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DEVELOPMENT OF AN AQUIFER, STORAGE AND RECOVERY (ASR) SITE SELECTION SUITABILITY INDEX IN SUPPORT OF THE COMPREHENSIVE EVERGLADES RESTORATION PROJECT

Chris J. Brown[1]
Rebecca Weiss[1]
Robert Verrastro[2]
Steve Schubert[3]

[1]U.S. Army Corps of Engineers, Jacksonville, Florida
[2]South Florida Water Management District, W. Palm Beach, Florida
[3]U.S. Fish & Wildlife Service, Vero Beach, Florida

In support of the Comprehensive Everglades Restoration Plan (CERP), the U.S. Army Corps of Engineers, U.S. Fish & Wildlife Service, South Florida Water Management District, and others, are currently engaged in the execution of four Aquifer, Storage and Recovery (ASR) pilot projects located throughout the Everglades region. Through data collection efforts and thorough testing, the four pilot projects will enable the project team to better grasp the technical uncertainties associated with implementing ASR on a grand scale. At the same time, the ASR Regional Study is focused upon the development of a numerical model to provide a better understanding of the south Florida environment's ability to support a proposed 333 well ASR system, the largest such system in the world. One effort that has been completed as part of the Regional Study is the preliminary optimization of ASR well site selection in support of the proposed 333 well system. After developing an ASR site selection suitability index, an interagency team utilized Geographic Information Systems (GIS) and the new site suitability methodology to evaluate and propose an initial array of potential ASR well locations. The suitability index was based on the premise of maximizing ASR effectiveness while minimizing any attendant impacts.

INTRODUCTION

The Greater Everglades Ecosystem, located in southern Florida, is a myriad of tree islands, marl prairies, wet prairies, sawgrass ridges, open-water sloughs, estuaries and coral reefs. The Everglades is a broad, flat expanse of wetlands inhabited by innumerable plants and animals. Dubbed the "River of Grass" by Marjorie Stoneman Douglas (Douglas, 1947), the sustainability of the Everglades ecosystem is in trouble. The distribution of water, its timing, quality and quantity, have all been changed over the last 100 years by a combination of water resources development, agriculture, and urbanization (Davis, 1994).

The *Central and Southern Florida Project Comprehensive Review Study (USACE & SFWMD, 1999),* developed jointly by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers (USACE), presents a framework for Everglades restoration. Now known as the Comprehensive Everglades Restoration Plan (CERP), this plan contains 68 components, including structural and operational changes to the Central and Southern Florida (C&SF) Project. The primary purpose of CERP is to restore the Everglades by improving the quantity, quality, timing and delivery of water for the natural ecosystems of south Florida that comprise the Everglades. A key component in the overall restoration strategy is the provision of more dynamic storage of freshwater. Additional storage of freshwater should provide supplementary opportunities to restore Everglades hydrology and concomitant ecology.

The CERP water storage strategy proposes the use of both above-ground storage reservoirs and underground storage via deep wells. The deep wells proposed are Aquifer, Storage and Recovery (ASR) wells. ASR is a simple concept, in which water is stored in subsurface aquifers when excess water is available and extracted during times of need. According to the British Geological Survey (Jones et al., 1999), ASR is a sub-set of artificial recharge and is defined as:

"*Storage of treated, potable water in the aquifer local to the borehole(s) that is (are) used for both injection and abstraction. A high percentage of the water injected is abstracted at a later date and the scheme may utilize an aquifer containing poor quality or brackish water, although this does not exclude the use of aquifers containing potable water. ASR schemes enable maximum use to be made of existing licensed resources"*.

Pyne (1995) has defined ASR as "*the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed*."

Artificial recharge of groundwater through wells has been explored in diverse settings worldwide (Harpaz, 1971; Bichara, 1974; Khanal, 1980; Bouwer et al., 1990; Bureau of Reclamation, 1997, Calleguas, 2004). Groundwater recharge has been utilized in South Florida since 1983 with the construction of the first ASR system located near Lake Manatee (CH_2M Hill, 1984). Scientific investigations of groundwater recharge and recovery from the confined Floridan Aquifer System (FAS) were initiated in the early 1980s (Merritt et al., 1983) by the U.S. Geological Survey and the U.S. Army Corps of Engineers. The successful operation of pilot artificial recharge sites and operational experience at Lake Manatee and other south Florida ASR sites led to significant development of the technology within the study area. In the late 1990s, as Federal, State and local agencies struggled to develop a coherent and holistic restoration plan for the Everglades, it became apparent that ASR technology could play an important role.

The CERP restoration scheme is an ambitious plan to fully utilize up to 333 ASR wells to store water from Lake Okeechobee and the lower east coast of Florida. To date, the largest existing ASR system comprises less than 50 wells (Pyne, 1995), making the CERP project unprecedented in size and scope. The original CERP plan proposed 200 of the wells to be located north of Lake Okeechobee, 44 wells to be located within the Caloosahatchee River Basin, and the remaining wells to be located within the urbanized lower east coast. Figure 1 depicts the general locations of the proposed ASR wells within the south Florida study area along with the planned artificial recharge capacity. The exact location of the wells was to be determined at a later time as ASR scientific and engineering studies progressed. The scientific and engineering studies for the CERP ASR program are focused upon planning, design and construction of 4 ASR pilot wells and an ASR Regional Feasibility Study. The ASR Regional Feasibility Study or Regional Study, is designed to reduce technical uncertainties with the proposed CERP ASR plan. The Regional Study includes multiple components such as field investigations, groundwater modeling, geochemical testing, groundwater sampling, bioassays, ecological studies, and limited plan formulation and optimization. The original goals of the Regional Study were outlined in the Project Management Plan (USACE & SFWMD, 2003) and are presented herein:

· Address outstanding issues of a regional nature that cannot be adequately addressed by the authorized ASR Pilot Projects.

· Reduce uncertainties related to full-scale CERP ASR implementation by conducting scientific studies based on existing and newly acquired data and evaluate potential effects on water levels and water quality within the aquifer systems, and on existing users, surface-water bodies, and the flora and fauna that inhabit them.

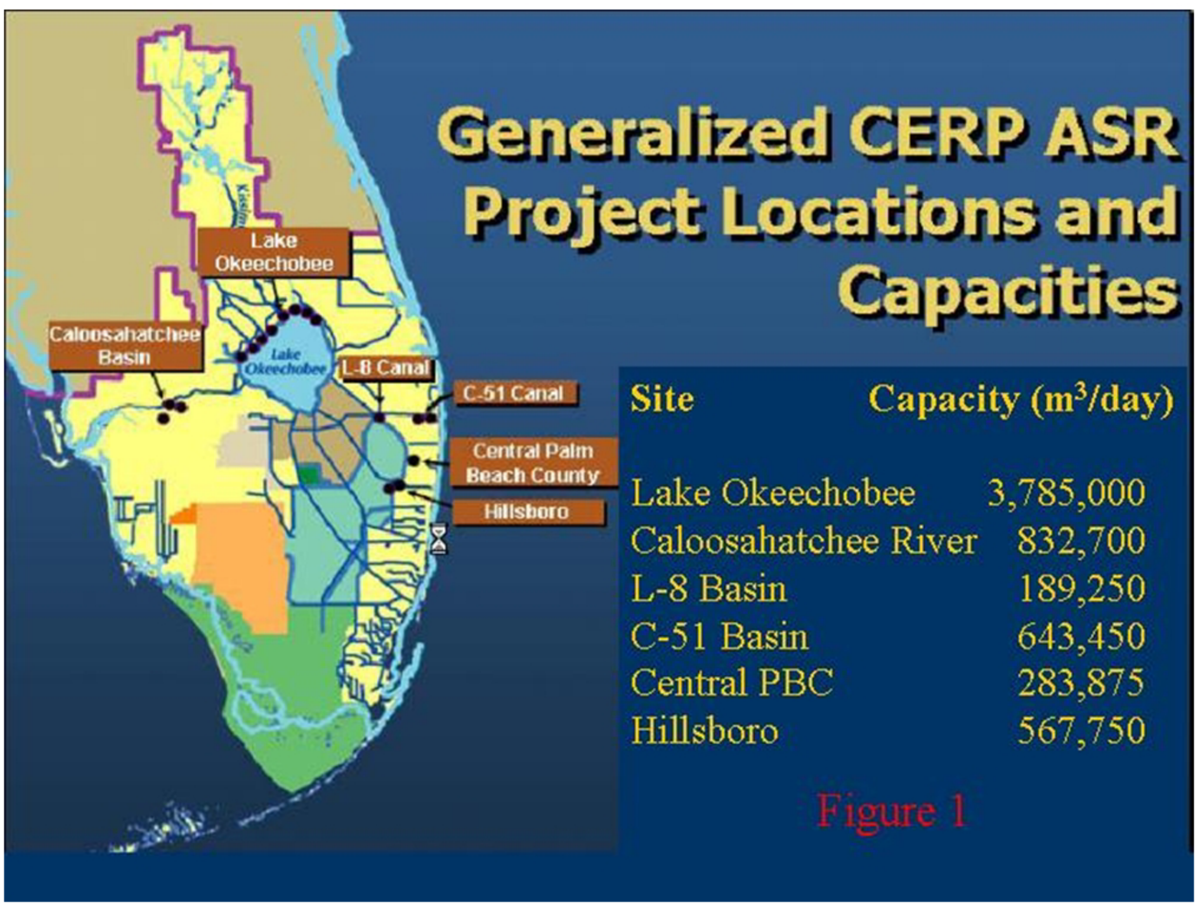

Figure 1. Generalized CERP project locations and capacities.

- Develop a regional groundwater model of the FAS and conduct predictive simulations to evaluate the technical feasibility of the proposed 333-well CERP ASR system, or if determined to be infeasible, identify an appropriate magnitude of ASR capacity with minimal impact to the environment and existing users of the FAS.

In order to develop a numerical model to satisfy the third goal, identification of more precise locations for the proposed ASR wells was necessary in order to provide accurate data input. An interagency and interdisciplinary team was formed to develop ASR well site selection criteria in order to carry out a preliminary "desktop" optimization of potential ASR well sites for the CERP. The various site selection criteria were focused upon the key performance indicators for CERP ASR projects. Ultimately, the site selection criteria were normalized into an ASR site selection suitability index from 0 to 1.

PREVIOUS WORK

The USACE has traditionally utilized site selection evaluations to minimize impacts to environmental systems through application of water resources planning principles promulgated in 1983 (U.S. Water Resources Council, 1983). Water resources projects, including development of flood control and navigation projects, sought to maximize national economic development while minimizing impacts to the "environmental quality account" of each project. Typically, a series of overlap maps were prepared that presented planning factors like topography, soils, hydrology, location of threatened or endangered species, or location of other affected populations. Overlay methodology has been utilized by many Federal and State agencies (FDOT, 1999) and is discussed in more detail by Focazio et al., (2002). Overlay methods have been shown to be well suited for feasibility studies evaluating artificial recharge.

Oklahoma State University used multiple planning factors in its evaluation of artificial recharge feasibility in Northwestern Oklahoma (Pettyjohn and White, 1985) including:

- Source of recharge water
- Proximity to source
- Topography
- Permeability of near-surface materials
- Quality of source
- Quality of water in the aquifer
- Availability of source water

Both the Denver Basin aquifer recharge demo project (Bureau of Reclamation, 1997) and the Washoe County, Nevada recharge demo project (Bureau of Reclamation, 1996) included both regulatory and institutional considerations in their planning efforts. The St. Johns River Water Management District utilized both site selection criteria (overlay methodology) and institutional/ regulatory considerations in locating new rapid infiltration basins (Rabbani and Munch, 2000).

With the advent of Geographic Information Systems (GIS), more sophisticated overlay evaluations are now possible. Shahid (2000) discusses the use of overlay methodology in combination with remote sensing and GIS to evaluate vulnerability of groundwater aquifers to pollution. A similar approach was undertaken for this study.

Combining various GIS coverages into normalized site selection indices has been a recent technical advance. Tegelmark (1998) combined factors such as regional climate, topography, soil properties, and vegetation into a suitability index to predict natural Scots pine forest regeneration. Tegelmark used multivariate regression models in combination with overlay maps to find most suitable regions for reforestation. Xinhai et al. (2002), used GIS to combine information on topography, vegetation, rivers, roads, and location of villages/towns in order to develop a suitability index for Crested Ibis habitat. The habitat suitability index was normalized between values of 0 and 1. An integrated map of Ibis habitat quality was prepared and compared to actual distribution of Ibis in regions of China. Tseng et al. (2001) combined five GIS themes into a site selection index for locating optimal artificial reef sites. A decision support system was also used to supplement the GIS themes and ensure objective ranking of various criteria.

ASR PERFORMANCE FACTORS

The hydrogeology in most of South Florida consists of layers of aquifers and confining units. The three primary aquifers in the study area include the Surficial Aquifer System (SAS) ranging from 100 to 300 feet thick; the Intermediate Aquifer System (IAS) located within the Hawthorn Group sporadically; and the massive Floridan Aquifer System (FAS) that can be as thick as 1,500 feet. Generally, the SAS is separated from the FAS by an extensive confining unit consisting of interbedded sands, clays and carbonate units. The Intermediate Confining Unit (ICU) occurs between 150 and 850 feet below land surface in the study area and is usually synonymous with the Hawthorn Group. The FAS is a carbonate, confined aquifer and can generally be subdivided into several permeable zones, separated by low-permeability limestones. It is composed of limestone and dolostone units generally dipping to the east and south, and contains brackish to saline water. The permeable zones within the FAS are regionally grouped into upper and lower units, separated by a middle confining unit. These units are informally designated “Upper Floridan Aquifer”, “Middle Floridan Aquifer Confining Unit”, and “Lower Floridan Aquifer” (Miller, 1997). ASR wells located in south Florida generally store water in the brackish FAS (Reese, 2002). The proposed CERP ASR system is evaluating the Upper Floridan Aquifer as a storage zone.

The performance of an ASR system in this environment is a complex process that may be affected by operational design, subsurface heterogeneity, density-dependent flow processes, and biogeochemical processes. One constraint to ASR implementation is aquifer zones with inadequate transmissivity that would not be able to accommodate large storage volumes due to unsustainably high induced aquifer pressures. In addition, highly heterogeneous aquifer zones may lead to enhanced mixing and hydrodynamic dispersion (Merritt, 1986; Anderson and Lowry, 2004). Cavernous or “karst” zones within the ASR storage zone may be especially problematic. Groundwater with high concentrations of total dissolved solids (TDS) may lead to poor quality water being recovered by the ASR well (Pavelic et al., 2002), thereby limiting overall recoverability. In addition, high TDS values may cause buoyancy stratification of stored water due to density differentials between the ambient brackish groundwater and the recharged freshwater (Missimer et al., 2002). Due to the complex hydrogeological environment in south Florida, ASR site selection should be considered carefully to maximize performance while minimizing potential problems.

In addition to hydrogeological related performance factors, other important ASR site selection factors include:

- Availability of source water for recharge
- Quality of the source water

· Distance from the source water to the ASR well

· Landuse and availability

· Access constraints (e.g., roads for access and construction)

· Location of ecologically valuable habitats, including endangered species

· Location of system demands

· Location of existing groundwater users

· Availability of power

· Operational flexibility

All of these site selection factors were evaluated in order to optimize the CERP ASR well locations. Of the factors listed, availability of the source water and distance from the source water to the ASR well are undoubtedly the most important factors to consider for a potential ASR system.

ASR SITE SELECTION PROCEDURE

The CERP ASR site selection effort was completed in two separate tiers. First, three "pass or fail" criteria were examined to determine all potential suitable lands available within the study area that could support ASR well construction and operation. Lands failing any of the three criteria were deemed unsuitable and were eliminated from further consideration. The remaining areas were then sub-divided into ASR site selection polygons of varying size and complexity. Secondary site selection criteria were then developed and applied to the site selection polygons. These criteria were then combined into an ASR suitability index with a normalized value between 0 and 1.

The three pass or fail criteria were intended to focus the site selection efforts on those lands that showed the most promise to provide the benefits predicted by the CERP plan. The resolution of the land use GIS coverages were considered in the pass or fail criteria. The "minimum mapping area" (e.g., level of accuracy) for the data sets utilized in the evaluation was five acres for upland parcels. This size would also allow installation of a small ASR well cluster and associated water treatment plant. Therefore, no parcel smaller than five acres was carried forward into secondary screening. In addition, land use was utilized as a pass or fail criterion to select land use categories most compatible with the proposed ASR program. The three criteria used were:

· Distance from Lake Okeechobee or a source water body (keep within three miles of Lake Okeechobee, conveyance canals or major waterways to minimize pumping costs)

· Minimum project size of five acres for ASR well cluster plus water treatment plant (minimum mapping unit is five acres for upland land covers and two acres for wetlands according to GIS metadata supporting Land Use maps)

· Land Use [Based upon FDOT Land use definitions, (FDOT, 1999)]

The land use criterion was applied based upon customized queries of the GIS database. Only a group of acceptable land use categories were carried forward into the secondary screening process. Acceptable land use types are:

o Undeveloped land in urban areas

o Agricultural lands

o Lands occupied by exotic species such as Brazilian pepper

- Rural lands in transition
- Borrow Areas
- Spoil Areas
- Fill Areas
- Burned Areas
- Canals and Locks
- Electric power transmission lines/right of way
- Water supply plants

Unacceptable land use examples are:

- Urban and commercially developed areas
- Housing sub-divisions and developments
- Lakes, streams and reservoirs
- Wetlands (over two acres), swamps, mangroves, submerged aquatic vegetation
- Coastal habitat areas (mud-flats, beaches, oyster beds)
- Forested or wooded lands
- Sewage treatment plants
- Solid waste disposal facilities (landfills)

Since this effort was conducted as a preliminary site selection procedure, the disposition of forested or wooded lands was debated among the interagency team. ASR proponents argued that since ASR footprints are generally very small compared to other water resource options, the impacts to forest ecology would be small. The interagency biologists argued that in a preliminary analysis, it would be prudent to exclude all lands that could have significant habitat values for wildlife, including Federally listed species. In addition, since the ASR system is planned to support the largest environmental restoration project in the United States, every effort should be made to limit even small environmental impacts. Following the friendly and practical debate, the interagency team agreed to exclude native forest lands from further consideration for the preliminary site selection activity.

After the pass or fail criteria were applied to the GIS maps, the area under consideration for ASR site selection was reduced substantially. Figure 2 shows the area remaining for secondary screening activities along with the locations of primary surface water features and the outline of the United States Geological Survey's (USGS) 1:24,000 quadrangles. The surface water features and the quadrangle outlines were then utilized to identify 97 ASR site selection polygons. Due to the broad nature of the site selection process, the interagency team opted to conduct further screening at a polygon level.

Along the east coast of Florida, within the urbanized zone of the study area, site selection polygons entrained many small parcels ranging in size from a few acres to hundreds of acres. The final distribution of ASR site selection polygons is shown on Figure 3. Each of the site selection polygons was then ranked against eight secondary screening criteria as follows:

- Ecological Suitability – Based on rarity, sensitivity, and/or value of habitat for plants, fish, and wildlife, and likelihood of presence of Federally threatened or endangered species (Rank 0 to 2; 2

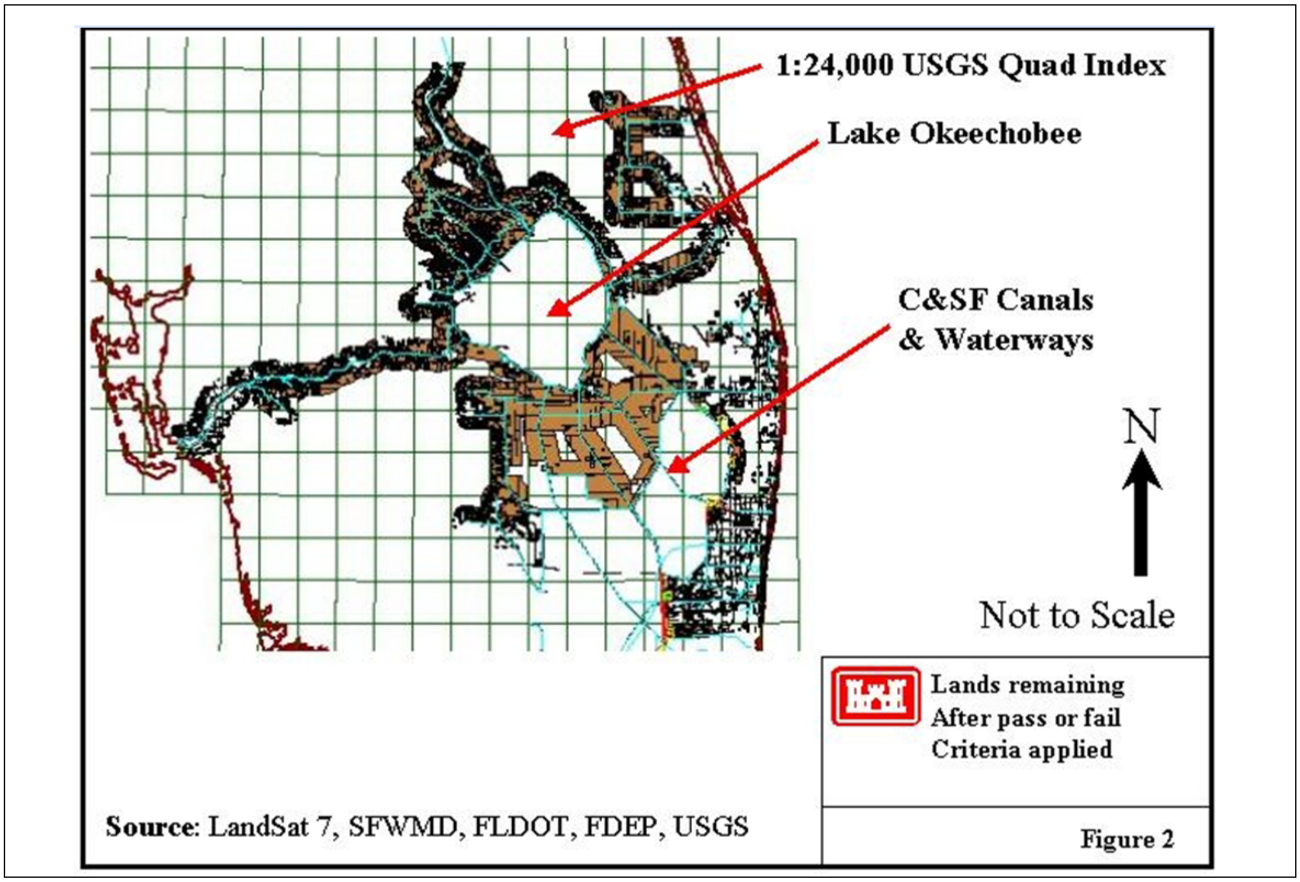

Figure 2. Lands remaining after pass or fail criteria applied.

for high suitability, 1 for medium suitability, and 0 for low suitability)

- o Use and Density Factor – Known Floridan Aquifer System well users (Rank 0 to 2; 2 if no wells are located in a polygon, 1 if 1 to 5 wells within polygon, and 0 if more than 5 wells within polygon)

- o Water Quality Assessment – Based upon published characterization of source water quality under the FDEP 305b clean water program (Rank 0 to 2; Rank 2 if source water fully meets standards, 1 if source water partially meets standards, and 0 if source water does not meet standards)

- o Groundwater Quality of UFAS (Rank 0 to 2; Rank 0 if chloride concentration of the upper UFAS groundwater is less than 250 mg/l or greater than 3,000 mg/l., rank 1 if chloride concentration of UFAS is between 1,500 and 3,000 mg/l, and rank 2 if chloride concentration of UFAS is between 250 and 1,500 mg/l.

- o Road Density (Construction/O&M Access) (Rank 0 to 2; Rank 0 if density of roads are low, 1 if density of roads are medium, and 2 if density is high)

- o Locate near existing power lines (Rank 0 to 2; Rank 0 if not adjacent to existing power lines, 1 if near small KVA lines (in mostly urban areas), 2 if near major transmission lines)

- o Pressure induced changes or high dispersive mixing potential, based upon aquifer transmissivity (Rank 0 to 2; Rank 0 if $T<5{,}000$ ft^2/day or if $T>25{,}000$ ft^2/day, 2 if T is between 5,000 to 25,000 ft^2/day)

- o Operational Flexibility (Rank 1 to 2; Rank 2 if close to Lake Okeechobee and major canal or

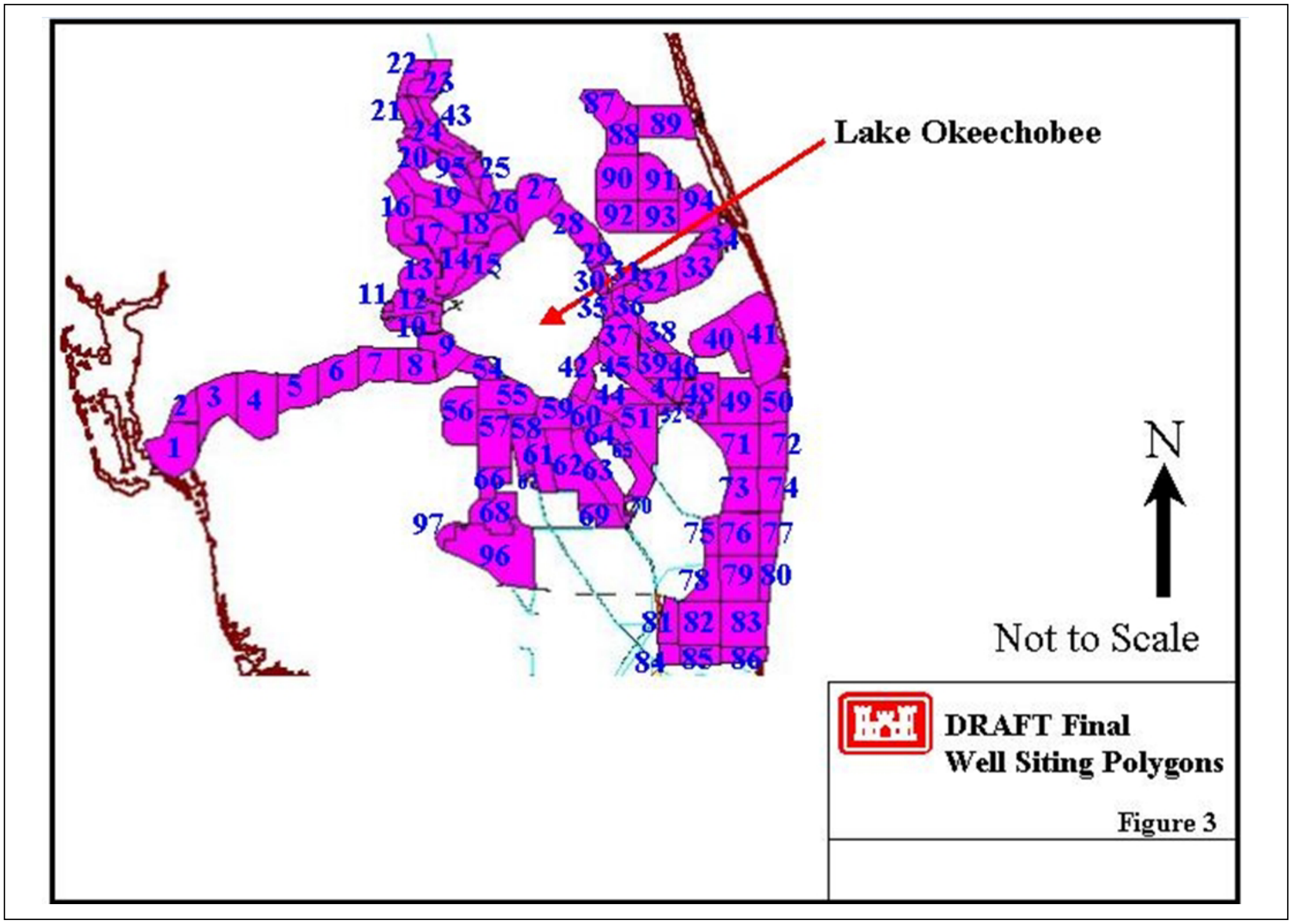

Figure 3. Draft final well siting polygons.

major canal and CERP Impoundment or STA from Everglades Construction Project; Rank 1 for the rest)

Each criterion was then applied to all 97 site selection polygons and raw scores were developed for each polygon. Figures 4 and 5 depict examples of the scoring basis for groundwater quality of the UFAS and ecological suitability, respectively.

After each polygon was scored against the secondary site selection criterion, the raw scores for each site were multiplied by a weighting factor ascribed to each criterion. The weighting factors were developed through a consensus-driven approach among the interagency team. The weighting factors underwent several iterations of changes during the process. Some of the weighting factors were reduced to account for the size of the ASR project footprints. As ASR project footprints are generally small, avoidance of sensitive habitats could be considered for the ecological suitability criterion. A similar rationale was utilized for the water quality of the source water. The final weighting factors ranged from one to four, with only the most important ASR performance factors weighted at greater than one. Only the ambient groundwater quality criterion garnered a weighting of four since it affects both recoverability of stored water and potential impacts to biota caused by the recovered water. The pressure induced changes and the location of existing users criteria each earned a weight factor of three. Ecological suitability was assigned a weight factor of two. All other selection criteria were assigned a weight factor of one. After the weighting factors were applied, all of the scores were normalized from 0 to 1 and plotted on a final set of GIS map coverages. Figure 6 depicts the final color- coded ASR suitability index map developed for the project. The polygons with the highest

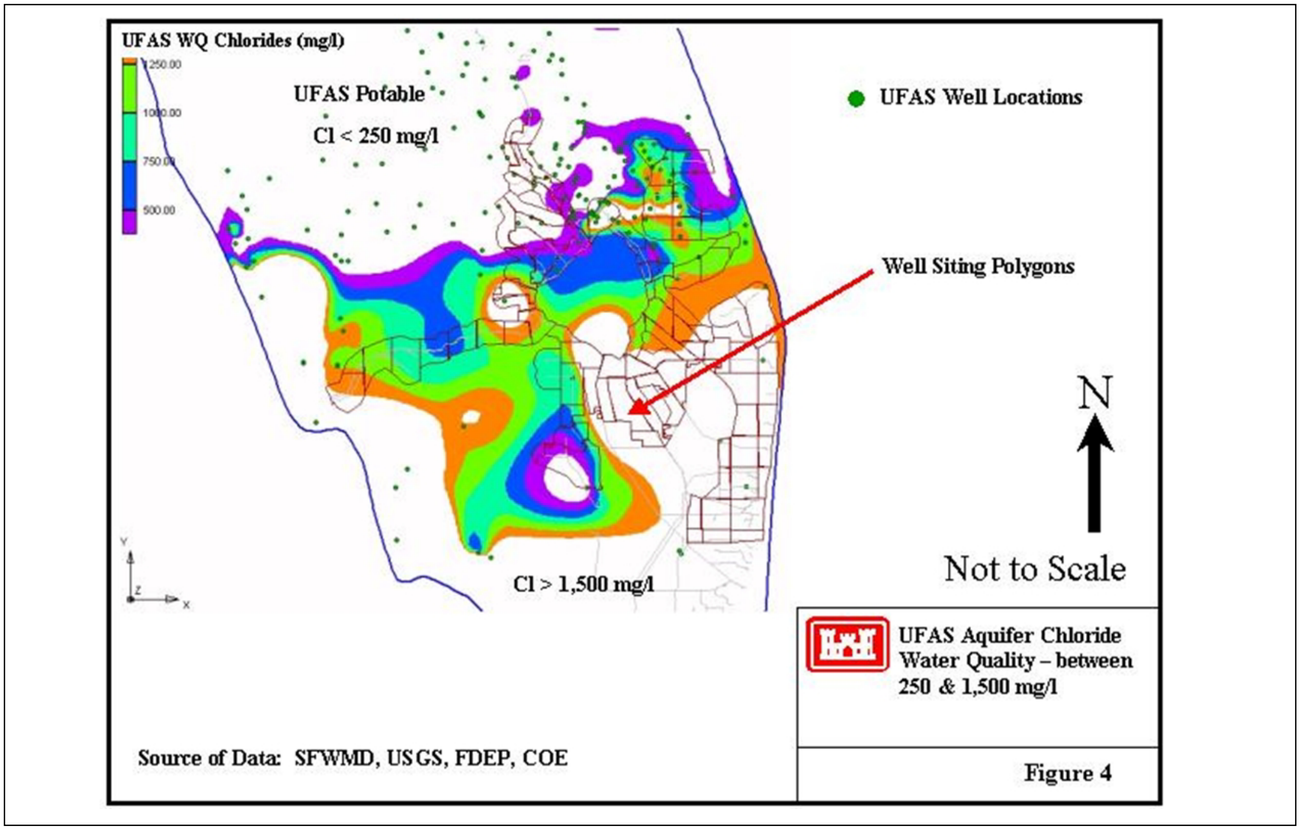

Figure 4. UFAS aquifer chloride water quality - between 250 and 1500 mg/l.

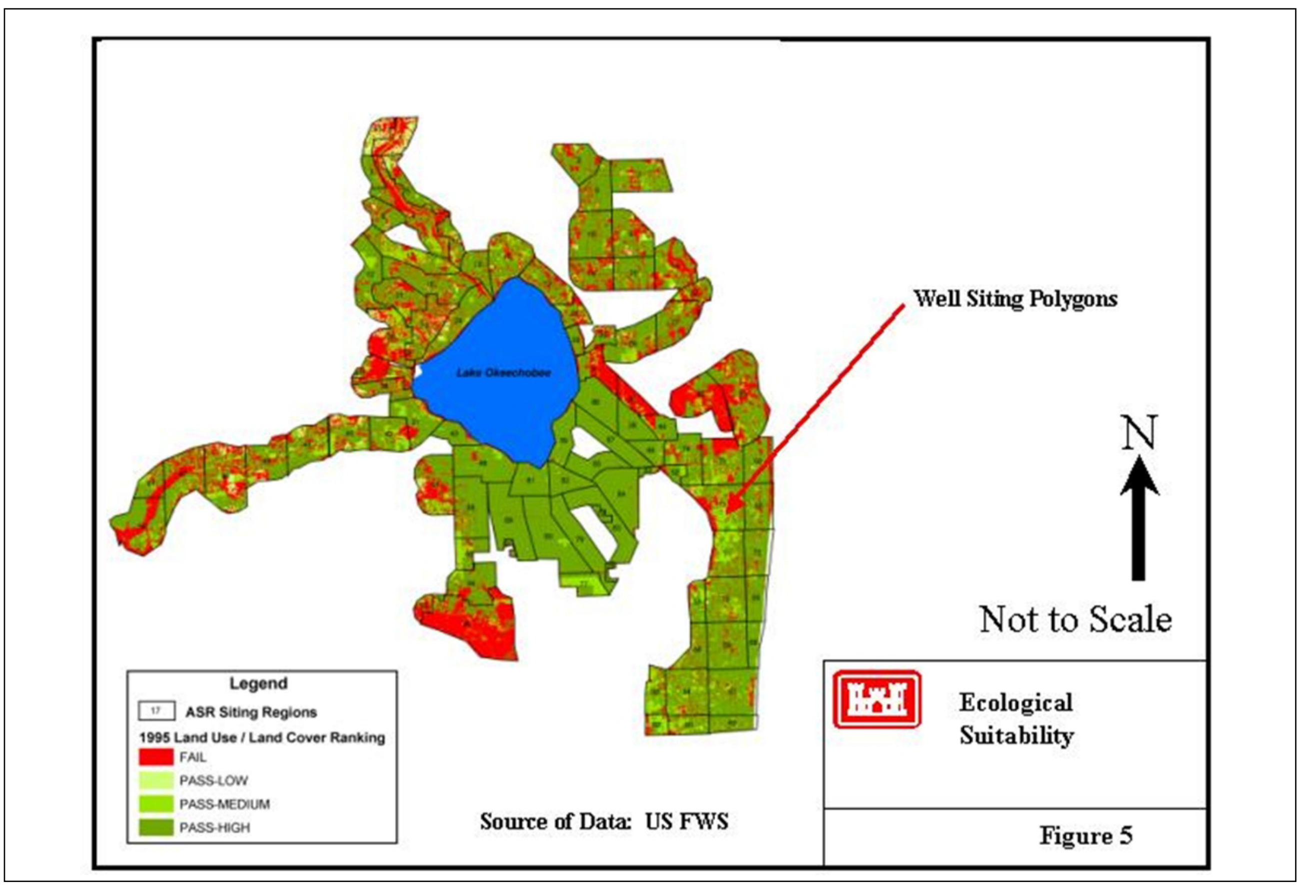

Figure 5. Ecological suitability.

ASR site suitability have an index greater than 0.75. Polygons with an index of 0.25 or less are probably poor candidates for any ASR projects. Figure 6 also depicts the location of the ASR Pilot Projects. The site selection evaluation has also provided confirmation of the pilot locations as good project locations.

CONCLUSIONS AND SUMMARY

As the four pilot ASR projects move forward, it is critical to capture the data from the operations of these ASR wells to define parameters within the Regional ASR model. The refined regional model will be used to simulate the proposed 333 ASR wells as envisioned in the CERP. To this end, the interagency team has narrowed the evaluation of the proposed ASR well systems to areas deemed suitable based on various geological, hydrological, ecological, and infrastructure criteria. By defining pass/fail criteria and developing suitability indices, the team was able to eliminate, score, and select site selection polygons for further study. In addition, the development of an ASR site selection suitability index has advanced the plan formulation efforts for the CERP. The polygons most suitable for ASR development will be the focal point of detailed numerical modeling. Ultimately, the Regional Study will provide the technical basis upon which to evaluate the proposed CERP ASR system. The Regional Study will also aid in the evaluation and planning of operational considerations, as well as define suitability and sustainability within the south Florida environment.

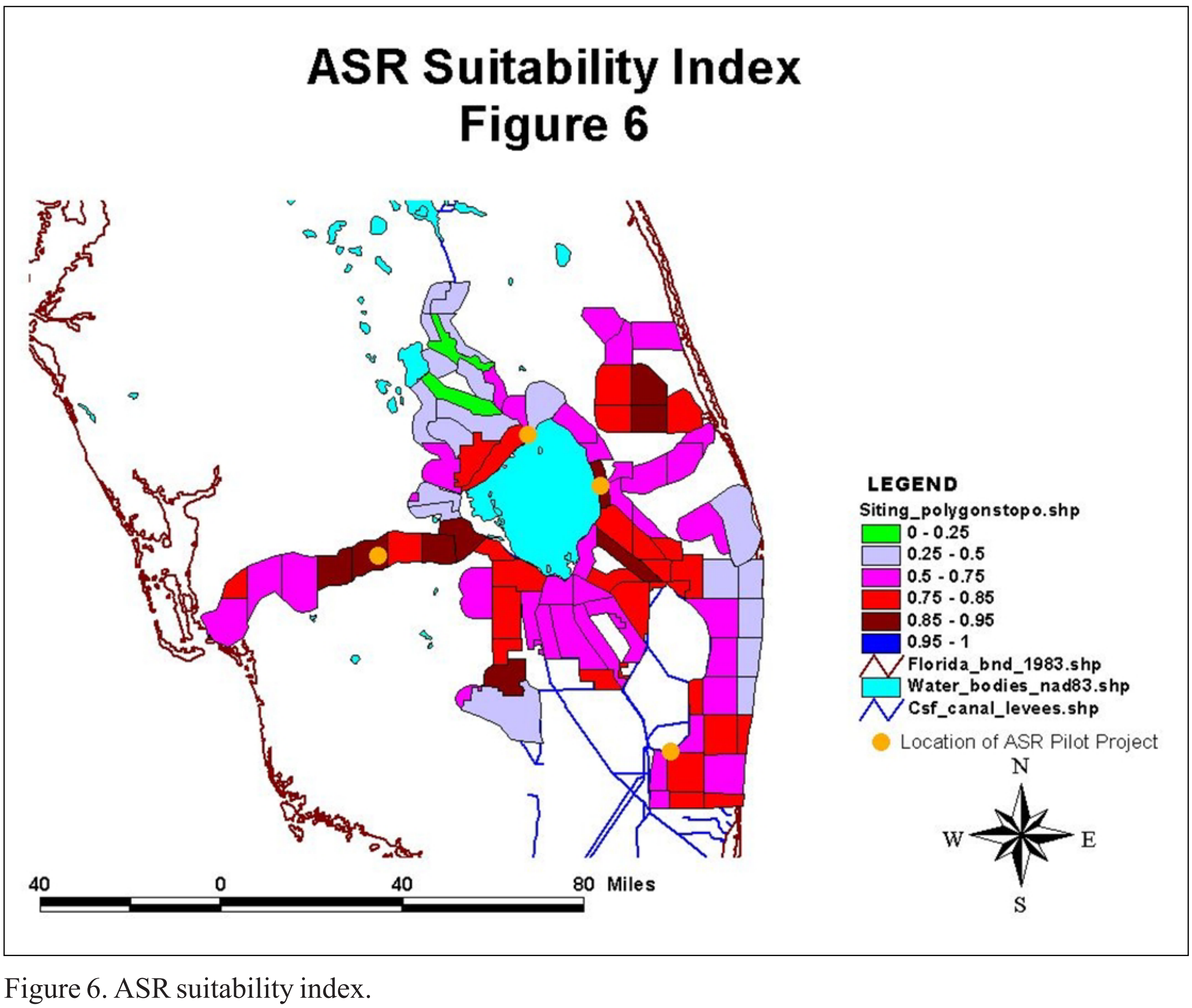

Figure 6. ASR suitability index.

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ADDRESS FOR CORRESPONDENCE
Chris J. Brown
U.S. Army Corps of Engineers
701 San Marco Blvd, Prudential Bldg-3 West Jacksonville,
Florida 32207
USA

Email: christopher.j.brown@usace.army.mil