greater demand for surface water in the Mooki and cause water to be traded upstream from Lower Namoi.

8.3.5 Summary

The results presented above have useful applications for policies designed to target water use or salinity reduction, and the impact it has on basin crop production. It can be seen that the impact of environmental targets, in the form of environmental flows or salinity reduction, will have varying impacts on production activities depending on the irrigation technology used and the possibility for water trade.

Initially, without water trade, the main areas reliant on surface water are upstream Caroona and Breeza, while downstream Ruvigne relies mainly on groundwater. Where DD caps are imposed to mitigate salinity contribution, both surface and groundwater users are affected since the DD cap indiscriminately reduces drainage from both water sources. Much of the impact occurs in Ruvigne, because groundwater is used primarily in this area. However, DD caps cause groundwater extraction to be reduced below its sustainable level, which leads to a sub-optimal outcome because the full capacity of groundwater resources is not used. In addition, surface water extractions are relatively less affected which means that a smaller amount of environmental flow is generated.

On the other hand, where the objective is to achieve greater environmental flows through limiting surface water extraction by imposing a cap, only irrigators sourcing surface water are affected. This means groundwater use remains at the estimated sustainable extraction rate according to groundwater Water Sharing Plans. Without water trade, much of the economic burden of water caps is incurred upstream in Caroona and Breeza. However, where water trade is possible, water is traded downstream to Ruvigne where it has the greatest productive value. Ruvigne becomes the main area of irrigated production. This suggests that, rather than clawing-back surface water from upstream Caroona and Breeza, where most surface water is initially used, it may be optimal to rely on market mechanisms and encourage surface water to be traded downstream. This allows inefficient users upstream to voluntarily exit the irrigation industry, and also enables environmental flows to be sourced at the least-cost. There is an additional benefit in that irrigation is concentrated in Ruvigne and reduced in upstream Caroona and Breeza, leaving a greater area of Upper Namoi for environmental conservation purposes.

Overall, it can be concluded that environmental targets would have different impacts on basin crop production, depending on the technological setting and the possibility for water trade. The associated opportunity cost of achieving environmental targets will therefore vary under these different circumstances, and will also depend on how stringent the targets are. The cost of achieving environmental targets, and how they can be achieved at least-cost, is considered in the following sections.

8.4 ESTIMATED COSTS OF ENVIRONMENTAL FLOWS

In this section, the cost to the irrigation industry associated with meeting environmental flow targets is analysed. A comparison of the total cost (TC) of achieving environmental flow targets, between each treatment, is made. A TC function is estimated for each scenario under Treatment One (status quo), Treatment Two (no water trade, with alternative irrigation systems – AIS) and Treatment Three (with trade and AIS). The effect of increased environmental flows was simulated by successively reducing surface water allocations from 59,000ML to zero, and the TC functions are calculated relative to the profit under Treatment Three. That is, the cost functions obtained represent the opportunity costs of providing environmental flows, relative to the basin profit in the presence of water trade, without requirements for additional environmental flow above that stipulated in the surface Water Sharing Plan.

As can be seen in Figure 8.23, these cost functions are fairly linear. This is an artefact of the assumption that, as water supply is reduced irrigators do not reduce water use per hectare. Instead, the area under irrigation is reduced such that each area receives the full crop water requirement. In this way, the value of water is reflected in the additional *area* that can be irrigated and translates to linear cost curves as water supply declines.

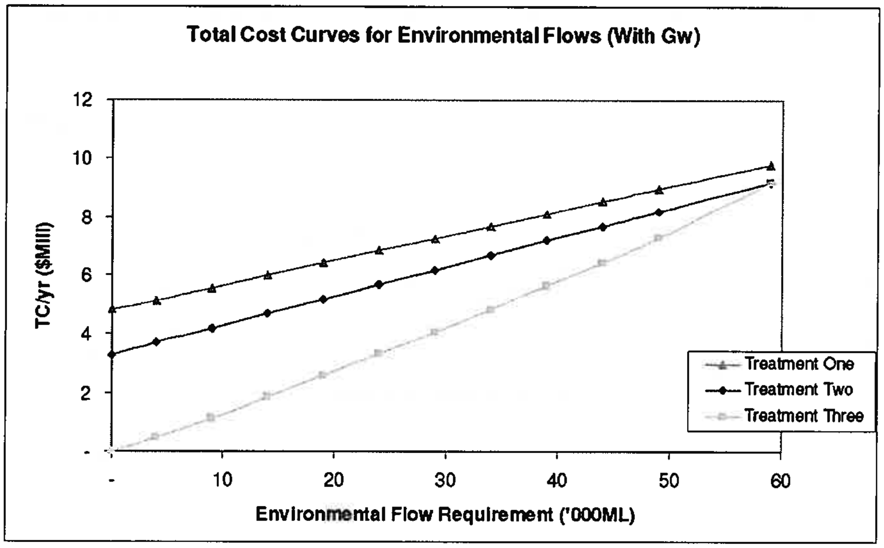

Figure 8.23: Total cost of meeting environmental flows.

The difference between the TC functions for Treatment One and Two represents the value of having the option to choose among various alternative irrigation systems (AIS), while the difference between TC functions for Treatment Two and Three represents the value of having a water market in the catchment, for any given environmental flow requirement. The cost difference between the functions suggests that, when the option of choosing among various AIS is present the total opportunity cost of meeting environmental targets can be reduced by $1.5Mill/yr. When the water market is in place in the catchment, the opportunity cost can be reduced by $3.3Mill/yr. The distance between the TC functions under each treatment is the greatest at low environmental flow requirements, and becomes smaller as environmental flows increase. That is, as the environmental flow requirements increase, the values of having the water market or having the option of AIS both diminish, and tend towards the same point. The non-convergence where all extractive water is reallocated to environmental flows is due to the available groundwater, which has a different value under different technological settings (water has a different value where AIS is used since it is used more productively, compared to furrow irrigation).

This trend implies that the benefit of AIS and water market is limited if extractive water use is reduced substantially, since the use of water trading or AIS can only do so much to reduce the opportunity cost incurred. If a significant amount of extractive water is reallocated towards the environment, there would be significant economic costs imposed regardless of what adjustment mechanisms are available. Unless there is a high valuation of the environmental benefits that the conserved water would provide, it may not be efficient to reallocate a substantial share of extractive water towards environmental purposes. The efficient allocation of water between extractive and non-extractive uses should be where the marginal value in production equates with the marginal value of water for environmental purposes.

8.4.1 Marginal Costs of Environmental Flows

The equilibrium shadow values of surface water, under water trade (Treatment Three), are presented in Figure 8.24. These shadow prices also represent the marginal cost of providing extra environmental flows diverted from extractive allocations. Where the catchment manager wishes to source environmental flows from the water market, the shadow values provide a useful guide for the marginal cost of additional environmental flows. It can be seen that the value of surface water is relatively constant, since the shadow price is unchanged for a range of surface water allocations. Again, this is an artefact of the assumption that irrigators use extra water to expand production. The shadow value of water reflects the additional area that could be irrigated, rather than the increased rate of irrigation. This also explains the relatively constant TC curves observed in the environmental flow cost functions in Figure 8.23. In addition it suggests that, for various environmental flow targets, the marginal costs are not different and a greater volume of water could be obtained without increasing the marginal cost incurred by irrigators.

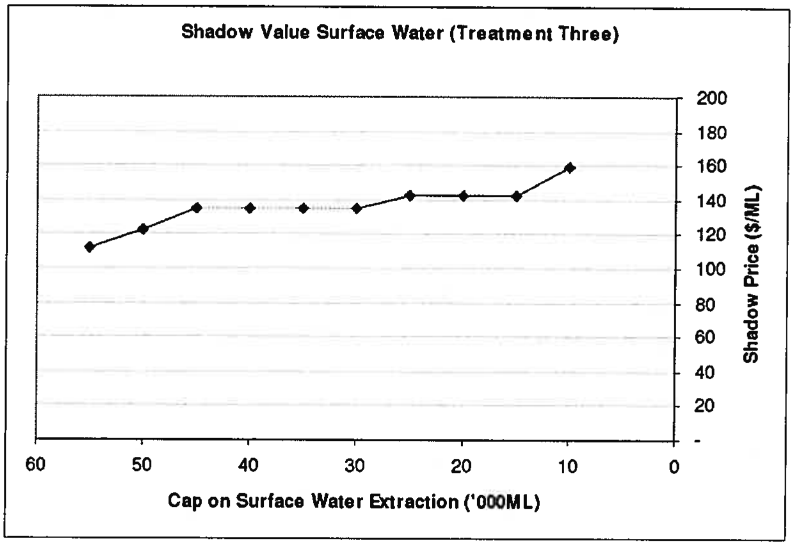

Figure 8.24: Shadow value of surface water at different surface water allocations, under Treatment Three.

8.4.2 Summary of Estimated Costs of Environmental Flows

It can be seen from the above results that investing in water efficient technologies and establishing a water market will be valuable for the Mooki basin, since it can improve the productivity of the irrigation sector significantly, as well as minimise the opportunity cost of securing environmental flows in the river. For the Mooki, it appears that the marginal cost of providing additional environmental flows is fairly constant, and environmental flows could be increased without increasing the marginal cost incurred by irrigators. While this suggests that setting a higher environmental flow standard will not increase the marginal economic impact, the overall cost will still be high. Efficient water allocation should be where its marginal value in production equates with the marginal value of water for environmental purposes.

8.5 DUAL INSTRUMENTS: DEEP DRAINAGE AND SURFACE WATER CAPS

In the previous section, the costs of achieving environmental flows were presented in order to assess the impact of environmental flow objectives, and how alternative irrigation systems (AIS) and water trade can reduce the economic burden. Suppose now that the catchment manager is also concerned about the level of deep drainage (DD), and must evaluate the usefulness of DD caps as an additional instrument to manage salinity, independently of environmental flow policies.

In this section, the economic cost of imposing DD constraints on the basin, in conjunction with surface water constraints, is analysed. The outcomes represent the impact of 'dual-instruments' that may be used by a catchment manager to control salinity and environmental flows separately. These results could shed light on the current situation in NSW catchments, whereby an end-of-valley salinity target has been imposed as part of the MDB Salinity Management Strategy. This has been introduced on top of surface Water Sharing Plans for individual valleys in NSW, with the prospect of increased environmental flows in the near future. The question is whether the combined use of a separate instrument is useful in controlling the 'joined' pollution, given water use and DD are interrelated.

Firstly, a comparison of the resource use, profit and the associated salt load, under the Base Case scenario of each treatment, is presented. This is done in order to appraise the estimated level of DD and salinity contribution from the Mooki, and put into perspective the effect of water and DD instruments. This is followed by an assessment of using dual-instruments to manage salinity risk, under Treatment One (status quo), Treatment Two (no water trade, with AIS) and Treatment Three (with water trade and AIS).

8.5.1 Salt Loads

A summary of outcomes under the Base Case scenario of each treatment is presented in Table 8-9.

Table 8-9: Comparing outcomes under Base Case scenarios.

	Base Case scenarios					
Treatment	Profit/yr ($Mill)	Deep drainage (ML/yr)	Salt load (t/yr)	Surface water use (ML/yr)	Groundwater use (ML/yr)	Total water use (ML/yr)
One	35.32	25,419	8,693	53,628	56,059	109,687
Two	36.85	24,200	8,277	58,698	56,200	114,898
Three	40.15	24,710	8,451	59,000	56,241	115,241

The EC reading[10] for Mooki was reported as 534µS/cm, which means each megalitre of water carries 342kg of salt. This is based on the assumption that 1,000µS/cm equates to 640kg of salt per megalitre (NSW DPI 2006b).

It appears that DD and associated salt load are fairly similar between the three treatments, although there is a significant difference between the levels of water use. As observed in earlier results, water efficient technologies (AIS) seem to significantly improve water use efficiency. A reduction of 5% in DD is observed under Treatment Two (no trade, with AIS) relative to Treatment One (status quo). Where water trade is introduced (Treatment Three), DD and salt loads increase by 2% relative to Treatment Two, although a net reduction of 3% is still achieved relative to the status quo. This suggests that, even without additional policy instruments, DD and salt load could be partially reduced by simply encouraging the use of AIS and water trading in the basin.

The salinity concentration of water in the Mooki (534 µS/cm) is not a significant concern for the Namoi, since it is not sufficient to cause crop damage to cotton which has a salt tolerance level of 1,700 µS/cm. However, the main implication of saline return flows is its downstream impact on the Barwon-Darling system. It is thought that Mooki and the Peel River are the main contributors of salinity to the Namoi catchment. Considering that the Namoi end-of-valley salt load target is 127,600t/yr, the estimated contribution from the Mooki, of around 8,693t/yr, represents just 7% of the target. However, the salt contribution from Mooki relative to its area is moderately high. The Mooki study area, of 397km^2, comprises 1% of the total area of Namoi of 41,998km^2. This suggests that the proportional salt contribution from Mooki should be 1% of 127,600t, or 1,276t/yr. Compared to the estimated salt load of 8,693t/yr, the salt input from the Mooki is seven times greater than the proportion it may be expected to be contributing.

Where the objective is to reduce salt load below the Base Case scenario level of 8,693t/yr, an additional instrument to control DD contribution may be required and would

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[10] Electrical conductivity (EC) is the measure for water salinity.

be imposed separately to surface water caps to control the conjoint pollution. The results of an analysis of such a dual-instrument are presented in the next section.

8.5.2 Dual-Instruments

Under each of the three treatments, DD constraints were reduced successively from 26,000ML to zero drainage. This is done under different water cap scenarios, holding available surface water at 59,000ML, 45,000ML and 25,000ML. The DD constraint is set on a basin-scale, such that the total DD across the 53 HRUs cannot exceed the target drainage level. The opportunity cost under each treatment are in terms of annual profit, and is relative to the profit under Treatment Three (with water trade), at 59,000ML surface water allocation without any constraints on DD. At zero allowed drainage, the HRUs are forced to produce dryland crops only. The total cost (TC) at zero DD is therefore a proxy for the value of irrigated crops, given the surface water allocation and treatment. To better convey the changes in TC between treatments, the results are discussed in the order: Treatment Three (water trade and alternative irrigation systems – AIS), Treatment Two (no water trade with AIS), Treatment One (status quo: no water trade, no AIS).

8.5.2.1 Treatment Three

Under Treatment Three, the impact of DD caps is considered in the presence of a water market and AIS. This is done while simultaneously capping surface water at 59,000ML (full season water allocation), 45,0000ML and 25,000ML.

For the set of TC functions in Figure 8.25, the impact of DD constraints are exemplified through the *slope* of the curves, reflecting the change in shadow price at different DD targets. The impact of reduced surface water availability is shown through the *shift* in the TC curves, which reflects the opportunity cost of diminished water availability relative to the full-scale water supply of 59,000ML.

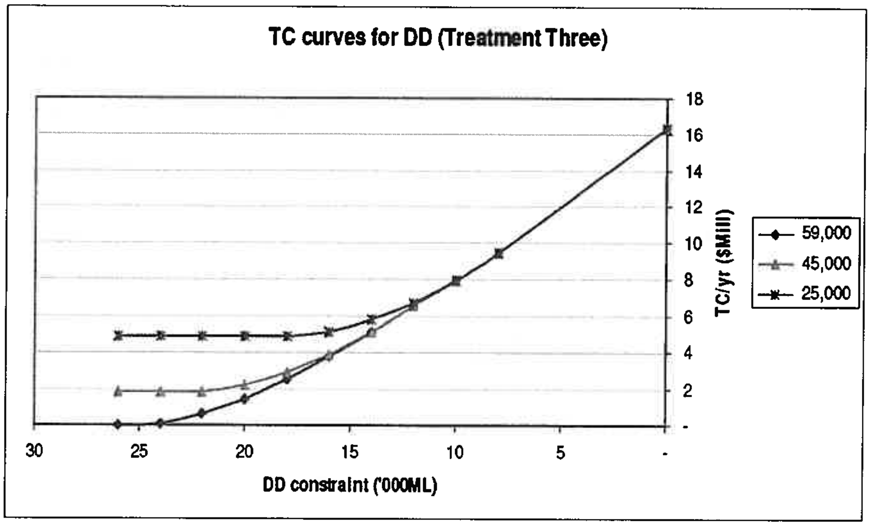

Figure 8.25: Total cost (TC) of DD constraints under Treatment Three, with Water Caps.

In the presence of a water market and AIS, the slope of the TC functions are initially different across the water constraint levels, but converge as the DD target falls below 13,000ML. This suggests that, at tight DD constraints, the shadow value of DD is unchanged under different surface water caps, such that the impact of DD targets does not vary much for different water constraint levels. That is, if a stringent drainage constraint is set, it would not affect the marginal cost incurred by the irrigators. On the other hand, at lax DD targets, the marginal cost of drainage reduction depends on the water availability. It appears that for some water caps, the marginal-cost of DD is actually zero. This is implied by the point of inflection in the TC functions, whereby at lower water availabilities its slope does not begin to rise until tighter DD targets. For example, with a water constraint of 25,000ML, the marginal cost of DD targets is zero until the DD target falls below 16,000ML. Under a water constraint of 59,000ML, the marginal cost is $630/ML for the same drainage target. This is because when water use is reduced, DD is invariably reduced also. Therefore, it appears that stringent water and DD constraints can be simultaneously imposed without additional economic impact. However, it is perhaps meaningless having an extra constraint on DD if its occurrence is already limited by the reduced availability of the surface water supply. This is a consistent trend observed under each of the treatments, which are discussed in turn below.

8.5.2.2 Treatment Two

Under Treatment Two, the impact of DD caps are considered where there is no possibility to trade water in the water market; however there is the option to invest in AIS. Like in Treatment Three, water caps are simultaneously imposed at 59,000ML, 45,000ML and 25,000ML.

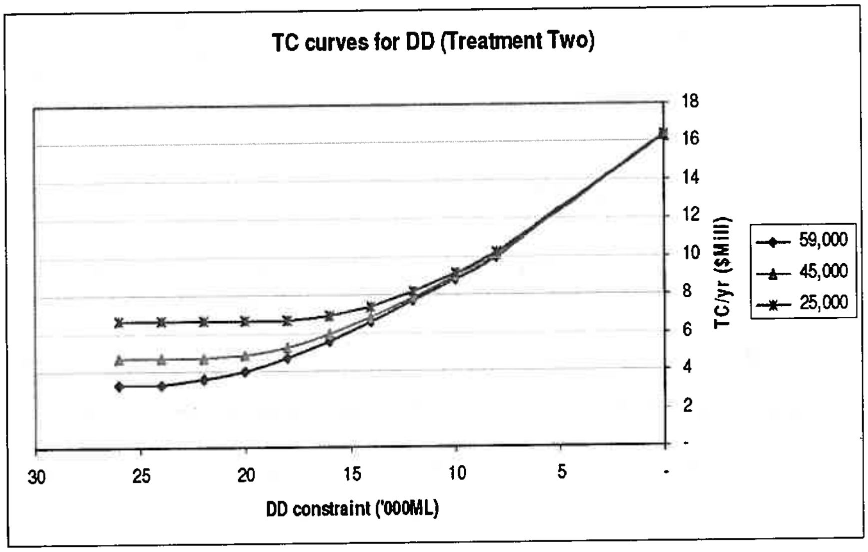

Figure 8.26: Total cost (TC) of DD constraints under Treatment Two, with Water Caps.

Under Treatment Two (no water trade, with AIS), the TC functions shift up relative to Treatment Three, reflecting the opportunity cost of water trade (Figure 8.26). The impact of DD is exemplified through the slope of the TC functions, which are slightly less steep than Treatment Three. This suggests that, without water trade, the shadow price of DD is lower because water has not been reallocated to its highest value use. Therefore without water trade, the marginal impact of DD caps are less than when water market is in place, although the total opportunity cost of no trade (expressed through the upward shift in TC functions) is significant.

Similarly to Treatment Three, the slopes of the TC functions initially vary at lax drainage caps. Its marginal cost under low surface water availability is low and sometimes zero, as implied by the flatness of the TC functions. The inflection in the TC does not occur until tighter drainage constraints, since DD occurrence is already reduced by the water cap. For example, under a surface water allocation of 25,000ML, the opportunity cost of reducing DD is zero until DD targets fall below 16,000ML. For the same DD target, at a higher water allocation of 59,000ML, the marginal cost is positive, at $430/ML. This reiterates the finding under Treatment Three, which suggests that an additional DD instrument may be superfluous if a water cap has already been implemented.

8.5.2.3 Treatment One

Under Treatment One, only furrow irrigation is used and there is no opportunity for water trading. DD caps are imposed while holding surface water caps at 59,000ML, 45,000ML and 25,000ML.

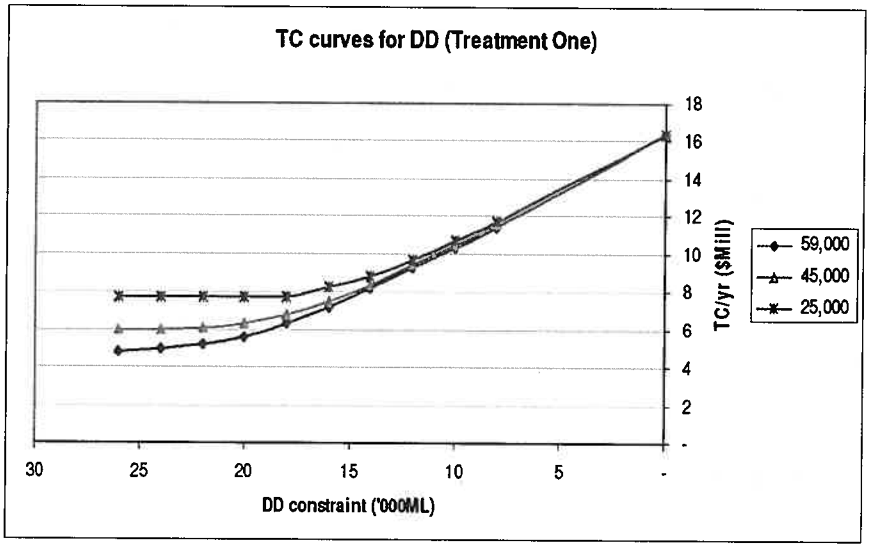

Figure 8.27: Total cost (TC) of DD constraints under Treatment One, with Water Caps.

Under the status quo (Treatment One), the TC functions shift up further compared to Treatment Two, which represent the value of having options to choose AIS to the irrigators in the catchment (Figure 8.27). The shadow price of DD is also reduced relative to previous treatments, as indicated by the gentler slopes. This is due to the lack of water trading to shift water to its highest value use, and also because water is used inefficiently under furrow irrigation so each unit of DD has a lower marginal value. Consequently, irrigators incur lower marginal costs for reducing drainage under Treatment One. However, the overall cost of not using AIS or the water market is significant, as indicated by the upward shift in the TC functions.

As was the case previously, the slope of the TC appears to be relatively unaffected by the water availability at tight drainage constraints. This result reiterates the finding that, even with stringent DD targets, it is not significantly more costly to reduce drainage given there is no substantial difference in the marginal cost of DD under different water supplies. The main difference between the TC functions is the point of inflection, which occurs at a more stringent DD constraint as water supply is reduced. With a 25,000ML water cap, the marginal cost of DD is zero for some drainage target levels, whereas the same DD at higher water supplies has positive marginal cost. This is a consistent trend, which is also observed under previous treatments.

8.5.3 Summary of Results for Dual-Instruments

The implication from the above results is that, although it may be difficult determining an efficient DD target at a basin scale, the difference in the *marginal* cost of reducing DD while simultaneously imposing water caps will not be excessive. This is evidenced by the similarity in the slope of the TC functions for drainage reduction, across different water caps. This implies that the marginal cost of reducing DD is independent of water supply for most DD targets, and may be set separately. The *total* cost incurred for stringent drainage targets, however, is considerable, and at tight DD constraints the overall economic impact on irrigators will be significant.

Under stringent water cap levels, for some DD constraints the marginal cost to reduce drainage is zero because drainage occurrence is limited by water availability. While this suggests that surface water and DD constraints can be jointly imposed without additional economic impact, an extra instrument to control the conjoined pollution, in the form of DD, may be unnecessary. This is because its occurrence is already reduced by low surface water supply.

It therefore stands to reason that water caps on its own would suffice in achieving DD (salinity) reduction. However, water caps also have associated opportunity costs of production. If one instrument suffices in achieving the desired outcome in water resource use or in salinity reduction, the question then becomes, which instrument could achieve the objective most cost-effectively. A comparison between DD and surface water caps are made in the following section, and will illustrate the effectiveness of each instrument under different treatments.

8.6 SEPARATE INSTRUMENTS: DEEP DRAINAGE v SURFACE WATER CAPS

The efficacy of deep drainage (DD) and water instruments to independently achieve DD reduction, under each treatment, is presented in this section. The total cost (TC) of each instrument under Treatment One (status quo), Treatment Two (no water trade, with alternative irrigation systems – AIS) and Treatment Three (with water trade and AIS) is examined. The opportunity cost is relative to the annual profit where full water allocations are received and with no constraint on DD, under the given treatment. Where the drainage or water cap is zero, all producers must grow only dryland crops to satisfy the constraint. This causes the TC function under each instrument to converge at the origin.

8.6.1 Treatment One

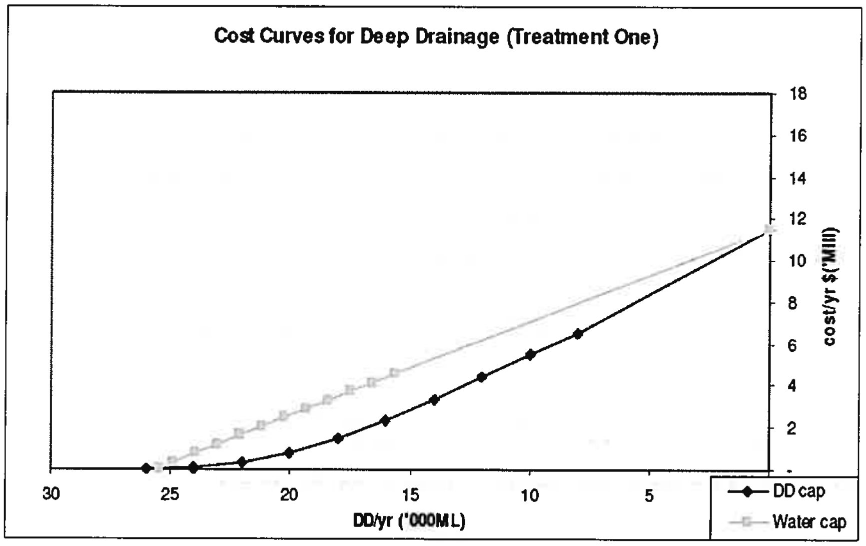

Figure 8.28: Total cost (TC) of deep drainage reductions under Treatment One, comparing instruments.

In Figure 8.28, the TC functions of achieving DD reductions under Treatment One (Status Quo), are presented. As the DD target becomes stringent, the shadow price of DD with surface water caps (pink line) appears to be fairly constant, since the TC function is linear. In contrast, when DD caps are imposed (blue line), the shadow value appears to increase at a slightly increasing rate.

Under a water cap, only irrigators sourcing surface water are forced to forgo water use, whereas under a DD cap both users of surface and groundwater are affected. Since the constraint on DD causes the most inefficient irrigators to forego water use regardless of the water source, the DD cap has a cost-advantage of up to $2Mill/yr. However, water caps have an additional benefit of generating extra environmental flows since it reduces only extractions from the river. On the other hand, under a DD cap, in-river extractions are not reduced as significantly (Figure 8.29).

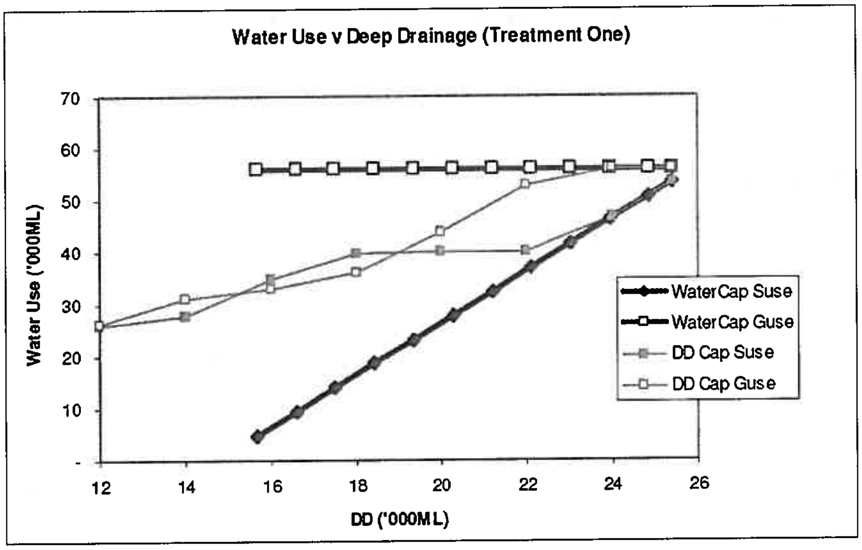

Figure 8.29: Water use under each instrument, Treatment One.

It can be seen that with water caps (Figure 8.29, blue lines), only surface water use (Suse) is reduced while groundwater extractions (Guse) remain unchanged. However, with DD caps (red lines), some reduction in groundwater use occurs as DD constraints become stringent. This is because DD caps impinge on overall water use, such that both surface and groundwater users are affected. While this allows the least-cost way of reducing DD, it also means that there is less environmental flow provision under DD caps for most target levels. Furthermore, groundwater extractions are reduced to a level below the estimated sustainable extraction rate according to the groundwater Water Sharing Plan. Water caps allow groundwater extractions to be maintained at the sustainable rate of use, while at the same time generating greater environmental flows (Figure 8.30).

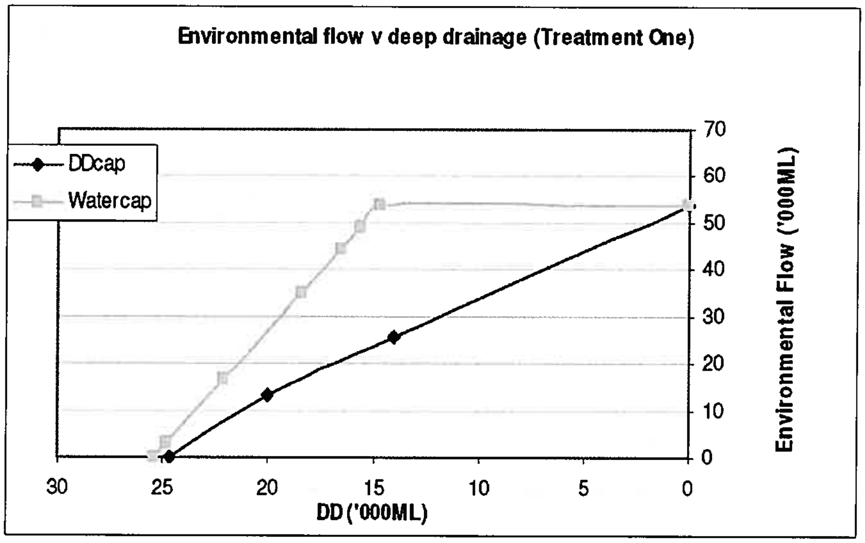

Figure 8.30: Environmental flows v deep drainage, Treatment One.

The above figure shows the environmental flow generated for a given drainage occurrence, under each instrument. It can be seen that, for all drainage levels, water caps have a significant advantage over DD caps in generating environmental flows. If the catchment manager has the dual-objective of providing for environmental flows and DD reduction, water caps could achieve this objective more cost-effectively than DD caps for most target levels.

8.6.2 Treatment Two

The results under Treatment Two (no trade, with alternative irrigation systems (AIS)) are similar to results under Treatment One, except the cost differential between the two instruments is diminished (Figure 8.31). The TC function under a water cap is again fairly linear, which implies that the shadow price on the DD constraint is constant where water cap is imposed. Where a DD cap is used, the TC function increases at a slightly increasing rate.

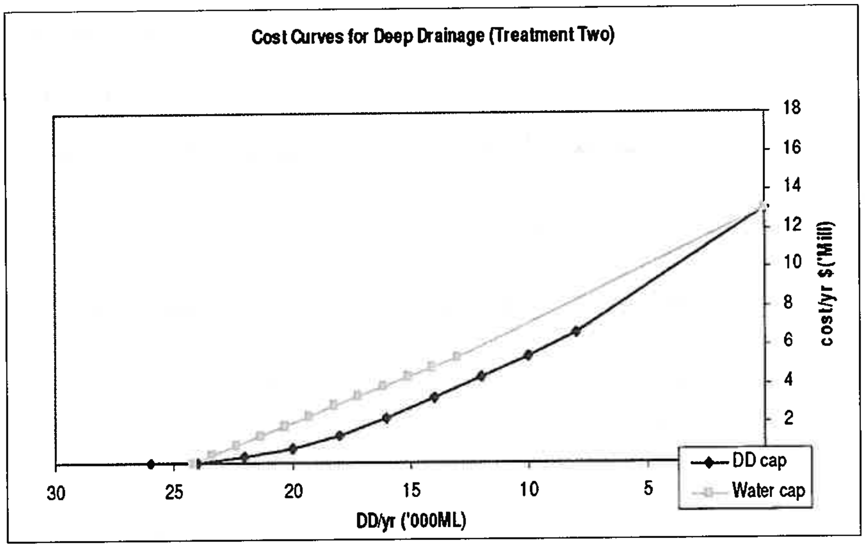

Figure 8.31: Total cost (TC) of deep drainage reductions under Treatment Two, comparing instruments.

Like Treatment One, DD caps affect overall surface and groundwater use, and allow for the least-cost means of achieving DD reduction. However, it also reduces the rate of groundwater use to below the estimated sustainable level of extractions, according to the groundwater Water Sharing Plan. This can be seen in Figure 8.32.

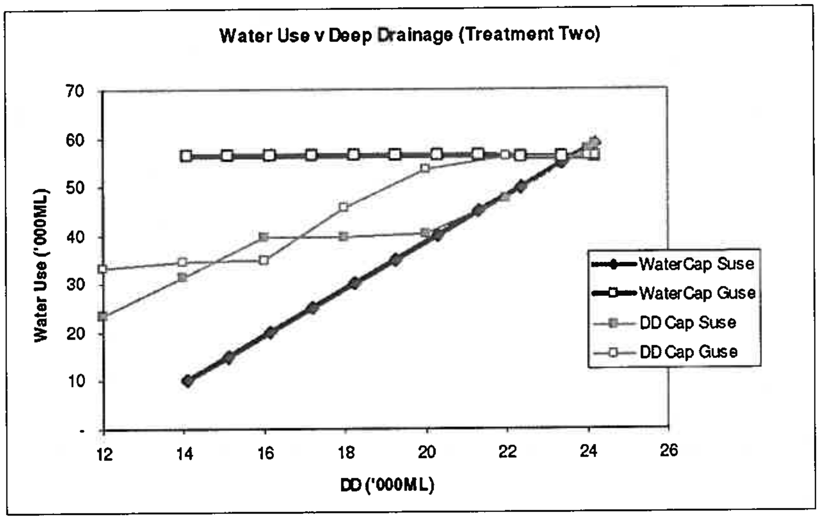

Figure 8.32: Water use under each instrument, Treatment Two.

The two instruments appear to have similar impacts on surface (Suse) and groundwater use (Guse) initially, at lax levels of DD constraint. However, for drainage constraints below 20,000ML, DD caps leads to significant reductions in groundwater use. Again, this brings groundwater extractions below the sustainable level, as well as resulting in smaller reductions in surface water extraction. Similarly to Treatment One, for a given DD occurrence, the level of environmental flow provision is significantly greater under water caps than under DD caps, for most DD target levels (Figure 8.33). Where the objective is to generate environmental flows and significant DD reduction, a water cap could achieve this aim more efficiently.

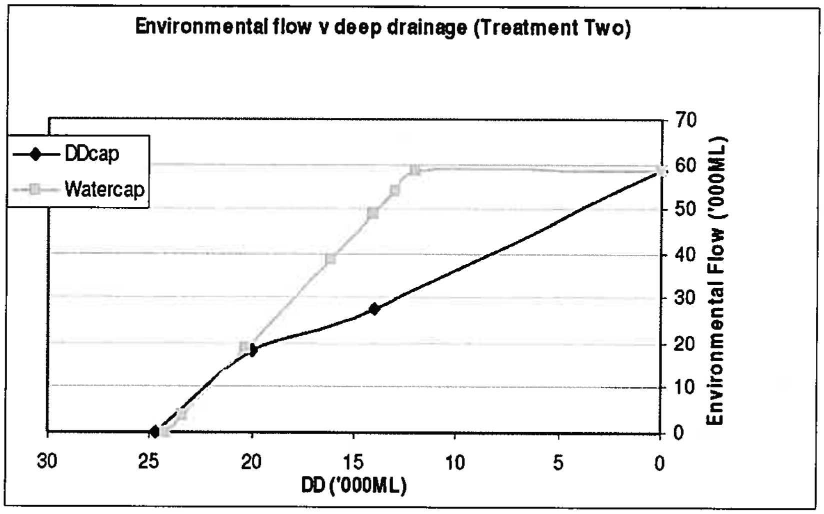

Figure 8.33: Environmental flows v deep drainage, Treatment Two.

8.6.3 Treatment Three

The TC curves under Treatment Three are relatively steeper than under previous treatments, essentially due to the increased shadow value of DD as water is shifted to its highest value use with trade (Figure 8.34).

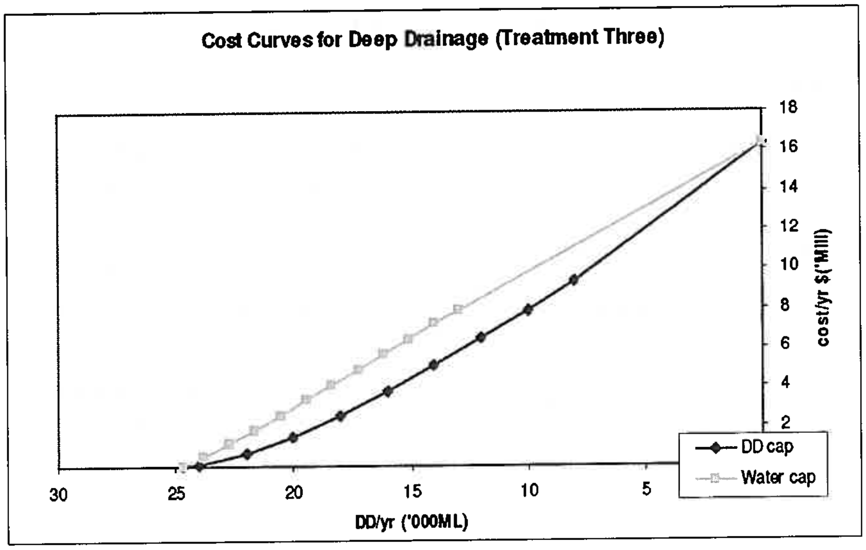

Figure 8.34: Total cost (TC) of deep drainage reduction under Treatment Three, comparing instruments.

While the overall TC is greater with trade, the discrepancy in TC under water quantity and DD instruments are not significantly different; DD caps are also more cost-effective, and can reduce the opportunity cost by approximately $2Mill, under Treatment Three. However, the most distinguishing difference is the change in water use under the two instruments (Figure 8.35).

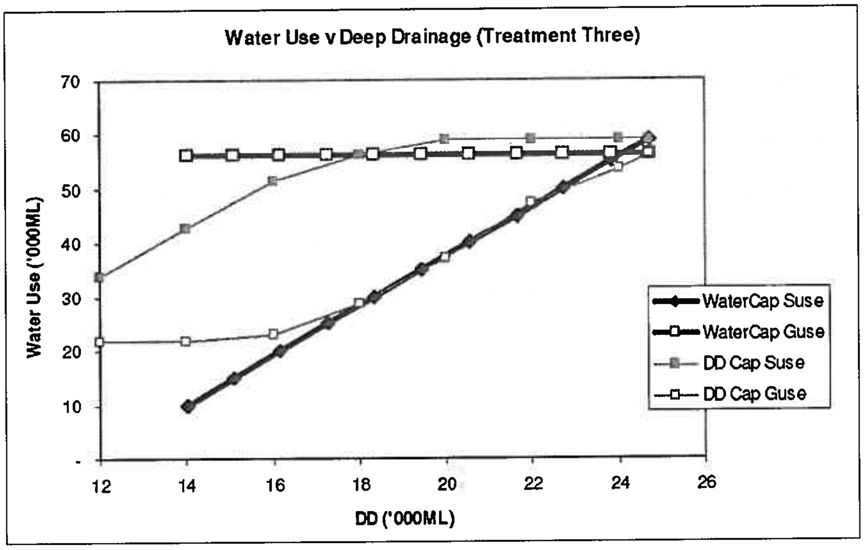

Figure 8.35: Water use under each instrument, Treatment Three.

Under DD caps, groundwater use (Guse) appears to be the main source of water that is reduced to meet the drainage constraint. This is while surface water use (Suse) is relatively unaffected until DD targets fall below 17,000ML. This means that under a DD cap, in-stream environmental flows are not increased even at very tight levels of DD constraints, because surface water extractions are not reduced. Instead, the level of groundwater use – which is set to the estimated sustainable extraction level – is reduced to a level that is far below its full capacity. The use of DD instruments therefore imposes unnecessary costs on the irrigators, while at the same time it does not generate greater environmental flow benefits. For all levels of TC incurred, the environmental flow generated is greater under water caps than under DD caps (Figure 8.36).

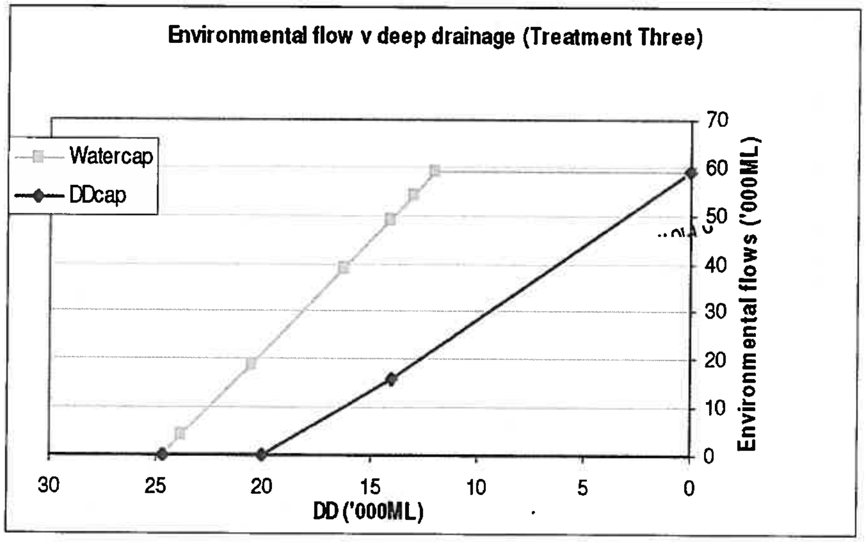

Figure 8.36: Environmental flows v deep drainage, Treatment Three.

8.6.4 *Shadow Price of Deep Drainage*

The shadow price of DD under each treatment is presented in Figure 8.37 (Treatment One), Figure 8.38 (Treatment Two) and Figure 8.39 (Treatment Three). The shadow values obtained represent the marginal cost of reducing DD at the catchment level. It can be seen that as AIS (Treatment Two) and water trade (Treatment Three) are introduced, the shadow value of drainage increases. Also, as the DD constraint approaches zero the shadow prices appear to increase and then plateaus out as the drainage target becomes stringent. This explains the shape of the TC functions for DD reduction observed in the above sub-sections, which increases at an increasing rate but gradually becomes linear.

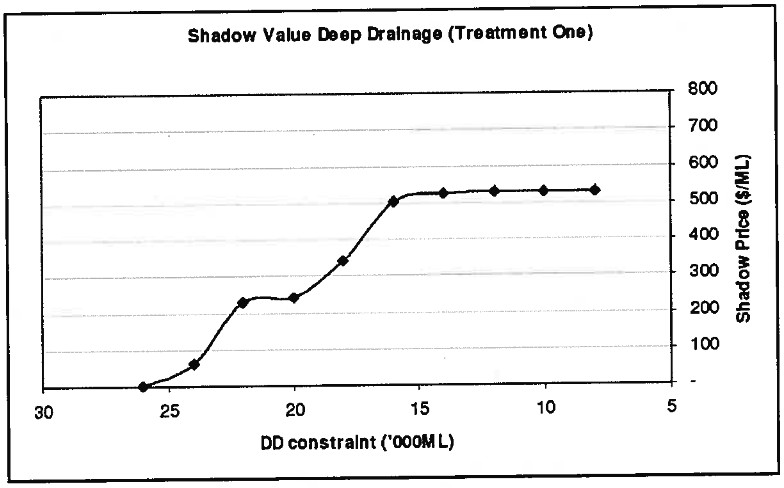

Figure 8.37: Shadow price of deep drainage under Treatment One.

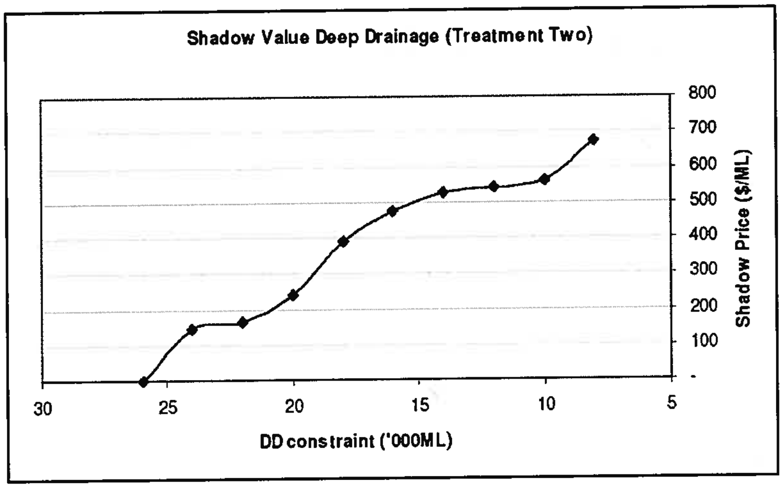

Figure 8.38: Shadow price of deep drainage under Treatment Two.

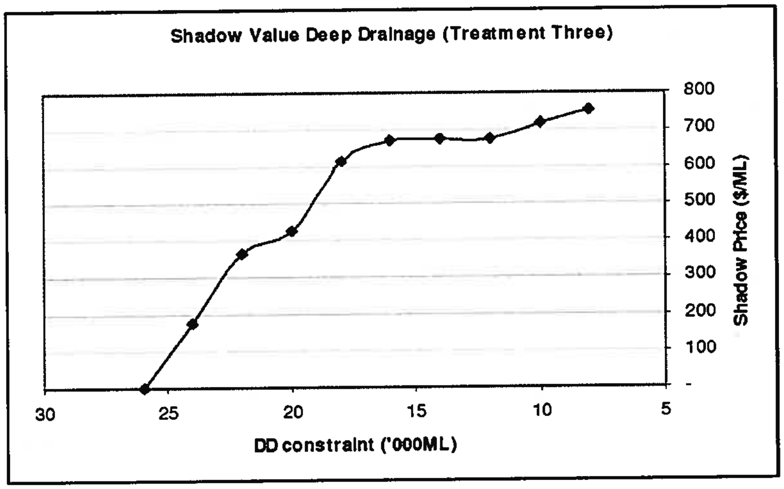

Figure 8.39: Shadow price of deep drainage under Treatment Three.

If a price-based rather than a quantity-instrument is considered for controlling drainage, these shadow prices for DD will be useful for determining appropriate DD prices. Both price and quantity instruments should theoretically achieve the same outcome, such that the results in previous sections should also hold if there is an efficient DD pricing system in place. For catchments which have chronic salinity problems and very high levels of DD, it may be optimal to use price or quantity instruments to target DD directly, since it has a greater cost-advantage over water instruments. However, the cost-advantage of DD instruments can easily be outweighed by the extra administrative cost of setting up such a system. While DD pricing would provide the correct conservation signals and achieve DD reduction, a significant knowledge gap remains regarding the actual occurrence of DD across a large landscape.

8.6.5 Summary of Separate Water and Deep Drainage Instruments

The discussion above indicates that the choice of a preferable instrument should depend on the catchment manager's objectives. If it is realised that the level of salinity contributions is in fact excessive, it may be worthwhile creating separate DD instruments to control its occurrence. Drainage instruments have the advantage of providing the least-cost means of achieving salinity targets, by forcing the most inefficient irrigators to forego wateruse, rather than causing only surface water users to relinquish allocations at higher cost. However, DD caps also have significant opportunity costs, because groundwater must also be reduced to a sub-optimal level of water use, and lead to unnecessary income losses. This is while in-river extractions are not reduced, such that less environmental flows are generated for a given DD target. In a broader context, for salinity instrument to be preferred, it would have to be insured that the benefit to downstream users from reduced water salinity must be greater than the cost incurred by upstream users in mitigating salt loads.

Alternatively, reduction of surface water allocation can reduce drainage effectively without affecting groundwater use. Given that the overall drainage occurrence and total water use is comparable under both scenarios, there is no significant difference between the effects of both instruments. Therefore, if deep drainage is not at a critical level, it may be more efficient to adopt instruments that regulate surface water use rather than deep drainage. This could provide additional benefits in the form of greater environmental flows and fresh flushes to dilute saline runoff, and avoid excessive administrative costs in creating a dual instrument. Also, given the knowledge gap regarding drainage (Vervoort 2007, pers. comm.), the economic cost for setting a 'wrong' target is likely to be high.

A factor which may affect the results relates to the technical configuration of the biophysical model. The SWAT is configured in such a way that surface water cannot be stored in on-farm storages, so that when river water is available it is pumped directly onto the field. Irrigation using surface water therefore only occurs when the opportunity arises, which is more infrequent than groundwater. Given the uncertainty of surface water supply, irrigation volume and frequency is lower, hence drainage per hectare is lower. As a result, to achieve the same drainage reduction as DD caps (which affect both surface and groundwater use), a more stringent surface water cap becomes necessary. If configurations could be made in SWAT to store surface water in on-farm storages, the security of surface water supply would increase and the frequency and volume of irrigation would also increase. Surface water users would enjoy the same security of supply as groundwater users, so that irrigation volume and DD would be very similar between the two water sources. The reduction in either water source would therefore lead to a similar fall in drainage, and translate into very similar DD cost functions between drainage and water instruments. This further strengthens the conjecture that water caps on its own would suffice in achieving the dual target of environmental flows and salinity reduction.

This concludes the comparison between water and drainage instruments, under the three treatments. For the following section, the focus moves to the results in Treatment Four, which consider the impact of increased competition for surface water from an agent that is external to the Mooki basin.

8.7 EXTERNAL WATER TRADING

The impact of an external agent entering the regional water market is assessed in this section. It is assumed that a mine begins operations in the Mooki region and enters the water market to compete for water at various (exogenous) market prices. For a given water price, P_w, irrigators could choose to trade internally to other irrigators who will use water for crop production, or externally to the coal mine. It is assumed that only surface water could be traded. For simplicity, the gain from external water trade is calculated in terms of net benefit to the external agent, based on its derived demand for water. The water price is parameterised in the interval from zero to \$160/ML and irrigators can only profit from the quantity that is traded at the given price, both internally and externally.

The coal mine's derived demand for water is assumed to be $W^* = 12,522 - P_w/15.48$, based on the quadratic production function of $Coal = -0.1721W^2 + 4318.2W$ and coal price of $P_y = \$45$ per ton (ABARE 2006). This was obtained through econometric estimation using data from a large Australian coal mining company (see Section 7.3.5). The impact of an external buyer is compared to where only internal water trade is possible, to evaluate the degree of competition for resources. It is assumed that the annual allocations are 59,000ML for every year in the planning period. The results reported are therefore based on the outcome for one year, which is representative of all seasons.

8.7.1 Treatment Four – Base Case

Under the Base Case scenario of Treatment Four, the price of water is assumed to be zero and water trade between the HRUs in the catchment is costless. The solution essentially represents the theoretical optimal water allocation for maximum basin profit given annual surface water allocations of 59,000ML. There are no additional requirements for environmental water flow except for the stipulated level in the surface Water Sharing Plan. The volume of water sold ("internal sell") exactly equals the volume of water demanded ("internal buy"), of 37,500ML (Table 8-10). The profit from cropping alone is close around \$40Mill where the market price for water is zero, such that irrigators can trade water at zero cost.

Table 8-10: Outcome under Scenario 4.1.

Pw ($/ML)	Profit/yr ($Mill)	Internal buy ('000 ML)	Internal sell ('000 ML)
0	40.15	37.5	37.5

8.7.2 *Treatment Four – Internal Trade Only*

Where there is only internal trade, the volume of water traded remains the same until P_w increases to above $115/ML (Table 8-11). Above this price, the market supply begins to diverge from demand.

Table 8-11: Internal trading only.

Pw ($/ML)	Profit crop only ($Mill)	Internal buy ('000 ML)	Internal sell ('000 ML)
55	38.09	37.5	37.5
70	37.52	37.5	37.5
85	36.96	37.5	37.5
100	36.40	37.5	37.5
115	35.60	37.5	39.6
130	34.38	37.2	45.0
145	33.69	34.7	46.1
160	32.48	19.1	51.8

This reflects the shadow price of water shown in Section 8.3.4, of $111.45/ML, which represents the market clearing price of water. At higher prices, there is a net inflow of water into the market, leading to excess supply. The internal demand for water remains relatively inelastic and does not begin to fall until P_w increases above $145/ML. An interesting observation is that the market-clearing price of around $111.45/ML is similar to the current temporary trade value for the Lower Namoi regulated systems of $100-$120/ML (WaterExchange 2007). There are no head-dams in the Mooki unregulated system, such that there is no risk of stranded assets when trade is opened between the two regions.

8.7.3 Treatment Four – Internal and External Trade

In this scenario, an external agent (coalmine) enters the regional water market and competes for water resources. The results are presented in Table 8-12.

Table 8-12: Internal and external trading.

Pw ($/ML)	Profit crop only ($Mill)	Internal buy ('000 ML)	External buy ('000 ML)	Internal sell ('000 ML)	External net benefit ($Mill)
55	38.09	37.5	-	37.5	-
70	36.32	34.9	11.1	46.0	953
85	35.68	33.6	12.5	46.1	1,213
100	35.17	33.6	12.5	46.1	1,213
115	34.67	33.6	12.5	46.1	1,212
130	34.17	33.6	12.5	46.1	1,212
145	33.68	31.8	12.5	46.1	1,212
160	32.48	19.1	12.5	51.8	1,212

For water prices below $55/ML, no water is sold to the coal mine. This suggests that water has a greater value in production below this market price. However, between the price range of *$70/ML<* P_w*<$130/ML,* there is increased competition for water between internal and external users. A volume of 3,600ML of water that was traded internally is instead sold to the external user. Furthermore, the presence of an external buyer presents a more profitable alternative to cropping, such that a further 8,600ML of water becomes sold in the water market to meet external demand. Above a price of $160/ML, there is excess supply in the market and the external agent merely soaks up some of the excess supply without infringing on internal demand, placing a market value to the excess water which has no value internally.

From the above results, it can be concluded that in order to compete with internal users when the price is below $70/ML, the external buyer needs to pay a premium to meet its full demand, since internal users have a high value for water at this market price. However, offering a price above $85/ML would allow its full demand to be met without the need to pay a premium. This is because irrigators find it more profitable to sell their allocations than to use it for crop production, and market supply increases relative to where only internal trading exists. For water prices above $160/ML, there is excess supply and there is no competition with internal users; the limiting factor then becomes the external user's demand. However, the maximum water demanded by the external user across the price range considered is only 12,500ML/yr, or 21% of total basin water supply. This suggests that, while external competition for water will affect some irrigators, it should not pose a significant competition for the regional irrigation sector. In fact, it may be profitable for some producers to sell allocations at a premium to the coalmine, without compromising the integrity of agricultural production in the region. For example, selling some water at $85/ML would lead to a 2.7% drop in annual profit from cropping ($1Mill), while representing a net benefit of $1billion for the mining industry in the region[11]. This is also considering the sizeable area in the catchment that appears to be more suited to dryland cropping.

8.7.4 Summary of External Water Trade

While there have been some concern of the impact of increased competition for water on the regional irrigation sector, it appears that the overall impact of a coal mine in the Mooki basin will be relatively small. The maximum demand for water by the external user only comprises a fairly small portion of what is available, and leads to a reduction in the annual profit from cropping of 2.7%. This is while the net benefit that the water represents for the coal mine exceeds $1billion. These results indicate that the Namoi region would accrue net gains from the coalmine. However, these results are dependent on the assumptions made regarding the coal mine's demand for water. While the derived demand was based on empirical data from the coalmining industry, the actual volume of water required depends on the size of the coal reserve in Gunnedah, which is currently unknown. This conclusion also does not consider the secondary effects on employment and other industries, nor the environmental externalities created from mining operations. The results of this analysis may vary once these external effects are factored into the costs of coal production. Nevertheless, the direct impact of increased competition for water from external users, based on the assumptions of the model, is not likely to jeopardise the regional irrigation industry.

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[11] The net benefit is calculated based on the area under the coalmine's demand function for water.

8.8 SPATIALLY DELINEATED RESULTS

In previous chapters, it was highlighted that the advantage of using a GIS-based biophysical model, was to provide spatially differentiated results. This is possible using the SWAT model, which delineates the Mooki basin into HRUs as unique combination of soil type and landuse. The location of each HRU in the Mooki is presented in Figure 8.40, which was produced using the GIS program linked to SWAT. For each HRU, the optimal landuse, activity, resource use, and shadow values have been determined through the economic optimisation model. The solutions obtained for each scenario under each treatment could be implemented on ground since each HRU could be identified using this graphical representation of the basin. Although due to technical limitations GIS layers for each simulation outcome were not produced, the solutions from the economic optimisation are included in Appendix E and could be used to create layers to superimpose on the figure below (Figure 8.40). This can be useful for policy analysis, since the desired outcomes of various policies and its impacts could be assessed with a high degree of spatial detail.

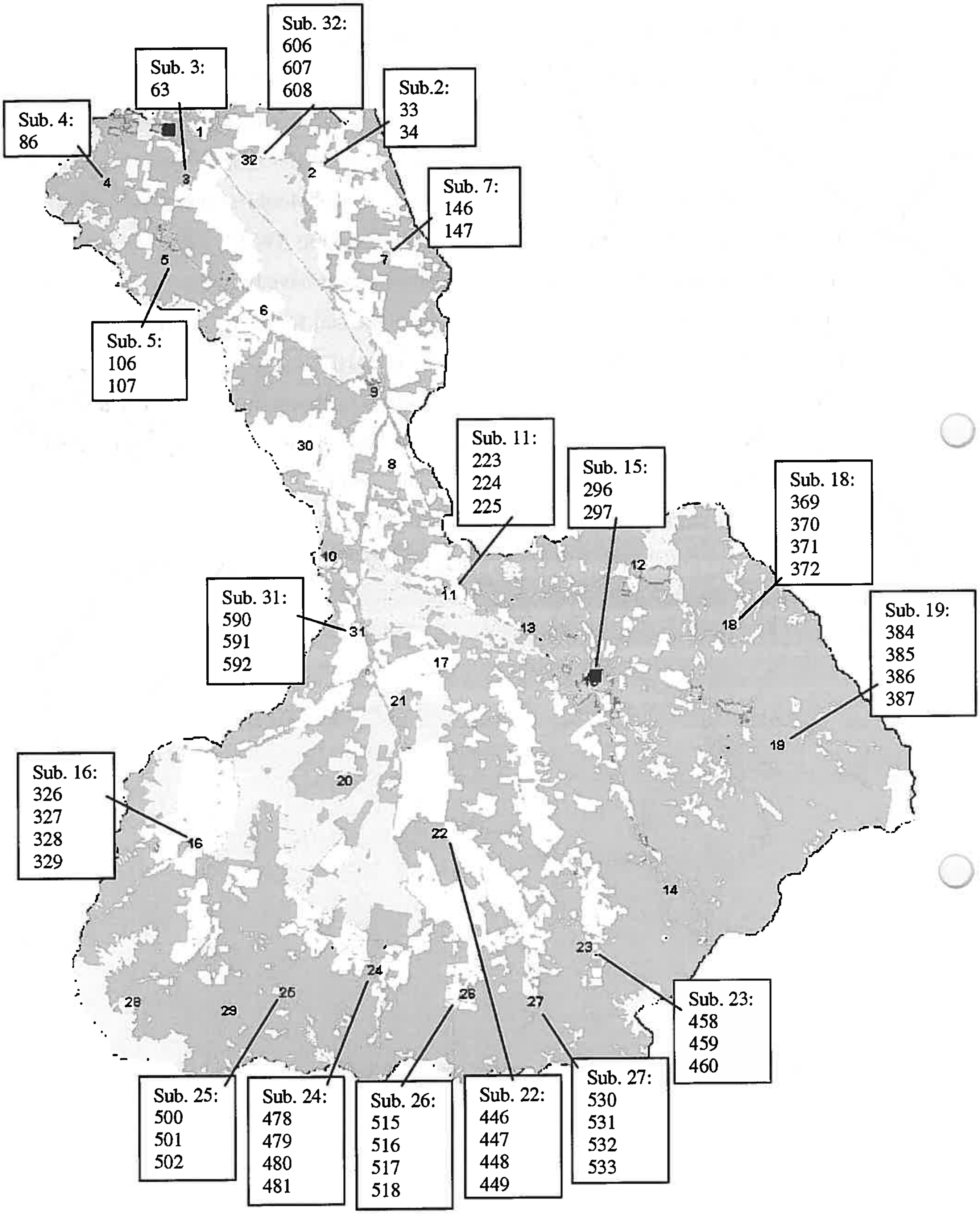

Figure 8.40: Location of the HRUs delineated in SWAT.

8.9 SUMMARY OF CHAPTER 8

Simulation of a water allocation model of the Mooki basin was developed, using an interdisciplinary approach to analyse the impact of various environmental policies on a spatially explicit scale. The objective was to determine how environmental targets pertaining to environmental flow provision and salinity reduction could be achieved at the least-cost. This involved an examination of the changes in resource use and production activities in each irrigation area, under each policy instrument and constraint. Additionally, the economic impact of a dual-instrument, and the use of separate instruments to meet environmental objectives were assessed. This was conducted in order to shed light on the usefulness of current basin policies such as Water Sharing Plans and end-of-valley salinity targets in achieving environmental goals, and the associated economic trade-offs. Furthermore, the consequences of increased competition for water from agents external to the irrigation district were analysed, to evaluate the potential impact on the stability of the irrigation industry. The value that water efficient technologies and water trade represents for the case study basin was evaluated under each policy setting, by comparing the outcomes to the status quo. In addition, consideration was given to the shadow values associated with water resources and the conjoint pollution, in the form of deep drainage that induces salinity, to explain the outcomes under each scenario. A general assessment of the inter-temporal nature of groundwater use, given stochastic surface water supplies, was also discussed at the beginning of the chapter.

From the results obtained, the findings and suggestions are as follows:

1. Overall, it was found that the use of alternative irrigation systems (AIS) and the presence of a water market would improve the economic profit generated by irrigators in the Mooki basin. Under the present surface and ground Water Sharing Plan stipulations of water allocation and environmental flow requirements, AIS on its own could reduce the occurrence of deep drainage (DD) by 5% and an increase in annual profit by 4%, relative to the status quo situation where only furrow irrigation is used. Of the two irrigation technologies

considered, pivot and drip, it appears that pivot systems provide the greatest benefit to irrigators, while drip systems are not as economically viable as pivot due to its high capital outlay. In the presence of a water market, overall catchment profit could increases by 10% and DD could fall by 3%, relative to the status quo. This is due to the increase in surface water use due to the mobility of water allocations.

2. Groundwater carry-over rules are useful where surface water is stochastic since groundwater allocations can be banked or borrowed, subject to its two-year and three-year extraction limits. However, where surface water is deterministic and constant, there is little need for banking or borrowing since the optimal rate of groundwater use should be at its annual sustainable extraction level. For an ephemeral river system like Mooki, where surface water is stochastic, groundwater carry-over rules are useful to hedge against uncertainty. However, the optimal strategy is to utilise annual allocations almost fully each year due to the limits on carry-over allowances.
3. The early system of area-based irrigation licensing has led to an inefficient allocation since it does not match water to its highest value use. This is observed through the results under each treatment, which shows that under the status quo surface water is used in the upstream irrigation areas, Caroona and Breeza, whereas its value is highest in downstream Ruvigne. It is optimal to create a fully functional water market in the Mooki region to encourage the trade of surface water downstream, since upstream regions have high conservation value while water has higher productive value downstream.
4. Where surface water is reallocated from extractive use towards environmental use, the overall opportunity cost is reduced significantly where a water market is in place. The use of AIS also reduces the economic cost incurred, since irrigation water is used more efficiently. However, it is not as effective in mitigating the costs incurred by irrigators compared to where water market is in place. Nevertheless, where environmental flow requirements are high and much of the extractive flows are redirected towards environmental purposes, the ability for AIS or water trading to alleviate the economic burden is limited. The benefit of

additional environmental flows must justify the economic cost incurred by the regional irrigation industry.

5. Considering the high level of estimated salt load from the Mooki basin, there is a cause for concern over its contribution to the salinity level of the downstream Barwon-Darling system. It appears that, where a dual-instrument is implemented to target environmental flows and salinity reduction, there is no significant difference in the marginal cost of meeting these targets at stringent levels. It appears that dual-instruments may be simultaneously set without excessive costs. However, it also suggests that one instrument is sufficient to achieve the dual-objective of salinity reduction and environmental flow provision.
6. Where water caps and DD caps are imposed separately, each instrument can generate some environmental flows and drainage reduction since the level of surface water use is reduced. However, the most distinctive difference is the source of water that is affected by the instrument. Water caps only impinge upon surface water use, while drainage caps lead to reductions in both surface and groundwater use. Each instrument has its advantage: the general trend observed under all treatments show that water caps generate greater environmental flows and maintains groundwater use at its sustainable rate of extraction. On the other hand, drainage caps can achieve DD reductions at the least-cost, but causes groundwater use to drop to levels below sustainable levels and produce lower environmental flows. In the case of the Mooki basin, water caps on their own can achieve environmental flow provisions and salinity reduction more effectively.
7. Irrigators in the Mooki basin have expressed concern over the impact of increased competition for water from a potential coalmine in the region. However, the economic impact from the water competed away for coal production is around 2.7% per year. Compared to an increase in value of $1billion from coalmining over the same period, there is a substantial net gain from the new mine for the irrigation district. This has not factored in other flow-on effects such as employment or environmental damage.

Chapter 9.

CONCLUSION, DISCUSSION AND SUGGESTIONS FOR FURTHER RESEARCH

In this study, the aim was to develop an economic modelling framework that can help assess the economic impact and effectiveness of various environmentally-oriented water policies. The model was developed based on the case study of the Mooki basin in the Namoi Valley, but can also be transferred to other catchments to examine the impact of various policies on a catchment-specific level. The empirical results were used to determine the cost of various environmental targets and also the least-cost means of achieving these objectives. In this chapter, a synopsis of the thesis provided, followed by some conclusions and recommendations drawing from the results of the empirical study, and some limitations which leads to a discussion of future work. The conclusions and discussion is based on the empirical case study of the Mooki, which derive from the review of water policies affecting the basin, the available data and literature that formed the foundations of the economic modelling, and the results of the analysis.

9.1 GENERAL OVERVIEW OF THE THESIS

At the start of this thesis, the main objective was to provide an overview of the water economy in Australia. Much attention was given to exploring the problems in water allocation that has arisen in Australia due to its geographical characteristics, and from a policy perspective. At the crux of the issue is level of river diversions in the Murray-Darling Basin, which has long been at an unsustainable rate. This was driven by earlier policies inherited from the 'expansionary phase' of the Australian water economy, which has created a situation of water over-allocation. As the water economy approached a 'mature phase', the focus fell on demand-side management. Furthermore, the capital and operational costs of water infrastructures have not been recouped. This formed the impetus for the cost-recovery process, the purpose of which was to incorporate the true cost of water services in the water price. This was but one of the myriad of Government water policies initiated since the early 1990s, in recognition of the need for a sustainable approach to water management. This includes the cornerstone agreement in 1994, the COAG Water Reform Framework that led to a succession of intergovernmental water agreements. A discussion of the various arrangements was provided in this chapter, including the Murray-Darling-Basin Agreement, the National Water Initiative, Living Murray Initiative, and the recently proposed Commonwealth National Plan for Water Security (although part of this National Plan was to replace the intergovernmental arrangements under the MDB Agreement with one Federal Government minister). These policies have the objective of reallocating water more efficiently amongst competing uses, through the use of market-based instruments which has been widely adopted in most Australian catchments (e.g. the creation of water markets). Other policies to mitigate salinity were also implemented through Murray-Darling Basin Commission initiatives, including end-of-valley salinity targets. However, the effect of various environmentally-oriented policies on the economic performance of the affected industries is uncertain, and needs to be understood. This forms the impetus for this thesis.

A review of water economics literature was then provided, to highlight the different aspects of water management and the difficulties involved. Firstly, a review of studies using a GIS-integrated framework was conducted. This was to emphasise the advantage of creating an integrated management approach, which would enable better allocation of scarce water resources. This was then followed by an evaluation of price-based and quantity-based instruments that have been promoted in natural resource management. Other complexities in water management relating to groundwater hydrology, particularly return flows and deep drainage, was also explored. These earlier chapters set the foundation for the remainder of the thesis, which focused on creating a framework for the efficient management of water on a basin-scale, in light of the complexities and current water resource policies discussed thus far.

The selected modelling approach was a combined linear programming (LP) and dynamic programming (DP) framework, due to the inter-temporal nature of groundwater use and the static nature of production decisions. The use of market-based instruments for water and deep drainage to achieve such outcomes was also discussed. The theoretical solution obtained using the LP and DP framework was then analysed, to illustrate how the efficiency criteria are met through the chosen economic modelling framework. The use of the model was focused on the impact of various environmental targets, in particular environmental flows and salinity reduction, on the regional irrigation industry. Following from this objective was an evaluation of the effectiveness of market-based instruments to achieve efficient outcomes, and the consequence of increased competition for water from external users to the catchment. Characteristics specific to the case study, the Mooki basin in the Namoi Valley, was analysed in order to customise the modelling assumptions. These include specific government policies which affect the Mooki, in relation to the institutional arrangements discussed in earlier chapters. These assumptions were then used to create the specific model in this thesis. A summary of the findings of this empirical study is given below.

9.2 SUMMARY OF THE SIMULATION RESULTS AND ANALYSIS

The following summary is based on the results of the simulation scenarios under each treatment considered in this study. In general, it is indicated that the water resources in the basin are scarce and that earlier policies on water distribution have translated into an inefficient allocation of water in the basin. There is scope for a more efficient management of water in the Mooki basin, as indicated by the discrepancy in resource allocation and production between the status quo and alternative treatments, which were conjectured to improve allocative efficiency.

9.2.1 Summary Statistics

Of the irrigation technologies considered (furrow, pivot and drip), on average, pivot systems generate the highest returns and represent the most profitable investment for the Mooki basin. Pivot systems can achieve a lower irrigation rate, lower deep drainage occurrence, and higher yield per hectare irrigated. The yield increase offsets the capital investment required. In contrast, drip systems are the least cost-effective, although they achieve the highest water savings and deep drainage reduction. This is because the yield increase is insufficient to cover the capital outlay, which is double the cost of pivot systems.

For any irrigation system, groundwater consistently produces better yields and profit compared to its surface water counterpart. This is due to the reliability of its supply, which ensures the full irrigation is delivered to the crop at the scheduled time of irrigation. Groundwater could therefore produce relatively higher profits, despite higher costs of pumping. While yield and profit is higher compared to irrigation with surface water, the water use and drainage is also higher since more water can be applied.

Where water efficient technologies are used, the productivity of water resources is increased. This is indicated by the increase in annual profit by 4% and a fall in deep drainage by 5%, where pivot and drip irrigation systems are used. When water markets exist, the annual profit increases by 9% and deep drainage falls by 3%. This is due to the mobility of surface water allocations, so that the productivity of water is significantly improved.

9.2.2 Inter-temporal Resource Use

The use of groundwater banking and borrowing through the carry-over rules is dependent on the certainty of surface water supply. When it is deterministic, and constant, groundwater use is close to annual allocations without any banking or borrowing. However, when surface water supply is stochastic, the rate of groundwater extraction moves in the opposite direction of annual surface water supply. This was an expected result, since groundwater banking is beneficial where it is used to compensate for the shortfall in the alternative water supply.

9.2.3 Production Activity Changes

The initial allocation of water according to irrigation area leads to an inefficient outcome, whereby water supply is not used where it has the highest value. As a result, where water is inefficiently allocated, irrigators in these upstream areas of the Mooki (Caroona and Breeza) are the most affected by water caps and the overall opportunity costs incurred is also inflated. Where water trade is possible, almost all surface water is traded downstream for irrigated production in Ruvigne. As water is reallocated to its highest value use, introducing a water cap in the presence of water trade allows environmental flows to be sourced at the least opportunity cost. This leads to an efficient outcome, whereby irrigated production in the upstream irrigation areas which have high conservation value is reduced, while the basin profit is increased from greater production in downstream Ruvigne. Where DD caps are imposed to mitigate salinity contribution, under all treatments, much of the impact occurs in Ruvigne where groundwater is used as the primary water source. Drainage caps thus cause groundwater extraction to be reduced below its sustainable level, which leads to a sub-optimal outcome because the full capacity of groundwater resources is not used.

9.2.4 Application of Environmental Flow Policies

The economic impact of environmental flows can be minimised simply by encouraging the use of water efficient technologies or by encouraging water trade. Where a water market exists, the opportunity cost is reduced by around $3.3Mill per year or around 9%. Using water efficient technologies could also reduce the economic impact of environmental flows, by around $1.5Mill per year or 4%. However, at stringent environmental flow targets the ability for alternative irrigation systems and water trade to mitigate the economic cost is reduced, since these mechanisms can only do so much to keep the opportunity costs low. It was also found that the additional cost to the catchment manager to source an extra unit of environmental flow is relatively constant, as indicated by the constant marginal cost of foregoing surface water. This is because of the assumption that irrigators reduce the area under irrigation rather than the rate of irrigation, such that the marginal value of water is reflected in the area of cotton it can produce.

9.2.5 Application of Deep Drainage Policies

The contribution of salt load from the Mooki to the end-of-valley target for the Namoi Valley is 7%. While this figure is relatively low, proportional to the area of the Mooki the salinity contribution should only be 1%. This is despite the lack of incentive for irrigators to internalise the impact of salinity into their production decisions, since salinity-inflicted productivity loss within the Namoi is minimal. A cap on deep drainage could be used to reduce salinity contribution to downstream river systems, and it is expected that a drainage cap could be imposed simultaneously with a water cap without much increase in the costs borne by irrigators. However, it also appears that a single instrument is sufficient to provide conservation signals with regards to water use and thereby a reduction in deep drainage. For the Mooki case study, it seems that a cap on surface water extractions is more appropriate than drainage caps, since for the same opportunity cost a greater provision of environmental flows and some salinity reduction is achieved. Also, groundwater use is maintained at its sustainable level. On the other hand, deep drainage caps have a cost-advantage over water caps, since it can achieve salinity reduction at the least-cost by forcing the least efficient irrigators to forego water use, regardless of the water source. However, since both surface and groundwater users are affected, the level of groundwater use could be reduced to a sub-optimal level whereby the full capacity of the sustainable recharge is not exploited. This is while in-stream water extractions are not reduced as significantly as water caps, thereby generating relatively less environmental flows.

9.2.6 Competition from an External Water Consumer

Increased competition for water resources from an agent external to the regional irrigation sector will cause the annual profit from cropping to fall by 2.7%. This is while the water competed away by the external agent, in the form of a coal mine, generate a value of $1billion. Competition between the internal and external users occurs across water prices of $70-145/ML, with the external user demanding at most 12,500ML. Of this, 3,600ML is directly competed away from internal buyers, while 8,600ML of water that was used for cropping where there was only internal trade, is instead sold to the external buyer. Above $160/ML, there is excess supply and the external agent merely adds value to the excess water that has not value internally.

9.3 CONCLUSIONS AND DISCUSSION

Conclusions of the thesis are drawn from previous chapters are as follows:

1. It is worthwhile for irrigators in the Mooki to invest in water efficient irrigation technologies and to participate in water trading, as a way of mitigating the impact of increasingly stringent environmental policies. However, if the environmental targets are excessively stringent these adjustment mechanisms could only do so much to reduce the economic burden. While environmental protection is important, it should not be set too stringently even if water efficient technologies are utilised and water trading is in place.
2. The groundwater carry-over rules are beneficial for irrigators in the Mooki, considering the ephemeral nature of the surface water supply. Where supplies are stochastic, it is optimal to hedge some groundwater allocations from year to year. Given the in-river supplies for the Mooki are known to be extremely variable, carry-over rules are particularly important to ameliorate the economic burden of surface water scarcity.
3. Water trade within Upper Namoi (UN) will result in surface water being traded downstream to Ruvigne, which was found to be the most productive irrigation area in Mooki. Encouraging water trade in UN would therefore lead to an optimal outcome where water is traded away from upstream irrigation areas of Breeza and Caroona, which can be left for environmental conservation. Considering the shadow price of surface water in UN is almost at par with the market in regulated Lower Namoi (LN), there is the potential for trade between these systems, which may circumvent the 'thin market' situation that is often cited as a problem in Australian water markets. However, if groundwater entitlements for the Mooki are further reduced below Water Sharing Plan stipulations, then the shadow value of surface water in this area is likely to increase. Under such circumstances, opening water trade between UN and LN may lead to water being traded to UN. This would conflict with the catchment authorities' objective to protect the environment in UN where there is high conservation value. Furthermore, due to the salinity of the aquifer system in Namoi, increased return flows as a result of

water being traded upstream may accentuate the salinity problem by compounding the amount of salt load carried downstream. Given these implications, and also considering the significant cuts in entitlement already imposed, it is appropriate that groundwater entitlements are not further reduced.

4. For most irrigators in the catchment, pivot and drip irrigation systems are shown to be a worthwhile investment even where the full cost of the investment is borne by the irrigators. This implies that there is no need for subsidisation of these technologies as there is sufficient incentive for efficient irrigators to make the investment. If the cost of water efficient irrigation systems is subsidised, as intended in the Commonwealth Plan for Water Security, it would inflate the value of irrigation enterprises in UN and distort the allocation of water, precluding an efficient distribution through water trade. Also it will increase the structural adjustment required to retire irrigation areas that are inefficient. The priority should be increasing the security of water supply to persuade irrigators to adopt irrigation technologies that require large capital expenditure. Producers need the assurance that their investment can be recouped in the long run.
5. Salinity may not be a problem within the Namoi, but the downstream impact on the Barwon-Darling catchment should be taken into account when making production decisions upstream for a socially optimal outcome to be achieved. However, drainage capping may not be the best instrument to aid in this objective. Without the opportunity for trade, capping resource use leads to reductions only at a farm level without necessarily increasing overall basin efficiency. Even with trade, the overall effects on water use and drainage are very similar regardless the instrument used to control resource use; hence there is little incentive to create separate instruments. While drainage caps have a cost advantage over water caps, by allowing only the most inefficient irrigators to sacrifice water, there are significant disadvantages in terms of information and administration expenses, which can outweigh any perceived benefits. Furthermore, its impact on groundwater use, which is scheduled to be reduced considerably in many zones, will lead to a sub-optimal outcome. In this sense, the author concludes that a water market on its own may provide the best, if not optimal, means of

contending with conjunctive pollution, it the form of deep drainage associated with irrigation.

6. Although a 'sustainable' rate of groundwater extraction has been estimated in the groundwater Water Sharing Plan, the existence of such a sustainable use is debatable. Since the groundwater systems are in a state of equilibrium that is dependent on the recharge and discharge rates, when water is extracted from the confined aquifer, the recharge and discharge rates shift to a new equilibrium. This means that the recharge and discharge rates will not remain the same; recharge would increase while discharge would decrease due to the draw-down effect as water is pumped. The implication of this is that, users both upstream and downstream of the point of extraction will experience a reduction in groundwater resources. The 'sustainability' of groundwater use then becomes a question of the acceptable economic trade-off between upstream-downstream uses. In this thesis, it was assumed that the annual groundwater extractions stipulated in the groundwater Water Sharing Plan could be sustained indefinitely. However, as a future study, the trade-off between groundwater use in the Mooki and neighbouring irrigation areas sourcing the same aquifer system could be established. This is needed to be able to determine the opportunity cost of the groundwater resource to irrigators in other irrigation districts sharing the same hydrological system.
7. The entry of an external water user in the form of a coalmine should not pose a significant threat to the regional irrigation industry. This can be concluded considering the relatively minor change in overall benefits from cropping and the small volume of water demanded by the coalmine. Based on the assumptions of the derived water demand, the water competed away for coalmining represents significantly greater value to the mining industry relative to cropping. This is evidenced by the increase in water sold into the water market in the presence of an external buyer, which provides a more profitable avenue for water users in the Mooki. Irrigators could therefore stand to gain from the introduction of coalmining in the region by selling some of the basin surface water supplies, and at the same time maintain the integrity of the irrigation industry.

8. A GIS-linked economic optimisation model could be used to provide greater transparency and reduce the information cost of accurate estimations of resource use across a large landscape. From the information provided by the integrated modelling approach, specific HRUs may be identified, for example, for buying-back entitlements to provide for environmental flows or to reduce salinity contribution. It is a useful tool that can be adopted cost-effectively. A national initiative is already in place to improve access to, and availability of spatial information in Australia (Geoscience Australia 2007), which reduces the set-up cost of an integrated system of resource management. Other than the requirement for trained technical staff to operate GIS programs and develop GIS-layers, the fixed and variable costs of setting up integrated studies can be relatively low. This can then become a low-cost option to make transparent water information and management, in line with the National Plan for Water Security objective.
9. More research in the field of groundwater hydrology is required, as it remains a field for which there is limited understanding, and that has significant implications for the management of water resources. It is particularly important that accurate assessment of feedback-mechanisms relating to return flows are established on a catchment-specific basis, since the role of return flows vary from basin to basin. In the case of the Mooki, it is expected that return flows will have greater negative than positive externalities and should be minimised, due to the salinity of its shallow aquifer. This may not be the same for other catchments, which may have fresher return flows that may improve groundwater quality and contribute to water supply. The net impact of altering the hydrological interrelationships should be carefully assessed on a case-specific basis prior to the implementation of policies affecting water use.

9.4 LIMITATIONS

There are several limitations of this study that need to be acknowledged.

1) It is important to note that the accuracy of the economic analysis is dependent on the accuracy of the GIS data, and the assumptions made with respect to the biophysical parameters in SWAT. The assumption for parameter values, e.g.

percolation and soil conductivity or crop growth, will have implications for the policy outcomes. Much effort has been put into ensuring the parameter values are as accurate as possible, however it is important that results are further verified through ground-truthing to confirm the findings on-ground.

2) The assumption made with respect to the initial allocation of water resources has significant implications for the relative outcome under different treatments. A starting point that is close to an efficient water allocation will underestimate the value of water trade and water efficient technologies. On the other hand, an initial allocation that is very far from an efficient water allocation will overestimate the value of trade and alternative technologies. Again, much attention was given to the accurate distribution of water allocations according to actual use, but due to the fact that this information is private and that the irrigators are reluctant to disclose it only inferences on individual water extractions could be drawn.
3) A limited number of production activities were considered for the purposes of this study. Alternative irrigation activities may occur in the Mooki basin, such as irrigated wheat or sorghum, which have not been analysed. The focus was the economic impact on the irrigated cotton industry, so the scope of the analysis was confined to one irrigated crop.
4) In this study, the research was limited to a cost-side analysis. Ideally, the social benefit accrued from various environmental flow and deep drainage targets could be incorporated to determine the distribution of water between extractive and non-extractive uses that maximises social benefit. This would have required that expensive and time consuming methods of non-market valuation be carried out to gauge the willingness to pay by the public for various environmental targets. This was beyond the scope of the thesis.
5) Technological limitations precluded the incorporation of return flows on downstream water supply. While this was not a significant issue for the Mooki, since return flows were considered detrimental to water quality, it constrains the transferability of the modelling framework to other basins where return flows have significant positive externalities. A suggested framework to incorporate the feedback mechanism from return flows is provided in Appendix D, and with

access to technical expertise and computer resources this robust model could be created.

6) Some limitations of the modelling process are related to the functioning of the SWAT model:
    a) Changes in water quality are not included in the SWAT model. While factors relating to the hydrological movement of water in a basin are well captured, the relationship between water use and water quality are not simulated. There are intricacies in the soil hydrology which might suggest a non-linear relationship between deep drainage and groundwater salinity. In this sense, deep drainage may only need to be reduced slightly to achieve a large drop in salinity, or conversely a greater reduction in drainage may be required to achieve a small drop in salinity.
    b) Linearity was assumed for the demand functions and input requirements per hectare. This assumption could be relaxed by allowing for non-linear input functions. However, the functioning of the SWAT model is such that relationships between inputs and outputs are determined using physically based equations rather than regression equations of crop growth. This complicates the process of determining the marginal rate of substitution between various inputs e.g. labour and capital.
    c) On-farm storages to pump and contain passing river flows were not modelled in SWAT. As a result, surface water use was more irregular since simulations of water were only applied to the field if there is water passing at the scheduled irrigation event. If on-farm storages are included in the modelling, surface water would become readily available and the irrigation frequency is expected to become similar to where groundwater is used.

9.5 SUGGESTIONS FOR FURTHER RESEARCH

1. Due to time and computational constraints, it was not possible to produce GIS layers of the solutions. The next step for this thesis would be to integrate a GIS program into the economic model, to extrapolate the optimisation solutions graphically and seamlessly.

2. The interregional competition model used in this thesis could be expanded into a spatial equilibrium model, and include the Lower Namoi to determine the value of inter-regional trade between these areas. Groundwater trading between users in the Mooki and neighbouring irrigation areas, sourcing the same aquifer system, could also be simulated. This is to determine the opportunity cost of the groundwater resource to irrigators in other irrigation districts sharing the same hydrological system.
3. Alternative deep drainage reduction mechanisms such as growing perennial crops or salt interception plants could be included as alternatives to meet drainage targets.

While efficient water management is crucial in the current state of Australia's water economy, it is equally important that policies implemented with the aim of improving the distribution of water result in net benefits to society. From the results of this thesis, it appears that there is significant scope for improving the water use efficiency in the Mooki basin. This is also likely to be the case for many catchments in the Murray-Darling Basin, for which the situation of oversupply and inefficient use has long been highlighted. In this thesis, a spatially-explicit, integrated economic modelling framework for catchment management has been developed for the purposes of improving the allocative efficiency of water. This allows for catchment policies to be specifically designed for particular irrigation areas, rather than imposing blanket policies that may impose unjustified costs on irrigators.

While there are a number of economic studies which attempt to capture the biophysical component in water management, the use of a GIS-based model in this thesis means there is the advantage of a higher degree of accuracy and spatial applicability. The results from this analysis are directly applicable to the case study basin, and at a high level of spatial detail. The modelling framework is flexible enough to be transferred to other catchments given data availability, and could be used to examine the influence and effectiveness of environmentally-driven catchment policies.

This thesis is an attempt to improve the effectiveness of natural resource management through an interdisciplinary framework, which utilises the strength of GIS in economic analysis. The results demonstrate how advances in computational technology can be exploited to enhance existing economic modelling of natural resource problems, allowing a more in-depth understanding of these issues on a case specific level. The ultimate contribution of this research is to help improve the accessibility and reliability of information available at the fingertips of decision-makers, and help guide future policy directions towards a socially desirable outcome.

APPENDIX

Appendix A: Groundwater Hydrology

The definition of groundwater is water in the saturated zone of earth materials under pressures greater than that of the atmosphere (Neitsch et al. 2001 p. 159). The groundwater contains regions of high conductivity, made up of coarse-grained particles that allow water to move easily, and regions of low conductivity, made up of fine-grained particles that restrict water movement. There are confined and unconfined aquifers, which are defined as "a geologic unit that can store enough water and transmit it at a rate fast enough to be hydrologically significant" (Dingman 1994 in Neitsch et al. 2001). The following figure illustrates the two types of aquifers.

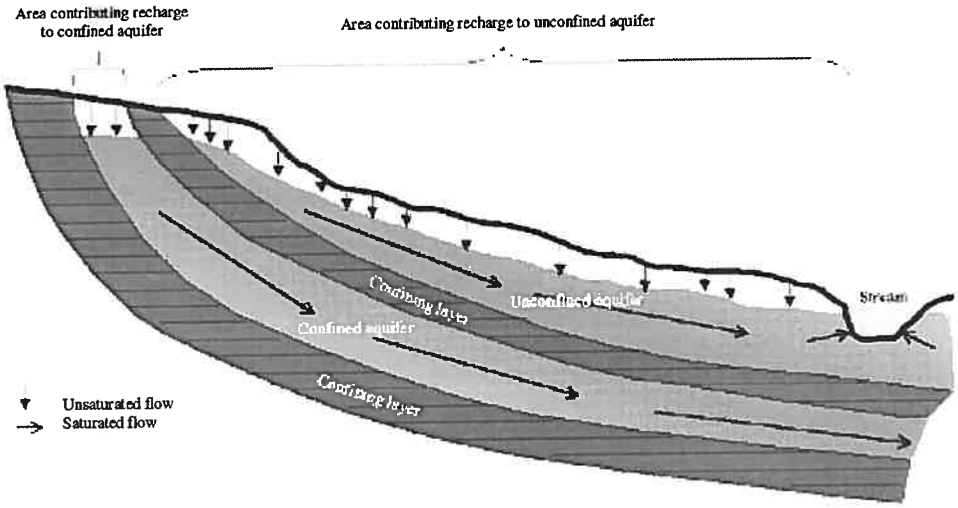

Figure A 1: Unconfined and confined aquifers (source: Dingman 1994 in Neitsch et al. 2001 p. 160).

Recharge to unconfined aquifers occurs via percolation to the watertable from a large portion of the land surface, while recharge to confined aquifers from the surface only occur at the upstream end where the aquifer is exposed at the surface and flow is not confined. Topography of an area affects the recharge and discharge of a groundwater body significantly. Recharge is defined as the portion of groundwater flow that is directed away from the watertable, and discharge being defined as the flow that is directed towards the watertable at or near surface water bodies (e.g. river).

The lag in time that recharge enters the shallow aquifer, however, depends on the height of the watertable and the hydraulic properties of the groundwater zones. The time delay cannot be directly measured and must be estimated through an iterative process of altering the lag value and comparing the simulated variations in watertable with observed values (Neitsch et al. 2001, p.162). A recent study of the Namoi's river-aquifer connectivity to be quite high, hence it is assumed the time lag between deep drainage and recharge to be minimal. This has implications for the impact of deep drainage and salinity contribution, since shallow aquifers in the Mooki are very saline, and has the potential to increase soil and deep aquifer salinity.

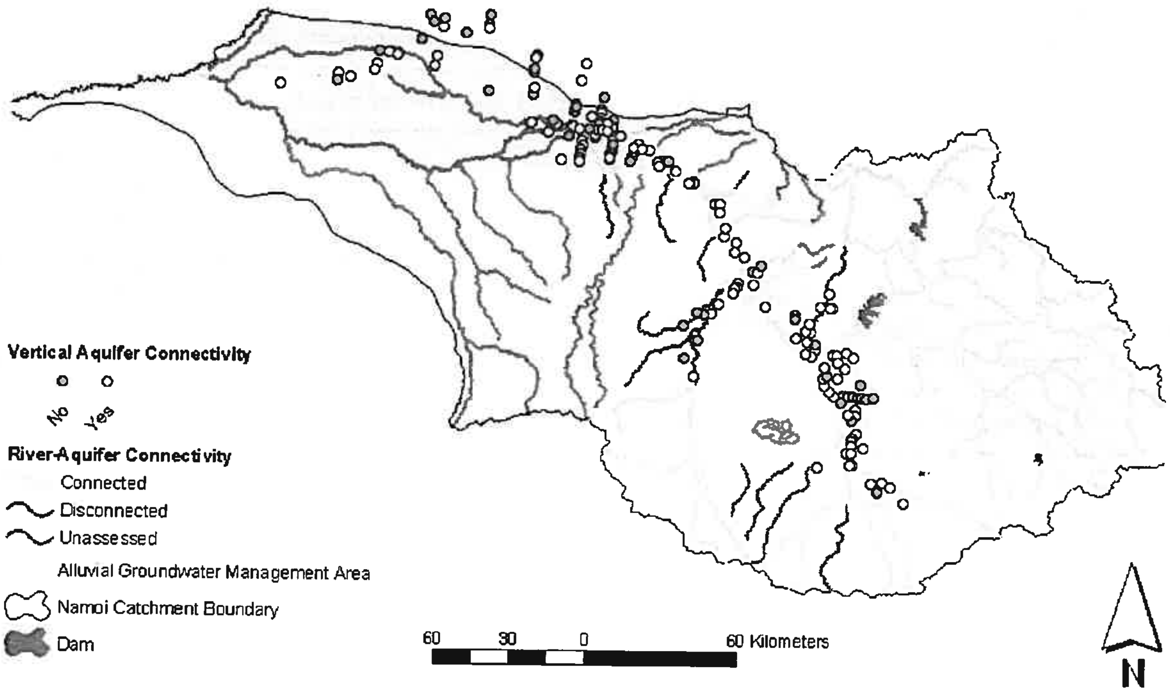

Figure A 2: River-aquifer connectivity in the Namoi (source: Ivkovic 2005, pers. comm.)

Appendix B: Recharge Levels Determined in the Groundwater Water Sharing Plan (source: Aquillina 2003 p.1 and 5).

Upper Namoi Zones	Description	Recharge ML/yr
1	Boramil Ck Groundwater Source	2,100
2	Cox's Ck (Mullaley to Boggabri) Groundwater Source	7,200
3	Mooki Valley (Breeza to Gunnedah) Groundwater Source	17,300
4	Namoi Valley (Keepit Dam to Gin's Leap) Groundwater Source	25,700
5	Namoi Valley (Gin's Leap to Narrabri) Groundwater Source	16,000
6	Tributaries of the Liverpool Range (South to Pine Ridge Road) Groundwater Source	14,000
7	Yarraman Ck (East of Lake Goran to Mooki River) Groundwater Source	3,700
8	Mooki Valley (Quirindi – Pine Ridge Road to Breeza)	16,000
9	Cox's Ck (up-stream Mullaley) Groundwater Source	11,400
10	Warrah Ck Groundwater Source	4,500
11	Maules Ck Groundwater Source	2,200
12	Kelvin Valley Groundwater Source	2,000

Appendix C: Method to Determine Accurate HU Irrigation Scheduling

Cotton Irrigation Scheduling – by Heat Units

Heat-units (HU) refer to the amount of energy received by plants, for which a minimum amount must be received to reach certain stages of growth. Irrigation events could be scheduled according to the HU received, since the amount of irrigation water required by the crop depends on the stage of growth. For cotton, the first irrigation should occur halfway between squaring (emerging cotton flower bud) and flowering, and the final irrigation should occur when 60% of cotton bolls are open. For heavy soils in northern NSW, the recommended practice is to stop irrigation at 20% open bolls or mid-March. Irrigation should be at even intervals from the first irrigation, which is approximately every 162 HU received (every 12-14 days) (Milroy et al. 2002). The heat-units required to reach each developmental stage in cotton's growth was based on data from Myall Vale in Namoi. The minimum day degrees (HU) required and the dates at which each stage occurred are shown in Table A1. HU scheduling was then devised based on this information and tested for its yield response in SWAT.

Table A1: Minimum heat units required for cotton development (source: CCCRC 2005).

From planting to:	Minimum day degrees required	Crop stages for Myall Vale
Emergence	80	12th October
5th True leaf	330	9th November
1st Square	505	27th November
1st Flower	777	19th December
Peak Flower	1302	25th January
Open boll	1527	11th February
60% open	2050	25th March

However, HU irrigation scheduling generated poor yield response functions. Crop growth for all HRUs was low and no distinct relationship could be drawn between the irrigation level and yield. It was concluded that perhaps too much water was available in the soil, so the plant had full access to moisture and little irrigation was required. This was related to the timing of irrigation in the HU scheduling, which was probably occurring when the plant did not need it, and only few of the irrigation events were occurring at the correct time. This was most likely due to miss-timing in the growth stages, because the same HU irrigation scheduling was applied to all HRUs regardless the soil type. Therefore, advice was sought from an agronomist and the recommendation was that field capacity of the soils (soil water holding capacity) should be taken into account in order to set an appropriate heat unit schedule. The greater the field capacity the less frequent and less irrigation is required and vice versa.

Campbell (2006, pers. comm.) suggested using separate scheduling for each soil type according to its field capacity. The advice was to group the HRUs into like soils and observe the amount of time it takes for a full field capacity to be used up. Irrigation should then be timed to occur with about 10% field capacity to prevent water stress. Accurate HU scheduling could be devised in the following manner:

1. Alter the input file in SWAT to produce simulation output in daily-time steps;
2. Determine which groups of soil should be aggregated into like soils (heavy clay or permeable soils) by checking soil input files;
3. Looking at the output files, take the sum of evapotranspiration (E_t) over the period it takes to use up total water capacity. Then time irrigation to occur at around 90% of soil water capacity to prevent stress;
4. However, since SWAT only allows irrigation scheduling by HU or date, not E_t, the HU associated with 90% soil water capacity need to be determined. The HU received over the number of days it takes to use up total water capacity is found using the following equation:

$$GDD = \sum Y_{Days} (T_{mi} - T_b)$$

This reads as: heat units received = sum over Y days of the difference between mean temp, T_{mi}, of day y and base temperature, T_b, for cotton (12°C). This allows the HU received to be associated with the soil water capacity.

5. Once *GDD* is obtained, irrigation events in SWAT could be scheduled according to the amount of HU received for every time soil water capacity is down to 90%.

However, due to limited computer capacity, it was extremely difficult to obtain the output required from SWAT through brute-force. This was due to the computer memory requirement in producing daily-step files for all HRUs. The second-best option was to use date scheduling, which generated reasonable yield responses to irrigation and was also computationally inexpensive.

Cotton Irrigation Scheduling – by Date

The most basic irrigation scheduling is by date, following a set irrigation path. The problem with date-scheduling is that irrigation takes place regardless of when rainfall has occurred. Irrigation would take place on the specified date even if a rainfall event has just occurred, and no irrigation takes place even if crops are water stressed and there no irrigation is scheduled. In reality, irrigators often use neutron probe readings of soil moisture to determine when irrigation should occur. It would therefore be more realistic to schedule according to HU, however for the reasons above, it was not possible to extract exact HU-scheduling for all HRUs. The yields produced using date-irrigation was reasonable, and was adjusted to a discrete distribution of cotton yields for north-eastern NSW to better correspond with the yields obtained in the Mooki basin.

Appendix D: Developing an Optimiser to Incorporate Return Flows

In order to incorporate return flows into the decision making process, there needs to be a feedback mechanism in SWAT to account for the impact of upstream landuse on downstream water supply. The suggested framework for finding an optimum is to enumerate the entire range of possible outcomes or use the differential evolution algorithm, suggested in Figure A 3.

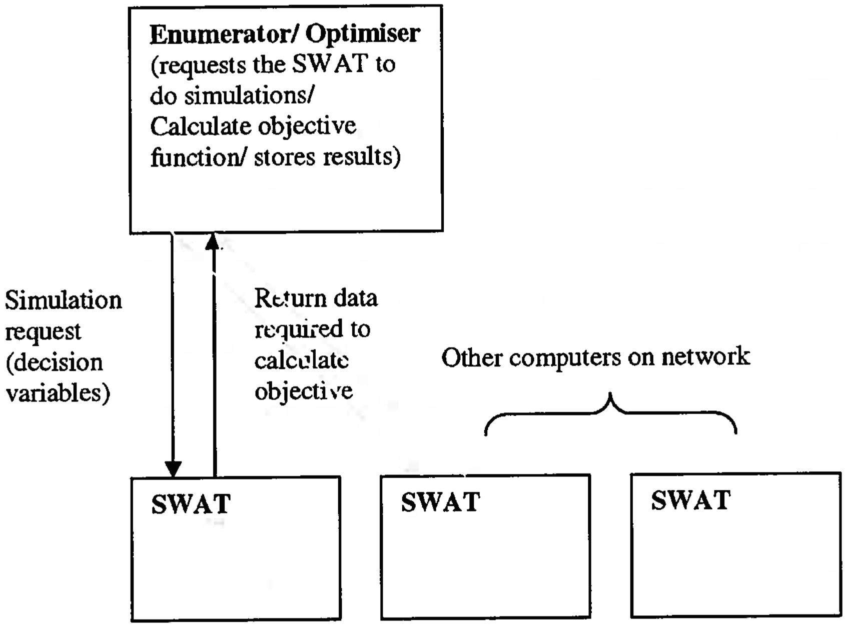

Figure A 3: Optimiser/enumerator schematic (source: Neal 2005, pers. comm.).

Following the optimisation problem in this thesis, each of the 53 HRU has nine possible production activities. For the purposes of confining the problem to a finite space in the optimiser, it is assumed that once a production activity is chosen, all of the area of the HRU must be produced under the selected activity. This leads to nine possible outcomes for each HRU.

Without hydrological links between each HRU, the optimisation problem is quite manageable, with just $9 \times 53 = 477$ combination of outcomes. However, the complexity arises where the impact of return flows on downstream water supply are taken into consideration. Given there are 53 HRUs, the decision made at each HRU affects the return flows downstream and hence influences the water supply. Given there are nine possible outcomes for each of the 53 HRUs, the total combination of HRUs and decision variables are $9^{53} = 3.76 \times 10^{50}$.

Advances in computational power means it is possible to simulate every one of the 3.76×10^{50} scenarios – eventually. Each SWAT simulation takes approximately 5 minutes. Hence to find the optimal combination by enumeration (calculating every possible combination) would require $5mins \times 3.76 \times 10^{50} = 1.88 \times 10^{51}\ minutes$. In other words, it would take $1.88 \times 10^{51} / (60mins \times 24hrs) = 1.31 \times 10^{48} days$ for *one* standard computer. If a computer network of 40 computers was available fulltime, approximately $1.31 \times 10^{48} / 40 = 3.28 \times 10^{46}$ days would be required for complete enumeration.

If stochastic optimisation techniques were used to find “near optimal” solutions, then complete enumeration may not be required, reducing the computation load. One example is the Differential Evolution algorithm (Neal 2005, pers. comm.). The objective to be maximised would be the profit from all farm activities less a costly weight multiplied by the amount by which constraints are exceeded. For example:

Objective = Profit - weight1 × excess salinity - weight2 × water over-consumption

The steps required are as follows:

1. Set SWAT up to run simulations and return the information required to calculate the objective function above, which will require coding in FORTRAN (programming code in SWAT).
2. Create/modify code for either:

   a) An *enumeration* algorithm that will request SWAT to do simulations and store results.

   b) An *optimisation* algorithm that will request SWAT to do simulations and store results (e.g. the Differential Evolution algorithm).

3. Buy supercomputer time, or parallelise the problem so it can be run over a network of computers.

While the use of an enumerator or optimiser would be the first-best option for the simulation problem considered in this thesis, limitations on technical expertise and time mean that it is not possible to develop an appropriate simulator within the available timeframe.

Appendix E: Solutions from the economic optimisation.

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