an extended period using historical climate records so as to capture responses to season-to-season climate variability, and to provide input data to the economic model for risk assessment. All management and farm design attributes are derived from a detailed farmer interview.

3. ECONOMIC ANALYSIS

3.1. Partial budgeting framework

The economic analysis framework involves a *partial budget*, which only considers the change in costs and revenue resulting from the use of recycled water. If the additional annual net cash return is positive, then the use of recycled water is worthwhile. Specifically considered in the additional annual net cash return calculation are changes in annual cash income and annual variable costs from crop production, and additional annual cash overhead (fixed) costs, all attributable to recycled water irrigation. Due to the unique financial circumstances of each farm, annual net cash returns have not been adjusted for tax deductions and payments.

3.2. Biophysical data used in economic analysis

The annual net cash return calculation relies on biophysical data specific to the benchmark and recycled scenarios. Data relating to crop yields (including wheat protein levels), quantity of nitrogen fertilizer, quantity of irrigation applied to the crops, quantity of water pumped to the storage from the sump, bores and river is sourced from the APSIM simulations. A benefit of the use of long-term climate data to generate simulated results over an extended period is that it allows for the assessment of expected variability in annual net cash returns.

4. CASE STUDY: MIXED CROP PRODUCTION ON THE DARLING DOWNS, AUSTRALIA

4.1. Background

The Darling Downs, Queensland, Australia is facing a critical and worsening shortage in irrigation water supply and increased demand for water as indicated by the 48% increase in the number of OFWS's from 1997-1999. Access to recycled water from a range of urban wastewater treatment plants offers an opportunity to supplement irrigation water supply on the Darling Downs. The case study presented in this paper is taken from a commissioned study to assess the economic and environmental benefits and risks of recycled water based irrigated crop production incorporating on-farm water storages on the Darling Downs (Brennan et al 2003). The proposal would involve pumping recycled water from selected treatment plants in Brisbane and surrounding areas to the Darling Downs (200-250km) via a new reticulation network. Both 'without' recycled water (benchmark) and 'with' recycled water scenarios are modelled in the bio-economic framework described in this paper.

4.2. Description

The case study farm (769ha) is fully irrigated from bore (860ML/year) and on-farm water storage (1180ML capacity + 120ML sump receiving overland flow from a 10,000ha catchment) sources. The current rotation is cotton/short fallow/maize/wheat/long fallow. With the receipt of 1000ML of recycled water per annum, the farmer is interested in increasing his cropping intensity by displacing a summer fallow with an additional cotton crop and to displace wheat with chickpea as the principal winter crop. The farmer would also look to increase his OFWS capacity (to 1680ML) to accommodate the increased water supply. One hundred mm of irrigation is invoked when soil water deficit in the top 900mm of soil reaches 60mm (the 'trigger'). It is assumed in the model run that the bore water is pumped into the storage prior to being used for irrigation. The initial salt concentrations in each layer of the root zone to 1.8m are based on measured concentrations for the farm. The irrigation salt concentration is 640ppm for the benchmark irrigated scenario and 1000ppm for the recycled water scenario. The delivery of recycled water is assumed to be spread uniformly throughout the year at 3 day intervals (i.e. 122 delivery events each year). The nutrient content of the recycled water is ignored in the model. The cost and price assumptions used in the economic analysis are reported in Table 1. These include crop product prices, nitrogen fertiliser price, and other variable costs associated with irrigated crop production. Crop prices and variable production costs were mainly sourced from the Queensland Department of Primary Industry (www.dpi.qld.gov.au/fieldcrops) and from the farmer in question. The shift to the recycled water scenario is taken to involve an additional labour cost of $50 000 per annum and $250,000 to extend the OFWS. In this case, where an additional capital cost is incurred, it is incorporated into the annual budget using an annuity, which can be likened to an annual debt repayment for a given repayment period (15 years) and interest rate (9%). Recylced water prices of $0, $100, $150, $200 and $250/ML were used in the analysis. The supply of recycled water is a fixed annual cost because the full supply allocated to the farm must be purchased, regardless of the level of usage.

4.3. Results (see Appendix for a complete summary)

OFWS Water Balance and Irrigation: The principal source of irrigation water for the benchmark design is from bores with, on average, the full allocation pumped into the OFWS each year (45 year average of 861ML/year) (Appendix A). The other main source of water is overland flow, with an average of 340ML pumped each year, representing about 72% of the average annual overland flow (45 year average of 473ML/year). The shift to the recycled water scenario involves the receipt of an additional 1000ML/year of recycled water. Coupled with this is an increase in irrigation demand associated with the replacement of the summer fallow with another irrigated cotton crop, and the replacement of the wheat crop with a more intensively irrigated chickpea crop. In response to this increased demand, the total irrigation volume pumped from the OFWS almost doubles to 2137ML/year, with the majority of this sourced from recycled water and the residual from bore and overland flow. There is a small decrease in the average overland flow transfer figure (to 278ML/year). Bore transfer is virtually unchanged. The absence of substantial overflow events in the benchmark and recycled water scenarios coupled with the extent of bypass suggests the potential for further gains through more effective capture of overland flow. This might be achieved through the removal or lessening of the sump to OFWS pumping restriction in the recycled water design (OFWS volume must be less than 200ML for transfer to take place) or through increased pumping and storage (both sump and OFWS) capacity.

Table 1. Assumptions used in economic analysis. PH = Prime Hard Wheat. AH = Australian Hard Wheat. APW = Australian Prime Wheat. PSW = Prime Soft Wheat.

Crop / Input etc	Price	Variable cost
Cotton	$485/bale	$1215/ha & $80/bale
Cotton seed	$206/t	
Maize	$180/t	$200/ha
Wheat	$150/t AH $135/t APW $120/t PSW/Feed	$120/ha
Chickpea	$421/t	$218/ha
Nitrogen		$1/kg
Recycled water service fee		$500/yr
Pumping cost: OFWS to field		$3/ML
Pumping cost: Sump to OFWS		$4/ML
Pumping cost: Bore to OFWS		$30/ML

Yield: Long-term cotton yields under the benchmark design range from 4.9 to 13.9 bales/ha with an average of 9.0 bales/ha. The transition from the irrigated benchmark design to the recycled water design results in an ~6% increase in long-term average cotton yields to 9.50 bales/ha and a doubling of the area under cotton. The increase in yield per hectare is a response to increased irrigation (45 year average of 2.2ML/ha of cotton for the benchmark versus 2.7ML/ha of cotton for the recycled water design). This amounts to an increase in average annual total cotton production across the whole farm from 2290 bales to 4872 bales. Interestingly, cotton yield variability increases with lower minimum and higher maximum yields. This can be attributed to increases in both cropping intensity and irrigation application rate, which effectively altered the distribution of the irrigation resource across the various crops resulting in certain crops having more irrigation available in some years and less in others. Long-term maize yields under the benchmark design range from 0.87 to 11.70 t/ha with an average of 6.69 t/ha. With the transition to the recycled water scenario, average annual maize yield increased to 8.15 t/ha, once again due to increases in applied irrigation (1.5ML/ha to 1.7ML/ha). The impact varied somewhat over the course of the simulation period, with yield reductions in 15 of the 45 years. This again can be attributed to increases in both cropping intensity and a shift in the cropping rotation, altering the distribution of the irrigation resource across the farm. Average annual total maize production across the whole farm increases from 1772 tonnes to 2086 tonnes.

Wheat is replaced by chickpea as the principal winter crop upon shifting to the recycled water scenario. Long-term average wheat and chickpea yields for the benchmark and recycled water scenarios are 2.40 t/ha (0.46 to 5.49 t/ha) and 2.22 t/ha (0.59 to 3.52 t/ha) respectively.

Drainage / farm runoff: Annual drainage under the benchmark design ranged from nil to 299mm with an average of 58mm. Annual runoff ranged from 1mm to 279mm with an average of 57mm. The transition to the recycled water design results in a decrease in average drainage to 25mm/year in response to the increased cropping intensity. Farm runoff increased by a small amount to 61mm/year.

Salt balance: At the commencement of the 45 year simulation, a total of 4.7 t TSS/ha was assumed to exist in the soil profile to a depth of 1.8m. Salt addition through irrigation over the 45 year period amounted to 33.9 t TSS/ha for the benchmark scenario and 97.6 t TSS/ha for the recycled water scenario. The larger amount for the recycled water scenario arises from a greater irrigation volume per unit area and higher salt concentration in the irrigation water. Salt leached from the base of the root zone is larger under the recycled water scenario (61.7t TSS/ha compared with 31t TSS/ha for the irrigated benchmark design). In both designs there is a net gain of salt in the root zone amounting to 2.8 t TSS/ha for the benchmark scenario and 35.9t TSS/ha for the recycled water scenario. Consideration of the average salinity level calculated across all root zone layers to a depth of 1.8m on January 1 of each year of the recycled water simulation, gave a maximum salinity of 0.51dS/m in the final year of the simulation.

Economic analysis: On average, annual net cash returns are higher under the recycled-water irrigated scenario than the benchmark situation for the range of recycled water prices investigated (results not shown). A price of $150/ML for the recycled water scenario is economically more attractive than the current situation. At this price, an average additional annual net cash return of $825,518 could be expected under the recycled-water irrigation scenario, compared with the benchmark situation. On a $/ha basis, for 768ha, this amounts to $1 075/ha additional return each year. At this price one ML of recycled water irrigation generates an average return of $826. The annual returns are highly variable (results not shown). However, with the exception of just one year, the recycled water scenario always generated a higher additional annual net cash return at the $150/ML price. The difference in additional annual net cash return ranged from -$38 756 to $1 575 056 over the 42 years of simulated data. The large difference in returns is attributable to an increase in average gross margin for cotton, and to a lesser extent for irrigated maize, under the recycled water irrigation scenario. This mainly reflects the increase in average yield gains as avoided pumping costs attributable to the displacement of bore and overland flow are very small.

5. CONCLUSIONS

The model presented in this paper represents a novel integration of a process-based dynamic farming system model with a partial budgeting framework. The scope of this integrated modelling capability provides for analysis, comparison and optimisation of a wide range of farming systems. APSIM provides the ability to simulate the growth and development of a number of crop types under contrasting management, soil and climatic conditions. In this study, the capability has been extended to capture a wide range of irrigation management and design options including different irrigation sources such as bore, river, recycled water and overland flow. When integrated with the soil water balance model in APSIM it is possible to simulate the whole farm water balance taking into account both the above ground movement of irrigation water onto and about the farm as well as below-ground water movement. The farm scale partial budget analysis framework captures the key fixed, capital and variable costs associated with a particular setup and, based on key biophysical inputs from the farming system model, provides for estimation of the change in economic performance associated with a shift from the existing benchmark design to an alternative scenario. In the case study presented in this paper, this integrated modelling capability is used to investigate the biophysical and economic risks and benefits of investing in recycled water for irrigation purposes for a farm on the Darling Downs, Australia. More specifically, the implications in terms of yield, above ground water balance including the impact on pre-existing water sources, the accumulation of salt in the root zone and subsequent loss of salt below the root zone and, the financial implications for the farmer are considered.

It should be noted that the biophysical model does not capture all the yield limiting constraints such as weed competition, disease and insect damage, waterlogging and severe weather effects. Furthermore, some parameters and constants used in the configuration of the model such as catchment size, runoff potential, irrigation water salt concentration are difficult to estimate or are likely to vary over the course of the simulation. Notwithstanding these caveats, the modelling framework presented captures the most important farm scale processes, events, design and management considerations helpful to this type of analysis. While not providing the ‘ultimate solution’, the model is a powerful decision support tool for exploring a range of questions relating to the optimum design and management of the farm taking into account production, economic and environmental considerations.

6. ACKNOWLEDGEMENTS

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APPENDIX

Maximum, minimum, mean and median annual statistics for key model outputs calculated over the 45 year simulation period.

	Benchmark				Recycled			
	Mean	Upper	Lower	Median	Mean	Upper	Lower	Median
Bore-OFWS transfer (ML)	861.0	1192.3	434.7	861.0	860.5	1396.9	301.8	842.0
Recycled-OFWS transfer (ML)	-	-	-	-	1011.8	1013.8	1011.1	1011.1
OFWS evaporation (ML)	82.4	92.3	70.4	83.4	116.8	126.8	109.7	116.3
OFWS rainfall (ML)	59.8	90.2	35.3	60.0	85.3	128.5	50.3	85.5
OFWS overflow (ML)	0.9	11.5	0.0	0.0	0.0	0.0	0.0	0.0
OFWS irrigation (ML)	1178.8	1688.8	320.0	1174.8	2136.5	3393.0	800.1	2252.3
Overland flow-OFWS transfer (ML)	340.1	1076.5	0.0	271.6	278.4	1138.5	0.0	187.2
Catchment runoff (ML)	473.3	2144.2	0.0	306.6	473.3	2144.2	0.0	306.6
Bypass (ML)	137.1	1534.6	0.0	10.8	196.6	1951.9	0.0	10.9
Cotton yield (bales/ha)	8.95	13.85	4.90	8.46	9.48	15.95	4.38	9.05
Cotton irrigation (ML/ha)	2.2	3.1	0.8	2.2	2.7	4.0	1.3	2.8
Maize yield (t/ha)	6.69	11.70	0.87	6.57	8.15	12.20	1.45	8.95
Maize irrigation (ML/ha)	1.5	3.2	1.1	1.3	1.7	4.2	0.0	1.8
Wheat yield (t/ha)	2.40	5.49	0.46	2.17	-	-	-	-
Wheat irrigation (ML/ha)	0.8	1.3	0.0	0.8	-	-	-	-
Chickpea yield (t/ha)	-	-	-	-	2.22	3.52	0.59	2.25
Chickpea irrigation (ML/ha)	-	-	-	-	1.0	2.0	0.0	1.2
Farm runoff (mm)	56.5	279.0	1.1	41.2	60.6	213.5	0.5	47.1
Drainage (mm)	58.2	299.0	0.0	25.7	25.4	231.4	0.0	47.1