DEVELOPMENT OF AN ENVIRONMENTALLY SUSTAINABLE WATER SUPPLY SYSTEM: A CASE STUDY FROM TAMPA, FLORIDA, USA

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ABSTRACT

Tampa Bay Water, an intergovernmental agency and wholesale water supply utility, provides potable water to its member governments in the Tampa Bay region on the Gulf coast of Florida. Historical groundwater production from eleven inter-connected wellfields has lowered local surficial aquifer levels and stressed thousands of acres of wetlands. In order to relieve wetland stress and develop an environmentally sustainable water supply system, Tampa Bay Water has developed the following initiatives:

- The Master Water Plan, which includes the development of the country's largest seawater desalination plant, surface water supply from area rivers and the construction of an 445 ha (1,100 ac) above ground reservoir.
- The Optimized Regional Operations Plan (OROP), an integrated ground water-surface water model which rotates among sources so as to maximize surficial aquifer water levels.
- The Phase 1 Mitigation Plan, which provides a rehydration plan for hydrologically stressed wetlands and lakes.

This case study will focus on the research aspects of the OROP and the Phase 1 Mitigation Plan. As the new water supply sources of the Master Water Plan come on-line, the OROP and the Phase 1 Mitigation Plan will work to ensure that water production does not result in unacceptable adverse environmental impacts and that historical impacts from groundwater production are addressed.

The OROP minimizes production impacts to wetlands and lakes by rotating among sources in response to target levels set in surficial aquifer monitoring wells. These target levels were determined by statistical correlations between minimum levels established for wetlands and lakes and surficial aquifer water levels. The establishment of minimum wetland and lake levels was based on regulatory criteria that relate environmental health to indicators of historical wetland and lake levels (known as historical normal pool).

The Phase 1 Mitigation Plan began with a study that assessed wetland hydrologic impacts, and predicted wetland water level recovery, based on aerial photo-interpretation, GIS analysis and integrated surface water – groundwater modeling. Based on the results of that study, rehydration plans are being developed for those wetlands that are predicted not to recover to their minimum levels (on a long-term average basis) after the Master Water Plan projects are operational. These mitigation plans will include surface drainage alterations (e.g. ditch blocks, water control structures), rehydration with reclaimed water or excess surface water, and possibly groundwater augmentation.

The inter-relationships of the various elements (OROP, Master Water Plan, Phase 1 Mitigation Plan) required to provide an environmentally sustainable water supply system will be discussed.

Key Words: Water Supply Management, Environmental Management, Optimization Model, Wetland Mitigation

1 INTRODUCTION

Tampa Bay Water is Florida's largest wholesale water supplier, serving more than 2 million people with the annual average demand of 0.935 million m^3/d or 247 million gallons per day (MGD). It was established in 1974 as the West Coast Regional Water Supply Authority by State Legislation through a five-party agreement among Hillsborough, Pinellas and Pasco counties and the cities of St. Petersburg and Tampa. The city of New Port Richey joined the Agency in 1984 as a non-voting member. The Agency's mission has been to develop, store, and supply water for municipal purposes in such a manner that gives priority to reducing adverse environmental effects of excessive or improper withdrawals of water from concentrated areas. Conflict between meeting water demands and preventing harm to wetland and lake systems was intensified in the early 1990's, making it difficult under the existing Authority's organization to manage wellfields effectively. In 1996, the Authority was mandated by the Legislature to develop regional water solutions and a comprehensive answer to the water needs of the Tampa Bay area. As a result, two actions occurred, (1) the Authority was reorganized into Tampa Bay Water and obtained ownership and control over the regional water supply facilities, and (2) Southwest Florida Water Management District (SWFWMD) and the Authority and its Member Governments entered into a new agreement, the Partnership Agreement, which requires new water sources be developed. It also requires a reduction in pumpage from eleven existing wellfields in three phases: an immediate reduction from 0.727 million m^3/d (192 MGD) to 0.598 million m^3/d (158 MGD); then to 0.458 million m^3/d (121 MGD) by 2003; and finally to 0.341 million m^3/d (90 MGD) by 2008. In return, SWFWMD committed up to $183 million to assist with developing new, alternative water supply sources (see Figure 1).

A Master Water Plan developed prior to the reorganization was modified to include many new projects with a more challenging time schedule. Within the next 10 years 0.42 million m^3/d (111 MGD) of new public water supply capacity as well as treatment facilities and conveyance for that supply must be developed in the Tampa Bay area to enable mandated wellfield cutbacks and meet growing demand. The plan includes development of 0.344 million m^3/d (91 MGD) of new water supply capacity by 2007 and another 0.076 million m^3/d (20 MGD) in supply by 2010. The program will meet the regions needs with environmentally sustainable, diversified, drought proof and/or drought resistant, and cost effective new sources. Components of the plan currently in the final design stage include the hemisphere's largest seawater desalination plant; an "enhanced surface water system" comprised of three supply sources, a 57 million cubic meter offstream reservoir and a new regional surface water

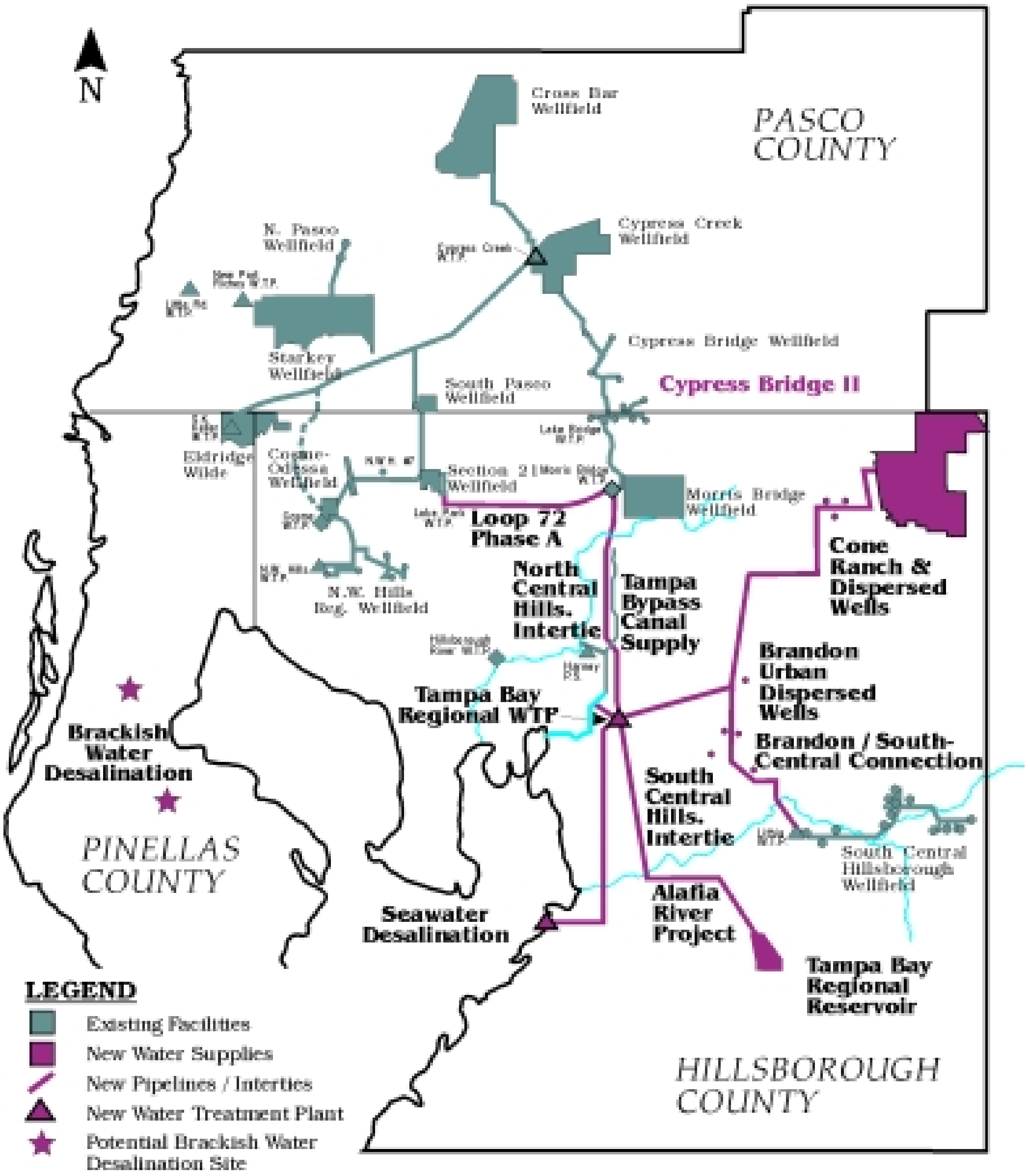

Figure 1. Existing and proposed Tampa Bay Water Facilities

treatment facility; a redesigned and refurbished wellfield; and more than 129 km (80 mi) of interconnecting pipelines. Plan components currently in the conceptual design stage include limited new development of fresh and brackish groundwater resources.

At present, about 71% of the demand is met by 12 regional wellfields with the remaining 29% met by surface water reservoir owned and operated by City of Tampa. . Eleven of Tampa Bay Water's regional wellfields are interconnected which, if the future supplies are adequate, will facilitate the rotation of pumpage based on environmental, physical and regulatory constraints. It is obvious that Tampa Bay Water has to start implementing an innovative water supply management program to effectively manage the existing wellfields and the up-coming new water sources in an environmentally sustainable manner.

Concurrent with the implementation of the Master Water Plan and Partnership agreement , a Consolidated Water Use Permit (CWUP) was issued by SWFWMD (1999) for the 11 interconnected regional wellfields with some conditions that addressed a wellfield operations plan, an environmental management plan, a monitoring program, and a wetland mitigation plan. This paper will discuss some works done under two major components of the CWUP namely, the operation plan and the mitigation plan. The paper will also discuss some major components of the Master Water Plan and their environmental monitoring programs.

2 OPTIMIZED REGIONAL OPERATION PLAN

The Special Condition 4.A of the CWUP provides specifically for development of an Optimized Regional Operations Plan (OROP) for the eleven regional wellfields. The following sub-sections discuss those requirements pertinent to the optimization model development.

2.1 Provide protocol to select among interconnected supply sources

The OROP defines the process and procedures by which Tampa Bay Water operates eleven listed wellfields (Cosme-Odessa, Cross Bar Ranch, Cypress Bridge, Cypress Creek, Eldridge-Wilde, Morris Bridge, North Pasco, Northwest Hillsborough, Section 21, South Pasco, and Starkey). Since January 22, 1999, the operation of these wellfields with regard to weekly production rates and schedules has been controlled by the OROP, which is comprised of a hydrologic simulation model and an optimization routine. Development of the optimization model is described in a report referred to as the Revised OROP (Tampa Bay Water, 1998). Subsequent modifications were reported in OROP Annual Reports (Tampa Bay Water, 1999 and 2000A)

Every two weeks , all production wells not out-of-service for maintenance or otherwise limited in availability and all sources that can contribute to meeting demand at specific demand points (referred to as points of connection) are listed. Minimum run-time requirements to maintain well clearance standards and minimum wellfield production rates for metering and line maintenance for the forecast period of four-weeks are also specified. The optimization algorithms are applied to determine individual weekly-averaged well production rates and operational priority for the forecast period in a two-step process.

The first step uses a long-term base scenario of 52 weeks based on average hydrologic conditions and demand, and develops a rule curve using plus/minus one standard deviation of the average historic demand for the six-year period 1992-1997. The 52-week base scenario is intended to capture monthly and seasonal variability in both projected demand and anticipated rainfall conditions, and it establishes an anticipated rotational schedule to occur within the bounds of the rule curve.

The second step is a short-term analysis of four weeks which accounts for the prevailing environmental conditions and near-term demand forecasts. Operations and Facilities Management staff operate wells on a daily and hourly basis in a manner intended to meet the weekly limits specified by the optimized solution of individual well rates, allowing for variations in actual demand from projections and short-term (less than two weeks) maintenance activities.

2.2 Provide protocol to rotate among sources to minimize environmental stresses

Rotation of production among individual wells is based on an optimized production schedule specifying weekly average rates by well that are forecasted to meet projected demand at the points of connection. Currently in the optimization model there are 11 points of connection, which are: the Cypress Creek WTP, Pasco Interties (West Loop and US 41), Pinellas County Distribution System, Lake Park Water Treatment Plant (WTP), Cosme WTP, Northwest Hillsborough WTP, Lake Bridge WTP, Morris Bridge WTP, Keller WTP, and the South Pasco Meter Pit.

The production forecast process includes a bi-weekly update of the four-week wellfield production projections based on current hydrologic conditions, using the 52-week base run (described above) as the reference scenario. The short-term production schedule is updated twice-monthly and incorporates the latest available historical data for actual production and water-level conditions. The 52-week base scenario is updated quarterly as seasonal data are accumulated for actual rainfall, water levels, and production.

Production well rotation is guided by permit limits on production (by well and by wellfield), the 52-week upper and lower rule curve limits, minimum and maximum operating requirements to maintain functional system performance, and actual versus desired groundwater level conditions (based on observed water levels compared to target levels at monitoring sites in the surficial aquifer system). While meeting demand and system maintenance requirements, rotation is scheduled in order to drive groundwater levels across the region toward their specified target levels.

2.3 Use groundwater elevations as a surrogate for wetland and lake levels with increased groundwater elevations denoting reduced environmental stress

Management of the groundwater production facilities to address environmental concerns is based on management of groundwater levels influenced by the facilities. In areas of environmental stress, an increase in groundwater levels is sought through managed rotation that reduces drawdown in an effort to increase lake and wetland water levels. Monitor wells provide a basis for evaluating water-level conditions and responses to groundwater management. Correlation and regression analyses between historical aquifer, wetland, and lake water levels are used to set target levels in the surficial aquifer system that correspond to Minimum Levels in nearby wetlands and lakes. Observed groundwater levels compared to target levels are used to weight the priorities for reducing pumping in areas of stress and increasing pumping in areas with high prevailing water levels.

2.4 Analyze relationships between groundwater withdrawal at the wellfields and aquifer system drawdown using available hydraulic models

The Integrated Surface/Ground Water (ISGW) model, developed by SDI Environmental Services, Inc. (1997, 1999) for Tampa Bay Water, covers the entire region of the 11 wellfields.

This simulation model is based on Hydrologic Simulation Program- Fortran (HSPF -Johanson et al., 1984) and MODFLOW (McDonald and Harbaugh, 1984) which simulate all essential components of a basin's hydrologic cycle in sequence. The hydrologic processes considered include precipitation, evapotranspiration (ET), surface water withdrawals, infiltration/percolation, and overland flow in HSPF; and the processes of aquifer flow dynamics, recharge, leakage, baseflow, spring flow, ET, and groundwater extractions in MODFLOW. The integration between the surface water and groundwater in ISGW occurs by transferring flow between the two modules while maintaining the sub-basin delineation in the surface water model and grid-based description in the groundwater component. Simulation time steps are hourly for the surface water component and daily for the groundwater component in weekly stress-periods.

The model study area located in the Central Northern Tampa Bay area (CNTB) covers over 3600 square miles and includes all or parts of seven counties. The hydrologic setting involves a multi-layer leaky aquifer system and a number of physiographic settings that include coastal swamps, gulf coast lowlands, ridges, plains, wetlands, and upland areas. Within the model area there are a number of land uses that include agriculture (31%), wetlands (27%), forests (17%), urban (13%), and rangeland/water bodies (12%). The average precipitation in the model area is about 50 inches per year. Potential evapotranspiration is estimated to range between 35 and 55 in/year while actual ET is estimated to be in the range of 31 to 49 in/year (SDI Environmental Services, 1997). A number of surface water features overlay the landscape of the model area. These include six rivers and their tributaries, several smaller streams and lakes. A number of karstic springs in the model area feed the surface water bodies. All major hydrologic features are represented in the model.

The hydrogeologic units in the model area are the Surficial Aquifer System (SAS), the Intermediate Confining Unit (ICU), and the Upper Floridan Aquifer System (UFAS). The thickness of the UFAS within the model area ranges from 700 to 1100 feet. This formation is the source of ground water supply to the area via the 11 wellfields operated by Tampa Bay Water.

2.5 Select optimal groundwater withdrawals using available mathematically-based optimization software such that groundwater levels in the surficial aquifer system are maximized

There are three decision variables to be determined, namely: pumping rates at each production well in the system for each week of the forecast period; the resultant transmission network flow required to deliver the required quantities of water to the Member Government Points of Connection; and the ground-water levels in monitoring wells for both the SAS and the UFAS. The optimization program seeks to maximize ground-water levels at a selected set of monitoring sites in the SAS while all withdrawals are from the leaky confined unit of the UFAS. The following mathematical formulation accounts for variations in future water levels for a specified forecast period, and applies preferential weighting to monitoring sites according to their prevailing ground-water levels compared to established target levels. Notations used in the formulation are given at the end of this paper.

The objective function is given as,

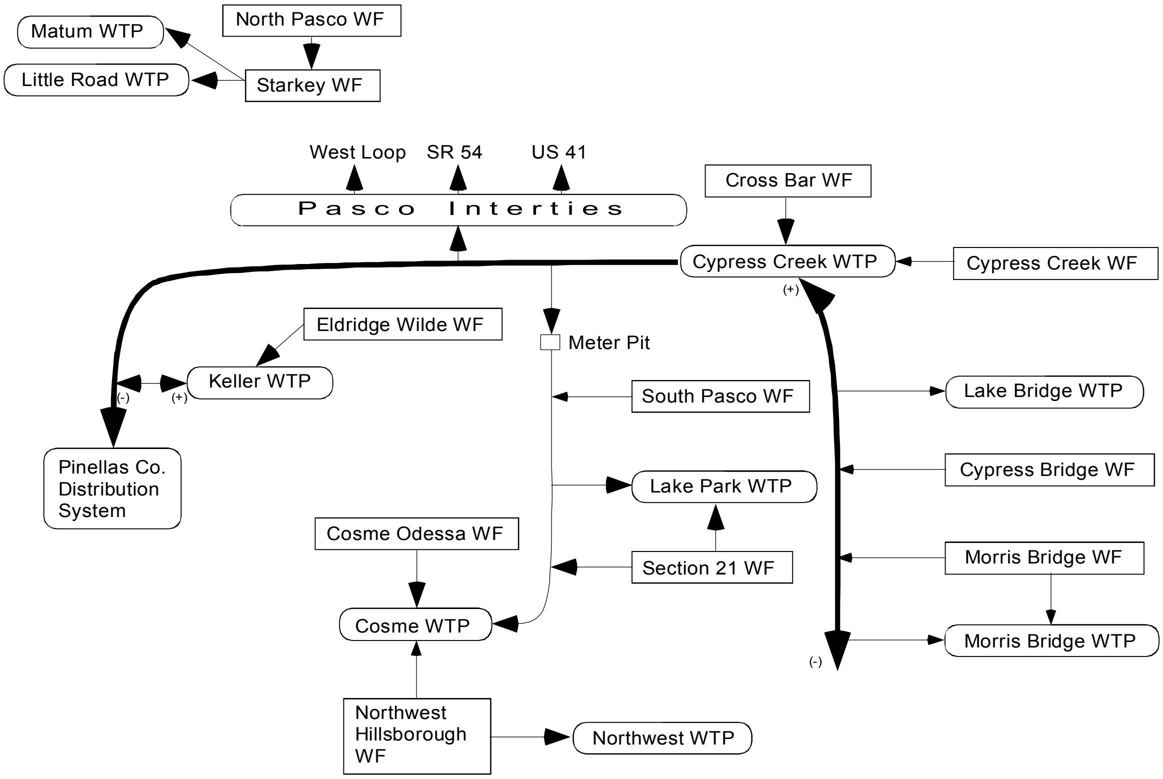

Figure 2. Schematic of interconnected wellfield and Points of Connection

$$Maximize\ \ Z = \sum_{i\in R^u} \sum_{t=1}^{T} \omega_i h^u_{i,t} \tag{1}$$

Figure 2 depicts the schematic diagram of the interconnected “Regional System” between sources and demand points. The current model addresses a network of supplies from groundwater sources, being the 11 wellfields shown by the rectangular boxes. There are 12 points of connection, which mostly are the influents to water treatment plants (WTP), shown as the rounded corner boxes. Wellfields and demand points are connected through high capacity water transmission pipes and are represented by connected lines with directions of possible flow shown by arrows. The constraint sets that show relationships between wellfields and demand points; as well as the balance of flow in the network; can be represented as follows:

Morris Bridge:
$$d^{MB}_{cc,t} + d^{MB}_{mb,t} \ge D^{MB}_t;\ \sum_{j\in w_{mb}} q_{j,t} - d^{MB}_{mb,t} - d^{CC}_{mb,t} = 0,\quad \forall\ t = 1,\dots,T \tag{2}$$

Lake Bridge:
$$d^{LB}_{cc,t} \ge D^{LB}_t,\ \ \forall\ t = 1,\dots,T \tag{3}$$

Lake Park:
$$d^{LP}_{cc,t} + d^{LP}_{s21,t} \ge D^{LP}_t;\ \sum_{j\in w_{s21}} q_{j,t} - d^{LP}_{s21,t} - d^{CC}_{s21,t} = 0,\quad \forall\ t = 1,\dots,T \tag{4}$$

Cosme:
$$d^{CM}_{nwh,t} + d^{CM}_{cc,t} + \sum_{j\in w_{cm}} q_{j,t} \ge D^{CM}_t,\quad \forall\ t = 1,\dots,T \tag{5}$$

NW Hillsborough:
$$d^{NW}_{nwh,t} \ge D^{NW}_t;\ \sum_{j\in w_{nwh}} q_{j,t} - d^{NW}_{nwh,t} - d^{CM}_{nwh,t} = 0,\quad \forall\ t = 1,\dots,T \tag{6}$$

Keller: $d_{cc,t}^{KL} + \sum_{j \in w_{ew}} q_{j,t} \geq D_t^{KL}, \quad \forall\, t = 1,\ldots,T$ (7)

Pinellas System: $d_{cc,t}^{PC} \geq D_t^{PC}, \quad \forall\, t = 1,\ldots,T$ (8)

Little Road & Matum: $\sum_{n \in \{np,st\}} \sum_{j \in w_n} q_{j,t} \geq D_t^{LR} + D_t^{MT}, \quad \forall\, t = 1,\ldots,T$ (9)

Pasco Interties: $d_{cc}^{PI} \geq D_t^{PI}, \quad \forall\, t = 1,\ldots,T$ (10)

Regional (Cypress Creek WTP) and sub-regional pipe flow water balance:

$$\sum_{j \in w_{cr}} q_{j,t} + \sum_{j \in w_{cc}} q_{j,t} + d_{cb}^{CC} - d_{cc,t}^{PC} - d_{cc,t}^{PI} - d_{cc,t}^{MP} - d_{cc,t}^{KL} = 0, \quad \forall\, t = 1,\ldots,T \qquad (11)$$

$$\sum_{j \in w_{cb}} q_{j,t} + d_{mb,t}^{CC} - d_{cc,t}^{LB} - d_{cc,t}^{MB} - d_{cb,t}^{CC} = 0, \quad \forall\, t = 1,\ldots,T \qquad (12)$$

$$\sum_{j \in w_{sp}} q_{j,t} + d_{cc,t}^{MP} + d_{s21,t}^{CC} - d_{cc,t}^{CM} - d_{cc,t}^{LP} = 0, \quad \forall\, t = 1,\ldots,T \qquad (13)$$

The ground-water withdrawals must comply with the permitted limits specified as the wellfield 36-month running averages and the well and wellfield monthly averages (summed by weeks in this formulation):

$$\sum_{j \in w_n} \sum_{\tau = t-155}^{t} q_{j,\tau} \leq 156 P_n^y, \quad \forall\, n = 1,\ldots,N;\ t = 1,\ldots,T \qquad (14)$$

$$\sum_{j \in w_n} \sum_{\tau = \max(1,t-3)}^{t} q_{j,\tau} \leq \min(4,t) P_n^m, \quad \forall\, n = 1,\ldots,N;\ t = 1,\ldots,T \qquad (15)$$

$$\sum_{\tau = \max(1,t-3)}^{t} q_{j,\tau} \leq \min(4,t) P_j^m, \quad \forall\, j \in w_n;\ n = 1,\ldots,N;\ t = 1,\ldots,T \qquad (16)$$

The current WUP does not set regulatory ground-water levels, but these are retained in the model based on previous permit conditions as non-cumulative and cumulative weekly-average water levels at the regulatory wells and minimum water levels at saltwater intrusion monitoring wells:

$$h_{i,j} \geq H_i - 3, \quad \forall\, i \in R;\ t = 1,\ldots,T \qquad (17)$$

$$\left(\sum_{\tau = -W_{-1}}^{t} h_{i,\tau} \right) / W_t \geq H_i, \quad \forall i \in R;\ t \,|\, W_t > 8 \qquad (18)$$

Facility constraints are specified as weekly minimum and maximum production based on operational limits for satisfactory operation of meters, treatment systems, and other system components:

$$\underline{Q}_n^{wf} \leq \sum_{j \in w_n} q_{j,t} \leq \overline{Q}_n^{wf}, \quad \forall\, n = 1,\ldots,N;\ t = 1,\ldots,T \qquad (19)$$

$$\sum_{j \in w_{cr}} q_{j,t} + \sum_{j \in w_{cc}} q_{j,t} + d_{cb}^{CC} \leq Q^{cc}, \quad \forall\, t = 1,\ldots,T \qquad (20)$$

The ground-water levels at selected monitoring points serve as state variables and are related to the control variables through a Unit Response Matrix (URM). An Integrated Surface and Ground Water (ISGW) model developed by SDI Environmental (1997, 1999) is used to generate the URM. The system of equations that relates water levels and pumpage is expressed in terms of URM elements. To avoid non-linearity, an incremental analysis is used where ISGW predicts water levels from projected pumpage and the URM indicates water level changes for increments of pumpage. The optimization routine adjusts the projected pumpage so that the change in water levels will satisfy the objective function:

$$h_{i,t}^{u} = \varphi_{i,t}^{u} - \sum_{j} \sum_{k=1}^{K} u_{i,t,j,k}^{u} \Delta q_{j,k}, \quad \forall\, i \in R^{u};\ t = 1,\ldots,T \tag{21}$$

$$h_{i,t} = \varphi_{i,t} - \sum_{j} \sum_{k=1}^{K} u_{i,t,j,k} \Delta q_{j,k}, \quad \forall\, i \in R;\ t = 1,\ldots,T \tag{22}$$

Finally, the necessary variable bounds and non-negativity are:

$$\underline{Q}_{j} \ \leq \ q_{j,t} \ \leq \ \overline{Q}_{j}, \quad \forall\, j \in w_{n};\ n = 1,\ldots,N;\ t = 1,\ldots,T \tag{23}$$

$$d_{cc,t}^{r} \geq 0, \quad \forall r \in \{LP, CM, MB, MP\};\ t = 1,\ldots,T \tag{24}$$

$$d_{mb,t}^{MB} \geq 0, d_{mb,t}^{CC} \geq 0, d_{s21,t}^{LP} \geq 0, d_{s21,t}^{CC} \geq 0, d_{nwh,t}^{CM} \geq 0, \quad \forall\, t = 1,\ldots,T \tag{25}$$

With the incremental analysis, prevailing hydrologic conditions (i.e., actual ground-water levels) do not play a direct role in deriving the optimum solution. Instead, preferential weights (the ω_i in Equation 1) are used to establish priority water-level recovery sites that relate to recent field data at the SAS monitoring wells. High antecedent rainfall and previous pumpage reductions can cause water levels at certain locations to be relatively higher. Wells or wellfields near these locations will be the prime candidates for rotation to increase production.

MINOS (Murtagh and Saunders, 1995) is used to solve the above OROP optimization problems.

2.6 Include a weighting/ranking system to reduce environmental stress preferentially at selected locations based on surficial aquifer monitor wells

In order to establish a meaningful target value for a surficial aquifer monitoring well in the Operations Plan, it is necessary to relate the water levels in the monitoring well with water levels in a nearby wetland or lake. The selected approach uses linear regression as a form of correlation analysis, which mathematically represents the relationship between two variables as a “best fit” line, to compare surficial aquifer water levels to water levels in a nearby wetland or lake. The regression analyses are updated annually based on the collection of additional data.

An example is provided to illustrate the concept and its application. Figure 3(a) presents the mathematical association between observed water levels at a surficial aquifer monitoring well on the Starkey Wellfield (2B-East) and a nearby wetland (S-75). Based on the relationship derived from these observed data, any particular level in the wetland can be associated to a corresponding water level in the monitoring well. A water level of -0.113 m (-0.37 ft) RLS (relative to land surface) for S-75 is indicated on Figure 3(a). This level is equivalent to 13.71 m (44.99 ft) NGVD, which is the minimum level for this wetland necessary to maintain its environmental health. The associated water level in the surficial aquifer, 13.71 m NGVD, called H_T in Figure 3(b), is the corresponding target water level for monitoring well 2B-East. As water levels in this well fall below this target, the weighting factor in the optimization program, given on the x-axis in Figure 3(b), increases. The increased weighting factor signals a preference to increase water levels at this site, and causes the optimization program to reduce pumpage in nearby production wells, thus allowing water level recovery in the surficial aquifer, wetlands and lakes in the vicinity.

Actual recent water levels at the monitor wells (based on observed data) are compared to the target levels on a twice-monthly basis. The individual weighting factors for each site are updated twice monthly based on observed water levels, and are used in revising the four-week short-term analysis for pumping distributions. The weights are based on relative measures of water levels compared to the target levels set at each monitor well and are applied to reflect the deviation between actual and target levels. The weights function as a ranking system for the optimization algorithm that causes the search for an optimal solution to preferentially reduce drawdown (increase water levels) at locations with greater weight, thereby driving those water levels toward their target levels. Equal weights apply to all cases in which current water levels are equal to their respective targets. The weighting system is strongly non-linear. Sites with large water-level deficits receive considerably more weight than those where current water levels are near their targets. In certain cases, actual water levels may be above their target levels, which would result in a preference for production in that vicinity as compared to other locations in the region where water levels are below target levels.

The maximum water level (H_U) and minimum water level (H_L) depicted on Figure 3(b) are merely limits on anticipated levels resulting from a review of period of record data. These values serve mathematically as scaling coefficients for the numerical calculation of the weighting factor, and result in all sites which have water levels equal to their target levels to be weighted equally. For the optimization routine, the weight equals 10 when the observed level achieves the target level. The target level (H_T) is the reference point that controls the response of the optimization program and is the level that the program attempts to maintain.