AST/R-based Water Reuse as a Part of the Total Water Solution for Water-Stressed Regions: An Overview of Engineering Practice and Regulatory Prospective

Dr. Y. Jeffrey Yang, P.E., P.G.[1*], Dr. James A. Goodrich[1], Dr. Sylvana Y. Li[2], Roy C. Haught[1]

1. U.S. EPA, National Risk Management Research Laboratory, Water Supply and Water Resources Division, 26W Martin Luther King Dr., Cincinnati, Ohio 45268
2. U.S. Department of Agriculture, Foreign Agriculture Services, 1400 Independence Ave., Washington, DC 20250

ABSTRACT

Water supply and demand are increasingly unbalanced in many parts of the world. To address the imbalance, the total water solution methodology simultaneously considers regulatory, engineering, environmental and economic factors to optimize risk management solutions for an entire water system. As one component of this methodology, aquifer storage, treatment and recovery (AST/R) has the potential for large-scale applications in the U.S. and Middle East. However, the AST/R process is not fully understood particularly in the fate and transport of nutrients and residual contaminants passing through treatment (e.g., pesticides, endocrine disrupting compounds). Residual pathogen growth and viability in subsurface is also poorly understood. In a reverse engineering approach, groundwater quality and end-use health risk management objectives are first established leading to effluent treatment requirements for specific site conditions. This approach can offer improved risk management among uncertainties and alleviate public perceptions surrounding the AST/R practice. Further research, however, is needed to advance the concept.

INTRODUCTION

Approximately two-thirds of the world's population is exposed to water-borne disease each year and nearly 70% world's population lives in water stressed environments. Globally, agriculture – particularly irrigated agriculture, is responsible for 80-90% of water use. Other water demands include municipal and industrial use. Resulted water imbalance and shortage is a challenge in water resource management to meet the increased water demand; the latter is directly a result of improved living standards, higher water usage per capita, increased populations, growing economic activities, demographic changes, and other natural factors such as global climate change. Sustainability in conventional water resource management was questioned by Angelakis et al.[3] who evaluated the water demand status and described the needs for wastewater reuse as an unconventional resource in the Middle East, North Africa and other Mediterranean countries. In the United States, water and wastewater reuse has spread to 27 states for artificial aquifer recharge and treatment. Total wastewater reuse reached 6.4×10^{6} m^3/d in 2002 [35]. This fact has prompted U.S.EPA [35,36] to publish guidelines for this unconventional water resource practice. These developments were summarized in Miller [22] who articulated the need for an integrated wastewater reuse in order to systematically address the technological, regulatory and public perception difficulties. Qadir et al [25] further analyzed the water demand and supply imbalance in water scarce countries, mostly in the Middle East, and further related sustainable wastewater reuse to food securities. Such analysis and conclusions are echoed in a number of publications [3, 24, 16, 33, 18].

[*] Corresponding author, Tel., (513) 569-7655; Fax, (513) 569-7185; yang.jeff@epa.gov

Wastewater reuse through aquifer storage, treatment and recovery (AST/R) to supplement agricultural, municipal, and industrial water demands has been long practiced in the U.S. and the Middle East [35, 39, 31, 17]. While sharing similar physical attributes, the two regions differ in their approaches. In the U.S., AST/R-related policy, research and engineering practices have focused on addressing concerns over health effects and environmental impacts [35, 22, 5, 26]. Comparatively, the focus in Middle East centers on health effects, public perceptions and the economic benefits of irrigation sustainability and field crop yields [15, 16, 11, 24].

For both regions, we have observed that the competing AST/R regulatory, engineering and economic considerations can be analyzed systematically in the context of a total water solution. Through a reverse engineering approach, receiving groundwater quality and health risk management objectives can be first established for better defined treatment and monitoring objectives under specific site conditions. This proposed optimization methodology analyzes and prioritizes technical uncertainties, risk and public perception factors, and regulation compliances in AST/R planning, implementation and operations. Details of the approach and its reverse engineering techniques will be presented elsewhere. In this paper we will discuss the concept in the context of the AST/R applications in the U.S., Israel and Jordan.

AST/R: A TOTAL WATER SOLUTION COMPONENT

The total water solution components

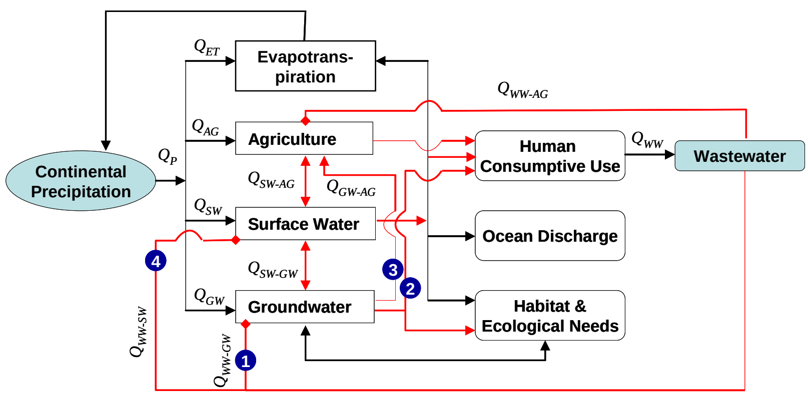

Figure 1 Conceptual schematic showing water distributions among major and secondary water process units. Also shown are possible flow vectors for wastewater generation and re-distribution in a water system. Wastewater reuse pathways are numbered for further analysis of beneficial and adverse impacts.

The concept of a total water solution systematically analyzes and identifies the principal components of a water cycle, which affect downstream environment and human activities (Fig.1). In the concept, precipitation that controls the water resource abundance and availability is partitioned into 4 primary water process units: evapotranspiration, net surface water storage, net groundwater storage, and net agriculture consumption in the order of decreasing magnitude. In evaluating the water system for a given area (or watershed) at a specific time, the process units are balanced in volumes $(V_p, V_{ET}, V_{AG}, V_{SW}, V_{GW})$, flow rates $(Q_p, Q_{ET}, Q_{AG}, Q_{SW}, Q_{GW})$, and water quality requirements. Water flow into each unit must be equal to outflow to the secondary processes including human consumption, habitat and ecological needs, and oceanic discharge, and satisfy specific water quality requirements by each secondary units (Fig.1). These general requirements provide the basis to use optimization techniques in water resources management. The optimized technical solution accounts for major water transfer and water quality interactions among the process units and offers the minimum negative economic, ecological and public health impacts. Mathematical framework and computational methodology will be presented elsewhere.

Figure 1 shows flow vectors and interactions between process units of a water system. Imbalance occurs as the flow rates and process unit volumes are mismatched, for which water redistribution (ΔQ_i) must occur for corrections. A new consideration proposed in this paper is the water quality requirements that can materially affect the water flow (Q_i) in a water system. Agricultural irrigation is a familiar example of water redistribution (Fig.1) as it consumes a significant amount of fresh water and converts carbon, water and nutrients into consumable hydrocarbon and protein products. Their long-distance transportation and international trades are mechanisms of fresh water redistribution in regional and global scales. In water-poor regions, irrigation agriculture competes directly with human consumption of potable water unless unconventional water resources such as treated wastewater or storm water are developed.

The total water solution concept is a basis for one to systematically analyze the water resource components, evaluate their interactions and develop optimal solutions for sustainable water resources development and agricultural production. It is similar to the concept of integrated water resource management [33, 2, 12]. However, the total water solution approach treats the water distribution and redistribution – both through human activities and natural processes – in the form of a unit process when management and engineering options are evaluated for optimization. It also considers wastewater as a component to mitigate supply deficiencies, which is often overlooked in conventional resource development. The approach has been considered, not explicitly, in general concept [24, 33], Texas [32], China [9], Europe [4], Israel [12], water-stressed gulf countries [2] and the Mediterranean region [13].

Engineering and management consideration and uncertainties in AST/R Applications

In a water balance optimization, the supplemental supply of treated wastewater effluent in an upstream unit must match the requirements in both flow rate and water qualities for downstream applications (Fig.1). This demand-driven reverse engineering approach applies to the AST/R operations (Fig.2) and is subject to the following optimization requirements:

$$Q_{WW-GW}(t,Y) = Q_{WW} - Q_{WW-SW}(t) - Q_{WW-AG}(t,Y,C,A,ET) - Q_{GW-AG}(t,Y,C,A) \quad (1)$$

$$C_{WW-SW} \equiv \left| \begin{array}{l} \overline{C} \\ C_{\max} \end{array} \right. \quad (2)$$

$$C_{WW-AG} \equiv C_{\min} \quad (3)$$

$$C_{WW-GW} \equiv \begin{cases} C_{GW-AG} + \Delta C_{ST} \equiv C_{GW}^{std} \\ C_{GW-AG} + \Delta C_{ST} + \Delta C_{GW} = C_{\min} \\ C_{GW-AG} + \Delta C_{ST} + \Delta C_{GW} \equiv C_{DW}^{std} \end{cases} \quad (4)$$

Eq.1 simply states that under optimal conditions, water flow or outflow into an AST/R aquifer $[Q_{WW-GW}(t,Y)]$ is a function of AST/R wastewater flow rate $[Q_{WW} - Q_{WW-SW}(t)]$, the seasonally and geographically varying agricultural water demand $[Q_{WW-AG}(t,Y,C,A,ET)]$, and irrigation use of reclaimed groundwater $[Q_{GW-AG}(t,Y,C,A,\psi)]$. The flow vectors are shown in

Figure 1. Variables t, Y, C, A, ET are time (season), geographic location, crop types, acreage and evapotranspiration, respectively.

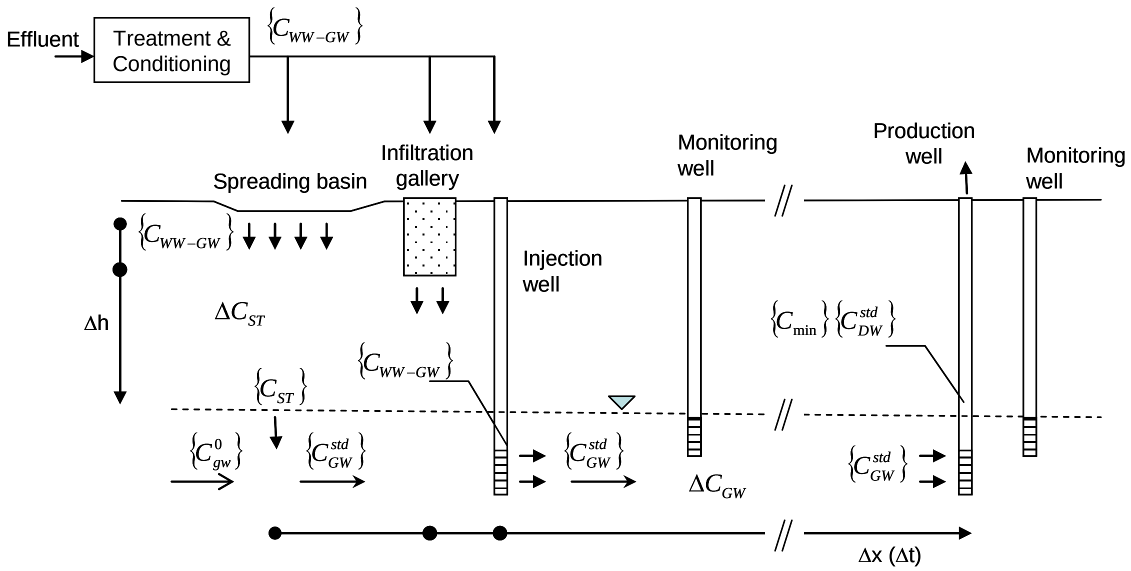

Figure 2 Process optimization schematic for AST/R design and operations. The end-use water quality requirements are first determined to define the requirement for effluent composition after treatment/conditioning, the soil treatment ΔC_{ST}, and change in groundwater ΔC_{GW}. Optimization is governed in Eq.1-4.

When AST/R is considered (Fig.2), the effluent water quality (C_{WW-GW}) is determined by the end use objectives and corresponding engineering designs: indirect potable water reuse, agricultural irrigation reuse, and aquifer recharge. In an optimalized engineering for best risk management, the 3 end use options are tailored to meet the drinking water standards (C_{DW}^{std}), agricultural irrigation requirements $(C_{\min})$, and the groundwater standards (C_{GW}^{std}), respectively. Wastewater effluent composition and treatment requirements are then configured to meet water quality requirements in Eqs.2-4 after water quality changes in soil treatment (ΔC_{ST}) and groundwater migration (ΔC_{GW}). In the U.S., discharge to surface water is governed by EPA's National Pollution Discharge Elimination System (NPDES) permits. Water quality of the treatment plant effluent (C_{WW-SW}) is required to comply with effluent concentration limits in monthly average $(\overline{C})$ and maximum $(C_{\max})$ values (Eq.2). For direct irrigation reuse, the effluent water quality $(C_{\min})$ is defined in considering types of field crops, long-term soil salinity and sodicity management, and pathogen dispersion. The reverse engineering attempts to find optimal process assemblies among C_{WW-GW}, ΔC_{ST}, ΔC_{GW} and engineering economics.

Research Needs for Standards and Better Process Control

Substantial knowledge gaps exist on the AST/R process and wastewater effluent migration in groundwater. This limitation can lead to negative public perceptions and questions in regulatory oversight [11, 38, 41]. Since wastewater reuse was planned in the beginning of the last century, a substantial amount of research has been conducted in laboratory soil column experiment studies [7, 19], field investigations at wastewater reuse sites [40, 27], and by computer modeling and simulation [42, 29]. These studies often produce inconclusive, if not contradictory results. For example, some studies suggest that most contaminants are removed in the upper 1-1.5 m soil layer [14, 40]. However, breakthroughs of toxic organic contaminants [7], organic matter [21], emerging contaminants [27], inorganic compounds [20], and pathogens [19, 6] have been observed in laboratory and field studies, which have been considered in the wastewater reuse guidelines of World Health Organization (WHO) [41]. The inconsistent findings are possibly the result of varying soil and groundwater conditions, organic carbon content and contaminant matrix in wastewater effluent, and aquifer recharge engineering and operations. These variables can affect contaminant adsorption, biological and abiotic degradation, transport in unsaturated and saturated soils, as well as aerobic conditions and other environmental conditions in the soil. To qualify these factors, several areas of research are warranted:

- Fate and transport of emerging and recalcitrant contaminants in AST/R operations. Scheytt et al. [27] described the mobility of pharmaceutical compounds in the soil at wastewater reuse sites, and Toze [34] listed these contaminants along with endocrine disrupting compounds and pathogens as a concern in reuse applications.
- Long-term changes in the receiving aquifers. Sheng [32] showed no substantial impact to the capacity and groundwater quality at the El Paso, Texas AST/R sites after 20 years of operation. However, alteration of aquifer geochemical properties was observed at the Cape Cod, MA aquifer of glacial deposits contaminated with partially treated effluent [10]. So are the AST/R impacts to the Central groundwater basin in the Los Angeles after 40 years of operation [28]. Apparently ΔC_{ST} and ΔC_{GW} in Eq.4 differ by location and operations, and their controlling factors have not been quantified.
- Minimum effluent composition requirements for different soil types under representative weather conditions. This is important for engineering control over survival and viability of virus, bacteria, and protozoa in vertical soil profiles.
- Aquifer types and groundwater composition can impact chemical and biological contaminant attenuations at an AST/R site [14]. The impact is a function of aquifer hydrogeology and AST/R operation characteristics, which demand for a thorough and systematic review and investigation.

TAILORING AST/R PRACTICE TO LOCAL CONDITIONS

In the U.S., more attention has been allocated to AST/R reliability and regulatory compliance in a regulation-driven environment. In the Middle East, engineering economics and practicality of an AST/R practice are emphasized. In this section, the U.S. practice is illustrated in the aspect of large-scale water resource management and the need for environmentally sound AST/R-based applications. The AST/R applications in Israel and Jordan are discussed in light of the reverse engineering and its potential to improve public opinions.

AST/R Applications and Potentials in US

The AST/R applications in the U.S. are closely related to the prevalence of water stress in the western states, Texas and Florida where wastewater reuse has been applied to compensate for irrigation and potable water imbalance. As of 2002, at least 27 states have water reclamation facilities and have enacted regulations over AST/R practices (Fig.3). Of $6.4\text{x}10^6$ m^3 water reuse in the U.S., Florida and California had $2.2\text{x}10^6$ m^3 and $2.0\text{x}10^6$ m^3, respectively [35].

The acceptance of AST/R practice reflects the overall water resource balance in the continental U.S. In the last 5 decades, precipitation (Q_p) is unevenly distributed with definable long-term changes. As shown in Figure 4, Oregon and Washington received the greatest average monthly precipitation as high as 5.5 in/month. This contrasts with much of the Great Plains states and California that received a monthly average <1.5 in. The precipitation increase is apparent in the U.S. and particularly in the eastern coastal states. The 2.5 in/month contour line shifted northward toward Wisconsin, and in the northwest the higher precipitation extended into northern California (Fig.4). The change accelerated in the 1980s and 1990s. The overall distribution pattern, however, is largely unchanged.

In Figure 1, consumptive water use for human activities is the variable with significant changes and material impact to water balance. This is a result of demographic changes that can be observed from the U.S. census data. The U.S. population size has increased since 1900 and the rate of increase has accelerated since the 1970s (Table 1). It is worthwhile to note that in 5 water-poor states (Nebraska, Arizona, Florida, Utah, and Nevada), the growth rate is the largest and above the national average in the last 3 decades; the growth rate in Nebraska will level off in the next 25 years (2006-2030). Like other Great Plains states, however, Nebraska has high fresh water usage per capita largely due to agriculture irrigation (Q_{AG} in Fig.1) and >50% fresh water is derived from groundwater aquifers (Table 1). As the long-term precipitation and evapotranspiration rate remained fairly constant, the population-induced imbalance would require the reuse of water and wastewater through aquifer recharge or AST/R for non-potable agricultural irrigation. This need and potential can be assessed using advanced numerical modeling techniques such as the neural network model described in Chen et al. [8]

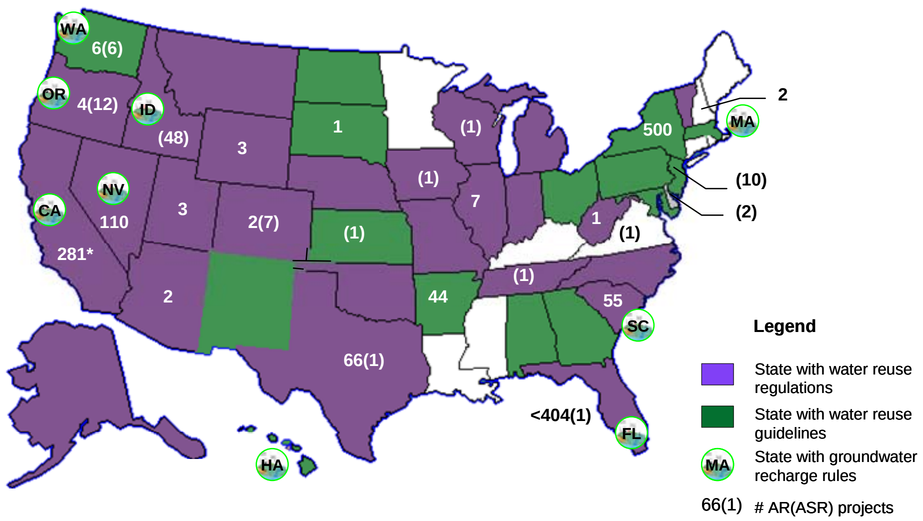

Figure 3 Map showing states with wastewater reuse regulations, guidance, aquifer recharge (AR), aquifer storage and recovery (ASR) projects. Data from U.S.EPA [35].

The existing aquifer recharge and AST/R projects are mostly located in the water-stressed Great Plains states (e.g., Nevada, Arizona, Idaho, Texas, etc.), Florida, and California (Fig.3). Their long-term sustainability depends on two considerations for which further studies are required in resource management and regulatory policy-making. First, groundwater in these states is a principal potable water source; the fraction is as much as 50% (Table 1). The EPA groundwater protection programs and safe drinking water regulations require that the AST/R process meet the water quality requirements. Compliance also depends on effluent quality and water quality changes $(\Delta C_{ST} + \Delta C_{GW})$ in the AST/R process. Therefore, the AST/R engineering must be tailored to site-specific conditions that control the fate and transport of inorganic metals, emerging contaminants, pesticides and herbicides, and pathogens. Second, agriculture irrigation is one of the major end applications in the water-stressed states. Salt accumulation in plant root zones and contaminant uptake in agriculture produce have demonstrated as a principal concern [30], for which further investigations are needed.

AST/R Application and Considerations in Middle East

The Middle East is similar to the water-stressed Great Plains states in climatologic and hydrologic conditions, but with more severe water imbalance due to higher evapotranspiration rates and less precipitation. Combined with the long-held negative public perception and varied sophistication of treatment technologies, the Middle East is an ideal case to illustrate the need for wastewater reuse and the role of reverse engineering for improved risk management. In Jordan, the 4×10^8 m^3/yr safe groundwater yield is far less than the national water demand of 1.33×10^9 m^3/yr in 2005 and the projected 1.45×10^9 m^3/yr in 2010. Groundwater over-pumping is widespread and has resulted in near 25-m water level decline for more than 500 wells in the Azrag basin [1]. Similar imbalance in the water budget is observed in Israel where wastewater reuse has been actively pursued as a part of

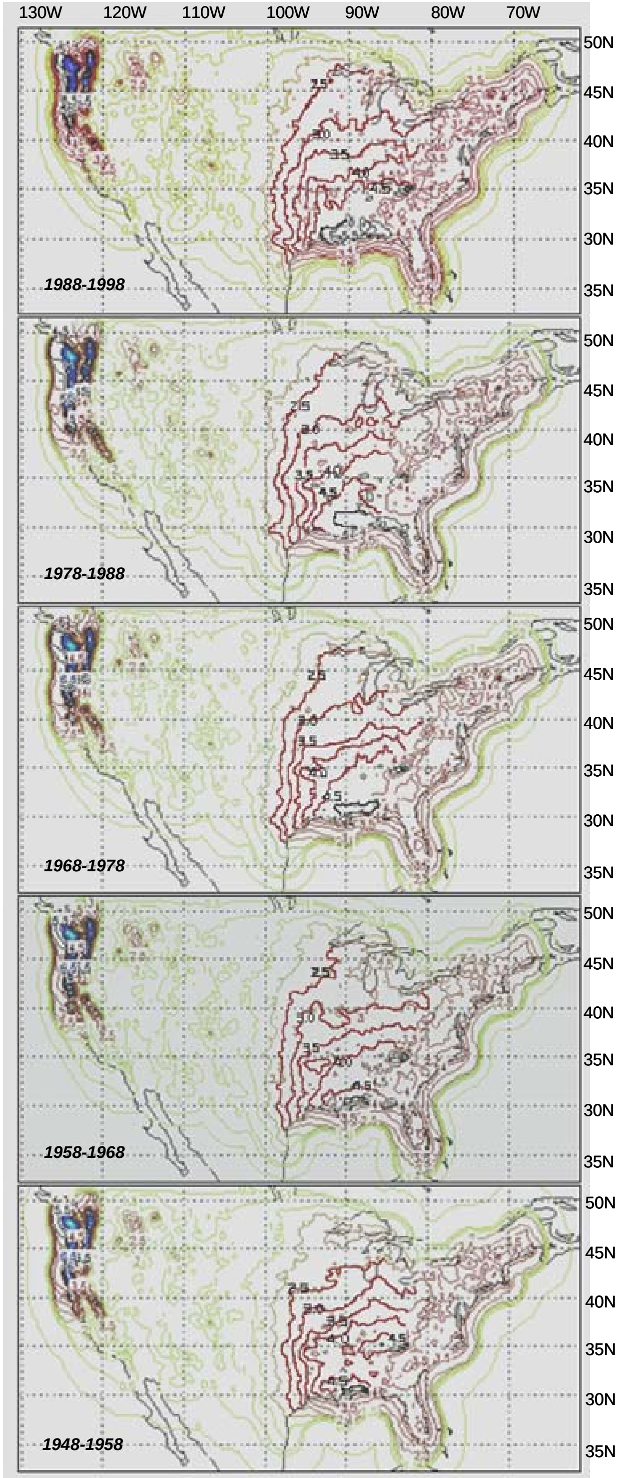

Figure 4 Temporal and spatial variations of monthly average precipitation (cm/moth) in the continental U.S. (1948-1998). Data come from the NOAA precipitation database.

sustainable water resource management [12].

Public perception in the region against wastewater reuse is rooted in the cultural tradition of virgin water as a precious resource and in the fear of negative impacts from AST/R practices [11]. In Israel, agriculture irrigation is the primary form of wastewater reuse accounting for two-thirds of the 3×10^8 m^3 of wastewater generated in 1989. The Dan Region wastewater reclamation project is a large-scale AST/R operation started in 1987 with a 2.7×10^5 m^3/yr processing capacity. Some publications indicated that the AST/R operations have been successful [17]; yet detailed investigations have revealed potential water quality impacts from non-ionic surfactants [43], hydrophilic organics [21], chloride and conductivity [31].

The potential passing through of chloride, salts and other emerging contaminants in reclaimed groundwater and the associated negative public perception have driven the AST/R policy-making and proposed engineering practices in Jordan, where the domestic wastewater generally has high BOD levels due to small dilution factors. The AST/R applications are used for non-potable agricultural irrigation such as dates production. Compared to neighboring Israel and in the U.S., the wastewater reuse activities in Jordan are mostly in pilot demonstration stage for direct agriculture irrigation and for public confidence-building [23]. Large-scale AST/R practices have not been adopted although preliminary feasibility studies indicated favorable hydrogeological conditions in Azraq basin, Jafr basin, and the northern Jordan valley. In all cases, the reserve engineering concept described in this paper can provide valuable guidance in final evaluation and optimal design of AST/R systems.

SUMMARY AND REMARKS

AST/R for wastewater reuse is an integral part of the total water solution. At the first level, water resources management addresses the balance both in quantity and quality among major water process units including precipitation, evapotraspiration, surface water, groundwater, and consumptive usage. Wastewater reuse is a process element potentially used for correction of water imbalance in a given watershed basin. To optimize AST/R engineering design and operation, a reverse engineering optimization technique is proposed to define the water quality requirements for a specific end use and establish the optimal process parameters between wastewater effluent processing and the subsequent soil-aquifer treatment.

A number of knowledge gaps exist for proper and optimal design of the AST/R processes. These gaps include long-term fate and transport of emerging contaminants, pesticide/herbicides, and pathogens, long-term salt accumulation and soil yield deterioration, and their relationship with irrigation practices. Further scientific advances in these areas and corresponding regulatory guidance would help alleviate negative public perceptions in the U.S. and the Middle East.

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Conclusions and opinions presented in this paper are those of the authors, and do not necessarily represent the position of the U.S. EPA and USDA. Mention of commercial products, trade names or services in the paper does not convey, and should not be interpreted as conveying official EPA approval, endorsement, or recommendation.

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Table 1. Water consumption and water reuse in water stressed Great Plains states, California and Florida.

State	1990 population (million)	Fresh water usage Per cap. (gpd)	Fresh water usage State (mgd)	Water source GW (%)	Water source SW (%)	wastewater Domestic* (mgd)	wastewater reuse (mgd)	Est. population 2010 (million)	Est. population 2020 (million)	Est. population 2030 (million)	Domestic wastewater 2010 (mgd)	Domestic wastewater 2020 (mgd)	Domestic wastewater 2030 (mgd)
Arizona	***3.67***	***1,790***	***6,560***	***42%***	***58%***	***275***	***183***	***6.64***	***8.46***	***10.71***	***498***	***634***	***803***
Arkansas	2.35	3,330	7,835	60%	40%	176	0	2.88	3.06	3.24	216	230	243
California	***29.76***	***1,180***	***35,117***	***42%***	***58%***	***2,232***	***133***	***38.07***	***42.21***	***46.44***	***2,855***	***3,166***	***3,483***
Colorado	3.29	3,850	12,682	22%	78%	247	3.7	4.83	5.28	5.79	362	396	434
Florida	***12.94***	***582***	***7,530***	***62%***	***38%***	***970***	***170***	***19.25***	***23.41***	***28.69***	***1,444***	***1,755***	***2,151***
Idaho	1.01	19,600	19,737	38%	62%	76	0	1.52	1.74	1.97	114	131	148
Nebraska	***1.58***	***5,660***	***8,931***	***54%***	***46%***	***118***	***0***	***1.77***	***1.80***	***1.82***	***133***	***135***	***137***
Nevada	1.20	2,780	3,342	32%	68%	90	11	2.69	3.45	4.28	202	259	321
New Mexico	1.52	2,300	3,485	51%	49%	114	0	1.98	2.08	2.10	149	156	157
Oklahoma	3.15	452	1,422	47%	53%	236	0	3.59	3.74	3.91	269	280	293
Texas	***16.99***	***1,180***	***20,043***	***37%***	***63%***	***1,274***	***56***	***24.65***	***28.63***	***33.32***	***1,849***	***2,148***	***2,499***
Utah	1.72	2,540	4,376	22%	78%	129	39	2.60	2.99	3.49	195	224	261
U.S.	252.336	1,340	338,130	16%	84%	18,925	750	308.94	335.80	363.58	23,170	25,185	27,269

Note: # - Data from U.S.Geological Survey [37].
* - Calculated using wastewater generation rate 75 gal/day/capita.
States in bold itallic have population growth rate above the national average in next 25 years.