

# HYDROLOGY, IRRIGATION DEMAND AND SUPPLY: AN INTEGRATED MODELLING APPROACH USING MATLAB

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## ABSTRACT

The environmental effects and performance of proposed large scale irrigation schemes are traditionally assessed using several different software programs. This method of evaluating the effects of irrigation storage schemes often requires data to be transferred between several software programs which can be time consuming and inefficient. This paper describes the methodology of a model developed in Matlab which integrates hydrology with irrigation demand and supply, and allows the interaction between these different components to occur within the model simulation.

The hypothetical case study presented in this paper describes a project which involves delivering water to the supply area from a run-of-river scheme when water is available in the river, with the shortfall in demand being made up with water from storage. Water can also be released from storage to enhance the environmental condition of the downstream river environment. The availability of water affects the irrigation requirements and this interaction between supply and demand is a significant advantage of having all the scheme processes modelled within a single program. During periods when the river flow exceeds environmental needs of the river and the irrigation requirements, water will be harvested into the storage reservoir to replenish if required.

## KEYWORDS

**Hydrology, Irrigation, Demand and Supply, Matlab**

## 1 INTRODUCTION

Proposals for large scale irrigation schemes have become more widespread throughout New Zealand over the last few years. The traditional way of evaluating the effects of irrigation storage schemes often requires data to be transferred between several software programs which can be time consuming, inefficient and limiting. This paper describes the methodology of a model developed in Matlab which integrates hydrology with irrigation demand and supply, and allows the interaction between these different components to occur within the model simulation avoiding the need for such information transfer. This single program approach also allows the availability of irrigation supply to influence the irrigation demand requirements.

Matlab is an advanced programming and visualization environment used in R&D in many high tech industries. Due to the high level nature of the language and the conventions it adopts, code development is extremely efficient. Coupled with its visualization capabilities it proves to be an extremely effective tool in engineering consultancy.

In this paper we describe a hypothetical case study in which a major tributary of a river is used as a direct source of irrigation supply and to fill a storage reservoir to supply a large scale irrigation scheme thereby modifying the natural flow in the tributary. The natural hydrology of the river is further modified by reservoir releases during the irrigation season. Therefore upstream of the take point(s) of the scheme the river/dam system creates a redistribution of the natural flows in the river. Changes to the natural hydrology may be complex and somewhat

contentious. Irrigated computer modeling of irrigation demand and water supply provides an opportunity to study the

- modified hydrology and relate it to the natural hydrology of the river, and
- measure the effectiveness of the scheme in terms of its ability to maintain productive soil conditions

Water is delivered to the supply area from a run-of-river scheme when water is available in the river, with the shortfall in demand being made up with water from storage. The availability of water will often lead to a combination of run-of-river water and water from storage being delivered to the supply area. Water can also be released from storage to enhance the downstream river environment. During periods when the river flow exceeds environmental needs of the river and the irrigation requirements, water may be harvested into the storage reservoir.

The model developed for this project has several different components. The irrigation component estimates the irrigation demand of the command area based on land use, soil type, type of irrigation (i.e. border dyke, spray irrigation), evapotranspiration and rainfall and the history of irrigation water supplied during the preceding days. The supply component of the model calculates the availability of run-of-river supply and the storage requirements based on measures for irrigation reliability of supply. Using the model it is possible to assess the effects of the proposed scheme in terms of natural and modified river flows, summary statistics, flow duration curves, histograms, reliability of supply and time series of soil moisture levels. It also provides clients with the ability to get an overall impression of different options.

## **2 INTEGRATED VERSUS TRADITIONAL APPROACH**

### **2.1 TRADITIONAL APPROACH**

In assessing the environmental effects and expected performance of proposed large scale irrigation schemes several different components of the scheme need to be analysed. These different components are:

- Irrigation: Estimation of the expected irrigation demand of the command area based on land use, soil type, type of irrigation and climate data.
- Supply: Estimation of the availability of run-of-river supply and the storage requirements based on the allocation regime in the river and measures for irrigation reliability of supply.

In the traditional approach these two components are often modelled separately using different software packages such as Excel or commercial software to simulate supply and demand. Additionally a 'hydrological' data processing software package may be required for pre- and post-processing of the data.

### **2.2 INTEGRATED APPROACH**

The model developed for this case study combines all the different components of a large irrigation scheme into one integrated demand and supply model. The immediate benefit of this integrated approach is that interaction between the hydrological and irrigation components occurs within model simulations avoiding the need for information transfer between different programs, which is both computationally inefficient and limiting. The main advantages of integrating different components into one model are:

- Efficient code
- Flexible post processing
- Ability to exploit linkage between different components of model.
- Once the code is developed for the particular scheme components it is very easy to run and evaluate different options.

Because Matlab is a high level computing language code development is fast compared to a language like C. In addition it can handle large data sets while maintaining fast execution times. Matlab uses vectorisation which means that the need to write loops or use if/then statements is significantly reduced. As a result the code is very compact, easy to de-bug, and encourages good programming practice. Post-processing code is written ground-up meaning that one can display any information of interest in visual format or as summary statistics. Data mining is straightforward which means one can extract any subset of the output. Once the code has been optimized execution time is very quick (5-10 seconds in this case) meaning that multiple simulations can be run quickly to compare the effects of different model assumptions.

### 3 CASE STUDY

#### 3.1 DESCRIPTION OF THE IRRIGATION SCHEME

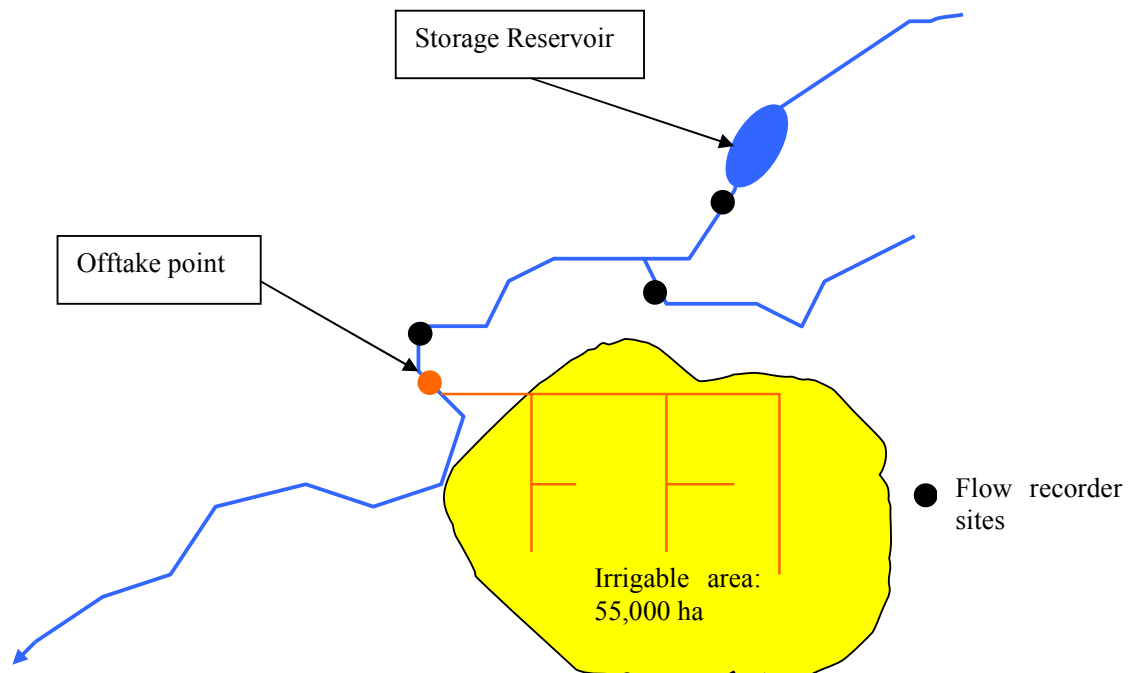
In this case study we assume an irrigable area for the project of 55,000 ha and the irrigation season is taken to be 1 October through 31 May. The project will involve the taking of water from a river and routing through a system of water races to the command area.

The key elements of the project include:

- A dam and consequent reservoir on one of the branches of the river to provide storage for irrigation.
- An off-take on the river approximately 15 kilometres downstream of the storage reservoir.
- A distribution network of water races across the irrigable area providing water to all shareholder properties in the scheme.

A layout of the key elements of the irrigation scheme and existing flow recorder sites is provided in Figure 1.

Figure 1: Layout of Irrigation Scheme



The scheme operates subject to the following rules:

- On days when there is an irrigation demand water is first abstracted from run of river water subject to the minimum flow and allocation conditions of the flow regime.
- When there is a deficit in run of river supply, water is then abstracted from the storage reservoir.
- During periods when the water supply exceeds the demand water will be harvested into the storage reservoir subject to maintaining an environmental outflow of 7 m<sup>3</sup>/s and occasional releases for flushing flows.

### 3.2 MODEL METHODOLOGY

The model integrates hydrological routing and water balance with irrigation demand and is driven by hydrological input data and irrigation demand.

The principal hydrological input data are the inflow into the reservoir, a flow record from one of the tributaries and a flow record just upstream of the offtake point. These (generally short term) flow records, have been extended to obtain a continuous flow record for the modelling period of 36 years using a combination of statistical and hydrological techniques.

To model irrigation demand it was assumed that the scheme area may be divided into 4 soil types with different water holding capacities. Representative evapotranspiration and rainfall data sets have been used to update daily soil moisture content.

All irrigation areas are assumed to be spray irrigated. The following irrigation rule has been assumed for areas which are spray irrigated: a sub-area has an irrigation demand when the soil moisture balance for that area falls below 55% of the PAW (profile available water), and the daily irrigation demand continues until the PAW is reached.

The way the hydrological routing has been coded is as follows: it has been assumed that all inflow into the storage is harvested subject to maintaining an environmental flow condition at the outlet of the reservoir. If the natural flow is less than the environmental flow on that tributary a release is made to meet the environmental flow condition.

If there is an irrigation demand, water is first abstracted from the run of river flow subject to a flow allocation regime. If there is a deficit (i.e. irrigation demand > run of river supply), water is released from storage into the river to allow the irrigation demand to be abstracted.

### 3.3 INPUT DATA

#### Climate data

Monthly summaries of synthetic daily rainfall and Potential Evapotranspiration (PET) data and temperature data within the command area is shown in Table 1

*Table 1: Monthly Rainfall, Evapotranspiration and temperature data for the Command Area.*

<b>Month</b>	<b>Rainfall (mm)</b>	<b>Evapotranspiration (mm)</b>	<b>Temperature (°C)</b>
January	47	133	17.25
February	49	105	16.89
March	58	83	14.66
April	51	48	11.68

May	50	29	8.36
June	57	20	5.75
July	66	20	5.27
August	65	32	6.80
September	57	56	9.32
October	60	88	11.34
November	53	108	13.05
December	55	127	15.86
Total	668	848	11.35

The data indicates that there is a shortage of water, especially in the summer months where PET is significantly higher than rainfall, which indicates the need for irrigation.

### **Soils and PAW**

The soils in the project area have been classed into four different categories based on their estimated PAW for the purpose of modelling irrigation water demand, namely 60, 90, 120 and 150 mm

### **Hydrological Inputs**

The hydrological inputs consist of historical data and synthetic data for three sites on the River as shown in Figure 1. To construct the synthesized hydrographs regression techniques have been used to obtain a continuous record for the 36 year modelling period.

## **3.4 FLOW REGIME AND MINIMUM FLOW CONDITIONS**

The minimum flow site located just upstream of the offtake point determines the amount of run-of river flow that can be taken from the river. In this case study it is assumed that the minimum flow year round will be 20 m<sup>3</sup>/s, so that water cannot be abstracted for irrigation when the flow is below this value. In addition to the minimum flows it has been assumed that the flow regime has a 1:1 flow sharing provision which limits the proportion of the available flow that can be abstracted for irrigation at flows above the minimum flow of 20 m<sup>3</sup>/s. This minimum flow is based on the 7 day Mean Annual Low Flow (MALF) at the recorder site.

In order to maintain minimum environmental flow conditions on the tributary of the river where the Dam will be located a minimum flow release has been set at the outlet of the storage site. This minimum environmental flow would normally be based on recommendations of ecologists taking into account instream values of the River. For the purpose of this paper the minimum environmental flow release at the proposed dam site was set at 7 m<sup>3</sup>/s.

## **3.5 RESULTS**

Matlab has strong post-processing and visualization capabilities. The results described in this section present the type of information that is normally required to assess the impact on the river and the reliability of the various irrigation scheme options.

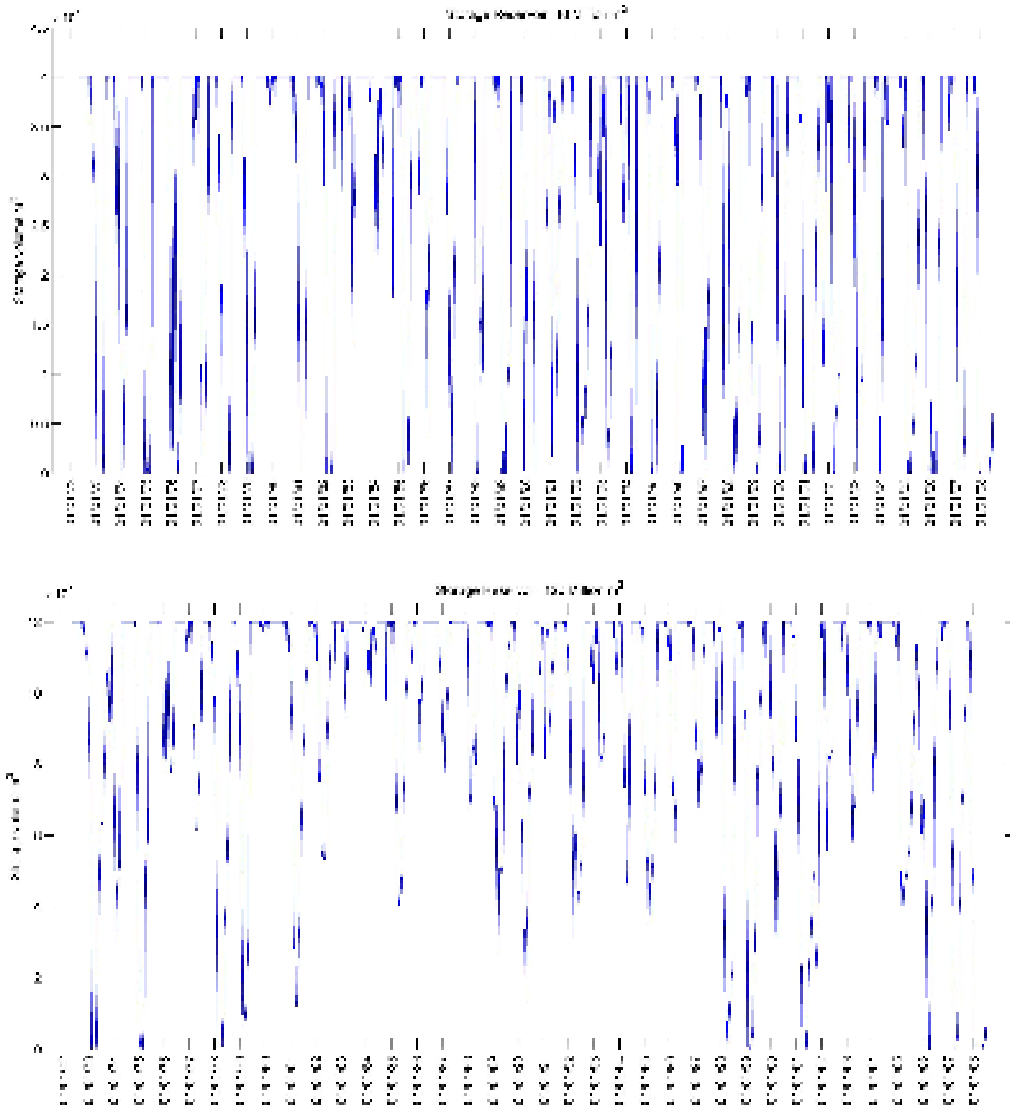
The results presented here are for two simulations with the input parameters described above. The first simulation assumes a storage reservoir of 40 million m<sup>3</sup> and the second simulation a storage reservoir of 120 million m<sup>3</sup>. The effects of those two different scenarios are assessed in terms of reliability of supply and effects on river flows at several different locations in the river. This provides an indication of the effects of changing

input parameters (i.e. storage reservoir volume) on reliability of supply (resulting in an increase or decrease of production) and the environment (i.e. river flows).

### 3.5.1 STORAGE VOLUMES OVER TIME

Figure 2 shows estimated available storage in the reservoir during the simulation period assuming 40 million m<sup>3</sup> of storage and 120 million m<sup>3</sup> of storage.

Figure 2: Available Storage over time with storage volumes of 40 million m<sup>3</sup> and 120 million m<sup>3</sup>



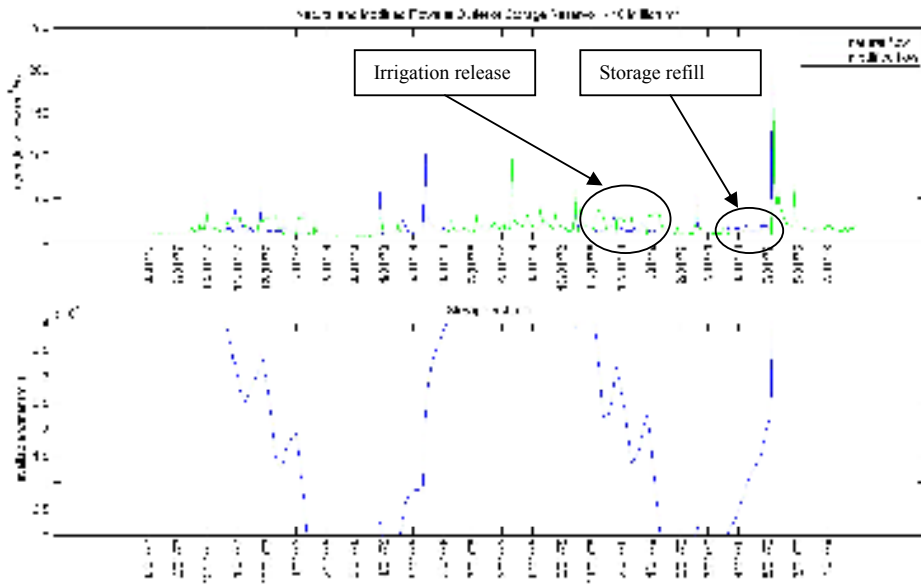
In the simulation with 40 million m<sup>3</sup> of storage the full amount storage is used 31 years in 36 years whereas only 9 years out of 36 years the full amount of storage is used when assuming a storage volume of 120 million m<sup>3</sup>.

### 3.5.2 EFFECTS ON FLOW IN THE RIVER

The effect of the proposed storage reservoir on river flows have been assessed by comparing natural flows with modified flows at several locations in the river. These locations are the outlet of the storage reservoir and just upstream and downstream of the off take point.

An overlay plot of modified and natural outflows at the storage reservoir together with the available storage volume between 1977 and 1979 is given in Figure 3.

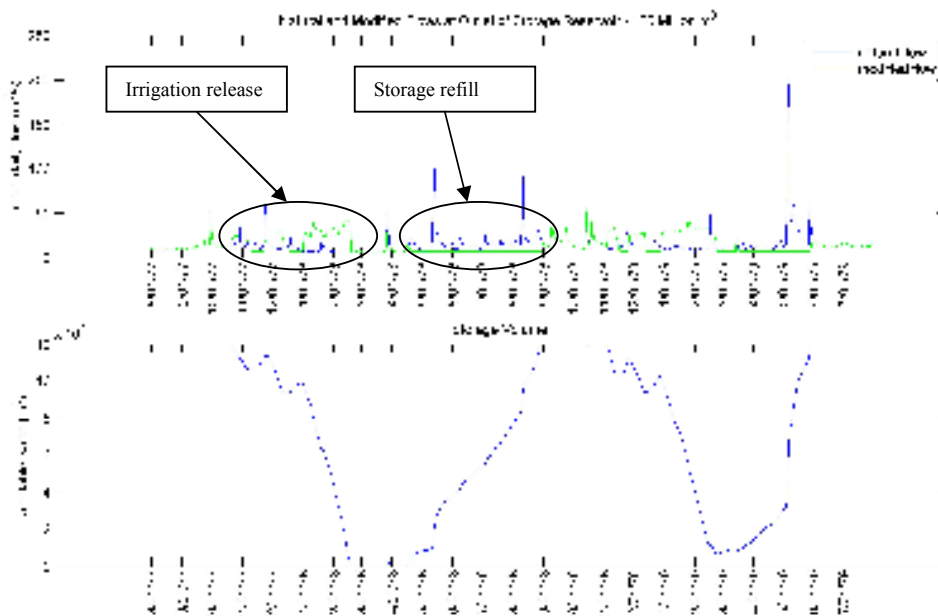
Figure 3: Natural and Modified Flows and Available Storage in the Reservoir with 40 million m<sup>3</sup> of storage



Typically the period between December and April shows the greatest irrigation demand which is reflected in the flows at the outlet of the storage reservoir. During these periods modified flows are bigger than the natural flows. However with 40 million m<sup>3</sup> of storage the reservoir empties in both 1978 and 1979 and releases can only be made up to January. At the end of the irrigation season flows are harvested into storage and flows are flatlined at the minimum environmental flow release of 7 m<sup>3</sup>/s (approximately April through to the end of May in Figure 3) for the reach from the reservoir outlet to the confluence with the downstream tributary stream. After this period of refilling the reservoir, modified flows are similar to natural flows because the reservoir is full.

Figure 4 shows an overlay plot of modified and natural outflows at the storage reservoir together with the available storage over time assuming a total storage volume in the reservoir of 120 million m<sup>3</sup>.

Figure 4: Natural and Modified Flows and Available Storage in the Reservoir with 120 million m<sup>3</sup> of storage



The general picture is similar to Figure 3, however the period of irrigation flow release is significantly longer. In 1978 a flow release can be made through to the end of February (storage goes empty) and in 1979 the available amount of storage is sufficient to meet irrigation demand throughout the irrigation season. Due to the larger amount of storage the period when water is harvested into storage at the end of the irrigation season is significantly longer as well. In the scenario with 40 million  $m^3$  of storage a period of approximately 2 months is required to refill the storage reservoir whereas in the 120 million  $m^3$  scenario it takes 3-5 months.

Figure 5 shows flow duration curves for three locations in the river for the scenario with 40 million  $m^3$  storage.

Figure 5: Flow duration curves for three different locations in the river (40 million  $m^3$ )

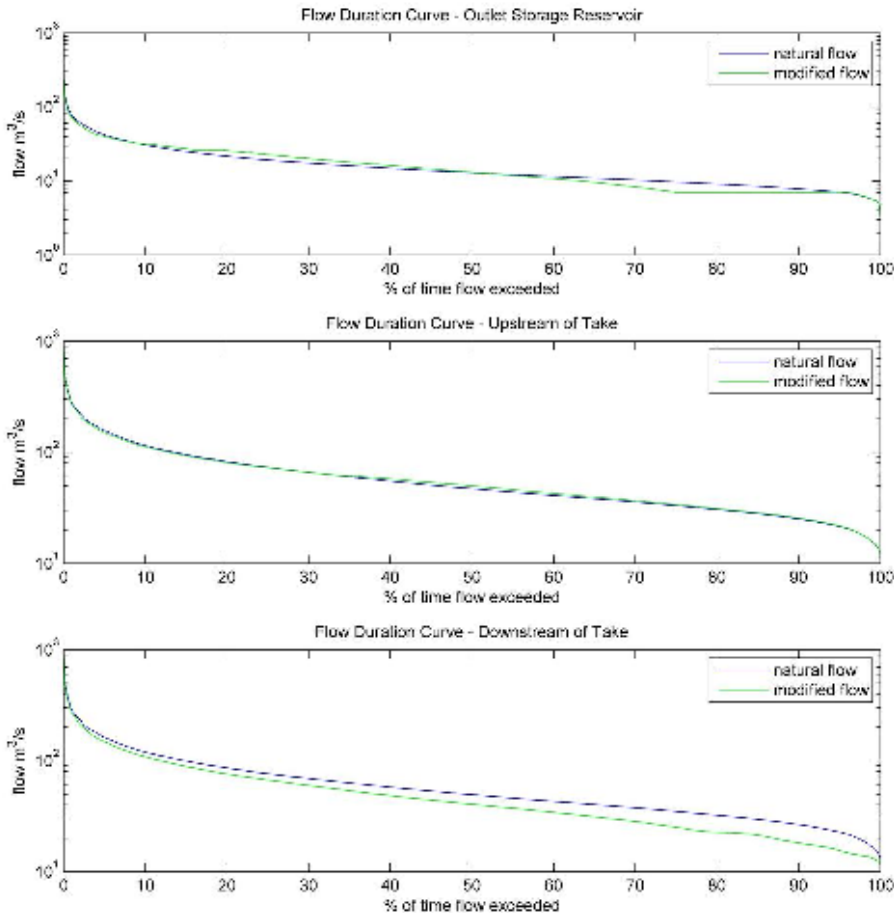


Figure 5 shows that at the outlet of the storage reservoir modified flows between 7 and 10  $m^3/s$  are exceeded less often and flows between 25 and 35  $m^3/s$  are exceeded more often compared with the natural flows. The straight line between 75% and 95% in the modified flows represents the time when flows are harvested into storage and a minimum environmental flow of 7  $m^3/s$  is maintained at the outlet. The flows between 25 and 35  $m^3/s$  in the modified situation represent irrigation flow releases from storage.

The second site where the effect of the proposed scheme on flows is evaluated is located just upstream of the offtake (see Figure 1). The flow duration curve for the modified flows at this site is similar to the natural situation with flows between 40 and 50  $m^3/s$  being exceeded slightly more often than in the natural situation corresponding to irrigation flow releases made from storage.

The overlay plot of the flow duration curves for natural and modified flows downstream of the Offtake show that modified flows are significantly lower than natural flows. This is due to the amount of water that is taken out of the river from both available run of river water and water from storage. This difference between the natural and modified flows at this location is mainly due to the flow allocation regime as described in section 3.4.



Figure 6 shows similar flow duration curves for three locations in the river for the scenario with 120 million  $m^3$  storage.

Figure 6: Flow duration curves for three different locations in the river (120 million  $m^3$ )r

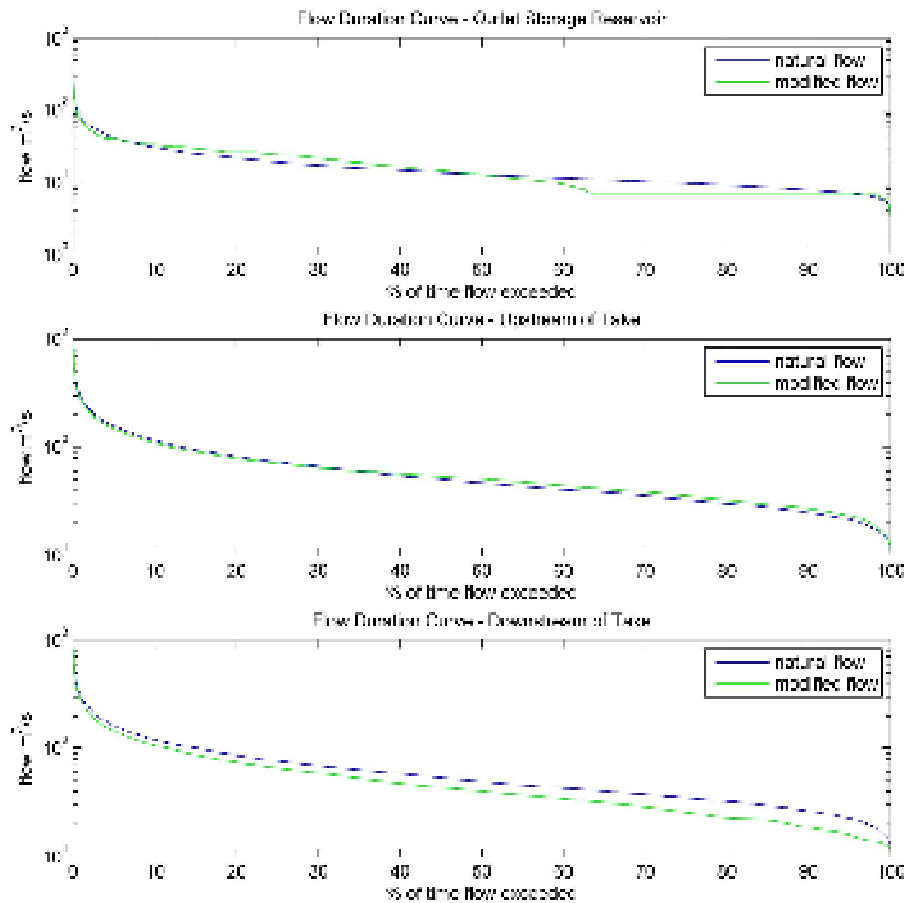


Figure 6 shows that at the outlet of the storage reservoir modified flows between 7 and 10  $m^3/s$  are exceeded less often and flows between 25 and 35  $m^3/s$  are exceeded more often compared with the natural flows. The pattern is similar to the scenario with 40 million  $m^3$  of storage, however the period that flows are harvested into storage and a minimum environmental flow of 7  $m^3/s$  is maintained at the outlet is significantly longer. The straight line at 7  $m^3/s$  is between 63% and 98% which indicates that 63% of the time flows exceed a flow of 7  $m^3/s$ . This compares with 75% in the 40 million  $m^3/s$  scenario.

The difference between the natural and modified flows at the flow evaluation locations upstream and downstream of the take are similar in both scenarios.

It is worth noting that while flow duration curves are a common form of summary used to compare hydrological effects they may not adequately convey the actual effects of the scheme; it is plain that on individual days, or over certain periods, flow may be substantially altered by, say, the release of irrigation water. This may not be reflected in a flow duration curve since these periods may be matched with periods when flows are low due to harvesting of water, so that in a distributional sense modified flows may appear comparable to natural flows. This is particularly the case when other tributary flows contribute to the flow evaluation point (see the middle plots in Figures 5 and 6). As a result it is important to look at the data on a finer time scale and summarise the effects in a way that reflects actual change.

### 3.6 RELIABILITY OF SUPPLY

Figures 7 and 8 shows the total number of days that supply does not meet demand for each irrigation season.

Figure 7: Total number of days supply < demand with storage volume of 40 million m<sup>3</sup>

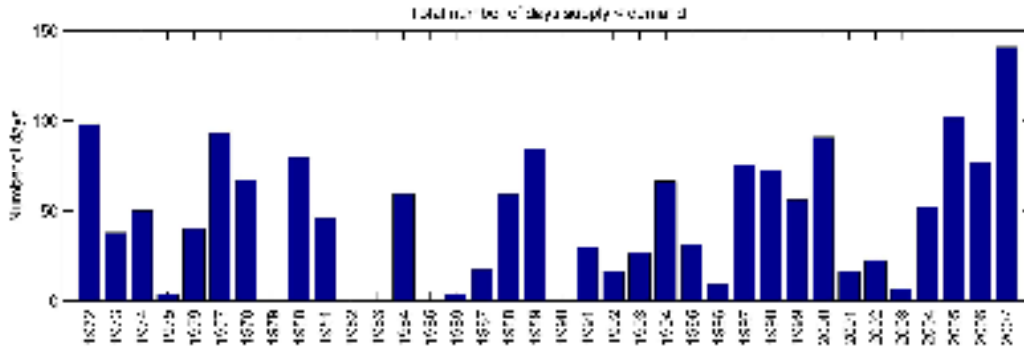
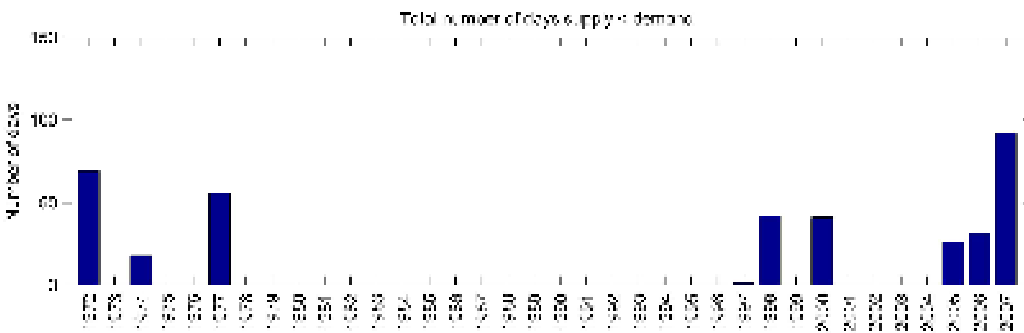


Figure 8: Total number of days supply < demand with storage volume of 120 million m<sup>3</sup>



There are 31 years in which supply does not meet demand throughout the irrigation season when assuming a storage volume of 40 million m<sup>3</sup> which indicates a low reliability of supply. The reliability of supply in the scenario with 120 million m<sup>3</sup> is significantly better with only 9 years out of 36 years when supply does not meet demand.

There are many measures of reliability which use different statistical summaries to quantify the reliability of an irrigation scheme. For the sake of comparison suppose that an irrigation year is counted as reliable if supply meets demand every day of the irrigation season. A scheme is said to be *N*-% reliable if in *N*-% of irrigation years supply always meets demand.

Table 2 summarises the reliability defined above for different storage volumes for the proposed scheme:

Table 2: Storage Reservoir Volume against Reliability of Supply

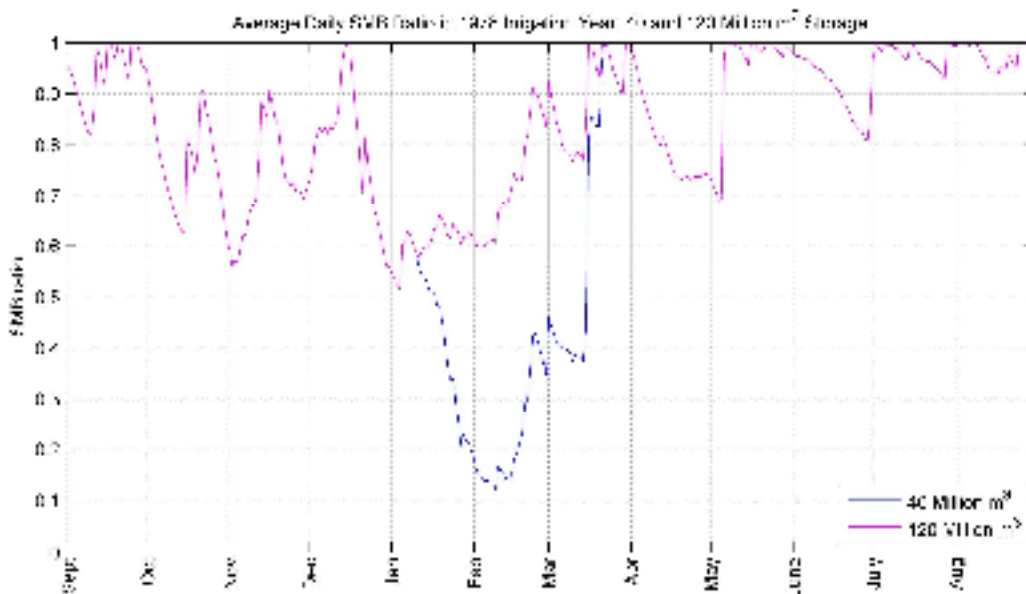
Storage Volume (million m <sup>3</sup> )	Reliability
40	14 %
60	33 %
80	50 %

100	67 %
120	75 %
140	83%
160	89%

For these options, how do we decide which option is best? Is the reliability measure defined above useful? Why is there so little difference in the reliability between 140 and 160 million m<sup>3</sup>? Which of the years in Figures 3 and 4 should actually be counted as bad years? The questions are as countless as the different measures of reliability.

Perhaps a more informative way to look at reliability is to consider the effects of the scheme on productivity. It is clear that for both storage options 1972 and 2007 are bad years: there are significant numbers of days when supply does not meet demand, whereas for 1978 only the 40 million m<sup>3</sup> looks bad. Figure 5 shows plots of the average soil moisture balance ratio, average SMB ratio, (the ratio of soil moisture to the profile available water (PAW) and averaged over the soil types) for 1978 for both of these options. Pasture growth is considered not to be inhibited when the SMB ratio for an individual soil type is greater than 50 %.

Figure 9: Average Soil moisture balance ratio for two different storage options



As can be seen in Figure 5 the soil conditions remain optimal throughout the 1978 irrigation year for the simulation with 120 million m<sup>3</sup> of storage. However with 40 million m<sup>3</sup> of storage the Soil Moisture Index drops below 50% from the middle of January indicating that plants get stressed and production suffers. This corresponds with the period when the storage goes empty as shown in Figure 7.

This approach to summarizing the effectiveness of the scheme by relating it to the ability to maintain soil moisture conditions is perhaps more helpful for the farmer, although, however one ultimately assesses the reliability of the scheme, it is important to recognize that bulk storage options are designed to provide insurance to maintain farm productivity during times of low river flow. As a consequence, the ultimate sizing of the reservoir will depend on the acceptable risk profile and economic viability.

## **4 DISCUSSION AND CONCLUSIONS**

The case study presented here only considered a change in storage volumes and its effect on flows in the river and reliability of supply. However other parameters of the model can easily be changed, or further assumptions can be built into the model. A few examples are:

- The minimum environmental flow releases at the outlet of the dam and/or the flow allocation regime changes as a result of a minimum flow review for the river.
- The need to make environmental flushing flows to remove nuisance algae like periphyton or didymo.
- A change in irrigable area or a change in land use as a result of a change in the economic climate (i.e. differences between dairy farming, beef farming and viticulture will result in changes in water demand.)
- Climate change: Expected changes in the amount of rainfall and frequency of droughts may change the supply of water in the future warranting a conservative approach in storage volumes.

These scenarios can be assessed in terms of the environmental (hydrological) effects and scheme reliability once a model is up and running. Since execution time is brief (5-10 seconds) it is easy to run multiple simulations and compare the effects of different model assumptions. It is also easy to extend the postprocessing, and provide tailored information to clients and specialists on the effects of the scheme. For the abstractive water users this can be done at both a scheme wide scale and at an individual farm scale.

Furthermore, as discussed above, since irrigation demand is directly linked to water supply and storage, one can estimate the scheme's ability to maintain productivity throughout an irrigation season. A thorough and interactive assessment of all these components in the early feasibility and consenting stages of a project may result in significant cost savings in later stages of the project.

### **ACKNOWLEDGEMENTS**

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### **REFERENCES**

N/A