Integrated Watershed Management Modeling: Optimal Decision Making for Natural and Human Components

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Abstract

Complex interactions among components of a watershed system necessitate the evaluation of management options within a watershed framework in order to realize the full impact of management decisions. A generic optimization model was developed to evaluate a broad range of technical, economic and policy management options within a watershed context. With continued development and urbanization, human impact on the hydrology of a watershed can be significant such that it not only impacts but dominates the system. Therefore, the model integrates natural and human elements of a watershed system. Since water demands consist of concurrent requirements for both water quantity and quality, the model was developed considering both the flow and the concentration of constituents to evaluate the full impact of management decisions. The initial application of the model to the upper Ipswich River Basin in Massachusetts is a linear programming formulation where quantity is considered in management decisions. A future version will include a nonlinear solution to the combined consideration of the quantity and quality impacts of various decisions.

Initial results demonstrate the relative efficacy of undervalued management options. The results also document the merits of integrated water resources management by demonstrating the value of management strategies that serve several integrated functions. For example, increased infiltration benefits both stormwater and water supply management. The model also successfully reveals that the apparent economic inefficiency of demand management occurs when consumptive demand is reduced and

the pricing of wastewater services is based on water demand rather than actual wastewater flows.

***"When one tugs at a single thing in nature,
he finds it attached to the rest of the world."***

John Muir (1838-1914)

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Chapter 1 - Introduction: The Watershed Management Challenge

Definition of the Challenge

Integrated water resources management (IWRM) is a rapidly developing field encompassing many disciplines including ecology, engineering, economics and policy. Numerous models that integrate various aspects of the complex, coupled natural-human watershed system are being developed to assist decision makers. IWRM models combine the natural hydrologic cycle with the human water system's technical, socioeconomic and political components as represented in Figure 1 (Jamieson and Fedra 1996; Labadie et al. 2000; Zagona et al. 2001; Donigian and Imhoff 2002; Fisher et al. 2002; Draper et al. 2003; Letcher et al. 2004; and Yates et al. 2005). Most such IWRM models are site specific or simulation based. Site specific models may be difficult for managers with various levels of expertise to adapt to their watershed. Simulation models are not efficient for evaluating and ranking the myriad of options available for watershed management because numerous scenarios must be run to determine the optimal combination of management decisions. Also, many models were originally developed for simulating the natural watershed and do not fully incorporate the human components of the water system. Therefore, there is a need for a technically and financially accessible decision support system that integrates the comprehensive natural-human watershed system including the representation and optimization of the myriad of possible management options.

This study is an initial effort to develop a generic, watershed management optimization model that considers a comprehensive set of options for managing the quantity, quality, routing and use of all available sources and sinks of water throughout the watershed including traditional water sources, direct and indirect water reuse, aquifer storage and recovery, demand management, stormwater management and land use management. The model is developed in accessible, familiar spreadsheet software to facilitate the generalize application and modification of the model.

Evolution of the Challenge

Water resources management has evolved from the relatively straightforward task of water delivery to the more complex, multidisciplinary challenge of watershed management. When human civilizations settled and formed growing population centers, the original challenge was delivering water to these locations, a supply problem. This initial task of water conveyance progressed from simple trenches and aqueducts utilizing gravity flow to the transport of water to a central city location to elaborate distribution networks via underground pipes delivering water to individual households. As populations grew, however, water demand grew and challenges relating to water quantity and reliability were presented. The most common solution was the construction of water supply impoundments for times of water shortage. As industries developed and populations grew, water quality emerged as the next problem. This challenge was met by the invention of water treatment processes to improve water quality obtained from sources before use. In addition, wastewater treatment commenced to improve discharge quality at point sources. The number of water and wastewater treatment processes continues to grow as treatment is required for an ever increasing number of constituents. Addressing the problem of point source pollution, however, only partially improved water quality because non point sources were not addressed such as the quality of runoff from different land uses and land management practices.

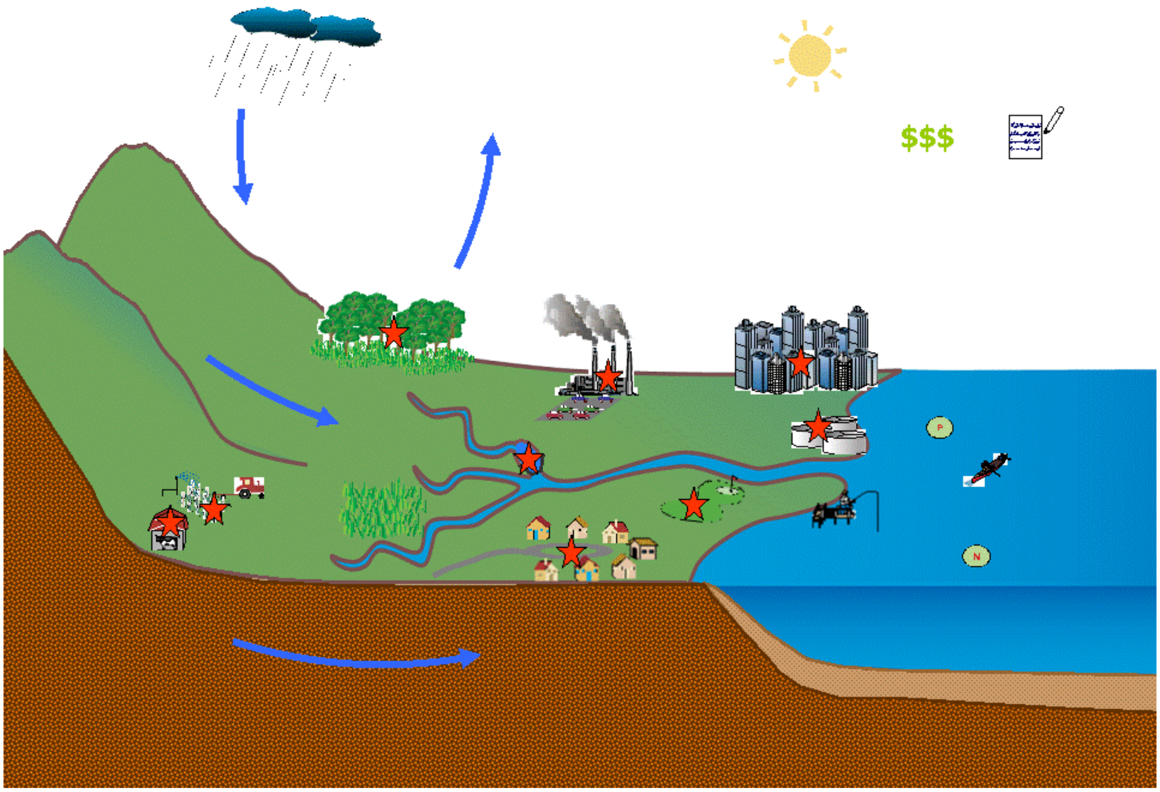

Figure 1. The Natural and Human Components of the Watershed System.
Figure 1 shows stakeholders who often have conflicting objectives such as the farming community, industry, residential neighborhoods, urban centers, and passive recreational users such as fishermen and kayakers. The two circles with N for nitrogen and P for phosphorus in the water represent water quality concerns. The dollar signs and written document represent the impact of financial and political constraints, respectively. Locations of possible management intervention are marked by stars.

As this brief summary of the evolution of water resources management suggests, sustainable water resources management requires a comprehensive approach to account for all of the effects of human activities and management decisions on the interrelated natural and human components of the watershed system. A wide-range of management options must be considered including traditional and alternative water sources with a watershed management tool which models the quantity, quality, reliability, routing and use of water as it flows through the watershed. Traditional water sources include rivers, lakes and aquifers. Alternative water sources include water reuse through additional water treatment and direct nonpotable reuse or indirect reuse through aquifer storage and recovery. Demand management is often considered a virtual supply source as reduced demand results in more supply available to satisfy the remaining water need. There are numerous human demand management tools such as increasing the price of water and wastewater services, low flow water fixture and appliance rebates, watering restriction policies and education. System demand management tools include the repair of potable water distribution infrastructure leakage.

The third category of management options is multi-functional management tools. These are management decisions that are often made by those other than water managers because their origins and primary functions are not water supply management. For example, most land conservation's primary purpose is to protect habitat for various species of animals. However, conserving forest land and therefore preventing additional development can have a significant impact on the ratio of runoff to infiltration and the resulting water quality. Another example is stormwater management in urbanized areas where runoff from impervious surfaces is often collected and routed directly to the nearest surface water body. This results in increased peak flows and no treatment before discharge. Stormwater management tools such as bioretention can significantly increase infiltration and reduce the concentration of pollutants. The need to consider so many possible management tools has resulted in a progression from simple water distribution models to IWRM models which are essentially multidisciplinary, multi-objective watershed management models.

Previous Answers to the Challenge:

Literature Review

Initially models dealt with only one component of the watershed system such as hydrologic simulation of natural watersheds (Crawford and Linsley 1966), reservoir operations (Hall 1968), wastewater treatment (Adams and Panagiotakopoulos 1977), or water distribution design (Shamir 1974). More recently, IWRM models have been formulated that integrate various aspects of the complex, coupled natural-human watershed system. IWRM models combine the natural hydrologic cycle, the human water system and technical, economic, social, and political constraints (Jamieson and Fedra 1996; Labadie et al. 2000; Zagona et al. 2001; Donigian and Imhoff 2002; Fisher et al. 2002; Draper et al. 2003; Letcher et al. 2004; and Yates et al. 2005). The complexity of these models has consequently prompted the development of decision support systems (DSS) which refers to the user interfaces and optimization algorithms built on top of IWRM models to facilitate their application and the utilization of their output.

One characteristic by which IWRM models may be classified is whether they are generic or site specific. Site specific models are developed for a particular watershed system and require considerable resources for modification and application elsewhere. Zagona et al. (2001) discuss the evolution and advantages of generic models. In the 1970s and 1980s, technological limitations of software and hardware led to the development of site specific river basin models in which the physical systems and policy realities at the time of development were hard wired into the software (Zagona et al. 2001). With changing circumstances and requirements in terms of detail, complexity or simply system expansion, the lack of flexibility and adaptability leads to expensive and extensive investment in recoding or obsolescence (Zagona et al. 2001).

Generic models are developed with more flexible components and relationships where parameters are specified by the user. However, Zagona et al. (2001) argue that if the model requires the modification and recompilation of code for a specific application then it is not effectively generic. One example is the Hydrological Simulation Program – FORTRAN (HSPF) which was developed from the Stanford Watershed Model, "the foundation for hydrologic-response simulation programs" (Donigian and Imhoff 2002). HSPF has continued its development from its initial formulation in 1966 as a watershed hydrology model to encompass "Special Actions" in 1984 which enables users to re-set or increment the value of variables to represent human interventions, water regulation and accounting in 1997 and best management practices in the latest 2001 version (Donigian and Imhoff 2002). Although integrating more of the human water system, the development continues to focus on simulating more details and complexity associated with the effects of land management on the quantity and quality of river flow rather than comprehensive watershed management modeling. In addition, despite 40 years of development, HSPF lacks a user friendly interface and requires extensive training and expertise (Yates et al. 2005, Donigian and Imhoff 2002). These qualities limit its utility in a field where the system continually changes and management options continually expand.

Since the goal of this study is to develop a generic model that may be easily adapted by watershed managers, the literature review focuses on truly generic IWRM models. Modular Simulator (MODSIM) (Labadie et al. 2000) and RiverWare (Zagona et al. 2001) are both generic models of river and reservoir operations. They provide limited optimization of water allocation for various model configurations. While they are both generic and include some optimization, their application for watershed management is limited by their focus on reservoir operations. These models may be more appropriate for prescribing and scheduling the operations of reservoirs once the required withdrawals, instream flow and water quality values or range of values are identified by a more comprehensive watershed planning model.

MULtisectoral, INtegrated and Operational (MULINO) DSS also requires an external hydrologic model but is more comprehensive than MODSIM or RiverWare (Mysiak et al. 2005; MULINO 2007). MULINO is linked with the Soil Water Assessment Tool (SWAT) which is a detailed and highly developed watershed model that simulates hydrology and water quality in basins with varying soils, land use and management practices (Arnold and Fohrer 2005). SWAT can simulate the effects of changes in land use and agricultural management on streamflow, sediment and agricultural chemical yields (Arnold and Fohrer 2005). SWAT mostly focuses on land based changes and management practices while MULINO focuses on stakeholder involvement and providing various methodologies for decision making. MULINO utilizes SWAT output and uses multi-criteria analysis to choose among various management options. In combination they provide a simulation and consideration of land based watershed management options but with limited applications in comprehensive watershed management and without management optimization capabilities.

Simulation models may be preferred after screening all the available options as they usually provide more insight into system dynamics and sensitivities than optimization models. However, while comprehensive simulation is important, optimization capabilities are critical. As illustrated in Figure 1, there are a myriad of management opportunities in a watershed. Since the combinations of options are effectively inexhaustible, the utility of simulation models for watershed planning is limited. As shown in Table 1, only one generic model, WaterWare, has the ability to optimize management alternatives. In all other models, numerous scenarios must be constructed and evaluated requiring extensive time investment.

Table 1. Summary of Model Components.

Model	**Natural**	**Human**	**Management Optimization**	
HSPF (Donigian and Imhoff 2002)	Yes	Limited	No	
MODSIM (Labadie et al. 2000)	Partial	Partial (Reservoir systems)	No	Flow and reservoir operations only
RiverWare (Zagona et al. 2001)	Partial	Partial (Reservoir systems)	No	Flow and reservoir operations only
MULINO/SWAT (Mysiak et al. 2005)	Yes	Partial (Reservoir systems, Land Use)	No	
WaterWare (Jamieson and Fedra 1996)	Yes	Yes	Yes	Sophisticated user level, Run time, Affordability
WEAP (Yates et al. 2005)	Yes	Yes	No	Flow allocation only, Management scenarios

Although the DSS in MULINO may be useful in its thoroughness and future utilization as the end component for various decision making methodologies, the first challenge is to screen the myriad of management options by determining their effects on the watershed system in a comprehensive and integrated optimization model. Once the options are reduced to near optimal solutions and the decision space is reduced, then a finite number of scenarios may be generated for evaluation, trade offs among stakeholder objectives may be analyzed and the difference among various decision methodologies may be evaluated.

One of the most comprehensive, generic watershed management models that also offers management optimization is WaterWare. It includes a detailed simulation model, management optimization and multi-criteria analyses that define and examine trade-offs between conflicting objectives (Jamieson and Fedra 1996, WaterWare 2007). It is also comprehensive in its representation of natural and human watershed components and management options. The represented management options include structural changes such as additional reservoir capacity, water reuse and artificial groundwater recharge, demand management such as human demand management and reduction in distribution and collection losses in pipelines, supply management such as additional pumping capacities, desalination and water harvesting, quality management through treatment nodes and alternative allocations by changing the priority of or benefits gained from a water user (WaterWare 2007).

Although WaterWare is the most comprehensive model reviewed, it requires expertise and training for use and extensive, expensive hardware and software support. For example, WaterWare uses a "multi-stage, multi-objective, multi-criteria optimization approach …. implemented as a combination of heuristics, local gradient search, a genetic programming framework, a discrete multi-criteria method combining a satisficing screening level to generate feasible and non-dominated Pareto efficient solutions for a subsequent interactive discrete multi-criteria {reference point} approach to identify efficient compromise solutions (WaterWare 2007)." Such a detailed and complex optimization module may be intimidating for most water resources managers and even engineers. Detailed and complex models may take a prohibitive amount of time for setting up and running and require extensive training or hiring of an expert or consultant for implementation, all of which may be expensive. In addition, the cost for the basic simulation software is over USD 70,000 and for the basic optimization module is over USD 60,000 with additional costs for other optimization modules, auto-calibration software, water quality modeling, land use change modeling and support services (WaterWare 2007). Therefore WaterWare does not meet the goals of this study as a technically and financially accessible model.

Of the models that were reviewed, Water Evaluation And Planning Version 21 (WEAP) was the model that most closely meets the intended goals of this study. WEAP integrates the "bio-physical system" or natural components of the watershed and the "socio-economic system" or the human water system (Yates et al. 2005). The model links land use, surface water and groundwater dynamics in a simplified hydrologic model. It is detailed enough to maintain the representation of important hydrologic processes but simplified enough for computational efficiency (Yates et al. 2005). Balancing the advantages and hindrances of complex versus simple models is critical not only for accurate modeling and computational efficiency but also for usability and transparency (see Rogers 1978 and Ford 2006 for example discussions on appropriate level of model detail and complexity). The usability characteristic includes technical and economic considerations and WEAP meets both with a simplified yet accurate model relative to WaterWare and a two-year license costing between USD 1,000 to USD 2,500 (WEAP21 2007). Although WEAP meets the criteria for generic, comprehensive, integrated and accessible, it does not provide management optimization other than a simple optimization algorithm which balances water supply reservoir storage contents. It has the capacity for simulating the management features of WaterWare and for each scenario the flow allocation is optimized in each time period but there are no overall management optimization features.

Returning to the original intention of providing a generic watershed management model with a comprehensive representation of the natural and human components of the watershed system, a wide-range of management options, management optimization and technical and financial accessibility, no appropriate models were found. While there are numerous models described in peer reviewed journals, they are not commercially or publicly available and are mostly being developed as site specific models. Although they may later be generalized, their focus is on modeling and providing a decision support system for a specific case study. In review, most of the existing generic IWRM models are detailed simulation models requiring a high level of user training and repetitive runs to determine the optimal solution. Also, many were originally developed for simulating the natural watershed and do not fully incorporate the human components of the water system. While detailed models are necessary for determining operating policies, there is a need for a generic optimization model that can efficiently and economically screen a wide range of management options.

Chapter 2 - Model Formulation

Background on Watershed Management Options

Each management option that is integrated into the model is described and its effects are summarized in Table 2. These options and components are often modeled separately by the responsible management agency such as water suppliers modeling water treatment or stormwater managers modeling detention ponds. All the options are simultaneously considered in the model so that the positive and negative effects of each option on all components and objectives of the watershed system and its management from water supply to surface water quality are recognized and accounted for in the net benefit calculation of any set of management decisions.

Table 2. Summary of Management Options and Impacts.

Management Option	Action	Impact
Land Conservation	Purchase forest land	preserve runoff & percolation quantity & quality
Stormwater BMPs	Install bioretention units	reduce runoff, increase recharge, treatment
Water Supply & Treatment	Pump surface water	reduce demand from other sources
	Pump groundwater	reduce demand from other sources
	Produce potable water	treatment, meet potable human demand
	Repair leaks in distribution system	reduce demand for water quantity
Wastewater Treatment	Secondary treatment	improve quality of receiving water
	Water reuse facility/ tertiary treatment	improve quality of receiving water, produce water for nonpotable demand and ASR
	Repair infiltration into collection system	reduce wastewater treatment demand
Nonpotable Distribution System	Construction of distribution system for nonpotable water	reduced demand for potable water
Aquifer Storage & Recharge (ASR)	Recharge groundwater with surface water or treated wastewater	increase recharge, treatment, increase supply
Human Demand Management	Price increase for water provision services	reduce demand for water quantity
	Mandatory outdoor watering ban	reduce demand and consumptive use

BMPs = best management practices

Water and Wastewater Treatment

Most water utilities are addressing the need to upgrade their distribution and metering system in order to reduce unaccounted for water which includes leakage in old pipes, illegal connections, and non-metered accounts. Fixing the leakage of potable water from the distribution system to the groundwater can effectively reduce demand and can be considered as a demand management option. In the Town of Ipswich, Massachusetts a leak survey was completed that showed that 13% of the total demand was due to unaccounted for water (EarthTech 2004). Reducing unaccounted for water by fixing leaks in the distribution system is included as a management option. A maximum feasible repair limit may be specified as fixing 100% of the leaks is not necessarily financially feasible nor does the cost remain linear beyond a certain threshold.

A similar option is available for the wastewater collection system in which the infiltration of clean groundwater can constitute approximately 40% of the wastewater arriving at the treatment plant (MWRA 2007). Therefore, repairing the leaks in the collection system is also included as an option with a maximum feasible repair limit. Another option under wastewater treatment can be to construct or upgrade a secondary treatment plant to tertiary treatment. The treated wastewater can be routed to a nonpotable water distribution system for direct reuse or to surface water and groundwater resources for discharge and indirect reuse. By including water reuse as an option, the model will be able to determine when it is economically feasible and efficient to begin additional wastewater treatment. Quantifying the benefits of water reuse can increase its appeal and acceptance as a water supply management option.

Additional Water Treatment Options

The case study application guided the decisions on which management options to include in this initial model. Although desalination is becoming a cost effective option even in the United States for increasing water supplies, it is not under consideration in the IRB. Desalination will be incorporated in a future version.

Another option that is not represented in the model is the internal recycling of water within water users. Through incentives or legislation, large water users such as industrial facilities can be encouraged to invest in internal water treatment and reuse. This would reduce demand and may therefore also be considered a demand management technique. Again, this option will be incorporated in a future version.

Human Demand Management

Demand management or water conservation began as a short-term tool to restrict water use during droughts (AWWA 2006). However, demand management is also an effective approach for increasing the long-term efficiency of water use. It is not merely reducing water use but increasing efficiency such that the same objectives may be accomplished with less water (AWWA 2006). For example, the goal is not to restrict residential or economic activities but to accomplish the desired activities with less water. Demand management techniques may be technical, institutional or educational. Technical approaches are intended to reduce the physical flow rate including low flow fixtures such as low flow toilets or faucet aerators and water efficient appliances such as clothes and dish washers. Institutional tools include lawn watering restrictions or increasing the price of water services. Educational approaches aim at increasing awareness of the value of water and modifying human behavior voluntarily.

Demand management addresses one root cause of water supply problems which is unsustainable demands on a finite system. Vörösmarty et al. (2000) conclude from their prediction models that rising demand due to economic development and population growth will be a more significant impact on the global water system in the next 25 years than stresses due to climate change. However, a recent report by the Pacific Institute on the future of California's water indicated that even with continued population growth and economic well being, under a "high efficiency" scenario, water use in 2030 could be 20% less than in 2000 (Gleick et al. 2005). Therefore, demand management is a critical consideration that can make the difference between meeting future demands and depleting water resources.

Demand management reduces forecasted *demand* and quantifies the volume of actual water *need* that must be met. Traditional cost-benefit analyses do not capture the full benefits of demand management because they do not account for the indirect or secondary benefits of reducing demand. For example, when demand is reduced, water treatment plant expansions can be delayed. Reductions specifically in nonconsumptive water uses such as showering and clothes washing can also delay the need for additional wastewater treatment plant capacity. In addition, the cost-benefit analyses often compare demand management with the development of additional source water. However, there are several indirect costs associated with source development and protection such as the purchase of land buffers surrounding the water source and discharge permitting and enforcement in the source's watershed or the source itself. These secondary costs are not always considered. Although demand management may reduce revenues, use of full cost pricing, a fundamental requisite for sustainable water supply management, should allow municipal water utilities to maintain balanced budgets.

Water utilities must set prices so that they at least achieve cost recovery because if services deteriorate than there will be even less willingness to pay (Azevedo and Baltar 2005). The price of clean water signals its relative value. This value must be a "behaviourally relevant price" so that it provides an incentive to use water efficiently and reduce pollution (Howe 2005). To further enhance the effect of increased pricing, more frequent billing cycles may be implemented. However, in addition to economic efficiency and cost recovery, equity among users and access to a minimum volume for basic needs must also be considered (Howe 2005).

Effects of water pricing was recognized and researched as early as 1971; Gysi and Loucks (1971) suggested increasing block rate and summer pricing. Price elasticity, the percent change in demand per one percent change in price, is often used to quantify the effects of price on consumer demand. Mays (2004) cites 17 studies from 1967 to 1994 with estimated price elasticities ranging from -0.06 to-0.86 with about two thirds of the studies between -0.25 and -0.65. There is evidence of reduction in demand with increasing price, yet only 9% of community water systems use increasing block rates according to the largest sample set of 1,200 systems surveyed by the U.S. EPA (2000).

However, there are limits to demand management. For example, once all houses are outfitted with water efficient appliances continued gains could not be expected. In addition, certain programs must be implemented simultaneously. For example, offering rebates for water efficient appliance must also include education and outreach not only to advertise the program but to ensure that with more water efficient appliances people will not begin to use their water more generously (Platt and Delforge 2001).

Demand management is a complex and multifaceted management option. In this model two demand management options are incorporated into the model which are (1) changing the pricing structure and (2) mandatory summer restrictions on outdoor watering.

Stormwater Management

Stormwater best management practices (BMPs) such as detention ponds and bioretention units can have a significant effect on the timing and quality of the water routing through the watershed. Runoff is captured by the bioretention unit or detention pond and over time discharged to the groundwater and surface water bodies, respectively. Depending on the type of BMP, it may improve surface water quality through settling during detention, serve as source of water by increasing groundwater recharge, reduce peak flow serving as flood control or reduce the required wastewater treatment capacity in urbanized areas where stormwater is collected and treated.

For the case study application, bioretention units are modeled as the BMP option because the Ipswich River Basin (IRB) is focusing on increasing groundwater recharge to counteract the runoff from pervious surfaces. In this highly urbanized basin of the Ipswich River, this is one of the main strategies being implemented to increase baseflow and sustain sufficient streamflow in the summer months.

Aquifer Storage and Recharge (ASR)

Aquifer storage and recovery is an effective storage system for the augmentation of water supplies with purification benefits (Bouwer 2002). Essentially, it can be an additional ‘source’ of water during dry periods. The option in the model reroutes and injects surface water or treated wastewater into groundwater. Increased groundwater storage may be beneficial for restoring groundwater levels, augmenting surface water baseflow or recovering it for human use.

Interbasin Transfer

Interbasin transfer of water and wastewater is a significant approach in numerous basins with large cities and metropolitan areas. For example, numerous towns in Massachusetts including Boston and surrounding suburban towns are served by the

Massachusetts Water Resources Authority that delivers water primarily from reservoirs in western Massachusetts. Although this management option is not desirable when targeting sustainable watershed management, it must be considered as an alternative and included in models if a current water supply system utilizes interbasin transfer to ensure accurate model calibration. When running the model for planning scenarios, this management option can be phased out.

Land Use

The impacts of land use on the quantity and quality of water resources has been recognized and studied for decades (Haith 1976). In consideration of water quantity, Falkenmark and Rockström (2006) cite that 90% of the total human water demand is utilized in the production of agricultural products and livestock for human consumption and only about 10 % is directly consumed by humans. To explain this Falkenmark and Rockström (2006) also define the concept of “blue water”, the liquid water traditionally considered in water supply management, and “green water”, the water vapor lost through evapotranspiration. A large portion of the “blue water” utilized in the production of biomass is lost as “green water”, which varies with the type of vegetation. By explicitly managing land use and the types of vegetation grown, evapotranspiration can be reduced to provide more blue water through additional percolation and runoff. In the Northeastern United States evapotranspiration may be approximated as 40% of the total precipitation. If precipitation is considered the quantity of renewable water supply of which half is historically lost to evapotranspiration, then the potential for increasing blue water supplies by rerouting precipitation through land use management is significant.

Land conservation, which is the protection of land from development and urbanization, can also have a significant impact on water quality. The American Water Works Association (2004) cites that in a comparison of watersheds, a ten percent increase in forest cover can reduce water treatment costs by 20%. The magnitude of this effect is maintained up to about 60% forest cover. There are not enough data on watersheds with greater than 65% forest cover that would allow for the extrapolation of this effect (AWWA 2004). Therefore land conservation can preserve the availability of blue water and high water quality. Undeveloped land areas may be conserved while accommodating population increase and economic development through increased density on already developed land.

The model introduced here incorporates a land conservation management option to enable the preservation of currently undeveloped land when modeling future build-out scenarios. Essentially, land use and stormwater management options enable the optimal routing of precipitation in the watershed into percolation or runoff which in turn affects the water quantity and quality.

Model Details

The watershed management model introduced here is a generic and parsimonious, lumped parameter model that integrates the natural hydrologic cycle, human water system and a wide range of management options. To accommodate fast solution times for the future development of an interactive DSS, the model is spatially aggregated and runs on a monthly time step for one year. The initial model is developed for within-year water supply systems that are common in the Northeastern United States. The assumption is that groundwater and surface water levels are the same at the beginning and end of the year; hence a one year time horizon is adequate to capture the system dynamics.

The model was developed in Microsoft® Office Excel software. The model schematic is shown in Figure 2. All variables, parameters and their definitions are listed in Appendix A. *In general*, the nomenclature of the model follows the same logic. The first part of the name indicates whether the variable is a volume (*Vol)*, flow (*Q)*, concentration (*Conc*), percentage (*Per)*, area (*A*) or other quantity. The second part of the name, indicated by a second capital letter, specifies to which component the quantity belongs. For example, *VolGw* refers to the volume of the groundwater component. For flows, the third part of the name indicates which component the flow is going to such as *QGwDwtp* refers to flow going from groundwater to the drinking water treatment plant.

The natural components of the watershed system are depicted in Figure 2 with light grey backgrounds. These include runoff, percolation, surface water, groundwater and external surface water and groundwater. Surface water, representing rivers and other landscape sources of water, are assumed to have negligible storage capacity and hence empties completely within each time step. Since the model runs on a monthly time step, this is a reasonable assumption for most watersheds. Minimum instream flow requirements may be specified on a monthly basis. Groundwater is the only natural component with storage capacity. External inflow and outflow of groundwater and surface water are included to enable the modeling of smaller hydrologic units than an entire watershed and for cases where surface water and groundwater watersheds do not coincide with each other.

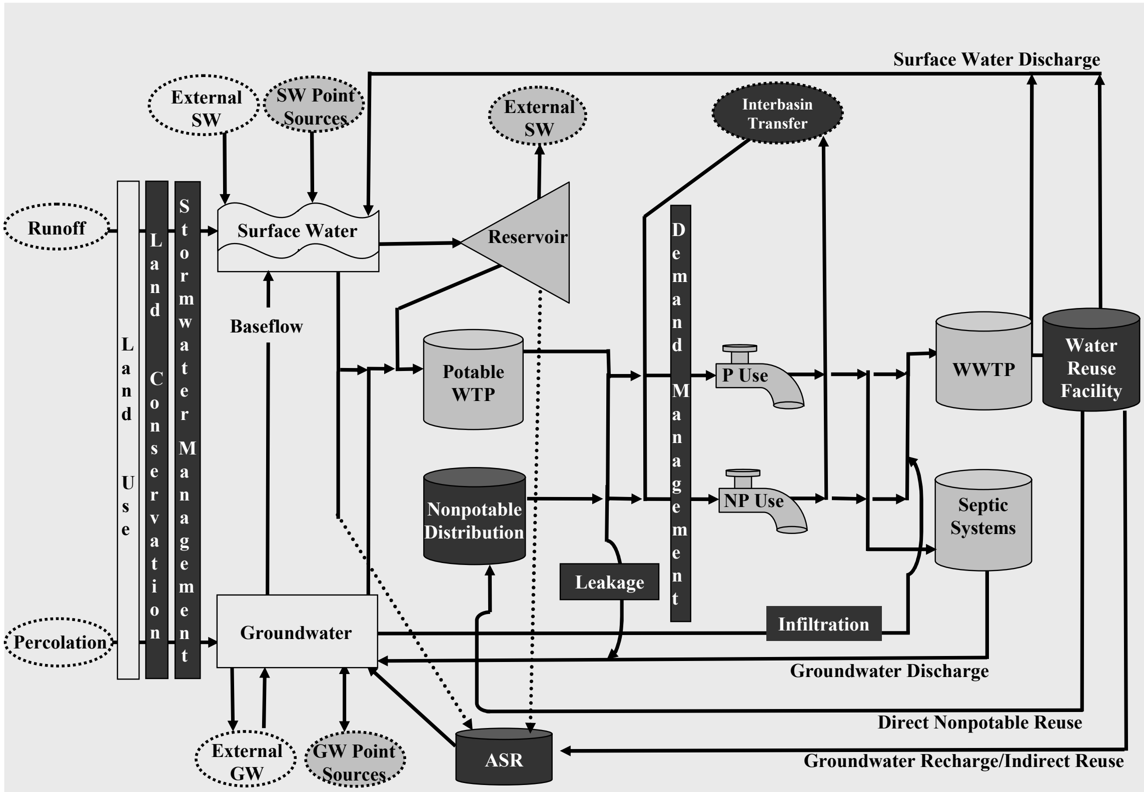

Figure 2. Schematic of the model.

The components of the human water system are shown with dark grey and black backgrounds. Dark grey components indicate those that typically already exist and are managed by water and wastewater utilities. Black components indicate those that typically do not exist or are not typically managed. The human system includes the reservoir, potable water treatment plant and distribution system, wastewater treatment plant, water reuse facility, nonpotable distribution system, septic systems, surface water and groundwater point sources, aquifer storage and recovery (ASR) facility and potable and nonpotable water users. The reservoir is the primary human water system component with storage capacity and may be either a single reservoir or the sum of many reservoirs within the watershed that are all assumed to be operated together as a single reservoir system. The potable water treatment plant treats water from surface water, reservoir or groundwater sources to drinking water standards. The wastewater treatment plant is a secondary wastewater treatment plant that treats wastewater to meet surface water discharge quality standards. Its effluent may also be further treated by tertiary wastewater treatment at the water reuse facility. The water reuse facility effluent may be directed to 1) a nonpotable distribution system for direct nonpotable reuse, 2) the aquifer storage and recovery facility for recharge and indirect reuse or baseflow augmentation and 3) surface water bodies for discharge. Wastewater from users is also directed to septic systems at a specified percentage. There is one time step, or a month, delay in flows entering the groundwater system from the septic systems and ASR facility. Since there are set requirements for septic systems and ASR facilities for distance from potable aquifers, this is an acceptable assumption. The actual time delay will depend on a number of factors including local hydrogeology, rate of natural soil and aquifer treatment, expected quality of influent and regulatory requirements.

Relationships between model components are based on the laws of conservation as described below in Flow Balance and Mass Balance sections.

Flow Balance

For components with storage, the volume at the end of time step (*t)* is calculated based on the previous time step's volume, current time step's inflows and outflows and magnitude of the time step (*dt)* which is one month:

Groundwater (Gw)

$$VGw_t = VGw_{t-1} + (QPerc_t + QExtGwIn_t + QPtGw_t + QWtpGw_t + QAsrGw_{t-1} + QSepGw_{t-1}$$
$$- QGwWwtp_1 - QGwWtp_t - QGwSw_t - QExtGwOut_t) * dt$$

where VGw = volume of groundwater, QPerc = percolation flow, QExtGwIn = inflow of external groundwater, QPtGw = inflow of groundwater point sources or discharges within the basin, QWtpGw =

leakage of water from distribution system, QAsrGw = flow from ASR facility to groundwater, QSepGw = inflow from septic systems, QGwWwtp = infiltration into wastewater collection system, QGwWtp = flow from groundwater to water treatment plant, $QGwSw_t = k_b * VGw_{t-1}$ = baseflow with groundwater recession coefficient, k_b, QExtGwOut = groundwater flow to outside of basin.

Reservoir (Res)

$$VRes_t = VRes_{t-1} + (QSwRes_t - QSwExtOut_t - QResAsr_t - QResWtp_t) * dt$$

where VRes = volume of reservoir, QSwRes = inflow to reservoir from surface water bodies, QSwExtOut = flow to surface water bodies outside of basin, QResAsr = flow to ASR facility, QResWtp = flow to water treatment plant.

For components without storage, the inflows in any time step equal the outflows in that time step:

Surface Water (Sw)

$$QRunoff_t + QExtSwIn_t + QPtSw_t + QGwSw_t + QWwtpSw_t + QWrfSw_t = QSwRes_t + QSwWtp_t + QSwAsr_t$$

where QRunoff = total runoff from watershed, QExtSwIn = surface water inflow from outside of basin, QPtSw = inflow from surface water point sources or discharges, QWwtpSw = discharge from wastewater treatment plant, QWrfSw = discharge from water reuse facility, QSwWtp = flow to water treatment plant, QSwAsr = flow to ASR facility.

Water Treatment Plant (Wtp)

$$QResWtp_t + QSwWtp_t + QGwWtp_t = QWtpUseP_t + QWtpUseNp_t + QWtpGw_t$$

where QWtpUseP = flow to potable water use, QWtpUseNp = flow to nonpotable water use.

Potable Water Use (UseP)

$$(QWtpUseP_t + QTrUseP_t) * (1 - PerConsUseP) = QUsePWwtp_t + QUsePSep_t + QUsePTr_t$$

where QTrUseP = inflow from interbasin transfer, PerConsUseP = percent consumptive use for potable water use, QUsePWwtp = flow to wastewater treatment plant, QUsePSep = flow to septic systems, QUsePTr = flow to interbasin transfer.

Nonpotable Water Use (UseNp)

$$(QWtpUseNp_t + QWrfUseNp_t + QTrUseNp_t) * (1 - PerConsUseNp) = UseNpWwtp_t + UseNpSep_t + QUseNpTr_t$$

where QWrfUseNp = inflow from water reuse facility, QTrUseNp = inflow from interbasin transfer, PerConsUseNp = percent consumptive use for nonpotable water use, QUseNpWwtp = outflow to wastewater treatment plant, QUseNpSep = outflow to septic systems, QUseNpTr = outflow to interbasin transfer.

Wastewater Treatment Plant (Wwtp)

$$QUsePWwtp_t + QUseNpWwtp_t + QGwWwtp_t = QWwtpWrf_t + QWwtpSw_t$$

where QWwtpWrf = outflow to water reuse facility.

Water Reuse Facility (Wrf)

$$QWwtpWrf_t = QWrfSw_t + QWrfAsr_t + QWrfUseNp_t$$

where QWrfAsr = outflow to ASR facility.

Septic Systems (Sep)

The overall percent of septic system users is calculated based on the specified percentage of each water consumer sector's septic use weighted by their respective flows. Percent septic use is a constant because it is not currently a management option to connect septic system users to the sewer system.

$$QUsePSep_t + QUseNpSep_t = QSepGw_t$$

Aquifer Storage and Recovery Facility (Asr)

$$QSwAsr_t + Q\,\mathrm{Re}\,sAsr_t + QWrfAsr_t = QAsrGw_t$$

Mass Balance

For components with storage (*Groundwater and Reservoir*), the concentration of each constituent in each component at the end of the time step is calculated based on the previous time step's concentration, influent concentrations and a user specified removal rate, if any, for each constituent in each component:

$$Conc_t = (1 - Per\,\mathrm{Re}\,m / 100) * (Conc_{t-1} * V_{t-1} + \sum_i (Conc_{i,t} * Q_{i,t}) * dt) / V_t$$

where Conc = concentration of constituent, PerRem = percent removal of that constituent, V = volume of water in component, Conc = concentration of constituent in inflow of water, i = number of inflows, Q = inflow from other component.

Outflow concentrations equal the concentrations in the storage components from the previous time step.

For components without storage (*Sw, Wtp, Wwtp, Wrf, Sep and Asr)*, the outflow concentration of each constituent is calculated based on the composite inflow concentration of each constituent and a user specified removal rate, if any, for each constituent in each component:

$$ConcOut_t = (1 - Per\,\mathrm{Re}\,m / 100) * \sum_i (ConcIn_{i,t} * QIn_{i,t}) / \sum_i QIn_{i,t}$$

where ConcOut = concentration of outflow from component, ConcIn = concentration of inflow, QIn = inflow from other component.

Removal rates for constituents may be specified for flows through the water and wastewater treatment plants (*Wtp, Wwtp, Wrf)*, the ASR facility for pretreatment of recharge and the groundwater storage component for natural soil aquifer treatment. Additional components without storage are *UseP and UseNp.* In these components, the outflow concentration is calculated based on the inflow concentration plus specified loadings from each water consumer sector for each use:

$$ConcOut_t = ConcIn_t + \sum_s Load_{s,t} / Qout_t$$

where s is the index for each sector of water user, Load = weight of constituent added by each water user, Qout = outflow from water user.

Land Use Allocation, Runoff and Percolation

Land use management was integrated into the model to provide the ability to manage the runoff to recharge ratio and water quality. The type of land use in terms of vegetation and human activities determines both the routing of the water to evapotranspiration, runoff, or groundwater and the amount of pollution in runoff and groundwater. The incorporation of land use, however, required the integration of a daily simulation based model without compromising the ability to efficiently optimize.

Certain watershed processes such as runoff and management tools such as stormwater best management practices (BMPs) must be modeled on a daily time step. For example, whether precipitation runs off or percolates depends on antecedent moisture conditions, such as the five day antecedent soil moisture in Soil Conservation Survey's (SCS's) curve number method (USDA 2003). This antecedent condition is used to determine a correction factor for the curve number which determines the partitioning of precipitation into runoff and percolation. Therefore, a method was developed for incorporating a daily simulation model of watershed processes into this monthly watershed management optimization model.

The parsimonious, lumped parameter watershed model TMDL2k was used to obtain daily runoff and percolation flows per land area and concentrations of these flows from different land use types (Figure 3.) (Limbrunner 2005). TMDL2k is a combination and enhancement of a parsimonious watershed model (Limbrunner et al. 2005) and the Generalize Watershed Loading Function model developed by Haith (1987). These models are based on the SCS curve number method and a hydrologic budget. TMDL2k also incorporates the application of BMPs such as detention ponds, bioretention and swales for stormwater quantity and quality management.

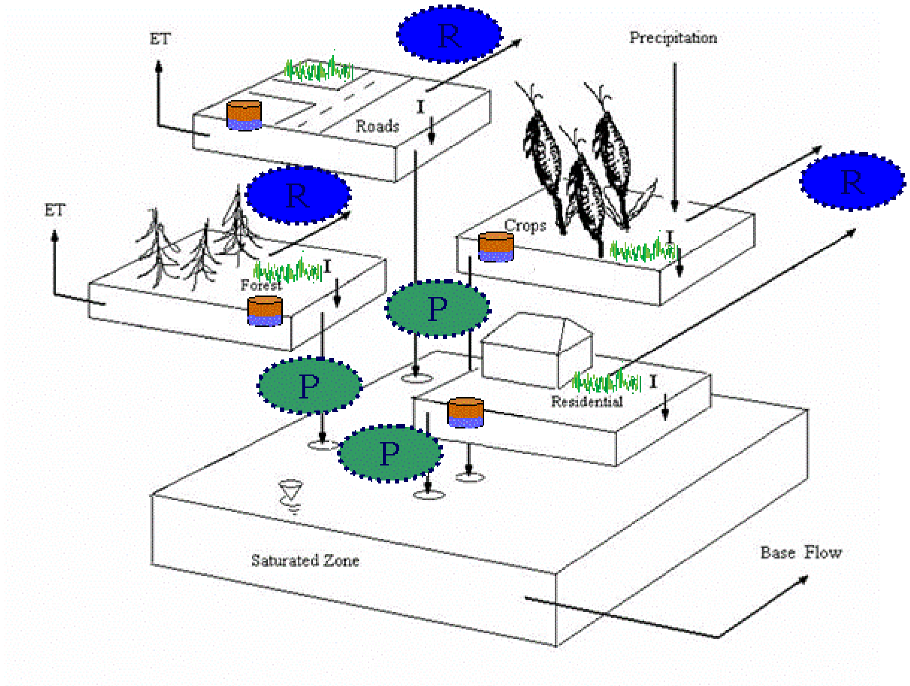

Figure 3. Illustration of the watershed as simulated byTMDL2k.

TMDL2k is calibrated for the watershed of concern and unit values of runoff and percolation quantity and quality for existing land uses are obtained. A second run is performed with the addition of BMPs for stormwater management. This yields 16 land uses total, 8 regular and 8 with BMPs. The unit values from TMDL2k are aggregated on a monthly time scale per land use. Total monthly runoff and percolation flows (*QRunoff, QPerc*) are calculated based on these input values of unit runoff (*uQRunoff*) and unit percolation (*uQPerc*) and decisions of land use area allocation (A_L):

$$QPerc_t = \sum_L A_L * uQPerc_{L,t}$$

$$QRunoff_t = \sum_L A_L * uQRunoff_{L,t}$$

where L = land use index.

Flow weighted averages are calculated for concentrations of monthly runoff and percolation flows:

$$ConcPerc_t = \sum_L (ConcPerc_{L,t} * A_L * uQPerc_{L,t}) / QPerc_t$$

where ConcPerc = concentration of constituent in the percolation flow.

For the BMP land use, the specific BMP that is modeled is determined by the user specified BMP parameters of contributing area, storage volume, groundwater and/or surface water outflow constants and constituent removal percentage.

Utilizing this approach allows for the incorporation of two land use related management options which traditionally require the incorporation of daily simulation models, thereby prohibiting optimization due to model run time. One management option is land conservation where area from a regular land use maybe transferred to another regular land use at some cost that reflects the purchase, conversion (if any) and maintenance of the land. The second is stormwater management where area from a regular land use may be transferred to a corresponding BMP land use at a cost that is calculated based on the area transferred, the area serviced by a unit of BMP and the construction and maintenance of a BMP unit.

Minimum and maximum areas for each land use in each management option may be specified to reflect physical, technical, political and social limits on change. For example, for the land conservation decisions the area of existing urban land use can be specified as a minimum area limiting the possibility of converting existing urban areas to any other type of land use. A maximum area limit may also be imposed based on existing zoning laws and development regulations. For wetlands land use, the minimum may be the area protected by wetlands regulations and maximum may be the existing wetlands area. For forest land, the minimum may be the area protected by existing land trusts. For the stormwater management decisions, a maximum may be imposed on the available area for BMP land use. This maximum, for example, may reflect that in urban land uses there may be portions that are completely developed without physical room for a certain type of BMP such as detention ponds. A maximum does not necessarily have to be specified but other land use minimums will indirectly impose maximum values on other land uses.

Two constraints are not optional. First, total land area in the watershed (A_T) must be conserved through all land use area reallocations:

$$A_T = \sum_L A_L$$

Second, land area transferred from a regular, A_{LReg}, to a corresponding BMP land use, A_{LBmp}, must be less than or equal to the regular land area for each land use:

$$A_{L\mathrm{Re}g} <= A_{LBmp}$$

Demand Management

A human demand management option is affecting water use by consumers through increased pricing of water and wastewater services. The percent change in price is decided and the corresponding change in demand is calculated based on the flow weighted average of user specified price elasticities for each sector:

$$PerDemand = Per\,\mathrm{Pr}\,ice * Elasticity$$

where PerDemand = percent of change in demand, PerPrice = percent change in price, Elasticity = elasticity with respect to price.

The maximum percent change in price may be specified.

Demand for potable water may be reduced through the use of the water reuse facility and nonpotable distribution system. Since the percent consumption for potable and nonpotable water may be significantly different depending on the end use, separate percent consumptive use values may be specified. If the nonpotable water use option is implemented, a new percent potable water consumption must be calculated. For example, if the nonpotable water is used for toilet flushing, a non consumptive use, then the percent consumptive use for the remaining uses of potable water will be different. This new percent consumptive use for potable water is calculated by:

$$\text{PerUsePConsumeNew} = (\text{PerUsePConsume} - \text{PerNpMax} * \text{PerUseNpConsume}) / (1 - \text{PerNpMax})$$

where PerUsePConsumeNew = revised percent consumptive use in potable water use, PerUsePConsume = original percent consumptive use in potable water use, PerNpMax = maximum percentage of nonpotable water, PerUseNpConsume = percent consumptive use in nonpotable water use.

Costs and Revenues

All implemented management options incur costs that may include an initial fixed cost (*CostI)* in addition to variable operations and maintenance cost (*CostOM*) (Table 3.). Initial costs are annualized according to:

$$\text{CostIA} = \text{CostI} * ((\text{PerInt}/100 * (1 + \text{PerInt}/100)\text{^ YrsPlan})/((1 + \text{PerInt}/100)\text{^ YrsPlan} - 1))$$

where CostIA = annualized initial cost, PerInt = interest rate and YrsPlan = number of years in the planning period over which the cost is annualized.

Certain existing components such as wastewater treatment plants have a finite life cycle and replacement costs beyond the life cycle must be included if the planning period is greater than the life cycle. Total annualized cost (*CostIAT*), is the annualized cost of new construction plus the replacement annualized cost of existing capacity, if any, once the existing life cycle expires:

$$CostIAT = CostIA * QAddl + CostIA * QMax * (YrsPlan - YrsExist)/YrsPlan$$

where QAddl = additional capacity to be built, QMax = existing maximum plant capacity and YrsExist = remaining number of years in the life cycle of the existing plant.

Total cost for each management option is the sum of total annualized initial costs plus annual operations and maintenance costs. Total cost for each management plan is the sum of the costs of each utilized management option.

$$CostAT=CostIAT+CostOm*QTotal$$

where QTotal = total flow through facility during planning period.

Total revenue (*RevT*) is the sum of potable and nonpotable water sales and wastewater services provided at the final rates after the price management option is decided:

$$RevT = RevUseP * QUsePT * (1 + PerPrice/100) + RevUseNp * QUseNpT * (1 + PerPrice/100)$$

where RevUseP = original purchase price for potable water, RevUseNp = original purchase price for nonpotable water, QUsePT = total annual demand for drinking water and QUseNpT = total annual demand for nonpotable water.

Net economic impact is the net benefit of watershed management defined as the sum of the revenues from water users minus the total cost of all implemented management options.

$$NetBenefit = \mathrm{Re}vT - \sum_{i=1}^{m} CostAT_i$$

Linear Programming Optimization of Water Quantity

In this initial version of the model, water flows and quantities are optimized. Water quantity and quality will be integrated in the next version of the optimization algorithm along with a nonlinear solver.

The objective function for the linear program optimization is to maximize the net benefit of watershed management while meeting all standards or constraints. The linear program is formulated as:

Maximize $$Z = \mathrm{Rev}T - \sum_{i=1}^{m} CostAT_i$$

Subject to

Human demand $QWtpUseP + QTrUseP \geq QUsePMin$

$QWtpUseNp + QWrfUseNp + QTrUseNp \geq QUseNpMin$

Instream flow $QSwMin \leq QSw\mathrm{Res}$ (Surface water flow within basin)

$QSwMin \leq QExtSwOut$ (Surface water flow out of basin)

Land area restrictions $A_T = \sum_L A_L$

$A_{L\mathrm{Reg}} <= A_{LBmp}$ (Stormwater management)

$A_L >= A\min_L$ (Land conservation, Stormwater management)

$A_L <= A\max_L$ (Land conservation, Stormwater management)

Facility capacity $Q \leq QMax + QAddl$ (Water treatment plant, Wastewater treatment plant, Water reuse facility, Aquifer storage and recovery facility, Surface water and groundwater pumping capacities)

Volume limits $V \leq VMax$ (Groundwater, Reservoir)

$V \leq VMin$ (Groundwater, Reservoir)

Within year system $VInitial \leq VFinal$ (Groundwater, Reservoir)

Management limits $Per\mathrm{Pr}ice \leq Per\mathrm{Pr}iceMax$

$PerWtpLeakFix \leq PerWtpLeakFixMax$

$$PerWwtpLeakFix \leq PerWwtpLeakFixMax$$

All variables are greater than or equal to zero.

By Changing

PerPrice	Percent of increase water and wastewater services price
PerWtpLeakFix	Percent of potable distribution system leakage to fix
QWtpAddl	Additional water treatmen plant capacity
QWtpPumpGwAddl	Additional groundwater pumping capacity
QWtpPumpSwAddl	Additional surface water pumping capacity
VResAddl	Additional surface water storage volume
QWwtpAddl	Additional capacity for the Watewater treatment plant
PerWwtpLeakFix	Percent of wastewater collection system leakage to fix
QWrfAddl	Additional capacity for the Water reuse facility
QAsrAddl	Additional capacity for the Aquifer storage and recovery facility
QNpMax	Maximum capacity of Nonpotable distribution system
QGwWtp	Flow from Groundwater to Water treatment plant
QExtGwOut	Flow from Groundwater to External groundwater
QSwAsr	Flow from Surface water to Aquifer storage and recovery facility
QSwWtp	Flow from urface water to Water treatment plant
QExtSwOut	Flow from Reservoir to External surface water
QResWtp	Flow from Reservoir to Water treatment plant
QResAsr	Flow from Reservoir to Aquifer storage and recovery facility
QWtpUseNp	Flow from Water treatment plant to Nonpotable water use
QWwtpWrf	Flow from Wastewater treatment plant to Water reuse facility
QWrfAsr	Flow from Water reuse facility to Aquifer storage and recovery facility
QWrfUseNp	Flow from Water reuse facility to Nonpotable water use
QUsePWwtp	Flow from Potable water use to Watewater treatment plant
QUseNpWwtp	Flow from Nonpotable water use to Wastewater treatment plant
ALc1	Area of land use 1 after land conservation
ALc2	Area of land use 2 after land conservation
ALc3	Area of land use 3 after land conservation
ALc4	Area of land use 4 after land conservation
ALc5	Area of land use 5 after land conservation
ALc6	Area of land use 6 after land conservation
ALc7	Area of land use 7 after land conservation
ALc8	Area of land use 8 after land conservation
ASm1	Area of land use 1 after stormwater management
ASm2	Area of land use 2 after stormwater management
ASm3	Area of land use 3 after stormwater management
ASm4	Area of land use 4 after stormwater management
ASm5	Area of land use 5 after stormwater management
ASm6	Area of land use 6 after stormwater management
ASm7	Area of land use 7 after stormwater management
ASm8	Area of land use 8 after stormwater management

Frontline Systems' Premium Solver Platform linear programming solver is used to solve for the values of the decision variables that maximize the objective function subject to specified constraints.

Chapter 3 - Application

Background

The Ipswich River Basin (IRB) in Massachusetts is used as a case study for the application of the model. Meeting the water needs of communities in the Boston metro area is an increasingly challenging task. With continued development and population growth the demand is increasing while supplies are pushed to or beyond their sustainable yield and endangered or compromised by human impact. The upper IRB, which is the watershed of the South Middleton Gaging Station of United States Geological Survey (USGS) on the Ipswich River (Figure 4), experiences low and no flow events during summer months. Extensive efforts are being invested in the dual objective of restoring adequate flow for the ecosystem while continuing to meet increasing water supply demands. The model is applied to the upper IRB to evaluate a broad range of management options for meeting these objectives.

A detailed modeling study of the IRB watershed system was conducted by Zarriello and Ries (2000) of the USGS. That study compiled extensive information and data on the basin which were used here. Relevant background information is summarized below and reader is referred to the 2000 study for a detailed watershed description.

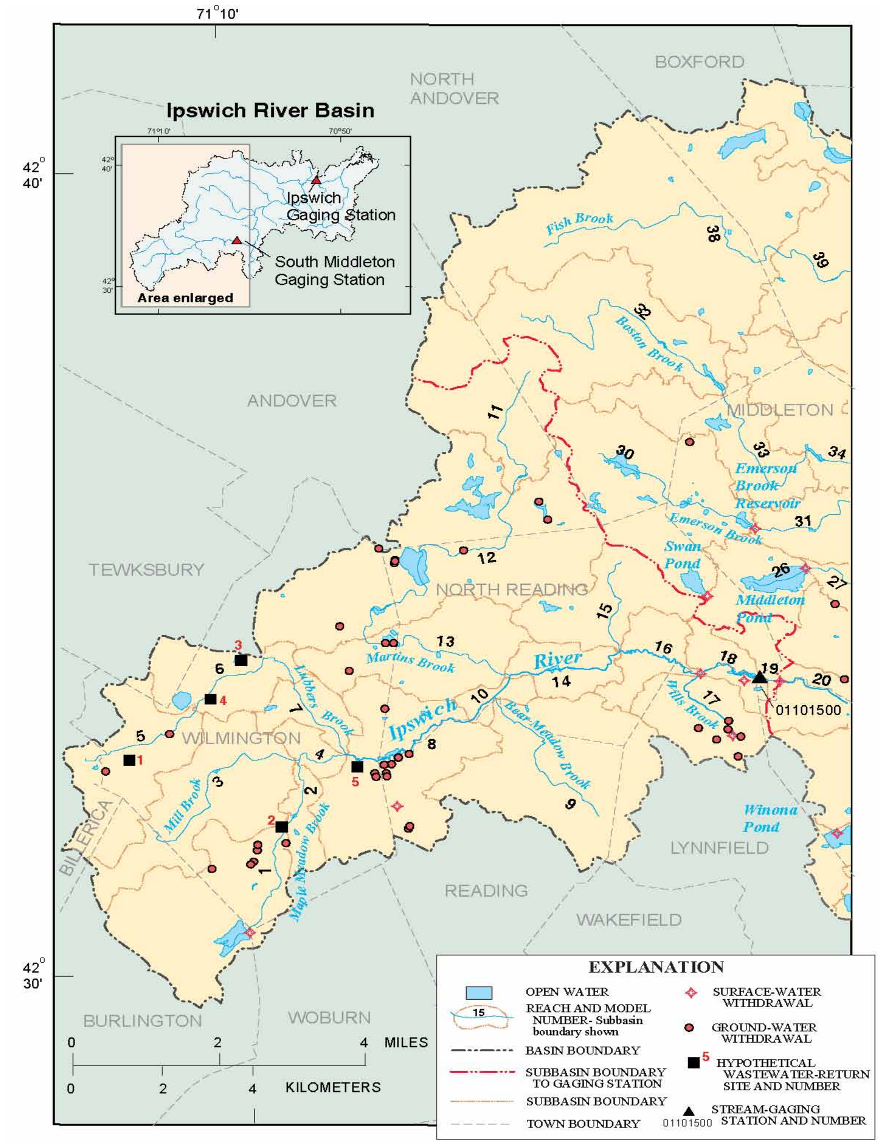

Figure 4. Map of the Upper Ipswich River Basin (Zarriello and Ries 2000).

The upper IRB covers approximately 44 square miles out of the total IRB area of approximately 150 square miles. Of this land area, 77% is developed. Detailed land use information is provided in Table 3. It comprises 14 towns but only four of these towns, Reading, North Reading, Wilmington and Lynnfield, utilize the upper IRB for their water supply. The town of Lynn is not located in the upper IRB but obtains 16% of its water supply from it (Zarriello and Ries 2000). These five towns consist of the users of the upper IRB for water supply. Table 4 lists the percent of each town's area within the upper IRB, their percent of water supply obtained from it and their resources for water and wastewater withdrawal and discharge.

Table 3. Land Use in the Upper Ipswich River Basin in 1999.

1999 Land Use	**Percent of Total**
Low Density Residential	47
Medium Density Residential	13
High Density Residential	2
Commercial/Industrial/Transportation	15
Forest	14
Rural Open	5
Pasture	2
Crop	2

Data from MassGIS 2007.

Groundwater is almost exclusively the source of water supply except for Lynn which also lies outside of the basin. There have been legal disputes and resistance to a collaborative approach in addressing the severe low flow and no flow events experienced in this part of the basin. As this model demonstrates, individual actions affect the whole watershed system and cooperation will be required for a sustainable solution.

The majority of the wastewater is discharged outside of the basin. At first, it may appear that majority of the wastewater is recharged via septic systems; however, only North Reading is entirely within the basin boundary. Therefore, even septic systems are discharging some wastewater to other basins and not recharging the IRB and augmenting the flow of the Ipswich River. Extensive groundwater withdrawals and the export of wastewater have been recognized as the most significant contributor to the low and no flow events in the late summer in the basin (Zarriello and Ries 2000).

Table 4. Towns Utilizing the Upper Ipswich River Basin for Water Supply.

Town	**Area in Watershed**	**Supply from Watershed**	**Water Source**	**Wastewater Discharge**
North Reading	100%	100%	Gw (Import:summer, <1.5 MGD)	Septic
Reading	48%	100%	Gw	Sewer (discharges out of basin)
Wilmington	83%	100%	Gw	84% Septic (16% discharges out of basin)
Lynn	0%	16%	Sw	Sewer (discharges out of basin)
Lynnfield	32%	100%	Gw (Sw:Apr to Nov)	Septic

Data from Zarriello and Ries 2000.

A joint study between several Massachusetts state departments examined the Ipswich River streamflow requirements to protect aquatic habitat (Armstrong, Todd and Parker 2001). That study is on-going and the most recent recommendation for seasonal instream flow for the restoration of the Ipswich River Fisheries was specified in Zarriello (2002). Precipitation and average river flow at the South Middleton Gage in 1999 and the recommended instream flow and human demand are listed in Table 5. The third column in the table shows the percent of flow that occurred in 1999 relative to the recommended target. It is evident that April through September the target is not met and less than a third of the target flow is achieved June through August.

Table 5. 1999 Hydrologic Conditions.

	Target Flow	Streamflow		Precipitation	Human Demand
Date	**(ft^3/s)**	**(ft^3/s)**	**(as % of Target)**	**(in/month)**	**(ft^3/s)**
Janurary	44	106.2	240%	6.9	8.4
February	44	135.0	305%	4.5	8.2
March	111	128.9	116%	4.0	8.1
April	111	49.1	44%	0.9	8.9
May	66	30.6	46%	3.3	10.3
June	**22**	**4.7**	**22%**	**0.1**	**11.1**
July	**22**	**0.9**	**4%**	**4.7**	**11.6**
August	**22**	**0.2**	**1%**	**1.5**	**10.9**
September	22	19.1	88%	9.3	10.3
October	22	32.7	151%	4.9	9.0
November	44	46.1	104%	2.4	8.3
December	44	48.3	109%	2.3	9.8

Data from Zarriello, 2002 and Zarriello and Ries, 2000.

The combination of increased human demand, reduced precipitation and increased evapotranspiration sharply reduces instream flow starting in April. As the groundwater reserves are depleted by human withdrawals, even the baseflow of the river is diminished and low and no flow conditions occur June through August. In fact, in some cases municipal wells are so close to the river and pump at such a high rate, that the river is the primary recharge source for the wellfield (Riverways Program, 2007). Therefore, not only is baseflow from groundwater reduced but in some cases, streamflow infiltration is induced and the river pumped to the groundwater wells.

Model Setup

Data on the monthly withdrawals of groundwater and surface water in the upper IRB were extracted from the USGS model (Zarriello and Ries, 2000). These values were used in the calibration of TMDL2k (the hydrologic simulation model by Limbrunner et al. (2005)), the simulation setup of the management model and set as the total monthly water demand in the optimization runs of the management model. A 50 year planning period and five percent interest rate were used.

To obtain unit runoff and percolation values, TMDL2k was setup and calibrated for data from 1999. A comparison of the observed monthly streamflow and the model simulation for 1999 is shown in Figure 5. The model calibration was deemed acceptable and will be improved upon as the TMDL2k is further developed and refined for watersheds heavily influenced by human development such as the IRB. In addition, some original error due to the compilation of water use data from various sources and its extrapolation to 1999 may have been significant and could not be adjusted for just by calibration (see data collection description in Zarriello and Ries, 2000).

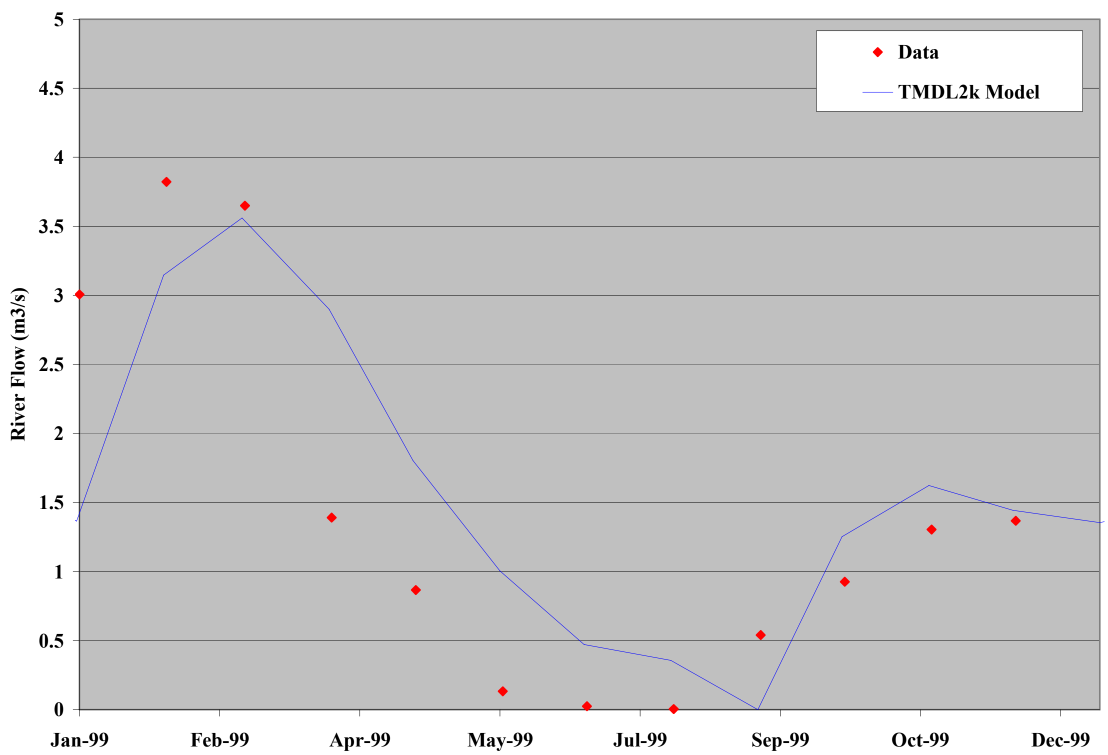

Figure 5. TMDL2k model streamflow versus USGS streamflow data.

The runoff and percolation quantity and quality unit values from TMDL2k and 1999 data were entered in the management model to obtain a simulation of 1999 conditions. The comparison between observed streamflow and model simulated streamflow is shown in Figure 6. Although there are evident errors in the simulation, further calibration and adjustment of the hydrologic simulation of the watershed was not attempted in this initial study because the objective of this model is to explore management modeling rather than hydrologic modeling. Instead, it is assumed that a hypothetical watershed is simulated and subsequently optimized for management options. This allows the focus to remain on management modeling. All model results were analyzed relative to the 1999 simulation.

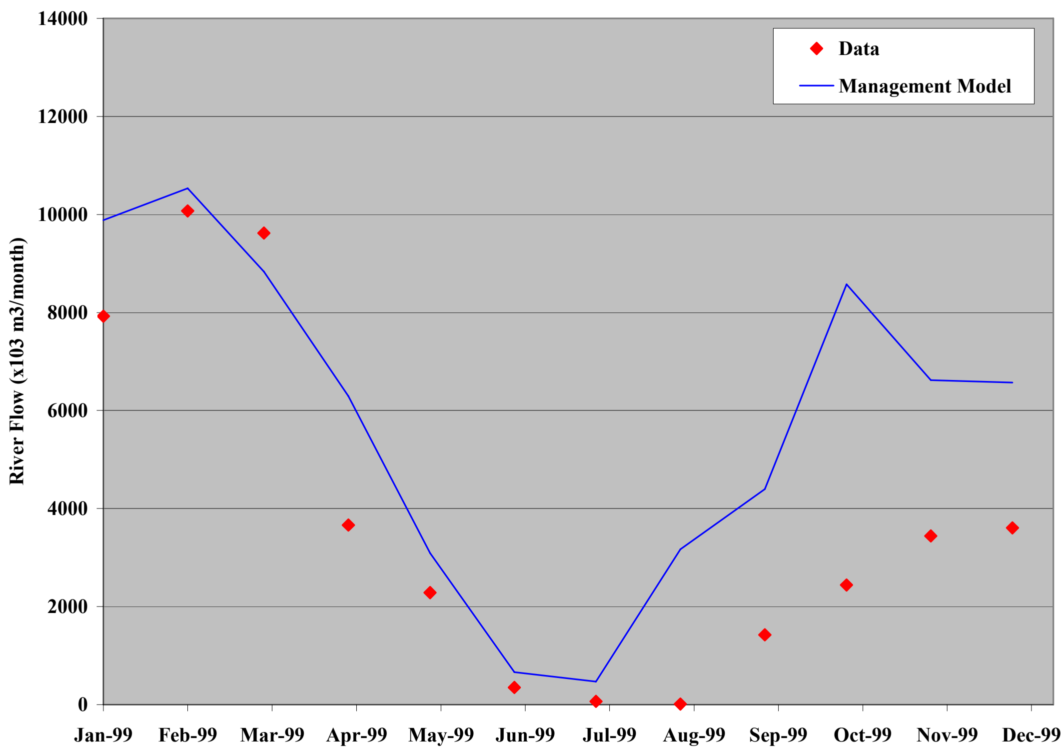

Figure 6. Watershed Management Optimization model streamflow versus USGS streamflow data.

Five management scenarios were setup for optimization and utilized to study the system behavior. In the first scenario, immediate management options were considered. These options are flow allocation decisions where the amount, timing and source of withdrawals were the available management options. The current maximum capacities for all components constrained the range of values. For example, surface water and groundwater withdrawals could be made up to the current surface water and groundwater pump capacities, respectively.

The second scenario included the near term management options referring to management tools that can be implemented in the two to three year range. These options include flow allocation as in the first scenario, human demand management through increases in the price of water and wastewater provision services, demand management through the repair of leaking distribution infrastructure and the management of stormwater through the installation of bioretention best management practices. Bioretention units were chosen for this application based on experience with the TMDL2k model (Limbrunner, 2006). The increase in the price of services was limited to ten percent because of the short planning horizon.

The third through fifth scenarios included the availability of long term management options that can be implemented in the greater than five year range. The long term management options include wastewater infrastructure repair, additional capacities for surface water storage, surface water pumping, groundwater pumping, potable water treatment plant, wastewater treatment plant, aquifer storage and recovery facility and water reuse facility, construction of a nonpotable distribution system and a land conservation program to prevent anticipated development. The limit on increasing the price of services was 50% to reflect the longer planning horizon.

Since the utilities in the upper IRB export their sewered wastewater, this wastewater export was allowed for scenarios one through three and limited to the current level of use. The third scenario was therefore long term management options with the availability of wastewater export. The fourth scenario was the long term management scenario without the availability of the interbasin transfer of wastewater.

The fifth and final scenario consisted of the fourth scenario with the inclusion of a mandatory outdoor water use ban in the summer months. This was modeled by reducing human demand by 75% of the difference between winter and summer water demands. In other words, it was assumed that outdoor water use would be reduced by 75% with the outdoor water use ban. This scenario led to counter intuitive results which generated additional runs with the fifth model to explore the effects of separate metering for water and wastewater services.

Costs associated with the implementation of management options are listed below in Table 6. Revenues for water and wastewater services were sold at $1.80 per 100 cubic feet for water and $4.64 per 100 cubic feet for wastewater. These values were compiled from literature as well as direct contact with water and wastewater provision utilities in the IRB. A list of references for each management cost and revenues is detailed in Appendix B – Data Sources.

Table 6. Summary of Management Costs.

Management Option	Initial Cost	O&M Cost
Land Conservation	$140,000/ ha	$2,000/ yr
Stormwater - Bioretention	$30,000/ unit	$1,500/ yr/ unit
Water Treatment - Surface water pumping	$311,198/ MGD/ month	10% of initial/ yr
Water Treatment - Groundwater pumping	$512,366/ MGD/ month	10% of initial/ yr
Water Treatment - Potable	$4,464,620/ MGD/ month	$206,064/ MGD/ month /yr
Water Treatment - Leak repair	$455,000	10% of initial/ yr
Wastewater Treatment - Secondary	$8,929,240/ MGD/ month	$412,128/ MGD/ month/ yr
Wastewater Treatment - Reuse facility	$9,551,406/ MGD/ month	$1,291,456/ MGD/ month /yr
Wastewater Treatment - Infiltration repair	$1,000,000	10% of initial/ yr
Nonpotable Distribution System	$180,248/ % of customers	10% of initial/ yr
Aquifer Storage & Recharge	$1,879,058/ MGD	10% of initial/ yr
Human Demand Management	-	$2000/ yr
Interbasin Transfer - Potable water import	$69,130/ MGD	-
Interbasin Transfer - Wastewater export	$184,346/ MGD	-

Results

The simulation and five management optimization scenarios allowed for the comparison of the effects of the availability of management options relative to the current circumstances, meeting increasing instream flow requirements, instituting a mandatory outdoor water use ban in the summer months and separate metering of water and wastewater services.

Effects of Diversity of Management Options

Withdrawal allocations that were implemented in 1999, Current Allocation scenario, result in a negative net benefit or total cost of $5.44 million per year to meet water supply and wastewater demands as shown in Table 6. In the immediate management options scenario, Optimal Allocation scenario, the allocation of withdrawals was optimized to maximize net benefit while meeting a quarter of instream flow targets and constrained by the current groundwater and surface water withdrawal infrastructure capacities. Implementing the optimal allocation of withdrawals decreased the annual total cost by almost $40,000 or less then one percent. The cost reduction resulted from the maximum utilization of surface water in all months rather than just the summer months as seen in Table 7. Surface water pumping is less expensive than groundwater pumping because of the energy associated with lifting water from aquifers.

Table 6. Management Recommendations with Increasing Management Options.

Management Options	***Units***	***Current Allocation***	***Optimal Allocation***	***Near Term Optimization***	***Long Term Optimization with WW Export***	***Long Term Optimization without WW Export***
Consumer's Rate Change	%	NA	NA	**10% (Max)**	**50% (Max)**	**50% (Max)**
DWTP Infrastructure Repair	% of Leaks	NA	NA	**100%**	**100%**	**100%**
WWTP Infrastructure Repair	% of Infiltration	NA	NA	NA	0	**100%**
Stormwater BMPs	# units	NA	NA	0	0	0
Land Conservation	Ha	NA	NA	NA	0	0
Nonpotable Distribution System	% of Consumers	NA	NA	NA	0	0
Additional Surface Water Storage	MG	NA	NA	NA	0	0
Additional Capacity:						
Surface Water Pumping	MGD	NA	NA	NA	**5.4**	**5.4**
Groundwater Pumping	MGD	NA	NA	NA	0	0
Drinking Water Treatment	MGD	NA	NA	NA	0	0
Wastewater Treatment	MGD	NA	NA	NA	0	**1.6**
Aquifer Storage & Recovery	MGD	NA	NA	NA	0	0
Water Reuse Facility	MGD	NA	NA	NA	0	0
Annual Net Benefit		**($5,444,400)**	**($5,407,539)**	**($824,178)**	**$7,993,825**	**($3,084,187)**

Table 7. Water Supply Withdrawals in Million Gallons per Day.

Scenario:	Current Allocation			Optimal Allocation		
Source:	Groundwater	River	Reservoir	Groundwater	River	Reservoir
January	5.42	0.00	0.00	5.20	0.22	0.00
February	5.33	0.00	0.00	5.11	0.22	0.00
March	5.25	0.00	0.00	5.04	0.22	0.00
April	5.73	0.01	0.00	5.52	0.22	0.00
May	6.65	0.05	0.00	6.48	0.22	0.00
June	7.02	0.18	0.00	6.98	0.22	0.00
July	7.31	0.21	0.00	7.31	0.00	0.22
August	6.91	0.16	0.00	6.85	0.00	0.22
September	6.55	0.12	0.00	6.45	0.00	0.22
October	5.78	0.05	0.00	5.61	0.00	0.22
November	5.36	0.00	0.00	5.15	0.00	0.22
December	6.34	0.00	0.00	6.13	0.00	0.22
Total Annual	73.66	0.77	0.00	71.83	1.30	1.30

In addition to reduced costs, with better timing of surface water withdrawals, low flows decreased. A quarter of the instream flow targets were met all months with the Optimal Allocation scenario. As shown in Table 5, the current allocation withdrawals resulted in streamflow below the recommended flow in the months of April through September. On an annual basis, there is enough streamflow to meet the recommended instream flow targets. The average flow in 1999 was 50.1 ft^3/s and the average flow required to meet the instream flow target is 47.8 ft^3/s. Therefore, meeting instream flow is a matter of timing withdrawals to meet both human and environmental needs each month. Since streamflow decreases and human demand increases in the same months, some storage must be accumulated during other months. Since the upper IRB's reservoir storage is negligible, the main storage component is groundwater aquifers. However it must be recognized that withdrawing groundwater any month is essentially utilizing surface water from a previous time step which has recharged instead of being withdrawn.

The near term management options had a dramatic effect on the cost of meeting human and environmental demands with a reduction of over $4.5 million or approximately $800,000 per year. Price increases in water and wastewater services were fully utilized at a maximum of ten percent increase. The repair of distribution system infrastructure was also fully implemented with all of the leaks fixed. No bioretention systems were constructed for stormwater management.

Adding in more management options in the long term scenario results in a positive annual net benefit or profit of almost $8 million. Price change and distribution system repair were again fully implemented. In addition, increasing surface water pumping capacity was available with the long term options and a great reduction in cost was again achieved from an almost complete transition from groundwater to surface water withdrawals. Groundwater withdrawal occurred only in the month of July.

In the final scenario of varying management option availability, long term management options were made available but wastewater export was discontinued. The annual total cost of the scenario was a little over $3 million. This reflects the addition of wastewater treatment plants to handle the previously exported wastewater and the fixing of groundwater infiltration into existing sewer pipes. Although fixing leaks in distribution infrastructure is a commonly implemented management tool, repairing sewer pipes to prevent the infiltration of groundwater into sewer pipes is generally considered too costly because of the deeper and larger diameter pipes. However, here the model suggests that treating less wastewater saves more money than the cost of repairing sewer pipes. One caution on this result is that currently the optimization model does not explicitly consider the concentration of constituents. With less infiltration of clean groundwater, the concentration of wastewater may increase which in turn may increase treatment price. Additional treatment and costs may or may not occur and will be confirmed in the next generation of the model where both quantity and quality are simultaneously and explicitly considered.

Each management scenario was run several times to determine the maximum instream flow that can be achieved by each. A summary of these results is shown in Figure 7. The annual net benefits for each scenario are shown in parentheses. The flow allocation and near term optimization scenarios met quarter of the instream flow target while both long term management scenarios were able to meet the full target. With more management options, the model effectively reallocated water from periods where instream flow was greater than the target to utilize during periods where the full instream flow target was previously not met. For example, the long term management option results in lower instream flow in January and August through December than the other management scenarios but meets the full instream flow target in all months. In the other management scenarios, the instream flow is greater in those months but only meet a quarter of instream flow target in one or more months.

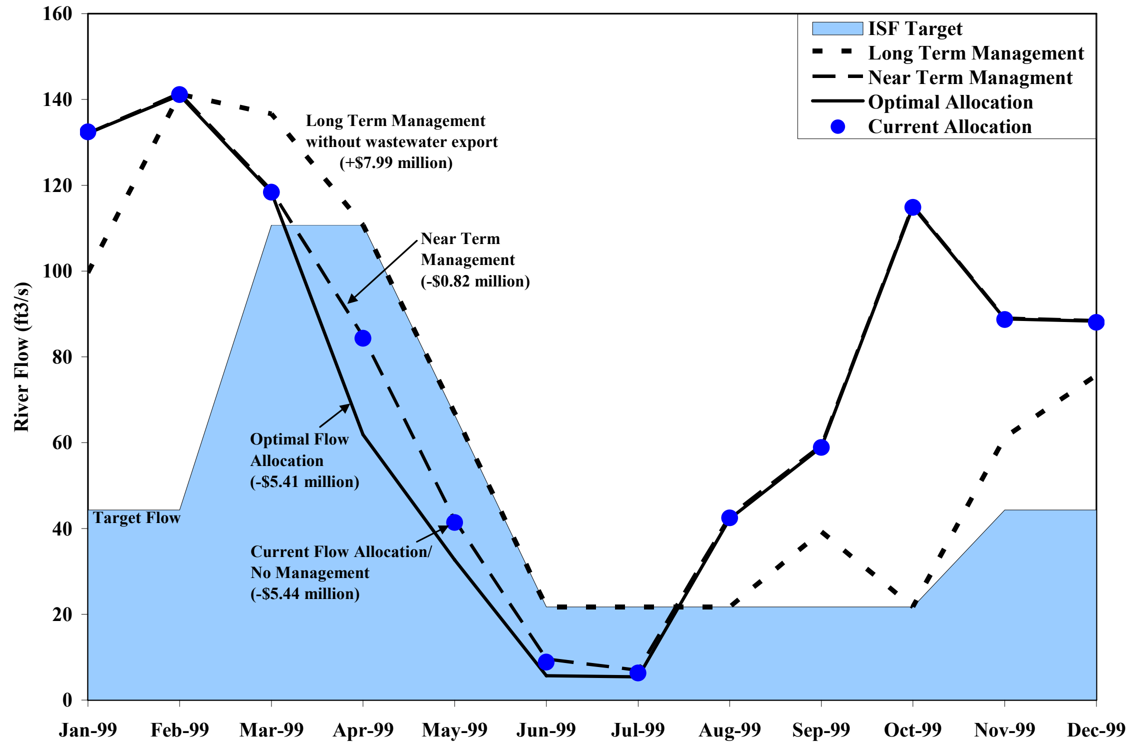

Figure 7. Maximum instream flow achieved by each management scenario showing the annual net benefit for each in parentheses.

In general, the model demonstrated that with the consideration of more management options the net benefit of meeting human and environmental water demands can dramatically increase. These results also confirm the importance of management plans that address both near and long term needs and constraints and consider both near and long term management options.

Effects of Instream Flow Requirement

To explore the effect of meeting an increasing percentage of the instream flow recommendation, the long term management scenario without wastewater export was run with various instream flow requirements. The results of meeting human and increasing environmental demands are shown in Table 8.

Table 8. Management Recommendations with Increasing Instream Flow Requirement.

Management Options	***Units***	***¼ ISF***	***½ ISF***	***Full ISF***
Price Change	%	**50%**	**50%**	**50%**
DWTP Infrastructure Repair	% of Leaks	**100%**	**100%**	**100%**
WWTP Infrastructure Repair	% of Infiltration	**100%**	**100%**	**100%**
Stormwater BMPs	# units	0	0	**120**
Land Conservation	ha	0	0	0
Nonpotable Distribution System	% of Consumers	0	0	0
Additional Surface Water Storage	MG	0	0	0
Additional Capacity:				
Surface Water Pumping	MGD	**5.4**	**5.4**	**5.0**
Groundwater Pumping	MGD	0	0	0
Drinking Water Treatment	MGD	0	0	0
Wastewater Treatment	MGD	**1.6**	**1.6**	**1.6**
Aquifer Storage & Recovery	MGD	0	0	**18**
Water Reuse Facility	MGD	0	0	0
Annual Net Benefit		**$3,084,187**	**$3,066,407**	**($9,530,879)**

ISF=Instream Flow; the fraction of instream flow met in scenario

As may be expected, with increasing instream flow requirement, the net benefit of meeting demands turn from a positive net benefit of $3 million per year at a quarter of instream flow to a cost of $9.5 million per year at full instream flow. The important insight revealed from this series is that meeting one half of instream flow target incurs less than $20,000 per year loss in net benefit. On the other hand jumping to meeting full instream flow requires the installation of bioretention units and an aquifer storage and recovery (ASR) facility which eliminates the positive annual net benefit and creates a cost. This relationship between net benefit and instream flow is highly nonlinear. To explore this relationship, additional runs were performed. The resulting Pareto frontier in Figure 8 shows the tradeoff between meeting an increasing fraction of the instream flow target and net benefit.

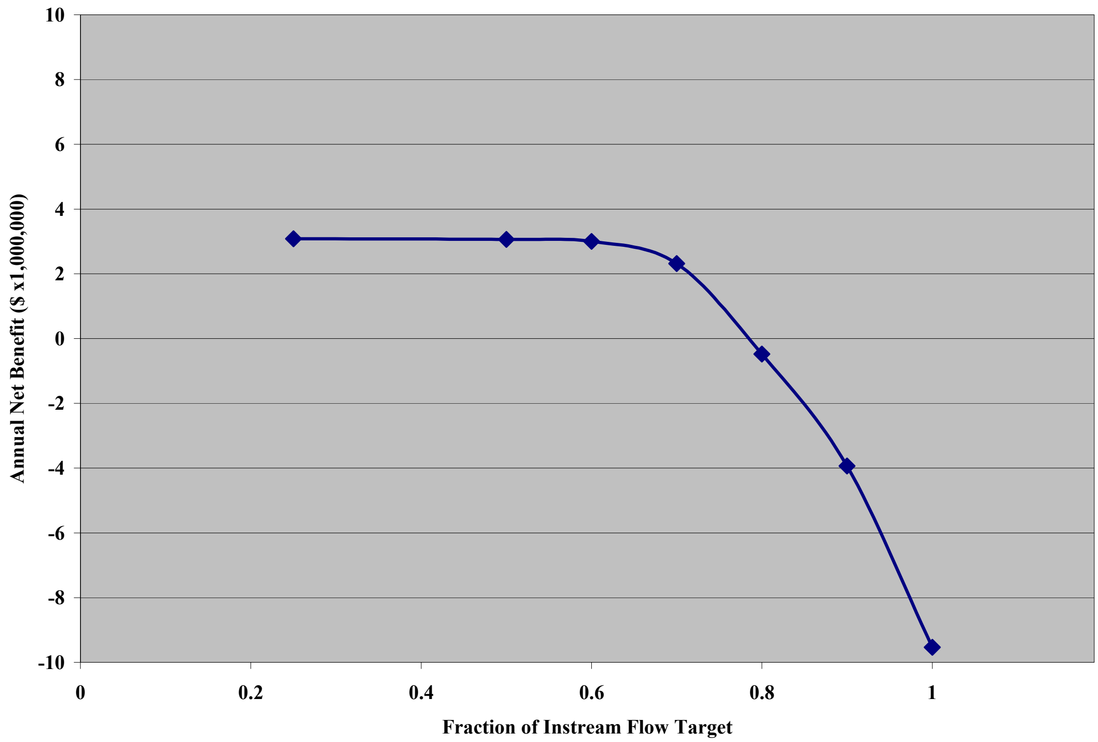

Figure 8. Tradeoff between instream flow target and net benefit.

In addition, the utilization of stormwater management through bioretention units and ASR facility highlights the need to increase groundwater recharge in the basin. This is in agreement with the current strategy in the IRB to increase recharge through various technologies to counteract the reduced infiltration due to development.

Further scenarios may be run to study the effects of and tradeoffs between bioretention units and aquifer storage and recovery facilities. They have similar functions in that they increase the recharge of groundwater. However, ASR is more versatile in its source of recharge water, flexible and controllable in the extent of its utilization, and can be located so that surface water for recharge is extracted after the water has flown through river segments with severe low flow conditions and critical habitats (U.S. EPA 2004). Although ASR with treated wastewater is not yet legal in Massachusetts, it is widely accepted and utilized in other parts of the United States and the world (U.S. EPA 2004). In addition, the ASR facility in the model only utilizes surface water.

The most interesting aspect of the model results is that both bioretention units and ASR approaches are recommended. Traditionally, it may be assumed that one is more economically efficient than the other. For example, it may be expected that after there is enough need to invest in ASR, the bioretention systems would no longer be recommended. However, they are both utilized. In water ban scenario (see results below), the ASR quantity is reduced and bioretention units are increased. This also suggests that it is not just the larger initial ASR construction cost that matters in which option is recommended. The long term scenario may be run for increasing instream flow in smaller increments to determine if one approach may be recommended before the other. In addition, the groundwater and streamflow may be plotted to discern what differences exist between the hydrologic effects of bioretention and ASR.

Effects of Mandatory Summer Outdoor Water Use Ban and Separate Water and Wastewater Metering

To explore the effect of a mandatory outdoor water use ban in the summer months, the long term scenario was run with a reduction in summer demand by 75% of the difference between winter and summer human demand. The results are shown in columns three and four of Table 9 where the results of the original long term scenario are repeated and the results of the watering ban are added. The results are counterintuitive because with less demand, it may be expected that the cost of services would be reduced. In this case, the cost increases by ~$500,000.

In examining the detailed results, it was noted that revenue decreased not only from water provision but also from wastewater services. Since outdoor water use is consumptive, its increase or decrease in demand should not affect wastewater services. However, in a large majority of the United States, wastewater services are billed based on the utilization of water services. Therefore, lower water demand and lower water revenues also result in lower wastewater revenues. However, the actual amount of wastewater treatment that is necessary does not change.

Table 9. Management Recommendations for Watering Ban and/or Separate Metering.

Management Options	***Units***	***Original***	***Watering Ban***	***Separate Metering***	***Separate Metering & Watering Ban***
Consumer's Rate Change	%	**50% (max)**	**50% (max)**	**50% (max)**	**50% (max)**
DWTP Infrastructure Repair	% of Leaks	**100%**	**100%**	**100%**	**100%**
WWTP Infrastructure Repair	% of Infiltration	**100%**	**100%**	**100%**	**100%**
Stormwater BMPs	# units	**120**	**153**	**120**	**153**
Land Conservation	ha	0	0	0	0
Nonpotable Distribution System	% of Consumers	0	0	0	0
Additional Surface Water Storage	MG	0	0	0	0
Additional Capacity:					
Surface Water Pumping	MGD	**5.0**	**4.5**	**5.0**	**4.5**
Groundwater Pumping	MGD	0	0	0	0
Drinking Water Treatment	MGD	0	0	0	0
Wastewater Treatment	MGD	**1.6**	**1.6**	**1.6**	**1.6**
Aquifer Storage & Recovery	MGD	**18**	**17**	**18**	**17**
Water Reuse Facility	MGD	0	0	0	0
Annual Net Benefit		**($9,530,879)**	**($10,038,601)**	**($20,337,430)**	**($19,726,834)**

In effect, wastewater utilities have been charging for services that they have not provided, at least in the summer months. Therefore, for accurate billing there should be an adjustment in the amount of wastewater that is calculated based on winter water use or a decrease in the price of summer wastewater services. The ideal solution would be the separate metering of water and wastewater flows. Another solution is to base summer wastewater charges on winter water use rates. A few examples were found of towns that adjust their sewer rates and billing. For example, the City of Lawrence, KY bases sewer charges for the year based on water use in December through February for residential customers and have applications for the adjustment of sewer rates due to water use that is not sewered (City of Lawrence, 2007).

To examine the effects of separate water and wastewater billing, another set of scenarios were run where wastewater services were billed based on actual wastewater flow rather than water demand. In this case, the watering ban does prove to be cost effective as overall costs are reduced as shown in the last two columns of Table 9. However, the overall costs for the separate billing cases are double that of the scenarios without separate pricing. This is due to the reduced wastewater charges which are usually significantly greater than water prices. Therefore, although accurate billing is recommended, it must be implemented simultaneously with the adjustment of wastewater prices that provide full cost recovery. These changes may need to be preceded with extensive public outreach to prevent misunderstanding and mistrust due to previous billing practices and to ensure the acceptance of new procedures.

System Behavior Validation

The model cannot be validated against actual data since the management options similar to those recommended by the model have not been implemented. Currently, the U.S. EPA is sponsoring pilot projects that decrease demand such as low flow fixtures and appliance rebates and increase infiltration such as stormwater BMPs. In addition, the USGS is conducting additional modeling using HSPF to explore the optimal timing and location of withdrawals and water storage options. The fact that these actions are similar to those recommended by the model provides some credibility for the model and its results.

In addition, the model was run for a different year to validate the modeled system's behavior. Since 1999 was an average year for total annual precipitation from 1961 to 2001, 1980s, which is a 1 in 20 dry years, was chosen for the additional run's precipitation data. All other parameters were retained. The scenario with long term management options without wastewater export was utilized. Streamflow and precipitation in 1980 are shown in Table 10 with the previously shown recommended instream flow target and human demand. Total annual precipitation is reduced from 45 inches in the average year in 1999 to 34 inches in the dry year in 1980. The average flow in 1999 was 50.1 ft^3/s and the average flow required to meet the instream flow target is 47.8 ft^3/s. However, the average flow in 1980 was only 11.7 ft^3/s.

Table 10. 1980 Hydrologic Conditions.

	Target Flow	**Streamflow**		**Precipitation**	**Human Demand**
Date	**(ft^3/s)**	**(ft^3/s)**	**(as % of Target)**	**(in/month)**	**(ft^3/s)**
Janurary	44	9.8	22%	0.6	8.4
February	44	3.7	8%	0.9	8.2
March	111	24.2	22%	5.1	8.1
April	111	36.9	33%	4.9	8.9
May	66	27.1	41%	2.0	10.3
June	22	6.0	28%	3.3	11.1
July	22	5.9	27%	4.0	11.6
August	22	3.9	18%	1.6	10.9
September	22	0.6	3%	1.7	10.3
October	22	5.4	25%	5.1	9.0
November	44	10.2	23%	3.6	8.3
December	44	6.8	15%	1.2	9.8

These hydrologic conditions are reflected in fact that full instream flow was not feasible in the dry year optimization run. The highest instream flow that could be met was

60% of the recommended target. Figure 9 shows the resulting instream flow for the average and dry year conditions.

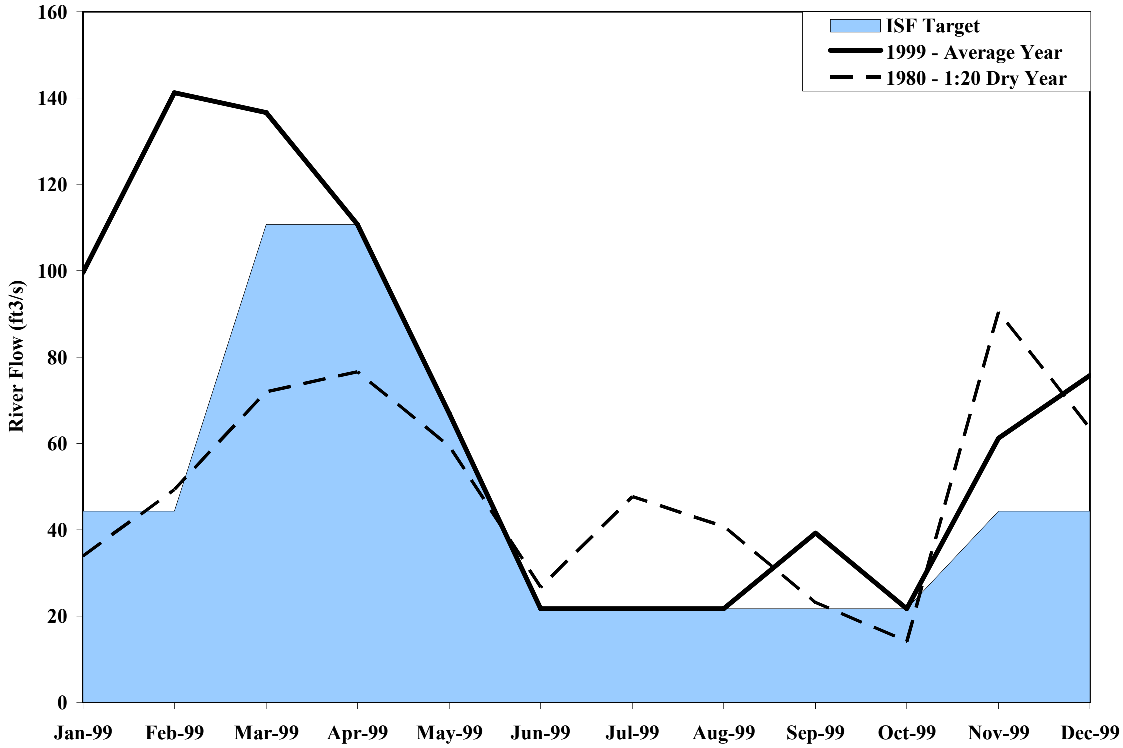

Figure 9. Maximum instream flow achieved during average and dry year conditions.

To compare the net benefit between an average and dry year, the model was run under both conditions for meeting 60% of the instream flow target. The results comparing the average year (1999) and the dry year (1980) management recommendations are shown in Table 11. The net benefit to meet 60% of the instream flow target in the dry year was at a cost of approximately $7.7 million while in the average year it cost less than $3 million. The significant difference between the two years is similar to the behavior seen in meeting an increasing fraction of instream flow with the same hydrologic conditions.

Table 11. Results for an Average (1999) and Dry Year (1980).

Management Options	Units	Dry Year (1980)	Average Year (1999)
Consumer's Rate Change	%	**50%**	**50%**
DWTP Infrastructure Repair	% of Leaks	**100%**	**100%**
WWTP Infrastructure Repair	% of Infiltration	**100%**	**100%**
Stormwater BMPs	# units	0	0
Land Conservation	ha	0	0
Nonpotable Distribution System	% of Consumers	0	0
Additional Surface Water Storage	MG	0	0
Additional Capacity:			
Surface Water Pumping	MGD	**5.7**	**5.0**
Groundwater Pumping	MGD	0	0
Drinking Water Treatment	MGD	0	0
Wastewater Treatment	MGD	**1.6**	**1.6**
Aquifer Storage & Recovery	MGD	**50**	0
Water Reuse Facility	MGD	0	0
Net Benefit		**(7,651,874)**	**(2,999,195)**

The similarity is logical as increasing the environmental demand, which is instream flow, or reducing the supply available to meet the demand, which is precipitation, have similar effects on the total water availability and both require the implementation of more management options to counteract their effects. There is further confirmation in that the management tools utilized in the dry year are also the same as those utilized in the average year when meeting full instream flow (see Table 8).

Chapter 4 - Summary

Conclusion

A watershed management model for supporting informed water resources management decisions and strategies was introduced. Developing such a generic, comprehensive and integrated watershed management model has many potential utilities, applications and extensions. The initial model described here was used to evaluate management options within a watershed system context in order to realize the full impact of management decisions.

The model's application to the upper IRB yielded insightful results about the watershed system and its behavior. The model demonstrated that with an increasing diversity of management options, the cost of providing water and wastewater services can decrease and net benefits can increase. The results also revealed that meeting an increasing fraction of the instream flow recommendation yielded a nonlinear increase in cost. The Pareto frontier of tradeoff between meeting instream flow and management cost showed that the change in cost is relatively small in meeting up to 70% of the recommended instream flow. This can be valuable information to motivate management and policy changes to meet at least 70% of the instream flow.

The model results also showed that water conservation is cost effective if wastewater services are charged based on actual wastewater flow rather than water utilization. This is important confirmation that water conservation is not only effective reducing demand on a finite quantity of renewable water supply but that it is also financially efficient if separate water and wastewater pricing is practiced. Along with the recommendation for separate water and wastewater pricing was the need for full cost pricing on water and wastewater services to enable full cost recovery and financial sustainability of water and wastewater utilities.

In addition, the results indicated that demand management through price changes and the repair of leakage in water distribution and wastewater collection pipes are effective management options as they were selected in all scenarios where they were available. The results of the model application to the upper IRB demonstrate not only the relative efficacy of undervalued management options, but also document the merits of integrated water resources management.

Limitations

The foremost limitation of this initial model is that the optimization only considers water quantity. Since water quantity is the dominant concern in the IRB, the model application to the upper IRB resulted in relevant management recommendations that are similar to those currently being implemented in the basin. In addition, some water quality measures are inherent in the model because all wastewater must flow through at least the secondary wastewater treatment facility. However, full incorporation of the water quality component in the optimization algorithm is essential for a truly comprehensive representation of the watershed and consideration of all possible management tools. Once water quality is incorporated, the optimization will require a nonlinear solver and the appropriate approach among the numerous nonlinear solvers must be evaluated.

Another limitation is the level of temporal and spatial aggregation. A detailed examination of the calibration revealed that the majority of the error in streamflow was caused by the baseflow. Therefore, monthly temporal aggregation may be too coarse and a weekly time step should be tested. An additional modification may be required to limit or cease baseflow to the surface water when the groundwater levels drop below a certain threshold.

The additional concern of spatial aggregation can be tested by comparing the model with the case study setup in a distributed simulation model such as WEAP. In addition to testing the validity of the spatial aggregation, it would also contribute to the general validation of the model since direct validation by data is not possible as discussed Chapter 3 – Application. Also, the model may ultimately be most utilized as part of a detailed simulation model. The management model can extract the necessary data from the simulation model, screen the management options and return the constrained decision space to the simulation model. The simulation model can then be used to obtained detailed results.

Additional refinement of the model calibration to streamflow data may be achieved by obtaining runoff and percolation coefficients from a more developed and detailed model with more extensive representation of human components than TMDL2k which is still in a developmental phase. One option for this particular case study of the IRB may be utilizing the USGS HSPF model of the basin which has been developed over several years and validated for the basin.

Future Work

In addition to addressing the limitations of the model, continued model development is planned. One continual development will be the addition of management options not yet incorporated in this initial model. Some available management options to include may be internal recycling within water users especially industrial facilities, additional types of stormwater BMPs and additional demand management techniques.

Another future consideration is a DSS interface to provide extensive output analysis to aid in recognizing and understanding relationships and tradeoffs, thereby supporting informed decision making. Extending the model from a decision support system to a negotiation support system will require a module that will utilize alternate objective functions. Although the initial model optimizes for maximum net benefit, it is constructed such that each stakeholders' interest can be represented as an objective function or as a constraint. The model can be run numerous times trading out each stakeholder's interest as the objective function. For example, maximum instream flow may be the objective one run with minimum human demand specified as a constraint while in another run maximum human demand may be the objective with a minimum instream flow specified. Reducing the decision space in this manner maintains the optimal solution for each stakeholder and produces a decision space within which to negotiate. This approach will facilitate the development of the model as a negotiation support tool.

Another future enhancement may be the incorporation of uncertainty. Incorporating uncertainty will require developing a stochastic module. Series of Monte Carlo analyses of the model may be automated in order to map uncertainty in model parameters and input data onto the decision space. This will allow for the evaluation of the robustness of the model and solutions. The results can be translated into prediction interval type metrics, providing decision makers with a range of outcomes that can be expected from various management strategies when considering uncertainty.

Appendix A - Variables

Decision Variables

PerPrice	Percent of increase water and wastewater services price
PerWtpLeakFix	Percent of potable distribution system leakage to fix
QWtpAddl	Additional water treatmen plant capacity
QWtpPumpGwAddl	Additional groundwater pumping capacity
QWtpPumpSwAddl	Additional surface water pumping capacity
VResAddl	Additional surface water storage volume
QWwtpAddl	Additional capacity for the Watewater treatment plant
PerWwtpLeakFix	Percent of wastewater collection system leakage to fix
QWrfAddl	Additional capacity for the Water reuse facility
QAsrAddl	Additional capacity for the Aquifer storage and recovery facility
QNpMax	Maximum capacity of Nonpotable distribution system to be built
QGwWtp	Flow from Groundwater to Water treatment plant
QExtGwOut	Flow from Groundwater to External groundwater
QSwAsr	Flow from Surface water to Aquifer storage and recovery facility
QSwWtp	Flow from urface water to Water treatment plant
QExtSwOut	Flow from Reservoir to External surface water
QResWtp	Flow from Reservoir to Water treatment plant
QResAsr	Flow from Reservoir to Aquifer storage and recovery facility
QWtpUseNp	Flow from Water treatment plant to Nonpotable water use
QWwtpWrf	Flow from Wastewater treatment plant to Water reuse facility
ALc7	Area of land use 7 after land conservation
ALc8	Area of land use 8 after land conservation
ASm1	Area of land use 1 after stormwater management
ASm2	Area of land use 2 after stormwater management
ASm3	Area of land use 3 after stormwater management
ASm4	Area of land use 4 after stormwater management
ASm5	Area of land use 5 after stormwater management
ASm6	Area of land use 6 after stormwater management
ASm7	Area of land use 7 after stormwater management
ASm8	Area of land use 8 after stormwater management

Input parameters

VolGwI	Initial Volume of Groundwater
VolGwMin	Minimum Volume of Groundwater
VolGwMax	Maximum Volume of Groundwater
VolResI	Initial Volume of Reservoir/Surface water storage
VolResMin	Minimum Volume of Reservoir/Surface water storage
VolResMax	Maximum Volume of Reservoir/Surface water storage
QSwResMin	Minimum instream flow from Surface water/River to Reservoir/Surface water storage
QExtSwOutMin	Minimum instream flow from Reservoir/Surface water storage to External surface water
QExtGwOutMin	Minimu Flow from Groundwater to External groundwater
QPumpSwMax	Maximum existing Surface water pumping capacity
QPumpGwMax	Maximum existing groundwater pumping capacity
QWtpMax	Maximum existing capacity of Water treatment plant
QWwtpMax	Maximum existing capacity of Wastewater treatment plant
QWrfMax	Maximum existing capacity of Water reuse facility
QAsrMax	Maximum existing capacity of Aquifer storage and recovery
QTrInMin	Minimum Interbasin transfer in to basin
QTrInMax	Maximum Interbasin transfer in to basin
QTrOutMin	Minimum Interbasin transfer out of basin
QTrOutMax	Maximum Interbasin transfer out of basin
QExtSwIn	Inflow from External surface water
QExtGwIn	Inflow from External groundwater

Additional Variables

ABmp1	Area of land use 1 under BMP management
ABmp2	Area of land use 1 under BMP management
ABmp3	Area of land use 1 under BMP management
ABmp4	Area of land use 1 under BMP management
ABmp5	Area of land use 1 under BMP management
ABmp6	Area of land use 1 under BMP management
ABmp7	Area of land use 1 under BMP management
ABmp8	Area of land use 1 under BMP management
QGwSw	Flow from Groundwater to Surface water; Baseflow
QGwWwtp	Flow from Groundwater to Wastewater treatment plant; Infiltration
QSwRes	Flow from Surface water to Reservoir
QWtpGw	Flow from Water treatment plant to Groundwater; Leakage
QWtpUseNp	Flow from Water treatment plant to Nonpotable water use
QWrfUseNp	Flow from Water reuse facility to Nonpotable water use
QWwtpSw	Flow from Wastewater treatment plant to Surface water
QWrfSw	Flow from Water reuse facility to Surface water
QTrInUseP	Flow from Interbasin transfer to Potable water use
QUsePSep	Flow from Potable water use to Septic systems
QUsePTrOut	Flow from Potable water use to Interbasin transfer out
QTrInUseNp	Flow from Interbasin transfer to Nonpotable water use
QUseNpSep	Flow from Nonpotable water use to Septic systems
QUseNpTrOut	Flow from Nonpotable water use to Interbasin transfer out
QSepGw	Flow from Septic systems to Groundwater
QAsrGw	Flow from Aquifer storage and recovery facility to Groundwater
RevUse1T	Total Revenue from Potable water use
RevUse2T	Total Revenue from Nonpotable water use
CostConsT	Total Cost for Land Conservation
CostSwmT	Total Cost for Stormwater Management
CostWtpT	Total Cost for Water treatment plant
CostWtpLeak	Total Cost for Water treatment plant infrastructure repair
CostWwtpT	Total Cost for Wastewater treatment plant
CostWwtpLeak	Total Cost for Wastewater treatment plant infrastructure repair
CostWrfT	Total Cost for Water reuse facility
CostPreT	Total Cost for Pretreatment for Aquifer storage and recovery
CostAsrT	Total Cost for Aquifer storage and recovery
CostTrT	Total Cost for Interbasin transfer of water and/ or wastewater
CostPriceT	Total Cost for Pricing change in water and wastewater services
CostNpdistT	Total Cost for Nonpotable distribution system
CostResT	Total Cost for Reservoir/Surface water storage
NetBenefit	Net Benefit of watershed management
VolGwF	Final Volume of Groundwater
VolResF	Final Volume of Reservoir/Surface water storage

Appendix B - Data Sources

Management Option	Data Source for Cost
Land Conservation	LandandFarm.com 2005
Stormwater - Bioretention	Limbrunner et al. 2005
Water Treatment - Surface water pumping	U.S. EPA 2000
Water Treatment - Groundwater pumping	U.S. EPA 2000
Water Treatment - Potable	North Reading Water Department 2007
Water Treatment - Leak repair	Massachusetts Water Resources Authority 2007
Wastewater Treatment - Secondary	Richard 1998
Wastewater Treatment - Reuse facility	Richard 1998
Wastewater Treatment - Infiltration repair	Massachusetts Water Resources Authority 2007
Nonpotable Distribution System	U.S. EPA 2000
Aquifer Storage & Recharge	Richard 1998
Human Demand Management	Rogers 2004
Interbasin Transfer - Potable water import	Massachusetts Water Resources Authority 2007
Interbasin Transfer - Wastewater export	Massachusetts Water Resources Authority 2007

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