



**The Berg River Dynamic Spatial  
Equilibrium Model:  
A New Tool for Assessing the Benefits and  
Costs of Alternatives for Coping With  
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and Climate Change in the Western Cape**

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# **The Berg River Dynamic Spatial Equilibrium Model: A New Tool for Assessing the Benefits and Costs of Alternatives for Coping With Water Demand Growth, Climate Variability, and Climate Change in the Western Cape<sup>1</sup>**

John M. Callaway, Daniël B. Louw, Jabavu C. Nkomo, Molly E. Hellmuth, and  
Debbie A. Sparks

## **1. Introduction**

The Berg River Basin is located in the Western Cape Region of South Africa. The upper Berg River Basin provides the bulk of the water for household, commercial, and industrial use in the Cape Town metropolitan region. It also provides irrigation water to the lower part of the basin to cultivate roughly 15,000 hectares of high-value crops, primarily deciduous fruits, table and wine grapes, and vegetables both for domestic and export use with strong multiplier effects in the domestic and national economy. Since the early 1970s, water consumption in municipal Cape Town has grown at an average annual rate of about 3%. As the population of the metropolitan Cape Town region grows, the competition for water in the basin has become even more intense, and farmers have responded by dramatically improving their irrigation efficiencies and shifting even more land into the production of high-value export crops. Meanwhile, over the past two decades, a number of national and regional

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commissions have been set up to investigate options for coping with the long-term water supply problems in the basin.

One outcome of these efforts was the authorization of the Berg River (originally Skuifraam) Dam. In June 2004, after almost twenty years of debate about its economic feasibility and environmental impacts, final agreement was reached on the construction of the dam. It will consist of a 130.1 million cubic meter storage reservoir and a pumping site to pump water from below the dam back to it. The dam is expected to be operational sometime during the period 2008–2010.

The region has also recently experienced a number of unusually dry years, the most recent in the summer of 1994–1995, when peak storage in the upper basin was only about one-third of average. At the same time, concerns about the effects of global warming on basin runoff have been growing, along with suggestions that recent climatic anomalies may be associated with regional climate change. Not surprisingly, planning for the Berg River Dam and other water supply and demand options in the basin has, up until this point, failed to take into account the possibility that the buildup of greenhouse gases in the global atmosphere is already affecting and will continue to affect the regional climate by reducing runoff in the basin.

## **2. Objectives**

The context for this paper consists of three main elements in the Berg River Basin.

The first is the increasing competition for water between urban and agricultural water users because of growing urban water demands; second is the threat of unusual

climate variability and/or climate change to exacerbate that competition; and third is the planning and policy responses to these issues. Putting the three together, we came up with the need to develop a policy-planning model that can be used to evaluate a wide range of structural, nonstructural, and technological measures for coping with basin water shortages. The model we have developed to do this is called the Berg River Dynamic Spatial Equilibrium Model (BRDSEM).

The objectives of this paper are, first, to describe the structure BRDSEM (section 3); second, to illustrate some of the ways the model can be used to assess the benefits, costs, and risks of avoiding climate change damages by increasing maximum storage capacity in the Berg River Dam and/or implementing a system of efficient water markets (section 4); fourth, to present the results and major conclusions of this analysis for three deterministic climate scenarios (section 5); fifth, describe the limitations of the current version of the model and analysis methods and outline future plans for improving the model and analytical methods (section 6).

### **3. The Model**

BRDSEM is a dynamic, multiregional, nonlinear programming (DNLP) model patterned after the “hydro-economic” surface water allocation models developed by Vaux and Howitt for California (1984), Booker (1990), and Booker and Young (1991, 1994) for the Colorado River Basin and by Hurd et al. (1999, 2004) for the Missouri, Delaware, and Apalachicola-Flint-Chattahoochee river basins in the United States. This type of model is a more specific application of spatial and temporal price and allocation models due originally to Samuelson (1951) and Takayma and Judge (1971)

that have been widely applied in many natural resource sectors (McCarl and Spreen, 1980). Hydro-economic models have been used by Hurd et al. (1999, 2004) to estimate the economic impacts of climate change in the four large U.S. river basins. In these two studies, the authors provided estimates for the economic losses due to climate change that took into account only short-run adjustments to climate variability. They did not specifically assess the benefits of long-run measures for avoiding climate change damages, such as investments in storage capacity and changes in water allocation institutions and laws.

Building on this past work, BRDSEM was designed specifically to estimate the economic value of the damages due to climate change with and without long-run adaptation measures and thereby isolate the benefits and costs of avoiding climate change damages. This paper represents the first attempt, we know of, to quantify the benefits of avoiding climate change damages in economic terms in a water basin context using such a model.

BRDSEM is also an extension of a static spatial equilibrium model developed by Louw (2002) for the Berg River Basin to examine the potential of water markets in the region (Louw and Van Schalkwyk, 2001). Much of the data from that model is used in BRDSEM, but is being updated on a continuous basis. Significant modifications were made to Louw's model to add the spatial relationships between runoff, water storage, water conveyance, transfers, return flows, and water use in the natural and man-made hydrological systems and to account for the intertemporal aspects of reservoir operation in the upper and lower parts of the basin.

One of the important features added for BRDSEM is that it can determine, endogenously, the “optimal” (i.e., economically efficient) capacity of planned reservoirs and other structural works, or capacity can be fixed, exogenously. The model does this by satisfying an economic efficiency (i.e., Kuhn-Tucker) condition, namely, that the marginal capital cost associated with the “optimal” storage capacity is equal to the present value of storage in all periods where storage levels are at this maximum. The maximum capacity is determined in year 1 for all future periods and remains fixed thereafter.

### **3.1 Model overview**

Figure 1 is a schematic diagram of BRDSEM and the models that feed information to it. This figure shows three external sources of information inputs to BRDSEM:

- *A Regional Climate Model*: This model downscales general circulation model information about total precipitation and average daily temperature, by month, over 30-year periods for specific weather stations in the basin for climate variability/change scenarios.
- *A Regional Hydrologic Model*: This model—WATBAL (Yates, 1996)—converts the spatially differentiated monthly temperature and precipitation data for 30 years from the regional climate model into: 1) Monthly runoff at different runoff gages, 2) monthly reservoir evaporation coefficients for each storage and farm dam, and 3) monthly crop water use adjustment factors based on variations in potential evapotranspiration.
- *Inputs about Policies, Plans, and Technologies*: This represents the source of information that can be used to alter various parameters in the programming

model to reflect alternative demand- and supply-side policies, plans, and technologies.

The core of BRDSEM, shown in the box labelled “Dynamic Programming Model” consists of four main elements, linked together in a nonlinear mathematical programming (NLP) framework. The NLP was constructed using the General Algebraic Modelling System (GAMS) and solved simultaneously for thirty, twelve-month periods using the MINOS and CONOPT solvers<sup>1</sup>. The four main elements in the NLP portion of the model are:

1. A nonlinear (quadratic) objective function that characterizes the normative objectives of the agents in the model;
2. An intertemporal, spatial equilibrium module/matrix that characterizes the spatially distributed flow of water and water storage in the basin,
3. An urban water demand and supply module/model that is linked directly to the objective function, and the intertemporal spatial equilibrium matrix, and
4. A regional farm/irrigation module/demand model that is linked directly to the objective function and the intertemporal spatial equilibrium matrix.

The objective function and three modules are interlinked, dynamically and spatially, at different points of use in the basin and are solved together as a dynamic, nonlinear programming model over thirty twelve-month periods, using the monthly inputs from the hydrology module. The output of the model (i.e., solutions for endogenous variables) consists of (but is not limited to):

- Measures of the economic value of water (i.e., net returns to water) for water users, broken down by urban sector and farm region,

- The optimal storage capacity of the Berg River Dam,
- Various shadow prices for water transfers between reservoirs, water transfers from the upper to the lower section of the basin, for urban and agricultural uses and for instream flows, from which water “prices” can be constructed,
- Monthly reservoir storage releases and transfers, and reservoir evaporation for main storage and farm reservoirs, and
- Monthly water diversions and consumptive use by urban sector, farm regions, and irrigated crops in each region.

### **3.2 The NLP model structure**

The structure of the NLP model is described in much greater detail in Nkomo et al. (2006). As stated previously, the main elements of the NLP are:

- Objective function
- Spatial equilibrium matrix
- Urban demand and supply module
- Regional farm module

#### *3.2.1 Objective function*

The objective function of the model is to maximize the net present value of the net returns to water in the basin over thirty twelve-month periods. Thus, it is consistent with welfare maximization by water consumers, farmers, and water managers, and, thus, simulates the competition for water in efficient markets. However, the normative character of the objective function can be partially overridden by constraining water flows and water storage in the model to reflect different allocation and environmental

policies. The objective function also serves as an accounting mechanism for valuing the economic welfare of agents in the model—water users and water managers. As such, the net returns to water in BRDSEM (as reported in this paper) are defined as the discounted sum over a 30-year planning horizon of the following monthly stream of benefits minus costs:

### ***Benefits***

- Willingness-to-pay for water by the six urban consuming sectors in Cape Town and the municipalities in the basin, and
- Long-term farm income for the seven regional farms.

### ***Costs***

- The costs of operating the reservoirs and delivering water to both municipal consumers and the seven regional farms and pumping and transactions costs;<sup>2</sup>
- Long-term (investment) and short-run (variable) costs for the seven regional farms, including water delivery and on-farm pumping costs; and
- The capital cost of the Berg River Dam and Berg Supplemental Site (when the capacities are determined endogenously by the model).

### *3.2.2 Intertemporal spatial equilibrium module (matrix)*

BRDSEM is a spatially differentiated trade model, in which runoff nodes, reservoirs, and points of water use or diversion are physically (and algebraically) connected by flows of water in a way that is physically faithful to the natural and man-made hydrologic system. This part of the model is a matrix of linear equations and

constraints in the mathematical programming model that characterizes the water balances in the basin reservoirs—both storage and regional farm dams—and the spatially distributed physical linkages between runoff, water storage, and points of water use.

A schematic overview of the Intertemporal Spatial Equilibrium module, showing the physical connections between runoff points, major storage reservoirs and water users in BRDSEM is presented in Figures 2 and 3 (upper and lower sections). A more detailed hydrologic representation of both the upper and lower sections of the Berg River Basin can be found in Hellmuth and Sparks (2005) and Nkomo et al. (2006). There are six “sites” in the upper basin of BRDSM. Three of these sites constitute the major storage reservoirs in the model: Theewaterskloof (TWAT), Wemmershoek (WMRS), and the Berg Dam (BERG). There are two urban water demand sites: URB1 for the area around Stellenbosch and URB2 for Cape Town. The final site is the Berg Supplemental Site (BERGSUP), a pumping station below the Berg River Dam that collects runoff from below the dam and pumps it back to the Berg Reservoir.

Table 1 shows the runoff sources for each site, as well as the deliveries from and to other sites for each of the four upper basin sites as depicted in Figure 2. The runoff site labeled “OUTSIDE,” which provides water to URB2 (Cape Town) represents a small, fixed part of Cape Town’s water supply from reservoirs that were not explicitly characterized in the model. In future versions of the model we plan to explicitly model runoff and reservoir operation for all of Cape Town’s sources of municipal water supply in the larger, Boland Region.

Figure 3 depicts the flow and use of water in the lower part of the basin by the seven regional farms. These farms are located sequentially downstream of one another: Berg 1, Suid-Agter Paarl (SAP), Berg 2, Noord-Agter Paarl (NAP), Berg 3, Perdeberg (PB), Riebeek-Kasteel (RK). The available supply for each downstream farm (after BERG1) is equal to the sum of 1) the undiverted portion of the supply available to the previous user (or instream flow) as designated by F1 through F7 in Figure 3, 2) the return flows from the previous user, and 3) runoff from sources between the two users. The on farm use of water is depicted in the box in the lower right of Figure 3. Each farm has the following mix of options for using water. It can either divert and pump water from the river to irrigate crops or divert and transfer water to a farm reservoir for irrigation use later in the season. Part of the water used to irrigate crops, whether it comes directly from diversions or farm dam storage, is used consumptively by crops (as determined endogenously by BRDSEM), and the remainder returns to the river as return flow.

### *3.2.3 Urban water demand and supply module*

The quadratic willingness-to-pay function for water in the objective function for each of the six urban demand sectors is represented as the integral over monthly, linear Marshallian inverse water demand functions. Urban water demand water functions do not exist for Cape Town or the municipalities in the region, nor are there any empirical estimates for the price elasticities of demand. Gathering and assembling billing data and estimating new demand functions for BRDSEM was not possible because of limited project resources but is planned for the future.

The urban demand module in the original version of the model (Louw 2001, 2002), based on the positive mathematical programming (PMP) calibration method (Howitt, 1995), was significantly modified and simplified for this project for the following reasons. First, the nonlinear demand functions were local, Cobb-Douglas approximations that contained no choke price and caused unrealistic price-induced consumption substitutions. Second, the original algorithm incorrectly estimated and understated consumer surplus. Third, the use of PMP made the model inflexible for simulating demand growth that was significantly greater than observed consumption. This is because the shadow prices that were introduced into the demand formulation penalized consumption that was greater than the observed consumption data to which the demand and supply equations were calibrated, thus penalizing increases in water consumption due to economic development in the basin. Finally, lacking any information on waterworks costs, the water works supply curve in the original model by Louw was based on assumed and undocumented supply elasticity and both the slope and intercept of this function were fit using this information by means of PMP. Thus, the water works supply function played an important role in establishing urban water prices that was out of proportion to the data available to estimate its parameters. We decided not to use it, but we plan to estimate such a function in the near future.

The demand functions developed for BRDSEM are based on two pieces of information developed by Louw (2001, 2002) estimates of the price elasticities of water demand for the six consumer classes and estimates of base consumption and price data for the period 1972–2003.

The parameters A and B of the linear inverse demand functions

$P_{imt} = A_{imt} - B_{imt} * Q_{imt}$ , were fit by ordinary least squares using the following

equations:

$$A_{imt} = \bar{P}_{im} \frac{\varepsilon_i}{\varepsilon_i} \text{ and } B_{imt} = \frac{\bar{P}_{im}}{\varepsilon_i * F(1+g)^t * \bar{Q}_{im}} \text{ for all } i, m, t \quad (1)$$

where  $i$  is the urban demand sector,  $m$  is the month,  $t$  is the year,  $P$  and  $Q$  are the simulated water prices and consumption volumes,  $\bar{P}$  and  $\bar{Q}$  represent the base water prices and consumption volumes, and  $\varepsilon$  is the sector-specific own price elasticity of water demand. The expression  $F(1+g)^t$  is used to shift the demand curves out over time, consistent with linear aggregation of representative demand functions, from a fixed multiple of the base volume,  $F$ , by  $g$  percent per year to simulate demand growth over time.

Finally, the urban demand and supply module includes a provision to constrain the delivery of water on an annual basis from both TWAT, WMRS, and BERG reservoirs to urban demand, based on existing and proposed (for BERG) regulations. One part of simulating efficient water markets involves relaxing these constraints and allowing allocations to urban demand be determined competitively, based on relative water prices.

### 3.2.4 *The regional farm module*

The regional farm module was based on the linear programming regional farm formulation in Louw (2001, 2002). In each region, dynamic linear farm programming models simulate crop production and irrigation water use. Each regional farm model is linked to the spatial equilibrium model through the objective function, the on farm consumptive use balances, and dynamic balances for the on-farm reservoirs.

Each regional model contains production possibilities for seven dryland, and nine irrigated crops. Crops are further broken down on a short-term (annual) and long-term (perennial) basis. Each crop has a crop budget associated with it that specifies crop yield per unit area, input requirements per unit area, variable input costs per area unit, and crop price. Long-term crops (perennial crops) include the same information by growth stage from the establishment of the crop to re-establishment once the trees and vines have reached the maximum age at which they can be cultivated, plus investment costs for newly established trees and vines and carrying costs for the initial inventory already established. There are three irrigation technologies in the model (regular, supplemental, and deficit). Monthly irrigation intensities (consumptive water use) used in the farm models varied by crop, month, irrigation type, and growth stage (for perennial crops, except pasture) were taken directly from Louw (2001, 2002). A monthly annual adjustment is made for each climate change scenario, using crop factors (Hellmuth and Sparks, 2005; Nkomo et al., 2006) based on the potential evapotranspiration of each crop under higher/lower temperatures for each climate scenario.

Each farm model also includes flexibility constraints, required to set the upper and lower bounds from observed crop production areas. These restrictions are also used

to provide for risk since it is impossible to capture individual farmers risk behavior in such an aggregated model. However, these restrictions—particularly, the lower bounds—can also have the effect of preventing reallocation of water from farm to urban areas as water becomes scarcer. Therefore, the lower bounds on both long-term and short-term crop area were reduced in the climate scenario simulations to 10% of the land available for cultivation. Since almost all of the possible land that can be cultivated in the basin is currently under cultivation there was no need to change the upper bounds on crop area.

Finally, this module includes a provision to constrain winter and summer diversions of water by each of the seven farm regions on an annual, based on existing regulations. The second part of simulating efficient water markets in the basin is to relax these constraints and allow monthly water diversions to be determined competitively, based on relative water prices.

#### **4. Model Application: Methods and Scenarios**

##### **4.1 Economic methods**

The economic framework used in this paper for evaluating the costs and benefits of measures to avoid climate change damages was first presented in Callaway et al. (1998). It was extended to link adjustments (adaptation) to climate variability and climate change and to situations in which “regrets” occur when the climate that occurs, *ex post*, is not the same as the climate planners and policy makers anticipated in formulating and implementing their plans and policies, *ex ante* (Callaway, 2003, 2004a, b).

Table 2 illustrates the basic framework for estimating various benefits and costs associated with climate change and adaptation. In this table, it is applied to two climate states, the existing climate ( $C_0$ ) and climate change ( $C_1$ ), and a single long-run adaptation option, investments in reservoir storage capacity,  $K(C)$ , which is climate sensitive. The framework can be extended to multiple climate states and measures, including those that are not sensitive to climate in both deterministic and stochastic settings (Callaway, 2004b). Later on, in section 5, we show how this framework can be modified slightly to assess the effects of development on economic welfare and the net benefits of adjusting (adapting) to development.

The value of the net returns to water in each of the four cells is represented as  $W[C, K(C)]$ . This just means that the magnitude of net returns simulated by BRDSEM depends on the climate state and on the reservoir storage capacity that is determined, in part, by the climate state. From an *ex ante* planning perspective, the upper left cell characterizes welfare for the existing climate, with current water storage capacity adapted to the existing climate. The cell in the upper right represents the *ex ante* short-run “partial adjustments” that economic agents can be expected to make if the climate changes, but there is no new investment in reservoir storage. Note that water users and managers can adapt to many forms of extreme climate variability without knowing whether the climate is changing or not, by using short-run measures. For example, even though reservoir storage capacity is fixed at  $K_0$ , operating policies can be changed, cities can institute water restrictions and farmers can change their management. But unless people can detect climate change or are confident that it will occur, or estimate that the costs of planning for climate change are small if it does not

occur, generally, they will not undertake long-run measures. The cell in the lower right depicts the *ex ante* long-run welfare consequences that take place when economic agents fully adjust using long-run measures to adapt to the expected climate. The cell in the lower left, depicts an *ex ante* situation where water storage capacity is increased in anticipation of climate change that does not occur, a case of a proactive response.

Table 2 can also be used to measure the economic “regrets,” or costs, of implementing planning decisions based on *ex ante* climate expectations that are wrong in terms of *ex post* climate outcomes. There are two kinds of regrets: those associated with *caution*, which involve *not planning for climate change that is occurring* and those associated with *precaution*, which involve *planning for climate change that is not occurring*. In both cases, the net returns to water will be lower than if the *ex post* climate realization matched the *ex ante* climate expectation. In other words, regrets lead to costs.

Estimates of the costs of regrets can be made without assigning any explicit probabilities to different climate states but can also be cast in a Bayesian framework when better information is available to do so (Lindgren, 1968).

At the current time, lack of information about and our inability to predict the future behavior of the “drivers” of the Intergovernmental Panel on Climate Change emissions scenarios make it difficult not only to assign anything but uniform prior probabilities to do this, but also to conduct traditional expected value analysis, as shown in Callaway (2004b). A nonparametric approach, such as that embodied in the concept of regrets may be more appropriate for examining *ex ante* planning (i.e., long run) decisions that are affected by *ex post* states of nature about which we are truly

uncertain, whereas expected value approaches make more sense when risks can be quantified at some defined level of confidence. Finally, the concept of regrets is particularly relevant for long-run investments that are irreversible or costly to change, or have long lead-times and/or operational horizons, or whose performance is climate sensitive, such as water storage reservoirs.

Table 2 also can be used to illustrate the application of regrets theory to climate change. In an *ex ante*, *ex post* planning context, the cell entry in the upper right cell depicts the welfare consequences of planning for climate  $C_0$  (i.e., not planning for climate change) when the *ex post* climate turns out to be  $C_1$ . This represents an error of “caution”. The cell entry in the lower right represents a situation in which *ex ante* climate expectations and the *ex post* climate outcome coincide, while the cell entry in the lower left represents the welfare consequences of planning for climate  $C_1$  but the *ex post* climate turns out to be  $C_0$ . This represents an error of “precaution”. So-called “No regrets” measures (Smith and Lenhart, 1996) do not suffer from errors of caution since, by definition, their implementation improves welfare relative to the reference case, independent of the climate state change. For true no regrets options, the costs of caution will, in fact, yield net benefits (Callaway, 2004b). We will show how the concept of regrets can also be extended to development in section 5.

Using Table 2, one can construct the following series of definitions for various benefits and costs associated with planning (or not) for climate change:

- *Climate change damages (CCD)*– the *ex ante* welfare losses caused by climate change when economic agents only make short-run adjustments to climate variability or climate change (i.e., they do not adjust reservoir capacity) to

cope with climate change compared to the reference case:

$$CCD = W[C_1, K(0)] - W[C_0, K(C_0)].$$

- *Net benefits of adaptation (NBA)* – the *ex ante* welfare gains associated with reducing climate change damages by implementing long-run measures (i.e., adjusting the reservoir capacity) to avoid climate change damages, compared to the partial adjustment case:

$$NBA = W[C_1, K(C_1)] - W[C_1, K(C_0)].$$

- *Imposed climate change damages (ICCD)* – the *ex ante* welfare losses (climate change damages) that cannot be avoided by implementing long-run measures, compared to the reference case:

$$ICCD = W[C_1, K(C_1)] - W[C_0, K(C_0)].$$

- *The cost of precaution (CP)* – the *ex post* welfare losses that will occur as a result of planning for climate change that does not occur:

$$CP = W[C_0, K(C_1)] - W[C_0, K(C_0)].$$

- *The cost of caution (CC)* – the *ex post* welfare losses that will occur as a result of not planning for climate change that does occur (this is equal to the net benefits of adaptation, with the sign reversed):

$$CC = W[C_1, K(C_0)] - W[C_1, K(C_1)].$$

## 4.2 Policy scenarios

We wanted to illustrate how policy planners could use BRDSEM to the various benefits and costs associated with climate change and adaptation for different adaptation measures. We also wanted to show how to separate out both the effects of climate from those of development on basin-wide welfare and the net benefits of

adjusting to development from the net benefits of adapting to climate change. We selected two examples of adaptation measures that were relevant for the basin: building the Berg River Dam and replacing the existing regulatory framework for allocating water in the basin with a system of efficient water markets, an option that is currently being investigated in the context of the new national water law. We could have used other measures; however, these two seemed particularly important, both from a regional policy perspective and from the standpoint of the interaction of development and climate. These two measures were operationalized as follows:

- *Existing water use regulation:* Upper bounds were placed on summer and winter diversions by the seven regional farms as in Louw (2000, 2001) and on water diversions from TWAT and WMRS, consistent with current water allocation policy.
- *Efficient water markets:* We removed both the agricultural and urban allocation constraints to simulate the economically efficient allocation of water to both urban and agricultural users, without the Berg River Dam.

### **4.3 Climate scenarios**

We simulated the welfare consequences of the different policy options under both full (optimal) and partial adjustment for three deterministic, transient climate scenarios. A detailed explanation of the climate scenarios, the downscaling from the global circulation models to the basin weather stations, and the generation of the monthly hydrologic data used by BRDSEM is discussed in detail in Hellmuth and Sparks (2005) and Nkomo et al (2006). For this assessment, we used information provided by WATBAL for the following climate-hydrology scenarios:

- CSIRO SRES B2 REF Case (REF): 1961–1990 (applied to 2010–2039)
- CSIRO SRES B2 Near Future Case (NF): 2010–2039, and
- CSIRO SRES B2 Distant Future Case (DF): 2070–2099 (applied to 2010–2039).

We have monthly, downscaled climate information for the CSIRO and Hadley A2 and B2 scenarios. The CSIRO A2 and B2 scenarios project reductions in runoff (relative to the reference scenario) for both the NF and DF time periods, with the B2 scenarios being slightly more severe. The Hadley projections are mixed: the A2 scenarios show virtually no changes in runoff in the NF and DF time periods, whereas the B2 scenarios show reductions in runoff in the NF time period, but increases in the DF time period.

Our initial economic analysis uses only the CSIRO projections for the SRES B2 REF, NF and DF scenarios. There are two reasons for this: first, these scenarios showed the most severe effects on basin runoff and appeared to be more consistent with recent trends and, second, the long solution times of the CONOPT and MINOS solvers in conjunction with the large number of runs forced us to limit the analysis for the time being.

Each of these deterministic scenarios is time dependent (or transient), as indicated above, applying to specific years. We decided to apply all of the scenarios to the same period, 2010–2039, to avoid having to develop even more uncertain future scenarios for the 2070–2099 period. Thus, REF is a counterfactual reference case, assuming the same underlying runoff as in the period 2010–2039 as 1961–1990, while DF, instead of being a longer-term continuation of CSIRO B2, can be viewed as a more adverse

climate scenario, producing lower runoff and higher evaporation, compared to NF for the same time period.

#### **4.4 Urban water demand growth scenario**

Agricultural area in the basin has been relatively stable for the last half-decade and is not expected to grow much more due to limited land availability (Louw 2001, 2002). In addition, most of the irrigated land in the basin is already under drip irrigation and the potential for efficiency gains is quite small, and BRDSEM is capable of changing irrigation efficiencies on an endogenous basis. Furthermore, dryland agriculture is basically limited to areas without access to irrigation water and should conditions become drier and hotter, this lack of access is likely to drive this land out of production. For these reasons, we did not make any exogenous changes to the irrigated land base in the model.

However, urban water consumption in Cape Town is another matter. It has been growing rapidly at an average annual rate of about 3% since the mid-1970s (Louw 2001, 2002). In the real world and in our model, increases in water consumption over time will increase net returns to water as the sectoral water demand curves shift to the right. In other words, development increases welfare. But if we are to correctly estimate the costs and benefits associated with climate change and adaptation we need to be able to separate not only the effects of climate from the effects of development, but also the adjustments to development from the adjustments to climate as a result of the implementation of various adaptation options.

To illustrate how one can control for development and climate separately, we developed two urban water demand scenarios by adjusting the slopes of the monthly urban water demand functions (*Eq. 1*) using consumption data provided by the Cape Metropolitan Council (CMC)<sup>3</sup>. To do this, we first set the parameter  $F$  in *Eq. 1* to reflect current water demand growth from 2000 to 2010. Next, we set the parameter  $g$  in *Eq. 1* to reflect annual water demand growth rates in base-level water consumption, of 0% and 3%. The first adjustment to  $g$  holds the sectoral demand curves in place to reflect a counterfactual no-demand growth situation, whereas the second shifts the urban water demand functions horizontally to the right, as population and economic activity grows, but the intercept terms remain fixed. Thus, if water prices were held constant in the model, a shift of  $g$  percent in any sectoral demand curve would produce a  $g$  percent increase in water use.

#### **4.5 Other assumptions**

Economic values in this paper are calculated as constant South African Rand, based in year 2000 (Louw and Van Schalkwyk, 2001; Louw, 2002). This assumes that all input and output prices in the model are inflating at the same, constant rate. A constant, real discount rate of 6% was used to convert future value flows into constant present values. In sensitivity trials, reducing/increasing the discount rate had predictable effects on water use, increasing/reducing future consumption and, thus, increasing/reducing the endogenously determined maximum optimal storage capacity of the Berg River Dam.

### **5. Results and Main Conclusions**

Table 3 shows the simulated present values for the total net returns to water for four options, A–D, under three climate change, two urban water demand scenarios, with and without the Berg River Dam for the existing allocation system and water markets. The table also presents the “optimal” storage capacity of the Berg River Dam options C and D. All of the net returns to water depicted in this table represent the optimum values that can be achieved for each climate and urban demand scenario.

The first two conclusions we can draw from this table are fairly obvious: in all of the four cases, the net returns to water decrease as the annual average annual runoff in the climate scenarios decreases, holding urban water demand growth constant, and increase as urban water demand growth increases, holding climate constant.

Moreover, the percent reductions in the net returns to water become much sharper as urban demand growth increases. This directly raises the important question of how we can disentangle the effects of urban water demand growth from climate change in assessing these two options. This subject will be covered in Tables 4 through 6.

The results in Table 3 also show a consistent relationship between the net returns to water and the type of allocation method, namely: that allocation by water markets in cases B and D produces higher net returns than allocation by regulations in cases A and C. This should not be surprising, as BRDSEM is a normative model and the only differences between these two pairs of scenarios is that A and C are more highly constrained than B and D.

What is more important to note is that, as urban water demand increases, the differences in the reduction in net returns to water as runoff decreases due to the

allocation systems become more pronounced. In the no urban demand growth cases, the reductions in the net returns to water from the base case are around 5% for the DF climate and 10% for the RF climate for both allocation systems. However, when urban demand growth increases substantially, allocation by markets serves to moderate the decreases in the net returns to climate as climate change becomes more severe. Thus, simulating the substitution of efficient water markets in case B for the existing allocation system in case A reduces the percentage changes in basin-wide welfare from -22.6% (NF) and -40.1% (DF) in case A to -8.7% (NF) and -16.8% (DF) in case B. For cases C and D, the corresponding reductions in the percentage changes in basin welfare due to market substitution are -14.7% (NF) and -30.5% (DF) for case C (existing allocation system) and -6.9% (NF) and -13.3% (DF) for case D (water markets).

The last conclusions demonstrate forcefully that simulated water markets have a substantial moderating effect on the impact of climate change on basin-wide welfare as urban demand growth increases. But this is also true of dams, since the absolute values for the net returns to water are higher, and the percentage reductions due to climate change are smaller when storage capacity is added behind the Berg River Dam compared to the no dam cases, when urban demand growth is 3% per year. The fact that both dams and water markets influence the effects of climate change on basin-wide welfare again raises the issue of how we separate out both the effects of climate change and economic development on basin-wide welfare and the effects of these measures on climate change and development.

However, before we do this, we want to take one last look at the optimal reservoir capacity simulated for cases C and D due to climate change and development, at the bottom of Table 3. One thing is clear: as urban development increases, the need for additional storage capacity not only increases, but is also economically feasible. Nevertheless, two partly counter-intuitive results need further explanation. First, under the no urban demand growth scenario, optimal reservoir capacity is higher for water markets (Case D) than for the existing allocation system (Case C). This is because, at low urban water demand levels in the upper basin, reducing consumption is expensive in terms of consumer welfare losses, and the implementation of markets increases the marginal present value of storage capacity (or the opportunity cost of the lack of storage) more than the capital cost in this capacity range, leading to higher capacity levels in the market situation. As urban demand growth increases, markets tend to become substitutes for storage capacity, because the reductions in consumption (from very high prices) cost less, at the margin, than the additions to storage capacity at these very high storage capacity levels. Second, the pattern of storage capacity additions under high urban water demands is nonlinear with respect to climate change and the nature of this nonlinearity differs depending on the water allocation method. For option C, the optimal storage capacity of the Berg River Dam peaks under the DF climate scenario and then falls. This is because the marginal yield of the reservoir system due to increases in capacity falls sharply as runoff is reduced and development increases, leading to problems in filling the reservoir under the DF scenario and reducing the benefits of additional capacity. For option D, the optimal capacity decreases under the NF scenario and then rises. This is because lower basin runoff in the NF scenario varies in such a way relative to the upper basin that water

can be moved around by transfers much more easily to satisfy demand than by adding storage capacity, but this is not the case for the existing water allocation system.

Next, in Tables 4 and 5 we present the welfare results for two different strategies for incrementally adapting to development pressure, as represented in different assumptions about water demand growth, and climate change, as represented in the three-climate change scenarios. The strategy in Table 4 involves adapting, first, to development pressure and, next, to climate change by adding storage capacity under the existing water allocation system. The strategy in Table 5 involves adapting to development pressure in two steps, first by switching methods for allocating water to efficient water markets (A) and then by adjusting the storage capacity to be optimal for efficient water markets (B). Adaptation to climate change then takes the form of adding storage capacity under the market allocation system.

The first part of Table 4 looks at the effects of development pressure on the net returns to water and also estimates the benefits of adjusting to this development by adding additional storage capacity. The base case welfare for this analysis is R 58.724 billion (Part I: Row 1, Col. 1). When simulated urban water demand grows at 3% per year, but there is no increase in reservoir capacity in the basin (i.e., partial adjustment to development), basin-wide welfare increases to R 74.920 billion (Part I: Row 1, Col 2.). The net increase in welfare, R 16.196 billion (See Table 6), represents the *ex ante* net benefits of adapting to development pressure, holding climate constant at REF, and only allowing short-run adjustments to take place in response to urban water demand growth. However, if basin planners adjusted fully to this development pressure (but not to climate change) by adding  $151 \cdot 10^6 \text{ m}^3$  of storage capacity that was

optimal for this level of urban water demand growth, net returns to water would increase to R 90.116 billion (Part I: Row 2, Col. 2). This increase of R 15.196 billion represents the *ex ante* net benefits of adjusting (or adapting) to development pressure. This same amount with the sign reversed also represents the *ex ante, ex post* cost of not planning for development that does occur, or the cost of caution associated with development. If, on the other hand, the Berg River Dam was built at this level of capacity, but no increase in water demand growth occurred, *ex post* basin-wide welfare would drop to R 58.312 billion (Part I: Col 2, Row 1), which is R 412 billion less than the base case. This is the net welfare loss is the *ex ante, ex post cost* of planning for development pressure that does not occur, or the cost of precaution associated with development pressure.

The second part of Table 4 shows two different adjustments (adaptations) to climate change under the existing water allocation system that can be made in addition to the adjustment to development pressure:

- Adding 272 10<sup>6</sup> m<sup>3</sup> of water storage capacity to adjust to the NF climate scenario, and
- Adding 240 10<sup>6</sup> m<sup>3</sup> of water storage capacity to adjust to the DF climate scenario.

Both of these adjustments are presented in the same manner as Table 2, and the analysis is similar. The reference case for both of these adjustments is the post-development adjustment level of welfare, or R 90.116 billion (Part II: Col 1, Row1). If the climate changes and the level of urban demand growth is 3%, simulated net returns to water fall to R 76.683 billion (NF) (Part II: Col 2, Row 1) and R62.475 billion (DF) under partial adjustment to the two climate change scenarios. The

resulting welfare losses of R13.433 billion (NF) and R 27.641 billion (DF) represent the *ex ante* values of climate change damages. However, if basin storage capacity is increased from  $151 \cdot 10^6 \text{ m}^3$  to  $272 \cdot 10^6 \text{ m}^3$  (optimal for NF) or  $240 \cdot 10^6 \text{ m}^3$  (optimal for DF), *ex ante* net returns to water would increase to R 76.892 billion (NF) (Part II: Col 2, Row 1) or R 62.673 billion (DF) (Part II: Col 2, Row 4). The resulting increases in net welfare of R 0.209 billion (NF) or R 0.198 billion (DF) represent the *ex ante* values for the net benefits of adaptation under the two different climate scenarios, with urban demand growth at 3%. But these adaptation benefits are quite small relative to the value of climate change damages, so the simulated, *ex ante* imposed climate change damages are quite large, namely R 13.224 billion (NF) and R 27.443 billion (DF).

Following from this analysis, we can also estimate the *ex ante*, *ex post* cost measures associated with climate regrets. As, already stated, the cost of not planning for climate change that does occur (caution) are the same as the net benefits of adaptation with the signs reversed,  $-R 0.209$  billion (NF) or  $-R 0.198$  billion (DF). If the Berg River Dam is built but the climate does not change to NF or DF, then the *ex post* value of the net returns to water would be R 89.912 billion (NF) (Part II: Col 1, Row 2) or R 89.974 billion (DF) (Part II: Col 1, Row 4), which are R 0.204 billion (NF) or R 0.142 billion less than the reference case of R 90.116 billion. These are the estimated costs of precaution associated with the two climate change scenarios.

In Table 5, we show the results for the option of adjusting to development pressure by substituting efficient water markets for the existing allocation system and then increasing the storage capacity to  $138 \cdot 10^6 \text{ m}^3$  so that it is optimal for the market

allocation system. Adapting to climate change is then accomplished by changing storage capacity to  $128 \cdot 10^6 \text{ m}^3$  (NF) or to  $178 \cdot 10^6 \text{ m}^3$  (DF). Except for the two explicit steps (A and B) associated with the adjustment to development pressure, the logic of this table is the same as the previous one, and so we have dropped the cell references in the discussion that follows.

Part I of Table 5 shows that, if urban water demand growth increases at 3% per year, the *ex ante* net present value of welfare in the basin will increase from R 58.724 billion to R 74.90 billion, without any long-run adjustments by basin planners. If basin planners and managers adjust to this development pressure by instituting a system of efficient water markets, but do not build a storage reservoir, *ex ante* basin welfare will further increase to R 91.959 billion. If a storage reservoir is also built, and its capacity is optimal for the market allocation system and 3% urban water demand growth, then *ex ante* basin welfare rises even further to R 96.315 billion. This means that *ex ante* net benefits as a result of increased water demand growth are R 16.196 billion (See Table 6), the same for both strategies, since this development pressure is independent of the adaptation strategies. The net benefits of adjusting to the development pressure by switching to a system of efficient water markets to cope with the development pressure are R 17.039 billion (Step A). Adjusting the reservoir capacity to  $138 \cdot 10^6 \text{ m}^3$  so that it is optimal for the higher level of water demand growth and the new allocation system produces another R 4.356 billion in *ex ante* basin welfare, or R 21.395 billion (Step B), compared to the Base Case welfare level of R 58.724. Since the cost of caution is the cost of avoiding an error of caution (i.e., not anticipating the higher level of development pressure), one just needs to reverse the signs on the estimates for the net benefits of development. If efficient water

markets are implemented, *ex ante*, but the *ex post* level of demand growth is zero, net welfare in the basin would be R 59.847 billion and, if  $138 \cdot 10^6 \text{ m}^3$  of storage capacity were developed, *ex ante*, but the *ex post* level of demand growth remains at zero, basin welfare would increase just slightly from that to R 59.633 billion. These welfare levels are actually higher than the Base Case estimate of R 58.724. Thus, the resulting costs of precaution would be *ex post benefits* of R 1.123 billion and R 0.909 billion, illustrating nicely the “no regrets” character of these adjustments to development pressure.

The second part of Table 5 presents two different adjustments (adaptations) to climate change under the existing water allocation system that can be made in addition to the adjustment to development pressure:

- Reducing storage capacity to  $128 \cdot 10^6 \text{ m}^3$  to adjust to the NF climate scenario, and
- Increasing storage capacity to  $240 \cdot 10^6 \text{ m}^3$  to adjust to the DF climate scenario.

These adjustments can be interpreted in the same way as part II of Table 4, and so we will not present the details. The main highlights of this analysis compared to Table 4 (see Table 6 for comparative results) are as follows:

1. The market-oriented strategy (Table 5) increases basin welfare by a larger amount over the whole range of development and climate impacts and adjustments than the strategy relying on the existing allocation system (Table 4). The welfare difference is roughly R 12.8 billion (NF) to R 20.8 billion (DF), in favour of the market-oriented strategy, depending on the climate scenario.

2. The net benefits of adjusting to development pressure using the market-oriented strategy are R 1.8 billion to R 6.2 billion higher than those of the other strategy, depending on whether one just switches to efficient water markets or does this and also adjusts the reservoir capacity for the change in development pressure and water allocation system.
3. The development adjustment step in the market-oriented strategy also reduces the level of climate change damages by more than 50 percent compared to the other strategy for both the RF and DF climates. After the adjustment to development pressure, but before the adjustment to climate change, the level of climate change damages is R 6.8 billion (NF) to R 14.8 billion (DF) lower than for the other strategy, depending on the climate change scenario. As a result, switching to water markets acts like a “no regrets” insurance policy against having to adjust further to climate change.
4. Once water markets are instituted, the net benefits of adapting to climate change (in the market-oriented strategy) are quite small both in absolute terms and compared to the other strategy. This is because of the large reduction in climate change damages that occurs as a result of adjusting to development pressure.
5. For this reason and because the costs of both caution and precaution associated with climate change adaptation for the market-adjustment strategy are very low in both absolute terms and compared to the other strategy, the least-risky and most economically efficient option would involve adjusting to development pressure and climate change by implementing a system of efficient water markets (Step A) and increasing the reservoir capacity to  $128 \times 10^6 \text{ m}^3$  (Step B), without developing any additional storage capacity until more information is available about climate

change. Adding additional storage capacity above this level produces only small net benefits, but also has low costs of caution and precaution.

## **6. Limitations in the Analysis and Future Research**

BRDSEM, like many policy models, is a “work in progress”. Typically, models like this are never “final” and undergo numerous revisions as new data become available and new questions are asked. However, BRDSEM has reached the point in its development where it can be used to illustrate some of its policy uses, as done in this paper. Nevertheless, we would be remiss not only to identify its current limitations, but also how we plan to remedy them. The current version of BRDSEM and its application in this paper has the following limitations:

1. The parameters of the urban water demand functions are not estimated from empirical time series and/or panel data, but are “fit” algebraically using assumed elasticities and estimates of base-level consumption,
2. There is no upward sloping waterworks supply function to capture resource costs in purifying and distributing water to urban consumers, and we lack reliable data regarding the water supply elasticity to even “fit” these functions, algebraically,
3. The model lacks a full set of demand- and supply-side options for coping with demand growth, climate variability, and climate change,
4. The transactions costs associated with markets were ignored, and
5. The analysis was deterministic with regard to climate scenarios.

With future support from all of the elements of the regional and South African water and agricultural resources community, we plan to address the first four of these issues as follows:

1. and 2. Estimate the parameters of the urban demand and water works supply functions with empirical observations, using suitable econometric estimators to deal with the first two limitations.

3. Extend the model, generally, to the larger Boland Region to include representations of all current and alternative water supply sources, reservoirs and conveyance structures, and users in the region, as well as a larger set of demand- and supply-side options to overcome the third limitation.

4. In this analysis, we assumed that the transition from the current regulatory system to a system of efficient short- and long-run water markets would be frictionless and without cost. In the future, we plan to include a more realistic treatment of water transfers, including differences between long- and short-term water transfers and transactions costs.

5. The final limitation—the deterministic nature of the illustrative analysis in this paper—requires a bit more discussion. We used deterministic climate change scenarios, because downscaled stochastic climate scenarios don't currently exist for the region. The use of deterministic climate scenarios is adequate for demonstrating the model and the economic framework for estimating the benefits and costs associated with adjusting to climate change. But the results are unreliable because they do not reflect the underlying means, variances, and other moments of the partial and joint distributions of relevant meteorological variables at the appropriate spatial scales, nor does the runoff generated using the deterministic climate inputs. When such information becomes available, it will be possible to propagate the runoff,

evaporation and crop water use distributions through BRDSEM by maximizing the expected value of net returns to water for a single or for mixed climate distributions using the methods illustrated in Callaway (2004b). This will also allow us to explore the economic and physical consequences of runoff sequences that depart from mean values, that is: drier and wetter than average periods than reflected in mean runoff. Finally, it will allow us to explore more thoroughly the stochastic nature of *ex ante*, *ex post* regrets and the possibility of minimizing these regrets by policies and plans that are flexible over a wide range of mixed runoff distributions.

## Notes

1. The CPLEX solver has since replaced these solvers. A complete validation of the CPLEX solver results with the earlier ones is underway. Solution times have been reduced by two orders of magnitude, and the initial results show only small differences with the MINOS and CONOPT results.
2. One of the limitations of the current model is that it does not include urban water works and waste treatment costs because of lack of data.
3. Private communication with Cape Metropolitan Council (April, 2002): Excel spread sheet: “Monthly Water Supply Figures: calendar year 1970–2003”.

## References

- Booker, J. F. 1990. *Economic allocation of Colorado River water: Integrating quantity, quality, and instream use values*. Ph.D. thesis. Department of Agricultural and Resource Economics, Colorado State University, Fort Collins, CO.
- Booker, J. F., and R. A. Young. 1994. Modeling intrastate and interstate markets for Colorado River water resources. *J. Environ. Econ. Manage.* 26:66–87.
- Booker, J. F., and R. A. Young. 1991. *Economic impacts of alternative water allocations in the Colorado River Basin*. Colorado Water Resources Institute. Report 161. Fort Collins, CO.
- Callaway, J. M., L. Ringius, and L. Ness. 1998. Adaptation costs: a framework and methods. In: *Mitigation and adaptation cost assessment concepts, methods and appropriate use*, edited by J. Christensen and J. Sathaye. UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, Roskilde, Denmark.
- Callaway, J. M. 2003. *Adaptation benefits and costs—measurements and policy issues*. Environment Directorate: Environment Policy Committee, OECD. Report NV/EPOC/GSP (2003) 10/FINAL. Organisation of Economic Cooperation and Development, Paris, France.

Callaway, J. M. 2004a. Adaptation benefits and costs: Are they important in the global policy picture and how can we estimate them. *Global Environ. Change*. 14:273–282.

Callaway, J. M. 2004b. Chapter 4: The benefits and costs of adapting to climate variability and change. In: *The benefits and costs of climate change policies: analytical and framework issues*. Organisation of Economic Cooperation and Development, Paris, France.

Hellmuth, M. E., and D. Sparks. 2005. *Modeling the Berg River Basin: An explorative study of impacts of climate change on runoff*. AIACC Project Completion Report, Project No. 47. UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, Roskilde, Denmark.

Howitt, R. E. 1995. Positive mathematical programming. *Am. J. Agric. Econ.* 77:329–342.

Hurd, B. J., J. M. Callaway, P. Kirshin, and J. Smith. 1999. Economic effects of climate change on U.S. water resources. In: *The impacts of climate change on the U.S. economy*, edited by R. Mendelsohn and J. Neumann. London, UK: Cambridge University Press.

Hurd, B. J., J. M. Callaway, P. Kirshin, and J. Smith. 2004. Climatic change and U.S. water resources: from modeled watershed impacts to national estimates. *J. Am. Water Resour. Assoc.* 22:130–148.

Lindgren, B. W. 1968. *Statistical theory*. New York: MacMillan.

Louw, D. B., and H. D. Van Schalkwyk. 2001. Water markets: An alternative for central water allocation. *Agrekon*. 39:484–494.

Louw, D. B. 2001. *Modelling the potential impact of a water market in the Berg River basin*. Ph.D. thesis. University of the Orange Free State, Bloemfontein, South Africa.

Louw, D. B. 2002. *The development of a methodology to determine the true value of water and the impact of a potential water market on the efficient utilisation of water in the Berg River Basin*. Water Research Commission Report (WRC) No. 943/1/02. Pretoria, South Africa.

McCarl, B. A., and T. H. Spreen. 1980. Price endogenous mathematical programming as a tool for sector analysis. *Amer. J. Agr. Econ.* 62:88–102.

Nkomo, J. C., J. M. Callaway, D. B. Louw, M. E. Hellmuth, and D. A. Sparks. 2006. *Adaptation to climate change: the berg river basin case study*. Energy Research Center, University of Cape Town. Cape Town, South Africa.

Samuelson, P. A., Spatial price equilibrium and linear programming. *Am. Econ. Rev.* 42:283–303.

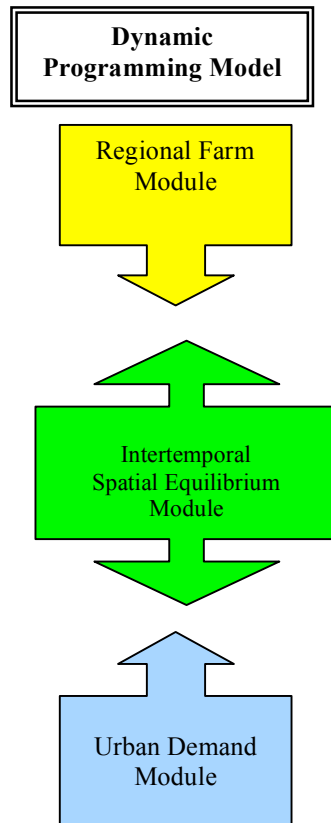
Smith, J. B., and S. S. Lenhart. 1996. Climate change adaptation policy options. *Clim. Res.* 6:193–201.

Takayama, T., and G. G. Judge. 1971. *Spatial and temporal price and allocation models*. London, UK: North Holland Press.

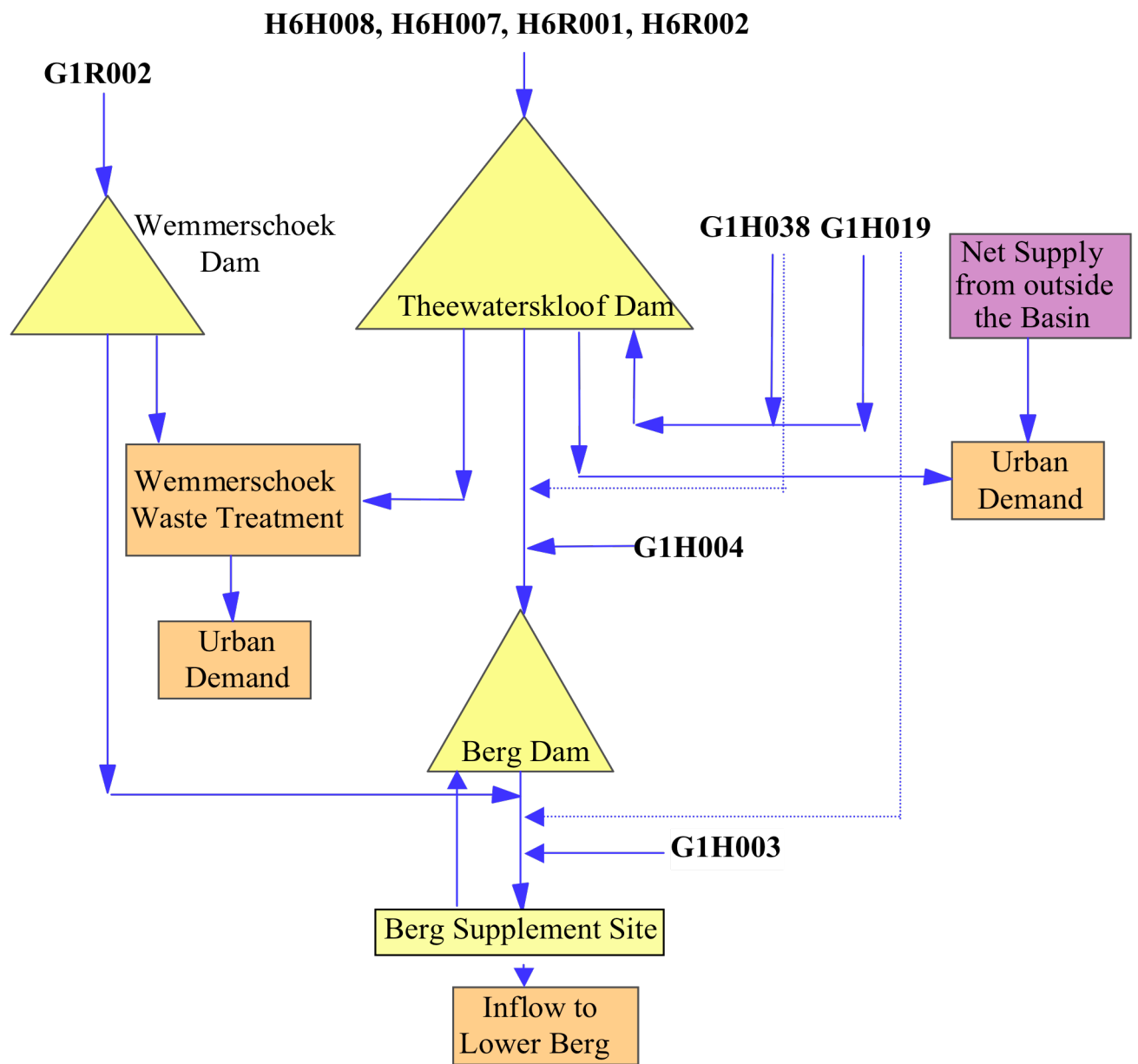
Vaux, H. J., and R. E. Howitt. 1984. Managing water scarcity: an evaluation of interregional transfers. *Water Resour. Res.* 20:785–792.

Yates, D. N. 1996. WatBal: an integrated water balance model for climate impact assessment of river basin runoff. *Water Resour. Dev.* 2:121–139.

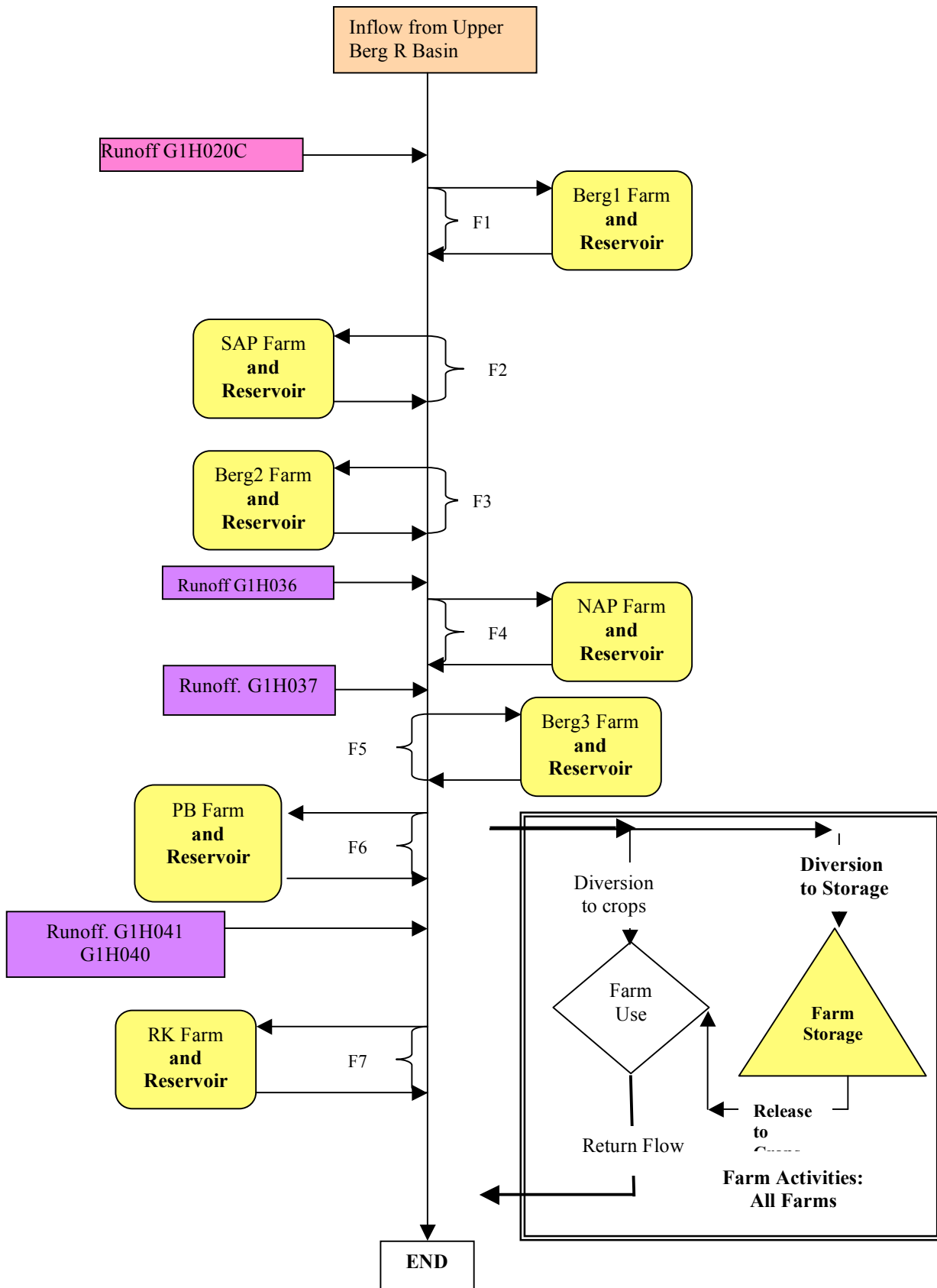
**Figure 1.** Schematic diagram of Berg River Spatial Equilibrium Model (BRDSEM).



**Figure 2.** Schematic diagram of the Berg River basin—upper section.



**Figure 3.** Schematic diagram of Berg River basin—lower section as depicted in BRDSEM.



**Table 1. Upper Basin Sites, Including Runoff Sources, and Deliveries From and to Other Sites**

Site	Runoff sources From WATBAL	Possible Deliveries from	Possible Deliveries to
TWAT	H6H007-8, H6R001-2, G1H019, G1H038	NONE	URB1 via WMRS waste treatment, and URB2
WMRS	G1R002	NONE	URB1 via WMRS waste treatment
BERG	G1H004, G1H038	TWAT, BERGSUP	BERGSUP
BERGSUP	G1H019, G1H003	TWAT, BERG	BERG, LOWER BERG
URB1	NONE	WMRS, TWAT	Urban demand - Municipalities
URB2	OUTSIDE	TWAT	Urban demand – Cape Town

**Table 2. Framework for Estimating Benefits and Costs Associated With Climate Change and Adaptation**

<i>Ex Ante</i> Climate Planning Options	<i>Ex Post</i> Climate States(C)	
	Existing Climate (C <sub>0</sub> )	Climate Change (C <sub>1</sub> )
Plan for current climate, reservoir capacity = K(C <sub>0</sub> )	Existing climate with current reservoir capacity. Net returns to water = W(C <sub>0</sub> , K[C <sub>0</sub> ])	Do not plan for climate change that occurs. Net returns to water = W[C <sub>1</sub> K(C <sub>0</sub> )]
Plan for climate change, reservoir capacity = K(C <sub>1</sub> )	Plan for climate change that does not occur. Net returns to water = W[C <sub>0</sub> ,K(C <sub>1</sub> )]	Plan for climate change that occurs. Net returns to water = W[C <sub>1</sub> , K(C <sub>1</sub> )]

**Table 3.** Simulated Present Value of Net Returns to Water and Optimal Storage Capacity of the Berg River Dam in the Berg River Basin (2010–2039) for Three Climate Scenarios, Two Levels of Urban Water, With and Without the Berg River Dam

	Climate Scenarios No Urban Demand Growth			Climate Scenarios 3% Urban Demand Growth Per Year		
	REF <sup>1</sup>	NF <sup>1</sup>	DF <sup>1</sup>	REF <sup>1</sup>	NF <sup>1</sup>	DF <sup>1</sup>
Ave. Annual Runoff (m <sup>3</sup> × 10 <sup>6</sup> ) (% Reduction from REF)	75.501	67.443 (-10.7)	58.892 (-22.0)	75.501	67.443 (-10.7)	58.892 (-22.0)
Allocation/Reservoir Scenarios	<i>Present Value of Net Returns to Water<sup>2</sup> (R 10<sup>6</sup>)</i>					
<b>A.</b> Existing water use regulation No Berg Dam (% Reduction from REF)	58,724	55,752 (-5.1)	52,820 (-10.1)	74,920	58,006 (-22.6)	44,897 <sup>3</sup> (-40.1)
<b>B.</b> Efficient water markets No Berg Dam (% Reduction from REF)	59,847	56,343 (-5.9)	53,135 (-11.2)	91,959	83,936 (-8.7)	76,516 (-16.8)
<b>C.</b> Existing water use regulation Optimal storage for Berg Dam (% Reduction from REF)	58,724	55,790 (-5.0)	53,564 (-8.9)	90,116	76,892 (-14.7)	62,673 (-30.5)
<b>D.</b> Efficient water markets Optimal storage for Berg Dam (% Reduction from REF)	59,850	56,802 (-5.1)	54,427 (-9.2)	96,315	89,705 (-6.9)	83,479 (-13.3)
Options	Optimal Berg River Dam Capacity m <sup>3</sup> × 10 <sup>6</sup>					
<b>C</b>	0	15	69	151	272	240
<b>D</b>	6	84	109	138	128	178
<sup>1</sup> REF: reference climate scenario, CSIRO model simulation for 1961-1990; NF: near future scenario, CSIRO model simulation for period 2010-2039 for SRES B2 emission case; DF: distant future scenario, CSIRO model simulation for period 2070-2099 for SRES B2 emission case. All climate scenarios are assumed to apply to 2010-2039 period. <sup>2</sup> All monetary estimates are expressed in present values for constant Rand (R) for the year 2000, discounting over 30 years at a real discount rate of 6%. <sup>3</sup> This scenario was infeasible because the urban regulation constraints were tight; consequently their right-hand side values were increased by 5% in every year.						

**TABLE 4. Simulated Present Value of Net Returns to Water<sup>1</sup> in the Berg River Basin (2010–2030) due to Simulated Adjustment to Development and Climate Change Under the Existing Water Allocation System (R 10<sup>6</sup>)**

<b>I. Adjustment to Development: Change Storage Capacity</b>		
<i>Ex Ante</i> Action: Change in Berg Reservoir Capacity Only	<b>Ex Post Scenario: No Development and 3% Development</b>	
	<b>No Development, REF Climate</b>	<b>3% Development, REF Climate</b>
Partial adjustment to development Capacity = 0 10 <sup>6</sup> m <sup>3</sup>	58,724	74,920
Full adjustment to development Capacity = 151•10 <sup>6</sup> m <sup>3</sup>	58,312	90,116
<b>II. Adjustment to Climate Change: Change Storage Capacity</b>		
<i>Ex Ante</i> Action: Change in Berg Reservoir Storage Capacity Only	<b>Ex Post Scenario: REF Climate and NF Climate</b>	
	<b>3% Development, REF Climate</b>	<b>3% Development, NF Climate</b>
Partial adjustment to NF climate change Capacity = 151•10 <sup>6</sup> m <sup>3</sup>	90,116	76,683
Full adjustment to NF climate change Capacity = 272•10 <sup>6</sup> m <sup>3</sup>	89,912	76,892
<i>Ex Ante</i> Action: Change in Berg River Storage Capacity Only	<b>Ex Post Scenario: REF Climate and DF Climate</b>	
	<b>3% Development, REF Climate</b>	<b>3% Development, DF Climate</b>
Partial adjustment to DF climate change Capacity = 151•10 <sup>6</sup> m <sup>3</sup>	90,116	62,475
Full adjustment to DF climate change Capacity = 240•10 <sup>6</sup> m <sup>3</sup>	89,974	62,673

<sup>1</sup> All monetary estimates are expressed in present values for constant Rand (R) for the year 2000, discounting over 30 years at a real discount rate of 6%.

**TABLE 5. Simulated Present Value of Net Returns to Water<sup>1</sup> in the Berg River Basin Due to Simulated Adjustment to Development and Climate Change by Switching to Water Markets and Adding Storage Capacity (R 10<sup>6</sup>)**

<b>I. Adjustment to Development: Efficient Water Markets</b>		
<i>Ex Ante</i> Action: Change Allocation System Only Change Storage Capacity	<b>Ex Post Scenario: No Development and 3% Development</b>	
	<b>No Development, REF Climate</b>	<b>3% Development, REF Climate</b>
Partial adjustment to development: Existing Regulations Capacity= 0•10 <sup>6</sup> m <sup>3</sup>	58,724	74,920
A. Full adjustment to development: Efficient Water Markets Capacity= 0•10 <sup>6</sup> m <sup>3</sup>	59,847	91,959
B. Full adjustment to development: Efficient Water Markets Capacity = 138•10 <sup>6</sup> m <sup>3</sup>	59,633	96,315
<b>II. Adjustment to Climate Change: Efficient Water Market +Change in Storage Capacity</b>		
<i>Ex Ante</i> Action: Change in Berg Reservoir Storage Capacity with Efficient Water Markets in Place	<b>Ex Post Scenario: REF Climate and NF Climate</b>	
	<b>3% Development, REF Climate</b>	<b>3% Development, NF Climate</b>
Partial adjustment to NF climate change Capacity =138•10 <sup>6</sup> m <sup>3</sup>	96,315	89,704
Full adjustment to NF climate change Capacity = 128•10 <sup>6</sup> m <sup>3</sup>	96,307	89,705
<i>Ex Ante</i> Action: Change in Berg Reservoir Storage Capacity with Efficient Water Markets in Place	<b>Ex Post Scenario: REF Climate and DF Climate</b>	
	<b>3% Development, REF Climate</b>	<b>3% Development, DF Climate</b>
Partial adjustment to DF climate change Capacity = 138•10 <sup>6</sup> m <sup>3</sup>	96315	83,444
Full adjustment to DF climate change Capacity = 178•10 <sup>6</sup> m <sup>3</sup>	96,255	83,479
<sup>1</sup> All monetary estimates are expressed in present values for constant Rand (R) for the year 2000, discounting over 30 years at a real discount rate of 6%.		

**TABLE 6.** *Present Value Estimates<sup>1</sup> for Climate Change Damages, Net Benefits of Adaptation, Imposed Climate Change Damages and Costs of Caution and Precaution for Two Adjustment to Development and Climate Change Cases (R 10<sup>6</sup>)*

<b>Estimated Benefit or Cost Measure</b>	<b>Adding Storage Capacity to Current Allocation System</b>	<b>Switching to Water Markets and Adding Storage Capacity</b>
Net Benefits due Development	16,196	16,196
Net Benefits of Adjusting to Development	15,196	A. 17,039 B. 21,395
Cost of Caution (Not planning for development that does occur)	-15,196	A. -17,039 B. -21,395
Cost of Precaution (Planning for development that does not occur)	-412	A. +1,123 B. + 909
Climate Change Damages REF to NF REF to DF	-13,433 -27,641	-6,611 -12,871
Net Benefits of Adaptation REF to NF (% of CCD) REF to DF (% of CCD)	209 (1.6%) 198 (0.7%)	1 (0.0%) 35 (0.2%)
Imposed Climate Change Damages REF to NF REF to DF	-13,274 -27,443	-6,610 -12,836
Cost of Caution (Not planning for CC that does occur) Plan for REF and NF occurs Plan for DF and REF occurs	-209 -198	-1 -35
Cost of Precaution (Planning for CC that does not occur) Plan for NF and REF Occurs Plan for DF and REF Occurs	-204 -142	-8 -60

<sup>1</sup> All monetary estimates are expressed in present values for constant Rand (R) for the year 2000, discounting over 30 years at a real discount rate of 6 per cent.