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Assessing the Economic Impact of Redistributing Water within a Catchment: A Case Study of the Musi Catchment in the Krishna Basin in India

Brian Davidson, Petra Hellegers and Madar Samad

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Contents

Summary

Our aim in this paper is to present the details of an economic modelling exercise we conducted on the Musi catchment of the Krishna Basin. This model was connected with a hydrological model and used to simulate various scenarios on the water situation facing users in the basin. The model presented in this paper has the unique characteristic of being able to value the water used on individual crops and in different regions. In addition to the agricultural valuation process, some account is made for the other uses of water and how they should be valued. The assumptions underlying the model, the data used and the results and implications drawn are fully detailed in this paper. In addition, the model is used to simulate a number of scenarios of interest to stakeholders in the Musi catchment. This model is the forerunner of similar modelling attempts on similar problems in other regions of the Krishna Basin and in the Murray Darling Basin of Australia.

INTRODUCTION

In this paper we present the documentation of a model capable of assessing the economic impacts of reallocating the water resources within a catchment. The aim is to assess the competing demands for a limited resource (water) between different uses and regions within a large catchment. This assessment is undertaken from the perspective of society as a whole, not just from that of the private stakeholders. Within a catchment while there are a number of ways of balancing the supply of water with the demands from agricultural, industrial and domestic users, there is also the need to generate electricity and the desire to provide environmental flows. These include principally either redistributing the resource amongst the users, reallocating it in the region or catchment or by investing in infrastructure to access more of the unregulated flow, such as building another dam or a plant to treat wastewater. All these types of changes, which are undertaken for a purpose, change the economic circumstances of users that, in turn, will affect the benefits society as a whole will derive from altering the allocation of water.

Numerous assessments of the economic implications of allocating water have been undertaken (for a brief overview, see Brouwer and Pearce 2005; Young 2005). In a general sense, Young (2005) argues that estimates of the value of water and the related technologies that move water are an attempt to understand the follwoing:

- Investments in water infrastructure.
- Inter-sectoral competition.
- Management of groundwater deposits.
- Changes in water quality.

Any economic assessment of the water sector can be classified as resolving one or more of these four categories. For instance, an assessment of the environmental influences of a new intervention in a catchment would involve some aspect of all four of these elements.

The purpose of the model documented in this paper is to determine, from the perspective of society, the impacts of reallocating water within a well-defined catchment. Three major components are needed if water allocations are to be modelled effectively. First, the quantity element assessed in the model should be exogenous changes in water allocations. To do this accurately requires a hydrological component in the model, or the provision of a link to one. Many economic assessments tend to suffer from an inadequate hydrological component as many are not multidisciplinary studies. Second, the value of water to users needs to be determined. This is difficult to determine as the price users pay for water is usually different to the costs of delivery, which can be different to the value users are willing to pay for water. Third, many subsidies and taxes occur within the water sector and a number of externalities are generated. A distinction needs to be made between the private and the social costs and benefits of water allocations. Social costs and benefits are those that the whole society faces and can be considered to be the true and complete costs and benefits in the absence of any market distortions. Private benefits and costs are those that any individual within a market faces.[1]

[1] A distinction must be made between social and private costs and benefits. The confusion arises when the social and cultural values associated with water, such as water allocations that contribute to improved income distribution or that encourage rural development or that reduce food costs are thought to be the “social” outcomes. Such social concerns lead governments to sometimes subsidize those uses of water that have a high social value, but low ability to pay (to avoid under-provision). In this study the strict economic definition of “social” is used, not the wider sociological definition. Thus, social costs and benefits include all costs and benefits, those that are derived from a market process as well as the values attached to it that can be classified as nonmarket values. However, some of the social concerns—such as sustainable groundwater use—are captured in this analysis and the model can be used to assess the costs of allocating water in a certain socially desirable way.

As the model is designed for use by policymakers, social costs and benefits will be assessed in this study. Thus, all costs and benefits exclude taxes and subsidies and some recognition of the external and non-market effects are accounted for.

In undertaking this task the various modelling efforts are collected within a Social Cost-Benefit (SCB) analysis framework, a well-established and accepted method of assessing the returns to society from an investment over time (Sinden and Thampapillai 1995; Brouwer and Pearce 2005). Crop water requirements and the allocation of water among users (collected together in a hydrological model) are exogenously determined in this process and form an input to the Cost-Benefit Analysis framework. A model capable of assessing the value of water will also have a link to the hydrological model, as it is the dynamics of the hydrology within the catchment over a long period of time that drives the economic outcomes.

Thus, the output of the hydrological model is an input to the economic model. This economic model includes a sophisticated component to determine the value of water used in agriculture (the major water user in most catchments) based on the residual method and elasticity techniques to determine the value of water to other users. In the model the returns to water are placed in a form that can be used for the economic evaluation of a wide range of possible scenarios. The scenarios evaluated in this study include both physical changes to water security (reductions in streamflows) and economic development proposals (transferring water from agricultural users to meet urban demand).

While a number of models have been developed to assess the physical flows of water, it should be noted that few techniques are available to consistently and comprehensively assess the economic impacts arising from hydrological changes, over a long period of time. The weaknesses with past efforts in modelling the economic impacts of redistributing water have been reviewed by Zaman (2005), Young (2005) and Appels et al. (2003). The weaknesses with these models do not lie in the approaches taken or the methods employed. Rather, from the perspective of this study, they lie in the fact that the models are not comprehensive enough to account for the variety of uses water is put to and to the different costs associated with supplying these demands. In this study the model will be required to:

- Determine the social value of water used in the agriculture, domestic and industrial sectors, and in the environment and power generation.
- Simulate, rather than optimize, the effects of different water allocations.
- Be linked to a dynamic hydrological component that has both surface water and groundwater systems.
- Account for the costs of delivering water from a variety of sources.
- Have the capacity to assess the costs and benefits to society of introducing new infrastructure to the existing water allocation system.
- Have the scope to be applied at the sub-catchment level and yet sum to the catchment level, so that it operates at a regional or irrigation zone level.
- Operate over a long period of time.

While other models have the ability to do some of these things, a model based on economic principles that does all of these has not been found to date.

The modelling approach presented in this report will be applied to the Musi catchment, a sub-catchment of the Krishna Basin in India. Subsequently, it will be used to assess other catchments in the same basin and irrigation schemes in Australia (something that is not undertaken in this paper). The aim of applying the model to the Musi catchment is not only to display the uses that it can be deployed to address, but also to support policymakers in their decisions on the basis of providing them with an insight into the trade-offs that occur in reallocating water amongst users and regions over time. While any model of an industry should be assessed according to a range of measures, a critical element in any assessment should be how it deals with the problems faced by those who need to use it. In this paper, the problems policymakers face in the Musi catchment is not resolved. It should not be the preserve of analysts to undertake such a task. Rather, the aim is to present a method and a model through which these problems could be addressed.

In undertaking these tasks, first it is necessary to look at the complexities involved in modelling water allocations (see section on *The Complexities Associated with Modelling Economic Impacts of Water Allocations*). Then details of the overall structure of the model, its constituent parts and the data needed to construct it are presented in the section on *The General Approach to the Model*). Within this section the methods employed to value water use in different pursuits are presented in the sub-section on *Valuing Water*. This is followed by the general specification of the SCB model. It is within the SCB component of the whole model that the various elements are finally drawn together and the measures of the performance of the water allocation system are produced. Finally, an application of the *model to the Musi catchment* is presented. The application of the model is subjected to some diagnostic tests, in particular sensitivity tests of the key parameters and assumptions. In addition, a number of policy scenarios are assessed to ascertain the economic benefits derived from changing the allocation and distribution of water in the Musi catchment. Some conclusions and future uses of the model are discussed in the sub-section on *Scenario Testing in the Musi Subbasin.*

THE COMPLEXITIES ASSOCIATED WITH MODELLING THE ECONOMIC IMPACTS OF WATER ALLOCATION

Davidson (2004), Hellegers and Perry (2004) and Young (2005) argue that water itself presents a number of problems that make modelling it a complex task. In particular they note that:

- Water is mobile.
- It has a highly variable supply.
- It has varying quality aspects to it.
- There is a high degree of interdependency amongst users.
- Problems tend to be site-specific.
- Water exhibits large economies of scale.
- Market failures abound.
- Water is not traded widely amongst users.
- It has a cultural, religious and social dimension to it.
- It is provided as a “service,” yet is traded as a “good” and treated as a “right” by users.

Before commencing any modelling exercise it must be asked; what is to be measured? Clearly, in the case of the sub-catchments of the Krishna Basin what is in contention is the allocation and distribution of a public resource, water. Yet this resource could be measured in many different ways. In addition, no single method of measurement can capture all the dimensions associated with distributing and allocating water. The purpose in this section is to outline the dimensions of the problem at hand. These can be usefully segregated into quantity issues, valuing complexities and other (mainly) institutional concerns.

The Quantity of the Resource

Water is nothing more than a physical resource that exists above, on and below the earth. From an economic perspective however, what is important is the water that is controlled, i.e., the water that is stored, distributed, used and regulated by humanity. This means capturing the resource, concentrating it into some manageable whole and then distributing it as desired. To that end, of real interest is the water that is captured on the surface and/or liberated from below the ground. Any use of airborne water (notably rain) or that beyond the clutches of humanity is not controlled, but its impact on human uses can be used subject to some degree of probability.

From an economic point of view, controlling water for its own sake is a useless exercise. Its control must have a purpose that, in turn, leads to choices being made. Rivers are regulated to move water in time and space. In doing this, agriculture and all the uses water can be put to, are also moved in time and space. In other words, what is important with controlling water is what you can do with it. From an economic standpoint that means measuring the benefits derived from controlling water, while accounting for the costs of undertaking such an act and hopefully, but not necessarily, resulting in the benefits outweighing the costs.

The Value of the Resource

Valuing water is an extremely complex task. Although a few minor exceptions exist, generally water is not a commodity that is actively traded on a bourse or in a local market. Thus, analysts need to rely on a variety of techniques to infer a value for water, rather than observing one. Young (2005) argues that the methods employed can be segregated into inductive and deductive methods. Inductive methods rely on inferring a value from generalized observations. The techniques involved include taking observations of selected transactions estimating market relationships using econometric techniques, contingent valuation, choice modelling, etc. Deductive methods rely on inferring a value from logical processes. Arguably the most used technique to infer values of water are "residual valuation methods" (something that is employed in this study), a deductive approach.

As water is an input to a production process, it is imperative to understand that the value of the water in that production process is dependent on the value of the things derived from water, not just the water itself. Consequently, the output price of the final good and the quantity produced (its yield) need to be accounted for in the valuation of a single input, water. In addition, given that water is combined with other inputs to produce outputs, then it is also essential that only the value water adds to outputs is measured. This can be a difficult task as a mixture of inputs is used to generate output. Despite this difficulty, the prices and quantities of other inputs are needed if the value of water is to be determined.

In this study, the aim is to measure the economic effects of changing the distribution and flows of water. What are measured are the economic surplus changes that result from changing what water is used for (see Figure 1). The supply and demand schedules represent the marginal costs and benefits curves, respectively, from water used to produce outputs in an economic system (Briscoe 2005). Economic surplus is the value society derives from the production and consumption of a good. It is equivalent to the area between the supply and demand schedules over the range of the quantity produced. This area can be separated into two elements. First, the consumer surplus, which can be interpreted to be the benefits consumers receive by purchasing each unit of the good for a price which is less than what they would be willing to pay for it. Second, the producer surplus, which is the benefits producers receive for selling each unit of the good at a price which is higher than what they would be willing to sell it for.

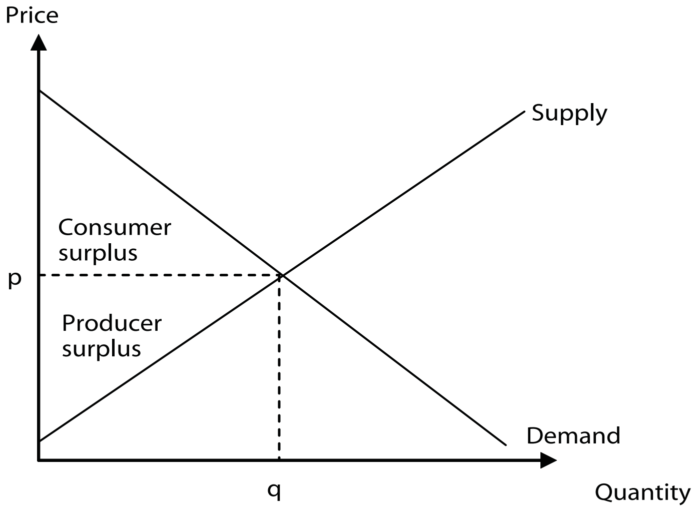

FIGURE 1. The economic concept of value.

Any change to the allocation of water flows will result in the marginal cost curve shifting outward, in the case of more water being distributed to the production of the good in question, or shifting towards the origin in the case of water being restricted. Any change in the marginal cost curve will change the area of economic surplus. It is this welfare change that economists prefer to measure (Sinden et al. 2003).

In this study the own-price elasticity of demand for water (the responsiveness of a change in the quantity demanded to a change in its price) by agricultural users is assumed to be perfectly elastic. In other words, the demand curve in Figure 1 is horizontal. This is not an unreasonable assumption, as farmers are, in an economic sense, price takers (i.e. that they must accept the price offered in the market and cannot affect that price). It is assumed that the products they produce are sold in the world market at world market prices. For domestic users, the demand schedule could be expected to be highly inelastic as not many substitutes for water used for domestic purposes exist. The demand schedule for industrial uses of water can be considered to be somewhat more elastic, as they may have relatively more substitutes. In addition, users are assumed to receive a fixed allocation of water in each period. Thus, it can be assumed that the supply schedule in Figure 1 is perfectly inelastic, or vertical. Again, this is not an unrealistic assumption in most cases where water is not actively traded. However, the supply of water to urban regions can be usually determined in a block fashion, with different quantities of water being sourced from different sites, each incurring a different cost. In this way, water to urban centers can be thought of as being upward-sloping, but in a stepwise manner.

Other Concerns

The flow of water is essentially governed by institutional factors. According to the Constitution of India, the states have responsibility for water, except if it crosses into a neighboring state. Over a number of years, the provision of water has been subsidized, especially in the form of capital works and because the costs of operation, maintenance and administration have not been recouped from consumers. In addition to the bodies that control water, there are a number of other ways that institutions/ governments impose themselves on and have an impact on the distribution of water. Water, while essential to most elements of life, is not in itself sufficient to promote life. It needs to be combined with other resources and inputs to produce outputs. Governments effect the prices of these other inputs and outputs as well. In India, until 2001, agricultural outputs tended to be taxed implicitly through a set of low procurement prices, while other inputs, especially fertilizers and electricity were, and in some cases continue to be, subsidized (Gulati and Narayanan 2003).

In India, water takes on a far more important role than just being a factor of production. It has a religious and cultural dimension to it as well. Some may even argue that these social issues are of greater importance than the economic ones. At a somewhat controversial level, it could be argued that water allocation policies are designed to reduce the extent of urban drift that occurs in India. This political question, like most social issues, is important. However, they are beyond the scope of this study. While, these effects are usually hard to value, or are of a secondary nature, policymakers are interested in these questions. Using the model presented in this paper it is possible to calculate the benefits and costs of meeting these social concerns. So even though it is recognized that the economic value is only one of the foundations on which water is allocated, it is still a relevant one. Other factors, such as equity among different users, food self-sufficiency and rural development, and knowledge of the economic value of water to different users in different regions are of assistance to policymakers.

In a similar vein, as a catchment is an environmental entity, it is impossible to ignore the effects water regulation may have on nature. While these effects can be pervasive, in general, they can be classified as an externality. Externalities are uncompensated spill overs, or the unintended side-effects of a production process that are not accounted for in a market setting. In other words, they are the results of regulating a river, which are not captured in the price mechanism. They can be both positive and negative. The classic case of an externality in this study is the release of untreated sewerage from Hyderabad City entering the Musi River and its concomitant downstream impacts. The negative externalities of this are reflected in poor health outcomes for society and lower yields for crops. However, downstream farmers may make use of the extra moisture and at times the nutrients that exist in the rivers as they irrigate their crops for which they do not pay the citizens of Hyderabad. In this study, it is important to capture and measure some of these external effects. However, others, such as salinity, turbidity, etc., are hard to estimate and capture.

Summary

What is measured in this study is the economic impact of changing the way water is controlled in catchments for society as a whole. For instance, what could be assessed is the cost to agricultural producers along the Krishna of taking more water to Hyderabad from the Nagajuna Sagar Dam. In addition, it may be possible to evaluate the worth of investing in wastewater treatment plants in Hyderabad City. The economic assessment must be undertaken in such a way that it is governed by the physical flows of water, accounts for the environmental and social components and is adjusted for the institutional factors, but measures the economic outcomes only.

THE GENERAL APPROACH TO THE MODEL

The model developed in this study has three principle and interrelated components (see Figure 2). They are a hydrological element, a module that can be used to determine the value of water to users and a structure that binds the components together. The dynamic driving force in this model is the changes that occur in the allocations of water to different sectors and regions. In a hydrological model, the sources of water and where it is directed (into different regions and sectors) are called "nodes." Using this dichotomy, one can think of a hydrological model as having a set of supply and demand nodes, relating respectively to the sources of water and where (or what) it is used for. In an economic model it is essential to first value the water used in each demand node. This valuation must be conducted within a region, which can be termed a "zone."[2] Then it is necessary to value the costs of getting the water from each supply node to each demand node. This may well include any improvements or changes made to the infrastructure of the system, but not to the existing network. Given that any water allocation system will be in existence for many years to come, it is necessary to incorporate this into an SCB analysis, the structure that binds the model together. In this study the stream of costs and benefits over a period of years, from the present will be discounted to find the present value of all future costs and benefits.

The purpose, in this section, is to discuss the general approach to the model. Much of what follows, especially that related to understanding the value people place on water, is derived from Young 2005. An algebraic representation of the issues discussed in this section is presented in appendix A.

Social Cost-Benefit Analysis

An SCB analysis of a public project is undertaken to help answer the important question: "Will the project be of net benefit to society?" It is designed to promote the maximization of social net benefits, in an economy-wide context (as opposed to, say, investment analysis conducted by a private firm, which examines purely the private profitability of some new project). An attempt is made to put all costs and benefits arising from a project into monetary terms, to enable sensible comparisons between alternatives.

In estimating this model three separate components are needed. An SCB model is required to gather all the disparate elements together and to provide the outputs from the process. Within this component the costs of allocating water play a central role. Second, there is a need to consider how the values of water to both users and to society as a whole are influenced by the hydrological changes. This hydrological component drives the model and is exogenous to the valuation process. Finally, there is a need to value the water used in different pursuits. This is considered to be the most complex and crucial element in the modelling exercise.

[2] Nodes are the points between which water is transferred. There are supply nodes (where water is sourced from) and demand nodes (where water is used). Demand nodes relate a region or a zone, which is made up of different types of users (agriculture, domestic, etc.).

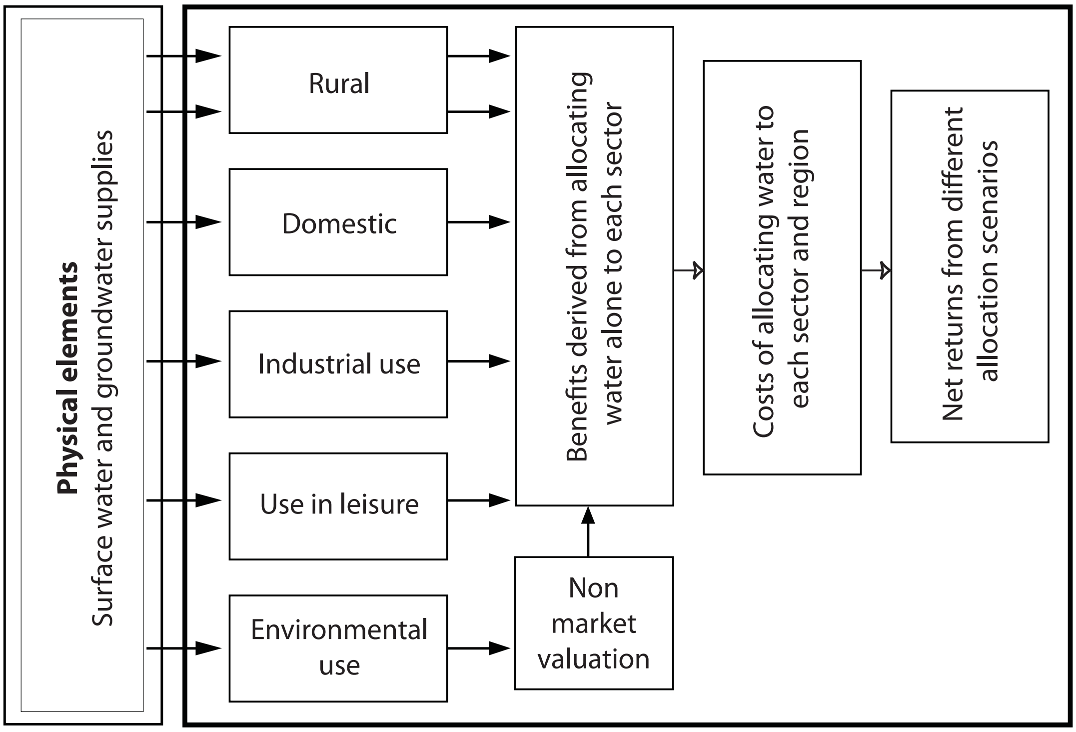

FIGURE 2. The general structure of the model.

An SCB analysis is usually carried out on a national level, but it is also applicable to the catchment level. An SCB analysis has been widely used in the water sector to estimate a number of different issues confronting the industry. Brouwer and Pearce (2005) have collected together a number of applications of the method. It should be noted that each application is specific to the problem at hand. Despite this, a number of general principles exist that are needed to apply the method in any circumstance.

The essence of an SCB analysis is to attempt to estimate the size of the benefits and costs of any action, usually prior to their implementation. If the costs are less than the benefits, then the action is deemed to be acceptable. Complications arise because of the long-term nature of projects (requiring a discounting adjustment to account for time), the fact that certain costs and benefits cannot be accurately determined (requiring a procedure to estimate it) and having a benchmark upon determining one action over another (necessitating the choice of an appropriate measures of comparability).

The essential characteristics of costs and benefits in the analysis are that:

- They belong to particular actions ("projects" in cost-benefit terminology) and each decision implies at least two alternative courses of action (to do or not to do).
- They are particular to persons or groups and that the same action can involve different costs and benefits for different people.
- They involve the future consequences of current decisions, not faits accomplis.

An SCB analysis is an attempt, as far as possible, to put all costs and benefits arising from a project into monetary terms, to enable sensible comparisons to be made between alternatives.

In undertaking an SCB analysis an attempt is usually made to gain a complete picture of all the costs and benefits that arise from a project. Included in that picture are not only the marketable commodities (valued in a free market) and those marketed in a distorted market (where the value is corrected for using shadow prices), but the nonmarketable commodities. Some of these can be valued using a variety of tools, such as recreation values being determined by the Travel Cost Method, as well as nature values being determined by the Contingent Valuation Method.

It is important to measure the real and direct effects of a project. Real effects are actual changes in outputs or resources used. They are positive or negative changes in welfare. Real effects can be further subdivided into direct and indirect, where direct impacts accrue to the intended beneficiaries, while the indirect effects are the unintended impacts. An alternative to real effects are known as pecuniary effects and these are the secondary impacts reflected in changes in prices and incomes. These may include income redistribution effects. Given the nature of a society's wide view of a project, in many cases gains in one region are offset by losses in another. Consequently, pecuniary effects would be a double count and should be ignored.

An SCB analysis has three essential components to it. First, the specification of the benefits, which include the benefits from distributing water principally to agriculture (the main activity) and also to the domestic and industrial sectors, should be detailed. Second, in the tabulation of the costs of distributing water, including those associated with the externalities, the costs need to be estimated. Finally, the reconciliation of benefits less the costs, discounted over the life of the proposal, needs to be analyzed. In this model, all these elements are required and should be reflected in a summary table that overlays the underlying calculation of benefits and costs over the period determined from the hydrological model, after the current period (in this case 2007). It should be noted that in an SCB analysis the period in which the analysis starts is important. Any activity that occurs in the past is considered to be "sunk." Therefore, past periods need not be assessed, as policymakers cannot influence the past.

The Hydrological Component

The basis of the problems investigated in this study stems from the hydrology of the catchment. Changes in the flow of water will govern the flow of net benefits. As a consequence, the mechanism that controls this model is a hydrological one. All other components react to changes in the hydrological model.

Details of the hydrological model that can be linked to the models presented later in this paper are found in George et al. 2007. These models are either constructed in REALM or some other computable program employing hydrological methods and techniques. In these models the flow of water between a set of nodes is specified and is distributed according to a set of priorities specified by the policymaker. These nodes represent the supply and demand points for water in each catchment. The size of this node depends on the hydrological factors involved in collecting water, including runoff, evaporation, the size of the dams, rainfall, etc.

However, a complication arises in the way hydrological models work with respect to the water allocated to agriculture. The process used within a hydrological model is to specify a set of priorities for the available water. That priority is usually to first supply water for human consumption, then to other uses, prior to supplying agricultural needs and last to the environment. If water is in short supply the amount available might not be sufficient to plant the entire command area of an irrigation scheme. While this is of little concern to a hydrologist, it has a profound impact on the value of water in a region.

In accounting for this difficulty it is important to remember that a constraint in the model is that the water allocated to a region must be equal to the quantity demanded. Given that the hydrological models are usually expressed in the absence of rainfall, the quantity demanded should be expressed in terms of the total evapotranspiration of the irrigated crops in a region. As the quantity supplied excludes rainfall, it becomes equal to what is supplied through surface irrigation and what is pumped from the ground in a sustainable way to irrigate alone. Thus, to account for the shortfalls in water delivery, between what could be potentially planted if water were available to supply the whole command area and what is actually available to plant a reduced area, requires the assumption that when faced with water shortages farmers reduce the area planted alone. They do not attempt to plant the whole command area and expect a reduction in yields.

Vinod (International Water Management Institute, Hyderabad, pers. comm. 2006) argues that during a period of severe water shortage in 2004, farmers in the Nagarjuna Sagar command areas in the Krishna Basin received no surface water supplies. Farmers reacted by not cultivating their fields. If they did anything, it was to put in a dry rain-fed crop and even then they did not crop all the land available. Thus, the assumption that irrigation farmers, who are reliant on irrigation supplies for their livelihoods, choose not to plant when faced with water shortages is not unrealistic. To plant without adequate water is a risk farmers are assumed not to take. Thus, the assumption that farmers adjust the area planted, rather than lose output, would appear to be reasonable.

In light of water shortages, the actual area cropped can be calculated as being equal to the total command area available multiplied by the quantity actually supplied to the region divided by the total quantity of water demanded if the whole command area were to be planted. All variables are known. See appendix A for a mathematical description of how this adjustment is made.

In this model the water delivered to each demand node needs to be valued (see the following section). The value of water for the regions as a whole is dependent on the quantity and the choice of crops grown, both of which in turn are dependent on the water allocated to the node. In addition, the costs of getting the required quantity of water to each demand node must be measured. Thus, the information embodied in the relationship between the areas cropped and the water available is a crucial link between the hydrological and economic components. It reconciles information on the quantity of water supplied and demanded in a zone. However, it is not the only link required. The quantities of water supplied to each zone need to be valued as well.

Valuing Water

The benefits from allocating water are derived by those who use it. In a catchment those users can be segregated into domestic and industrial consumers (usually based in cities and municipalities), agricultural producers outside urban areas and power generation, along with environmental flows. As water is only one of numerous inputs into a production process it is necessary to account only for the benefits water adds to that value-adding process, not the totality of the benefits from that process.

In this study, deductive (i.e., those where a value is implied from logic) methods are employed to estimate the values of water to users. This is required because water is not a freely traded commodity where prices and quantities are readily observable. With industrial and domestic consumers the value of water is calculated from estimates of the own-price elasticities of demand. For agricultural users, the value of water is determined using a residual valuation technique. Finally, the values for *in situ* uses, power generation and the environmental uses are estimated using a technique that estimates the return on output.

Domestic and Industrial Consumers

For domestic consumers, while drinking water is a necessity of life, the other uses of water within households make life more comfortable. Given that domestic consumers (especially in Hyderabad) usually face shortages in water, its value can be expected to be very high. The own-price elasticity of demand can be expected to be highly inelastic, as there are not many substitutes for domestic water use. In addition, any further provision of water, beyond what is currently supplied in 2007, would be consumed and valued much more than by any other user group. Thus, in the model, water for domestic consumption can be expected to have a marginally higher value than the next highest users' value of that same quantity of water. The implication of this expectation is that it is always more valuable to supply water to the domestic users and if any water is diverted away from this sector a loss will result in net benefits. This belief is realistic given the severe water shortages Indian cities face and the way people prioritize their choices regarding water. This order of prioritization is embodied in the hydrological models that dictate water flows in this study.

Industrial users could well be expected to have a more elastic demand for water as substitutes may well exist. In addition to that, the quantity of water used by industry is generally lower than that used by domestic or agricultural users. These two factors will result in a lower estimate of the consumers' surplus from industrial uses of water than that from domestic use.

The value that domestic and industrial consumers place on water is equal to the consumer surplus. From the perspective of society, this can be calculated by estimating the area under the demand equation, above the price paid for supplying the last unit of the good, over the quantity supplied. Undertaking this task requires an estimate of the domestic and industrial own-price elasticities of demand and the price and quantities used by each sector in any given year. Once these are known, the specification of the demand curve can be calculated using a point elasticity formula from which the intercept of the demand curve on the price axis can be determined by setting the demand equation equal to zero. Finally, consumer surplus is equal to half the difference between the price and the price intercept, multiplied by the quantity used. This is equivalent to the area under the demand equation, above the price paid for the water. From the perspective of society, this price is not the price paid by consumers, which can be heavily influenced by government taxes or subsidies, but is the true cost of providing the last unit of water. The average value of the water to each sector is equal to the consumer surplus divided by the quantity demanded by each sector. A mathematical description of this process is detailed in appendix A.

With respect to estimating the producer surplus arising from the industrial and domestic consumption of water, this is equivalent to the benefits of selling the last unit of water, less the costs of provision of the quantity supplied to both industrial and domestic consumers. As water provision to a city can come from many sources, in incurring a different cost from each source, care must be taken to attribute the correct costs to each source.

Agricultural Water Demand—Theoretical Issues

In this study, there is a need to determine the value of irrigation water as the net income received by the farmer per unit of water applied. As the model will be used for simulation purposes only, there is no need to derive marginal returns to water (which is the extra income that a farmer would derive from an additional cubic meter of water used) but only the average values are necessary. In general, under conditions of water scarcity, the average value of water is a reasonable proxy for the marginal value because farmers are trying to maximize the return to the scarce resource. Since it is assumed that farmers have to take the price offered in the market and that the own-price elasticity of demand for the commodities they produce is perfectly elastic, it follows that the own-price elasticity for water is also perfectly elastic. This would mean that the average value of water would equal the marginal value of water. As in the case for the industrial sector, in calculating the value of water in agriculture it is important to value only the benefits derived from water. However, unlike the demand by the industrial sector, a great deal is known about the water requirements of individual crops. The best approach to do this, and the one employed by most analysts, is what is known as the Residual Valuation Method.

Young (2005) provides an extensive review of the residual method, detailing its theoretical foundations, uses, benefits and limitations. The idea is based on the concept of economic rents outlined by the classical economists Ricardo and Wicksteed and refined by Marshall (quoted in Young 2005). The basic approach relies on the fact that the value to a producer who produces a good is exactly exhausted by the summation of the values of the inputs required to produce it. If the price of one input is unknown, then the value of the marginal product of that input (which, in this study, is the value farmers place on water) can be found by simply rearranging terms so the unknown price is a function of the price multiplied by the quantity of the output, less the sum of the values (prices) of all known inputs multiplied by the quantities of those known inputs that are used, all divided by the quantity of the unknown input (water). The entire residual value of this process is ascribed to the input irrigation water.

Young (2005: 61) describes this as the "value of water" or the "net return to water" for a crop. It is, in the parlance of economics, the "residual value." The total benefits derived from agricultural use of water are equal to the residual value of water, multiplied by the area over which it is spread. Multiple crops can be accounted for, by summing over the production range. A mathematical description of this process is presented in appendix A.

Agricultural Water Demand—Modelling Issues

To arrive at the value agricultural users place on water in a region from a modelling perspective requires a number of (possibly heroic) assumptions and simplifications. First, some idea of the production process is required, including knowledge of the use of all inputs and their respective prices, with the exception of the one in question (which, in this study, is water). The problem is that if all inputs are not known, a highly likely scenario, then all missing inputs are valued as being a part of the "residual value." While this limitation cannot be overcome, it does need to be minimized by specifying the production process as completely as possible. Second, to make the method operational depends on whether the aim is to optimize or simulate. If the objective is to gain the optimal result, then a mathematical programming approach is ideal, where an objective function is set up and constraints are established. Alternatively, if the aim is to assess (or simulate) changes to an existing system, then a gross margins analysis is required. In this study, the aim is to simulate changes to an existing system. Third, it must be asked if "owned" inputs are adequately represented. This problem tends to manifest itself when fixed inputs such as land-asset values, labor and entrepreneurship are not represented in the production process. This limitation is similar to that of a missing input specified above. Thus, it is important in the gross margin analysis to include the costs of owner-operated labor in the analysis. However, what are more intractable are the asset values derived from owning land and water. Including these is somewhat difficult in a gross margins analysis. Finally, the analysis is based in part on information about farm input prices, crop yields and market values—all of which vary from season to season—but the sample data collected serve to highlight underlying issues and to estimate returns to water that are generally valid.

A good example of the processes involved in using the residual method is presented by Hellegers and Perry (2004). They developed a spreadsheet analysis to calculate the residual values of water or labor used on a farm. These worksheets were designed to calculate the water economy at a farm level. What they derived are a number of variables, including the costs and quantities of labor used and the costs and quantities of water needed to be extracted, and most importantly for this study, the average benefits from employing water on-farm. So, given the area farmed in the hydrological zone and the cropping pattern, along with the quantities of all inputs (labor, surface water supplies, fertilizers, pesticides) used, the yields of all crops produced, their respective evapotranspiration rates and the prices of all inputs and outputs, it is possible to obtain a partial budget of the farm. From this base, average values of all inputs other than water were calculated and that for water was derived.

In this analysis, the minimum data needed for each agricultural zone are the following:

- The area of each crop farmed.
- The yields from each crop.
- The output prices for each crop (not the ones received by the farmers, but the shadow prices received in the market, less the implicit tax).
- The prices for each input (once again net of any subsidies received).
- The labor requirements for each crop and the wage rate.
- The monthly surface water and groundwater requirements available in each zone.
- The fertilizer and seed application rates and costs.

As with Hellegers and Perry the indicative returns to land, labor and water could be computed. By subtracting the cost of other production factors from the gross production value, the net value added per unit of water is derived.

The method used in this study was developed from the original specification of Hellegers and Perry and is consistent with the residual method outlined above. However, their analysis was confined spatially to only the farm level. In this study, the basic design for a farm level can be upscaled to the regional (water node) level. The value of water for each crop in each node can be weighted by the areas cropped to determine the aggregate value of water used in agricultural pursuits. These, in turn, can be collected together and used in the SCB analysis, for comparative purposes and then multiplied by water allocations over the time period of the analysis to determine the present benefits from water. Finally, and most importantly, the water inputs used in the analysis are derived from the hydrological modelling efforts, detailed by George et al. (2007). The water inputs are segregated into the amounts derived from surface supply and pumped from the ground.

The returns estimated using this approach are difficult to precisely compute in the absence of a major modelling exercise. First, the precise technical coefficients (yield/ha, water use, etc.) will vary across farms and by year. Second, production costs are generally difficult to obtain and standard costs of production will not reflect variations among farmers. Besides, some inputs are difficult to capture accurately because they are not monetized (like family labor), or may be subject to distortions due to taxes or subsidies (market prices often differ from economic prices due to price policies). Furthermore, costs of fixed assets are not considered, as it is hard to translate financial costs of production into economic costs of production. Third, a precise analysis of the impacts of economic instruments would require identification of marginal as well as average returns, because these are the values that induce responses. In this study they are assumed to be the same.

Given that of interest in this study are the impacts that result from changing the distribution of water flows between zones, the concept of Hellegers and Perry, of fixing area and allowing any water shortfalls to be made up from more pumping of groundwater, is not ideal. Rather, it is more ideal to fix the quantity of groundwater and surface water available (an input from the hydrological model based on a sustainable groundwater yield) and adjust the area planted. The approach used to do this is outlined above in the section on *The Hydrological Component.*

Valuing Power Generation

Hydroelectricity generation is an important component of many water allocation systems and as such it must be valued. Its value will be determined by the price received for the electricity generated from each unit of water used, multiplied by the quantity of water needed to generate the electricity produced. The price of the power generated is usually specified in terms of energy generation (per kilowatt hours). The quantity of water used to produce the energy is usually governed by the generating capacity of the plant and is site-specific. The value of power generation to the system is simply the power generated, multiplied by the true social price of electricity divided by the volume of water used to generate it.

Valuing the Net Benefits of Environmental Uses

A great deal of effort has been expended in trying to establish the value of the environment (see Costanza et al. 1997, amongst many others). From a modelling perspective there is a need to establish a link between the flows of water and the environmental benefits derived. In addition, it could be argued that the regulation of water causes environmental damage.

To date, no useful information has been be found on the relationship between regulated water flows and net environmental benefits, especially in India. In addition, any information obtained from it could not be used as it would most possibly be site- specific. Furthermore, in India to talk of regulating water for environmental purposes is nonsense. Yet this is not to say that policymakers are not interested in doing this, or that the flows in 2007 possibly caused some environmental damage. The way to approach this problem is to assume that the environmental damage arising from regulating river flows is equal to zero. This is not an unrealistic scenario in the case of water in India where every drop of water is valued only for more traditional uses and the environmental benefits are not considered. In any developed country this assumption would possibly not hold.

Some environmental benefits do arise in any system. Those elements of regulated water that escape from the system through evaporation or leakages could be said to return to the environment. These can be valued at the lowest opportunity costs for water in traditional use. This alternative method of valuing water to the environment is employed in this model.

Valuing Non-consumptive and in Situ Uses

In many situations water flows through a system and people derive a value from it without extracting any of the resource. The most popular example of this use is recreation (fishing and boating). In some ways they could be considered to be an externality. However, the distinguishing feature of these benefits is that water is not substantially extracted or added to the system.

In less-developed countries, peri-urban agriculture can be a non-consumptive use. For instance, in the Musi catchment, paragrass (a variety of millet that is used to feed cattle and which can be grown with highly polluted sewerage) is grown on wastewater as it travels between urban dwellings and the river. In these cases, valuing the output is simply a case of multiplying the quantity produced by the price received. This total value needs to be weighted by the proportion of wastewater produced in each period, to obtain the average value of paragrass to the system.

Costs

Finally, and briefly, some mention must be made of the costs of allocating water assessed in this study. In this model, these costs are those associated with distributing water throughout the system and those resulting from the externalities inherent in the system. Given that the benefits were derived on an input demand basis, the other costs associated with agricultural and industrial production need not be assessed.

The cost of distributing water in the Musi need not be specified on a zone by zone basis, between each node. In addition, any costs associated with changing and improving the infrastructure associated solely with a specific simulation scenario must also be included. All these costs need to be incorporated into the SCB analysis component of the model.

In terms of the externalities inherent in the system, many kinds of costs exist. The most important are the full costs of handling wastewater and those associated with the impurities of pumping groundwater. This can mean anything from the tailings from an irrigation system through to raw sewerage and industrial wastes from urban areas. Obtaining an estimate of the costs associated with wastewater is not easy. However, it is known to affect the human health of those who work with it and to reduce the yields of crops grown with it and it may have a residual effect on the soil. Any external costs would, by their very nature, be site-specific.

THE MODEL OF THE MUSI CATCHMENT

Our purpose in this section is to apply the model specified above to the Musi River, a sub-catchment of the Krishna Basin in India. Initially, details of the Musi catchment are presented. Then the data needed to make the model operational are presented, prior to the specification of a base-run simulation and a set of sensitivity tests on the model.

In this exercise, the values are determined on the data of one year (2001-02) and these values, in turn, are first combined with the corresponding periods of data on water and then applied to hydrological data that occur over a number of years (2007 to 2031). The net present values of operating the scheme are calculated only over the period from 2007 to 2031, as any costs incurred or benefits gained prior to 2007 can be considered to be sunk and unaffected by any future use of the water.

Details of the Musi Catchment and the Rationale for Modelling It

The physical aspects of the Musi catchment are shown in Figure 3 and the controls placed upon surface water are shown in Figure 4. In general, water is collected in the head water of the Musi through two reservoirs, Osman Sagar and Himayath Sagar. This water is piped to Hyderabad City, where it is supplemented by supplies from other catchments, the Godavari and the Krishna rivers.

Then it is used by domestic and industrial users, before entering the Musi, usually untreated. This water is then utilized first by peri-urban farmers, to produce paragrass, and then by other farmers in the wastewater zone to produce rice, up to 40 kilometers downstream. Further downstream a small irrigation scheme exists, called the middle Musi command area, which again concentrates and distributes water to farmers in zone 3. Due to the regulation of the Musi, it rarely flows into its natural end in the Krishna River. The Musi enters the Krishna in zone 4, where farmers receive water from the left bank of the Nagarjuna Segar system too. In Figure 4, the groundwater elements are not shown. However, extensive use is made of groundwater throughout the catchment in zones 1 and 3. A sustainable groundwater yield is determined by the hydrological model, among others, on the basis of annual recharge flows.

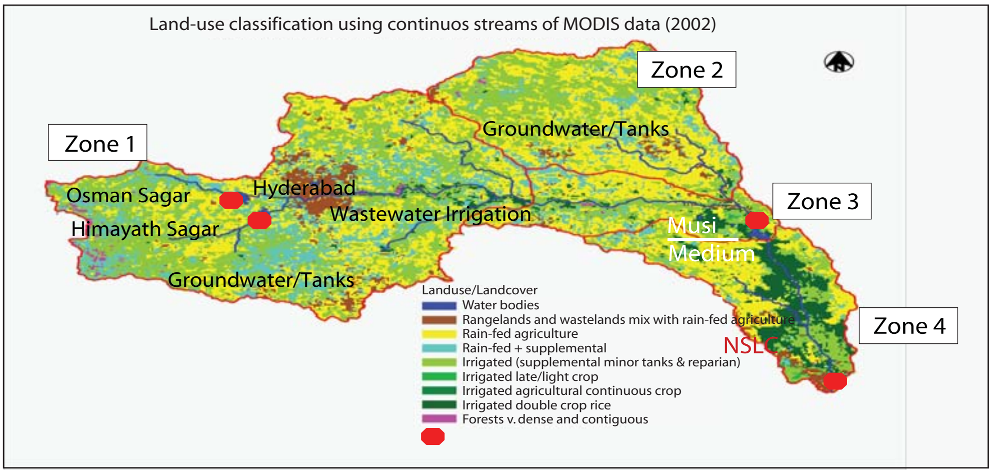

FIGURE 3. The Musi catchment.

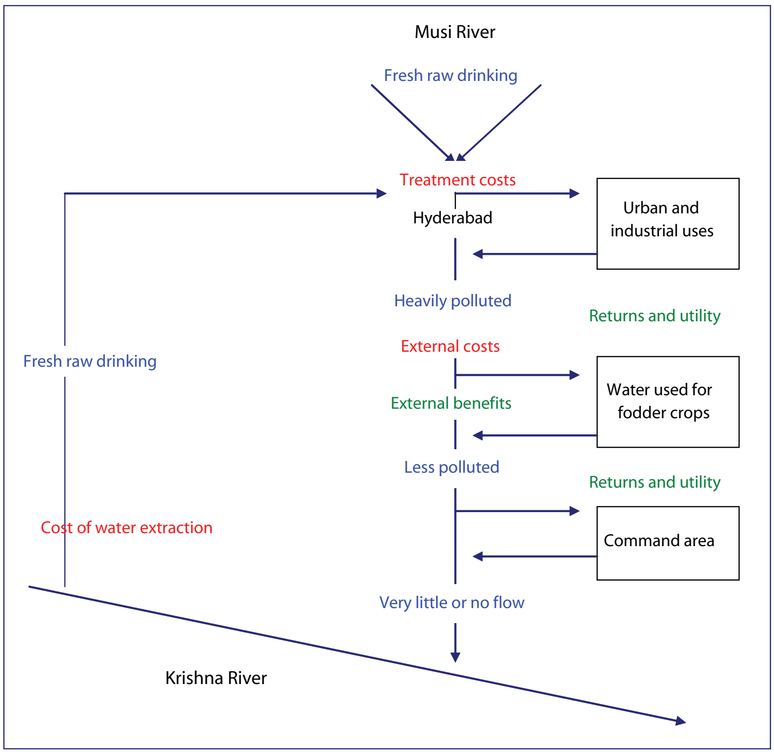

FIGURE 4. Surface water movement in the Musi catchment.

In Andhra Pradesh, responsibility for water is shared by a set of water user associations, government departments and municipal bodies. In general, it could be argued that the two most important organizations are the Andhra Pradesh Department of Irrigation, responsible for the distribution of water to agricultural users, and the Hyderabad Metropolitan Water Supply and Sewerage Board, responsible for acquiring and distributing the water throughout the city. Other surface water supplies throughout the catchment are, by and large, gravity-fed, while decisions on groundwater extraction are undertaken by individual farmers.

An externality exists in the Musi catchment in the form of the release of untreated sewerage from Hyderabad entering the river and being used downstream from the city. The negative externalities of this are reflected in poor health outcomes for society and lower crop yields. However, downstream farmers do not make use of the nutrients that exist in the rivers to produce crops. If anything, the nutrients in the crops are at such high levels, that the soil and plants are adversely affected. What is surprising is that farmers still fertilize their crops with inorganic fertilizers (Simmons, IWMI, Hyderabad, pers. comm. 2007).

Specification of the Model

In specifying the model of the Musi catchment it is first necessary to observe its hydrological characteristics. Then the value of water to users in each zone has to be determined. Finally, the SCB analysis is presented. It is assumed that there are no benefits to be derived from either recreation uses or flood mitigation in this study. This assumption is a limitation of the study as one of the reasons for first regulating the Musi River in the 1920s was to mitigate flooding. However, lack of available data on the costs of flooding and the benefits from mitigating floods makes this assumption unavoidable. The data used in this model and its sources, when not reported below, are specified in appendix B.

The Hydrological Component

Details of the hydrological model are presented in George et al., 2007. What is important for this application of the model is that there are five sources of water, supplying five agricultural zones and two domestic nodes (Hyderabad City and Suryapet in zone 4) and the industrial sector in Hyderabad. Of the five agricultural zones, farmers in one zone use the wastewater from Hyderabad (which is calculated to be equal to a share of domestic and industrial water use in Hyderabad), two zones (1 and 3) make use groundwater only and the other two have conjunctive uses. These zones are shown in Figure 3. In this model the effects of changing the distribution of water amongst the eight hydrological demand nodes are assessed.

The amounts of water flowing through the system in 2001-02 are shown in Table 1. These data were obtained from the hydrological model specified by George et al. (2007) and contain a number of restrictive assumptions. These data are simulated results from a model. Thus, they include a far higher flow of water to Hyderabad, as the whole Krishna water system is assumed to be in operation. In addition, as they are simulated, these flows incur all the limitations, errors and assumptions embodied in the hydrological model.

TABLE 1. The quantity of water supplied and demanded, 2001-02 (million m^3 [Mm^3]).

Item		Groundwater	Surface supply
Demand			
Agriculture	Zone 1	515	-
	Zone 2	285	-
	Zone 3	170	
	Zone 4	-	240
	Wastewater	-	148
Hyderabad	Domestic	-	323
	Industrial		60
Power generation			7,320
Environment			9
Supply			
	Nagarjuna		276
	Osman		36
	Himayath		36
	Singur and Manjira		102

Source: George et al. 2007.

Determining the Value of Water to Users

Industrial consumers: In valuing the economic surplus by the industrial sector, an elasticity of demand for water by industries is needed. Kumar (2006) estimated the own-price elasticity of demand for water by various industries in India, using an input distance function approach. With the exception of the drug and pharmaceutical industries, the own-price elasticity of demand for water by industry would appear to be nearly unitary elastic. Kumar suggests that, on average, the elasticity to use should be -0.902.

According to Young (2005), this elasticity can be used to determine the economic surplus derived from industrial use, by establishing the slope and intercept of the demand schedule at the supply price (of Rs 18/m^3), the amount paid by the water supply authorities for the last unit obtained from the Krishna scheme.

Three points should be noted regarding this estimate. First, the price paid by industrial users of water is Rs 35/m^3. However, this price bears little relationship to the social cost of obtaining the water. The Hyderabad Metropolitan Water Supply and Sewerage Board obtains water from various sources and the most expensive source is the Krishna River, at Rs 18/ m^3. It is this price that is considered to be the true reflection of the social cost of water. Second, only the benefits derived from water consumption are estimated in the model, not the demand for final goods. As a consequence, there is no need to account for the benefits derived from other inputs or the costs of those inputs as well. Third, the estimates of economic surplus derived from these data do not include the costs of treating and getting the water to the site. These are costs associated with providing and distributing water. Some debate exists about the degree to which water in Hyderabad is, or is not, treated.

Domestic consumers: For domestic consumers water is a necessity of life. As such, the value of water to these consumers is incalculable. The own-price elasticity of demand is assumed to be highly inelastic (at -0.17). This estimate was derived from Grafton and Ward 2007 and was taken from a study of water scarcity in Sydney, Australia. While the way water is used and supplied is very different in Hyderabad, this estimate was derived from a study of people who had to water gardens under somewhat restrictive conditions using only hand-held hoses. Even though this estimate of the elasticity is considered to be realistic, it will be subject to a sensitivity test.

It can be expected that any further provision beyond what was supplied in 2007 would be consumed and valued more highly than by any other user group, as Hyderabad only receives 65% of its water requirements (Van Rooijen et al. 2005). As with industrial use, in the model, water for domestic consumption is valued at the price Hyderabad Metropolitan Water and Sewerage Board obtains it from the Krishna Basin (Rs 18/m^3). This is considerably higher than what consumers actually pay for the water, but as water is subsidized, the higher value is considered to be the social price.

Agricultural users: By far the greatest user of water in the Musi catchment is agriculture. Individual residual valuation equations for water need to be derived for each major crop in each zone. The data needed to derive each value of water for each crop in each zone was obtained from the District Handbooks of the various regions (Government of Andhra Pradesh 2005), with other data on prices for outputs taken from FAO 2007 FAOSTATS. The data used to determine the value of water in 2001-02 are presented in appendix B. The results of this analysis are presented in the section on *Results*.

Power generation: Power generation occurs at the Nagarjuna Sagar Dam where the production capacity is 815.6 million watts (*www.answers.com/topic/nagarjunasagardam 2006*). The quantity of water used for power generation is given in George et al. 2007. In 2001-02, altogether 7,320 Mm^3 were used to generate electricity. If it is assumed that all of the water is used to produce the maximum capacity and that electricity is priced at Rs 3.50 kW/h in India (*www.iea.org/textbase/nppdf/free/2000/elecindia2002.pdf*) the return from power generation is equal to Rs 396.37/Mm^3 of water used.

Environmental flows: In this study, the value of water used for environmental purposes is assumed to be equal to the lowest value of an alternative use of the water. Water used in the wastewater zone is expected to be the lowest. The quantity of water entering the environment was derived from George et al. 2007 and for 2001-02 it is as reported in Table 1.

In situ values: The production of paragrass is considered to have an *in situ* value in the catchment. Paragrass is grown on the outskirts of Hyderabad, between the urban areas and the Musi River. This crop is fed from the raw sewerage outflow of households. The crop is used as fodder by the dairy herd of the city. The cost of the water to the paragrass industry is assumed to be zero. The quantity of water used to feed this industry is equivalent to the amount flowing from Hyderabad to the wastewater zone. The area harvested is 2,000 ha, and the yield is approximately 2 t/ha (Arif Ali Khan and Rama Krishna Reddy, Intensive Livestock Research Unit, Hyderabad, pers. comm. 2007). Thus, the return to paragrass has been estimated at Rs 4/kg.

The Costs of Supplying the System

The costs of supplying water from various supply points to Hyderabad City range from Rs 3/m^3 from reservoirs close to the city to Rs 18/m^3 from the Krishna River (see Table 2). As the supply system has grown, the costs of supplying water to Hyderabad have increased. Thus, the costs of supplying the system can be thought of as a set of block rates where the lowest costs are from the older parts of the system and the highest from more recent developments.

TABLE 2. Supply of water to Hyderabad 2001-02.

Source of supply	Price (Rs/m^3)	Quantity (Mm^3)
Osman Sagar	3	35
Himayath Sagar	3	28
Manjira and Singur	12	145.2
Krishna Basin	18	85
Groundwater	0.6	90

Source: George et al. 2007.

The costs of getting water from the Krishna Basin play a central role in this model. That price (Rs 18/m^3) is assumed to be the point where water supply equals demand in Hyderabad City. It is assumed that the costs of accessing extra water from this source remain constant at this price. The implicit assumption in using this value is that the costs of distributing water under the current (2007) arrangements are nonexistent.

The cost of accessing groundwater has been estimated at Rs 0.59/m^3. This price is estimated by taking the electricity cost specified above and multiplying it by the power required to lift water in a standard pump. These costs are needed and included in the calculations of the agricultural value of water.

The external environmental costs of wastewater use are set at Rs 1 million per year. These are assumed to be the costs of health care for residents in the zone. These costs are hard to discern as the specific cause of health concerns are difficult to identify. The far larger external costs of using wastewater occur in crop damage and these are already accounted for in the yields in the wastewater zone. Finally, it is assumed that there are no long-term residual effects and damage to the soils from using wastewater.

An additional external effect occurs with the use of groundwater. Groundwater in zones 2 and 3 in the Musi contains high levels of arsenic and fluoride. The costs of arsenic and fluoride contaminations are hard to estimate. As with the wastewater use, the costs of this contamination are assumed to be Rs 1 million per annum.

The Social Cost-benefit Component

This modelling exercise is collected together into an SCB model. The individual values of water to different users are multiplied by the quantities of water allocated to each use over a 39-year period from 1993 to 2031. This is the period over which the hydrological model was estimated. Over this period, it is assumed that policymakers implement what is known as Stages II and III of the Krishna scheme, a plan to supply more water to Hyderabad City from the Krishna River. The costs of allocating water throughout the system are taken from these benefits and the net present value is determined over the period from 2007 to 2031. The reason these details are not calculated from 1993 is that any costs and benefits that occurred prior to 2007 are considered to be sunk. The discount rate assumed to operate in this model is 8%. This rate will be subjected to a sensitivity test.

Results

The results of the modelling exercise are reported in this section. Initially the results from the valuation in water are presented and then the outcomes from the SCB analysis presented. This can be termed the "baseline scenario" and used for comparative purposes with other hypothesized scenarios.

In this model, the water supplied is insufficient to irrigate the whole command area. The water deficiency coefficient is the difference between the area that can be irrigated with available supplies and the command area. In 2001-02, this was estimated to be between 0.61 and 0.96. Thus, in the worst case, only 61% of the command area was irrigated in the wastewater zone (see Table 3). These coefficients are used to determine the value of water in the year in question (2001-02) and are not a constraint imposed in the SCB model.

TABLE 3. The average value of each unit of water to different users and regions (2001-02).

Item		Average value (Rs/m^3)	Deficiency Coefficient	Quantity used (Mm^3)
Agriculture	Zone 1	2.95	0.74	493
	Zone 2	1.13	0.74	315
	Zone 3	1.16	0.70	147
	Zone 4	1.37	0.80	1,260
	Wastewater	1.44	0.61	148
Hyderabad	Domestic	52.94	-	324
	Industrial	9.95	-	60
Power generation		0.01	-	6,988
Environment		1.44	-	9

Domestic users are estimated to derive the greatest value for water at Rs 53/m^3. They tend to pay somewhere between Rs 10 and 12/m^3 and the price to get the last unit of water to them is estimated to be Rs 18/m^3. Industrial users are charged Rs 35/m^3 and again the cost of supplying the last unit is Rs 18/m^3. However, it is estimated that they derive only Rs 10/m^3 (see Table 3). Within agriculture the *per* unit values are the lowest. In zones 2 and 3, the value of water is estimated to be an average of only approximately Rs 1.15/m^3, and in zone 1 (the highest) it is estimated to be only Rs 2.95/m^3. Overall, the agricultural value of water in the catchment is estimated to be Rs 1.81/m^3.

The value of individual crops varies greatly. For vegetables it was found to be Rs 107.6/m^3, while for groundnut it was estimated to lose nearly Rs 17/m^3. For rice, the most popular crop, the value to users was estimated to vary between a loss of Rs 0.4/m^3 in zone 1 and a gain of Rs 0.6/m^3 in zone 4. The values users place on water in individual crops and pursuits and within regions are reported in Table 4.

TABLE 4. The values of individual crops, 2001-02.

Crop	Zone 1	Zone 2	Zone 3	Zone 4	Wastewater
Kharif (June to October)					
Rice	-0.54	0.11	0.30	0.42	0.01
Vegetables	106.19	106.07	106.15	106.5	106.36
Chili	4.55	4.52	4.67	4.83	5.01
Fruits	24.26	24.20	24.37	24.59	24.68
Groundnut	-24.29	-24.66	-25.10	-24.23	-25.23
Maize	22.27	22.01	21.82	22.47	21.83
Cotton	-0.19	2.82	2.96	3.17	0.22
Other	-34.81	-35.31	-35.90	-34.77	-36.20
Rabi (November to February)					
Rice	-0.34	-0.15	0.04	0.16	0.08
Vegetables	21.53	21.50	21.68	21.83	22.03
Chili	1.21	1.19	1.38	1.50	1.75
Gram	15.50	15.49	15.66	15.78	16.03
Groundnut	3.75	3.73	3.89	4.04	4.25
Maize	3.17	3.14	3.32	3.46	3.67
Other	-4.46	-4.50	-4.37	-4.18	-4.04
Average	2.95	1.13	1.16	1.37	1.44

The net present value of allocating water through the Musi catchment is estimated to be Rs 211,934 million between 2007 and 2031. The net present costs of operating this system are estimated to be Rs 92,675 million over that period. These costs include Rs 16,744 million in the expansion of the Krishna scheme to bring additional water to Hyderabad City (see Table 5).

TABLE 5. Present benefits and costs of the Musi system, 2007-2031 (Rs million).

Item		Present value of water	Present costs of water	Net present value
Agriculture	Zone 1	17,288		
	Zone 2	3,225	5.5	
	Zone 3	3,355	5.5	
	Zone 4	12,302		
	Wastewater	2,330	11	
	Total agriculture	38,501	22	38,479
Hyderabad	Domestic	235,812	-	
	Industrial	9,652	-	
	Total Hyderabad	245,464	115,136	131,328
Power generation		44	-	6,988
Environment		158	-	9
Total system				175,850

The present value of benefits of delivering water to Hyderabad City for domestic use has been estimated to be Rs 242,464 million between 2007 and 2031. This represents the highest individual value for water use in the catchment. Over this period, industrial users have a present benefit of Rs 9,652 million.

The present benefits to agriculture are found to be quite low. Altogether, they are equal to Rs 38,501 million between 2007 and 2031. In zone 1 these benefits are greatest at Rs 17,288 million and lowest in the wastewater zone, where they are estimated to be Rs 2,330 million. These values tend to be determined by the cropping patterns and the yields obtained. In zone 1, a significant area is planted to vegetables, which receive much higher returns, when compared to other crops. In the wastewater zone, rice tends to be dominant, which is not as profitable as other crops. In addition, the yields for rice are not as high because they are irrigated from wastewater. The wastewater zone is a captive of its own unique set of circumstances. Higher returning crops cannot be produced as they are not tolerant to the impurities in the wastewater.

Sensitivity Tests

The sensitivity of the results to some of the key parameters and to the assumptions made is tested in this section. As the aim of the model is to assess whether a change in water allocations will be of net benefit to society, diagnostic tests will be performed only on those parameters that are expected to affect the net present value (present benefits minus present costs) significantly.

Since domestic water use accounts for 81% of the total gross present benefits of water (excluding costs), the sensitivity of the outcomes to the assumed own-price elasticity of -0.17 for domestic water use will be tested. If an elasticity of -0.10 is used the value of domestic water use increases from Rs 52.95 to 90/m^3, while an elasticity of -0.30 will lead to a decrease to Rs 30/m^3. Since the benefit cost ratio is more than 3, the gross benefits as well as the net present value are both very sensitive to the assumed own-price elasticity for domestic water use, especially if it is more inelastic. The relative differences in the total net present value of domestic use are 183 and 49% with an elasticity of -0.10 and -0.30, respectively.

The own-price elasticity of demand for water by industry is assumed to be -0.902. If the elasticity is assumed to be either 0.80 or 0.60, the value of domestic water use increases from Rs 9.98/m^3 to Rs 11.25 or 15.00/m^3, respectively. Since industrial use accounts only for 3% of the total gross present benefits, the relative difference in total net present value is less than 103%. This means that the outcomes are not very sensitive to the chosen elasticity.

The value of irrigation water would appear to be sensitive to the crop price and crop yield. As the net value of water is equal to crop yield times crop price minus all costs of inputs divided by the quantity of water irrigated, a percentage change in crop price or crop yield will have the same implications.

A 30% increase in crop yield will lead to a relative difference in total net present value of 113%. The relative difference in the gross present benefits of agriculture is, however, 159%, but agricultural use accounts only for 15% of the total gross present benefit. The value of irrigation water increases from Rs 2.13 to 3.37/m^3. A 30% decrease in crop yield leads to a rather similar impact in the opposite direction.

As the costs of water provision by the existing scheme to Hyderabad account for 82% of the total present costs, it is necessary to test the sensitivity of the outcomes to the assumed costs of provision per cubic meter. Water is supplied to Hyderabad from many sources, incurring a different cost for each source of Rs 3, 12 and 18/m^3 for supplying 3, 21 and 75%, respectively, of the water to the city. A cost of Rs 24 or 12/m^3 instead of Rs 18/m^3 for the 75% of the water provided will show a relative difference in total present costs of 125 or 75%, respectively. The relative difference in the net present value is, however, only 91 and 109%, respectively. It will affect the benefit cost ratio substantially and will be 2.67 and 4.05, respectively.

The assumed costs of groundwater pumping are Rs 0.509/m^3. Zero cost or doubling of costs shows a relative difference in total net present value of 104 or 96%, respectively. The relative difference in the gross present benefit of agriculture is again more substantial, 119 or 81%, respectively. It varies, however, substantially among the zones distinguished as in two zones only groundwater is used, in two other zones there is conjunctive use and in one zone no groundwater is used. The relative difference in the gross present benefit of agriculture varies between 100 and 141% in the case of zero costs and between 59 and 100% in the case of doubling the costs. This means that although the overall impact is relatively small, regionally the impact might be more substantial. The average value of irrigation water will be Rs 2.55 and 1.71/m^3, respectively, but again there are substantial regional differences.

The assumed area-based charge for surface water is Rs 100/ha. Doing away with this charge does not have a significant impact. The relative difference in the gross present benefits of agriculture, as a result of an area-based charge of Rs 1,000/ha will, however, be 95%. The impact on the total net present value is again small.

A discount rate of 4 and 12%, instead of 8% will result in a relative difference in the total net present value of 145 and 71%, respectively, with modest variation among the various benefit and cost components.

SCENARIO TESTING IN THE MUSI SUBBASIN

The model was used to simulate selected future scenarios. All seven scenarios were modelled, involving different operational allocation priorities, climatic effects and economic situations. In addition, a number of combinations of these scenarios were simulated. In this section, the scenarios conducted are detailed and the results reported. In particular, the results concentrate on the net present benefits derived from different agricultural zones, and industrial and domestic uses. In addition, details are presented on the net present value of running the whole system. What is important with these results is the need to concentrate on the changes to each of these variables, from the base scenario, as each scenario is tested. The results are reported in Table 6.

All these scenarios are compared with the baseline results presented above. From a hydrological perspective the baseline scenario was developed using the water demand data from 1993 to 2031 and simulated streamflow data from 1993 to 2004 assuming that a similar trend of streamflow situation will exist in future. For Osman Sagar, Himayath Sagar and Musi Medium the synthetic data generated using SYMHYD were used. The maximum supply from Nagarjuna Sagar into the city is restricted to 450 million m^3 (the allocation in 2007). Any future demand by Hyderabad cannot be met from any sources and it is assumed that per capita demand for water will fall. This includes Krishna I, II and III schemes throughout the whole period analyzed. This is a simplified assumption made by George et al. (2007). Agricultural demand and hydrological conditions are assumed to remain unchanged in the future. The actual release of water from Nagarjuna Sagar to the Lower Krishna Basin is used for power generation as there is no specific allocation made for it. This scenario assumes that the population grows at a rate of 3% per year in Hyderabad City.

TABLE 6. Changes in values from the base scenario after simulating the model for Musi, 2007-31 (Rs million).

Scenario no.	Net present benefits					Net present costs	Net present values
	Agriculture	Domestic	Industrial	Power generated	Total		
1	480	31,790	443	443	32,715	241,839	-209124
2 (10%)	-2187	116	323	323	-1760	-2237	477
2 (20%)	-5827	-2291	276	276	-7863	-1737	-6126
3	2,798	35,149	589	589	38,549	60,699	-22150
4	2,688	3,762	435	435	6,867	-396	7,263
5	5,070	1,560	138	138	6,813	-2883	9,696
1+2 (10)	-2301	31,628	443	443	29,760	242,250	-212490
1+2 (20)	-5332	31,009	420	420	26,081	252,068	-225987
1+4	2,798	35,149	589	589	38,549	245,044	-206495

Satisfying All Future Urban Demand from Nagarjuna Sagar (Scenario 1)

In this scenario all future demands are assumed to be met from Nagarjuna Sagar. It is assumed that 100% of the demand of Hyderabad was met from what was gained in 2007 from other sources and that the extra requirements are met from Nagarjuna Sagar. The difference with the baseline scenario is that the 450 million m^3 constraint on taking water from Nagarjuna Sagar is eliminated. The justification for this scenario is that the construction of new water storage facilities to meet the growing urban demand appears to be no longer feasible. Individual crop water requirements and hydrological conditions are assumed to remain unchanged in the future. However, the water supplied to agriculture will need to decrease, necessitating a reduction in the areas planted. The reduced releases from Nagarjuna Sagar are assumed to be shared between the left and right bank canals of Nagarjuna Sagar and for downstream uses. This will affect the water available for power generation. In this scenario it is assumed that the infrastructure is added as required in 124.38 Mm^3 (or 90 million gallons daily in the local engineering terminology) lots as it was with the Krishna project. The cost of the project was Rs 125,387 million for construction, the water grid in Hyderabad and the cost of new connections (Hyderabad Metropolitan Water Supply and Sewerage Board 2007). This means that the cost of getting the water to Hyderabad is an additional Rs 125,387 million each time the population grows to a point where the supply system capacity cannot satisfy the demand of the city. What occurred in 2007 is assumed to be repeated in 2017, 2023 and 2027. In the scenarios where streamflows decline by 20% the investment in 2017 will be required 2 years earlier.

This scenario shows that if Hyderabad is going to draw most of the growing demand from Nagarjuna Sagar in the future, the situation may well get worse over time. The results would suggest that if the investment required to enable this scenario to occur the system would lose Rs 209,124 million. This is the total loss society might have to incur if the future water demands of Hyderabad are to be met. This loss results from domestic users gaining Rs 31,790 million, but these are outweighed by cost increases of Rs 241,839 million. Agriculture would appear not to be greatly affected by these changes. What is interesting is that producers in zone 4 will actually benefit from this situation.

Streamflow Declines (Scenario 2)

The urban areas and industries in the upstream of both the Krishna and Musi basins are also being developed to take water from the system before it can be harvested by the existing infrastructure. In the recent past, a series of dry years has had a significant impact on the annual average streamflows into the reservoirs. The runoff coefficient has decreased from 20 to 6% since 1985. Therefore, it can be assumed that the security of inflows into the reservoirs is not guaranteed in the future, especially if the trends evident in 2007 continue. Scenarios were analyzed with a 10 and 20% decline in streamflows every year over the whole period and the demand remains unchanged. Power generation will be affected by this scenario and is expected to decrease. This scenario assumes the population will grow at a rate of 3% per annum, as in the baseline scenario.

Two different rates of streamflow decline were tested in this scenario, at 10 and 20% streamflow losses. A 10% streamflow loss was found to affect the net present value of the system negligibly. However, if streamflows are simulated to decrease by 20%, a loss of Rs 6,126 million will be incurred. Under these two scenarios agriculture incurs the greatest loss (Rs 2,187 and 5,827 million, respectively). Most of these losses are concentrated in zone 4.

Water Savings in the City (Scenario 3)

To keep pace with population and economic growth, Hyderabad City will need to identify and develop new supply sources almost continually. One suggestion is to supply from Nagarjuna Sagar and this situation was examined in Scenario 1. Another supply source for Hyderabad can be through better demand management and the reuse of urban runoff and wastewater. The conservation programs considered include a 5% conveyance efficiency improvement, reusing 90 Mm^3 of urban runoff, the adoption of water harvesting by 0.5 million households and the recycling of 120 Mm^3 of wastewater. This is estimated to save 310 Mm^3 of water. Population growth is, ceteris paribus, assumed to be 3% per annum.

The cost of gathering rainwater was calculated as follows. The cost of a 9,000-liter (or 9 m^3) tank has been estimated to be Rs 13,500. Thus, 1 m^3 costs Rs 1,500. Given that 90 Mm^3 are expected to be collected, the capital cost of the tanks is estimated to be Rs 135,000 million. This investment was assumed to be needed in the first year, i.e., 2007.

The cost of a sewerage recycling plant has been estimated by the Hyderabad Metropolitan Water and Sewerage Service Board (2007) to be Rs 3,390 million, which is capable of handling 216 Mm^3. Thus the cost of generating 300 Mm^3 a year was estimated to be Rs 1,883 million, in 2007.

If rainwater harvesting is considered, the net present value of the system losses would be Rs 22,150 million. This loss is approximately 10% of that from scenario 1. However, it could be argued that there is far less water associated with this scenario over-satisfying scenario 1. Domestic users gain Rs 35,149 million, yet society pays Rs 60,699 million. Agricultural producers also gain Rs 2,798 million from this scenario.

Releases to Lower Krishna Based on Irrigation Demand (Scenario 4)

In 2007, the releases to the Lower Krishna Basin were based on power requirements alone. If the releases are made according to irrigation requirements of the lower parts of the basin, it is believed that some water can be saved. This scenario assesses releasing the water to the Lower

Krishna Basin based on irrigation demand, rather than on the demands for power generation. All other variables remain the same. The constraints of the system mean that the whole command area is planted. This scenario can be used to provide the upper limits for the existing system as a whole. Everything needed comes at a cost to others outside the system.

Releases to the Lower Krishna result in the net present value rising by Rs 7,263 million. This scenario is really about better scheduling from the main supply point in the system. Agriculture gains greatly, with net present benefits of Rs 2,688 million. Interestingly, there are gains to be made from power generation, in the order of Rs 435 million.

Crop Diversification (Scenario 5)

Crop diversification is defined as a strategy of shifting from more water-intensive crops to low water-intensive crops by changing the crop variety and cropping system. In an attempt to match the supply and demand, the cropping pattern is diversified by reducing the rabi rice crop by 10% and the kharif rice crop by 15%. The water saved is allocated to all other crops equally. All other variables remain the same as in the baseline scenario.

This scenario results in the greatest gain to the system, with the net present value rising by Rs 9,696 million. The implication with this scenario is that producers make better decisions. Agricultural net present benefits rise by Rs 5,070 million and the costs of running the system fall by Rs 2,883 million. There are also gains to the domestic and industrial users.

Combined Scenarios

Numerous simulations of combinations of these scenarios were run and the results were as expected. It can be concluded that any attempt to bring more water from the Krishna to Hyderabad will dominate the results, causing large losses to the system. In economic terms, agriculture is adversely affected by this move, albeit not to a great extent.

CONCLUSIONS

Our purpose in this paper was to present a model that has the capacity to measure the economic impacts of changing the allocation of water within the catchment. The framework chosen was a simulation model that values exogenously determined water allocations across a number of regions, over a variety of uses and over a long period of time. The model was designed not to determine the optimal allocation of water but to determine the economic effects of changing the allocation of water. Thus, the model works in conjunction with an existing hydrological model.

The aim in making this model was to provide policymakers and stakeholders with a tool that would allow them to assess the social costs and benefits of reallocating water in any manner they would see fit. Consequently, the social costs and benefits of reallocating water are assessed, not the private costs and benefits to any individual stakeholder. Thus, an attempt was made to account for the externalities in the system and the impacts of transfers (taxes and subsidies).

With this model the region to be assessed can be said to be set at any level (farm to a complex basin), as long as there are subregions identified within it. For example, in the case of the Musi, discussed in this paper, five specific regions were identified. Some regions were reliant solely on groundwater or surface water supplies, while others used a mixture of the two. The variety of uses water can be put to in the model is also extensive. In the case of the model of the Musi catchment the use of water is for industrial, agricultural, domestic, power generation and environmental purposes. Any additional users could be incorporated into the model if the allocation of water to them is known and an own-price elasticity of demand for water is assumed.

In this study most emphasis is placed on determining the value of water to agricultural users. The importance placed on agricultural users is directly proportional to the amount of water used in this sector. A residual method is used to determine the values of water to each individual crop within a region. To determine the value of water to other sectors the consumer surplus for each use was calculated from an estimate from the own-price elasticity of demand at the cost of delivering the last unit of water to that use (which in the case of Hyderabad for industrial and domestic demands was Rs 18/m^3).

Once the value of water to each sector in each region is determined for a particular year, these values are then used to determine the costs and benefits over a long period of time. The framework on which this part of the model is built was based on an SCB analysis. This is needed as any investment in the changes to the allocation of water is usually very high and the costs are borne early in the process while its benefits are realized over many subsequent years. The limitation of this approach is that the valuation of a particular irrigation scheme is dependent on the data of a single year. If the year in question is not a typical year, then the analysis may well be flawed.

The model applied to the Musi catchment of the Krishna Basin provides a number of insights into the modelling process. The site was a complex one involving multiple uses of both groundwater and surface water across a wide spatial dimension while conjunctive use was also accounted for. It was found that in 2001-02 the value users placed on water varied from approximately Rs 1 to 3/m^3 for agricultural use, to nearly Rs 10/m^3 for industrial use and Rs 53/m^3 for domestic purposes. Environmental flows were assumed to have a value equivalent to those derived for water used in the wastewater zone of the Musi catchment (Rs 1.44/m^3) while power generation, a conjunctive use, yielded a return of Rs 0.01/m^3.

Over the period from 2007 to 2031, the net present value of delivering water to Hyderabad for domestic and industrial uses under the existing situation was estimated to be Rs 131,328 million, while agricultural uses were found to deliver Rs 38,479 of net present value and power generation yielded Rs 6,988 million. The overwhelming conclusion that can be drawn is that while a large amount of the water is used in agriculture and the highest costs are associated with delivering water to urban users in Hyderabad, the vast amount of the value derived from the allocation system comes from those users in Hyderabad.

This finding should not come as a surprise. In most irrigation systems around the world similar results could be expected to occur. However, the purpose in this model was to quantify those impacts. In addition, of interest are the economic impacts of changing the allocation of water.

Any results from simulating the model are subject to the sensitivities inherent in the model. Most models of this type are sensitive to the chosen discount rate. This was also the case in this model. In addition, it was found that the model was sensitive to the estimate of the own-price elasticity of demand for domestic water use and relatively insensitive to estimates of the own-price elasticity of industrial use or in changes in the yields or prices of agricultural outputs. This result was not unexpected as it was found that so much of the value consumers derive from the system comes from domestic users. However, this conclusion should not obscure the fact that any changes within a user group can have a profound impact on individuals within each group. For instance, a sensitivity test conducted on doubling the costs of groundwater extraction were found to have only a 4% reduction on the net present value of the whole system, but the impact on agriculture was to reduce net present values by nearly 20%. Within the individual zones the disparities in impacts were found to be even greater, registering a reduction of more than 40% in some groundwater-reliant regions.

The task of model construction in itself can be rewarding as it provides an insight into how a complex system works. However, to restrict the effort to the discovery of elements of a particular system alone undervalues the investment placed in that effort. Greater rewards can be gained by using the model to simulate changes in the system and by utilizing its principles in other regions and in different situations. The model effort presented in this paper was applied to model a number of scenarios in the Musi catchment and to model other catchments in both India (within the Krishna Basin) and Australia. They involve changes in both hydrological and economic factors affecting the basin. In each case, the impacts over the period from 2007 to 2031 will be assessed. In terms of coverage, the intention is to use the basis of the model presented above and apply it to the Malapraba and Upper Bhima sub-catchments of the Krishna Basin. In addition to that, it is proposed to utilize the principles of this simulation model in a project on System Harmonization being conducted on four different catchments in Australia.

APPENDIXES

Appendix A: Determining the Value of Water: A Mathematical Description

A1 Hydrological Issues

The process used within a hydrological model is to specify a set of priorities for the water available. That priority is usually to first supply water for human consumption, then to other uses, prior to supplying agriculture and the environment last of all. If water is in short supply, the amount available might not be sufficient to plant all of the command area. While this is of little concern to a hydrologist, it has a profound impact on the value of water in a region.

In accounting for this difficulty a constraint in the model is that the water supplied in a region must be equal to the quantity demanded. In other words, in each region "a":

$$\Sigma Q^{s}_{,} = \Sigma Q^{d}_{,i} \qquad \text{(A1)}$$

where, $Q_{s,i}$ is the quantity supplied from both groundwater and surface supplies in region "a"; and $Q_{d,i}$ is the quantity demanded by the crop i in region "a."

Given that the hydrological models are usually expressed in the absence of rainfall, the quantity demanded should be expressed in terms of the total evapotranspiration of the irrigated crops (ET_i) in region (a), or:

$$\Sigma Q_{d,i} = \Sigma ET_i \, a \qquad \text{(A2)}$$

As the quantity supplied excludes rainfall, it becomes equal to what is supplied through surface water irrigation (Q^s) and what is pumped from the groundwater (Q^g) alone. In other words:

$$\Sigma Q_{s,} = Q^{u}{}_{i} + Q^{g}{}_{i} \qquad \text{(A3)}$$

Thus, to account for the shortfalls in water delivery, between what could potentially be planted if water were available to supply the whole command area (a^c) and what is actually available to plant a reduced area cropped (a^d), requires the assumption that when faced with water shortages farmers reduce the area planted alone. They do not attempt to plant the whole command area and expect a reduction in yields. This is not an unrealistic assumption for irrigation farmers, who are reliant on irrigation supplies for their livelihoods. To plant without adequate water is a risk farmers are assumed not to take. The actual area cropped, in light of water shortages, can be calculated as:

$$a^d = a^c \, \{(Q^u + Q^g) \,/\, (\Sigma ET_i \; a^c)\} \qquad \text{(A4)}$$

In essence, what is embodied in equation (A4) is that the area cropped (a^d) is equal to the total command area available (a^c) multiplied by the proportion of the quantity supplied to the region ($Q^u + Q^g$) to the total quantity demanded in the command area ($ET_i \; a^c$), all of which are known.

In this model, the water delivered to each demand node needs to be valued. This value is dependent on the quantity of crops grown that, in turn, is dependent on the water delivered to the node. In addition, the costs of getting the required quantity of water to each demand node must be measured. Thus, the information embodied in equation (A4) is a crucial link between the hydrological and economic components. It reconciles information on the quantity of water supplied and demanded in a zone. However, it is not the only link required. The quantities of water supplied to each zone need to be valued.

A2 Value of Industrial and Domestic Allocations

The value domestic and industrial consumers place on water is equal to the consumer surplus. From the perspective of society, this can be calculated by estimating the area under the demand equation, above the cost of supplying the last unit of the good, over the quantity supplied. So, given an estimate of the elasticity (e) and the price (P) and quantity (Q) in any given year, the slope of the demand curve (b) can be calculated using a point elasticity formula, as follows:

$$\beta = \varepsilon P/Q \tag{A5}$$

From this base, the intercept term in a demand equation (a) can be determined by inserting the slope coefficient at the given price and quantity and rearranging the equation.

$$\alpha = Q - \beta P \tag{A6}$$

The intercept on the price axis (“) can be determined by setting the demand equation:

$$Q = \alpha - \beta P \tag{A7}$$

equalling zero. Finally, consumer surplus (V) is equal to half the difference between the price and the price intercept, multiplied by the quantity, i.e.

$$Vd = (\propto - P)\ Q/2. \tag{A8}$$

This is equivalent to the area under the demand equation, above the price paid for the water. From the perspective of society, this price is not the price paid by consumers, which can be heavily influenced by government taxes or subsidies, but is the cost of providing the last unit of water.

With respect to estimating the producer surplus arising from the industrial and domestic consumption of water, this is equivalent to the cost of providing the last unit of water (P), less the costs of provision, up to the quantity supplied to both industrial and domestic consumers (see Figure 1). As water provision to a city can come from many sources, when incurring a different cost from each source, care must be taken to attribute the correct costs to each source.

A3 Valuing the Agricultural Uses of Water

The basic approach outlined by Young (2005) relies on the fact that the value to a producer from producing a good is exactly exhausted by the summation of the values of the inputs required to produce it. In other words:

$$Y.P_y = \Sigma\ (P_i.X_i), \tag{A9}$$

where, Y is the quantity of output of the product y;
P_y is the price received for the product Y;
P_i is the value of the marginal product of input I; and
X_i is the input required to produce the product Y.

Expanding the equation to a two-input model, and assuming that the price of one input is known:

$$Y.P_y = P_j.X_j + P_w.X_w, \tag{A10}$$

where, P_j is the value of the marginal product of known input J;
X_j is the known quantity of input J required to produce Y;
X_w is the known quantity of input W required to produce Y; and
P_w is the *unknown* value of the marginal product of input W.

The value of the marginal product of W is unknown and can be found by simply rearranging equation (A10) to:

$$P_w = (Y.P_y - P_j.X_j) / X_w, \qquad \text{(A11)}$$

where, all variables are as defined above.

Young (2005: 61) describes the solution to equation (A11) as the "value of water" or the "net return to water" for crop "y." It is, in the parlance of economics, the "residual value."

The total benefits derived from agricultural use of water are equal to the residual price of water (embodied in equation A11) multiplied by the area over which it is spread, ($a^d_{i,n}$) which is equivalent to a_i in equation (A4). If the fact that multiple crops produced are accounted for then the value of water used in agriculture (B_n) can be specified as:

$$B_n = \Sigma\, a^d_{i,n} \{(Y_{in}P_y - \Sigma P_j X_{jn}) / ET_{i,n}\} \qquad \text{(A12)}$$

where, $ET_{i,n}$ is as specified in equation (A2) and is equivalent to the quantity of water demanded in agriculture.

Appendix B. Data Used to Determine the Value of Water Used in Agriculture

In this appendix details of the data used to calculate the agricultural users' value of water are presented. In addition, the links to the hydrological component are also highlighted, as these are inseparable from the valuation process. The model has five demand nodes, where altogether 15 crops are grown over two different growing seasons within one crop year (2001-02).

Initially, data are required to set up the model. Information on the units of currency, area, output yield, etc., are required, along with the year in question, names of zones, their sizes, the degree of irrigation efficiency and the names of the seasons (see Table B1). For the sake of simplicity, irrigation efficiency is set at 100% and the nodes are called Ag Zone 1 to 4 and the wastewater zone. The two seasons are kharif and rabi (both of which are consistent with common Indian practice). All that is achieved with this part of the input file is to set up the rest of the process.

TABLE B1. Basic data outline.

Item	Particular	Units	Particulars	Values					
	Year	2001-02	CBA period	2007-2031	CBA start year	2007			
Units									
	Currency	Rs	Question	Base run					
	Area	ha							
	Output	tonnes	Description	Test run of the model					
	Yield	t/ha							
	Fertilizer	kg/ha							
	Seeds	kg/ha							
	Water	m^3							
	Labor	days							
	Prices output	Rs/t							
	Seed prices	Rs/kg							
	Water prices	Rs/ha							
	Water prices	Rs/m^3							
	Fertilizer price	Rs/t							
	Labor price	Rs/day							
	Groundwater prices	Rs/000m^3							
	Pesticides	Rs/ha							
	Total values	Rs million							
Physical data									
Region names				Global	Ag zone 1	Ag zone 2	Ag zone 3	Ag zone 4	Waste water
Irrigation efficiency assumed									
		%		100	100	100	100	100	100
Region size		ha		Kharif	92,121	33,849	34,039	79,256	16,411
				Rabi	46,552	22,542	22,471	36,414	15,392
Labor force		no.			0	0	0	0	0
Seasons					150.53	166.60	166.02	145.94	193.79
		1	Kharif						
		2	Rabi						

Information is required on the areas cropped in each node in each season (see Table B2). Altogether 15 crops are specified over the two seasons. In general, the crops chosen are most popular amongst producers. As the model was to be aligned with a hydrological model, the data on cropped areas were derived from George et al. 2007.

TABLE B2. Areas cropped (ha).

		Ag. zone 1	Ag. zone 2	Ag. zone 3	Ag. zone 4	Wastewater
Kharif	Rice	18,454	8,117	8,950	21,951	5,566
	Vegetables	6172	224	170	200	418
	Chili	802	547	227	280	115
	Fruits	4,492	2,143	1,033	3,769	767
	Groundnut	844	2,064	859	6,521	117
	Maize/Jowar	21,303	855	4,822	10,935	404
	Cotton	8,275	6,235	5,758	7301	2,146
	Other crops	7,592	4,755	2,116	12,717	544
Rabi	Rice	23,395	12,474	10,878	19,213	8,260
	Vegetables	5,982	196	296	156	1,063
	Chili	659	227	105	243	21
	Gram	169	200	141	378	4
	Groundnut	1,032	1,710	558	4,432	68
	Maize/Jowar	2,953	1,801	3,822	4,685	34
	Other crops	137	1	0	146	0
Total area planted	Kharif	67,932	24,940	23,934	63,672	10,076
	Rabi	34,328	16,609	15,800	29,254	9,450
Water deficiency coefficient (%)		74.00	74.00	70.00	80.00	61.00

Note: The water deficiency coefficient relates to the proportion of the total area that can be planted given the water supplied.

Data on the yields of crops are mostly derived from various District Handbooks of Andhra Pradesh. Given the aggregate that occurs, the values for Ag Zone 1 were taken from Rangareddy, while Nalgonda values were used for the other Ag Zones (see Table B3). The yields for the wastewater zone were derived from Rob Simmons (IWMI Hyderabad, pers. comm. 2006) who is conducting research into the health aspects of wastewater use. These data on yields were checked by comparing them with those reported by the FAO (2007) and were found to be realistic.

TABLE B3. The yields of crops produced.

			Ag. zone 1	Ag. zone 2	Ag. zone 3	Ag. zone 4	Wastewater
Kharif	t/ha	Rice	1.787	2.718	2.718	2.718	1.787
	t/ha	Vegetables	11.766	11.766	11.766	11.766	11.766
	t/ha	Chili	2.059	2.059	2.059	2.059	2.059
	t/ha	Fruits	9.635	9.635	9.635	9.635	9.635
	t/ha	Groundnut	0.312	0.312	0.312	0.312	0.312
	t/ha	Maize/Jowar	2.622	2.622	2.622	2.622	2.622
	t/ha	Cotton	0.166	0.270	0.270	0.270	0.166
	t/ha	Other crops	0.405	0.405	0.405	0.405	0.405
Rabi	t/ha	Rice	2.368	2.718	2.718	2.718	2.133
	t/ha	Vegetables	11.766	11.766	11.766	11.766	11.766
	t/ha	Chili	2.059	2.059	2.059	2.059	2.059
	t/ha	Gram	9.635	9.635	9.635	9.635	9.635
	t/ha	Groundnut	1.344	1.344	1.344	1.344	1.344
	t/ha	Maize/Jowar	4.036	4.036	4.036	4.036	4.036
	t/ha	Other crops	0.405	0.405	0.405	0.405	0.405

Data on input use are presented in Table B4. Data on input use were not available for the different zones. As a consequence, input use rates are assumed to be the same for all. These data were obtained from the government-recommended rates for fertilizer use reported in the various District Handbooks (Andhra Pradesh). Labor use rates were taken from the Agricultural Compendium for Rural Development in the Tropics and Subtropics (Euroconsult 1989). The quantity of labor applies not to India itself, but to the labor required to produce tropical products.

TABLE B4. Inputs used.

		Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)	Seeds (kg/ha)	Labor (days/year)
Kharif	Rice	98.8	49.4	39.5	50.0	180
	Vegetables	19.8	49.4	0.0	0.0	180
	Chili	19.8	49.4	0.0	2.1	100
	Fruits	60.0	15.0	15.0	0.0	360
	Groundnut	29.6	39.5	49.4	150.0	100
	Maize/Jowar	118.6	59.3	49.4	15.0	120
	Cotton	118.6	59.3	118.6	50.0	160
	Other crops	125.0	30.0	40.0	6.0	110
Rabi	Rice	98.8	49.4	39.5	50.0	180
	Vegetables	19.8	49.4	0.0	0.0	180
	Chili	19.8	49.4	0.0	2.1	100
	Gram	60.0	0.0	0.0	45.0	65
	Groundnut	29.6	39.5	49.4	150.0	100
	Maize/Jowar	118.6	59.3	49.4	15.0	120
	Other crops	125.0	30.0	40.0	6.0	110

Output prices are required for both the primary products produced and for the by-products. Given that in this analysis an SCB analysis is undertaken, it is imperative that world prices are used. The prices used in this study were taken from the FAO database, FAOSTAT. The prices taken were producer prices for India (see Table B5). In 2001-02, a procurement price scheme was abolished in India.

TABLE B5. The world price of crops grown.

	World prices (Rs/t)
Rice	6,034
Vegetables	8,560
Chili	7,579
Fruits	10,961
Groundnut	16,231
Maize/Jowar	5,120
Cotton	53,778
Other crops	5,460
Rice	6,034
Vegetables	8,560
Chili	7,579
Gram	5,460
Groundnut	16,231
Maize/Jowar	5,120
Other crops	5,460

The data required for the price of seeds, labor and fertilizers are presented in Table B6. This information is separated according to the node and crop it is used on. No allowance is made for operator or household labor. As this study is from a social perspective, operator and household labor must be valued according to its next best use. The wage rates for labor are used.

TABLE B6. Input prices.

Nitrogen (Rs/tonne)	Phosphorus (Rs/tonne)	Potassium (Rs/tonne)	Seeds (Rs/tonne)	Labor (Rs/day)	Groundwater (Rs/000m^3)	Surface water (Rs/ha)
4,000	4,300	4,300	20	30 to 48	590	100

The pumping costs and water fees levied on surface water supplies have already been included in agricultural users' valuation of water. In India, farmers pay nothing for electricity costs. In this model the prices used should be the true costs of pumping groundwater (i.e., the price without subsidies). The cost of pumping is estimated to be Rs 0.59/m^3. It is recognized that the price farmers pay for surface water supplies most possibly do not reflect the true costs of provision. They pay a fee of Rs 100/ha. In this case the water fees levied on producers have to be used as the extent of subsidization is not known (see Table B6).

The water requirements per crop can be determined from the evapotranspiration rates. These rates should exclude rainfall. They represent what is known as the irrigation requirement. The irrigation requirement was derived from George et al. 2006 and is presented in Table B7.

TABLE B7. Water requirments (mm/month).

	January	February	March	April	May	June	July	August	September	October	November	December	Total
Rice						170.0	244.0	221.0	201.0	15.5			851.5
Vegetables									26	40		20	86.0
Chili	25.3							0.0	0.0	3.7	100.0	64.5	193.5
Fruits	94.7							0.0	0.0	48.9	105.3	110.5	359.4
Groundnut						4.3	0.0	11.6	0.0	0.0			15.9
Maize/Jowar						0.0	0.0	25.2	1.2	0.0			26.4
Cotton						4			30	43	74	32	183.0
Other crops						0.0	0.0	13.0	0.0	0.0			13.0
Rice	303.3	164.8								0.0	292.6	309.4	1,070.1
Vegetables	121	134	54								31	70	409.6
Chili	77.3	192.6	114.6	26.7							5.1	67.3	483.6
Gram	117.9	86.2									14.0	69.7	287.8
Groundnut	83.1	29.0								0.0	63.1	95.2	270.4
Maize/Jowar	83.1	73.6								0.0	63.1	100.3	320.1
Other crops	12.2									1.8	100.0	33.3	147.3
Total requirements	917.9	680.2	168.6	26.7	0.0	178.3	244.0	270.8	258.2	152.9	847.8	972.2	4,717.6

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