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Integrated surface water and groundwater modelling to support the Murray Drainage and Water Management Plan, south-west Western Australia

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Abstract: The Murray region in south-west Western Australia is characterised by a high water-table, sandy soils, wetlands of significance, and an extensive agricultural drainage system to relieve water-logging in winter months. Urban growth pressures in the region have led to the requirement of a Drainage and Water Management Plan (DWMP) to guide future water management. A key component of the DWMP involved the development of a regional surface water and groundwater model to determine groundwater levels and flows under various climate, drainage and development scenarios. The Murray regional model was constructed using the integrated surface water and groundwater model MIKE SHE, and consisted of unsaturated zone, saturated zone, channel flow and overland flow components. It had a constant grid spacing of 200 m, and covered an area of 722 km^2. Calibration was from 1985 – 2000 and validation from 2000 – 2009 using 45 groundwater bores and 7 surface water flow gauges. The normalised root mean square error of the calibrated model was 2.02%. Land development, drainage and climate scenarios were simulated and their results are discussed in this paper.

The process of model conceptualisation, construction, calibration and simulation is discussed, and provides an appropriate framework for model evaluation and a high level of confidence in modelling results. The Murray MIKE SHE model provided regional groundwater levels, areas of groundwater inundation, estimated drainage volumes from development areas, effects of sea-level rise, and changes in surface water flows for a variety of climate, drainage and development scenarios. The results were used to determine regional-scale hydrology affects resulting from future urban development. The model grid size and calibration error may prevent the usage of the model for detailed drainage design; however the model is suitable to act as a basis for developing higher-resolution sub regional and local models that are more appropriate for this type of evaluation. The results of the Murray MIKE SHE modelling exercise were used in the Murray Drainage and Water Management Plan, a key deliverable to the Western Australian Planning Commission, used to guide stakeholders in future urban water management in the Murray region.

Keywords: *MIKE SHE, integrated modelling, groundwater, urban development, Western Australia*

1. INTRODUCTION

The Murray region in south-west Western Australia is approximately 50km south of Western Australia's capital city Perth (figure 1), and is characterised by a high water-table, sandy soils, wetlands of significance, and an extensive agricultural drainage system to relieve water-logging in winter months. Urban growth pressures in the region have led to the requirement for a Drainage and Water Management Plan (DWMP) to guide stakeholders in future urban water management (Department of Water, 2010). A DWMP investigates the water management issues in a region (including water demand, supply and re-use, flood management, groundwater management, water quality management and ecological water requirements), and provides a framework to account for these issues in site-specific water management plans. They are a key step in the creation of district structure plans, which are required by the Western Australian Planning Commission and local government authorities.

A major component of the DWMP was the development and calibration of a regional-scale groundwater model, and the use of this model to run various climate and land-use change scenarios. The model was required to reflect the nature of the local environment which has a high degree of surface water/groundwater interaction (extensive water-logging in winter, and an extensive drainage network to alleviate groundwater inundation). Therefore, it was preferable that the model be an integrated surface water/groundwater model, to study both parts of its water regime. The model was used to deliver the following outputs for a range of climate and land use change scenarios:

- maximum, minimum, average annual maximum and average annual minimum groundwater levels (MaxGL, MinGL, AAMaxGL and AAMinGL);
- changes to water balance including groundwater and surface water discharges;
- likely impacts on acid sulfate soils;
- reuse opportunities such as shallow bores and surface detention;
- likely areas of waterlogging;
- likely impacts of climate change;
- impacts on water-dependent ecosystems (wetlands) and ecology;
- guidance for drainage design (surface water and groundwater infrastructure).

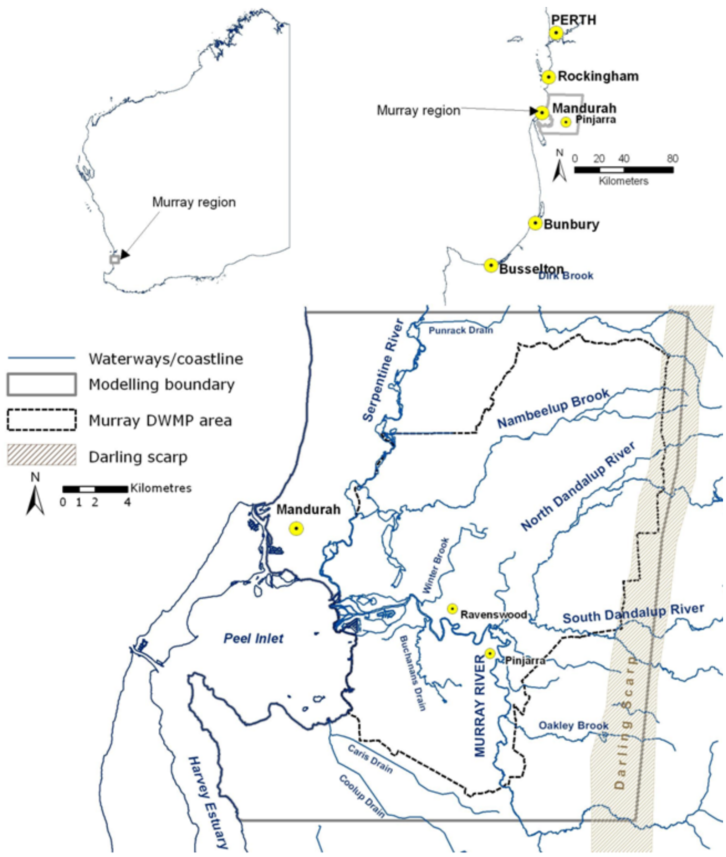

Figure 1. Location of the modelled Murray region in south-west Western Australia.

2. CONCEPTUAL MODEL

The conceptual model reflected data collation and analysis developed through an extensive literature review, stakeholder consultation, and hydrological, hydrogeological, geological, topological and climatic data interpretation.

The Murray region receives approximately 900 mm of rainfall per year and annual pan evaporation averages approximately 1540 mm. The area has a Mediterranean-style climate with hot dry summers and cool wet winters, typical of the south-west region of Western Australia. An average of 86% of the rain falls within the May – October period, and the average monthly distribution of rainfall is similar over the entire region. The average annual rainfall from 1877 – 1975 was 970 mm, which is 14% greater than the average rainfall between 1975 and 2008 (Figure 2), highlighting the recent drying climate that has been experienced in south-west Western Australia over the past 30 years. The mechanism for the drying climate in rainfall is due to the winter weather systems moving further south than previously. In the Murray study area, during the cool winter months, rainfall results from sub-polar, low-pressure cells that cross the region as cold fronts. These weather conditions are usually accompanied by strong winds and cloudy skies. Since 1968, the high pressure anticyclone belt in the Murray study area has moved southward, deflecting the cold fronts further south, resulting in a drier climate for the south-west of Western Australia (Davidson and Yu, 2006).

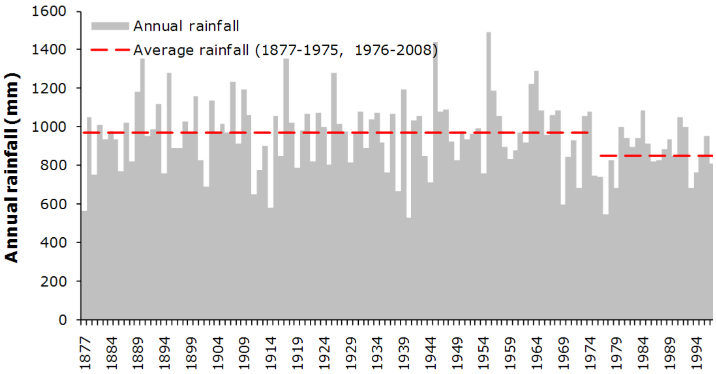

Figure 2. Annual rainfall from within the Murray study area displaying 'step-down' in average rainfall post 1975.

Geologically, the area is part of the Perth Basin, bordered by the Darling Scarp to the east and the Indian Ocean and Peel-Harvey estuary to the west. Most of the study area lies on the Swan Coastal Plain, where elevations range from approximately 0 – 80 m AHD (Australian Height Datum). The catchment is characterised by a high water table and an extensive drainage system throughout the catchment is used to relieve water-logging and flooding during winter months. Major waterways include the Murray River and Serpentine River which discharge to the Peel Inlet (Figure 1).

Over 500 bore logs were assessed and the lithology classified to construct a three-dimensional model of the geology between the ground surface and the top of the Cretaceous sediments which form the first confined to semi-confined aquifer, approx 15 – 50 m below the ground surface (Leederville Formation). The model includes ten sub-classifications in the superficial formation, plus the Rockingham Sand and Leederville Formation. Hydraulic properties and formation boundaries were interpreted using Passmore, 1970; Davidson, 1982; Commander, 1988; Deeney, 1989; Davidson, 1995 and Davidson and Yu, 2006. The resulting three-dimensional conceptual geological model is displayed in Figure 3, which contains all members of the

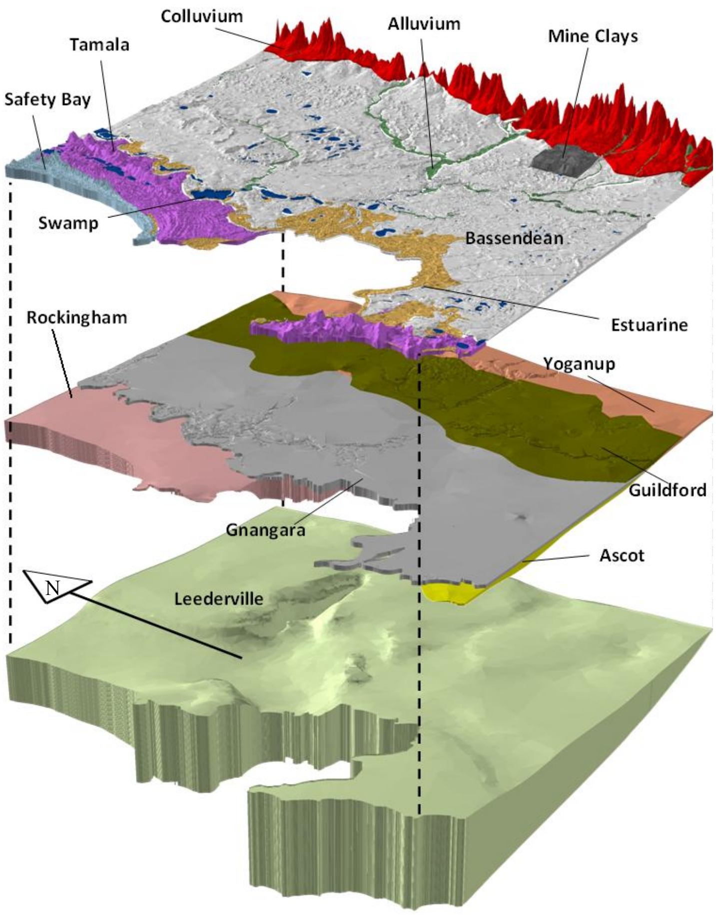

Figure 3. Conceptual geological model for the Murray region showing all members of the Superficial Formation, as well as the Rockingham and Leederville Formations.

Superficial Formation, as well as the Rockingham and Leederville Formations. The three major aquifers in the Murray study area are the Superficial, Rockingham and Leederville Aquifers. The Superficial and Rockingham are unconfined and are recharged through rainfall; the Leederville is confined to semi-confined and recharge is generally through heterogeneous recharge zones close to the Darling Scarp. Horizontal hydraulic conductivities range from around 1 m/d in clayey formations, 10 – 20 m/d in the sandy formations and up to 140 m/d in the Tamala Limestone. Phreatic and potentiometric surfaces indicate that the Superficial and Leederville Aquifers exhibit an east-west flow pattern intersected by the Murray River in the south and Serpentine River and Nambeelup River in the north. The conceptual model formed a basis for the construction and calibration of a transient numerical groundwater / surface water model.

3. CONSTRUCTION AND CALIBRATION

The Murray regional model was constructed using the modelling software package MIKE SHE. The model was constructed using available geological, hydrogeological, hydrological, soil and land-use information. The Murray MIKE SHE model consisted of unsaturated zone, saturated zone, channel flow and overland flow components. It had a constant grid spacing of 200 m, and covered an area of approximately 722 km^2. Groundwater bores and surface water flow gauging stations used in model calibration and validation are shown in Figure 4.

The calibration period was from 1985 – 2000 and validation between 2000 – 2009 using 27 groundwater bores and five surface water flow gauges. The normalised root mean square (RMS) error for the calibrated model was 2.02%. The RMS was 0.80 m, and the absolute residual mean (mean absolute error) and the residual mean error (mean error) were 0.55 m and 0.07 m respectively. The average absolute error, defined as the difference between the predicted and measured water levels was 0.52 m. The maximum positive error in the aquifer in predicted head was 2.80 m and the maximum negative error was -2.83 m. The model calibration satisfied the criteria of a water balance error <0.05%, an iteration residual error <0.1% and a scaled RMS error <5%.

Most of the simulated heads at the monitoring bores in the Superficial Aquifer had a response consistent with measured data. The monitoring bores maintained correct trends and the magnitude of the error was constant.

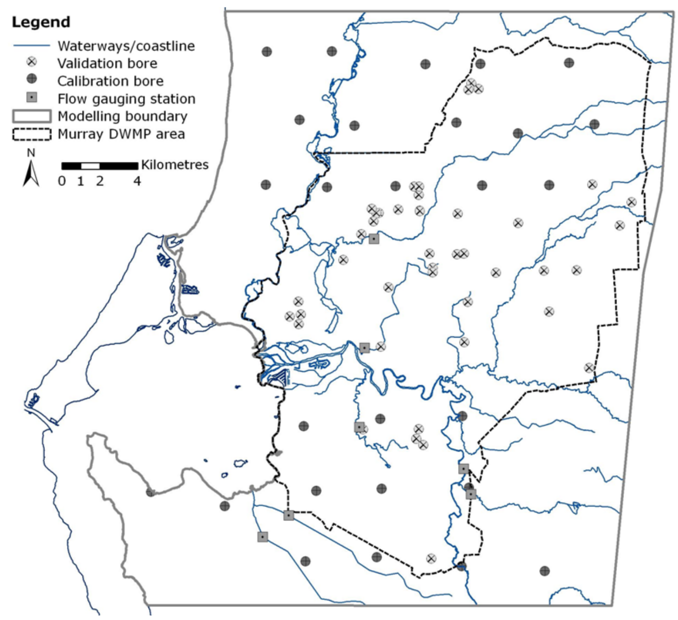

Figure 4. Calibration and validation groundwater bores and surface water flow gauging stations used in the Murray regional MIKE SHE model.

Model validation included an additional 40 bores which were drilled recently (67 in total) with monthly water level recordings from 2008. The location of all validation bores is shown in Figure 4. The normalised RMS error for the validation period was 2.03%. The RMS was 0.87 m, and the absolute residual mean (mean absolute error) and the residual mean error (mean error) were 0.58 m and 0.10 m respectively.The water balance was calculated for the entire Murray model and for the Murray DWMP area by using the post-processing water-balance tool included in MIKE ZERO's suite of tools. The flow rate and source of flow components were integrated over the period to obtain cumulative volumes. The water balance was determined for both the total regional model domain and the Murray DWMP area. The water balance for the major groundwater fluxes and for the surface and groundwater fluxes is presented in Table 1. The water balance for the superficial groundwater was consistent with the conceptual hydrogeological model. An error of <0.05% for the model domain satisfied the calibration criteria. The model predicted a gross recharge rate of 41% of rainfall and a net recharge of 12.3% for the regional model domain over the calibration period of the model (1985 – 2000).

A sensitivity analysis was undertaken, and indicated that the model was sensitive to horizontal conductivity in the saturated zone, and to most parameters apart from leaf area index (LAI) in the unsaturated zone. The model was insensitive to vertical hydraulic conductivity, specific yield, LAI and overland flow parameters.

The Murray regional model had a spatial resolution of 200 m and a maximum temporal resolution of one day. Based on these structural limitations of the model, the errors discussed in the previous section and the quality of the calibration, the model was considered suitable for:

- evaluating changes in the water balance due to drainage design and land-use changes (changes in recharge, drainage, evapotranspiration, horizontal flow etc.);
- the relative assessment of regional and subregional impacts due to changes in drainage, and abstraction from the shallow aquifer;
- district-scale groundwater-level evaluation (AAMGL, AAMinGL etc.) under various climate scenarios. This includes determining areas of seasonal water-logging and inundation. However, the inherent model error needs to be considered when using groundwater levels derived from the regional model. If the error is deemed too large for the purpose of the application, a localised model with a finer grid should be constructed and calibrated to achieve appropriate model accuracy.

The structural limitations suggested that the Murray regional model was not the preferred platform for the following applications: wetland or lake assessment, flood modelling, detailed drainage modelling, abstraction or sustainable yield assessment from the Leederville Aquifer.

Table 1. Average annual water balance for the modelling domain and for the Murray DWMP area (1978 – 2007).

Flux	Total model domain (mm)	Total model domain (%)	Murray DWMP area (mm)	Murray DWMP area (%)
Water balance for superficial groundwater				
Net recharge	103.8	100.0%	87.6	87.1%
Flow through	-12.2	-11.8%	13.0	12.9%
Abstraction	-14.3	-13.8%	-9.9	-9.8%
Drainage	-76.2	-73.4%	-90.5	-90.0%
Storage	-1.0	-1.0%	-1.1	-1.1%
Error	0.0	0.0%	-0.9	-0.9%
Water balance for surface water and groundwater				
Rainfall	843.6	100.0%	849.0	98.5%
Irrigation	0.0	0.0%	0.0	0.0%
Surface water flow	-82.7	-9.8%	-96.3	-11.2%
Flow through	-12.2	-1.5%	13.0	1.5%
Abstraction	-14.4	-1.7%	-9.9	-1.1%
Evapotranspiration	-733.1	-86.9%	-755.2	-87.6%
Storage	-1.3	-0.2%	-1.4	-0.2%
Error	0.0	0.0%	-0.9	-0.1%

3.1. PREDICTIVE SCENARIOS

Scenarios for the Murray regional model included:

- Land development scenarios based on mapping from the Draft South Metropolitan & Peel Structure Plan – Urban Growth Management Strategy. The development region was divided into 11 separate development areas. The development areas are shown in Figure 5. Domestic bore abstraction was also investigated in these regions.
- Drainage scenarios including depths of sub-surface drains at ground level with 1.0 m clean-fill, drainage at 1.0 m below ground level with no extra clean-fill and drainage at average annual maximum groundwater level (AAMaxGL).
- Climate scenarios based on the Intergovernmental Panel for Climate Change (IPCC) predictions, and included predictive changes in rainfall, evapotranspiration and sea level rise (IPCC, 2007). Sea level

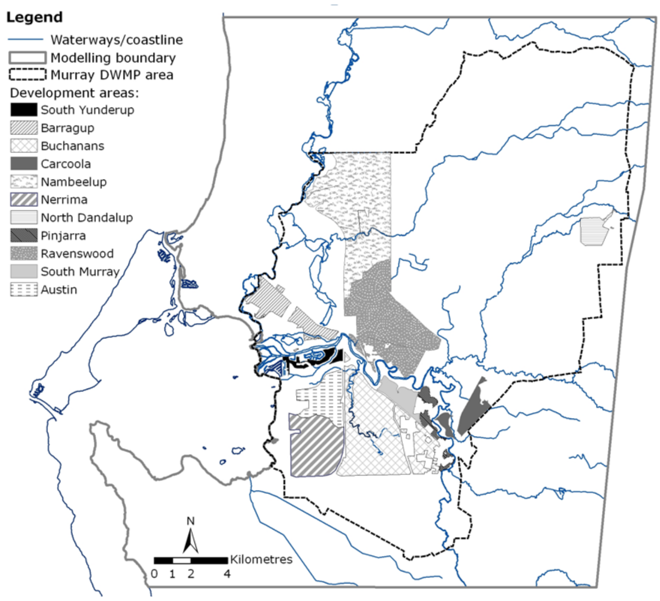

Figure 5. Development areas for the Murray DWMP.

rise scenarios included 0.2 m for the 2031 climate scenarios, and a worst case scenario of 0.9 m increase for the year 2100 (IPCC, 2007). For the Murray DWMP project the following climate scenarios were chosen, with respect to rainfall and evaporation:

- Future wet: -1.4% change in mean annual rainfall from 1975 – 2007
- Future medium: -8.7% change in mean annual rainfall from 1975 – 2007
- Future dry: -16.2% change in mean annual rainfall from 1975 – 2007
- Historical wet: +14.3% change in mean annual rainfall from 1975 – 2007

The future wet, medium and dry scenarios represented the 10th, 50th and 90th percentile average annual rainfall for a suite of 45 scenarios generated from global climate models, predicted for a rainfall sequence for 2030. As such, the "future wet" climate scenario had marginally less rainfall than the current climate scenario. The methodology and data generated from the 15 down-scaled global climate models simulated at global temperature increases of 0.7^{o}C, 1.0^{o}C and 1.3^{o}C was taken from CSIRO's South-West Sustainable Yields Project (CSIRO, 2009).

Scenario results were presented both spatially and quantitatively (changes in water balance). For the historical wet climate scenario, a 15% increase in rainfall resulted in a large predicted increase in surface water flow (87%), but a relatively small change in AAMaxGL (0.42 m). Conversely, the future dry climate predicts a large decrease in surface water flow (-43%), but also predicts a relatively small change in AAMaxGL (-0.56 m). To put this into context, regions of the south-west which had minimal seasonal water-logging predicted reductions in groundwater levels in excess of 10 m for the future dry scenario, according to the CSIROs south-west sustainability yields project.

These results make it apparent that in the Murray DWMP region, surface flow acts as a buffer for the change in maximum groundwater level. It should be noted that should rainfall continue to decrease, the areas of water-logging in the Murray region will also decrease and could effectively exhaust the buffer capacity. Should this occur, groundwater levels could decline more drastically with further changes in annual rainfall, causing seasonal wetlands to permanently dry and surface water flows will cease in many waterways.

Sub-surface drainage was modelled in 11 development areas in the Murray DWMP region at a range of drainage depths. The total drainage volume from all development areas was predicted to increase from 4.2 GL/yr (base case scenario with no development) to between 12 GL/yr (dry climate, drains at ground level) and 22 GL/yr (wet climate with the drains at 1.0 m below ground level).

The effects of a 0.9 m sea level rise are confined to the western coastal corridor and to the region surrounding the Murray River to Pinjarra, where groundwater levels are predicted to rise by approximately 0.2 m by 2030. Water-logging (groundwater inundation) was predicted to be extensive throughout the DWMP area for all climate scenarios, and was predicted to be most severe in the low-lying coastal plain, away from major rivers and sand dunes systems. The likely areas of water-logging over the period of modelling for the current climate pre-development scenario are displayed in Figure 6.

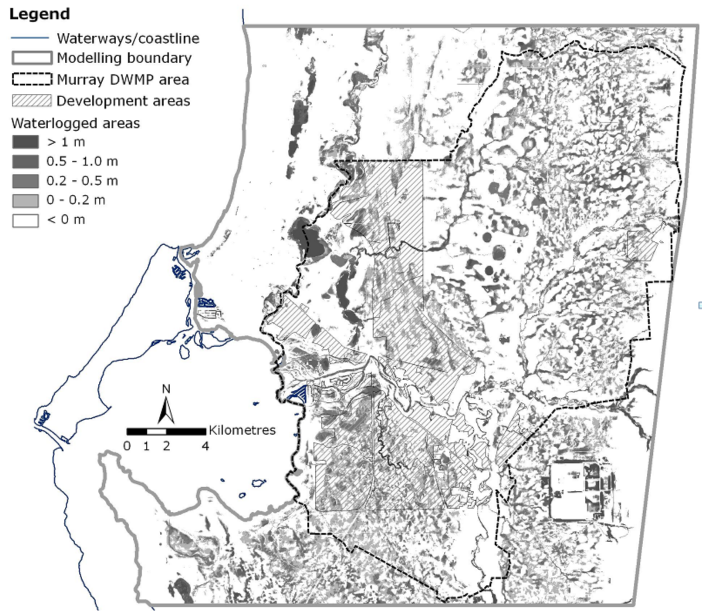

Figure 6. Predicted water-logging for the Murray region (Maximum phreatic surface for 1978 – 2007).

Domestic bore abstraction was modelled for the development areas. The use of domestic bores was predicted to have significant affects on sub-surface drainage quantities and on minimum groundwater levels. Average annual minimum groundwater levels were predicted to decrease by approximately 0.6 – 0.9

m compared to a similar scenario without garden bores, increasing the potential for acid sulphate soil issues. The use of domestic bores was predicted to significantly decrease sub-surface drainage volumes – a decrease from 12.4 GL/yr – 5.4 GL/yr was predicted for the future medium climate scenario modelled.

4. CONCLUSIONS

A regional integrated surface water and groundwater model was constructed and calibrated for the Murray region in south-west Western Australia. An integrated model was imperative in this catchment, which displays significant water-logging, extensive drainage networks to relieve groundwater inundation, and wetlands of significance. The process of model conceptualisation, construction, calibration and simulation provides an appropriate framework for model evaluation and provides a high level of confidence in modelling results.

Calibration to a series of groundwater heads and surface water flow gauge readins was undertaken for selected data between the years 1985 and 2000. The calibration resulted in an SRMS of 2.02%, an RMS of 0.80 m, and the average absolute error of 0.52 m. The model calibration satisfied the criteria of a water balance error <0.05%, an iteration residual error <0.1% and a scaled RMS error <5%.

The Murray regional model provided regional groundwater levels, areas of groundwater inundation, estimated drainage volumes from development areas, effects of sea-level rise, and changes in surface water flows for a variety of climate, drainage and development scenarios. The results were used to determine regional-scale affects and for guidance of groundwater management for future urban development. The model grid size and calibration error may prevent the usage of the model for detailed drainage design; however the model is suitable to act as a basis for developing higher-resolution subregional and local models that are more appropriate for this type of evaluation. The results of the Murray MIKE SHE modelling exercise were used in the Murray Drainage and Water Management Plan, a key deliverable to the Western Australian Planning Commission, used to guide stakeholders in future urban water management in the Murray region.

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