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ORIGINAL ARTICLE

A dynamic programming model for optimal planning of aquifer storage and recovery facility operations

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Abstract Aquifer storage recovery (ASR) is an innovative technology with the potential to augment dwindling water resources in regions experiencing rapid growth and development. Planning and design of ASR systems requires quantifying how much water should be stored and appropriate times for storage and withdrawals within a planning period. A monthly scale planning model has been developed in this study to derive optimal (least cost) long-term policies for operating ASR systems and is solved using a recursive deterministic dynamic programming approach. The outputs of the model include annual costs of operation, the amount of water to be imported each month as well as the schedule for storage and extraction. A case study modeled after a proposed ASR system for Mustang Island and Padre Island service areas of the city of Corpus Christi is used to illustrate the utility of the developed model. The results indicate that for the assumed baseline demands, the ASR system is to be kept operational for a period of 4 months starting from May through August. Model sensitivity analysis indicated that increased seasonal shortages can be met using ASR with little additional costs. For the assumed cost structure, a 16% shortage increased the costs by 1.6%. However, the operation time of ASR increased from 4 to 8 months. The developed dynamic programming model is a useful tool to assess the feasibility of evaluating the use of ASR systems during regional-scale water resources planning endeavors.

Keywords ASR · Aquifer recharge · Optimization · Coastal aquifers · Sustainability · Texas · USA

Introduction

Rainfall in semi-arid and arid regions tends to be erratic and characterized by short-duration, high intensity storms. In addition, the majority of the annual rainfall often occurs in few winter rainfall events where the demands for water are low. Therefore, sustainable management of water resources requires regulation of flows such that the relatively high supplies during the winter months are stored to meet the high demands that occur during parched summer months. Conventionally, surplus water is stored in above-ground dams and reservoirs. However, construction of new dams and reservoirs is becoming exceedingly difficult due to a variety of reasons including associated environmental costs, lack of suitable locations, rising land costs, deterioration of water quality during storage and diminished social acceptance. Also, in semi-arid and arid regions, evaporative losses can be significant rendering above-ground storage to be inefficient. As such, aquifers are increasingly being viewed as viable water storage structures and are increasingly being used to store water (Pyne 1994; Sheng 2005).

Two types of approaches are currently used to recharge aquifer resources. Basin recharge systems employ infiltration trenches where water is collected and allowed to percolate downward into the aquifer. Sets of extraction wells are placed in the vicinity of the recharge basin to extract recharged water (Bouwer et al. 1999). These systems are typically used to recharge shallow unconfined formations (Hantush 1967; Rai

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et al. 2001). Basin recharge systems are particularly beneficial to recharge aquifers with wastewater, as the underlying vadose zone assists in the immobilization and removal of pollutants. These systems are therefore referred to as the soil-aquifer treatment (SAT) systems (Bouwer et al. 1999). These systems in general tend to be land intensive and require suitable soils. As such they may not be feasible in densely developed areas and in small communities with little land holdings. Furthermore, these systems are not suited to recharge deeper semi-confined and confined aquifer formations.

Aquifers can also be recharged via direct injection and this approach can be used in unconfined, semi-confined and confined formations. The recharge and extraction can be accomplished using separate injection and extraction wells or using a dual-purpose aquifer storage and recovery (ASR) well. The use of dual-purpose wells leads to cost-effective solutions as the number of wells required for storage and recovery is reduced. The availability of a pump at the injection location is also beneficial, as the well can be quickly redeveloped in case it gets plugged during injection operations (Pyne 1994).

ASR technology is particularly suited when there is not sufficient land area or suitable soils for carrying out basin recharge. Unlike SAT systems, the water used in ASR recharge must be of high quality to prevent contamination of the aquifer as well as to avoid chemical and biological fouling of the well. In most instances, the recharge water has undergone tertiary treatment (Sheng 2005) or is treated to potable water standards prior to injection (Pyne 1994). As many water supply systems seldom operate at their design capabilities, the treatment of additional water during winter months may lead to economies of scale and steady-state operating conditions. The water supply costs may not be significantly higher if the water does not undergo sufficient deterioration in storage and is extracted out in a reasonable period of time.

In many barrier island communities along the coastal United States, water is supplied from nearby inland cities via pipelines. The demand for water tends to be low during the winter months, but increases significantly during the summer months (on the island and the inland city). This shift places a significant stress on water resource management and reduces water pressure in the pipelines, especially during the peak demand hours (Pyne and Howard 2004). Given the lack of sufficient land area and adequate alternative water supplies on these barrier islands, additional treated water can be obtained from the inland city during winter months (low demand months), stored in the island aquifer and extracted in the summer months (high demand months) to provide water at sufficient pressures. Not surprisingly ASR systems have been implemented in many coastal communities in FL, NJ and VA (Pyne 1994) and are being contemplated to meet the needs of Padre Island and Mustang Island—two barrier islands off the city of Corpus Christi in South Texas.

A variety of models have been developed to simulate recharge processes in infiltration basins of varying geometry (Hantush 1967; Marino 1974; Rai et al. 2001). In addition, system analysis techniques such as non-linear and dynamic programming methods have been utilized to guide optimal operations of SAT systems (Mushtaq et al. 1994; Tang and Mays 1998; Eusuff and Lansey 2004). While detailed specifications pertaining to the development of a comprehensive ASR program has been described (Pyne 1994), a systems-based model to characterize optimal operation of an ASR system has not been presented in literature. Such a model would quantify how much water to store (or extract) in any given period over a planning horizon (consisting of several periods). For example, in water resources planning endeavors, the model could be used to estimate how much water to store (or extract) each month (or quarter) of a particular year. Sensitivity analysis can be performed with the model to obtain preliminary storage volume requirements necessary to meet supply and demands and thus guide ASR design activities. The goal of this study was therefore to develop a design-oriented model for optimal operation of ASR systems. As the operation is a multi-stage system—the dynamic programming technique is employed for model development.

Mathematical formulation

Conceptual model

The typical functioning of an ASR system is depicted in Fig. 1. Water from an external source is used to meet the water supply needs of a service area. When the demand for the water is low any surplus quantities of water available from the external source can be diverted into an ASR well. Consequently, when the demand is high, the water stored in the ASR well is extracted to meet the high demands. While the concept of ASR is fairly simple, obtaining quantitative estimates of how much to store and when to store and extract, so that the costs of the water supply are kept to a minimum requires careful planning and analysis. From a strategic standpoint, the water supply corporation must analyze annual supply and demands and

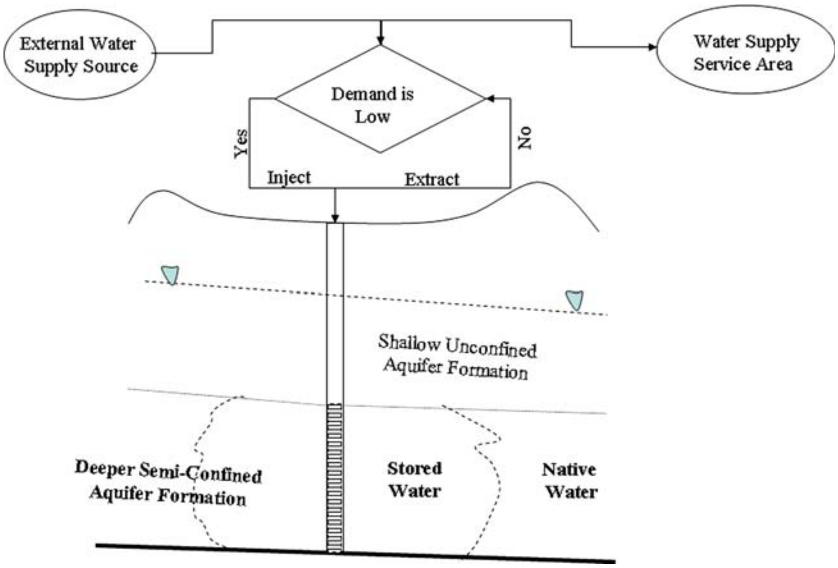

Fig. 1 A schematic depicting the operation of an aquifer storage and recovery (ASR) system

identify how much water must be stored and extracted on a monthly or quarterly basis so that the water supply needs are met at minimum costs. The information generated from strategic planning activities could then form the basis for tactical operations of managing water supply and demands on weekly, daily and diurnal time-scales.

This study concerns itself with the strategic operations of ASR facilities. Therefore, the planning horizon for strategic planning is assumed to be one year consisting of 12 monthly time-periods, as this scale is suited for evaluating the feasibility of this technology within the rubric of regional water resources planning. It should, however, be noted that the mathematical approaches adopted here can be easily extended to shorter (weekly and diurnal) time-scales when appropriate supply and demand data are available.

The study assumes that the local water supply corporation uses a water supply source that is external to the aquifer, for example, treated surface water, to meet the demands of its service area. The available supply exceeds demand during certain periods but owing to limited resources and/or competing demands, the water source cannot sufficiently meet the service area demands at other times. Clearly, surplus water needs to be acquired when available and used to meet the shortages at other times. However, the water supply corporation has limited capacity available in the aquifer to store surplus water. In addition, the stored water may undergo water quality deterioration and requires periodic monitoring and some in situ treatment. Also, hydraulic controls may have to be installed to keep the stored water ‘‘bubble’’ from drifting away. Thus, costs are incurred by the water supply corporation to store the water in the aquifer. These costs are collectively referred to as ‘‘holding costs’’ in this study and are assumed to be proportional to that the volume stored in the aquifer. The assumption of linear holding costs is reasonable for preliminary analysis, as greater the amount of water stored in the aquifer the higher will be the hydraulic control, monitoring and treatment costs and also because detailed cost data are not readily available to develop more comprehensive cost curves. The cost of procuring water from the external source is assumed to incur certain fixed costs (i.e., such as administrative costs) as well as certain variable costs such as for water treatment that are computed on a unit quantity of water (e.g., \$/1 m^3 or \$/1,000 l). The total cost (i.e., fixed cost + variable cost) is equal to zero when no water is produced from the external source. These costs are collectively referred to as ‘‘production costs’’ in this paper.

Once the water supply corporation has built some storage reserves, it needs to decide how much water should be obtained from external source and how much should be extracted from the storage to meet the demands during any time period. From a myopic standpoint, it makes sense to use up the stored water as it provides least cost water within any time period as most of the costs for the stored water have been paid in the previous periods. However, such short-sighted actions could be detrimental to meeting demands in the future. Hence, the decision as to how much water to extract from the storage must not hinge on minimizing costs during the current period alone but must be based on minimizing costs over the entire planning horizon to make sure all demands are met in an optimal manner.

Dynamic programming: background

The dynamic programming approach was developed by Bellman (1957) to deal with multi-stage decision-making processes. It differs from other mathematical programming approaches like linear programming in that the model consists of a set of equations that describe a sequential decision making process. Dynamic programming approach has been extensively used in water resources planning and management, especially for deriving policies for operating dams and reservoirs. Yakowitz (1982) provides a comprehensive introduction to this approach and discusses its utility in the field of water resources. Briefly, dynamic programming models are best suited for problems that can be divided into several stages with a decision required at each stage. In this application, the stage is the time-period (month) of interest. Each stage is characterized by a set of associated states. The states describe the information necessary to make an optimal decision. In the context of this ASR application, the state describes the storage in the ASR system at the beginning of a time-period (stage). It is not important to know how the ASR system arrived at a particular stage, the future decisions only depend upon the fact that the ASR system is at a given stage at a given period of time. The decision chosen at any stage indicates how the system moves from a given state to another. For example, if the ASR system had ~37,854 m^3 of water (stage 1) at the beginning of the month of March, the decision to extract 7,570.8 m^3 during the month of March would move the ASR system to another state at the beginning of April, one having ~30,279.2 m^3 of water (stage 2).

The principle of optimality states that given a current state, the optimal decisions for each of the remaining states must on depend on previously reached states or previously chosen decisions (Winston 1994). Assume that the least cost (call it $C_{\min}$) to meet the demands when the ASR is at stage i_0 at time zero and at i_T at some ending time T requires the state to be i_e at some intermediate time e. Then the cost incurred in going from state i_e to i_T must be the least cost to go from stage e to stage T. If this were not the case, one could move from stage zero to stage T at a cost less than $C_{\min}$ by simply appending the cost involved in moving from stage zero to stage e with the new minimum costs incurred while moving from stage e to stage T. Using the principle of optimality a recursive relationship can be set up to find optimal solutions. If the states for the problem have been classified into one of T stages, then there exists a recursion relationship that relates the cost (or reward) earned during stage $t, t+1, \ldots, T$ from stages $t+1, t+2, \ldots, T$. Mathematically, the recursion is stated as:

$$f_t(i) = \min_j \{C_{i,j} + f_{t+1}(j)\} \tag{1}$$

where $f_t(i)$ is the cost (or reward) associated with state i at a given stage t. $C_{i,j}$ is the costs associated with the decisions j made while at state i during time (stage) t and $f_{t+1}(j)$ is the cost (or reward) associated at stage $t+1$ while at state j during that period. Thus, if the state of the system at the final stage is known, Eq 1 can be used to work backward to identify states at times $t, t-1, \ldots, 1$. While dynamic programming models are often set up as backward recursions, it is also possible in some cases to work forward as well. While dynamic programming models yield more efficient solutions than plain enumeration, they become unwieldy when there are multiple states and multiple stages associated with multiple variables. This aspect is often referred to as the "curse of dimensionality" (Yakowitz 1982). Dynamic programming models do not place mathematical restrictions on the nature of cost functions employed. In other words, the cost functions can be continuous, discontinuous, convex, non-convex, nonlinear or even in the form of tables. However, general purpose computer programs for solving dynamic optimization problems are not available. In some instances, dynamic optimization problems have been set up and solved in spreadsheet environments without resorting to programming (Parlar 1989). However, for problems of moderate to high complexity, such as this application, developing appropriate computer programs is prudent. As such, the illustrative case-study described below was coded using visual basic for applications (VBA) programming language available in MS-EXCEL®.

Illustrative case-study

Problem description and data compilation

Padre Island and Mustang Island are two barrier islands off the city of Corpus Christi, TX and connected to mainland via a bridge. These island communities are currently served water via an existing 0.6 m underground pipeline crossing. The current average annual demand on Padre and Mustang Islands is estimated to be 9,000 m^3/day (9 Ml/day) based on 2000–2002 records (Pyne and Howard 2004). The area is undergoing substantial growth and the water demands are projected to be at about three times the current values in the next few decades. Even under existing conditions, the conveyance capacity of the system is limited to about 20,000 m^3/day (20 Ml/day) due to low system pressures on the mainland (Pyne and Howard 2004). Urbanization and water demands on the mainland Corpus Christi is going to further reduce the conveyance capacity of the existing system. The city of Corpus Christi is currently pursuing a comprehensive plan to meet the current and future demands of these barrier islands. A variety of options including—construction of another pipeline, brackish groundwater desalination and aquifer storage recovery systems are currently being contemplated (Turner Collie and Braden 2004). An 8,000 m^3/day (8 Ml/day) capacity ASR is one of the proposed demonstration facilities currently being evaluated as part of this process (Pyne and Howard 2004).

As extensive design data on the proposed ASR system were not available, certain assumptions were made in this illustrative study based on hydrogeology and other geographic constraints. These assumptions introduce conservatism necessary during future planning endeavors.

Being a rapidly growing barrier island system the area available for ASR was assumed to be an issue and the ASR system was assumed to have a radius of influence of approximately 50 m. Assuming a reported 65% efficiency (Pyne and Howard 2004), the average thickness of the underlying Gulf Coast aquifer to be equal to roughly 750 m, on the island (Baker 1979) and a porosity of 0.3, the maximum storage in the ASR system was estimated to be 3×10^5 m^3 (300 Ml). Thus, the system was assumed to be capable of supplying an average of 10,000 m^3/day (10 Ml/day) for a period of 1 month at its full capacity.

The average demand during the individual months is expressed as a function of the annual average demand. A relationship between the monthly demands and the average annual demand was developed using estimates from other comparable systems (CH2M HILL 1988) and is depicted in Fig. 2. Above average water demands are to be expected during the summer months of April–September, with the peak demands during the months of July and August. The average demand is assumed to be 12,000 m^3/day (12 Ml/day) and is higher than the current estimates of 9,000 m^3/day (9 Ml/day) for the islands (Pyne and Howard 2004) to represent a future planning scenario. The existing pipeline is assumed to convey on average 12,500 m^3/day (12.5 Ml/day) of water from the mainland to the island (or an average of 375,000 m^3/month or 375 Ml/month). The supply and demand schedule plotted in Fig. 3 indicates that surplus supply is available during the low demand (winter) months—October to March. Supply deficits arise during the peak summer months of July and August and the supply just equals the demand during the remaining summer months. Clearly, surplus water available during the winter months can be stored to meet the deficits of the summer months. The dynamic optimization model helps identify the optimal way of eliminating the deficit.

The cost of obtaining water from the pipeline was taken to be at ~$ 0.37 per m^3 ($ 0.37/1,000 l) based on available pricing estimates. The holding costs were assumed to be $0.018 per m^3 ($0.018/1,000 l) based on estimated infrastructure and operation and maintenance costs (Council 2004). Discrete dynamic programming approach requires the parameter space to be divided into several intervals (Winston 1994). The water obtained via pipeline and stored in the ASR system was divided into 75,000 m^3 (75 Ml) intervals for mathematical tractability and ease of interpretation of results. Therefore, the water stored in ASR system could be in one of the five states (0–4). Similarly, the maximum water that could be brought in via pipeline was equal to six units of 75,000 m^3 (75 Ml).

Results: identification of optimal costs and monthly production targets

The cost schedule corresponding to different beginning storage levels and months is one of the outputs obtained from the model and is presented in Table 1. As the beginning storage is assumed to be zero, the results indicate that the optimal annual costs for meeting the demands is close to $1.6 million under assumed conditions. Clearly, these costs go down if the ASR system starts with some initial storage and if it operated for only a few months of the year. The dynamic programming results (Table 1) indicate the costs associated under these conditions and as such are well suited for water resources planning.

The amount of water to be brought in each month from the mainland via the pipeline (production targets) at varying levels of beginning inventory is another model output and is presented in Table 2. Thus, the dynamic programming model output is not limited to specific starting conditions but is a complete enumeration of the amount of water to be imported from the mainland as well as the production costs for varying levels of initial storage in the ASR system. In addition to identifying how much water to import, the results from the dynamic optimization model are also useful to identify minimum levels of beginning storage that is required each month. For example, the ASR system should have at least 75,000 m^3 (75 Ml) at the end of

Fig. 2 A relationship between the monthly demands and the average annual demands

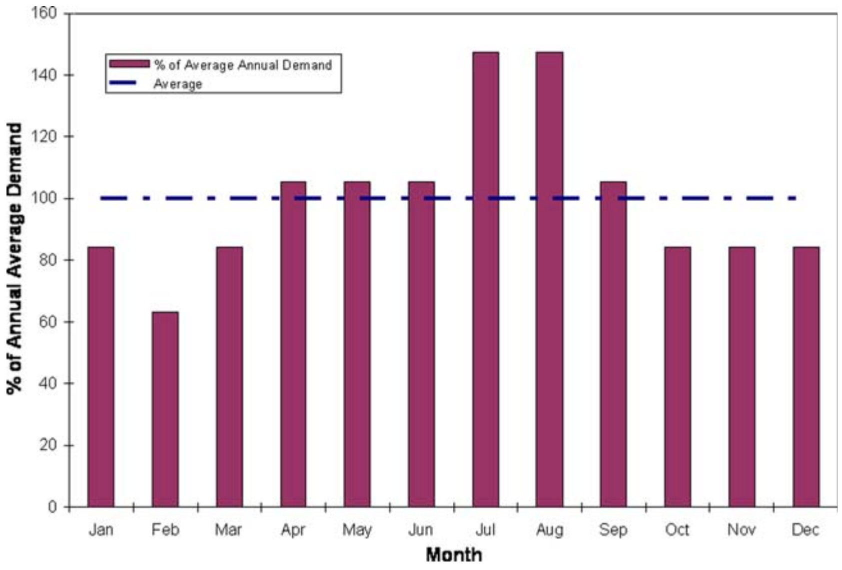

Fig. 3 Assumed monthly supply and demand schedules for the illustrative case study

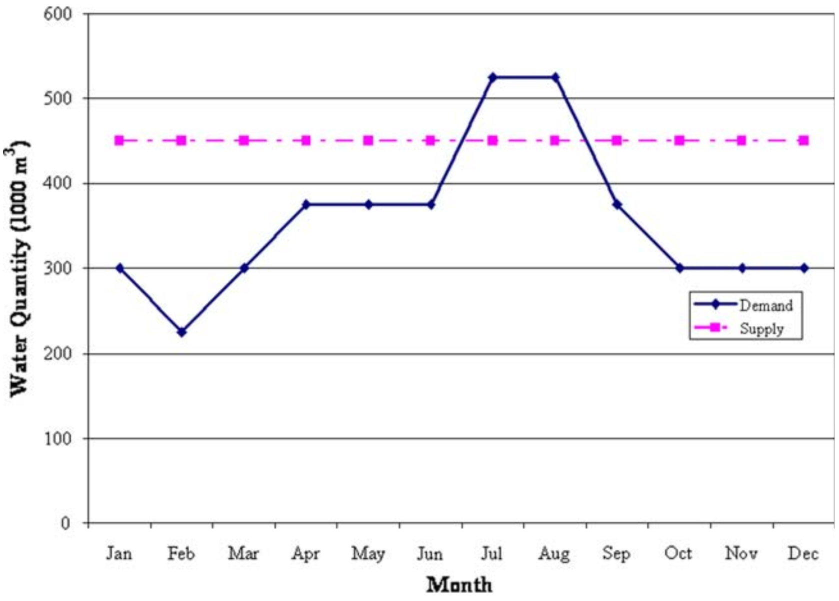

Table 1 Annual costs for operating the proposed ASR system, starting with different levels of storage and starting at different times

Storage	0 (0 m^3)	1 (75,000 m^3)	2 (150,000 m^3)	3 (225,000 m^3)	4 (300,000 m^3)
Jan	**$1,587,150**	$1,559,400	$1,531,650	$1,503,900	$1,476,150
Feb	$1,476,150	$1,448,400	$1,420,650	$1,392,900	$1,366,500
Mar	$1,392,900	$1,365,150	$1,337,400	$1,309,650	$1,281,900
Apr	$1,281,900	$1,254,150	$1,226,400	$1,198,650	$1,170,900
May	$1,143,150	$1,115,400	$1,087,650	$1,059,900	$1,032,150
Jun	NA	$975,300	$947,550	$919,800	$892,050
Jul	NA	NA	$806,100	$778,350	$750,600
Aug	NA	$638,250	$610,500	$582,750	$555,000
Sep	$471,750	$444,000	$416,250	$388,500	$360,750
Oct	$333,000	$305,250	$277,500	$249,750	$222,000
Nov	$222,000	$194,250	$166,500	$138,750	$111,000
Dec	$111,000	$83,250	$55,500	$27,750	$0

Note: The value in bold denotes optimal cost associated with the assumed zero initial storage condition

Table 2 Amount of water (in 1,000 m^3) to be imported from the mainland under different levels of inventory (in 1,000 m^3)

Inventory	0	75	150	225	300
Jan	**300**	225	150	75	0
Feb	**225**	150	75	0	0
Mar	**300**	225	150	75	0
Apr	**375**	300	225	150	75
May	**450**	375	300	225	150
Jun	NA	**450**	375	300	225
Jul	NA	NA	**450**	375	300
Aug	NA	**450**	375	300	225
Sep	**375**	300	225	150	75
Oct	**300**	225	150	75	0
Nov	**300**	225	150	75	0
Dec	**300**	225	150	75	0

Note: The values in bold indicate the optimal amounts corresponding to an initial storage of zero

May to meet the demands of June. Similarly, the ASR system should have at least 150,000 m^3 (150 Ml) (50% capacity) at the beginning of July to meet all the demands occurring during the month of July. There need not be water stored in the ASR system for the remaining months.

The optimal amount of water to be imported each month can be inferred from Table 2 in conjunction with the demand information presented in Fig. 2. These optimal import and storage quantities to meet the assumed demands are summarized in Fig. 4. Starting with a beginning storage of zero at the beginning of January, the optimal production (import) level prescribed by the model is equal to 300,000 m^3 (300 Ml), which is equal to the demand. Thus, the amount of imported water stored in the ASR system is equal to zero during the month of January. The amount of water to be imported during the month of February corresponding to the beginning storage equal to zero is equal to 225,000 m^3 (225 Ml) again equal to the demand for that month. Using similar logic, the amount of water to be imported for the months of March and April are exactly equal to the demands of these respective months and as such no water needs to be stored in the ASR system.

The storage in the ASR system at the beginning of the month of May is equal to zero. The model results indicate that the total water to be imported during the month of May is equal to 450,000 m^3 (450 Ml) while the demands during this month are specified to be 375,000 m^3 (375 Ml). Thus, a total of 75,000 m^3 (75 Ml) of treated water is stored in the ASR system during the month of May. The beginning storage level for the month of June is equal to 75,000 m^3 (75 Ml) and the optimal storage corresponding to this beginning storage level in Table 2 is equal to 450,000 m^3 (450 Ml). Therefore, a total of 525,000 m^3 (525 Ml) of water is available during the month of June to meet an anticipated demand of 375,000 m^3 (375 Ml) leaving 150,000 m^3 (150 Ml) of water in the ASR system. Starting with the beginning storage of 150,000 m^3 (150 Ml), and a corresponding import of 450,000 m^3 (450 Ml) during the month results in a surplus of 75,000 m^3 (75 Ml) to be stored in the ASR system once the total demands of 525,000 m^3 (525 Ml) for the month of July are completely met. The surplus 75,000 m^3 (75 Ml) stored during the month of July is combined with an optimal import of 450,000 m^3 (450 Ml) to meet the projected demand of 525,000 m^3

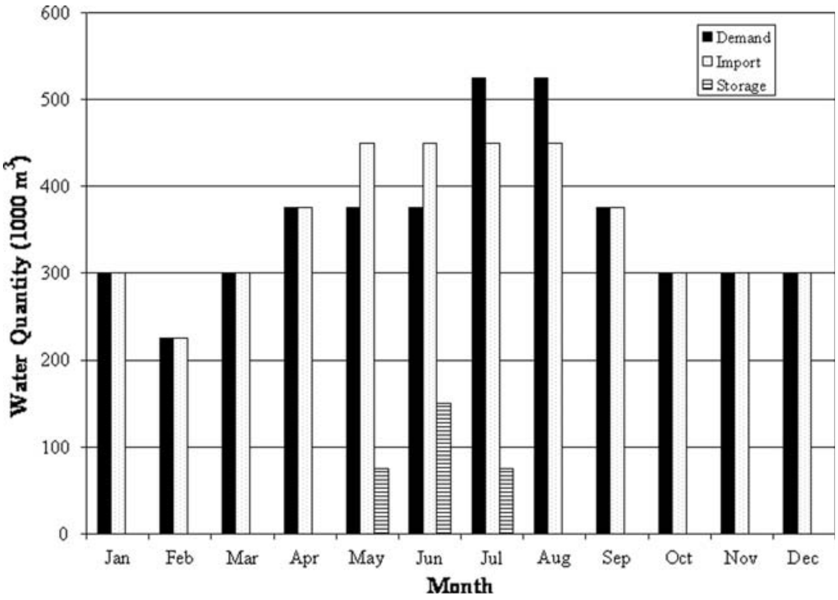

Fig. 4 Optimal monthly import and storage quantities required to meet the assumed demands

(525 Ml) for the month of August. The beginning storage level in the ASR system for the month of September is equal to zero and the expected demands for the remainder of the year is met by importing required quantities. Thus, for the given maximum level of water that can be imported via pipeline 450,000 m^3 or 15,000 m^3/day (450 Ml or 15 Ml/day), the ASR system is to be kept operational for a period of 4 months starting from May through August.

Sensitivity of ASR operations to changing external supplies

ASR systems are often used as a buffer against unreliable water supplies. As the population of the City of Corpus Christi increases, additional stresses will be exerted on water supplies to Padre Island and Mustang Island service areas. To assist with planning, the average monthly water supply from the pipeline was reduced from 15,000 to 12,500 m^3/day (15–12.5 Ml/day). Based on the assumed holding and production costs, this near 16% reduction in the supply only caused the associated costs to increase by about 1.6% (~\$1.59 to ~\$1.61 million) and all the demands could be met. Thus for the assumed cost structure, the ASR system could serve as a buffer against reductions in water available via pipeline due to projected growth in the mainland. The amount of water to be stored in the ASR system under different external supplies is schematically depicted in Table 3.

Table 3 ASR operations corresponding to two different maximum available imported water supply of 450,000 and 375,000 m^3/month

Month	Necessary supply		Demand	Surplus/ deficit		Water in storage	
	450	*375*		*450*	**375**	*450*	*375*
Jan	300	375	300	0	75	0	**75**
Feb	225	375	225	0	150	0	**225**
Mar	300	375	300	0	75	0	**300**
Apr	375	375	375	0	0	0	**300**
May	450	375	375	75	0	**75**	**300**
Jun	450	375	375	75	0	**150**	**300**
Jul	450	375	525	–75	–150	**75**	**150**
Aug	450	375	525	–75	–150	**0**	**0**
Sep	375	375	375	0	0	0	0
Oct	300	300	300	0	0	0	0
Nov	300	300	300	0	0	0	0
Dec	300	300	300	0	0	0	0
Costs	\$1.59	\$1.61					

Note: All supply, demand and storage values the units of 1,000 m^3 /month and the costs are in the units of \$100,000 per year. Values in italics correspond to available imported water supply. Values in bold correspond to months of ASR operation

As can be seen, a 16% reduction in external water supplies will cause the operation time of ASR system to change from 4 to 8 months (note that the stored water is extracted during the month of August). Further, the ASR system needs to be operated at its full capacity during the months of March through June. Other sensitivity runs not shown here also indicated that the demands on the Island cannot be met when the amount of imported water falls below 12,500 m^3/day (12.5 Ml/day).

Sensitivity of ASR operations to fluctuations in demands

The Padre and Mustang Islands are popular destinations for spring breakers and the city of Corpus Christi hopes to increase tourism on these islands. This increased tourism will in turn amplify the demands especially during the months of March and April. Hence, the optimal operation patterns under increased seasonal demands for these months were assessed as part of this study. The results of the study indicate that no storage is required as long as the demand for the month of March is less than or equal to the assumed baseline supply from the pipeline 450,000 m^3/day (i.e., 450 Ml/day). The ASR operations, corresponding to three different scenarios representing an increase of 22.22, 44.44 and 66.66% in the total demands during the months of March and April were assessed. These scenarios were labeled “scenario 1”, “scenario 2” and “scenario 3”, respectively. As seen from Fig. 5, no additional storage was required when the demand was raised by 22.22%. However, a total of 150,000 m^3 of additional storage was required when the demand was raised by 44.44% and a total of 375,000 m^3 of additional storage was required when the demand rose by 66.66%. As can also be seen from Fig. 5, the storage in February was significantly higher under scenario 3 (66.66% increase) when compared to scenario 2 (44.44% increase) depicting the nonlinear relationship of storage with demand.

Summary and conclusions

The primary goal of this study was to develop a monthly scale dynamic programming model for facilitating optimal operations of ASR systems. The model provides several outputs such as annual optimization costs under varying initial storage and demands; the optimal monthly import, storage and extraction sche-

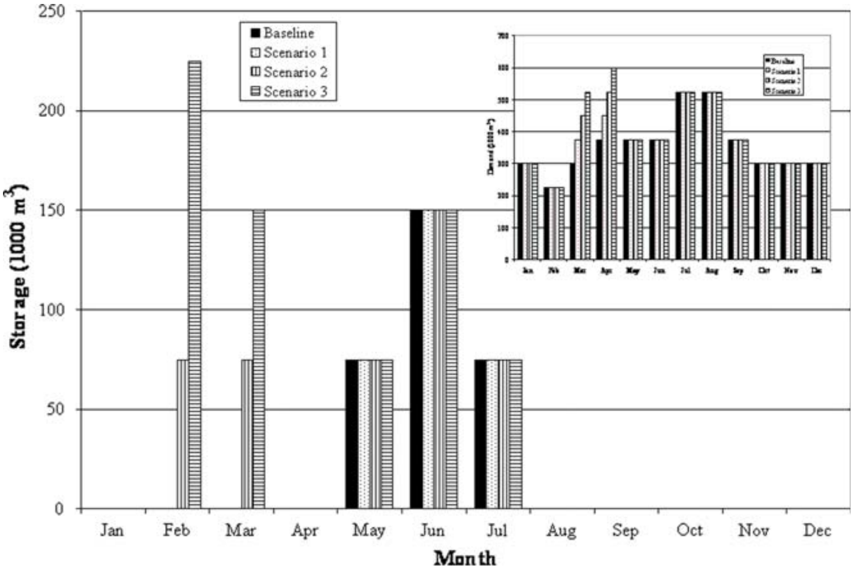

Fig. 5 Sensitivity of ASR operations to increasing demands during the months of March and April

dule that is of use in regional-scale water resources planning endeavors. The developed model was applied to study an ASR system modeled after a proposed facility that aims to augment water supplies for Mustang Island and Padre Island communities off the city of Corpus Christi. The results indicate that for the assumed baseline demands, the ASR system is to be kept operational for a period of 4 months starting from May through August Model sensitivity analysis indicated that a 16% reduction in imported water only increased the total costs of meeting the water supply needs by 1.6% based on assumed holding and production costs. However, the operation time of ASR increased from 4 to 8 months. Different water demand scenarios corresponding to increased activities during the months of March and April (spring break season) was also assessed. No additional storage was required when the total demand for the months of March and April was raised by 22.22%. However, a total of 150,000 m^3 of additional storage was required when the demand was raised by 44.44% and a total of 375,000 m^3 of additional storage was required when the demand rose by 66.66% indicating the nonlinear relationship of storage with demand. ASR systems can be useful to augment water supplies in fast-growing barrier island communities, with limited scope for expansion. The developed dynamic programming model is a useful tool to assess the feasibility of evaluating the use of ASR systems during regional-scale water resources planning endeavors.

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