

The Environmental Systems Modelling Platform (EnSym) to Assess Effects of Land Use Changes on Groundwater Recharge

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Abstract: This paper describes an application of EnSym (Environmental Systems Modelling Platform) to assess the impacts of climate change on the groundwater levels in Victoria. EnSym is a modular and user-friendly software platform to facilitate the use of environmental modelling tools. It enables easy and rapid evaluation of environmental outcomes due to changes in land management and climatic conditions. It contains a number of toolboxes that deal with different aspects of the environment including land based biophysical process, groundwater dynamics, spatial and contextual connectivity, and finally, a set of tools for systematic spatial and temporal reporting. In this paper, we apply the biophysical modelling (BioSym) toolbox of EnSym to estimate the amount of recharge to the Victorian groundwater system for specified land use scenarios. The groundwater recharge obtained from BioSym forms the transient inflow to the groundwater system. The modular three dimensional finite difference ground water flow model (MODFLOW) is used to simulate the response of the groundwater system to the transient recharge.

We report results of simulating climate change (with a focus on lower rainfall) and its impact on groundwater levels and storage over time. The results can be used as a catchment planning tool, a research tool or to aid cost-effective decision making when planning for future water resource use.

Keywords: Biophysical modelling; BioSym; DFlow; EnSym; groundwater modelling; recharge.

1 INTRODUCTION

It is well recognized that many parts of the world will face significant fresh water shortages in the future, due largely to growing populations and increased agricultural and industrial demands. Fresh water sources could also become impaired through the disposal of wastes, from excessive irrigation and fertilization practices in agriculture, or from simple overproduction and overexploitation. For many communities, the development of new water sources increasingly involves the combined use of surface water and groundwater. The effects of excessive and unsustainable groundwater development may not be immediately evident but ultimately can threaten our natural resources. To sustain groundwater as a long-term reliable resource, factors affecting both the quality and quantity of groundwater must be better understood to inform future decision making. These factors include its abundance, distribution, movement and pollution.

It is recognised that groundwater modelling is the best tool to support management of groundwater resources. In the last two decades, there has been a rapid development of the computational tools for groundwater modelling. In most cases these computer programs are very sophisticated, being able to address a wide range of water-related problems very efficiently, provided the appropriate

data are available to calibrate models in a reliable manner. However, such data are not usually available. The knowledge related to reliable data acquisition, data integration and data extrapolation, particularly regarding spatial data up scaling and spatio-temporal data integration is far less developed than the modelling techniques themselves. In the past few years, the Victorian Government in Australia has been funding a work program to develop reliable groundwater models for all the catchment management regions (watershed) of the State. This work program is still ongoing. Groundwater modelling also requires many source and boundary conditions. These include the location of water bodies, evapotranspiration rates and profile, extraction from and recharge to the groundwater system.

The primary aim of this paper is to report on the modelling system that we have developed to integrate surface and subsurface modelling to assess the effects of land use and climatic changes on groundwater. We call this modelling system EnSym - Environmental Systems Modelling Platform. The second aim is to present some preliminary results from an application of EnSym to case study of the responses of the groundwater system of the Corangamite catchment area due to normal and reduced recharge scenarios. The reduction could be the result of land use change or lower rainfall.

In this paper, we apply the biophysical modelling (BioSym) toolbox of EnSym to estimate the areal distribution of recharge for use as sources of supply to a groundwater flow and transport model. In this paper, we also take evapotranspiration into account in groundwater modelling. Again, we apply BioSym in supplying the information about the evapotranspiration surface and extinction depth. Different amounts of recharge to the groundwater system and a different evapotranspiration regime will result from different specified land use and climatic scenarios. The groundwater recharge obtained from BioSym forms the transient inflow to the groundwater system. In this paper, the modular three dimensional finite difference groundwater flow model (MODFLOW) is used to simulate the response of the groundwater system to the transient recharge. In this way, the impact of environmental changes on groundwater levels and storage over time can be estimated. The results can be used as a catchment planning tool, a research tool or to aid cost-effective decision making when planning for future water resource use.

2 ENVIRONMENTAL SYSTEMS MODELLING PLATFORM (EnSym)

In this section, we will discuss the Environmental Systems Modelling Platform (EnSym) and some of its toolboxes that we have developed for integrated surface and subsurface modelling of the environment at the catchment scale. EnSym is a modular and user-friendly software platform to facilitate the use of environmental modelling tools. It enables easy and rapid evaluation of environmental outcomes due to changes in land management and climatic conditions. It contains a number of toolboxes that deal with different aspects of the environment including land based biophysical process, groundwater dynamics, spatial and contextual connectivity and finally a set of tools for systematic spatial and temporal reporting.

The software provides a stand-alone package that allows user to operate in a “black box” mode, which hides implementation details and usages of the modelling tools. The overlying user interfaces are written in Matlab programming language using a modern design with graphical user interfaces. The environmental modelling tools can be written in any computer programming language. This may, in the long run, contribute to new ways of sharing scientific research. By sharing both data and modelling tools in a consistent framework, the integration and application of new modelling tools into environmental and natural resource management will be straight forward.

The input interface of EnSym will automatically subdivide a catchment and then extract model input data from map layers and the associated relational data bases for each catchment. Soils, land use, weather, management, model and topographic data are collected and transferred to appropriate model input variables. These data sets for modelling the Victorian environment had been collected over a number of years by the Victorian Government. The output interface allows the user to display output maps and numerical and graphical output data by selecting a point from the

map. Users can thus visualise, interpret and test outputs such as sensitive changes in climate, land use and land management practices through a single interface,

EnSym is developed by the Victorian State Government using a version control system to assist in collaborative development, documentation, and feature tracking. While users do not need to study EnSym's source code, collaborators are welcome to become involved and add new modelling modules, tools and functionalities. Matlab provides gateway wrappers to provide easy access to external modelling programs. One particular design aspect of EnSym is that it can handle dynamic model loading and can easily switch between different tools.

Two of the key toolboxes of EnSym are the biophysical (BioSym) and surface flow (D-Flow) toolboxes. The BioSym toolbox simulates daily soil/water/plant interactions, overland water flow processes, soil loss, carbon sequestration and water contribution to stream flow from both lateral flow and groundwater recharge. The agronomic models can be applied to any combination of soil type, climate, topography and land practice. BioSym can thus be used to evaluate the impacts of climate change, vegetation types (e.g. cropping, grazing, forestry and native vegetation) and land management (e.g. forest thinning and stocking rates) in different parts of the landscape. D-Flow predicts surface water flow directions from digital elevation model (DEM). Flow directions are needed in hydrology to determine the flow paths of water and the movement of sediments, nutrients and contaminants. These two toolboxes of EnSym as well as the groundwater flow model, MODFLOW, are described in the next sections.

2.1 Biophysical Modelling (BioSym)

BioSym is a continuous time model that operates on a daily time step. The objective in model development was to predict the impact of management on water, sediment, and agricultural chemical yields in the catchment. To satisfy the objective, the model (a) is physically based (calibration is not possible on catchment scale); (b) uses readily available inputs; (c) is computationally efficient to operate on catchment scale in a reasonable time, and (d) is continuous time and capable of simulating long periods for computing the effects of management changes. The modules in BioSym come from publicly available models. They include CAT (Beverly [2007]), PERFECT (Littleboy et al. [1989]), EPIC (Williams et al. [1989]) and SWAT (Neitsch et al. [2002]). Recently, we upgraded our 3PG+ forest model to its latest version (Feikema et al. [2010]). These models are widely used by the environmental modelling community. The readers are referred to the open literature for references of their developments and model validations.

The physically based models in BioSym provide detailed representations of fundamental processes such as plant growth, infiltration, evapotranspiration, runoff, erosion and sediment transport, nutrient and pollutant transport, stream transport and management practices. By modelling each process separately, the simulation is sensitive to climatic change, land use activities and management changes.

BioSym solves for physical processes conceptually by using simplified analytical solutions and empirical equations. The code for BioSym was written with the objective of simulating all major hydrologic components as simply and realistically as possible, and to use inputs readily available over large spatial scales to enhance the likelihood that the model would become routinely used in planning and water resource decision making.

2.2 D-Flow

D-Flow uses the principles of single and multiple flow algorithms, such as Deterministic 8 (D8) and D_{∞} , to direct the flow from each cell to one or more of its 8 neighbouring cells based on the steepest downslope drop. It borrows ideas from image processing to correct the shortcoming of the mentioned flow algorithms in their inability to route flow over flats and sinks as well as to take into account the retention capability of depression drained areas (Chua et al. [2009]). D-Flow follows the flow of water in the catchment, from land areas to streams and rivers, through lakes, to

estuaries and ultimately to the ocean. The use of D-Flow is to move the runoff from one part of the landscape to the next. Water movement is related to erosion, to sediment, nutrient and pollutant transport.

2.3 Groundwater Modelling

Groundwater modelling uses numerical models that approximate the solutions of governing partial differential equations that describe the flow of water in the ground. The ground is typically described as a porous medium with varying densities and water holding capacities. In this paper, the modular three dimensional finite difference groundwater flow model MODFLOW (McDonald and Harbaugh [1988]) is used to simulate the response of the groundwater system to the transient recharge.

3 SIMULATION RESULTS

In this section, we present the results of our preliminary groundwater modelling of the Corangamite Catchment Management Authority (CCMA) region of Victoria, Australia. The CCMA region covers over 1,335,000 ha or 6% of the State of Victoria. The region is bounded by the Victorian coastline to the south-east, the central highlands (Midlands) to the north, stony rises to the west and sedimentary/volcanic plains to the east (Robinson et al. [2003]). Figure 1 shows the DEM and geomorphology of the Corangamite region. The axes in the DEM figure are in cell units. Each cell is 200 m in length. The DEM is made up of 842 columns and 795 rows. The map of Figure 1(b) taken from the report of Robinson et al. [2003] shows the water bodies and the 3 broad geomorphic divisions of the Corangamite region including the Western Uplands, Western Plains and Southern Uplands.

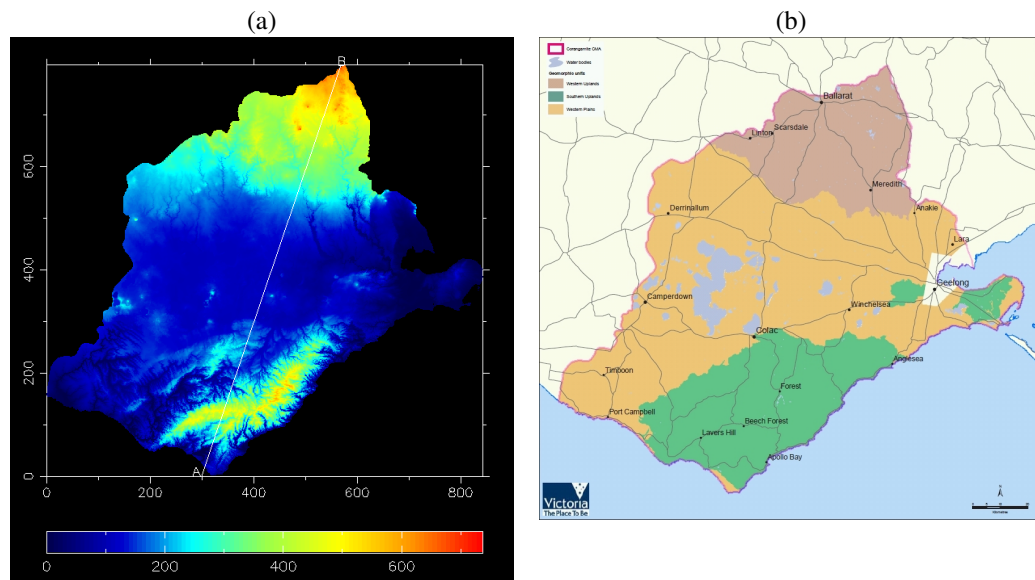


Figure 1: (a) DEM and (b) geomorphology of the Corangamite catchment, Victoria.

The model for groundwater flow is made up of 5 layers of 842×795 regular cells of dimension $200 \times 200 \text{ m}^2$. The height of each layer varies spatially. Not all the cells are active cells for groundwater flow. The cells coloured black in the DEM of Figure 1(a) are inactive cells. The 3-dimensional structure of the 5-layered model is shown in Figure 2. For clarity, only the land

surface and the bounding surfaces of layer 5 of the model are shown for two regions of the catchment. The horizontal coordinates in cell units give the precise locations of these two regions in the Corangamite catchment shown in Figure 1. Figure 2 shows the top surface of layer 5 of our groundwater model reaches the land surface at some parts of the catchment. The regions where the top surface of layer 5 becomes the land surface in Figures 2a and b are in the Western and Southern Uplands shown in Figure 1b respectively.

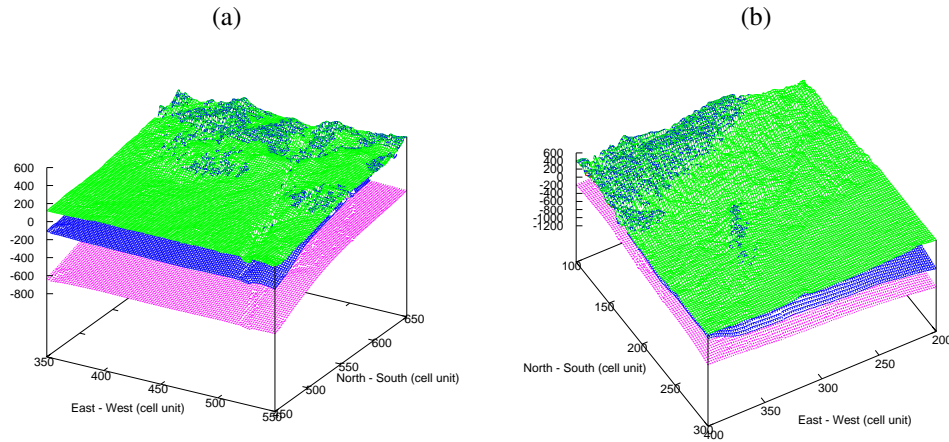


Figure 2: The layered groundwater model showing the land surface (green), the top (blue) and bottom (magenta) surfaces of layer 5 are shown for two regions of the catchment. For clarity, the other layers of the model are not shown. Figures (a) and (b) show the regions near the top and bottom of the catchment shown in Figure 1 respectively.

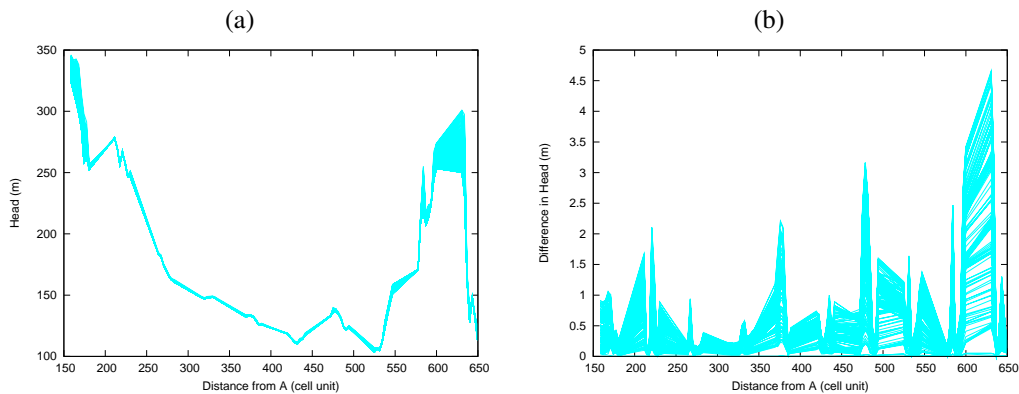


Figure 3: Cross-section of the surface of the head on the vertical plane through the line joining A and B of Figure 1a; (a) the temporal fluctuation of the heads of the normal recharge scenario; (b) the temporal fluctuation of the differences between the heads of the normal and reduced recharge scenarios.

The water bodies shown on the map of Figure 1(b) are constant head regions. We assume the initial head is the same as the elevation of the region. In the MODFLOW simulations carried out for this paper, the preconditioned conjugate gradient algorithm is used for solving the simultaneous equations resulting from the finite differencing of the governing equations of the groundwater problem.

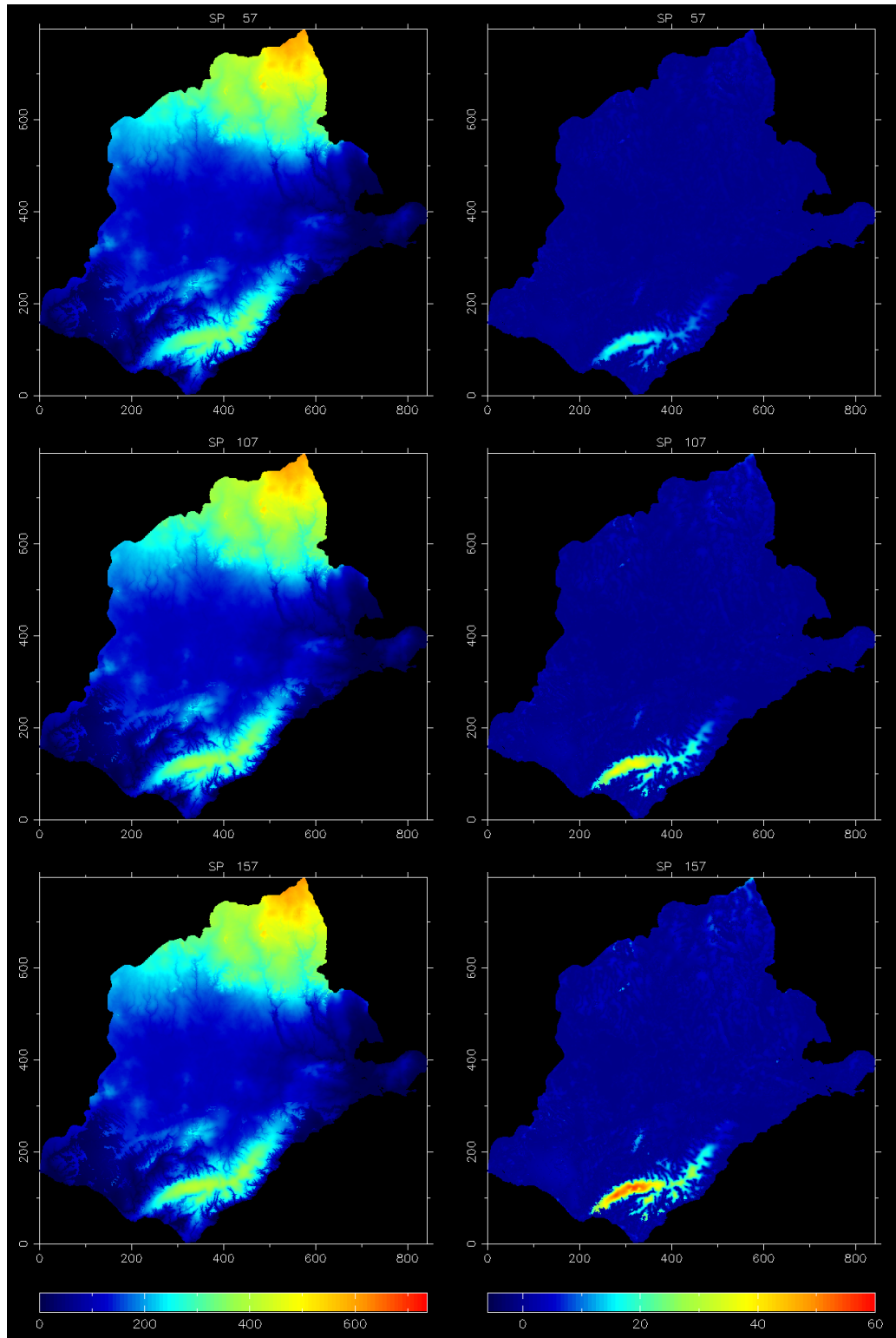


Figure 4: Potential head (left) and difference in head between normal and lower recharge scenarios (right) at 3 equally spaced stress periods.

Any water from rain and irrigation that are not consumed by vegetation in the landscape, stored in the soil, lost by evaporation or depleted by lateral flow is assumed to be recharge to the groundwater system. This source of water supply to groundwater is estimated from biophysical simulation of the CCMA region using BioSym. The BioSym simulation also provides the evapotranspiration surface and extinction depth data for the groundwater modelling using MODFLOW. Typically, BioSym simulation over a 50 year period is carried out. However, groundwater modelling demands much greater computer resources and CPU cycles. In the transient MODFLOW simulations we carried out for this paper, the modelling is done over 157 constant stress periods each of which is 7 days long. That is, the CCMA groundwater system is simulated for just over 3 years. In order to compare the effect of lower supply of recharge to the groundwater, the surface and subsurface simulations are repeated for reduced rainfall scenario so that the overall recharge is 50% below the normal scenario. It will be an interesting future study to examine the sensitivities of the groundwater system to different levels of overall recharge changes.

The results of the MODFLOW simulations are presented in Figures 3 and 4. On the left column of both figures, the results of the normal recharge scenario are shown. On the right columns of both figures, the difference between the heads of normal and reduced recharge scenarios are shown. In Figure 3, the vertical axis is in metres and the horizontal axis is in cell units measured from point A of Figure 1(a). Figure 3a shows the cross-section of the surface of the head on the vertical cut plane through A and B of Figure 1(a) for all the stress periods. Each curve in the figure represents the level of the head at a point in time. The vertical spread of these curves give a measure of the amplitude of head fluctuation with time. Figure 3b shows the differences resulting from subtracting the heads of reduced recharge scenario from the heads of normal recharge scenario. Again, the figure shows the cross section of the surface of this difference on the vertical cut plane through A and B of Figure 1(a). The figure shows the magnitudes of the differences vary with time. They can be fairly small at times but can be more than 4 m at other times. Figure 3a shows that the head levels change by small amounts in most places from A to B. Larger variations in the head levels occur near A and B. These large fluctuations in head levels occur in the Southern and Western Uplands of the catchment. In Figure 4, the head levels are colour shaded with low values represented by the blue end and high values represented by the red end of the rainbow spectrum. The results at the end of stress periods 57, 107 and 157 are shown. They show the lateral and vertical movements of the head with time in different parts of the CCMA region. For example, the Southern Uplands generally shows an increase in head levels with time. The southern part of the Western Plains, on the other hand, shows a decrease with time. Animations of the figures will show the dynamics of head movement with time more clearly. On the right columns of Figure 4, the difference between the heads of normal and reduced recharge scenarios are shown. The simulation results show that the major differences between the two scenarios occur in the Southern Uplands. It is not surprising to note that the heads for the reduced recharge scenario are lower for all times than that of the normal recharge scenario.

CONCLUDING REMARKS

In Section 2, we present the EnSym (Environmental Systems Modelling Platform) software platform to facilitate the use of environmental modelling tools and some of the toolboxes we have developed for it. Two of the toolboxes we used for obtaining the results for this paper are the BioSym and D-Flow toolboxes. The EnSym software platform can also launch external modelling tool such as MODFLOW that we use for modelling groundwater flow.

In this paper, we show an application example of how EnSym can be used to study the impact of land use and climatic changes on the groundwater system. In particular, we show the integration of surface and subsurface modelling through EnSym to predict environmental outcomes. Using the preliminary groundwater model of the Corangamite region, the BioSym and D-Flow toolboxes were applied through EnSym to obtain the required recharge and evapotranspiration data for groundwater modelling. The groundwater modelling results obtained in the last section show the expected lowering of head for the reduced recharge scenario.

Government policy area is one of the key drivers behind the development of EnSym and the continued improvement and validation of its modelling capabilities. In the area of water resource management, there is the need to develop a protocol for quantifying the State's groundwater budget. This information will be coupled with projected changes in land use and pumping demand to define the effects of several development scenarios on the community's water supply. Once developed, this protocol will enable other communities to decide how to best protect vital groundwater recharge areas, where precipitation replenishes local aquifers. This will also help communities examine how changes in groundwater levels will affect local streams, lakes and wetlands. The environmental systems modelling platform EnSym facilitates the incorporation of the various interactive influences into the resource management decisions. The simulation results presented in the last section demonstrate that EnSym can be used as a catchment planning tool, a research tool or to aid cost-effective decision making when planning for future water resource use.

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