FARMS, RIVERS AND MARKETS

DOING MORE WITH LESS WATER

OVERVIEW REPORT

More information

The Farms, Rivers and Markets series includes factsheets, an overarching project report, and in-depth reports on doing more with less water through innovative farming systems, modern river operating systems, new markets in water products and services, integrated research, and balancing the water needs of farms and rivers.
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FARMS, RIVERS AND MARKETS

OVERVIEW REPORT

Executive summary

ADAPTING TO AN UNCERTAIN, WATER CONSTRAINED FUTURE

Australia has one of the most uncertain climates on the planet. While prolonged droughts and widespread floods cause great community hardship they also stimulate adaptation, innovation and create the political will to implement much needed reforms.

The recent drought in south eastern Australia from 1997 to 2009 was the most prolonged in the historical record, and included an unbroken sequence of 15 years without a single wet month (illustrated in Figure 1). Evidence from the South Eastern Australia Climate Initiative (SEACI, 2010) reveals that global warming contributed to this drought and that south eastern Australia will receive less rain from the southerly weather systems which are moving south as the planet warms. SEACI found that the Sub Tropical High Pressure Ridge that circles the planet at the latitudes of southern Australia is strengthening and moving the southerly weather system further south.

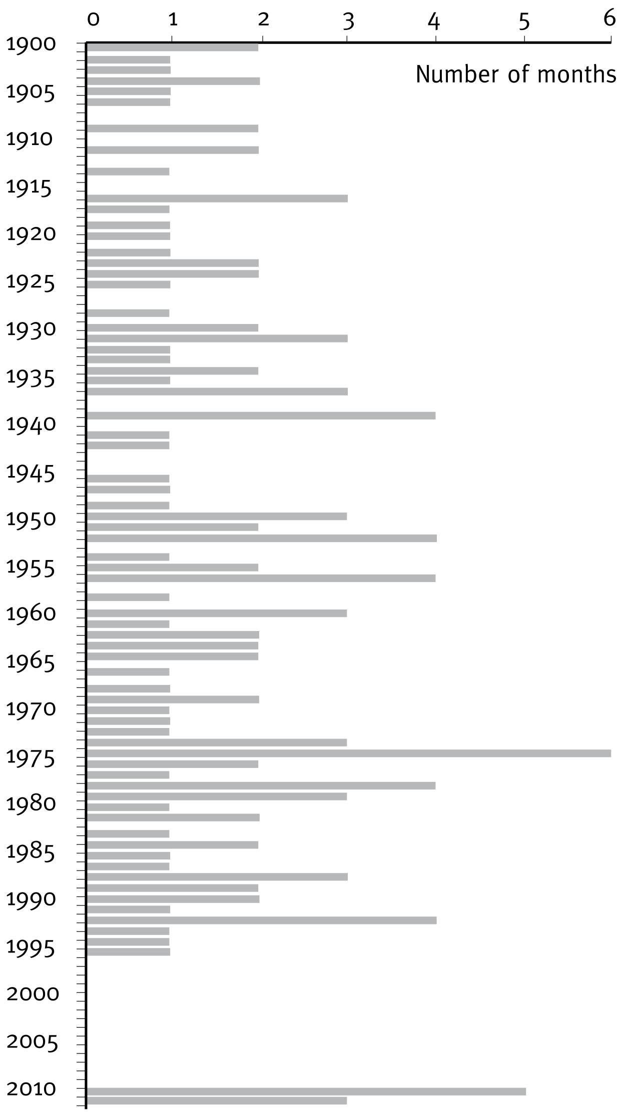


Figure 1: Monthly rainfall above the 90th percentile. Source: SEACI

This unprecedented drought brought the over allocation of irrigation water in the Murray Darling Basin into sharp focus. Seasonal allocations for irrigation fell from the prevailing allocations of 200% before 1997 to less than 30% in the irrigation seasons of 2007/08 and 2008/09. Community pressure for protection of the stressed river system created political momentum to pass the Water Act (2007), requiring preparation of a Basin Plan and setting of Sustainable Diversion Limits. These legislative changes were supported by purchase of water entitlements and investment in water efficiency to create environmental water holdings. The combination of climatic uncertainty and reduced water allocations for irrigation is a critical challenge facing the irrigation communities.

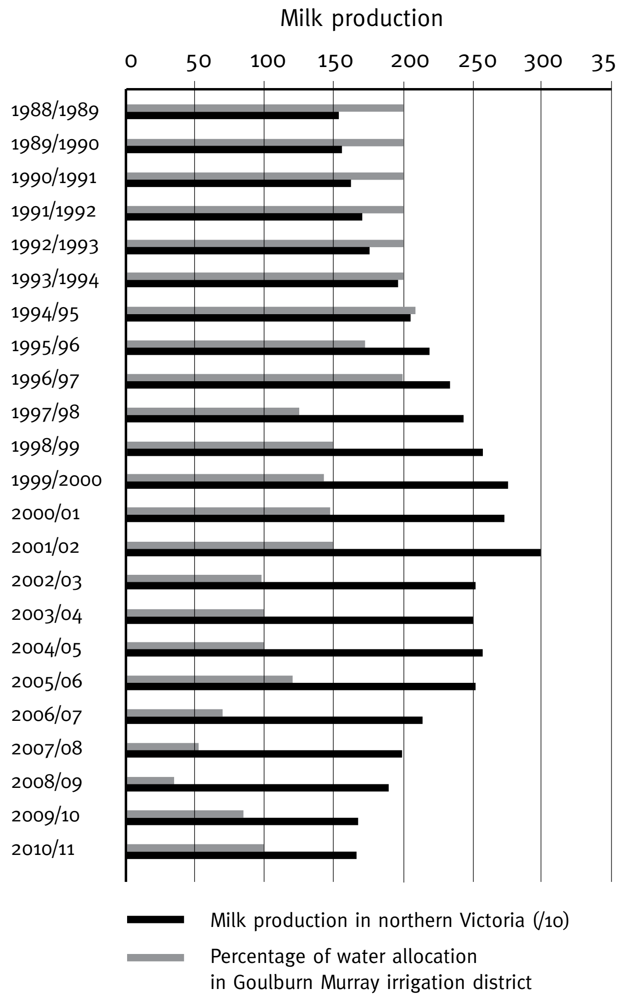


Figure 2: Relationship between milk production and seasonal water allocation in the Goulburn Murray irrigation district. Source: Goulburn-Murray Water and Dairy Australia

Figure 2 illustrates the adaptation of farmers through comparison of milk production in the late 1980s, when water allocations were 200% of entitlements, with the three years from 2003/04 to 2005/06. In the period 2003/04 to 2005/06, water allocations of 100% indicated that farmers produced three times the quantity of milk per unit of water allocation, with few if any signs of stress in the market for seasonal allocations. The eventual decline in milk production was as much to do with the international dairy market as it was to water availability.

But not all is doom and gloom:

- Farmers quickly **adapted** to the drought's challenges, substantially increasing their water productivity (Figure 2)
- The **water market reforms** were highly successful in supporting adaptation through water trading in the challenging conditions
- Large investments are being made in modernising irrigation delivery systems supported by **comprehensive real time measurement**
- Investment in environmental water holdings are creating **opportunities for improving river health outcomes.**

PROJECT BACKGROUND

To take advantage of these opportunities – including adaptation, modernised irrigation delivery systems, improved river health, and water market reforms – and inform the balance of farm profitability with river health, innovation and demonstration is essential. Innovation to do more with less water is a strong insurance policy for farm profitability and river health in a world of more constrained and uncertain water availability.

Farms, Rivers and Markets (FRM) research advanced Australia's capacity to do more with less water in agricultural and environmental systems under a highly variable climate, for improved returns to the community and environment. Its portfolio of research from 2008-11 drew on expertise from a multidisciplinary team spanning University of Melbourne faculties and schools including Land and Environment, Engineering, Business and Economics and Law, Monash University's Faculty of Science, and the Murray-Darling Freshwater Research Centre.

The research proposal was initiated in 2005 and developed by Professors John Langford and Snow Barlow, Dr Suzy Goldsmith and Associate Professor Roger Wrigley, with help from Dr Peter Cottingham.

Given the pace of adaptation research co-development with farmers, environmental water holders and other interested stakeholders was essential to the project's success.

To understand the interactions between farming systems, river and environmental management and the potential of water market reforms, a team integrating a wide range of research disciplines and experience is necessary. FRM's interdisciplinary research connected agricultural scientists and management specialists with economists, water resource hydrologists, control system engineers, freshwater ecologists and social scientists, illustrating the research team diversity necessary to pursue integrated catchment research. Co-development of research with farmers, and river and catchment managers further extends the range of integration. Lessons were learnt about the management of complex interdisciplinary research, and the management process was the subject of research in itself.

Selection of a suitable area for whole of catchment research is a challenging task. The study catchment must be large and complex enough to be realistic, but not so complex as to make the research too broad and difficult to conceive and manage. The Broken River was selected because it is relatively data rich, and has many characteristics and management issues in common with the southern Murray-Darling Basin. The Broken Catchment also includes the University of Melbourne's Dookie campus, home of Dookie 21 – a unique teaching and research centre that works in partnership with the community, industry and government towards producing twice the food with half the water and energy. Dookie campus' long scientific and water data records were a great asset throughout the Project.

FRM developed, informed and demonstrated "no regrets" adaptation strategies for farmers, environmental water holders and catchment managers in a more water constrained future, or a future similar to the historical climate. To develop "no regrets" farming strategies that are robust under both the historical climate and a dry climate, FRM tested farming systems under two climate scenarios:

- Historical climate 1901 to 2004 – in some cases the historical record was taken to 2009
- 2030 dry climate defined in CSIRO's Murray-Darling Basin Sustainable Yields study. This climate is sufficiently dry to provide a realistic stress test of farming systems, but not as dry as the 1997-2009 drought.

The Project was funded by the National Water Commission ($8.6 million), The Victorian Water Trust ($950,000), the Dookie Farms 2000 Project Fund ($100,000) and the University of Melbourne ($1.05 million). Of some 140 projects funded by the National Water Commission, FRM is the only one that addresses integration across the interdependent objectives of the National Water Initiative.

RESEARCH OUTPUTS

FRM findings are presented in terms of research outputs including:

- New knowledge supporting innovative ideas for a water constrained future
- Proof of concept for policy management and technological innovations
- Demonstrations of such innovations' potential value and investment cases
- Clarification of future directions, research and development for new concepts and innovations.

FRM outputs inform the development of:

- Innovative farming systems
- Modern river operating systems
- New markets in water products and services
- Balancing the water needs of farms and rivers
- The value of integrated research.

Innovative farming systems

- A comprehensive dairy farming system experiment established to measure profitability under low water allocations of 6 ML/ha, 3 ML/ha and 1.5 ML/ha compared to a historical base of 10 ML/ha, and operated successfully for a year providing valuable insights to management strategies. The experiment is work in progress and is continuing through a second season.
- Proof of concept smart bay irrigation.
- A comprehensive broadacre cropping and grazing farming system experiment to inform opportunistic farm management under a more variable climate. The outcome of the trials is important to inform the restructuring of irrigation and the reversion of irrigated land to dry land. The broadacre farming system trials are work in progress.
- Proof of concept of summer cropping as another option in a more uncertain climate with potentially wetter summers. This work is an excellent demonstration of the value of research co-development with leading farmers.
- Proof of concept of evapotranspiration measurements to automatically control horticulture crop irrigation. The software has been incorporated into a commercial irrigation system through co-development with MAIT Industries.
- Proof of concept that the plant based Crop Water Stress Index measurements can be used to trigger irrigation in smart irrigation control systems.
- A comprehensive experiment established to measure the performance of smart irrigation systems designed to improve the product quality and yield of horticultural/viticultural crops, and in turn water productivity (value/ML).
- Investment cases demonstrated that automated irrigation systems for border check irrigation in dairy farming systems, and drip/mini-sprinklers in horticulture are potentially a good investment.
- Optimising economic models that demonstrate both the economic consequences of reducing water allocations for dairy and horticultural enterprises, and evaluate the robustness of different farming systems in more water constrained futures.

Modern river operating systems

- Demonstration that targeted data collection can reduce uncertainties in water resource assessment, and that it can be a cost effective strategy to inform water resource management, trading and environmental water shepherding.
- Demonstration of the benefits of applying control engineering to river operations in terms of efficiency, level of service and environmental performance. A strong case now exists to invest in application of a control system to the Broken River, initially without installing control gates at Casey's Weir.
- Demonstration of the value of slackwater knowledge to inform active river flow management to improve habitat and ecological outcomes. The benefits of more precise river flow control enabled by a control system were also demonstrated.
- Information indicating that dual use of wetlands by irrigators and environmental water holders is an idea worth further investigation. Further, research on ecological consequences of wetland inundation is important to inform active management of wetlands for environmental purposes.

New markets in water products and services

- Demonstration that a renewed strategic focus on operations, supported by innovations in water market products and services, water ordering and a strengthened supplier role in coordination will generate a substantial performance dividend by enabling more responsive and cooperative decisions by all parties.

Balancing the water needs of farms and rivers

- A framework that enables a more comprehensive analysis of the changes and trade-offs in economic benefit to farmers, and the environmental outcomes resulting from different levels of water sharing.

The value of integrated research

- Documented lessons gained from managing complex, integrated river basin research bringing together a range of disciplines, and co-development of research with communities of practice and interest.

In conclusion FRM has established farming system experiments to evaluate their profitability and flexibility under water allocations below the range of historical experience. The potential of summer cropping as an adaptation to climate change has been quantified. Significant progress has been made in developing smart irrigation systems enabled by wireless sensor networks and the input of control engineers. Optimising economic models of farming systems have been developed as a tool to chart the decline in profitability of farming systems as water allocation and use declines, and to compare the value of farming options in slowing the decline in profitability.

Research using the Broken River as a case study demonstrated the value of short-term field measurement campaigns to provide more accurate estimates of transmission losses and water balances. Ecological research to inform the management of slack waters for fish habitat, the benefits of using billabongs for farm and environmental use, and the management of flood plain forests provided valuable input to river management. Development and demonstration of modern river operating systems capable of substantially improving operational water efficiency and more importantly the timeliness of water deliveries to farmers and environmental water holders was a highlight.

Research into markets focussed on the opportunities created by reform of water ordering and delivery systems and their governance. Farmers, environmental water holders and river operators can use the better understanding of each other's needs to expand the efficiency frontier to gain more benefit for both farmers and the environment.

By investigating farms, rivers and markets together FRM, has identified substantial opportunities for farmers and the environment gained from cooperating instead of competing with each other. Combination of the market reforms with modern river operating systems informed by farm and ecological research has the potential to transform water management in the southern Murray-Darling Basin.

Innovative farming systems

BACKGROUND

FRM provides farming systems-scale research for greater flexibility, profitability and water productivity. The Project is the first systems-scale research activity in southern Australia addressing the challenges facing irrigated livestock, cropping, and the horticulture and viticulture industries. Whole farming systems were studied, because solutions for commercial scale farms cannot be found by manipulating system components in isolation.

The principal questions of 'Innovative farming systems' research were:

- How can water be used more effectively and efficiently in farming systems so that farms remain economically viable, and the needs of other users of water are met under highly variable climatic conditions?
- Can more water-efficient systems offer greater flexibility for managing the risks of uncertain water allocations and unfavourable plant growth environments?

The research proceeded in three phases:

- 2008/09: Development
- 2009/10: Testing
- 2010/11: Application.

Three industry reference groups (IRG) were formed through local contacts to cover dairy, dryland broadacre and viticulture/horticultural farming systems. Reference groups consisted of leading farmers, industry representatives, and advisory and extension personnel and researchers from Victoria's Department of Primary Industries. IRGs played key roles in co-development and farming system experiments' management. This engagement process was linked to research presented in this report's section titled 'The value of integrated research'. Reference groups for the dairy and broadacre farming systems research were established to advise on the experiments, with members including farmers and service providers.

Research is continuing in 2011/12 in an attempt to expose farming systems to contrasting weather, e.g. extended dry periods. This research is a contribution to the Dookie 21 initiative at the University of Melbourne's Dookie campus.

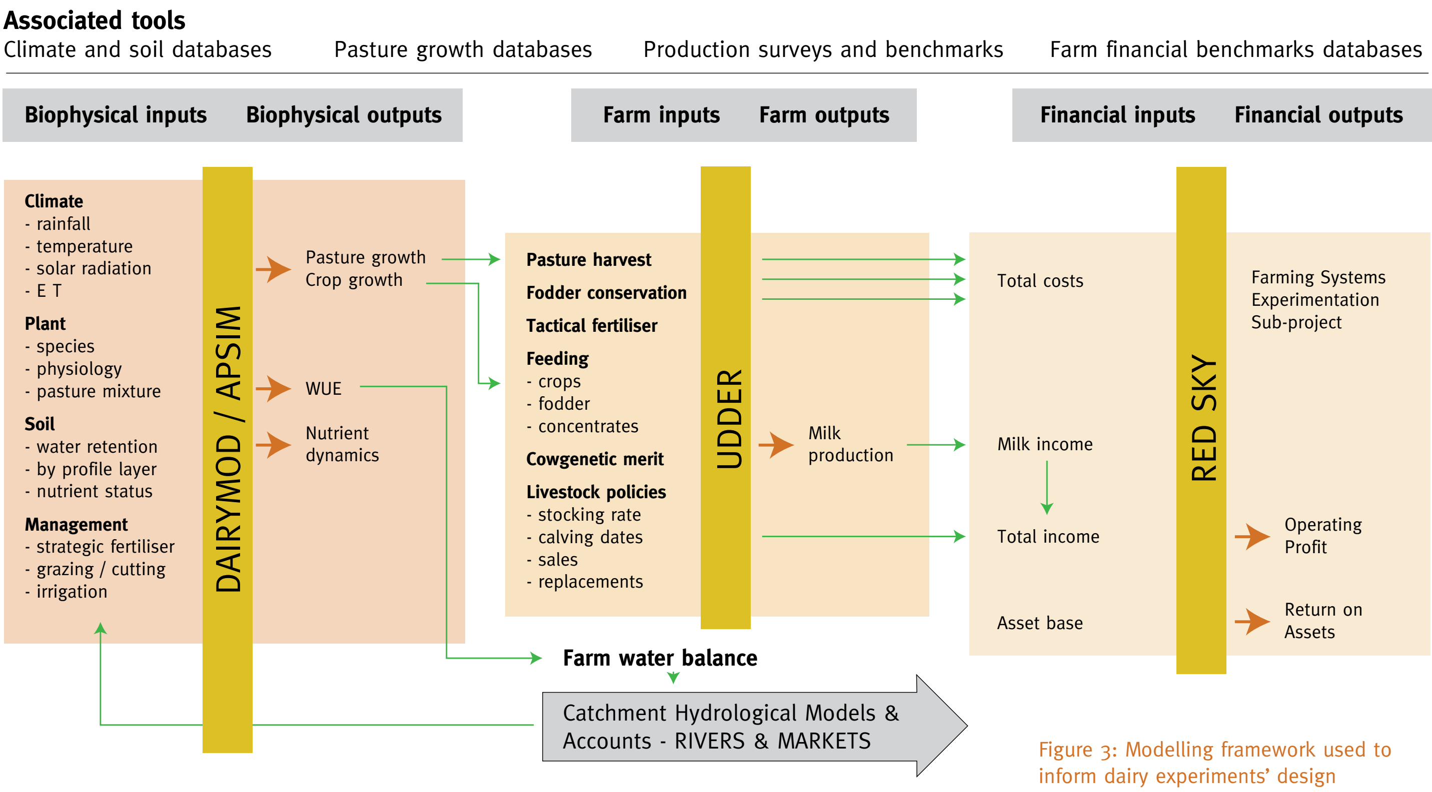


Figure 3: Modelling framework used to inform dairy experiments' design

IRRIGATED DAIRY SYSTEMS

Farm systems modelling

The irrigated dairy systems research development phase included pre-experimental farm systems modelling to evaluate and select the best farming experiment systems. Biophysical, production and economic models were used calculate productivity, profitability and water balances and informed design of the irrigated dairy, dryland cropping and grazing, and irrigated cropping experiments.

Figure 3 shows the modelling framework that informed dairy farming system experiment design, and illustrates the rigour applied to the design process.

Application of this modelling framework models predicted that dairy businesses could return competitive profits with approximately 1/3 of typical historical water allocations (10 ML/ha). This could be achieved through incorporating double cropping rotations (e.g. irrigated maize in summer followed by rain fed winter crops on 30% of effective farm area, and growing predominantly rain fed annual ryegrass pasture on the remaining 70% of effective farm area). Importantly, the calving date in such systems must move to April-May from the more traditional July-August to achieve efficient milk production per cow.

Experiment design

The irrigated dairy systems experiment is designed to be an efficient and well-documented system that has the flexibility to cope with seasonal variation in water allocation. The experiment design mirrors adaptation already occurring in northern Victoria, but it goes further and faster than current changes on farm and measures the outcomes of these changes in a systemic way. Therefore, the experiment essentially takes risks that farmers may not be prepared to take without better information on the total water demand, productivity and profitability of the system.

The dairy farm is divided into three equal experimental farmlets (13.2ha) and a herd of approximately 45 cows is allocated to each farmlet (stocking rate = 3.5 cows/ha).

Allocation of existing paddocks/irrigation bays to each farmlet is based on soil nutrient status and area. Approximately 70% (9ha) of each farmlet is allocated for pasture (annual) with the remainder (approximately 4.2ha) to be used for cropping (either double winter/summer forage cropping or single pasture/summer forage cropping). Use of home grown feed is maximised, while supplementary feed makes up the difference needed to ensure milk production and quality across the three farmlets are the same.

The three equivalent farmlets' feed production systems aim to achieve competitive profit with water allocations of 15% (1.5 ML/ha - Low) or less, 30% (3 ML/ha - Medium), and 60% (6 ML/ha - High) of a 10 ML/ha historical base. The lowest water allocations experienced historically were 29% for the Goulburn system and 43% for the Murray system. The selected experimental water allocations provide a realistic stress test for the farming systems in a potentially drier future.

Irrigation system

The irrigation system was upgraded to operate on a wireless telemetry network, which recorded time of gate/stop opening and closing for the bays watered during an irrigation event, and height of water in the channel (upstream and downstream from the device). Flow rates were recorded using the Farm Connect system. Manual and automated opening and closing of gates, and timing of the river and recycle dam pump use were recorded.

Moisture monitoring

Fixed soil moisture probes (Aqua Spy) were installed in three bays for each farmlet – two bays in the allocated double cropping areas and one in the allocated pasture area. Probes were installed at 1/3 of bay length from the irrigation outlet and to a depth of 1m. Sensors were installed at 10cm intervals starting from 10cm below the surface. Soil moisture probes were connected to a wireless network, with the bay outlets and channel stops, and relayed information into the Farm Connect system. Soil moisture content was recorded at each sensor at 15-minute intervals.

Results and discussion

Table 1 shows the feed costs, milk production and milk quality for the High, Medium and Low water allocations.

Under the extremely wet 2010/11 irrigation season there was little or no difference between feed costs because all pastures and crops had adequate water from rainfall. The season did however provide a rigorous test of measurement systems. Reporting to date includes complete data for the first lactation, and preliminary data from the second lactation (May to August 2011). The irrigated dairy system experiments are continuing and hopefully 2011/12 will be drier to tease out differences between the three farming systems.

Output: A dairy farming system experiment established to measure profitability under low water allocations and operated successfully for a year, providing valuable management strategy insights. The experiment is work in progress.

Feed	Cost		High	Medium	Low
	$/tonne of wet matter ○	$/tonne of dry matter	Tonnes of dry matter offered*		
Grass		$87	70	65	60
Brassica		$150	15.4	15.4	15.4
Sorghum#		$66	0	11.2	16
Maize silage Homegrown~		$204	30	30	0
Maize silage Purchased~		$220	0	0	30
Cereal silage		$211	66	66	66
Canola	$325	$361	30	30	30
Lucerne Hay	$255	$300	26	26	26
Concentrate+	$281	$312	98	98	98
Dry Agistment		$93	30	30	30
Milker Forage Bought in		$200	20	20	20
Total feed - tDM			**385**	**392**	**391**
Average milkers			50	50	50
Total feed - tDM / cow*			7.7	7.8	7.8
Average cost per t DM			**$219**	**$216**	**$217**
Average litres/cow^			7,780	7,800	7,750
Average MS/cow^ □			560	570	565
Stocking rate, cows/ha			3.85	3.85	3.85
Average litres /ha			29,953	30,030	29,838
Average MS/ha			2,156	2,195	2,175
Milk revenue per cow @ $5.50/kg MS (~40c/l)			$3,080	$3,135	$3,108
Feed costs per cow			$1,689	$1,695	$1,702

* Before wastage for mixer fed supplements
^ Average based on 300 day lactation, 25% carryovers
# Cost assuming one sowing
~ The High water group grew twice the amount that was used, the Medium water group was self sufficient, and the Low water group purchased all maize
+ Pellets include AcidBuf (buffer) at $8/wet t all year, and Bioplex Zinc ($4/wet t), and Bioti n for hoof health part of the year ($4 wet t) and Elitox (Mmycotoxin eliminator) ($10.5/wet t)
□ Average for year, with 3.5 cows/ha being target level
○ Dry matter for Canola and pellets at 91%, lucerne hay at 85%

Table 1: 2010/11 lactation feed cost summary for three dairy farmlets

DRYLAND BROADACRE FARMING SYSTEMS

Key objectives of the broadacre cropping and grazing farming systems trials were to:

- Compare specialist crop or livestock production systems with mixed crop/livestock systems, at a sufficient scale to estimate whole-of-system water balance, water use efficiency and profitability
- Evaluate environmental outcomes of zero tillage/control traffic cropping against livestock farming
- Generate high quality dataset systems to calibrate and validate biophysical and economic models and predict long-term impacts (agronomic, economic and hydrological)
- Establish an adaptive best management practice for future drier climates.

The trials consisted of large-scale 20ha experimental farmlets, each with three replicates. The experimental faming systems and their key features are set out in Table 2.

Treatment/farm system	Key features
1. **Specialist Livestock:** Control for livestock production and management	• Top industry 5% • July / August lambing • Perennial pasture base
2. **Integrated A:** Base integrated system	• Combines best elements of systems 1 & 2 • Crop / pasture rotation (6 years)
3. **Integrated B:** Adaptive management system	• Short-term pastures e.g. annual ryegrass, annual legumes – decisions using forage comparison trial results • All parts of farm to be sown every year • Cropping decisions based on soil moisture

Table 2: Broadacre farming system trials

The broadacre farming systems trials were established on Hay's block at the University of Melbourne's Dookie campus. Pasture paddocks were set up to meet stock needs of the three livestock treatments replicated three times, and the cropping area was sown to meet the needs of the cropping treatments. These systems trials are designed to run over a four-year cycle.

The abnormally wet year in 2010/11 interrupted trial implementation, with high rainfall stimulating strong pasture growth. On the Farmer Reference Group's recommendation, additional stock were brought in to try to keep on top of the massive amount of feed on offer. The trial was designed to hold 450 sheep, but even 2000 sheep could not keep up with pasture growth. Even with huge stocking rates across the block most pasture had to be mown because the grasses had run up and set seed.

While trials designed to make the best of a dry climate were interrupted in 2010/11, they provide a comprehensive data set on the effects of a wet season on pasture and crop development. Data for wheat, canola, lupins and phalaris, annual ryegrass and lucerne pasture were collected. Gross margins were calculated for the three pasture types using agistment (price per head of stock) and the results are set out in Table 3.

Pasture Type	Gross Margin $/ha
Phalaris	$1030
Annual Ryegrass	$92
Lucerne	$538

Table 3: Gross margin ($/ha) for different pasture types on broadacre farming systems trial

Output: A comprehensive dryland broadacre cropping and grazing farming system experiment to inform farm management under a drier climate. The outcome of the trials is important to inform the restructuring of irrigation and the reversion of irrigated land reverting to dry land (Northern Victorian Irrigation Renewal Project has expressed interest in the trials). The broadacre farming system trials are work in progress.

OPPORTUNISTIC SUMMER CROPPING

During the recent extended drought in Australia, the rainfalls in summer followed the historical average in contrast to the substantial declines in autumn, winter and spring rainfalls. Opportunistic summer cropping is therefore a prospective addition to current winter cropping enterprises depending on antecedent soil moisture content and seasonal weather forecasts. David Cook, an enterprising local farmer, and also a member of the FRM Farmer Reference Group was planning summer cropping trials when the FRM trials were being designed. The FRM team got together with David and helped him with the statistical design of the replicated trials and the necessary soil moisture, water balance, soil nutrient, production and economic data collection. The opportunistic summer cropping is an exemplar of FRM research co-development.

Five summer crops were sown between September and October 2009. Subsequent summer rainfall was above average (but below the extreme of 2010/11). The summer crops generally performed well with the standout performer being millet. Soil moisture sensors under 2009/10 summer crops indicated that moisture was drawn from depths of 80cm by most crops (the exception being millet which drew to 100cm). Moisture use by crops decreased dramatically at the end of the vegetative production and the start of flowering. There was little difference between the soil moisture under the crops and fallow at the end of the growing season. The gross margins ($/ha) of the summer crops are shown in Table 4.

Summer crop	Gross margin $/ha
Fallow	-$32
Safflower	$297
Sunflower	$119
Mung Beans	$125
Millet (Grain)	$1106
Millet (Hay)	$419
Lablab (Hay)	$478

Table 4: Gross margins ($/ha) of summer crops

The performance of subsequent winter crops is an important factor in evaluating the viability of summer crops in the region. Assessment of the wheat crop sown over the summer cropping trial site indicated that millet negatively impacted on wheat growth. The wheat growing on the former millet block showed visible signs of nitrogen deficiency. The reduction in yield following millet shows the need for good crop nutrition following summer crops. Follow up trials under drier conditions are needed to complete the data set on the implications of summer cropping on soil moisture.

This trial demonstrated the viability of summer cropping in the region, and in wet years the possibility of double cropping. David Cook, the host of this trial has already included millet in his rotation after losing winter canola crops to flooding, and in turn gained income off paddocks that would have otherwise generated a loss.

Output: Proof of concept of summer cropping as another cropping option in a more uncertain climate with potentially wetter summers. This work is also an excellent demonstration of the value of research co-development with leading farmers.

HORTICULTURAL AND VITICULTURAL SYSTEMS

Background

Mixed horticultural and viticultural plantings are common throughout the southern Murray-Darling Basin, requiring a complex range of management strategies depending on the market for each crop. It is not unusual for individual farms to include a diverse range of crops such as pome fruit, stone fruit, citrus and grapes. Irrigation requirements can vary dramatically depending on the variation in soils, the growth stages and desired quality requirements of each crop.

Horticultural tree crops overwhelmingly target the domestic and international fresh markets for their products leading to stringent fruit quality specifications in terms of size, shape, colour and maturity. Precise irrigation management can strongly influence fruit quality. The penalties for failing to meet these stringent fresh market requirements are harsh, resulting in large decreases in gross returns.

Development of irrigation systems that optimise product quality and value to meet market standards and assist in managing the complexity of horticultural enterprises are vital for the future. Optimising product quality could require application of more water than current irrigation practices. But horticulture industries use a relatively small proportion of irrigation water (15%), and any increases in water use can be readily accommodated through trading water with lower value enterprises. The new irrigation systems must control application of water in real-time, adjust to highly variable weather, and manage diverse crops at different development stages, growing in variable soil conditions.

Progressing development of automated, precision irrigation systems combining the discipline of control engineering with wireless sensor networks measuring soil, atmospheric and plant conditions is an important objective of FRM. Such irrigation systems have potential to optimise product value, reduce labour costs, improve farm profitability and use the volume of water necessary to do so and no more.

Three crops were used – Rival Apricots, Pink Lady Apples, and wine grapes (Shiraz) and four different irrigation strategies were investigated.

The irrigation strategies listed in increasing order of complexity and potential for optimising crop value were:

- **Time/date:** Fixed schedule – widely applied but limited potential
- **Soil moisture depletion (SMD):** Uses automated soil moisture monitoring with decision enabling software. This irrigation strategy is more responsive than time/date strategy but is challenged by the heterogeneity of soils and the costs of intensive soil moisture monitoring
- **Evapotranspiration (ET):** Calculates the theoretical plant water use from data derived from an onsite weather station. This strategy has potential for reducing labour costs but can be subject to systemic errors
- **Crop Water Stress Index (CWSI):** Uses canopy temperatures measured with infrared temperature sensors to calculate a relative stress index, enabling quantification of plant stress.

	Rival apricots (Prunus armeniaca)	Pink Lady apples (Malus domestica)	Shiraz wine grapes (Vitis vinifera)
Time/date	Control	Control	Control
Soil Moisture Depletion (SMD)		✓	✓
Evapotranspiration (ET)	✓	✓	✓
Crop Water Stress Index (CWSI)			✓
Productivity measurements	Yield	Yield	Could not be harvested*
Quality measurements	Fruit size	Fruit size, colour, TSS	Bunch number, bunch size, berry size and TSS
Water balance	Yes	Yes	Yes

* resulting from berry split and disease caused by the wet conditions

Table 5: The irrigation strategy to be compared for each enterprise along with production parameters measured, season 2010/11

Earlier research funded by the Victorian Government's Science Technology and Innovation (STI) program developed the capability of automated irrigation using soil moisture depletion. This demonstrated an increase of 73% in gross margins compared to industry practice of manual irrigation for Pink Lady apples. FRM therefore focused on developing automated systems based on ET and CWSI. The latter, using direct measurement of plant water stress is the most advanced and uses the plants as the sensors. Eventually a combination of soil moisture, evaporative transpiration and plant sensing is a more likely prospect.

Unfortunately for the experiments the 2010/11 irrigation season was exceptionally wet and a relatively small number of irrigations were needed as a consequence. There were no extended dry periods to expose differences resulting from the three irrigation strategies applied in 2010/11. However the irrigation experiments are continuing in 2011/12 and, hopefully, will provide a better test of the different irrigation strategies.

Irrigation system based on evapotranspiration

The evapotranspiration (ET) irrigation scheduling system calculates the theoretical plant water use from data measured at the onsite weather station. Sunshine hours, air temperature, humidity, rainfall, wind speed and direction were used to calculate a reference crop evapotranspiration (ETo) (water use of irrigated grass). Weather station data was collected at intervals of 15-minutes and the ETo was calculated every 24-hours at midnight each day and expressed in terms of mm/day. Kc is the crop factor to convert the ET of the grass reference crop to that of the particular crop being irrigated. This approach is based on the Penman-Monteith method and is compliant with the FAO 56 specifications.

The crop factor Kc changes throughout the growing season to reflect the changes in plant water requirements, due to the canopy size and fruit maturity. This was calculated from weekly measurements of canopy size until full canopy, and from monthly measurements after that. The canopy size measurements were based on the effective area of shade that entails taking three measurements over the course of a day at six different locations in the block. Each measurement entailed taking five light measurements with a light meter above and below the canopy. The average of the three measurements was used as a practical estimate of the actively transpiring leaf area of the canopy in a given block. Maximum and minimum soil moisture depletion settings were placed into the program to safeguard from miscalculation.

There are many advantages of the ET irrigation system, particularly that it continuously monitors plant water use and enables a spatial and temporal understanding of plant water use. It is not based on a point sensor and has the ability to control irrigation on large scale. There are fewer infrastructure requirements for ET compared to other systems that rely on installation of soil moisture sensor networks.

This system is a relatively low labour input option; however collecting data to determine crop factors via measuring the effective shade area takes some time. The system does display the potential for crop factor drift, possibly resulting in inaccurate results and is an indirect measurement of plant water use.

One of the major learnings from the implementation and operation of the ET strategy was the issue of determining and programming the effective rainfall, i.e. how much run-off occurs and how to manage the cumulative rainfall measurements when not all rainfall is effective? Alternatively a combination of soil moisture monitoring to record when the soil moisture store is full could provide a way forward.

The FRM research team worked closely with MAIT Industries in another exemplar of co-development. The ET irrigation system is now incorporated in MAIT Industries commercial software.

Output: Proof of concept and demonstration of evapotranspiration measurements to control irrigation of horticultural crops. The software has been incorporated into a commercial irrigation system through co-development with MAIT Industries.

Irrigation system based on Crop Water Stress Index

Output: Established proof of concept that Crop Water Stress Index can be used to trigger irrigation in smart irrigation control systems. Future research and development should proceed to build on the FRM research.

The Crop Water Stress Index (CWSI) irrigation system uses canopy temperature measured by infrared sensors to calculate a relative stress index enabling quantification of plant stress. Measurements were taken on a clear day between 12pm and 2pm, a time when daily radiation was at its peak and the crop was under the maximum evaporative demand. A wireless network enabled the CWSI to be calculated in real-time and with the capability to actuate irrigation events determined by preset threshold CWSI levels.

Figure 4 shows the CWSI as calculated from real time measurements for recently irrigated and non-irrigated rows of grapevines. The difference in plant water stress is apparent.

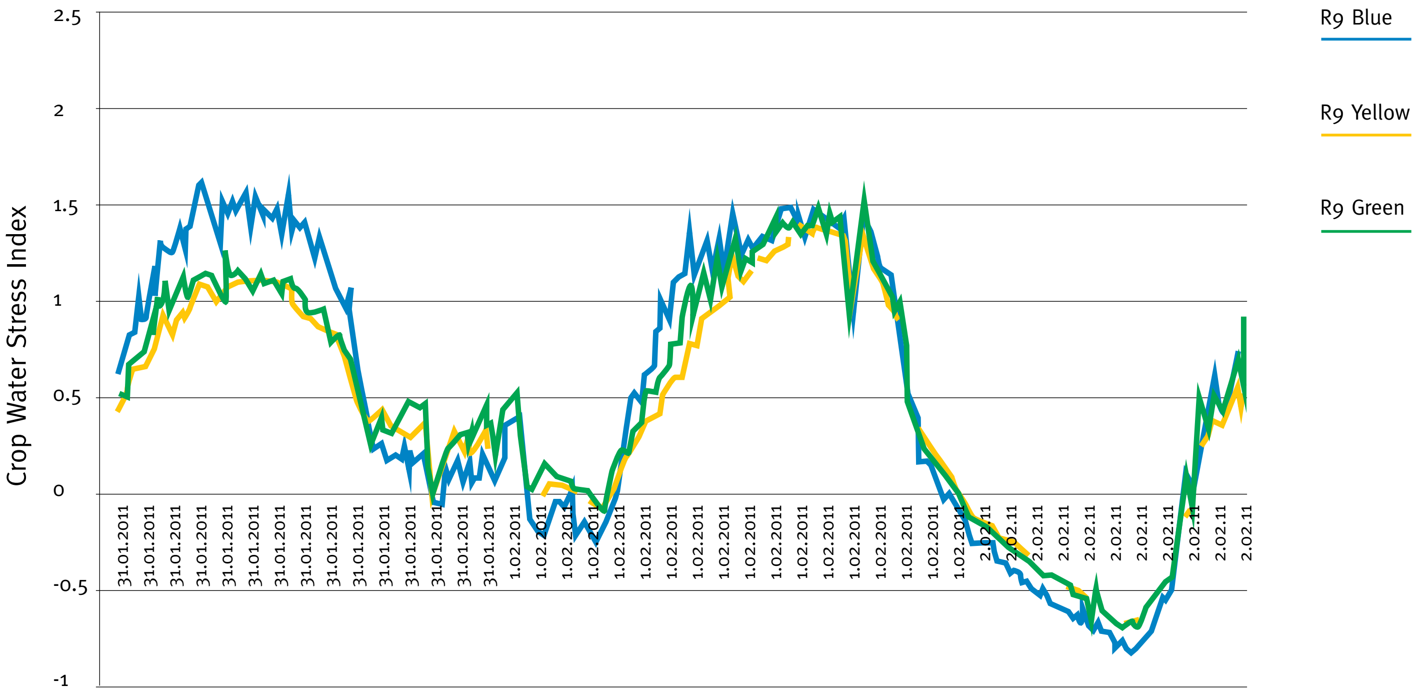


Figure 4: Crop Water Stress Index calculated in real-time. Yellow and green treatments irrigated 8 & 4 hours on 28 & 29th January respectively; blue irrigated for 4 hours overnight on 1st February.

The significant advantage of this irrigation scheduling system is that it enables a direct plant water use measurement and plant stress quantification. However technological issues mean that it is a long way from deployment at a commercial scale; the decision support software and sensors are not commercially available at present. Spatial data collection is limited by sensors that are commercially available and their cost. It is thought that thermography allows the semi-automated analysis of large canopy areas more efficiently than porometry. It is important to develop a local or specific baseline for each crop at a range of vapour pressure deficits under the same radiation level.

Although sensors were wired for the purposes of this investigation, the technology exists whereby infrared sensors could be transmitted by wireless and downloaded remotely. While plant based sensors measure plant responses such as plant water status, and transpiration via canopy temperature data are indicators of crop stress and infer when to apply irrigation, they do not indicate the volume of water to be applied. Technology also exists for data accumulated via IRT and CWSI to be used as input into other models or used in conjunction with ET and/or soil moisture sensors within irrigation software programs.

The research has demonstrated proof of the concept that CWSI can be used as a trigger of irrigation in smart irrigation control sensors. Since the CWSI measures plant water status directly it has more potential than either soil moisture or ET to control irrigation for optimum product quality. Ultimately a smart irrigation system based on all three triggers, soil moisture, ET and CWSI should be developed and future research should be directed to this end.

Measurement of crop yield, quality and value

Experiment design for each horticultural enterprise incorporated statistical rigour in testing a large fruit sample from within fully replicated commercial scale blocks. The comprehensive set of fruit yield and quality measurements implemented in 2010/11 combined with the water measurements allow accurate calculation of the value added by the smart irrigation systems tested. The extreme rainfall in 2010/11 suppressed any differences attributable to the smart irrigation systems, since all the crops had access to more than adequate water from rainfall. Confirmation that the smart irrigation systems and the measurements of fruit and water are working well provides confidence that the continuing horticultural and viticultural experiments will yield excellent results should 2011/12 be close to or drier than an average summer.

Figure 5 illustrates the statistical design of the experiments to evaluate SMD, ET and CWSI.

Output: An experiment that measures the performance of smart irrigation systems designed to improve the product quality and yield of horticulture/viticulture crops, and in turn water productivity (value/ML).

Evapotranspiration 3 sensors	Soil moisture depletion 3 sensors	Crop water stress index 3 sensors 4 levels of treatment
Soil moisture depletion 3 sensors	Time/Date **(control - industry standard)** 3 sensors	Evapotranspiration 3 sensors

Figure 5: An overview of the replicated sub block allocation to each irrigation treatment

INVESTMENT CASES: DAIRY AND HORTICULTURE IRRIGATION AUTOMATION

An analysis was conducted on the economic viability of investment in automated irrigation systems for dairy pastures and perennial horticulture, relative to existing manual systems. The investments were analysed from the farmer's viewpoint and demonstrated at the University of Melbourne's Dookie campus.

Available irrigation automation technologies include soil moisture-based control, advanced-front control, time-based control and evapotranspiration (ET)-based control. This analysis considers only soil moisture-based control for dairy and horticulture.

We represented typical dairy and orchard automation by coupling FRM data with other experimental data and agricultural industry information. Data on the costs and benefits of irrigation systems were obtained through a literature review (e.g. analysis from Victoria's Department of Primary Industries) and interviews with farm staff and suppliers. Enterprise budgets were used to derive cost and revenue estimates.

Border check irrigation on a dairy farm

Soil moisture-based automation (using sensors) is implemented through a network of radio nodes, automated bay outlets, automated channel stops and soil-moisture sensors located within irrigation bays. Radio nodes are powered by solar energy, so a single unit consists of solar power panels and a rechargeable battery. Irrigation is triggered by soil-moisture sensors, which send data via the radio network. The placement of the sensor down the bay is important for optimising the irrigation cut-off time. Irrigation cut-off is triggered when the advance wetting reaches this location Therefore the soil moisture sensor also acts as a wetting front sensor/detector.

The investment case for automation of irrigated dairy was based on information from 45ha of perennial pastures at Dookie, which consists of 22 bays of border-check irrigation. The system consists of irrigation bays of various dimensions consistent with industry practice. Bay length and width varies

to accommodate soil patterns and variability. Shorter and narrower bays were constructed on more permeable soils to maintain irrigation uniformity. Each bay was allocated a soil moisture sensor as necessary to capture variable pasture growth rates under rotational grazing. The layout of the irrigation bays influences the labour costs.

Horticulture farm information

The hypothetical horticultural farm was defined as 20ha with 20 blocks, each 1ha and populated with Pink Lady variety apples in accordance with experimental data. Consistent with industry standards it was assumed that the orchard already has established drip and sprinkler frost control systems. The labour savings as a result of irrigation automation were estimated to be 40 hours per week throughout the irrigation season.

Results and discussion

The investment cases show that automation is potentially a good investment in dairy and horticultural systems (Tables 6 and 7). This can largely be attributed to labour and water saving on irrigated dairy and improvements in crop quality and yield potential in horticulture.

In capturing benefits and costs in water use a conservative approach was adopted. Since water was saved in the dairy system, the price of water was assumed to be at lower bound ($100 per ML). Since more water was needed in horticultural systems under automation, price of water was assumed to be at upper bound ($500 per ML). As a result of automation the gross margin was increased from $345 per ML of water to $449 per ML of water for dairy.

	Manual	Automated
Mean Fruit Weight (g)	144	149
Irrigation water applied (ML)	1.5	1.9
Yield(kg/ha)	40	41
Price ($/kg)	2.97	3.24

Table 6: Farm parameters for manual and automated irrigation systems - horticulture

	Dairy	Horticulture
Area serviced by automation (ha)	45	20
Net present value ($)@ 10%	26,499	97,542
Internal rate of return	16%	23%

Table 7: Net present value and internal rate of return for investments

Output: Investment cases demonstrated that automated irrigation systems for border check irrigation used in dairy farming systems, and drip/mini-sprinklers used in horticulture are potentially a good investment.

FARM ECONOMIC MODELS FOR A WATER CONSTRAINED FUTURE

The social and political context for policy decisions in Australia is that incentives for change (by individuals, social groups and industries) need to be considered in evaluating and testing alternative ways to use the water resource. The technical feasibility of saving water and/or using it more efficiently and effectively must necessarily be established, but that is not sufficient for change to occur. Economic and social analyses can consider the incentives for mooted changes and provide information for decisions makers. This provision of information is an important contribution of FRM.

New economic models of farming systems in the Broken River catchment have been constructed using data from the FRM farming system trials and the wealth of historical information available. These are representative-farm models of the irrigated dairy, irrigated horticulture and irrigated cropping industries. They were constructed with the aim of being representative of these industries so that the results of the analyses are useful for policy makers and managers.

The economic models were based on linear programming (LP), and are capable of analysing management of farming systems to achieve a farm profit objective. Such optimising models have been widely used to assess questions of new technology and farming systems. The models developed in this project can also represent variability in the operating environment, so that risks in farm and catchment outcomes can be assessed.

These models are considered to be good representations of the decision framework faced by farmers (choosing the mix of activities to achieve profits with limited resources). They can be specified to represent detailed and interacting farm activities and are well suited to assess the impacts of reduced water supplies. They also can be constructed to allow water sales and purchases, and eventually water trading. These farming system models were applied to two climate scenarios reflecting historical and climate change (2030 dry). The output from these models can include changes in profitability and optimal farm enterprise mix, which comprise important information for future farming systems in a more water constrained future.

Irrigated dairy farm model

Victoria's dairy industry uses more than half the state's total irrigation water, and is vulnerable to reductions in water allocations. Irrigation water for growing pastures and forages is becoming less available and its price is rising. It is important that the dairy industry makes the best use of the available water to remain economically competitive. Perennial pastures have occupied 70-80% of the irrigated area of the farm with annual pastures occupying 20-30% and forage crops (mainly lucerne and maize) occupying only 2%. It is important to include outcomes from biophysical predictions in the whole-farm economic model to fully evaluate the impacts of financial performance. Linking the outputs of biophysical models with farming system tools can help to bridge this gap.

The objective function was the maximisation of the total gross margin for the farm, but subject to typical constraints or restrictions on resource availability, and is capable of optimising the dairy farming systems as the level of water allocation is reduced. The objective was maximised over a single year.

Dairy management options

Alternative water and feed supply, and feed utilisation management options were considered. The first management option involved soil moisture-based automation using soil sensors, wireless technology and automated bay outlets and channel stops. Changes in water use and pasture yield were assessed in a whole-farm context for changes in pasture type and farm income.

The second management option involved double cropping of maize to assess the use of water to grow irrigated crops for supplementary feed. The water and land requirements, variable costs and yield for conversion to silage were included in the analyses to assess this feed supply option.

The third management option involved changing the cow-calf calendar to split (spring, autumn) calving. This involved assessing whether the patterns of feed demand for a split calving herd could better match the seasonal pattern of pasture supply, and testing the impacts on farm profit.

Horticultural farm model

Orchard decisions can be both tactical and strategic. Strategic production decisions prescribe the size of an orchard, timing of sections to be replanted, the mix of varieties to grow and spacing. Tactical production decisions specify short run decisions such as thinning, irrigation and harvesting schedules, and level of irrigation. Thus the choice of the orchard system is made at planting, while important annual decisions are deciding optimal rate of thinning and irrigation regimes. These decisions also influence the costs and revenues by altering fruit yield and quality.

Maximising value from the orchard is subject to optimal replacement of trees, optimal mix of tree varieties, root stock selection, plant density, pruning and training (depending on rootstock and plant density), fruit load and other management practices. Here we only consider short run decision variables, namely the application of irrigation water and degree of thinning to manipulate crop load and fruit size and weight.

The horticultural model also optimised management of an orchard over a single year. A mathematical modelling approach was developed to explore economic implications of adopting different combinations of thinning and water management under varying water availability. This work developed a farm scale optimisation model able to allocate production activities to different land units (blocks) while maximising profit, but subject to several constraints. Mathematical programming models have shown to be suitable for such decision support as they have capacity to explore alternative possibilities.

The farm LP models were programmed so that they could be easily solved many times according to annual irrigation water availability. This capacity is a substantial advance on traditional LP model analyses that are conventionally conducted for a single 'average' year. The optimal farm management solutions for a variable climate sequence provide valuable information on how farm resource management might vary for different types of seasons and water allocations.

The methodological approach addresses the FRM aim of 'doing more with less water' by assessing farm management plans and predicted financial outcomes for different types of seasons. Indeed the results for the 104 years of historical climate data available provide farm resource management and income estimates for each of these years.

Dairy and horticultural industries in the Broken River catchment were studied to answer questions of likely change and adaptation in an uncertain future. The experimental design of analyses conducted is in Table 8.

	Climate patterns	
	Historical	**2030 Dry**
Dairy		
Base (status quo)	✓	✓
Water supply (automation)	✓	✓
Feed supply (double cropping maize)	✓	✓
Feed utilization (autumn calving)	✓	✓
Horticulture		
Base case (status quo)	✓	✓
Deficit irrigation strategies	✓	✓
Regulated Deficit Irrigation	✓	✓
Post Harvest Deficit irrigation	✓	✓

Table 8: Resource management and climate scenarios analysed

Horticulture management options

Strategies for reducing consumptive water use in horticulture are important under limited water supplies. Management options for achieving reductions in consumptive water use of orchard trees include Regulated Deficit Irrigation (RDI), Post Harvest Deficit Irrigation (PHDI), Deficit Irrigation (DI), and Parking Trees (PT).

DI involves application of a lesser amount of water than crop requirement throughout the irrigation season. DI strategies simulated were 90, 80 and 70 % of monthly crop water requirements. Investigations have suggested that there are crop developmental periods where water deficit is not detrimental to yield and fruit size, giving way to regulated and post harvest deficit irrigation strategies.

RDI can generate considerable water savings in terms of yield per ML of water applied by reducing excessive vegetative vigour and minimising irrigation and nutrient loss through leaching. RDI does not affect fruit size and quality in pear and peach crops. However, RDI is less suitable to apples. RDI reduces fruit size in apples and RDI for apples was not modelled.

PT involves applying only 30% of crop water requirement after complete removal of fruit, since water consumption of fruiting trees is 25-50% more than non-fruiting trees.

Water dimensions

The requirements of agricultural plants for water have a number of dimensions. There is a seasonal demand by pastures and crops for moisture to sustain growth, and these demands interact with temperature, day length and frost incidence. In analysing plant growth and (therefore) farm economic performance a 104-year time series of water availability was used. Source Rivers, a water resource and allocation model was used to calculate seasonal water allocations for each of the 104 years of stream flow data. Water availability was provided on a daily basis and was converted to monthly for the purposes of the economic modelling. The economic models optimised the farming systems for each year of the 104-year climate time series. Trends in the optimum farming systems as water allocations reduced could then be explored. In addition the outcomes of different faming systems under reducing water allocations could also be studied.

In presenting results of the whole-farm analyses, the aim was to show how farm economic returns and optimal farm plans varied with season and climate. But a question was how to represent seasonal variability. The best measure of seasonal variability was total irrigated water supply, because that supply depends on rainfall in the current and previous years, dam levels, and dam and tributary inflows. Hence the independent variable (x-axis) for the results graphs (Figure 6) is Total Irrigated Water Use (ML/farm). By presenting results in this way we show how the optimal farm plans vary as the water supply varies for both the historical and climate sequences, or how to 'do more with less water'.

The total annual water supply can conceal variations in water supply by month or season. Unlike the usual independent variable that is fixed in an experimental design, this measure also includes variability. Hence the dimensions of water are complicated and this must be remembered in considering the results of optimising the farming systems.

Distributions of whole-farm results showed that dairy industry predicted Total Farm Gross Margin (TFGM) was resilient to a reduction in irrigated water supply (proxied by a lower irrigated water supply) down to about 7 ML/ha, but at lower levels it declined directly with reduced water. Perennial pastures continued to be used down to about 7 ML/ha, after which they were gradually replaced by supplementary feed and irrigated and dry land pastures.

Three alternative dairy management options were compared with the base case – automation of water supply, a change in feed supply through using water to grow irrigated crops (double cropping with irrigated maize and dryland pasture for the rest of the year), and a change in calving pattern to better use existing feed supplies (see Figure 6).

Compared to the base case, the options of split calving and automation resulted in higher initial incomes (in the case of split calving) that remained higher as the water supply diminished. An average dairy farm TFGM of $500,000 required about 7 ML/ha of irrigation water, but this level of income could be maintained under split calving and automation as water use dropped to 3-5 Ml/ha. The split calving result is due in part to higher milk prices associated with maintaining milk production through winter. Double cropping was best in years where the water supply is low early in the irrigation season. In these years the base case management results in lower TFGM.

The ranking of management by average TFGM was consistently {split calving›automation›double cropping›base case} for 'low', 'medium' and 'high' water use. In the figure the advantage of double cropping over the base case is greater at lower levels of water use.

There is evidence of dairy farms in Victoria's north being reinstated and reinvigorated as water supplies have recovered after the drought.

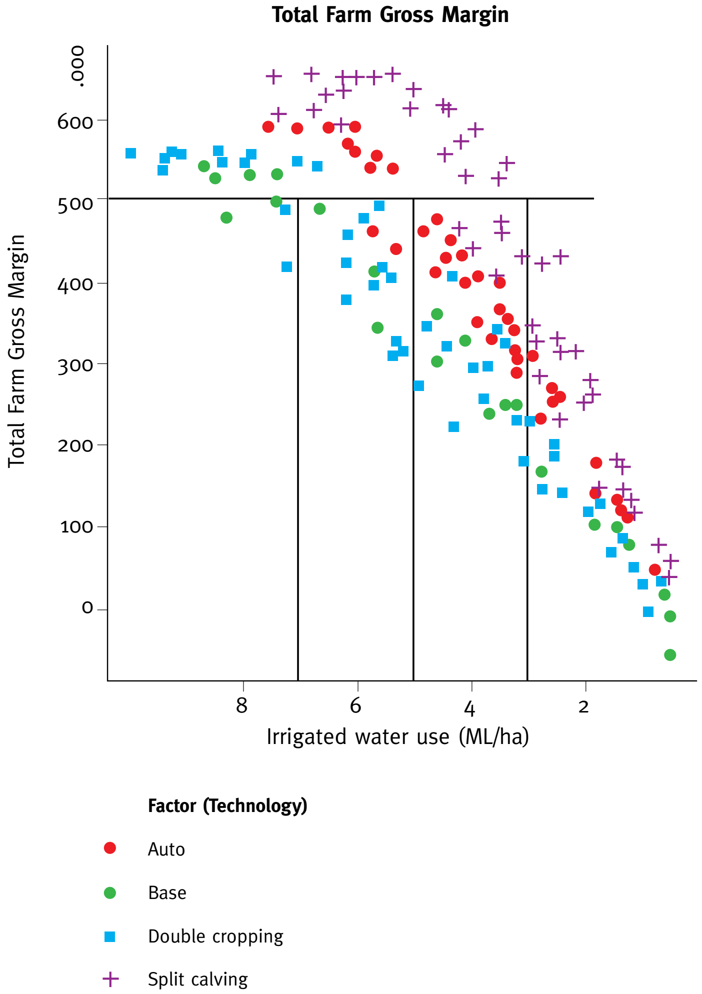


Figure 6: Total farm gross margin plotted against irrigation water use (ML/ha)

For horticulture farms the efficiency of water application is already relatively high (through the use of micro-jet and drip irrigation) and the focus is now on water productivity. The technologies assessed in this analysis were several deficit irrigation strategies. These technologies modify the timing of water application during the tree-growing season. In Figure 7 below the base management and the combined deficit irrigation technologies are plotted as a Cumulative Distribution Functions (CDFs).

In Figure 7, the y-axis is the probability that the outcome in any year will be less than any nominated TFGM level (shown on the x-axis). So there is a 50% probability that the base case income will be less than $140,000 and a 50% probability that the deficit irrigation strategy income will be less than $165,000.

The deficit irrigation strategies stochastically dominate the base results, so that they are expected to give an economic advantage in all types of seasons. This result agrees with the investment case for improved water-using technologies.

Output: Optimising economic models that demonstrate both the economic consequences of reducing water allocations for dairy and horticultural enterprises, and evaluate the robustness of different farming systems in more water constrained futures.

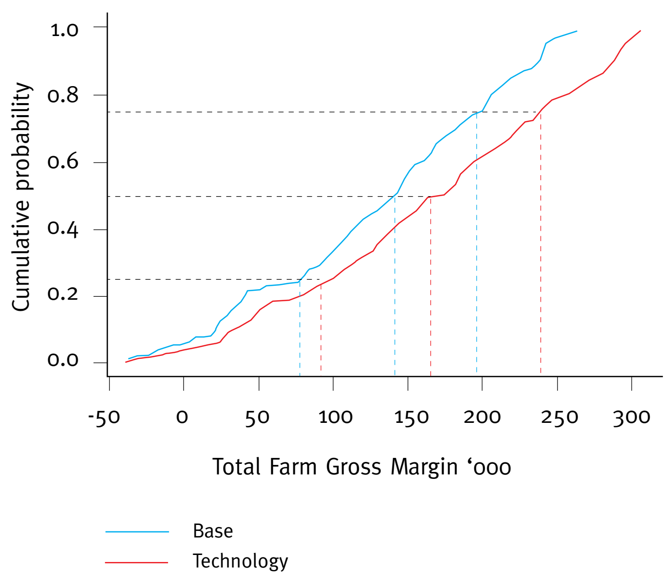


Figure 7: Cumulative probability of total farm gross margins

Modern river operating systems

The following five major topics are discussed in this section:

- **Demonstration of the value of comprehensive water measurement:** Targeted data collection can reduce uncertainties in water resource assessment, and can cost effectively inform water resource management, trading and environmental shepherding.
- **Application of control engineering to river operations:** This has the potential to improve water distribution efficiency, level of service to irrigators and environmental performance. An investment case now exists for a control system for the Broken River.
- **Managing slack water habitat:** Slack water measurement can inform active river flow management to improve habitat and ecological outcomes, supported by more precise river flow control enabled by a control system.
- **Assessing the feasibility of using water destined for irrigation to conserve wetland ecosystems:** Dual use of wetlands by irrigators and environmental water holders is an idea worth further investigation, and the ecological consequences of wetland inundation would be essential to inform active management of wetlands for environmental purposes.
- **Optimal management of environmental flows for the maintenance of flood-dependent forests:** Providing the environmental water holder with flexibility to trade and release at larger peak rates reduces the volume of water and cost of environmental watering. A mix of low and high security environmental water is likely to reduce the costs of environmental watering.

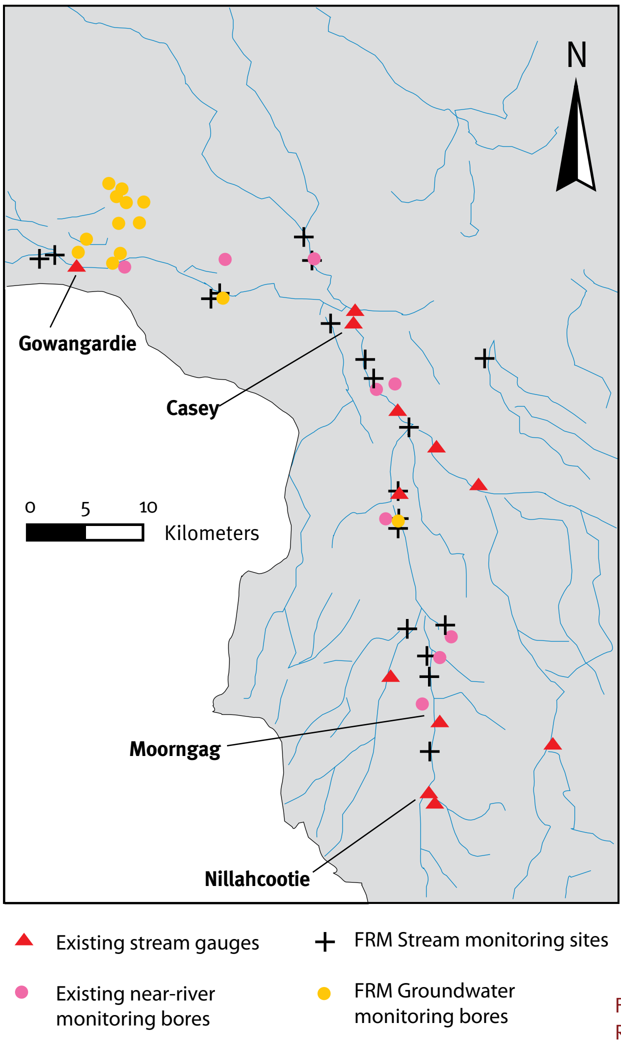


Figure 8: Existing and FRM monitoring network for the Broken River catchment downstream of Lake Nillahcootie

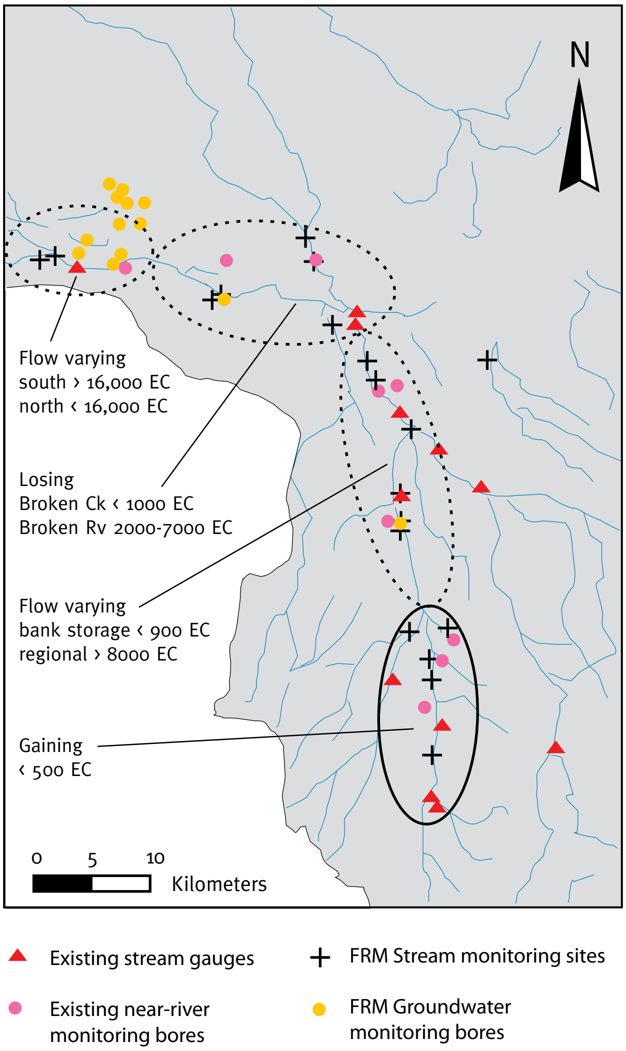
DEMONSTRATING THE VALUE OF COMPREHENSIVE WATER MEASUREMENT

Field data collection

- To answer a range of questions FRM invested in an extensive network of additional river level and flow measuring stations in the Broken River catchment below Lake Nillahcootie, both along the Broken River and on larger tributaries that were previously ungauged. This network was complemented by additional groundwater bores and more intensive monitoring and analysis of existing bores. Pre-existing measurement network and equipment installed by FRM are shown in Figure 8.
- Groundwater level measurements were complemented by geochemical sampling and analysis of both surface and groundwater to further explore interconnection. Hydrochemical sampling of streamflow was undertaken to characterise water quality and to identify possible groundwater discharge into the river. The analyses included major ions, stable isotopes (^{2}H, ^{18}O) and some naturally occurring radiogenic isotopes (^{222}Rn, $^{86}Sr/^{87}Sr$, $^{234}U/^{238}U$).
- The period of measurement included an abnormally dry year (2009/2010), and an abnormally wet year (2010/2011) with at least two flood peaks providing excellent opportunities to explore the surface water and ground water interconnections.

River-groundwater interactions

Results of FRM monitoring have changed our understanding of the spatial patterns of interaction between groundwater and the Broken River, as summarised in Figure 9. The hydro-chemical data (chloride and radon) provided independent estimates of discharge rates into the Broken River from groundwater in the gaining and flow varying reaches of the river.



The conductivity data range of groundwater is shown for each reach (EC=µScm-1).

Figure 9: Summary of river – groundwater connectivity gradients for the Broken River. The Victorian 20m digital elevation model forms the grey-scale image underlying the figure with the maximum elevation (1123 m) shown as white and the minimum elevation (108 m) shown as black

The estimated groundwater discharge rates into the Broken River below Lake Nillahcootie are quite modest relative to the stream flow. Large reductions in groundwater discharge rates were measured during the drought of 2009. Monitoring of gaining reaches under drought conditions would be a good precaution by water resource managers to protect minimum environmental flow requirements in regulated rivers.

The conductivity of water samples is commonly measured at designated sites (e.g. gauging stations) and routine measurement of chloride can facilitate 'snap-shot' estimates of groundwater discharge between sampling points. There are a number of major assumptions built into this approach (i.e. assumes that all surface inflow from tributaries have the same concentration as the upstream flow and that the groundwater end-member is representative). Greater confidence would be obtained by having supporting radon analysis done on a periodic basis.

Water balance and uncertainty modelling

A water balance analysis was undertaken, including a rigorous assessment of uncertainty. Tributary inflows were estimated using two different approaches: one with models transferred from the two streams with long-term flow records; and one using the historic data and short-term gauging provided by FRM.

The uncertainty analysis was undertaken using a water balance equation for each reach and a Monte-Carlo framework. The water balance included gauged inflows and outflows, private irrigation diversions, stock and domestic diversions and evaporative losses. The residual term was assumed to represent interaction between the river and groundwater. Errors in flow measurements were incorporated based on information about the accuracy of stream gauges and meters and errors in modelled tributary inflows were estimated using the GLUE (Generalised Likelihood Uncertainty Estimation) framework applied to gauged data. Models were transferred to ungauged tributaries by pooling all models developed for gauged tributaries. In the based case only data from Holland's Creek and Lima Creek was available. Data from five additional tributaries was available when the FRM data was included.

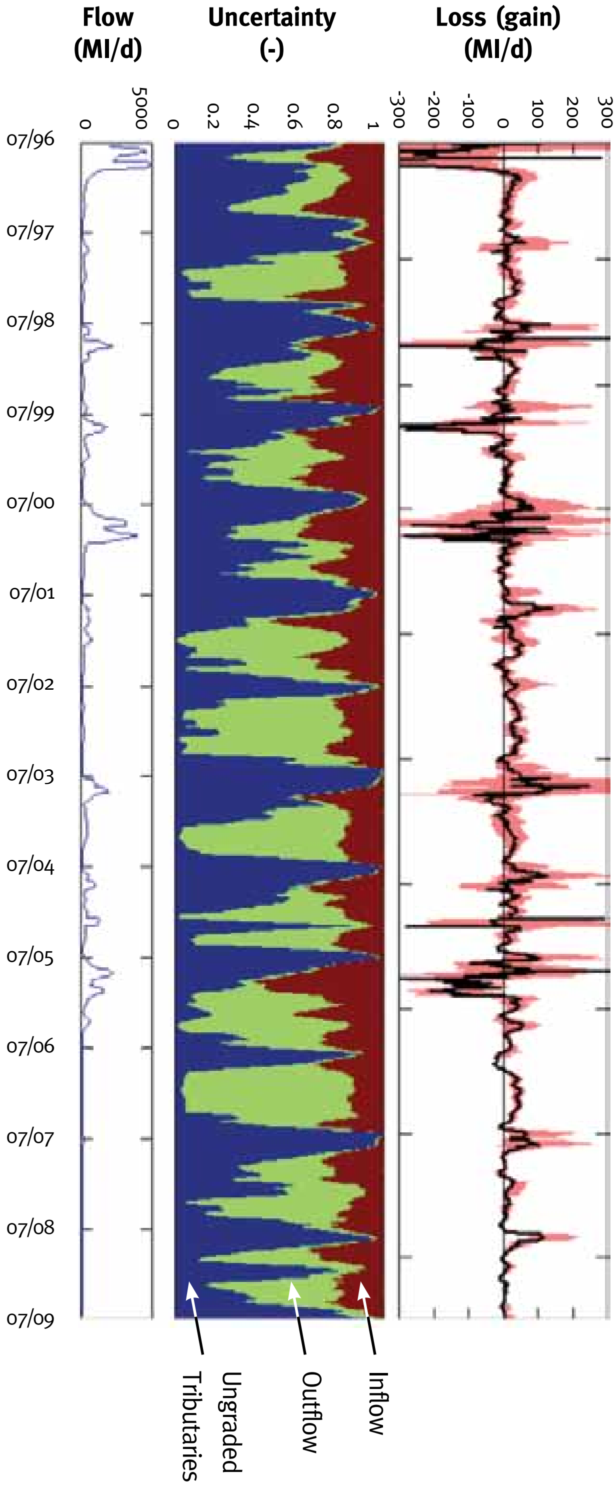


Figure 10: Residual term estimates (loss positive, gain negative) and associated uncertainties for the Morngag - Casey's Weir reach. The top panel shows the median and 5th to 95th percentile interval for the residual term, smoothed over a 30-day moving window. The middle panel shows the relative contribution of gauged outflows, gauged inflows and ungauged tributary inflows to the uncertainty in the residual term. The bottom panel shows the gauged outflow for context, also smoothed on a 30-day window.

Figure 10 shows the uncertainty analysis results, revealing useful insights into the data adequacy and the importance of different uncertainty sources, which change with flow rate. This analysis also demonstrates the value of short-term gauging records where gaps in the monitoring network exist.

The changes in estimates of loss (gain from) to groundwater are shown in Figure 11. The new data resulted in a loss reduction from +13 to -10 GL/y along the Broken River from Nillahcootie to Orrvale. The River was thought to lose 13 GL/y, however more comprehensive measurements showed that it was gaining 10 Gl/y resulting in transmission error losses of 23/GL/y. Earlier tributary inflows estimates were too high. These new results are consistent with the outcome of groundwater investigations.

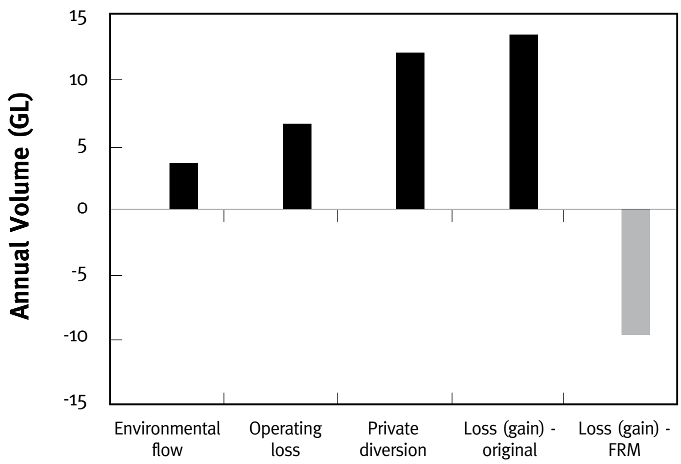


Figure 11: The change in estimated loss (gain from) to groundwater for the Broken River's main stem resulting from the additional data collection. Other volumes are provided for context.

A range of practical consequences stem from the overestimation of transmission losses including:

- Impacts on water resources assessments (over-estimation of modelled dam releases to meet irrigation demands)
- Potentially, larger releases from Lake Nillahcootie than necessary in expectation that a greater proportion would be lost (depending how much practical experience of system behaviour is built into operator decisions)
- Substantial implications for water trading and shepherding of environmental flows down the river.

Transferring hydrologic models calibrated against data from wetter tributaries to estimate flow from drier tributaries lead to an overestimate of tributary flows in all cases, resulting in an overestimation of transmission losses to groundwater. The error, which was caused by transferring information from hydrologically dissimilar catchments, could be minimised by statistically rigorous monitoring, site selection or through supplementary monitoring programs.

To fill gaps in the gauge network roving field campaigns of relatively short-term stream gauging designed to complement the existing long-term network could be initiated, supported by detailed hydrometric data relating water table elevations to river stage elevations, including;

- installation of additional monitoring bores close to the river and stage monitors in the river close to monitoring bores, with accurate surveying of the levels of bores and river monitoring stations; and
- hydrochemical data collection from stream flow and groundwater, including ionic, isotopic and radiometric data, to better estimate groundwater contributions to low flows.

In addition all river stage records should be related to Australian Height Datum to enable comparison with groundwater heads. FRM showed the value of approximately two years' additional monitoring, but a longer period is needed to avoid biasing the data towards dry or wet periods.

Value of additional data

FRM has identified value in collecting additional data for fine-tuning water resource management in a regulated catchment. Previous studies estimated Broken River net transmission losses in the order of 13.3-15.1 GL/year (without an uncertainty range), which is 35% of the reservoir storage capacity in the catchment. However the FRM water balance indicates the system is gaining around 10 GL/year, which is an error of 23-25 GL/year. The FRM water balance does not result in a 'saving' of water flowing out of the catchment but is likely to have important implications for water trading and shepherding.

The cost of collecting further field data to guide and evaluate the water balance analysis was in the region of $240,000 or, given the ~23 GL/year change in loss estimate, $10 per ML of annual flow i.e. $1/ML over a 10-year period. An investment case can be made for targeted field measurement campaigns to progressively develop more accurate calculations of transmission losses and their causes and hence the water resource. More accurate evaluation of water resources and transmission losses will be fundamental in a more water-short future, and when trading and shepherding of environmental water become widespread.

Output: Demonstration that targeted data collection can reduce water resource assessment uncertainties and be a cost effective strategy to inform water resource management, trading and environmental water shepherding.

APPLICATION OF CONTROL ENGINEERING TO RIVER OPERATIONS

Control of a river

In an automatic control system, real time measurements are used to decide on future actions to achieve certain desired objectives. In the context of FRM, based on current flow and water level measurements, the control system decides in real-time releases and flows along the Broken River in order to meet water demands from irrigators and the environment. For example, if the measured flow in the river is less than the desired flow needed to satisfy demand for water, the control system will use the upstream regulation gates to release more water so that the desired flow will be achieved.

Differences between control of irrigation channels and rivers

Modelling and control of irrigation channels have demonstrated that control systems can achieve significant improvements in the quality of service to irrigators and in the water distribution efficiency. However, unlike a river, there are no environmental constraints in an irrigation channel. For example, one can completely shut down the flow in an irrigation channel if there is no demand for water, while this is clearly not possible in a river. Furthermore, there are more storage and control points in an irrigation channel compared to a river. Hence, there are much shorter time delays between the points of supply and demand in an irrigation channel. These are all factors that make the control problem more challenging for a river.

Advantages of control compared to manual operation

In the Broken River it takes about four to six days for water released from Lake Nillahcootie to reach downstream locations such as Casey's Weir and Gowangardie Weir. Most demand is downstream of Casey's Weir, making control difficult since the water takes a long time to reach demand points.

Due to the long delay, under manual operation it is necessary to release water from the upstream end before it is needed. However, because there is time delay uncertainty, water needs to be released slightly early to ensure it reaches the point of demand on time. Moreover, to compensate for losses on the way and inaccurate flow measurements, more water than necessary is released as illustrated in Figure 12.

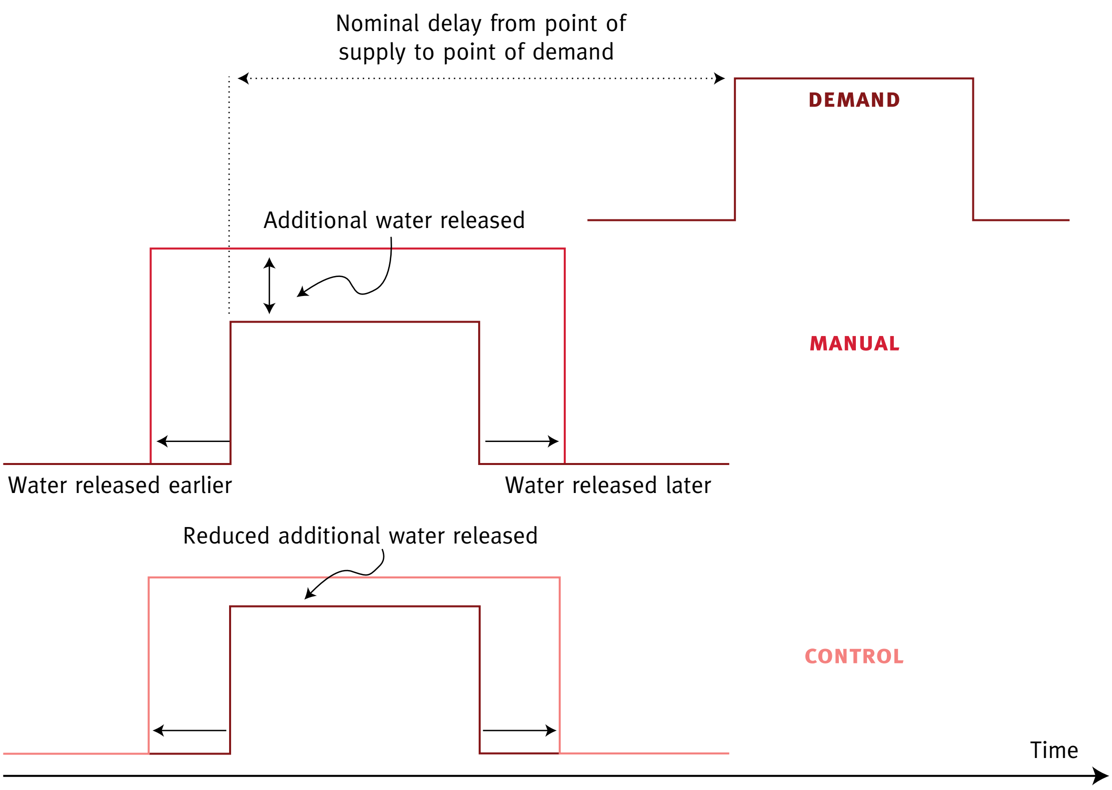


Figure 12: Release of water under manual operation and feedback control

In a control system it would still be necessary to release water early. However one could make adjustments to the release in real-time so that if a flow is short of what is needed, more water can be released. This reduces the total amount of water released as one can release less additional water.

The advantage of control

If there were no uncertainty, there would be no need for control as we could exactly predict what would happen and act accordingly. For any real world system, and for a river in particular, there are large elements of uncertainty, e.g. varying time delays, unknown in-flows from creeks, unknown withdrawals of water, and losses to or gains from the ground water. As a controller reacts to the actual measured flows and water levels, it is much more robust against uncertainty. The control system gets information about effects of the uncertainties through measurements and it takes appropriate corrective actions to improve operational efficiency.

Control objectives

Broadly speaking, the control system objectives are to ensure accurate and timely water delivery to irrigators and the environment, and to deliver without over-supply or causing undesired flow conditions along the river.

Subject to requirements from irrigators and the environment, the amount of water released from Lake Nillahcootie should be as small as possible. Figure 13 sets out the Broken River system and control infrastructure.

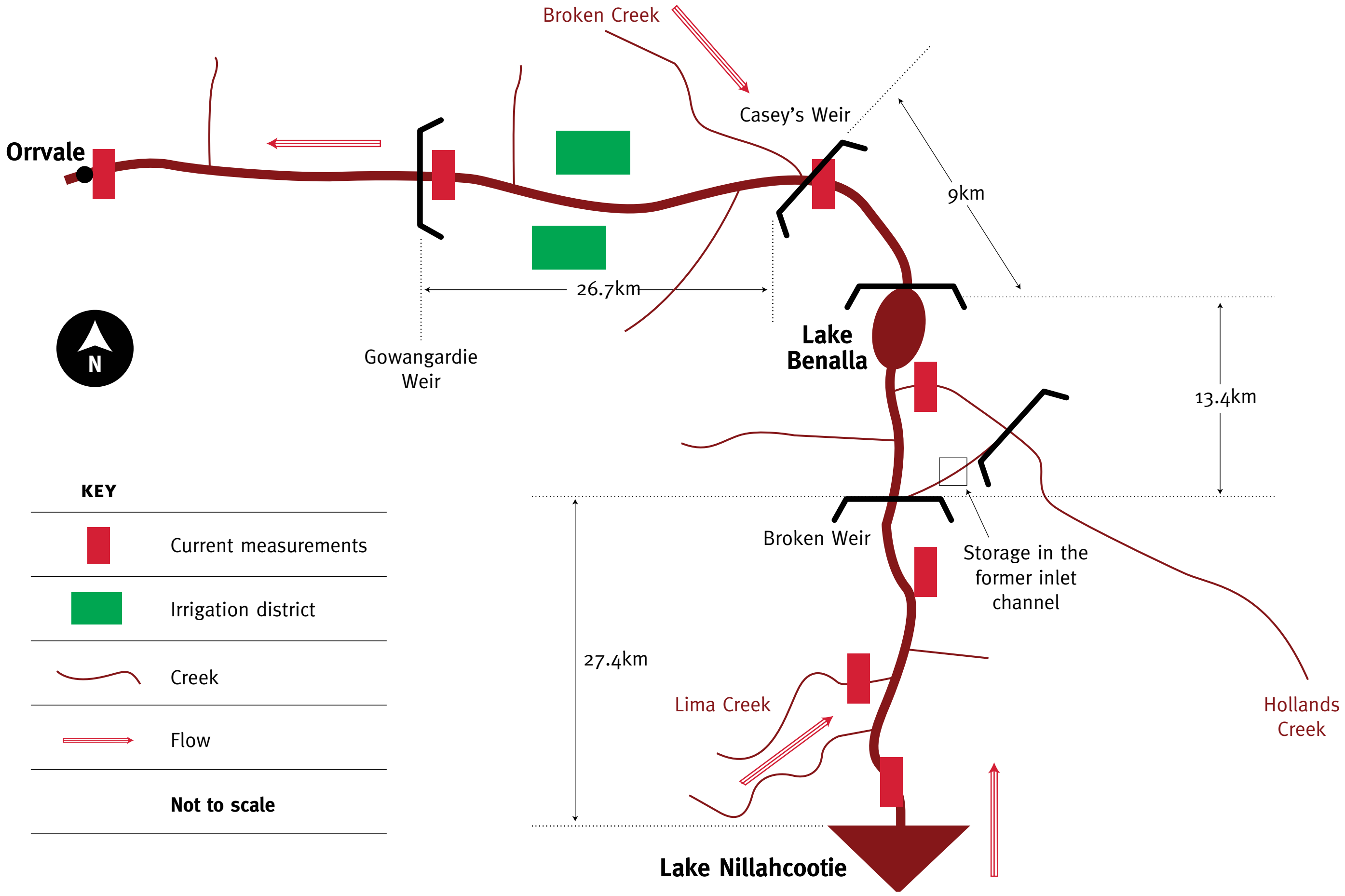


Figure 13: Key infrastructure and supply areas in the Broken River system. Control infrastructure locations are coloured red. The addition of automated control gates at Casey's Weir was considered in some design scenarios.

Simulation studies

In this section the designed control systems' performance is illustrated in a realistic yearlong simulation. The area we consider is from Lake Nillahcootie to Gowangardie Weir (see Figure 14). We will not consider control of the flows and water levels along Broken Creek, but will assume that certain flows have to be released into Broken Creek just upstream of Casey's Weir. As the geographical area we consider ends at Gowangardie Weir, all demand for water downstream of Gowangardie Weir (including environmental water and water for the Goulburn River) is aggregated into a desired flow over Gowangardie Weir. We consider inflow from the catchment's two major creeks, Lima and Hollands Creeks, and assume that all inflows can be aggregated into these two flows.

Locations where flows can be regulated

We assume that we can control the flow at locations including Lake Nillahcootie, Broken Weir, Casey's Weir, and in and out of the storage currently under construction in the former inlet channel to Lake Mokoan. At these locations the flow can be controlled with the existing infrastructure (or infrastructure soon to be put in place).

Casey's Weir is considered a separate option as the infrastructure investment would be significantly larger because control gates would have to be installed. However, being able to control the flow at Casey's Weir would lead to a better performing control system since water in the short term can be supplied from the weir pool at Casey's, which is much closer to the bulk of the demand than Lake Nillahcootie.

Control strategies

The following control strategies are considered:

- **Current practice:** Manual regulation of the release from Lake Nillahcootie. The flow is adjusted daily according to the known future demands and an extra 20 ML/D is added to account for uncertainty in the actual flow released and transmission losses. This is similar to current manual operations.
- **Decentralised control:** Decentralised control with and without the ability to regulate flow at Casey's Weir. Flows are adjusted every six hours. In a decentralised scheme the Broken River's reaches are controlled separately with some information exchange between controllers.
- **Centralised control:** Centralised control with and without the ability to regulate flow at Casey's Weir. Like the decentralised control, flows are adjusted every six hours. In a centralised scheme all reaches are considered together. Such schemes are more complex than decentralised schemes but give better performance.

External inputs

The external inputs are:

- **Orders of water from irrigators:** Historical usage data for the 2006-2007 season provided by Goulburn-Murray Water is used. The exception is usage along Broken Creek and downstream of Gowangardie Weir where 2007-2008 data are used. There was less usage in 2007-2008, and this is more representative for Broken Creek due to the recent water buybacks. This creates a bimodal demand pattern with spring and autumn peaks, and is anticipated to be more in line with future farming practices.
- **Environmental water demands:** Minimum flow values at Broken Weir, Lake Benalla and Casey's Weir are 22 ML/D and at Gowangardie Weir is 25 ML/D. Flows should be below 190 ML/D in summer to preserve slackwater habitat. Variation should be limited by requiring the average daily flow to be between 0.76 and 1.5 times the flow the previous day.
- **Inflow from creeks**: Inflows from Lima Creek and Hollands Creek are based on 2006-2007 measured flows.

Results

A control system allows the water authority greater flexibility in how to operate the river, and depending on the operational objectives set by the water authority, the amount of water released from Lake Nillahcootie can be reduced or the ordering times for the irrigators can be reduced.

Results when emphasis is on minimising water released from Lake Nillahcootie

In this simulation, the operational objective was to keep the releases from Lake Nillahcootie as small as possible. Figure 14 shows the total amount of water released from Lake Nillahcootie and the excess water flowing out of the study area at Gowangardie Weir. Excess is understood here as water not needed for environmental purposes nor ordered by irrigators.

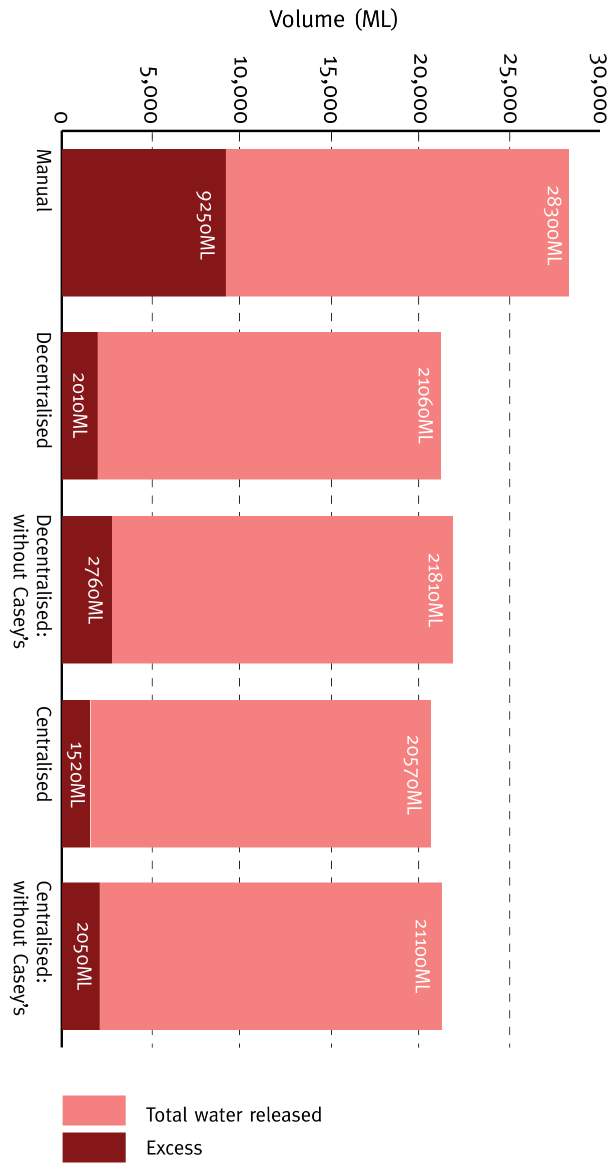


Figure 14: Total amount of water released from Lake Nillahcootie and excess water when the emphasis is on reducing the releases from Lake Nillahcootie

The simulations demonstrate that savings (water released in excess of irrigator and Broken River's environmental needs) of 25% in the volume released from Nillahcootie are achievable. Application of control engineering to river operations therefore has substantial potential for improving river operations' efficiency.

Results when emphasis is placed on reducing ordering time

In the case of Broken River, a question arises about water requirements downstream in the Goulburn River. If not enough water is delivered from the Broken River, the shortfall must be made up with releases from Lake Eildon. From an overall system point of view it may be better to use flows from the Broken River flows first so that more water can be held in Lake Eildon.

The simulation study showed that if releases were kept at the same level as with manual operation to supply water to the Goulburn River, then the ordering time to irrigators could be reduced to two and a half days without regulation at Casey's Weir, and even lower with regulation at Casey's Weir. The potential of modern operating systems to improve the service to irrigators and environmental water holders is a key benefit, allowing for more flexible farming practices and increased agricultural water productivity. Note that in this case it is an active operational decision to supply additional water to Goulburn River and it is not just a by-product of operational procedures.

Results: Environmental performance

Both the decentralised and centralised control systems work well in achieving the existing minimum environmental flow requirements for the Broken River, and performed considerably better than the manual operation in avoiding large changes in the flow.

Application of the control system also improved slack water habitat. This work is described in the following section.

Investment Case

A business case was constructed to assess the potential improved civil engineering infrastructures in the Broken River. These works involve installing two flume gates at Casey's Weir, alteration and SCADA integration at the Broken River Diversion Weir, and civil works at Casey's Weir. Goulburn-Murray Water (G-MW) is the body who would construct and implement such changes. A social Benefit Cost Analysis was conducted from the viewpoint of government, which was assumed to provide capital on behalf of the Broken River catchment community. Benefits and costs were considered within the Broken River catchment.

The estimated capital costs were $389,000 and compliance (3% of capital in the first year) and ongoing operating costs (2%) were included. The saved water was assumed to be available for further irrigation or environmental use within the catchment or downstream. A proxy value for the extra water is the traded water price, and a range of prices from $100 to $500/ML was used for the analysis. These values are traded prices for willing buyers and sellers and there is an assumption that the value of water used for environmental purposes is at least these levels for the investment case. These are not the amounts that G-MW receives for delivering water to customers, and are not necessarily the prices paid in the Broken River catchment.

The financial measures of net present value (NPV) and internal rate of return (IRR) were calculated for the cash flows over a 15-year period of the River Control system investment. The perspective is for a government investment of funds in river control structures to generate social benefits within the Broken River catchment.

The annual cash flows included estimated capital, compliance and operating costs and the value of water saved by the new control system. The values of water used (from recent traded water history) were $100, $200, $300, $400 and $500/ML. A discount rate of 10% was used for the NPV calculation. The results are in Table 9.

Variation in water price and estimated water savings did not reduce the NPV values below zero. In the table all IRR values are also large, showing a good return against the cost of capital.

Given the assumptions made in this analysis, the results indicate a very healthy economic return to the Broken River catchment community. The NPV values were positive and relatively large (Table 9) and the IRR figures were very high compared to the cost of capital. Because of the unquantifiable benefits this investment analysis is considered to be relatively conservative in offsetting the capital and ongoing costs. Despite this the investment in improved river control and management in the Broken River catchment is likely to generate a relatively large benefit to the catchment community.

Water Price ($/ML)	Catchment water saved (ML/year)			
	7300	5475	3650	1825
		NPV		
$100/ML	4.6	3.4	2.1	0.8
$200/ML	9.7	7.1	4.6	2.1
$300/ML	14.7	10.9	7.1	3.4
$400/ML	19.8	14.7	9.7	4.6
$500/ML	24.8	18.5	12.2	5.9
		IRR		
$100/ML	177	132	87	43
$200/ML	356	266	177	87
$300/ML	534	400	266	132
$400/ML	713	534	356	177
$500/ML	892	668	445	222

Table 9: NPV and IRR estimates for River Control in the Broken River catchment

Conclusions

The benefits of an automatic control system have been demonstrated through a realistic year long simulation. Reduced ordering times for the irrigators and/or reduced releases from Lake Nillahcootie are achievable, depending on the operational priorities set. In the simulation an ordering time of between one and two days was possible when the outflows were kept at the same levels as with current manual operating practice, leading to improved service to irrigators.

On the other hand, if the emphasis is on reducing water releases it was shown that they could be reduced. Moreover, it is an operational decision whether the releases or the ordering times (or both) should be reduced, and this offers the water authority greater flexibility in how the river should be managed to the benefit of both the irrigators and the environment. The control system is also capable of improving the environmental performance through improvement of slack water habitat. A positive investment case opens the opportunity to invest in a control system on the Broken River as a demonstrator of the technology for Australian river managers.

Output: The benefits of applying control engineering to river operations in terms of efficiency, level of service and environmental performance have been clearly demonstrated. The positive investment case opens the opportunity to invest in application of a control system to the Broken River, initially without installing control gates at Casey's Weir.

MANAGING SLACK WATER HABITAT

Introduction

There is a distinct lack of explicit relationships between river flows, particularly seasonal flow reversals during the irrigation season, and biotic response, yet there is an understanding that high flows during some parts of the irrigation season can be ecologically damaging. Active management of river flows and environmental water allocations is vital to achieving the environmental outcomes in the most cost effective ways, but is fundamentally dependent on availability of comprehensive knowledge of the effects of flow on river ecosystems.

An overview of the ecological role of slack waters, and a detailed hydraulic analysis of the linkages between stream flow and slackwater abundance are used to analyse the impacts of flow regime on slackwater habitat and the ecosystems.

Slackwaters, still and shallow aquatic environments within the river channel, have been found to contain significantly greater numbers (up to 10 times as many) of fish, shrimp and zooplankton than flowing water patches in lowland rivers. Slackwaters provide a good exemplar of the link between population dynamics of aquatic biota and hydraulic conditions and play a role in ecosystem processes including fine sediment dynamics, decomposition of particulate organic matter and primary production.

Slackwater abundance is likely to be influenced by river regulation, and specifically seasonal reversals in flow durations experienced within the river system. Many organisms associated with slackwaters have specific and narrow habitat requirements. Where biota have limited swimming abilities, such as juvenile fish or fish and shrimp larvae, or are affected by stream forces, such as macrophytic plants, survival and mortality can be closely related to spatial and temporal variability in the specific habitat. High water velocity has often been cited as the limiting factor in physical habitat availability and suitability.

Flow regulation and slackwaters have not been explicitly linked for Australian species or river conditions, even though they are both common features of Australia's lowland rivers. The relationship between the regulated flow regime and slackwaters has been quantified using two dimensional hydraulic models and field data. We define slackwaters based on a range of velocities (0.01 to 0.3 m/s) and depths (0.1 to 1 m).

Methods

A two-dimensional hydraulic modelling package was used to develop models for two sites on the lower Broken River. A combination of LiDAR (Light Detection And Ranging) and field survey of channel geometry in inundated areas was used to create a Digital Elevation Model. Large woody debris was also surveyed to help define hydraulic roughness parameters. The water surface profile along each reach was surveyed and velocity and depth measured at five cross-sections in each site using an Acoustic Doppler Current Profiler (ADCP) for a range of discharges.

Relationship between slackwater habitat and discharge

Both sites have bankfull discharges of approximately 140 m/s, and exhibit similar trends in slackwater area response to discharge. In general as discharge increases slackwater area decreases. As higher-level features in the channel such as benches are engaged (at approximately half bankfull discharge) slackwater area increases again but does not reach the same extent as for very low flows (Figure 15).

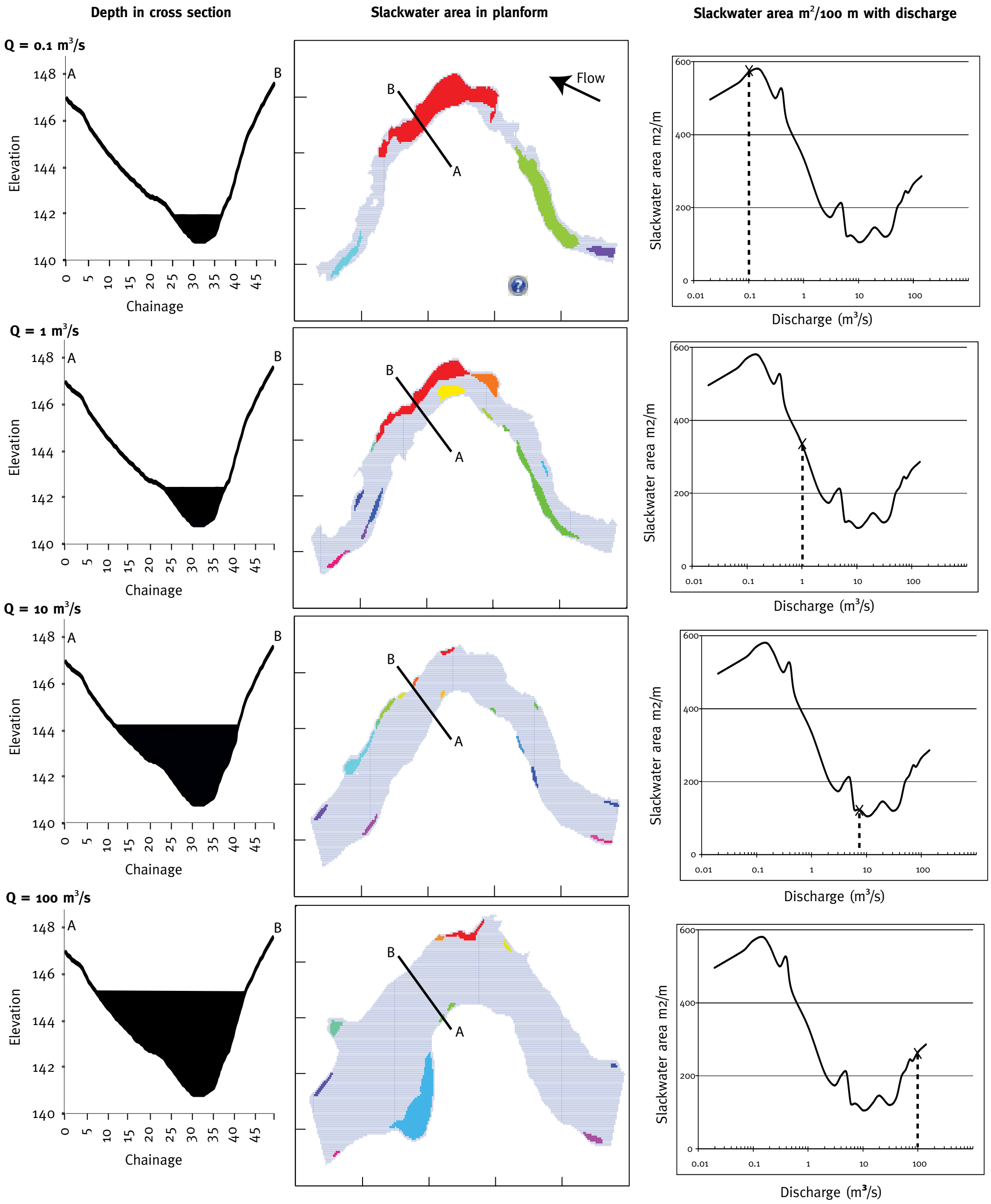


Figure 15: Slackwater area and distribution within the channel of Site 2 (Ballintine Rd) for four discharges (Slackwaters defined by V ‹ 0.05 m/s, d ‹ 0.5 m)

Impact of regulation on slackwaters

A generalised response curve was produced to demonstrate the impact of the regulated flows in summer on slackwater habitat area (Figure 16). This approach, justified by the similarity in the trends between sites, removes the site specific 'blips' in response and provides a general trend; considering the consistent trend demonstrated for the three velocity criteria less than 0.1 m/s, and the ecological focus on this range.

The impacts of both light and heavy flow regulation on slackwater habitat compared to the natural flow regime are clear:

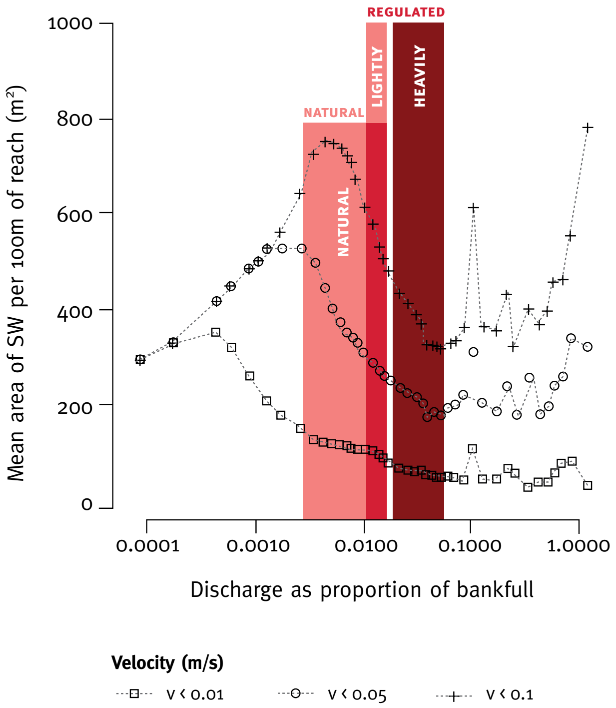


Figure 16: Slackwater habitat area (mean area of slackwater per 100m of reach) relative to discharge as a proportion of bankfull discharge for depth criteria of 0.5m and three velocity criteria less than 0.1 m/s. Vertical lines correspond to the 20th and 80th percentiles for summer discharges for natural, lightly regulated and heavily regulated flow regimes. Curves represent the summated response for Sites 1 and 2.

Potential of the modern river operating system to manage slackwater habitat

Figure 17 demonstrates the impact of an automated control system on slackwater habitat. The top panel shows slackwater under manual control and the lower panel shows slackwater under automated control with a 2.5 day lead time (i.e. compromise between minimising water releases and order times). The impact of automated control in increasing slackwater habitat is clear. The range of flows for that year is narrow due to dry conditions during the drought.

Output: Demonstration of the value of measurement of slackwater as a tool to inform active management of river flows to improve habitat and ecological outcomes. The benefits of more precise control of river flows enabled by a control system were also demonstrated.

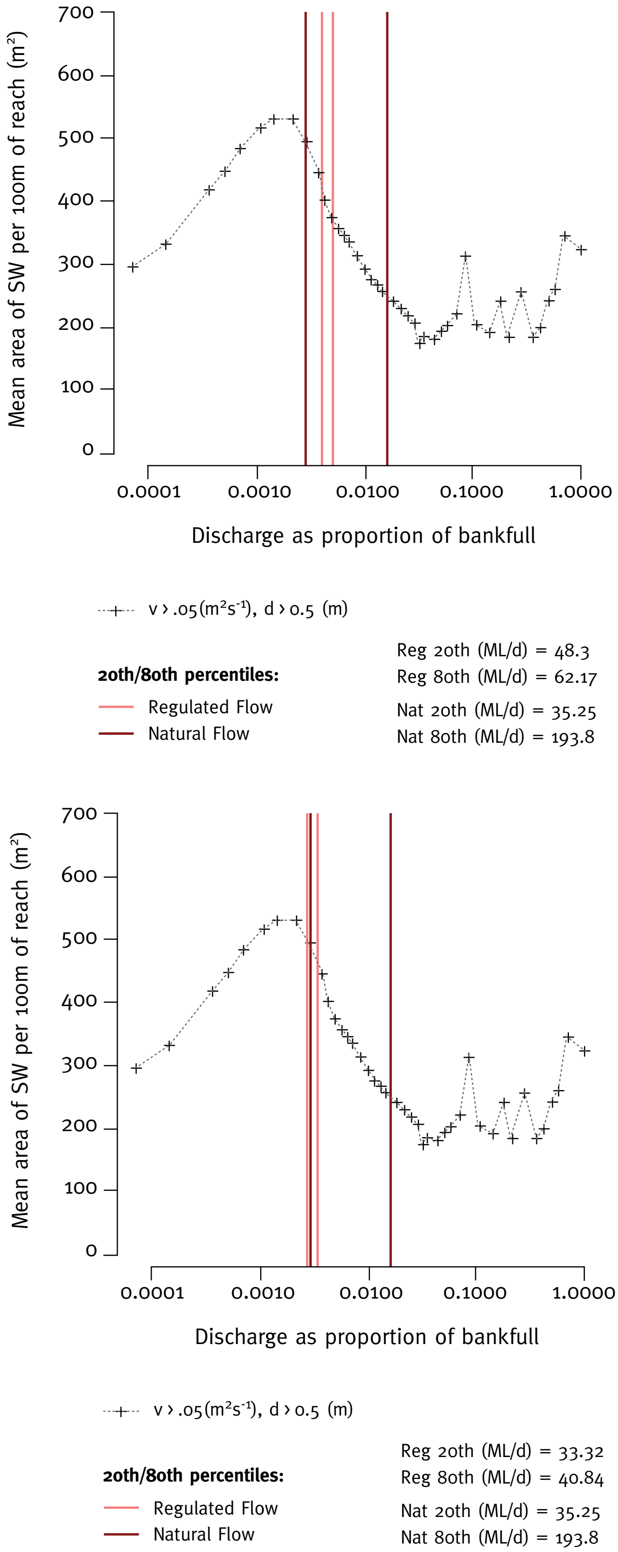


Figure 17: The impact of automated control on slackwater availability for the irrigation demands used in the simulation of the control systems

ASSESSING THE FEASIBILITY OF USING WATER DESTINED FOR IRRIGATION TO CONSERVE WETLAND ECOSYSTEMS

Floodplain wetlands are vulnerable to river regulation due to reductions in high flows, particularly the overbank flows that fill the wetlands. There may be an opportunity to use wetlands as temporary water storages for irrigators, to reduce summer flows in rivers creating more slack water habitat, and at the same time gaining ecological benefits of increasing the wetting frequencies of wetlands towards more natural levels.

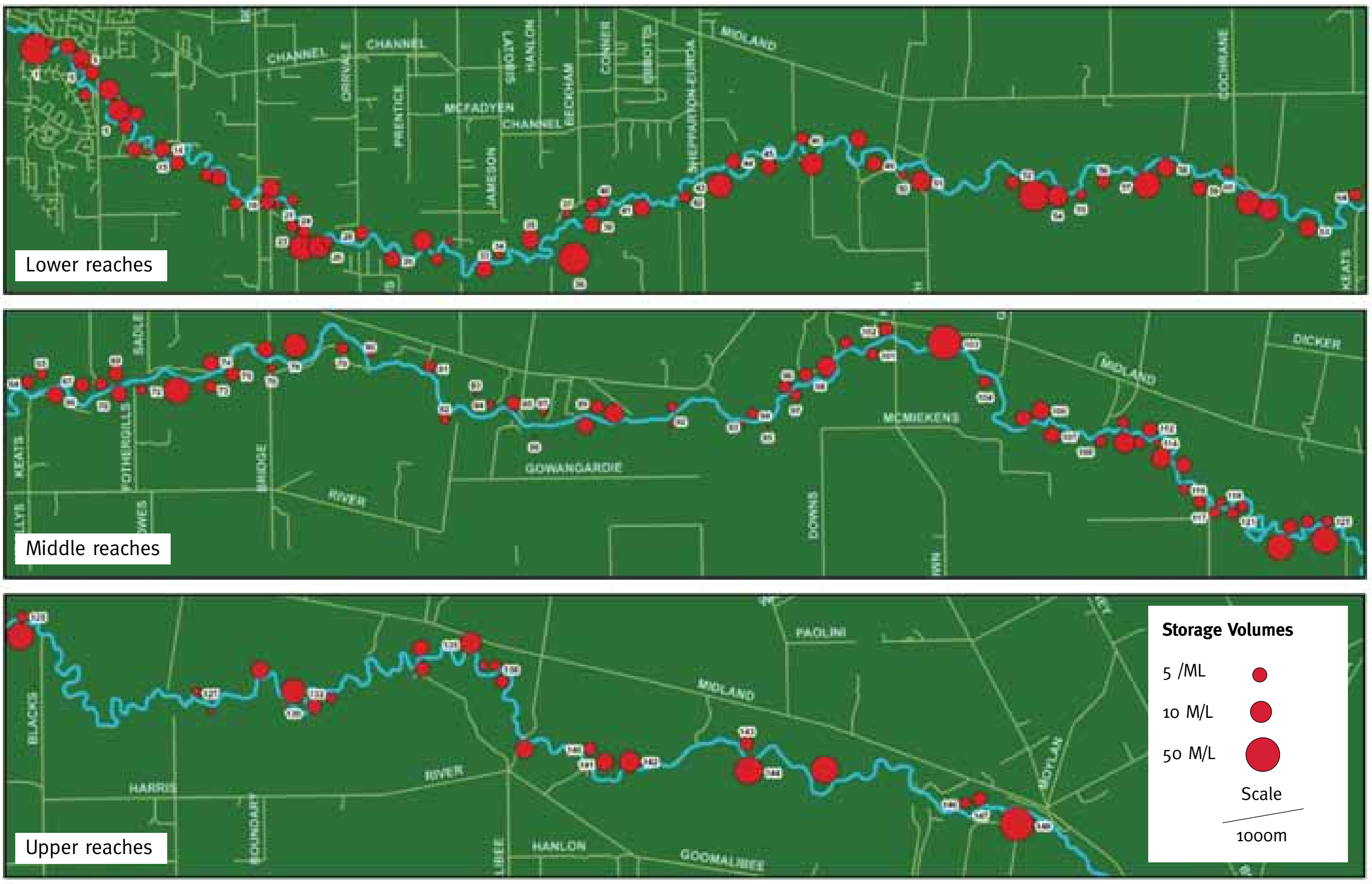
This research investigated this possibility by:

- Mapping wetlands along the lower Broken River from Casey's Weir to Orrvale
- Estimating wetland inundation frequencies for various flow regimes
- Quantifying water loss rates from wetlands
- Undertaking trial draw downs in mesocosms and natural wetlands to assess impacts on vegetation and zooplankton
- Assessing the storage potential of wetlands in relation to summer irrigation demands.

The mapping illustrated in Figure 18 found:

- 148 wetlands with >3 ML enhanced storage capacity over 80km of river length. Wetlands were spaced at 0.5km intervals on average
- Natural storage volumes for these wetlands had a 1.5 ML mean volume, a 3.4 ML median, seven had 10-46 ML capacities and total storage capacity was 497 ML
- Increasing the volumes of wetlands, by assuming bund walls could be placed to increase storage volumes, was also considered. In this case, the median storage volume was 10.3 ML, mean was 14 ML, 75 wetlands had 10-61 ML volumes and the total storage capacity was 2065 ML or 5% of the headworks storage capacity in the system.

Wetland locations (Natural volumes)



Wetland locations (Bund wall volumes)

Figure 18: Distribution of 148 wetlands along the downstream lowland reaches of the Broken River, Victoria. (Upper panel) natural volumes. (Lower panel) enhanced volumes.

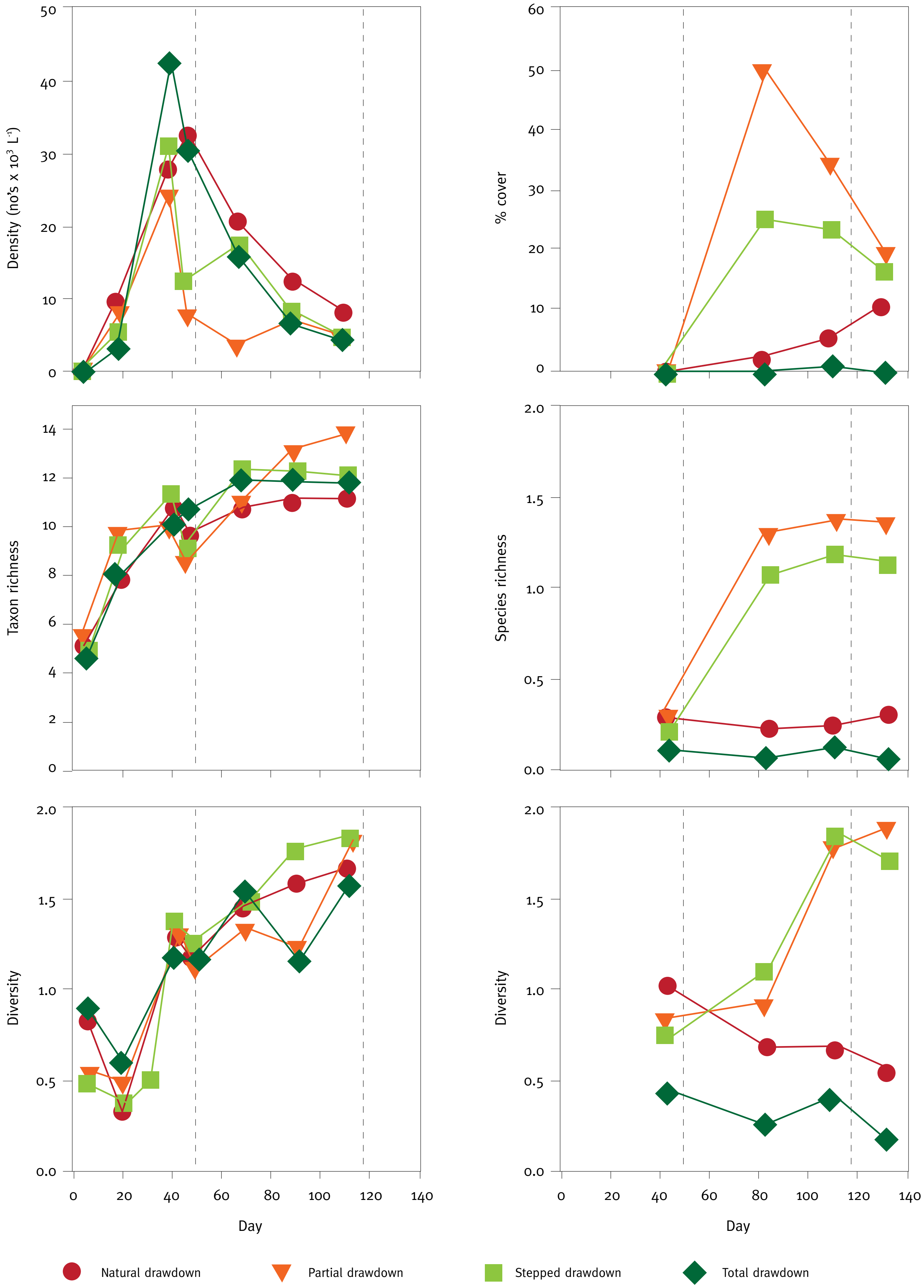
Across all the wetlands, inundation frequency was found to be around 1.3 times per year on average under natural flow regime with a 5% reduction under lightly regulated and a 46% reduction under heavily regulated river flows.

Wetland inundation is highly sensitive to climate change. Climate change (2030 dry scenario) coupled with light flow regulation leads to an 86% reduction in inundation frequency and a 96% reduction when coupled with heavy regulation. In these cases the durations of the high flow events are also significantly shortened. This reduction in inundation under this climate change scenario points to wetland and floodplain drying as being a large ecological risk under climate change. Long periods between wetting during the recent drought saw substantial declines in ecological condition of flood plains and these results point to such long intervals potentially becoming the norm. Adapting environmental water management to such conditions requires careful thought and the temporary storage option canvassed here could be a component of the response.

Losses from wetlands are significant and would need to be incorporated into any programs that utilised wetlands as temporary storages. For the wetlands considered in detail losses ranged from 35-63% of the storage volume, depending on the assumptions made about timing of filling and water use.

The field trials of partial drawdown in mesocosms (a summary of the ecological outcomes is shown in Figure 19) and Broken River wetlands found few differences between vegetation and zooplankton responses, compared with natural drawdown. This suggests that using wetlands as temporary stores may be ecologically feasible. However, it is noted that water will need to be maintained in wetlands in sufficient volumes and for sufficient duration of time to allow replenishment of the dormant egg and seed banks. While this time period is relatively short for zooplankton (days to weeks), a minimum of three months is required to allow submerged and amphibious plants to germinate, flower and set seed.

Figure 19: Mean density, taxon richness and diversity of zooplankton (left panel) and aquatic plants (right panel) sampled in each water regime during the mesocosm experiment



This report highlights the potential for the conjunctive use of wetlands as irrigation storages, providing ecological value from water for consumptive use. The construction of bund walls can provide a significant increase in storage volume.

Conclusion

Wetlands are a ubiquitous component of lowland rivers in the Australian landscape. They support considerable ecological values and are often identified as important assets, yet, due to river regulation the frequency and duration of wetland inundation is often greatly reduced. It seems reasonable therefore to consider how the two conflicting demands of environmental and irrigation can be unified to maximise the benefit of this water, i.e. dual use. The feasibility of their use as irrigation supply is firstly limited by location, volumes and losses relative to demand, secondly by timing and drawdown considerations for the ecosystems to be conserved and thirdly by the cost/benefit implications of infrastructure required to manage the wetlands as off river storages.

Output: Information indicating that use of wetlands for dual use by irrigators and environmental water holders is an idea worth further investigation. The ecological consequences of wetland inundation research would also inform active management of wetlands for environmental purposes.

OPTIMAL MANAGEMENT OF ENVIRONMENTAL FLOWS FOR THE MAINTENANCE OF FLOOD-DEPENDENT FORESTS

Operational management of environmental water is an emerging challenge for the newly created environmental water holders. This is a challenging problem involving a sequence of decisions on the timing and volume of water releases to achieve economic and environmental objectives under uncertainty about future water availability. Under the Australian Government's "buyback" program (DEWHA 2010), a portfolio of water entitlement holdings has been acquired with the purpose of protecting or restoring environmental assets of the Murray-Darling Basin. Environmental assets include wetlands and floodplains.

The ability to achieve environmental objectives efficiently can be influenced by a number of operational policy settings. A new model of environmental water operation was developed and applied to the problem of conserving river red gum stands (Eucalyptus camaldulensis Dehnh.). The model uses optimisation to develop rules for environmental water operation. The rules essentially relate to when and how much water to release and/or trade, depending on current storage and tree condition. In doing this it considers future uncertainty (climate variability) and the consequences that flow from making particular operational decisions (e.g. releasing water now or storing it) in determining the best principles or rules to maintain flood-dependent stands of trees over the extended future.

The modelling examined the impact of policy and infrastructure settings on the cost and effectiveness of environmental water management. The three particular settings examined were:

- Allowing for water to be traded for environmental purposes
- Increasing the maximum reservoir release capacity
- Modifying the portfolio of water entitlement holdings (the mix of high and low-security entitlements).

Our focus was not on the specific details of how to implement these options, rather it was on the potential benefits related to them. We measured benefits in terms of the condition of river red gum forests and the volume and monetary cost of environmental water releases to maintain red gum condition.

A case study of the Lower Goulburn Floodplain was undertaken with information on the current distribution of red gums over the flood plain and flow required to inundate different zones, coupled with relatively simple assumptions about tree response to flooding and tree decline rates between floods. An efficient water release strategy balances the immediate gains from creating a small flood that inundates only part of the floodplain with potential future gains from waiting and being able to inundate a larger area.

Our main finding is that there is substantial scope to reduce the cost of maintaining stands with assisted floods. Table 10 shows results assuming river red gum stands can persist for 20 years in the absence of flooding. Allowing the environmental water holder to (contra) trade and allowing higher maximum release rates from the storage led to the greatest reductions in the volume and monetary value of water required to meet a specified river red gum condition target.

One limitation of our measure of the cost of water is that it does not include the cost of inundating productive land and private water pumping infrastructure. An important next step in determining efficient strategies for maintaining river red gum stand is to consider these costs. The critical point here is that these results indicate that giving the environmental water holder flexibility to trade and having greater flexibility around possible release rates from storage both bring benefit in terms of reducing the cost and volume of water required to maintain red gum health.

Our analyses also highlighted that the form of entitlements held by the environmental water holder has a potentially important impact on cost. Environmental water holdings involving at least some low-security entitlements are probably more cost-effective than entitlement portfolios involving only high-security entitlements due to the high relative cost of the latter form of entitlement.

Output: Providing the environmental water holder with flexibility to trade and release at larger peak rates reduces the volume of water and cost of environmental watering. A mix of low and high security environmental water is likely to reduce the costs of environmental watering.

		High	Mixed	Low
Release limit	Trade	20GL/22.2GL/$551K	30GL/20.9GL/$572K	40GL/21.7GL/$290K
	No Trade	40GL/16.7GL/$483K	40GL/19.8GL/$483K	120GL/22.4GL/$289K
No release limit	Trade	10GL/21.1GL/$236K	10GL/18.4GL/$188K	20GL/19.6GL/$131K
	No trade	30GL/18.1GL/$551K	40GL/23.4GL/$542K	50GL/22.2GL/$271K

Table 10: Costs of maintaining tree condition at a level of at least 14 in flood zone 3 with reliability of 0.73 under alternative scenarios on water trading and reservoir release capacity when red gum dieback occurs over 20 years. The numbers in the cells are the entitlement volume/average annual volume used/a nominal average annual cost of water, including profit and loss from any trading.

New markets in water products and services

BACKGROUND

The National Water Initiative (NWI) (Council of Australian Governments, 2004) pursues "a nationally-compatible, market, regulatory and planning system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes". Taking action on the NWI's sound principles needs coordinated change as advances in agriculture, ecology, water services and markets are interdependent and must be integrated to maximise the whole water system's performance.

FRM's Markets research took a 'whole system' view of performance and explored how new ways of organising and governing decisions about water can generate a performance dividend. The research revealed that more interaction between buyers and suppliers is needed to achieve optimal results for consumptive and environmental water use.

An interdisciplinary team, including management and decision scientists, operations research and applied mathematicians, and environmental and property lawyers, brought diverse theoretical perspectives to the question of how decisions about water can be better coordinated to the benefit of multiple stakeholders. The proposition of the Markets research is (Goldsmith & Samson, 2010):

"When decisions about both supply and demand of water are made at the right organisational level by the right stakeholder, high levels of dynamism, through entrepreneurial behaviour, and stability and sustainability, through operational effectiveness, create new whole-of-system value."

This proposition has been described in terms of expanding the efficient frontier (Figure 20). The efficient frontier drawn in this figure represents the maximum value achievable for farm performance at given levels of environmental performance and vice versa. Drawing efficient frontiers allows exploration of the changes in system performance that can be achieved under alternative management strategies. The frontier denotes the maximum performance achievable for both farm and environment, so that the balance of value can be explored without needing to make prior judgments about the relative importance of each sector.

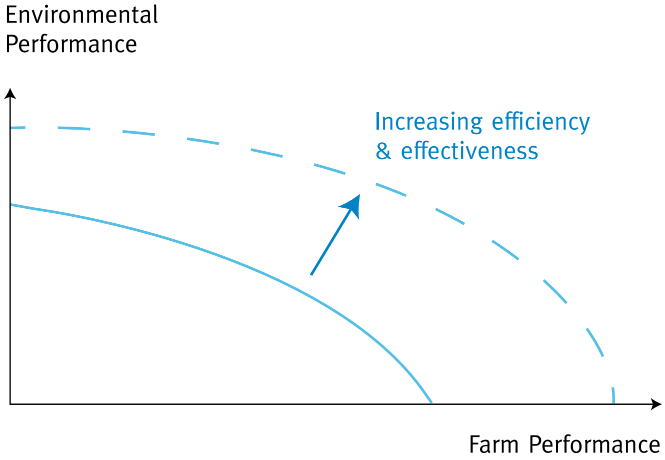


Figure 20: Expanding the efficient frontier
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COORDINATING DECISIONS

To explore how decisions can be better coordinated among multiple stakeholders and across spatial scales and timeframes, the Markets research uses a decision framework, shown in Figure 21. The structure of the decision framework serves to integrate the research agenda across the FRM project, as depicted in the boxes to the right-hand side of Figure 21 on the question of a whole system approach to doing more with less water.

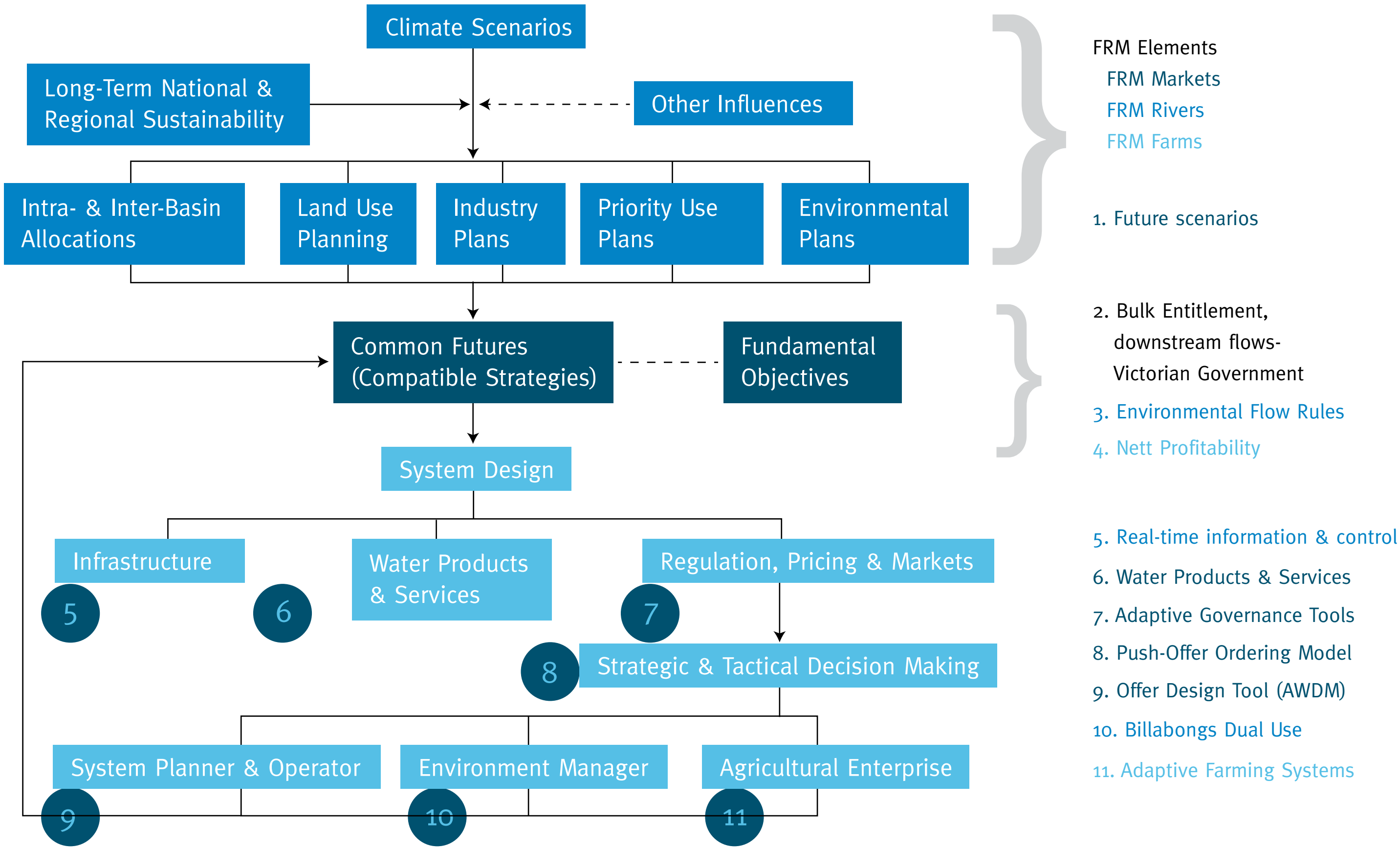

Figure 21: Decision Framework
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The decision framework depicts the five major elements of the Markets research. These are described below.

1. Future scenarios

Scenario planning techniques were used to generate three plausible futures; these test the strategic flexibility and resilience of alternative system designs. Future scenarios developed for use in the FRM project are:

- Geared for Export: A high agricultural value scenario
- Balanced Portfolio: Favouring downstream uses in dry sequences and making opportunistic use of water for production the rest of the time
- Vibrant Lifestyle: A high environmental value scenario accepting lower productivity from agriculture.

2. Water products and services

Water products and services describe both the water commodity (volume, quality) and the services that attach to it; for example, reliability, lead-time and price. Working from the analogy of airline seats, where seat availability and price depends on the time and day of travel and the services, such as meals and baggage allowance that are provided, water products and services are new targets of decision that promote cooperation between the supplier, environmental manager and agricultural producer. An example of a water product and service is 'supply to window', where the user can choose the size of window for water delivery, providing flexibility for the supplier to co-schedule deliveries and environmental requirements.

3. Push-offer water ordering model

The key advantage to water products and services lies in their flexibility. By continually adjusting – time period by time period – the quantity of each water product and service that is available, the supplier can communicate system restrictions and opportunities to users, and encourage their cooperation. However, the current approach to water ordering does not allow for this degree of flexibility. Termed the 'pull-order' system by the Markets research, water deliveries are driven by the decision of the user to order supplies.

This research proposes an innovative 'push-offer' model for water ordering, driven by the supplier's assessment of system condition, restrictions and the supplier's knowledge of user behaviour. All of these driving considerations for the supplier can be dynamic, leading to a degree of responsiveness on the part of the supplier that in turn generates information to encourage adaptation on the part of the user. The push-offer water ordering approach is a complete reversal of the water ordering cycle that greatly increases the number of decision points in the water management system.

The innovations in water products and services and the push-offer water ordering model enable integration across the decision framework depicted in Figure 21 and hence an adaptive water management regime.

4. Offer design tool

To design the offer of water products and services, demands new modelling capabilities. The Markets research has developed the adaptive water decision model as an 'offer design' tool as well as a tool for estimating the efficient frontier for alternative system designs. Using an optimisation approach the model enables mapping of the efficient frontier for the objectives and system component capabilities developed by the Farms and Rivers research (see blue and green coloured FRM elements in Figure 21), and under the settings implied by the future scenarios. Results of the modelling are outlined in the section 'Expanding the efficient frontier'.

5. Adaptive governance tools

Governance is essential to a stable society – one where rights, responsibilities and expectations can be debated, established and maintained. The mechanisms of governance protect the interests of individuals, groups and the broader public interest (e.g. environmental protection, regional lifestyles and diversity of economic opportunities) through a variety of tools, institutions and processes. The decision framework in Figure 21 must be supported by complementary and coherent governance tools. Drawing on the concept of property in land, and comparing it to water to identify the unresolved challenges, the Markets research specifies the missing governance tools required to support an adaptive regime. Results of this analysis are outlined in the section 'Enabling an adaptive water management regime'.

EXPANDING THE EFFICIENT FRONTIER

The adaptive water decision model has been developed by the Markets research to explore the value creating potential of the system design alternatives identified across the FRM project. The Broken River catchment in northern Victoria was used to validate the model and estimate whole system performance potential for a range of system designs. The model establishes the maximum performance achievable across the frontier between agriculture and environment.

Five alternative system designs are plotted on each of the climate scenarios. All the example system designs utilise the benefits of flexible farming systems addressed by the Farms research, for example, various combinations of permanent pasture, annual pasture and annual cropping for dairy production, varied according to water availability. The system designs presented are:

1. **No coordination:** The current 'pull-order' water ordering regime.
2. **Coordination period 2 days:** The 'push-offer' water ordering regime; using the tools of adaptive water management to promote cooperation among agricultural producers, environmental managers and the water supplier. The coordination period is the period above the minimum delivery time available for user and supplier to cooperate and adjust to each others' needs.
3. **Coordination with dual use billabongs:** 2 day coordination period with additional flexibility to use environmental water provided to billabongs as a secondary supply.
4. **Coordination plus water on-demand:** 2 day coordination period with minimum delivery time shortened by interim storage and real-time control.
5. **Coordination plus alternative supplies:** 2 day coordination period with additional flexibility to use privately held alternative supplies, e.g. bores and dams.

The results of the modelling are shown in Figure 22 using the historical data for climate and water availability and then using data adjusted to reflect the 2030 dry climate change scenario (Chiew et al., 2008). The results presented here reflect the 'Geared for Export' future scenario, where the value of agricultural production in the Broken River catchment is similar to that of catchments located downstream. Agriculture production is deemed high in importance compared to environmental performance in this scenario.

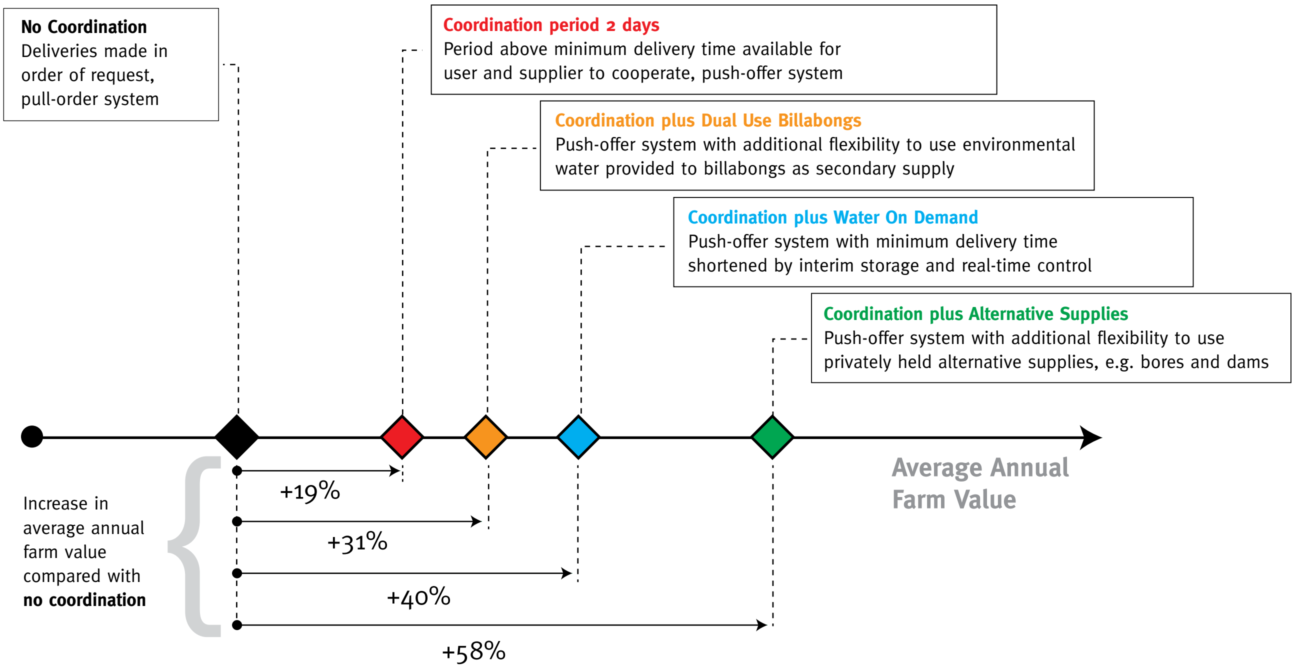
The modelling results demonstrate the performance dividend that can be achieved through the adaptive water management regime proposed by the Markets research. Facilitation of cooperative decisions about water management provides multiple stakeholders with a neutral venue to make their own choices, guided by information that is unique to them and often privately held, and deploying the flexibility available now or in the future through innovation.

Initial model runs demonstrated that, even with no coordination, the flexible farming systems create performance gains of between 35% and 40%; a finding that is supported by evidence of agricultural production values and how they were maintained during the recent extended drought. However, without coordination these performance gains from flexible farming systems vary over a substantial range. Cooperation allows the performance gains from flexibility to be stabilised at the high end of this range.

Using flexible farmer as a comparison (Figure 22), cooperation yields an average performance dividend of up to 19% under the historical climate, and 28% under climate change. Cooperation releases the full potential of innovations such as dual use of billabongs, water on-demand and scheduled use of alternative sources of supply. Deployed under the 'no coordination' regime, these innovations cannot generate significant performance gains. However, when deployed together with the cooperative regime proposed by the Markets research, they yield an average performance dividend of up to 58% under the historical climate, and 72% under climate change.

The results presented here are for comparison purposes only, they are not predictions; rather they provide proof of concept that the adaptive water management regime proposed by the Markets research creates opportunities for a major performance dividend in terms of agricultural value. The research has also identified that more flexible and managerially-relevant expressions of environmental requirements are needed in order to develop similar performance dividends in terms of ecological outcomes.

Historical Climate



Climate Change

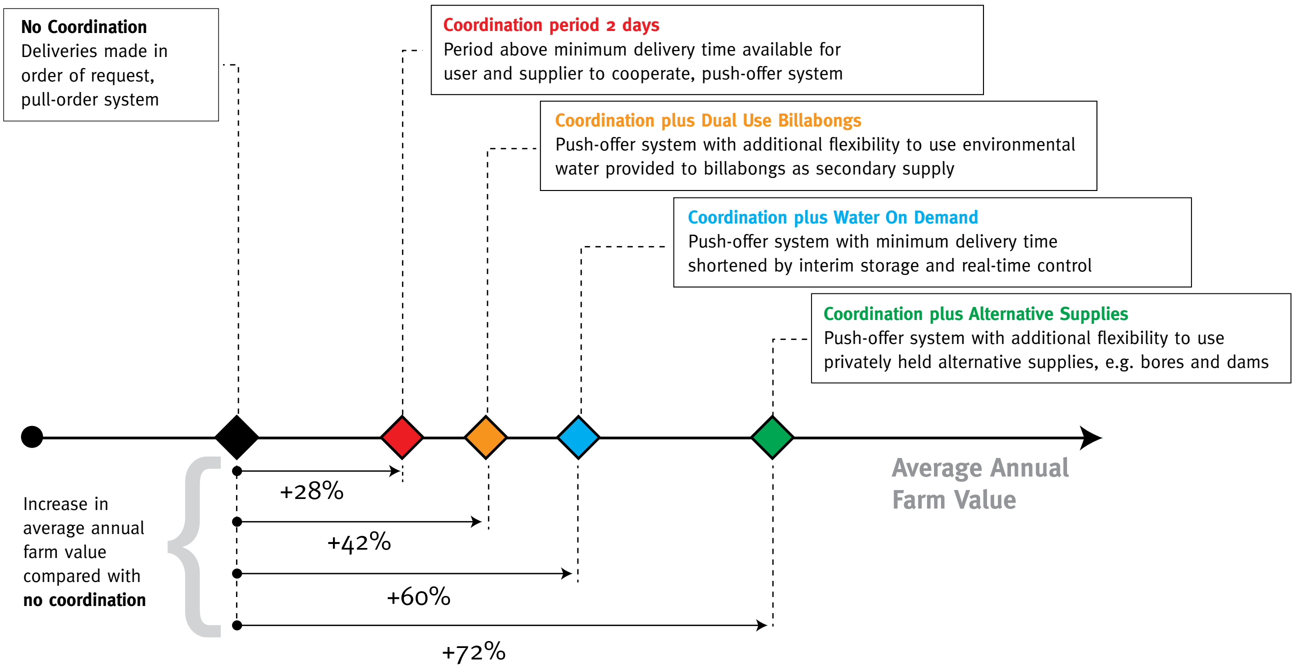


Figure 22: The impact of an adaptive water management regime on average annual farm value, using the Broken River catchment as an example

ENABLING AN ADAPTIVE WATER MANAGEMENT REGIME

The unbundling of water from land introduced by the National Water Initiative has encouraged agricultural water use to favour higher value production. However, current water management arrangements rely on historical arrangements designed when water was allocated not traded, and on a property concept adapted from existing related property concepts in land and shares and applied in circumstances of overallocation and overuse (Australian Government National Water Commission, 2011).

An adaptive water management regime both demands and supports new water governance tools. These must be tested by principles of good governance appropriate for water management. Water management requires skill sets and tools to meet the exigencies of droughts and floods and general inconstancy, as well as the expected contests created by allocation methods. Therefore these tools can only be designed if the issues in water management are precisely identified.

The need for additional tools is already acknowledged, but their specific design is proving difficult, illustrated by the programs to establish national water registers and water accounting systems. For a truly adaptive system, tool design is even more challenging.

Drawing on a rigorous comparison of property regimes in land and in water, the Markets research has identified governance tools, some of them missing or incomplete within the current water administration system. These are described briefly below.

- **Operations models** that can ground truth water facts, add reliability to estimates, provide continuous reconciliation of accounts, and distinguish between trends and variability. The key governance principle for the operations model is to align decision making opportunities as closely as possible to the person or organisation affected (the principle of subsidiarity).
- **Information systems** that generate widely understood information and enhance participation.
- **Flexible water tenures** that deliver robust entitlements, identify service components, expose restrictions on further trading and delivery, and enhance trading.
- Fit for purpose **water plans** that interact with policy alternatives, accommodate variation in settings, and enhance opportunities for stakeholder engagement.
- **Differentiated water products and services** that respond to uncertainties of supply and maximise whole of system value.
- **Trade regulation** that exposes the implications of any trade for whole of system performance.
- **Service delivery systems** that maximise whole of system value, including service disclosure statements.
- **Audits and assurances** that align operations to performance indicators and reportable outcomes.
- **Risk management and assignment** that account for errors in initial estimates, and eventually reduce risk of operations.

The Markets research demonstrates that a renewed strategic focus on operations, supported by innovations in water products and services, water ordering and a strengthened supplier role in coordination, will generate a substantial performance dividend by enabling more responsive and cooperative decisions by all parties. The resulting adaptive water management regime can be used to add vitality and resilience to the property concepts in water introduced by previous reforms for the purpose of trading.

Enhanced participation in decision-making will help achieve the objective of the National Water Initiative of a broader and deeper market. New commodities will enable more responsive and cooperative decisions by all parties: a water market with improved governance and capacity to innovate.

Output: Demonstration that a renewed strategic focus on operations, supported by innovations in water products and services, water ordering and a strengthened supplier role in coordination will generate a substantial performance dividend by enabling more responsive and cooperative decisions by all parties.

Balancing the water needs of farms and rivers

BACKGROUND

Agriculture and the environment are important users of water in Murray-Darling Basin rivers and elsewhere. These two uses interact in complex ways, sometimes synergistically, more often not. Both are viewed as valid and important water uses by the community. In managing water for these two purposes, the first order question is typically how much should be allocated to each. However, there are also important issues that go beyond volumes of water consumed, such as the seasonality of flow and some incompatibility in the timing of demands. Balancing these two sectors is an extremely challenging problem, which is demonstrated through recent debates about the Water Act 2007 and the draft Murray-Darling Basin Plan.

FRM tackled this challenge by developing detailed representations of ecological and farm economic responses for a generic catchment to analyse alternative water sharing arrangements. The resulting framework allows examination of the trade-offs between environmental and agricultural responses to different water shares within a catchment.

APPROACH

To explore the farm and ecological responses to different sharing of water between these two sectors we have used a modelling approach. The modelling is based on a generic catchment that has been selected to allow us to explore a wide range of sharing options unrestricted by existing infrastructure. It is broadly representative of the southern Murray-Darling Basin and the range of diversions from different systems. The generic catchment consists of a storage, an irrigation area and some tributary inflows between the storage and the irrigation area (Figure 23). This represents a somewhat lumped and simplified version of the typical situation in most of the major river valleys in the southern Murray-Darling Basin. It allowed us to examine the extremes of hydrological and ecological changes by examining flows upstream and downstream of the irrigation area.

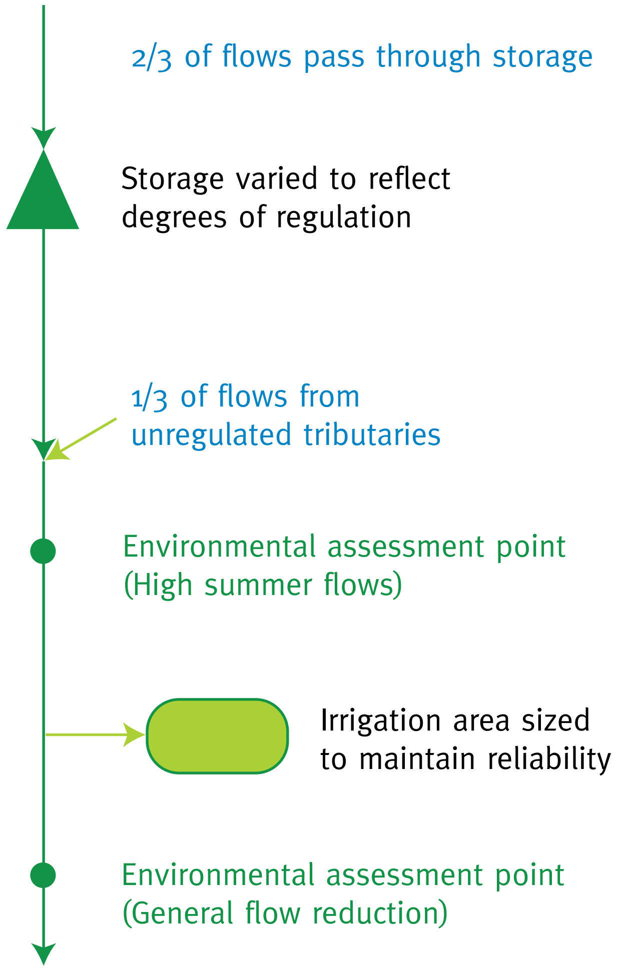


Figure 23: The generic catchment

Water use in the southern Murray-Darling Basin varies widely across the regions considered from some 5% in the Ovens to around 50% in the Goulburn-Broken and Murrumbidgee. We examined five scenarios with storage sizes varying across this range:

- Scenario 1 is reasonably close to the Goulburn River
- Scenario 2 is similar to the Campaspe region
- Scenario 3 is similar to the Lachlan (although there would be differences in natural seasonality)
- Scenario 4 is reasonably similar to the Broken River
- Scenario 5 is unregulated.

Two climate scenarios were examined: the historic climate; and the 2030 dry climate as used in the Murray-Darling Basin Sustainable Yields study. For the climate change scenarios we examined both maintaining the historic irrigated area, and an adaptation that involved reducing irrigated area to maintain historic supply reliability.

The modelling framework consists of five main components:

- A resource assessment of the supply
- An estimation of agricultural and environmental water demand
- An allocation model to distribute water to different demand centres
- Farm economic analysis
- Demographic (population viability) modelling for ecological assessment.

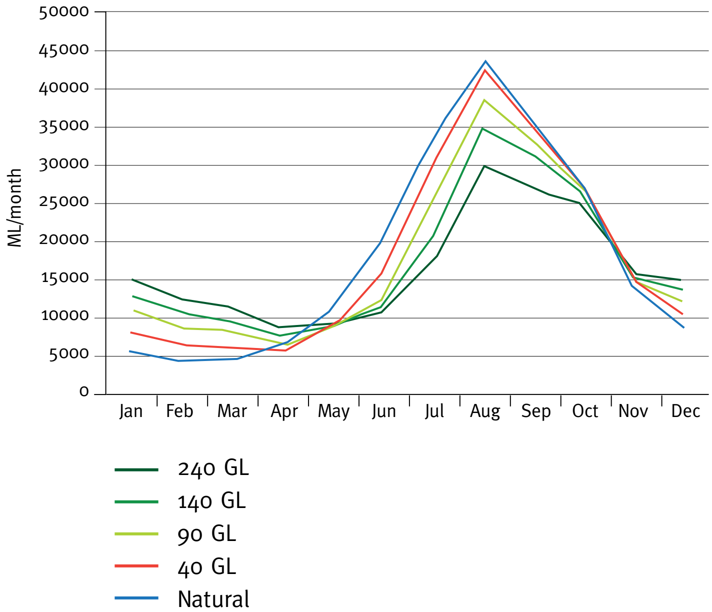
Catchment runoff was modelled with the Australian Water Balance Model, agricultural demands were modelled based on the FRM farm economic optimisation models, environmental demands were based on a series of flow rules developed in a consistent manner to the Victorian FLOWS methodology and an allocation model combined these to predict daily flows in the stream for 104 years.

The economic outcomes were then evaluated using the farm economic models and the ecological outcomes were evaluated with population viability models for four different fish guilds. Fish guilds are groups of fish with similar lifecycles and habitat requirements. Both the economic and ecological models represent significant advances on current practice.

RESULTS AND DISCUSSION

Hydrologic changes

The impacts of flow regulation on the river's flow regime were analysed by changing the storage capacity and irrigation areas as described in the scenario section. The reliability of irrigation supply has been kept constant at 95%. The percentage of natural end-of-valley flow diverted for irrigation varied from 16.4% to 45.2% in the regulated cases. The increase in river regulation results in marked changes in the hydrograph both upstream and downstream of the irrigation area. Since the peak irrigation demands were mainly concentrated in the dry period (November to March), the river flows upstream of the irrigation area during these months were high compared to the natural flows (Figure 24). This is mainly because of the releases from reservoir to meet the downstream irrigation demands. The flows during the winter months were low in the regulated conditions compared to the natural flows. This is because the catchment yield during the wet periods was stored in the reservoir to meet the summer demands. Downstream of the irrigation area flows are generally reduced, with the largest impact occurring in winter as the reservoir fills.



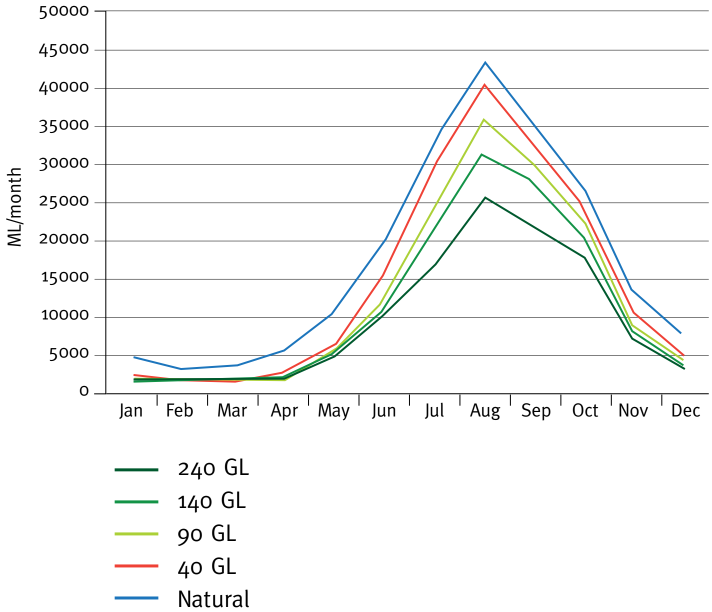


Figure 24: Mean monthly flows upstream (top) and downstream (base) of the irrigation area. Scenarios are identified by storage volume

An analysis was also undertaken of the impact of regulation and climate change on relatively frequent flood events. Figure 25 shows the ratio of the number of events exceeding a certain threshold flow normalised by the number of events under unregulated historic conditions. The flow thresholds chosen were the 50th, 20th and 10th exceedance percentile maximum annual daily flows. The results show that heavy regulation approximately halves the frequency of the typical natural annual flood and reduces the frequency of 10-year recurrence interval flows by around 30%. For climate change there is a dramatic decrease in flood frequency of over 80%. Climate change results were validated against historic records for the Murray River at Tocumwal and the Ovens River at Wangaratta, using the recent drought as a climate change analogue.

The results demonstrate the hydrologic sensitivity of flood plains to both regulation and climate change. There is strong evidence that this hydrologic sensitivity transfers into significant ecological sensitivity for species such as red gums.

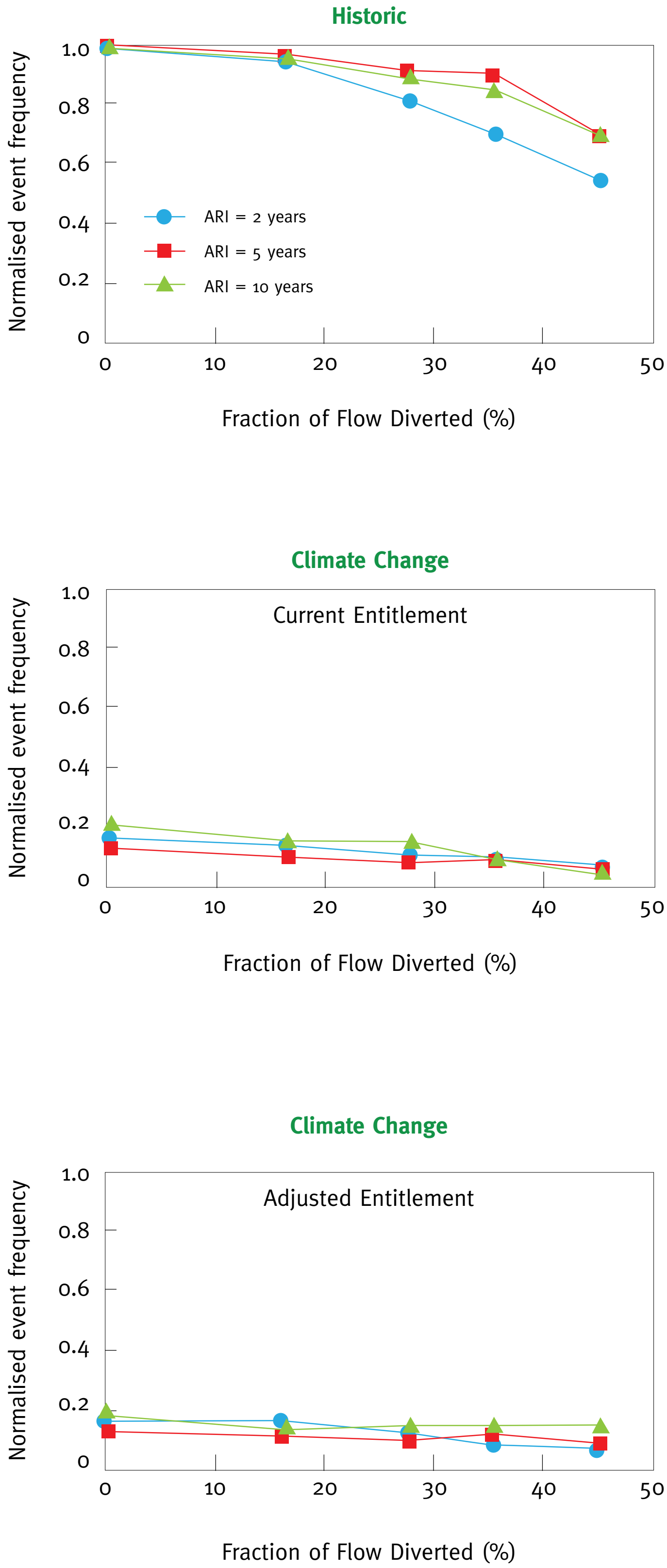


Figure 25: The impact of regulation and climate change on small floods. It should be noted that there is large uncertainty in changes in high rainfall events under climate change and thus large uncertainty in catchment responses.

ARI = Average Return Interval

Impact of climate change on system security

The impact of climate change has been analysed in two ways. When the historic irrigation area is maintained, the system reliability drops to 52% from 95% for 240 GL storage scenario. The environmental reliability has dropped to 46.2% for the same scenario. If the irrigation demand is scaled back in adaptation to climate change, the system reliability can be restored. Figure 26 shows the variation in volume supplied for the different irrigation demand and climate scenarios.

This provides some insight into the implications of managing entitlements under climate change adaptation. If historic entitlement volumes are maintained, there is a decline in system reliability for consumptive use. In addition the variation in annual volumes supplied is magnified for the larger multiyear storages. This implies increased volatility in the volume of supply farmers can expect. If entitlements are adjusted down to regain system reliability, the inter-annual volatility of supply is significantly reduced and volumes supplied in the 15-25% of years with least supply. The results also demonstrate, perhaps counter-intuitively, that large dams have less value if climate change reduces flows.

Ecological responses

The population viability models developed for a variety of species guilds enable the general response to regulation, climate variability and climate change of fish to be estimated. As an illustration, the meta-species model for the iconic Murray cod (Machullochella peelii Mitchell) was used to examine the response to regulation and drought.

The life stage-based population viability model was run on an annual time step and represents pre-breeding season populations. The simulation results for Murray cod under these scenarios can be seen in Figure 27. While these results are limited by the relatively small ecological databases on vital rates, they suggest that Murray cod abundance over time tends to decrease most under natural flows with long periods of drought. By contrast, species abundance persists under regulated scenarios that incorporate both types of short and long drought periods. The results also illustrate an important aspect of the approach relevant to environmental flow models, which is the ability to incorporate temporal sequences of drought and variability. This can be used to support scenario-based decision-making regarding temporal sequences of floods and drought and their effects on population persistence. Such modelling is currently rarely incorporated in contemporary environmental flow models.

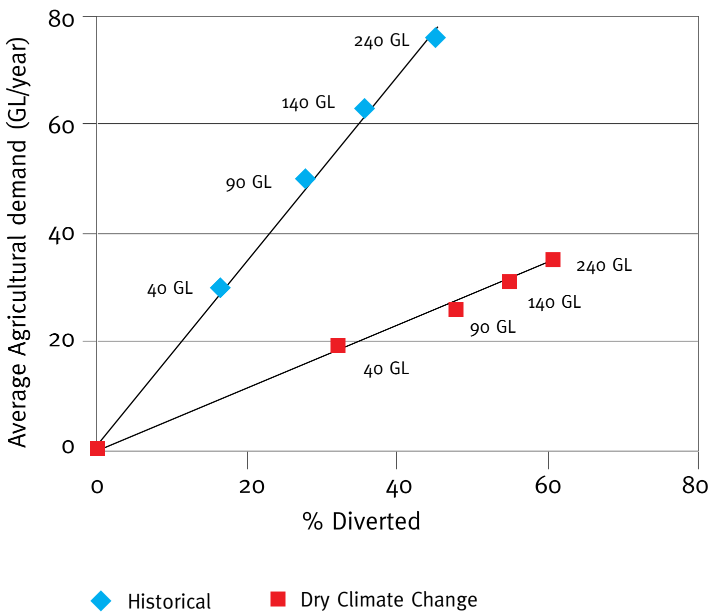


Figure 26: Change in agriculture entitlements under 95% supply reliability

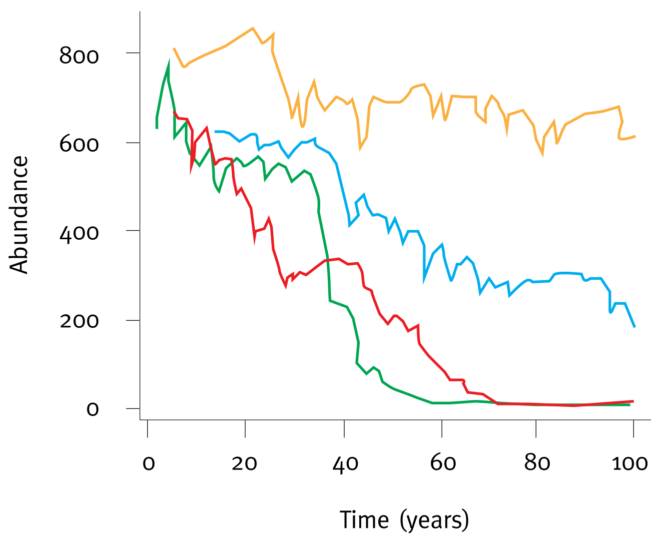


Figure 27: Simulation results for Murray cod for four different scenarios. Yellow and blue lines represent regulated flows, and red and green lines represent natural flows. Red and blue lines are long droughts; green and yellow lines are short droughts and high variability in drought/flood years. The lines are median population size.

The framework of population viability models developed here for fish can be extended to include other stream biota, such as vegetation and macroinvertebrates. Model outputs can be presented in a number of different ways demonstrating alternative representations of ecological outcomes. Multiple scenarios can be compared to identify general trends or can be used to select the best option from a set of scenarios. Similarly, general trends can be used to identify robust environmental flow rules. The ability to focus directly on ecological outcomes, and the ability to validate these outcomes, will make environmental water allocations more reliable. Central to the utility of this framework is the embedding of population viability models within an adaptive management cycle.

An evaluation of the joint ecological and agricultural outcomes of varying water shares

Figure 26 shows results that examine the variation in agricultural and ecological outcomes as the water share between these sectors varies. Each graph shows the percentage of end-of-valley flow corresponding to the climate scenario diverted to agriculture on the x-axis and a measure of outcome on the y-axis.

The top three rows correspond to different climate and irrigation demand combinations. From top to bottom they are:

- Historic climate with 95% reliability for irrigation
- Climate change with historic irrigation demand
- Climate change with irrigation demand reduced to achieve 95% reliability.

The two columns correspond to:

- Ecological outcomes upstream of the irrigation and downstream of the irrigation.

The bottom row corresponds to agricultural outcomes for dairy and horticulture respectively.

Upstream of the irrigation area there is seasonal flow reversal but little change in overall flow while downstream of the irrigation area, the seasonal pattern is maintained but there is an overall reduction in flow. A fixed proportion of land use allocated to each of dairy and horticulture is assumed here and all farms are assumed to be optimally managed.

The ecological outcomes are shown as the probability of persistence locally over a 104-year sequence. They vary in response to geographic location, degree of regulation, climate/entitlement and fish guild. This can be explained by differences in life cycle requirements.

For example, for main channel specialists (Murray cod), reductions in overall flow downstream of the irrigation area lead to ecological declines (lowered probability of persistence). Murray cod are more susceptible to regulation than climate change under the operating rules used here. At the same time species that require slack water habitat for recruitment (Carp gudgeon) are favoured due to the reduced flow. Carp gudgeon decline upstream of the irrigation area due to reduced slack water habitat caused by regulated irrigation delivery flows. Carp gudgeon are favoured by climate change also because of reduced flows.

Two general points can be made. First, where species are sensitive to hydrologic regimes, increased levels of regulation lead to greater changes, but these can be in opposite directions in different parts of the system. Second, if entitlements are not adjusted as we adapt to climate change, the ecological responses can be expected to be larger. This is because more water is extracted from the system and irrigation flows are higher where historic entitlements are maintained. This suggests that mechanisms to adapt sharing of water as climate change develops will be important. Undertaking the changes should occur in an adaptive management framework due to uncertainties in the predictions of both agricultural and ecological responses.

As expected, the levels of catchment agricultural income increase as more water is diverted under a historical climate sequence. Water diversions under climate change are predicted to be lower and so industry income is expected to be lower, even if reliability is maintained. The comparison of income responses between industries is influenced by the degree of management flexibility or adjustment options available. In dairy, purchased feeds are substitutes for feed grown with irrigation water. In horticulture, the industry is already relatively efficient and there are fewer options to manage a reduced water supply under climate change.

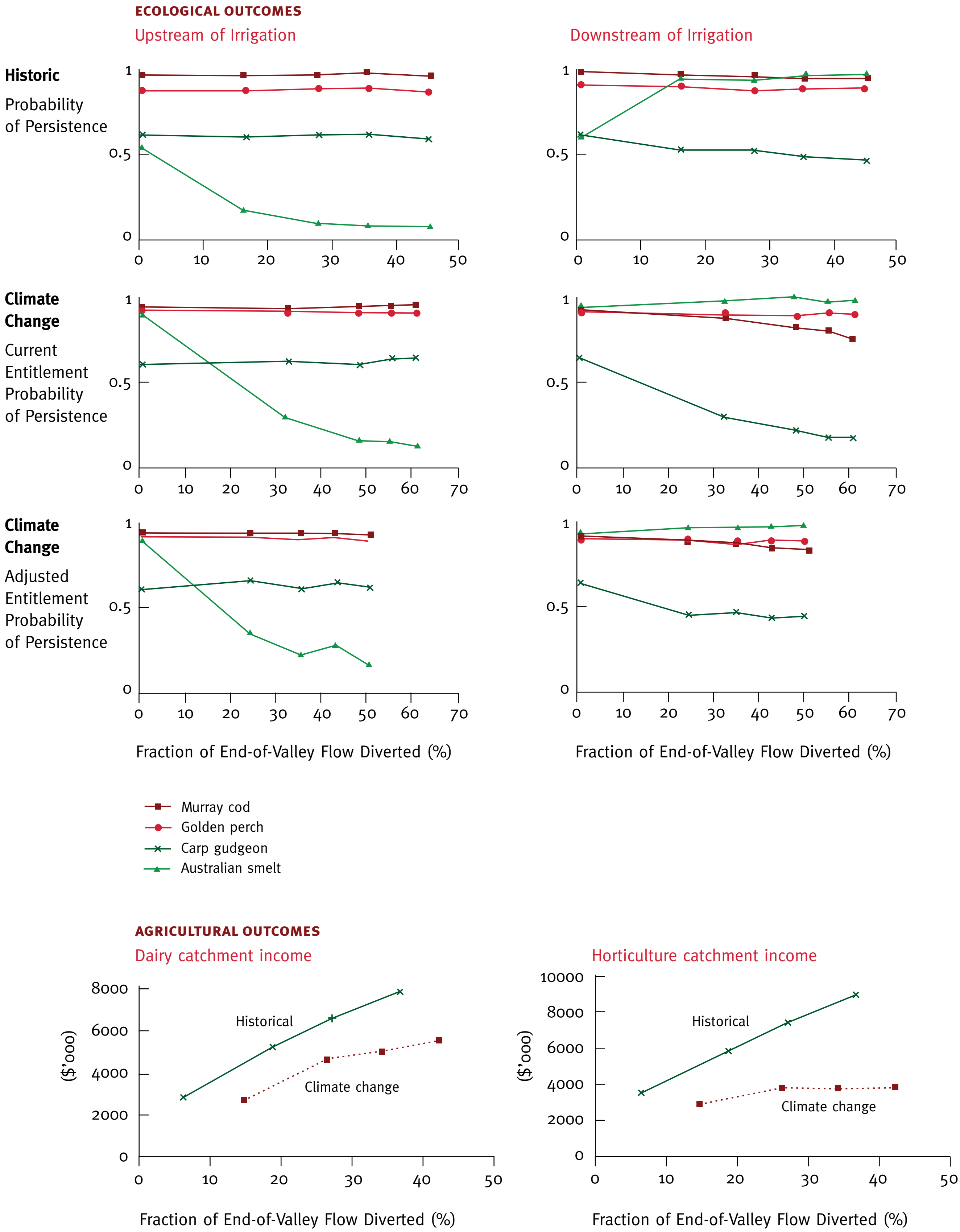


Figure 28: Predicted variations in ecological and agricultural outcomes for natural climate and climate change scenarios.

KEY OUTCOMES AND RECOMMENDATIONS

We have developed a framework that enables an analysis of the variation in benefits to both agriculture and the environment resulting from different levels of water sharing. The analysis is built on a combination of hydrological, agricultural economic and ecological demographic modelling. A significant advance is the incorporation of detailed response models in each of the relevant areas. The following summarises the outcomes and recommendations of this work.

- Joint benefits need to be characterised to make proper water sharing decisions. The framework presented here does this.
- Population viability, or more generally, demographic modelling, could become a useful tool to inform environmental water planning and operation. Investment in ecological data collection is critical to improving environmental water management. Notably we have not considered dispersal and spatial aspects of population demography in the present models. Nonetheless, a demographic modelling framework offers substantial benefits to habitat suitability models currently employed in most management applications.
- Different fish species respond differently to changes in flow and hence flows that favour one guild may disadvantage another. This is because of differences in life history and links between hydrology and the reproduction and survival of different life-history guilds. It is important to be clear on how different taxa will respond regarding prioritisation of ecological objectives in regulated systems.
- If inflows reduce as expected under climate change, most reservoirs will operate with significantly lower storage levels than previously (in other words they could be considered to be overdesigned) and if operations are not adjusted through changed entitlements/allocation rules, the proportion of water harvested will increase. Hence there is no or little scope for increased harvesting of water through new storages on developed systems.
- Regulation has a substantial impact on floods in the 1 to 10 year average recurrence interval range, reducing them by up to half. These floods are critical to floodplain and wetland health. Climate change will further reduce the frequency of flooding. This demonstrates the hydrologic sensitivity of flood plains to both regulation and climate change. There is evidence that there is also significant ecological sensitivity to flood occurrence for species such as red gums.
- Thus, it is important that mechanisms to efficiently adjust entitlements in adaptation to climate change be found so that appropriate shares are maintained.

A framework that enables a more comprehensive analysis of the changes and trade-offs in economic benefit to farmers, and the environmental outcomes resulting from different levels of water sharing.

The value of integrated research

Central to FRM was integration of the project's research efforts to identify innovative water management options for the Goulburn-Broken and other catchments in Australia. FRM research integration had the dual role of supporting the processes of integration and community engagement, and conducting research into the social dimensions of catchment management research using FRM as a case study.

The results of this research describe the challenges, benefits (value) and lessons that emerged from undertaking FRM as an integrated research project involving researchers working together across disciplinary boundaries and with practitioners and experts in the Goulburn-Broken and other catchments. The research identifies critical processes in doing integrated research and provides examples of integration and co-development that emerged from each FRM priority research area. It also evaluates FRM's community engagement design to provide recommendations for future interdisciplinary catchment management research.

BACKGROUND

Community engagement is central to better catchment management, and in particular, for the development of catchment management options and practices that account for multiple functions of water within the catchment landscape. FRM needed to engage with multiple communities and manage different types of participation in the Project. Three types of communities were considered essential in FRM's community engagement framework (see Figure 29 on the following page) (Harrington et al., 2008):

- **Research disciplines:** The FRM team includes researchers from a range of disciplines (e.g. farm systems modelling, freshwater ecology, engineering). Core to the Project is development of water management options that address the needs of farming and environmental water uses. Developing these options requires communication between disciplines and engagement of each research community with other research communities.
- **Communities of practice (Wenger, 1998):** Water management options will enter the catchment through the practices of farmers, water managers and policy makers. Engaging with these communities of practice and understanding the implications of proposed water management options for their practices is central to achieving changes in catchment management. Each FRM module addresses a particular practice group, and developing the linkages between researchers and practitioners is critical to reducing the errors associated with translating research into practice.
- **Communities of interest:** The communities of interest in FRM are those people and institutions who have a stake in project outcomes. For example, rural industry groups, catchment residents, recreational users of water, and government water policy makers.

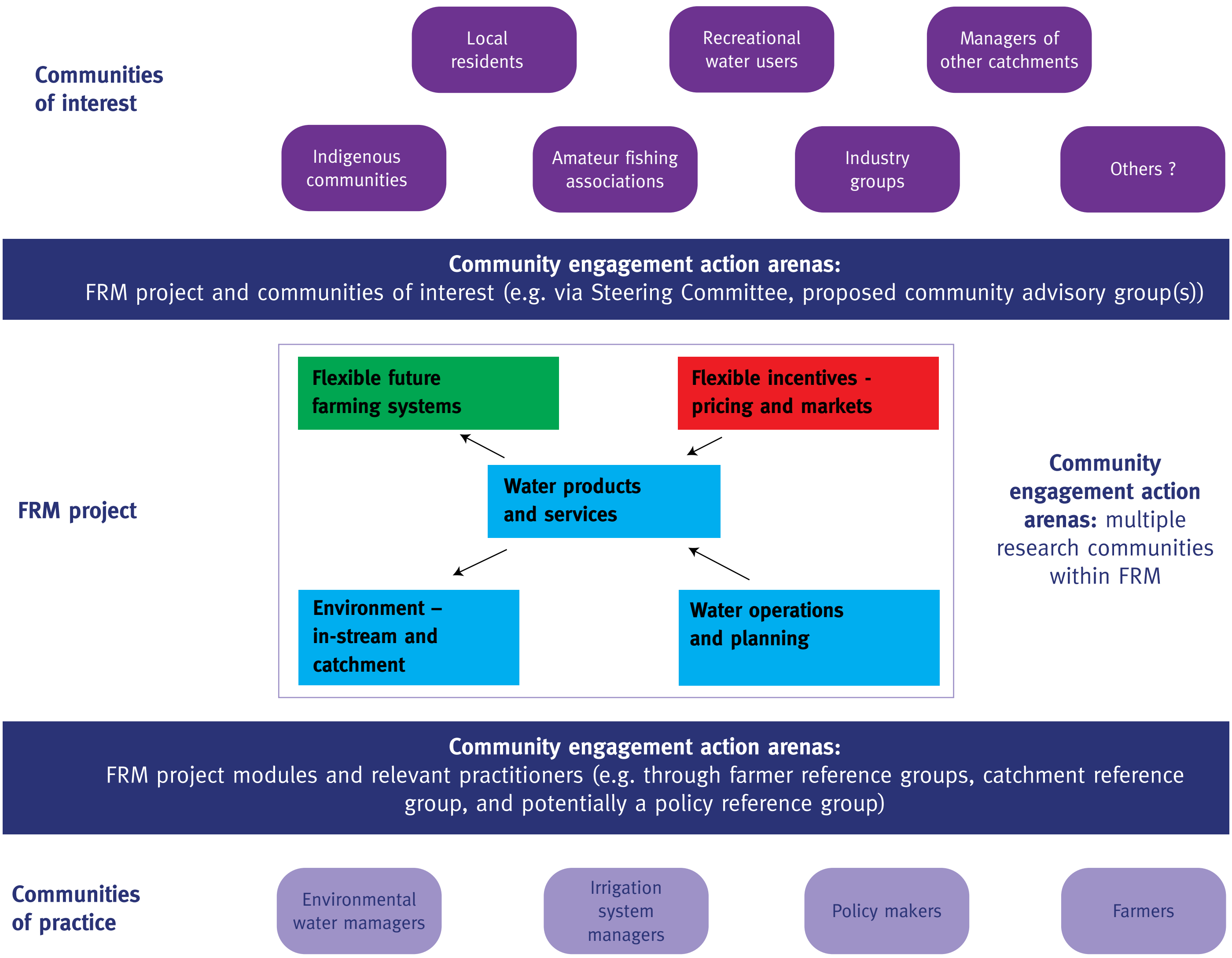


Figure 29: FRM community engagement research and practice framework

Delivery of the community engagement process designed around FRM knowledge communities involved supporting and facilitating research and practice activities within each of these knowledge community types. This included design, facilitation and observation of:

- Activities linking FRM modules with relevant communities of practice
- Activities with the FRM project team designed to encourage engagement between research disciplines
- Activities linking the FRM project team to local and national communities of interest.

KEY FINDINGS

Key findings of this research related to doing integrated research are:

- Integration proceeds in phases that reflect a joint inquiry and action (or learning) process defined by different integration 'needs'.
- Successfully managing transitions and progress in integration phases requires careful planning (as integral to project design) as well as the iterative design of processes to support integration.
- Knowledge partnerships between integrated research projects and diverse communities of catchment management practitioners and interest groups enable opportunities for social learning and practice change.
- Knowledge partnerships must be carefully planned and iteratively designed with communities of practice and communities of interest.
- Specialist skills in knowledge brokering and a role in facilitating joint inquiry and social learning are important in integrated research project design.
- Processes that support integration are characterised by: people-place connections; flexibility to emerge through 'intuition' and/or initiatives of researchers and collaborators; having time to mature; emergence through reflexive practice that enables learning and shared ownership; and a mutual commitment to integration.
- Processes that support co-development are characterised by: some level of shared power to make decisions; a mutual commitment to co-development; shared resource investment; and incentives for participation including processes to recognise and promote the value of diverse practices and knowledge/s.
- By actively problematising and facilitating the processes of integrated research, learning opportunities were enhanced and new possibilities for working together to change catchment management emerged.

Key findings about the value of integrated research are:

- The value of integrated research lies in the production of new research knowledge for changing catchment management as well as enhanced links to catchment communities and other stakeholders for implementing change.
- The value of integration is evident in the FRM project where this process has lead to new research questions and joint research outputs.
- The value of integrating the FRM disciplines in catchment management research was recognised by participants in the project as: the ability to address multi-scalar challenges (of research and management) and deal with complexity; the capacity to generate, re-combine and augment data from diverse sources (to produce new joint insights and research outputs); increased creativity in research; and an increased capacity of individuals and research teams and institutions to do integrated research in the future.
- An innovative FRM community engagement framework was developed. This framework was validated by the reflections and collective experiences of the three knowledge communities it defines and through research in FRM.
- Members of FRM communities of practice and communities of interest recognised the value of co-development as opportunities for: community engagement at appropriate times/places; identifying practice and policy challenges of research to inform adoption strategies; building social networks for catchment management; managing risk for research projects; exposing communities to new research ideas; and gaining equity outcomes by including communities in public-good research.
- Members of communities of interest in FRM identified a greater need to engage their members and emphasised the role of local knowledge and early engagement of communities in developing research questions that relate directly to their needs for practice and policy change.

KEY RECOMMENDATIONS FOR FUTURE INTERDISCIPLINARY CATCHMENT MANAGEMENT RESEARCH

For interdisciplinary research teams:

- An imperative or framework for integration is part of the design of integrated research projects.
- Integration needs to be actively managed and supported (resourced and facilitated) to identify and support the changing 'needs' for integration throughout interdisciplinary collaborations.
- Resources, skills and roles to support integration (i.e. social science/innovation research and facilitation expertise) are included in the research project design.
- Roles and responsibilities for motivating and being accountable for integration are collectively agreed at the beginning of research projects.

For research institutions:

- Seek to champion integrated research projects by showcasing research findings (i.e. in symposia and other public events).
- Provide incentives to researchers to do integrated research through faculty-based means of recognition (i.e. awards; interdisciplinary seed funding).
- Recognise social and experiential learning processes in integrated research as the acquisition of new research (including research management) skills to address complex research and development issues such as catchment management.
- Including field (applied) research and the places where catchment communities live and work in the design of integrated research projects is important for strengthening knowledge partnerships and experiential learning to support implementation and adoption.

For working with communities of practice in integrated catchment management:

- Communities of practice are engaged in the conception and planning phases of integrated research projects to identify development 'needs' and align these with research priorities.
- Formal partnerships with communities of practice are a strong basis for co-development and should specify: shared resourcing arrangements; roles and responsibilities of research and farmer partners; intellectual and commercial property issues; and an iterative co-development plan for ongoing research collaboration and representation of research outputs.
- Government, industry and community service providers and extension (change) agents along with leading practitioners are explicitly engaged early as key knowledge or 'innovation brokers' in integrated research projects to help identify co-development 'needs'.
- Devices for co-development that address specific practice-change challenges related to research question (such as the FRM investment cases) are developed to focus interactions with the catchment innovation networks for integrated research projects.

For working with communities of interest in integrated catchment management:

- Communities of interest are engaged in the conception and planning phases of integrated research projects to identify development 'needs' and align these with research priorities.
- Current local and regional initiatives are integrated into research projects to assist in framing co-development 'needs' that are consistent with other community priorities.
- Mutual benefits of co-development are explicitly identified and a process to monitor expectations and progress developed as part of participation/partnership agreements with communities of practice and communities of interest.

Investors in integrated catchment management research:

- Include resources for supporting integration and co-development in integrated research projects with project timeframes no less, and ideally more than, three years.
- Provide the imperative for co-development in integrated research by formalising co-development in project contracts and milestones including: appropriate stakeholder representative and knowledge/practice groups; incentives for stakeholder participation, for example, shared resource investment with collaborators (i.e. commercial farms; water supply companies etc).
- Deliberative forums, such as workshops and interactions in place, are used to support and develop close working relationships between integrated research teams and research investors.

Output: Documented lessons gained from managing complex, integrated catchment management research bringing together a range of disciplines, and co-development of research with communities of practice and interest for maximising opportunities for practice and policy change.

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