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Water Balance Dynamic Simulation Model-WBDSim for Water Policy options Analysis

Case Study: Murray Darling Basin - Australia

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Water is a key resource to sustain human life. Therefore, sustaining growth in the human population requires even more water to be available. Water sharing management is the major problem for water resources and irrigation management decision makers. The water Act 2007-Australia requires the newly formed Murray Darling Basin (MDB) Authority to develop an integrated plan which specifies amongst other things, long term sustainable diversion limits, water quality objectives, provision for critical human needs and environmental watering plans for all of the Basin's rivers.

A major challenge is to anticipate future water demands and supplies in a drying climate to accommodate the needs of Australia's most rapidly growing area. The MDB system is very complex and interconnected, posing significant difficulties in managing irrigation economically and environmentally. In formulating the new basin plan the Murray Darling Basin Authority (MDBA) is required to ultilise the best available scientific and socio-economic knowledge. Given the relatively short time frames for plan development, there is therefore a requirement for rapid integration and synthesis of much of what is known about the basin, its environment, industries and communities.

Therefore, it is imperative that innovative modelling approaches are employed to assist in better decision making by modelling the feedback loops inherent in the system and to analyse the impact of alternative land use and water policy scenarios (recommended by stakeholders) in order to better understand the trades off. These options include future land use changes, new water allocations, water buy back and carryover rules. Through the application of a system dynamics approach, a MDB-Water Balance Dynamic Simulation Model (WBDSim) was developed. The purpose of the WBDSim is to measure and identify the change in economic and environmental outputs of various allocations and demand scenarios. The WBDSim is forming the base to link irrigation economic impact, environmental response, and urban water economic impact of several water policy options.

This paper details a systems approach to developing WBDSim to enable these complex land and water use options to be evaluated in economic, social and environmental dimensions. A total of 45 catchments are modelled. Each catchment is modelled by the main interconnected five modules (Rainfall-runoff module, River flow module, Irrigation demand module, Rainfed agricultural and vegetation module and simple economic module) that lead to the quantitative indicators (environment, economic and social) values. This model is designed to operate on a monthly basis and can assist managers in analysing the system's behaviour under various management scenarios.The developed WBDSim model is being calibrated against recent CSIRO Sustainable Yields project climate scenarios carried out using a synthesis of the MDBC and State certified River operations Models for the MDB.

Preliminary results from the WBDSim are presented with an emphasis on calibration and validation results against sustainable yield flows data of changing climatic conditions and landuse planning. The WBDSim model tool developed a dynamic system that can provide water balance and uses overview. It can also provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods. It is not a detailed catchment hydrology model but is a tool that has the potential to help stakeholders to simulate and optimize the system, by evaluating and analyzing the key decisions.

Keywords: *Policy analysis, land use planning, Dynamic model, integrated modelling, irrigation demand, environmental flow*

1. INTRODUCTION

A reduction in water availability, conflicting water uses and other water-related environmental problems are rapidly increasing in many parts of the world. Moreover, water demand is driven by irrigation activities which result in altered the river flows that can have important ecological impacts. As an example, according to DLWC (1998), in the Murrumbidgee River Basin (South-East of Murray Darling Basin-Australia), irrigation extraction and intensive cropping systems have led to major impacts on the river environment and water availability. The water Act 2007-Australia requires the newly formed Murray Darling Basin (MDB) Authority to develop an integrated plan which specifies amongst other things, long term sustainable diversion limits, water quality objectives, provision for critical human needs and environmental watering plans for all of the Basin's rivers. The major challenge is to anticipate future water demands and supplies in a drying climate to accommodate the needs of Australia's most rapidly growing area. The MDB system is very complex and interconnected, posing significant difficulties in managing irrigation economically and environmentally. In formulating the new basin plan the Murray Darling Basin Authority (MDBA) is required to ultilise the best available scientific and socio-economic knowledge. Given the relatively short time frames for plan development, there is therefore a requirement for rapid integration and synthesis of much of what is known about the basin, its environment, industries and communities.

The CSIRO Murray-Darling Basin Sustainable Yields Project (2008) is providing critical information on current and likely future water availability. This information will help governments, industry and communities consider the environmental, social and economic aspects of the sustainable use and management of the precious water assets of the Murray-Darling Basin. However, the models used in this analysis are mainly physical models and hardly to be linked and represent the environmental, social and economic aspects of the sustainable. Given the complexity of the MDB system, thus there is a need to explore a new modelling and planning design approach. A capacity to assess the impacts of various water resource management options is required – in short a capacity to assess interrelated economic, social and environmental cost and benefits of alternative management interventions, across a large complex river system.. It is imperative that innovative modelling approaches are employed to assist in better decision making by modelling the whole river basin and the feedback loops inherent in the system and to analyse the impact of alternative land use and water policy scenarios in order to better understand the trades off. These options include future land use changes, new water allocations, water buy back and carryover rules. Through the application of a system dynamics approach, a MDB-Water Balance Dynamic Simulation Model (WBDSim) is developed. The purpose of the WBDSim is to simulate the water availability and measure and identify the change in economic and environmental outputs of various allocations and demand scenarios. The WBDSim is forming the base to link irrigation economic impact, environmental response, and urban water economic impact of several water policy options. Therefore, the overall goal of the current study is to present the MDB-Water Balance Dynamic Simulation Model developed in this study which is able to test different what if scenario and can assist MDB Authority to develop the integrated plan for Murray Darling Basin.

2. MURRAY DARLING BASIN AND IT'S MAIN ISSUES

Australia is the driest inhabited continent on Earth, and in many parts of the country – including the Murray-Darling Basin – water for rural and urban use is comparatively scarce. The MDB covers more than 1 million km2 (one-seventh) of mainland Australia including parts of Queensland, New South Wales, Victoria and South Australia and all of the Australian Capital Territory CSIRO (2008). The Basin is bounded by the Great Dividing Range in the south and east. The Darling (2740 km), the Murray (2530 km) and the Murrumbidgee (1690 km) are Australia's three longest rivers. The MDB is home to around two million people. Agriculture is the dominant economic activity in the MDB covering nearly 80 percent of the Basin and generating over 40 percent of the gross value of Australian agricultural production see figure 1.

The MDB uses 60 percent of all irrigation water in the country and is often referred to as Australia's 'food basket'. There is a wide range of climatic conditions in the MDB including a strong east–west rainfall gradient and a strong north-west to southeast temperature gradient. Rainfall is highly variable. Rainfall is summer dominated in the north and winter dominated in the south. Rainfall varies considerably between years in the north-west and less so towards the south-west. The recent drought is the first time that a limited supply has caused a major reduction in total use see figure 2. CSIRO (2008) reported that surface water availability across the entire MDB is expected to decline due to climate change. The future will be significantly drier on average but these conditions would be less severe than a continuation of the recent climate in the south of the MDB.

This reduction in surface water availability would reduce surface water use by 4 percent overall under current water sharing arrangements (CSIRO, 2008). In general, the impacts of climate change on the reliability of 'water products' vary greatly between the products, regions and states. Climate change resulted in low water allocation, reductions in reliability, reduction in surface water availability and increased in groundwater use. Into the future, climate change and other risks (including catchment development) are likely to exacerbate this situation and hence improved water resource data, understanding and planning and management are of high priority for Australian communities, industries and governments. To achieve this will require capacity to evaluate hydrologic and economic consequences of many related factors including climate change and drought and alternative water sharing, environmental water management, water market and trading rules and operational rules, including carry-over arrangements.

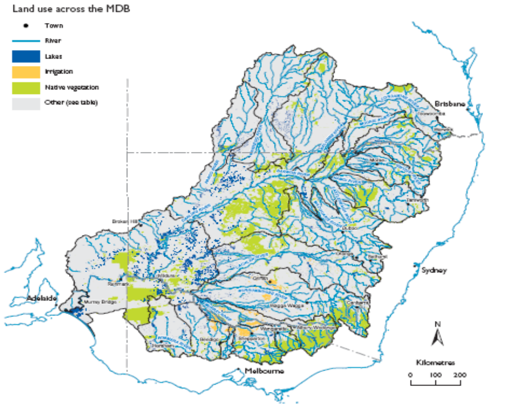

Figure 1. Murray Darling river basin: Land use

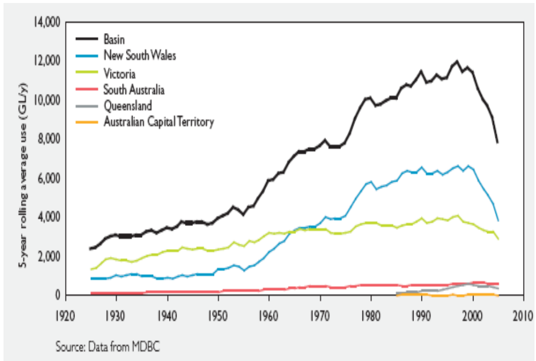

Figure 2 Water use in Murray Darling Basin

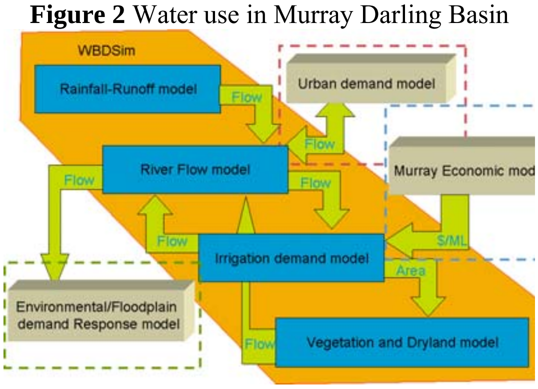

Figure 3 WBDSim Conceptual approach

3. WATER BALANCE DYNAMIC SIMULATION MODEL- WBDSim

Modeling of water resources systems can be undertaken using a variety of approaches. Given the complexity of the MDB system and relatively short time frames for plan development, there is therefore a requirement for rapid integration and synthesis of much of what is known about the basin, its environment, industries and communities. It is important that to select an appropriate approach, based on the model requirements (in terms of parameters, spatial and temporal resolution), data available, expertise of users and the degree to which processes are understood (series on model choice 2005). In this study, system dynamics modeling approach is utilized.

The purpose of the MDB-Water Balance Dynamic Simulation Model WBDSim is to measure and identify the change in economic and environmental outputs of various allocations and demand scenarios. WBDSim is adopted the water use account approach, it is a top-down model (Sivapalan et al., 2003 and Kirby et al 2006), based on simple lumped partitioning of rainfall into evapotranspiration and runoff and infiltration into a generalised surface store at the catchment level. However, the water use account developed to MDB using spread sheet is not represented the dynamics of the system and can not be linked with other socio-economic and environmental response models. Therefore, through the application of a system dynamics approach (VENSIM^{TM} platform), a MDB-Water Balance Dynamic Simulation Model (WBDSim) was developed. The WBDSim is forming the base to link irrigation economic impact, environmental response, and urban water economic impact of several water policy options see figure 3 and figure 4. This is done at the catchment level, with no attempt to model the spatial distribution of hydrological processes and storages within a catchment. A total of 45 catchments are modelled. Each catchment is modelled by the main interconnected five modules (Rainfall-runoff module, River flow module, Irrigation demand module, Rainfed agricultural and vegetation module and simple economic module) that lead to the quantitative indicators (environment, economic and social) values.

Rainfall-Runoff Module: To estimate runoff and infiltration using rainfall and evaporation data considering soil storage capacity and contributing area.

River Flow Module: To estimate river flow considering dam storage capacity, loss, channel storage and loses, diversion and supply.

Irrigation Demand Module: To estimate crop water requirements using crop factor, evaporation and rainfall, soil attributes data.

Vegetation and Rainfed Module: To estimate losses and floodplain inflow and return flow as a fraction of overbanked flow

Simple economic Module: To estimate the revenue of irrigation activities.

This integrated model (WBDSim) is designed to operate on a monthly basis and can assist managers in analysing the system's behaviour under various management scenarios. The WBDSim is applied to a basin divided coarsely into the major catchments. As an example, the major catchments of the MDB are shown in Figure 5. For each catchment, a simple, conceptual, mass balance model is assumed to apply, depicted schematically in Figure 6. Not all features appear in every catchment: upper catchments have no inflow from upstream, and some lack irrigation, for example. Groundwater is sometimes insignificant in the water balance (for the purposes of this study) and, in such cases, is not modelled. Some rivers in a basin may be disconnected, or are distributaries that end in wetlands (these are common features of the Murray-Darling system,). For these rivers, the outflow does not become the inflow to another river reach, but ends as evapotranspiration. Any element within the WBDSim, be it a dam, a river, a catchment or a whole basin obeys basic mass balance:

$$\sum \text{inflows} - \sum \text{outflows} + \sum \Delta \text{storages} = 0 \quad (1)$$

For example, the mass balance for rainfall-run off module is follow equation 2 for each month. Rainfall (P) plus irrigation (Ir) is first partitioned at the surface into the runoff (Ro) and infiltration (I), where conservation must be observed:

$$P + Ir - I - Ro = 0 \qquad (2)$$

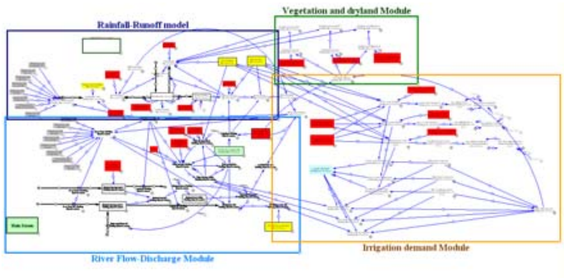

Figure 4 Schematic and interactions of the main modules for WBDSim

Figure 5 Sub-Catchment level and gauge stations in WBDSim

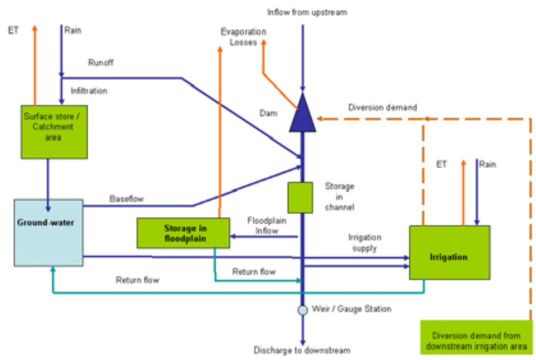

Figure 6 Mass Balance Conceptual approach for each river reach

Rainfall plus irrigation is the supply limit, whereas the unfilled portion of a generalised surface storage, ΔS_{smax}, is the capacity limit governing the partition and includes soil storage and small surface stores. A Budyko-like equation (Budyko, 1974) is used to smooth the transition from the supply limit to the capacity limit:

$$\frac{I}{\Delta S_{s\max}} = \left(\frac{\left((P + Ir)/\Delta S_{s\max} \right)^{a1}}{\left(1 + \left((P + Ir)/\Delta S_{s\max} \right)^{a1} \right)} \right)^{1/a1} \quad (3)$$

The a1 parameter determines how sharply curved is the relationship between infiltration and the incident rain, and thus how much runoff there is from the rain. Larger values of a1 mean more infiltration at lower rainfall. The evapotranspiration depends on the potential evapotranspiration (ET_{pot}, capacity limit) and the surface storage (S_s, supply limit). Although soil and other surface stores are not differentiated, the implication is that evaporation occurs from small ponds, puddles, and the soil surface, whereas transpiration comes from deeper soil storage. A similar equation to the above, with a second adjustable parameter *a*2, is used to smooth the transition from the supply limit to the capacity limit:

$$\frac{ET}{ET_{pot}} = \left(\frac{\left(\left(S_s^{t-\Delta t} + I\right)/ET_{pot}\right)^{a2}}{\left(1 + \left(\left(S_s^{t-\Delta t} + I\right)/ET_{pot}\right)^{a2}\right)} \right)^{1/a2} \qquad (4)$$

In all the rainfall-runoff model has two adjustable parameters a1 and a2 which will be used in the calibration. The a2 parameter determines how sharply curved is the relationship between ET and water stored in the surface of the landscape, and thus how much ET there is. Larger values of a2 mean more ET at lower amounts of stored water. This value interacts with a1, because more ET (higher a2) lowers the water store more quickly and leads to more infiltration and less runoff from the next rain event. The surface storage is increased by the infiltration and decreased by the evapotranspiration and a drainage-to-baseflow component, D_B:

$$S_s^t = S_s^{t-\Delta t} + I - ET - D_B \qquad (5)$$

where *t* is time and Δt is the timestep (one month). The drainage-to-baseflow component is modelled as a fraction of the generalised surface store:

$$D_B = c1\, S_s^{t-\Delta t} \qquad (6)$$

where *c*1 is a fraction of the surface store ($0 < c1 < 1$). Detail discussion and model formulation are not discussed here, since this paper goal is to present the integrated approach and the calibration and validation results.

4. MODEL CALIBRATION AND VALIDATION ANALYSIS

Four parameters have been defined and selected for calibration process. These four parameters are *a1, a2, Smax and river channel storage (*It governs the proportion of water that may be physically stored in the channel) and allowed to search for the global optimal solution using Powell's optimiser (will be described in briefly later) to calculate the objective functions. Once the model parameters are chosen, the optimiser will try to find the values for those parameters within its specified range that achieve the objective function that means making the model fit the data as closely as possible.

In this study, a single objective function is used. The most common single objective function in literature is the sum square error (see Equation 8). Where, O_i is the observed volume at time i and S_i is the simulated flow volume at time i, N is the number of time series. To measure the model performance for each validation test a standard two criteria has been defined comprising two numerical measures (Correlation and coefficient of efficiency). These criteria were selected in order to reflect the objectives of the modelling that are able to simulate river flows at multiple sites monthly along the MDB Rivers. The coefficient of efficiency is measuring the ability to simulate the variation in the flow hydrograph for a particular river gauging station see equation 9 (Nash and Sutchliffe, 1970)

$$F_1 = \sum_{i=1}^{n} (O_i - S_i)^2 \qquad (8)$$

$$E = 1 - \frac{\sum_i^N (O_i - S_i)^2}{\sum_i^N (O_i - \bar{O})^2} \qquad E = [0, 1] \qquad (9)$$

Where O_i = observed flow at times step i, S_i = simulated flow at time step i and $\bar{O}_i$ = is the mean of the observed flow. Values close to 1.0 for Nash and Sutchliffe indicate the model is able to capture or accurately simulate the variance of the flows in the river. Sometimes E called the coefficient of efficiency, it was chosen as the likelihood measure to evaluate the accuracy of both the magnitude and timing of predicted flows (e.g. Andersen et al., 2001; Vazquez et al., 2003; Tague et al., 2004; McMichael C. et al., 2006). Andersen et al (2001), indicate that when the value of E> 0.85, the model run is good.

4.1. Results

In this section the calibrated results are compared visually and quantitatively with the observed and simulated results. In brief summarised the calibration procedure as follow:

- WBDSim simulate the discharge of several gauging stations along the MDB Rivers for 30 water years (June 75-June 2005).
- The simulated results are compared with real data (observed) for each river reach points Inflow and outflow (gauge points).
- Calibrate the 15 years results by applying single objective method (Minimising the sum of square error between the data (observed) and simulated results) .
- Validate the model by applying the value of the parameter resulted from the calibration process to simulate the model for the validation period (for the rest of the 30 years, which is 15 years)
- Calculate the coefficient of efficiency for validation results excluding the calibration period

Moreover, Schlesinger et al. (1974) indicate that model validation concern the quality of match of simulated and real data with some interpretation of the appropriateness of the data for validation purposes. As mention above four parameters was used for calibration by Powell's methods search for their optimum values within its range (minimum value and maximum value) defined based on literature review and data from the local authorities see Table 1.

Table 1 parameters value and range for Paroo River

Parameter	min	max	Calibrated Value
a1	0.2	3	1.711
a2	0.2	3	0.9377
C2	0	5	0.1827
Smax	0.1	1	1

Using the optimum calibrated parameters value to simulate the rest of the years to validate the WBDSim. This paper presents the calibration and validation results for one of the MDB Rivers named Paroo River. The Paroo region covers less than 4 percent of the Murray-Darling Basin (MDB), is situated predominantly within southern Queensland, and has less than 0.1 percent of the Basin's population. It uses less than 0.1 percent of the surface water diverted within the MDB for irrigation. Qualitatively assessment showing good validation, as the simulated discharge matching the observed discharge data sees Figure 8. The peak and troughs is really in a good a match and consistent and have the same trend as the observed flows/discharge, especially with low flow conditions. This could be attributed to a better estimation of the calibration parameters and good selection of calibration period that is well represented by both dry and average years. Also, the quantitative assessment showing high correlation (R^2 = 0.85) between observed and simulated discharge for the period of 1991-2005years (Figure 9). Using the ranking system used by (Lorup et al., 1998; H. Henriksen et al., 2003) for E (E=0.8), and correlation, the model can be categorised or ranked as very good.

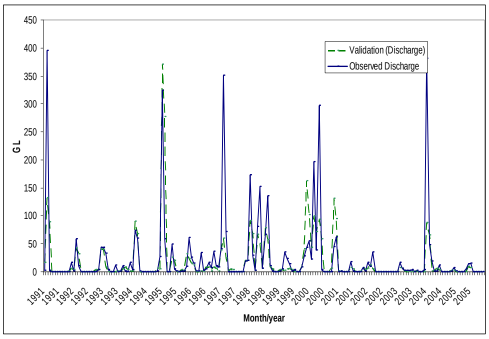

Figure 8 Observed and simulated river discharge

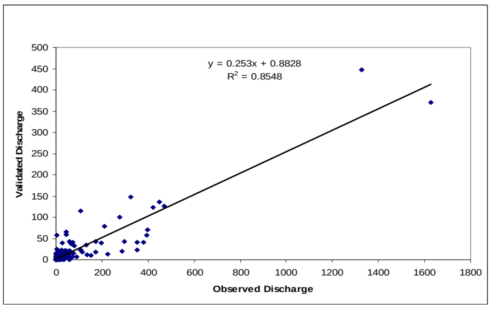

Figure 9 Observed and validated discharge correlation

5. DISCUSSION AND CONCLUSIONS

WBDSim model is calibrated and validated for 30 years period by using single objective to minimise the difference (sum square error) between observed and simulated discharge. Furthermore, two performance criteria have been applied to evaluate and assess the overall performance of the validation results. A ranking system has been used to understand the overall performance of the calibration methods which ranked the model as very good. These results indicate that the calibration results (the optimum parameters value) is better identifiable and a more well posed model structure with better performance.

WBDSim is a powerful integrated model of describing the overall water use and flow behaviour of a river basin. It captures the main aspects of the behaviour, both spatially and temporally (seasonally, annually), and the balance between different types of water use (dryland, irrigated, forest, wetland and other water uses). The WBDSim can be used to evaluate the proposed alternative that is defined by water availability and demand. This model is designed to operate on a monthly basis and can assist managers in analysing the system's behaviour under various management scenarios.

Finally, these results indicated that the WBDSim model tool developed a dynamic system that can provide water uses overview. It is also useful for systematic learning and hypothesis testing, and also helps the user rapidly identify gaps and limitations in the data. It can also provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods. It is not a detailed catchment hydrology model but is a tool that has the potential to help stakeholders to simulate and optimize the system, by evaluating and analyzing the key decision variables

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