Equilibrium Approach to Integrating Regional Surface Water Treatment and Limited Groundwater Pumping Capacity

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Abstract: The inexpensive nature of groundwater, combined with population growth, has resulted in many aquifers being pumped at unsustainable levels. Consequently, regulators in many states have acted to limit water withdrawals from affected formations. Communities subject to such restrictions must seek alternatives and will often choose to develop surface waters, a process involving substantial expenditures on treatment and conveyance infrastructure, costs that will be particularly burdensome for smaller communities. Regional treatment plants can take advantage of the economies of scale inherent in these facilities and will lower treatment costs, but these savings must be weighed against increased conveyance costs associated with a larger distribution area. Regional strategies must also consider how to integrate the development of surface water with use of the remaining groundwater pumping capacity. This work describes an equilibrium approach that balances the two antagonistic forces affecting surface water development, while simultaneously considering the efficient allocation of post-reduction groundwater capacity through tradable pumping permits. Unlike earlier regionalization work, this approach has each individual community select its least cost supply alternative, rather than the alternative that results in the lowest aggregate regional cost. The model is applied to a 15-county region of North Carolina facing substantial groundwater pumping restrictions. Results indicate that the inclusion of regional surface water systems and tradable groundwater permits can reduce the estimated cost of meeting the new restrictions in the region by as much as 35% in present value cost terms.

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Introduction

Unsustainable groundwater pumping practices are a growing water supply concern in the United States (NRC 2001). Well-known examples of threatened formations include the Ogallala and Edwards aquifers, and many other examples exist across the nation. Since its peak in 1980, groundwater consumption in the United States has leveled off, suggesting that development of the nation's aquifers has begun to approach its limits in many regions (USGS 2004). Currently, at least 27 states have regulatory mechanisms in place to protect aquifers through groundwater management areas, and at least 23 states have acted to limit or regulate groundwater withdrawals (Bowman 1990). In many cases, cities forced to reduce or limit groundwater withdrawals will meet demand via surface water. However, developing surface water sources requires treatment infrastructure that is quite expensive relative to that used in groundwater systems, which generally involves only disinfection. Converting to surface water may also require the development of new conveyance infrastructure to deliver water to former groundwater users without easy access to surface sources. The high costs of building surface water infrastructure may be particularly burdensome to many smaller communities, which comprise the vast majority of groundwater users and which often have limited financial resources (USEPA 2001).

When considering strategies for meeting water demand in regions subject to groundwater pumping reductions, one cost-effective approach can involve the development of regional surface water treatment plants. The small size of the typical groundwater user precludes it from taking advantage of the significant economies of scale inherent in surface water treatment (Clark 1987), but a larger system serving many small cities may significantly lower treatment costs. The benefits of the economies of scale in treatment must, however, be balanced against the increased conveyance costs that arise from an expanded conveyance network. Thus, the question is, how can the user integrate the remaining (i.e., post-cutback) groundwater capacity with the development of new surface water sources? Water markets are well established throughout the western United States, and have been shown to be useful in maximizing the allocation efficiency of water resources (Bush 1988; Characklis et al. 1999). Thus, issuing tradable groundwater pumping permits while also creating regional surface water systems may further lower the regional costs of responding to limits on groundwater withdrawals. Both regionalized treatment and water markets have been widely studied, but no one has considered their joint use in integrated water resource planning.

The general scenario investigated in this work involves a set of cities that obtain water from an aquifer system subject to a man-

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dated pumping reduction. Surface water resources are assumed to be available but have remained undeveloped because they are more expensive. An equilibrium approach has been developed to explore the costs associated with integrating the use of regionalized surface water treatment facilities and tradable groundwater permits. In contrast to earlier regionalization work, the model developed allows each individual community to choose the alternative that meets its demand at the lowest cost. The choice made by each community has an effect on the cost of the supply alternatives available to other communities in that, as more join the regional surface water system, the costs decline; but the demand has a similar effect, and hence influences the price for groundwater permits. The model identifies an equilibrium condition in which each community chooses its smallest cost alternative, and the groundwater permit price is just high enough to encourage the development of surface water treatment and distribution infrastructure sufficient to meet the shortfall created by pumping reductions. The model's approach is sufficiently general that it can be readily adapted for application to many regions facing groundwater scarcity. In this case, it is applied to the Central Coastal Plain (CCP) of North Carolina, an area facing groundwater pumping restrictions because water levels are declining and saltwater is intruding in regional aquifers (Winner and Lyke 1989). The CCP faces a situation that is not unique, one that involves a number of smaller rural communities that are almost all currently dependent on overpumped groundwater resources to meet their present and future demands. This is a situation that is likely to be repeated with increasing frequency throughout the midwestern and southwestern United States. As such, both the strategy and modeling approach described in this work may have increasing relevance in coming years.

Background

The concept of regionalized treatment facilities has been explored in previous work, but almost exclusively within the context of wastewater treatment. Models have been developed to determine the number, size, and location of regional facilities. Early models dealt with small sets of wastewater treatment plants located along rivers with little branching in the pipeline network (Converse 1972; Deininger and Shaw 1973). Later research began optimizing more complicated networks using a variety of techniques, such as mixed integer programming (Joeres et al. 1974; Leighton and Shoemaker 1984), heuristic algorithms (Chiang and Lauria 1977; Rossman 1978; Whitlatch and ReVelle 1976), and branch and bound methods (Brill and Nakamura 1978; Nakamura et al. 1981; Nakamura and Riley 1981). The ultimate objective of each of these models was minimizing total regional cost. This was sensible at the time, as the federal government was providing much of the funding for wastewater infrastructure, but these approaches did not give much attention to the costs such regional solutions might impose on individual communities. In situations where little external (i.e., federal) funding is available, as may often be the case when regional groundwater restrictions are established, communities are likely to pursue the solution that meets their individual needs at the lowest cost, rather than alternatives that lower aggregate regional costs. Researchers have partially addressed the potential for inequity in regional solutions by devising cost apportionment methods to divide costs among users once a minimum cost regional solution is specified (Giglio and Wrightington 1972). However, these methods do not ensure that each community is meeting its objectives at its lowest cost, only that its cost would be lower than if it were to act independently. Furthermore, scenarios in which each cost-apportionment method is disadvantageous to at least one participant, such that the participant is better off acting independently, despite the regional system's advantage to the region as a whole, can be generated. When external economic influences are not available to encourage participation in a regional system, it is likely more representative to model a region based on the choices of individual communities. This is particularly the case when analyzing water supply, as communities will often have several alternatives (i.e., surface and groundwater).

Strategies for conjunctive management of surface and groundwater have also been explored in the literature, but previous conjunctive use research has primarily focused on maximizing the combined yield of raw, untreated water from surface and groundwater resources (Belaineh et al. 1999; Onta et al. 1991; Peralta et al. 1995). While the costs of increasing raw water availability are important, a substantial fraction of municipal water expenses are related to water treatment, which can vary significantly between surface and groundwater. Treatment costs are, therefore, likely to be an important element in a conjunctive use analysis, but have rarely been addressed in previous studies.

Coordinating the development of surface water infrastructure with limited groundwater capacity is another area in which little work appears to have been done. A substantial body of research exists on the functioning of water markets and their development throughout the western United States and many other regions (Easter et al. 1998; Griffin and Boadu 1992; Howe and Goemans 2003; Kloezen 1998). In many cases, markets have proven to be an effective means of efficiently allocating water among users (Howe and Goemans 2003; Saliba 1987). Additionally, markets have been explored as resource management tools, particularly as transfers from agricultural to municipal use in the form of dry year options (Watkins and McKinney 1999). Nonetheless, integrated consideration of water markets and regionalized infrastructure development as a means of regional water resource management remains relatively unexplored.

Methodology

The modeling approach deterministically considers regional surface water treatment and conveyance systems, in combination with marketable groundwater permits, in the development of solutions for regions facing groundwater pumping restrictions. The general logic underpinning the model is that cities near surface water sources are more likely to find it attractive to join regional surface water systems and will, in turn, sell their groundwater permits to cities that are more distant from surface water sources. The model considers each city to be an individual actor, responsible for its own water supply and treatment costs (or its share of regional system costs). Consequently each city is expected to select its least expensive water supply alternative. The model balances several antagonistic forces in order to arrive at a solution. The economies of scale achievable through increasing treatment plant capacity are balanced against the increased conveyance costs that result from distributing water over a larger service area. The number of cities joining a regional surface water system is also linked to the price of groundwater permits. As more cities find surface water to be a less expensive choice, demand for groundwater permits will decrease and their price will decline, making groundwater permits more attractive to surface water users, and so forth. The goal of the model is to evaluate these circular interdependencies by altering the market price of groundwater permits until the point at which (1) the marginal cost of satisfying demand through the purchase of groundwater or joining a regional system is roughly equal; and (2) each city is making use of its lowest cost alternative. It should be noted that, while any number of potential regional treatment facility sites can be considered, the model does not endogenously select optimal sites, and these must be identified a priori by the user, particularly as geographical, political, and financial factors can all heavily influence site selection.

Each water supply user has an initial unit price at the tap prior to the enactment of groundwater restrictions. Alternative water supplies developed or purchased in response to groundwater pumping reductions will result in a net increase in each community's unit price at the tap, and cities are modeled as making choices that will minimize this increase. As such, the criterion used to evaluate water supply alternatives is the unit price increase at the tap, in dollars per thousand gallons ($/kgal), a measure that includes both amortized capital and operating expenses.

Through regulatory actions, all of the cities included in the model are to have their capacity reduced by a set amount, such that each city will retain a groundwater capacity equal to some fraction ($f_i < 1$) of its demand. Also, it is assumed that no city will need to pay for the fraction of its original groundwater pumping capacity that it retains. When seeking its lowest cost alternative, a city will compare the net unit cost increase at the tap of acquiring its supply entirely from surface water (P_{SW}) with the unit cost increase at the tap of purchasing sufficient groundwater capacity ($P_{\mathrm{GW}} \cdot (1 - f_i)$) to replace its lost capacity. Therefore, a community finds surface water less expensive if the price of groundwater exceeds that of surface water by more than $1/(1 - f_i)$. Under these conditions, a city joining a regional surface water system is assumed to be a rational actor that will sell its higher priced groundwater permits and replace them with lower priced (by a factor of at least $1 - f_i$) surface water. Such a deterministic mathematical formulation that selects the lesser of two cost increases clearly precludes the mixing of water sources.

Cost Equations

The cost of a regional surface water system is based on both treatment and conveyance costs, with each being comprised of capital and operating (O&M) expenses. Treatment plant capital costs are estimated using a power function (Clark and Morand 1981), such that

$$C_{\mathrm{cap}}^{\mathrm{plant}}(\$) = 2.43 \times 10^6 \cdot Q_{\mathrm{capacity}}^{0.67} \tag{1}$$

where Q_{capacity} = capacity of treatment plant (millions of gallons per day, MGD).

The capital cost relationship has been updated to 2002 dollars with Engineering-News Record (ENR) indices and has been calibrated using empirical data from treatment facility cost estimates developed for the study region (Wooten Company et al. 2000).

Operating costs are represented as

$$C_{\mathrm{O\&M}}^{\mathrm{plant}}(\$/year) = 4.45 \times 10^5 \cdot Q_{\mathrm{produced}}^{0.83} \tag{2}$$

where Q_{produced} = average daily production, $= 0.67 \cdot Q_{\mathrm{capacity}}$ (MGD).

Operating costs have also been updated with ENR indices and verified using utility data obtained from the state of North Carolina (NC DENR 2002). The average unit price of treatment is the sum of annualized capital and operating costs divided by average annual production, yielding values in $/kgal. Annualized capital costs assume a plant life of 30 years and a discount rate of 5.5%.

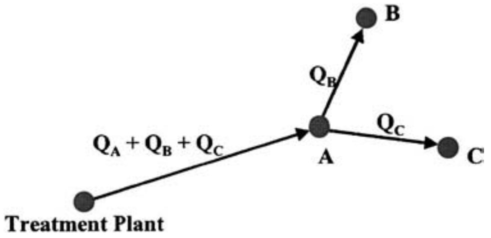

Fig. 1. Conveyance cost allocation example

All cities joining a regional surface water treatment system are assumed to pay the same average unit price for treated water leaving the plant.

Capital costs of pipeline conveyance are calculated using longstanding relationships (Linaweaver and Clark 1964) that were subsequently updated via ENR indices and verified with engineering data obtained from the study area (Wooten Company et al. 2000), such that

$$C_{\mathrm{cap}}^{\mathrm{pipe}}(\$/mi) = 5792 \cdot D^{1.3983} \tag{3}$$

where D = diameter (in.).

The operating costs of conveyance are primarily a function of pumping costs and are estimated using the Hazen-Williams relationship. These costs are multiplied by a factor (1.08) designed to account for maintenance, with the entire relationship expressed as

$$C_{\mathrm{O\&M}}^{\mathrm{pipe}}(\$/\mathrm{kgal}/mi) = (1.66 \times 10^{-2} \cdot (S_l + S_f) \cdot P/E) \cdot 1.08 \tag{4}$$

where P = cost of electricity, \$0.06/kW·h; E = pump efficiency, assumed to be 0.8; S_l = slope (ft/1000 ft); S_f = frictional headloss = $[Q/(405 \times 10^{-6} \cdot C \cdot D^{2.63})]^{1.85}$; and C = Hazen-Williams coefficient (steel = 120).

Unlike treatment costs, in which each city pays the same price for water leaving the plant, the costs of transporting water to each city will vary with its size and location. The capital and O&M costs for each pipe segment in the regional conveyance network are allocated proportionally to the fraction of flow each city receives from the segment. Fig. 1 illustrates an example of three cities (A, B, and C) connected to a regional water treatment plant. City B is responsible for all of the conveyance costs from A to B and for the costs corresponding to the fraction of average flow (Q) it uses from the treatment plant to A (i.e., $Q_B/[Q_A + Q_B + Q_C]$). Surface water conveyance costs are evaluated from the source to the point where water enters a city's distribution system. Groundwater is assumed to enter the distribution system at the point of withdrawal, so no conveyance costs are considered.

In addition to regional surface water systems and groundwater permit trading, many cities will also have other, "tertiary" alternatives available to them. These are water supply alternatives with constant costs that are essentially unaffected by the actions of other cities. Examples might include the drilling of wells into unregulated aquifers or the construction of a surface water treatment plant for use by a single city. Tertiary sources will be tapped to compensate for groundwater pumping cutbacks when they are less expensive than both purchasing additional groundwater permits or joining a regional surface water system. While tertiary costs are invariant, if cities choose to make use of these alternatives, the cost of surface water and groundwater for other cities can be affected. Tertiary alternatives form the "base-case" scenario to which model results containing regional solutions, such as regional surface water systems and groundwater permit trading, will be compared. Tertiary alternatives are also the only mixed solutions pursued within the model. In theory, tertiary alternatives could be non-mixed solutions, but within the study region, that is not a viable option. For instance, given the small size of the cities within the study region, it is unlikely that the sale of groundwater permits and gains in economies of scale would offset the costs incurred through the expansion of the surface water treatment plant capacity necessary for a non-mixed solution. Similarly, unregulated aquifers that are used to replace lost groundwater capacity tend to be smaller in size and have lower yields than the regulated aquifers, thus making them undesirable as sole water supplies.

The interdependent nature of the costs, and the ability of each city to make independent choices, results in previously developed analytic methods (e.g., linear programming) being less applicable. In this case, each city may select one of three alternatives: join a regional surface water system, purchase groundwater permits, or make use of a city-specific tertiary supply option. Each city determines the average unit cost increase at the tap from each alternative and selects its lowest cost alternative using a 1,0 decision variable (e.g., X_i, Y_i, or Z_i). The average cost increase at the tap associated with joining a regional surface water system ($\mathrm{Cost}_{\mathrm{SW},i}$, in \$/kgal) can be represented as

$$\begin{aligned}\mathrm{Cost}_{\mathrm{SW},i} = \frac{1}{\sum_{j=1}^{N} Q_j \cdot X_j} & \left[\alpha_1 \left(\sum_{j=1}^{N} Q_{\mathrm{cap},j} \cdot X_j \right)^{\beta_1} \right. \\ & \left. + \alpha_2 \left(\sum Q_j \cdot X_j \right)^{\beta_2} \right] \cdot X_i \\ & + (\mathrm{Conveyance}(Q_i, \mathrm{Dist.}, \mathrm{Slope}, X_1, X_2, \ldots, X_N) \\ & - C_{\mathrm{GW}}^{\mathrm{O\&M}}) \cdot X_i \end{aligned} \tag{5}$$

where i = index describing the city considered in [a]; j = index describing all cities considered within the model ($j = 1, 2, \ldots, N$); $Q_{\mathrm{cap},j}$ = maximum daily demand of city j (MGD); Q_j = average daily demand of j (MGD); $C_{\mathrm{GW}}^{\mathrm{O\&M}}$ = unit cost of pumping and treating groundwater (\$/kgal); $X_i = 1$ if regional surface water is least expensive for city i, 0 otherwise; α_1, α_2 = constants (\$/kgal); and β_1, β_2 = constants.

The first two terms in Eq. (5) represent surface water treatment costs (capital and O&M, respectively) converted to volumetric terms (\$/kgal). The third term describes conveyance costs for city i if it joins the regional system. As the costs of a conveyance network, and its subsequent apportionment to city i, are a function of many factors (i.e., demand, relative locations), these costs are written as a general expression until the subset of cities participating in the regional system is known and the network configuration is determined. The fourth term reduces the surface water treatment and conveyance costs by an amount equal to the costs of pumping and treating groundwater ($C_{\mathrm{GW}}^{\mathrm{O\&M}}$), consistent with the concept of an average unit cost increase.

The average unit cost increase at the tap associated with choosing to purchase groundwater permits ($\mathrm{Cost}_{\mathrm{GW},i}$, in \$/kgal) is calculated by multiplying the unit price of groundwater (P_{GW}, in \$/kgal) by the fraction of groundwater capacity that must be replaced.

$$\mathrm{Cost}_{\mathrm{GW},i} = \left(\frac{Q_i - Q_{\mathrm{permit},i}}{Q_i} \right) \cdot P_{\mathrm{GW}} \cdot Y_i \tag{6}$$

where $Q_{\mathrm{permit},i}$ = quantity of groundwater permits owned by city i; and $Y_i = 1$ if purchasing groundwater is least expensive for city i, 0 otherwise.

Eq. (7) calculates the average unit cost increase at the tap that results from choosing tertiary alternatives ($\mathrm{Cost}_{\mathrm{tert},i}$, in \$/kgal). As in Eq. (5), savings from the cessation of pumping and treating groundwater are included in the calculation.

$$\mathrm{Cost}_{\mathrm{tert},i} = \left[C_{\mathrm{tert},i} - C_{\mathrm{GW}}^{\mathrm{O\&M}} \cdot \left(\frac{Q_i - Q_{\mathrm{permit},i}}{Q_i} \right) \right] \cdot Z_i \tag{7}$$

where $C_{\mathrm{tert},i}$ = unit cost for city i to pursue a tertiary alternative (\$/kgal); $Z_i = 1$ if a tertiary alternative is least expensive for city i, 0 otherwise.

The methods of calculating revenue generated through the sale of groundwater permits, and by the institutions established to allow for transfers of these permits, can vary. Some water markets allow for individual transactions (Griffin and Boadu 1992) while others involve some form of "water bank." The bank concept involves sellers devoting their shares to a central authority, which conducts a series of blind auctions involving several bid-sell rounds (providing information to buyers/sellers on the success of their bids each time) to establish a single, market-clearing price. The bank then collects from the buyers and distributes the proceeds back to cities in proportion to the fraction of total permits the city contributed. Given the number of market participants in the study region and the incompatibility of an active market (that would eventually reach a market clearing price) with infrastructure decisions, the water bank concept is assumed to be employed in the study region, with Eq. (8) reflecting the revenue each city would realize from groundwater permit sales through such an institution.

$$\mathrm{G}W_{\mathrm{revenue},i} = \left(\frac{\sum_{j=1}^{N} (Q_j - Q_{\mathrm{permit},j}) \cdot Y_j}{\sum_{j=1}^{N} Q_{\mathrm{permit},j} \cdot X_j} \cdot \frac{Q_{\mathrm{permit},i}}{Q_i} \right) \cdot P_{\mathrm{GW}} \cdot X_i \tag{8}$$

Using the cost terms presented in Eqs. (5)–(8), a cost comparison function, which uses several 1,0 variables (X_i, Y_i, Z_i) to identify the least cost supply alternative, is defined and expressed as

$$\mathrm{Cost}_i = (\mathrm{Cost}_{\mathrm{SW},i} - \mathrm{G}W_{\mathrm{revenue},i}) \cdot X_i + \mathrm{Cost}_{\mathrm{GW},i} \cdot Y_i + \mathrm{Cost}_{\mathrm{tert},i} \cdot Z_i \tag{9}$$

such that $X_i + Y_i + Z_i = 1$, where Cost_i = minimum average unit cost increase at tap for city i to replace lost groundwater capacity (\$/kgal).

Note that Eq. (9) is a mathematical representation of the water supply choice faced by a single city, but Eq. (9) itself does not indicate the path or method the model must take to arrive at a solution for all the affected cities within a region.

Model Structure

The city's cost comparison Eq. (9) forms the basis of decision making within the model, and the market price for groundwater (P_{GW}) acts as the independent variable that plays a central role in determining the lowest cost alternative for each city. Conceptu-

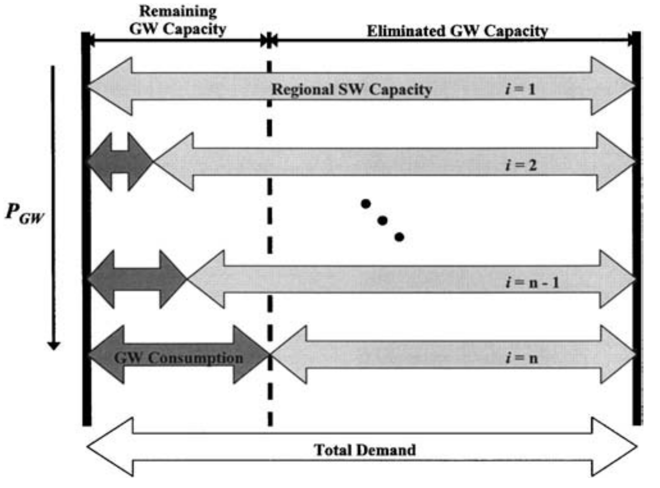

Fig. 2. Conceptual path to model's endpoint

ally, the model operates by setting an initial groundwater price sufficiently high that all cities find it more expensive to purchase groundwater permits than to join a regional surface water system or tap a tertiary alternative. This results in unused groundwater capacity, implying that the groundwater price is above a market clearing level. In subsequent runs, the groundwater price is incrementally lowered. As the price of groundwater declines, some of those participating in the regional surface water system will instead find that groundwater permits are a less expensive means of meeting their needs. Consequently, the costs of participating in the regional system will rise as the capacity of surface water infrastructure is reduced. The model reaches its endpoint when the groundwater price declines to a level at which all available groundwater permits have been purchased by cities that find groundwater to be their lowest cost alternative. At this point the groundwater price is considered market clearing and thus a regional equilibrium condition has been reached. This conceptual path to the endpoint is illustrated in Fig. 2. As one descends down the figure, P_{GW} is incrementally lowered and the quantity of groundwater permits that are purchased increases, until the endpoint is reached.

Fig. 3 is a flow chart of the model. Note that the iterative nature of the model relies on embedded loops, which progress outward as the model proceeds. The model input consists of $[VQ_{\mathrm{add}}]$, average daily demand for each city; $[VQ_{\mathrm{max}}]$, maximum daily demand for each city $(=1.5\cdot[VQ_{\mathrm{add}}])$; [elev], elevation for each city; $[\mathrm{GW}_{\mathrm{permit}}]$, quantity of groundwater permits each city possesses; and [dist], distance from each city to every other city, as well as to the selected regional treatment plant site.

Initial model inputs include $[VQ_{\mathrm{add}}]$, $[VQ_{\mathrm{max}}]$, [dist], and [elev], as well as a vector indicating which cities will be considered as potential participants in each regional surface water system. At each successive groundwater price, the model invokes a program module labeled REGIONALIZE, which generates cost estimates for joining the regional surface water system, purchasing groundwater pumping capacity, or developing a tertiary alternative. The first step involves establishing the conveyance network, a process that is somewhat involved. First, a minimal spanning tree algorithm (Phillips and Garcia-Diaz 1981) is used to create the network with the shortest total length that connects all regional system participants to the treatment plant. This network is then represented as a 1,0 mapping matrix, [N]. Second, the capital and operating costs of the network (and individual segments) are estimated using Eqs. (3) and (4) with inputs of pipe diameter, flow, length, and slope. Then, conveyance costs are apportioned among the cities using the procedure described in Fig. 1. It should be noted that the use of the minimal spanning tree involves a heuristic, but generally accurate, assumption that the shortest total network length results in the lowest cost network configuration for each participant.

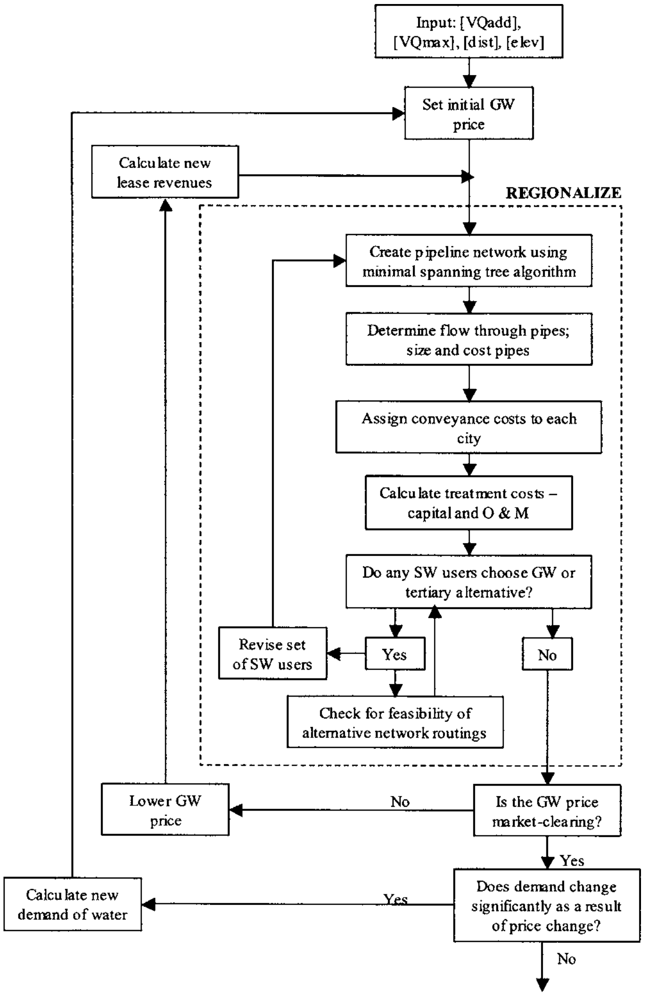

Fig. 3. Flow chart of model

Mapping of the surface water conveyance network and the resulting cost estimates allow Eq. (9) to become fully specified, and the model assigns the least expensive supply alternative to each city (i.e., $X_i=1$ or $Y_i=1$ or $Z_i=1$). If, at this point, one or more cities have exited from the initial set of regional surface water system users, then the costs of drawing water from the regional surface water system will increase for the remaining cities as capacity declines. Therefore, REGIONALIZE reiterates to evaluate the new costs of each city joining a surface water system and continues to do so until an unchanging set of surface water users emerges at the selected groundwater price. At this point, having fully specified an unchanging set of water supply decisions for all of the cities, REGIONALIZE terminates and sends output detailing the decisions, costs, and volumes of ground and surface water used to the next outermost loop in the model.

The model uses this output to compare the total quantity of groundwater permits being used with the capacity available, essentially testing whether the groundwater price (P_{GW}) is market clearing. If groundwater permits remain unused, P_{GW} is assumed

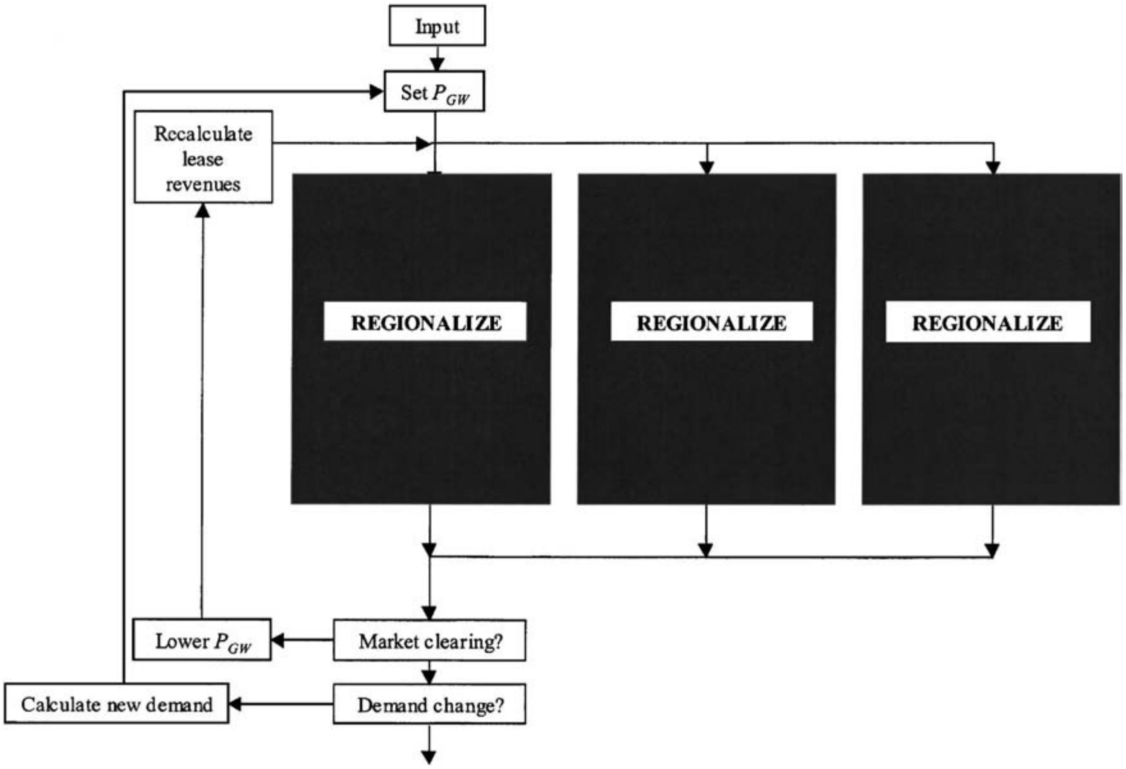

Fig. 4. Configuration of model that demonstrates consideration of multiple regional surface water treatment systems using REGIONALIZE

to be too high, therefore it is lowered by an incremental amount, usually \$0.01, and the model reiterates (after recalculating the groundwater sales revenues accruing to regional system participants). If, on the other hand, all the available groundwater permits have been sold, the market for groundwater permits has been cleared and an equilibrium condition exists; the model then moves to its outermost loop.

At this point each city has selected its lowest cost alternative, and the cost increase (compared to pre-cutback prices) has been calculated. As a result of this cost increase, there will be a commensurate decline in the quantity of water demanded relative to expected pre-cutback demands. Each city's consumption is therefore recalculated based on these price increases using Cobb-Douglas demand functions with an elasticity of −0.2. If the calculated price increase results in a significant change in the quantity demanded ($>2\%$), the model reiterates and finds a new market-clearing price using these new quantities. This process continues until the change in quantity demanded is below the 2% threshold. At this point the model run is complete.

In addition to considering surface water development and groundwater allocation simultaneously, the described approach is attractive in terms of its ability to consider multiple regional surface water treatment systems within a single groundwater market. The existence of REGIONALIZE as an independent module allows for parallel consideration of any number of multiple regional surface water systems within the groundwater pricing loop (Fig. 4). When considering multiple surface water systems, each city is assigned to a user-defined regional treatment node on the basis of location, another heuristic assumption, but one that seems reasonable for most applications.

As noted earlier, the use of the minimal spanning tree algorithm in the REGIONALIZE module represents a heuristic assumption in that the minimum length network does not necessarily always translate to the lowest cost. For example, a city with a large demand located at the end of a pipeline that connects with a series of smaller cities may find it less expensive to connect directly to the treatment plant. To combat this situation alternative network routings should be considered. This ancillary step is invoked each time a city, or group of cities, connected via the same pipe network chooses to drop out of the regional surface water system (see Fig. 3). If an alternative routing causes an exiting surface water user to again have lower surface water costs than the exiting user groundwater costs, then the exiting user rejoins the set of surface water users. Otherwise, the exiting user is not considered eligible for inclusion in the regional system during subsequent iterations. If a single city exits a regional surface water system, the only alternative routing considered is a direct connection between the exiting city and the treatment plant. If multiple cities simultaneously drop out of a surface water system, all the permutations of alternative pipeline routings that reconnect any subset of those cities to the regional plant are considered. If more than one configuration is capable of reconnecting a set of cities for less than it would cost them to purchase groundwater permits, the configuration that adds the greatest surface water capacity is selected. It is worth noting that, with respect to the study region considered here, none of the alternative routings provided a less expensive scenario than those developed using the minimal spanning tree algorithm. Theoretically, however, failure to consider such alternative routings could lead the model to terminate at a local optimum.

It is important to point out that this modeling approach involves reconciling a discrete number of demands with a discrete number of water supply alternatives. Thus, while an idealized regional equilibrium will be achieved when the fraction of groundwater capacity utilized is exactly equal to one, changes in groundwater price produce step changes in the volume of groundwater purchased. Equilibrium is therefore assumed to be reached when conditions are such that adding one more city to the group of groundwater users will result in an exceedance of available groundwater pumping capacity.

Study Region

The model is applied to communities in the Central Coastal Plain (CCP), a 15 county area in eastern North Carolina (Fig. 5). In the past, communities in the CCP have been almost entirely dependent on a group of high quality, high yield formations, known as the Cretaceous Aquifers, for their water supply. In recent years increased pumping rates have led to steeply declining water levels and saltwater intrusion. As a result, the state of North Carolina has declared the region a capacity use area (CUA), a designation that allows the state to regulate withdrawals from threatened water bodies. The aquifers of concern (Black Creek and Cape Fear) have been shown to have some degree of hydraulic communication, such that the state currently views them as a single entity for regulatory purposes (Winner and Lyke 1989). Cities within the CCPCUA face steep reductions in current pumping rates over a three-stage, 16 year period. Depending on location, each city pumping more than 0.1 MGD (there are 29 such cities in the region) will face cuts of either 10% or 25% during each of the three stages, or total reductions of 30% and 75%, respectively. As a result, affected cities will need to find alternative means to supply substantial portions of their water demand.

Two primary surface water sources, the Tar and Neuse rivers (Fig. 5), exist in the CCPCUA and are not regulated through the use of water rights. Some communities also have access to unregulated groundwater sources. Based on local considerations, and the results of some preliminary planning processes, three locations are identified as potential sites for a regional treatment facility: Greenville, Goldsboro, and a site just outside Kinston that would serve a newly formed consortium called the Neuse River Water and Sewer Authority (NRWASA).

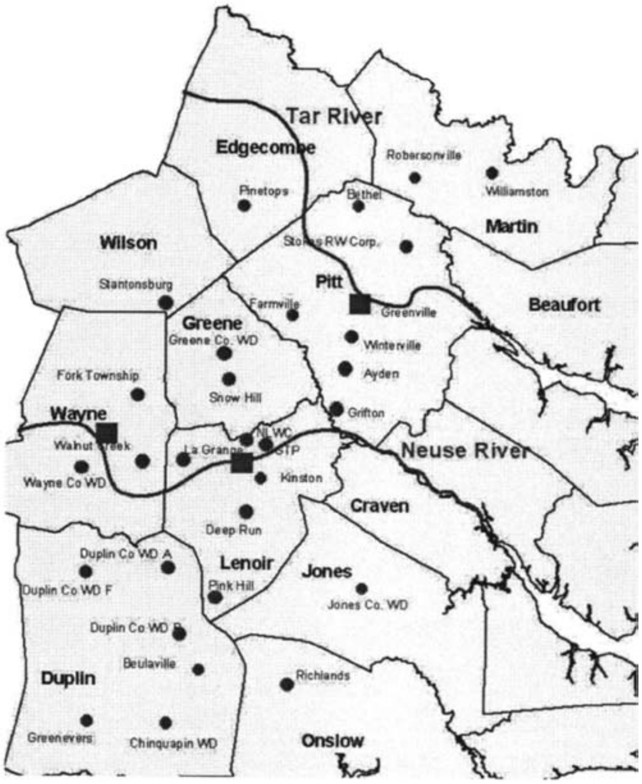

Fig. 5. Affected cities in the CCPCUA

The model simulates projected conditions in 2020, the year the mandated cutbacks will be fully enacted. Projected demands and groundwater pumping reductions for each city were obtained from the North Carolina Department of Environment and Natural Resources (NC DENR 2000). Spatial data was acquired using GIS databases available from the same source (NC DENR 2001). These data are used to create distance and elevation matrices ([dist] and [elev]) describing the relative location of each city in

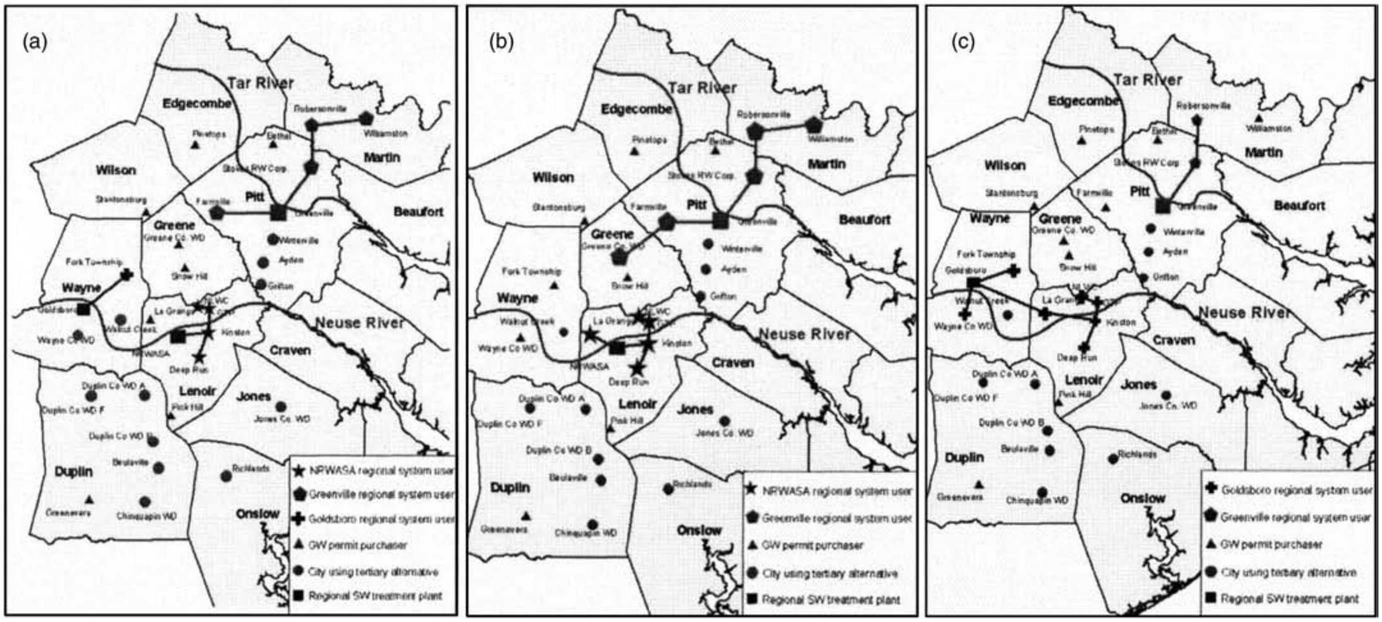

Fig. 6. Results of including groundwater permit trading: (a) illustrates results of Goldsboro-NRWASA-Greenville scenario; (b) illustrates results of NRWASA-Greenville scenario; and (c) illustrates results of Greenville-Goldsboro scenario

Table 1. Results of Modeling Regional Surface Water Systems, Groundwater Permit Trading, and Tertiary Alternatives

	Modeled regional SW configurations		
Result parameters	Goldsboro—NRWASA-Greenville	NRWASA-Greenville	Greenville—Goldsboro
Capital cost ($ MM)	$61.4	$66.1	$69.9
O&M cost ($ MM/ year)	$7.1	$7.1	$6.6
Present value cost[a] ($ MM)	$164.0	$169.2	$165.4
Regional SW users	9	10	9
GW purchasers	9	8	9
Tertiary users	11	11	11
GW purchased (MGD)	4.24	3.79	5.02

[a] 30 year life with a discount rate of 5.5%

the region. Distances do not reflect straight-line distances, but rather the distances between cities following state roads. This approach is designed to take advantage of the fact that the state is likely to grant free right-of-way. Such paths will also provide easier access during pipeline construction and maintenance.

Cost estimates for the tertiary water supply alternatives available to individual communities are derived from cost estimates generated as part of a regional water supply analysis (Golder and Associates 2002). These city specific supply projects form a “base case” in which each city acts independently to meet its water supply needs, without consideration for regional surface water systems or tradable groundwater permits. Within the CCPCUA, tertiary alternatives primarily consist of drilling wells into less productive, unregulated aquifers that exist near some cities.

Results

The estimated regional capital costs for the base case scenario are estimated at $107 million, and annual O&M costs for the region at $10 million. Assuming a 30 year lifespan and a discount rate of 5.5%, this results in a present value cost of $252.3 million for the region as a whole. Section I presents model results that consider regionalized surface water systems and regional groundwater permit trading. Section II describes the results from an analysis of various levels of regulatory groundwater reductions. In short, it asks how regional costs would vary if policymakers imposed less severe restrictions on withdrawals. Section III explores how regional costs would change if rules were put in place to limit the transfer of groundwater pumping permits between areas of greater and lesser aquifer drawdown.

Table 3. Effects of Various Groundwater Cutback Levels

	Cutback level		
Result parameters	25%[a]	50%[a]	75%[a]
Total capital cost ($ MM)	$41.9	$45.8	$61.4
O&M cost ($ MM)	$5.3	$5.9	$7.1
Present value cost ($ MM)	$119.1	$136.1	$164.0
Cities connecting to NRWASA	3	4	4
Cities connecting to Greenville	2	2	4
Cities connecting to Goldsboro	0	1	1
Qty. GW permits sold (MGD)	5.90	6.28	4.24

[a] Cutbacks in high damage areas. Cutbacks in low damage areas are 10%, 20%, and 30%, respectively.

Section I: Unrestricted Groundwater Permit Trading

Several combinations of the three potential regional treatment facility sites are considered: NRWASA and Greenville; Goldsboro and Greenville; and NRWASA, Greenville, and Goldsboro (Figs. 6(a–c), respectively). The scenario involving three regional systems results in the lowest cost (Table 1), with a total capital cost of $61.3 million and a total present value cost of $164.0 million, a savings of approximately 35% over the base case. Nine cities purchase 4.04 MGD worth of groundwater permits from nine surface water users at a (annualized) market clearing price of $\$1.84/\text{kgal}$, while 11 cities pursue tertiary alternatives. Both scenarios involving two regional surface water system sites are more expensive than the three system scenario, but each is significantly less expensive than the base case.

A sensitivity analysis is also presented to assess the impact of varying input parameters on results (Table 2). In general, model output does not change radically as input parameters are varied

Table 2. Sensitivity Analysis on Three Regional System Configuration (Greenville-NRWASA-Goldsboro)

Parameter	Variation	Regional capital cost ($MM)	Price of GW ($/kgal)	Average cost increase ($/kgal)	O&M cost ($MM/year)	Sold GW permits (MGD)
Capital	+20%	$69.68	$1.81	$1.02	$7.56	4.11
	0%	$61.36	$1.68	$0.96	$7.06	4.24
	−20%	$49.96	$1.55	$0.89	$7.08	4.26
O&M	+20%	$64.18	$2.16	$1.09	$8.76	3.25
	0%	$61.36	$1.68	$0.96	$7.06	4.24
	−20%	$59.77	$1.48	$0.83	$6.11	4.17
Demand elasticity	−0.1	$55.79	$2.06	$0.91	$6.95	3.53
	−0.2	$61.36	$1.68	$0.96	$7.06	4.24
	−0.3	$56.63	$1.84	$0.94	$6.50	3.31
Demand	+20%	$65.32	$1.53	$0.94	$8.92	5.26
	0%	$61.36	$1.68	$0.96	$7.06	4.24
	−20%	$52.84	$2.09	$0.96	$5.92	2.62
Discount rate	0.040	$61.44	$1.58	$0.90	$7.08	4.26
	0.055	$61.36	$1.68	$0.96	$7.06	4.24
	0.070	$58.74	$1.79	$1.01	$7.56	4.12

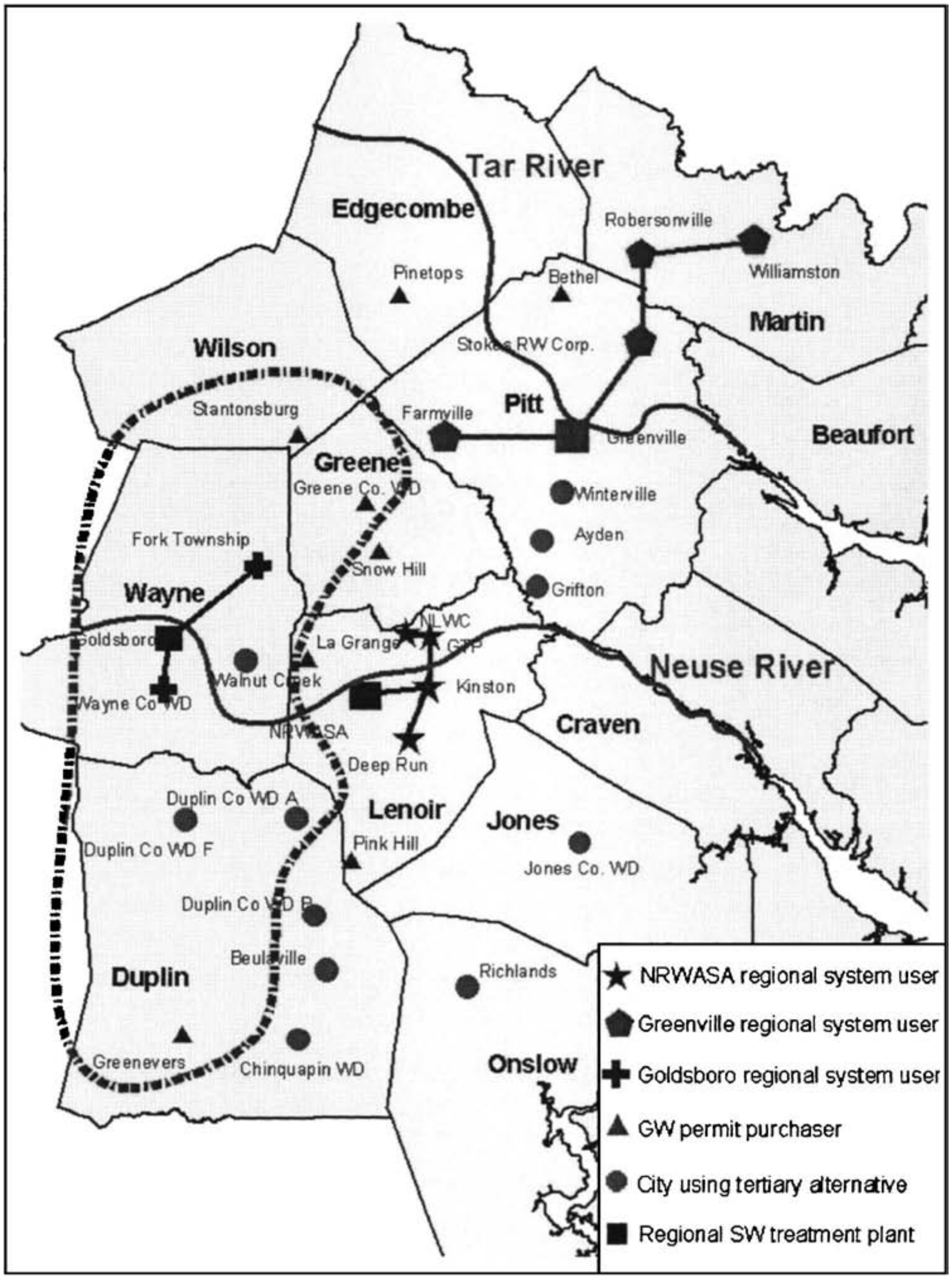

Fig. 7. Restricted groundwater permit trading

across reasonable ranges, implying that the solutions are relatively stable. The largest variations in regional costs come about with variation in the costs of treatment, both capital and O&M. Changing the estimated 2020 regional demand has a noticeable impact on results as well. In the "typical" run (the middle row of each parameter triplet), nine cities join regional surface water systems; however, increasing projected demand by 20% results in the addition of a tenth city to the regional surface water system. The changing number of surface water system participants accounts for the changing capital and O&M costs. Variations in both demand elasticity and discount rate have only a nominal impact on results.

Section II: Evaluating Regulatory Decisions

From a policy perspective, it may be useful to explore how regional costs vary with changes in the severity of the mandated pumping reductions. Evaluating a range of cutbacks in the CCPCUA could provide information on the marginal cost of reducing pumping capacity (Table 3) and might encourage decision makers to reconsider the size of the cutback. The estimated increase in present value cost incurred by increasing cutbacks from 50% to 75% is approximately $28 million (from $136.1 million to $164.0 million), substantially more than the $17 million increase in present value cost imposed by raising cutbacks from 25% to 50% ($119.1 million and $136.1 million, respectively).

Additionally, the model's ability to consider (or not consider) tertiary alternatives may be of interest to North Carolina regulators. In each model scenario, the only cities that choose tertiary alternatives are those that drill new wells into unregulated aquifers. The specific aquifer in question is the PeeDee, and its safe yield, as well as the amount of communication it may have with the regulated aquifers, is unknown. Modeling three regional surface water systems without the option of tertiary alternatives results in a present value cost of $172.8 million, an increase of $9 million over the scenario in which these are allowed. Such information could be useful to policymakers as they try to determine whether or not to take a precautionary approach to development of the PeeDee.

Section III. Restricted Groundwater Permit Transfers

In previous sections, it is assumed that withdrawals from any part of the regional aquifer system will have an equivalent impact on water levels, so groundwater permits are assumed to be completely transferable across the entire affected region. While this may be reasonable for formations that exhibit very high transmissivities (e.g., the fractured limestone of the Edwards Aquifer), it will not be a practical assumption for many regions. Concerns over localized areas of more severe aquifer drawdown (and the consequent effects of aquifer dewatering and saltwater intrusion) may therefore lead regulators to impose rules limiting the transfer of pumping capacity from less affected locations to those in danger of drawing water levels down to more damaging depths. The model can be adapted to these situations by separating groups in areas of higher damage from those in areas of lower damage. The model is then operated once for each set of cities. For example, in the CCPCUA, the two levels of mandated cutbacks (30% and 75%) differentiate the cities overlying the western part of the region, where drawdown has been limited, from the eastern cities, which are experiencing a more rapid decline in water levels. (See Fig. 7. Lesser damage occurs in the outlined area.) Here, the model is operated using just one REGIONALIZE module for the surface water system originating in Goldsboro. A separate model run is made for the cities overlying areas of greater drawdown, in this case incorporating two REGIONALIZE modules representing both Greenville and NRWASA. Regional capital costs for this scenario are $70.4 million, O&M costs are $8.3 million per year, with present value costs of $191.0 million. This represents a $26 million increase in present value costs over that estimated for the three-system scenario in which no transfer limits are imposed ($164.0 million). Preventing the importation of groundwater permits into the western region of the CCPCUA results in higher groundwater permit prices within that region. The increased permit revenues are high enough that the Wayne County Water District finds it more advantageous to join the Goldsboro regional surface water system and sell its groundwater permits than to continue to pursue a tertiary alternative.

Conclusions

The equilibrium approach developed in this work can be an effective tool for exploring the potential advantages of using regionalized surface water treatment and tradable groundwater permits in the pursuit of sustainable groundwater management strategies. The model's recognition of the interdependencies between individual decisions and their collective impact on costs, as well as the assumption that cities act as individuals, may provide a more representative means of modeling many regional scenarios than traditional linear programming techniques. The approach used allows for some flexibility in exploring various policy options related to alternative cutback scenarios and localized pumping restrictions in areas of severe aquifer damage. Additionally, the input requirements and modular structure are general enough that the model can consider numerous combinations of regional surface water systems as well as be applied to other study regions. Beyond the methodology itself, the combined strategy of regionalized surface water and tradable groundwater permits has the potential to yield considerable savings to regions that seek to reduce groundwater withdrawals to sustainable levels, particularly by enabling small cities to benefit from economies of scale arising out of the regional surface water systems. In the case of the CCPCUA, results suggest a potential savings of 35%, in present value cost terms, relative to a base case scenario in which all communities act independently.

Acknowledgments

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Notation

The following symbols are used in this paper:

$\mathrm{Cost}_{\mathrm{GW},i}$ = unit cost increase at tap when city i purchases groundwater permits ($/kL);
Cost_i = minimum average unit cost increase at the tap for city i to replace lost groundwater capacity ($/kL);
$\mathrm{Cost}_{\mathrm{SW},i}$ = unit cost increase at tap when city i joins regional surface water system ($/kL);
$\mathrm{Cost}_{\mathrm{tert},i}$ = unit cost increase at tap when city i pursues tertiary alternative ($/kL);
C = Hazen-Williams coefficient;
$C_{\mathrm{cap}}^{\mathrm{pipe}}$ = pipeline capital costs ($/km);
$C_{\mathrm{O\&M}}^{\mathrm{pipe}}$ = pipeline O&M costs ($/kL/km);
$C_{\mathrm{cap}}^{\mathrm{plant}}$ = treatment plant capital costs ($);
$C_{\mathrm{O\&M}}^{\mathrm{plant}}$ = annual treatment plant O&M costs ($/year);
$C_{\mathrm{GW}}^{\mathrm{O\&M}}$ = unit costs of pumping and treating groundwater ($/kL);
$C_{\mathrm{tert},i}$ = unit costs of tertiary alternative for city i ($/kL);
D = diameter of pipe (mm);
E = pump efficiency;
$\mathrm{GW}_{\mathrm{revenue},i}$ = revenue city i obtains from sale of its groundwater permits in average unit cost at tap terms ($/kgal);
i = index describing city considered in Eq. (5);
j = index describing all cities considered within model ($j=1,2,\ldots N$);
P = price of electricity ($/kW·hr);
P_{GW} = price of groundwater ($/kgal);
Q_{capacity} = capacity of treatment plant (MGD);
$Q_{\mathrm{cap},j}$ = maximum daily demand of city j (MGD);
Q_j = average daily demand of city j ($=2/3\ Q_{\mathrm{cap},j}$) (MGD);
$Q_{\mathrm{permit},j}$ = permitted daily groundwater pumping capacity of city j (MGD);
Q_{produced} = average daily production rate of treatment plant (MGD);
S_f = frictional head loss (ft);
S_l = slope head loss (ft);
X_i = 1 if city i chooses regional surface water, 0 otherwise. $X_i+Y_i+Z_i=1$;

Y_i = 1 if city i chooses to purchase groundwater permits, 0 otherwise;
Z_i = 1 if city i chooses to pursue tertiary alternative, 0 otherwise;
α_1, α_2 = constants ($/kgal); and
β_1, β_2 = constants.

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