PLANNING AND MANAGEMENT MODELING FOR TREATED WASTEWATER USAGE

L. Ahmadi[1]
G.P. Merkley[2]

ABSTRACT

Due to urban growth, some agricultural lands have been replaced by residential, municipal, and industrial areas. In some cases the remaining agricultural land will not have enough water because of transfers from agriculture to M&I users. Therefore, in many places, especially in arid and semi arid regions, the use of treated wastewater as a reliable source of irrigation water has already been or will be considered in the future. Due to its unique characteristics, this new resource has many challenges that cannot be ignored, such as health issues, water quality, long- and short-term effects on soils and crops.

This study considered the development of a new GIS-based model for planning and managing the reuse of treated wastewater for the irrigation of agricultural and green lands, considering various factors such as population and urban growth. The model is composed of several different modules, including an urban growth model. These modules help the user make better decisions for allocations of water resources to agricultural areas, considering factors such as crop types, crop pattern, water salinity, soil characteristics, pumping and conveyance costs and also by comparing different scenarios. Appropriate crops that can be grown with a specific water salinity and soil characteristics, proper water resources for each farm (according to pumping and conveyance costs, and analysis of water demand, and water supply) can be determined through the application of this model. The model can also rank agricultural areas and open spaces in and near an urban area according to their suitability for irrigated agriculture.

INTRODUCTION

This study considered the development of a new Geographic Information System (GIS)-based model for planning and managing of the reuse of treated wastewater for irrigation of agricultural lands and green areas, considering various factors such as population and urban growth. The new model will be coded in Microsoft© Visual Basic .NET and is composed of five different modules:

1- Agricultural Land Suitability Module.
2- Agricultural Land Availability Module.
3- Water Availability Module.
4- Water Storage Module.

[1] Graduate student, BIE Dept., Utah State Univ., Logan, UT 84321. Voice: (435) 797-2785. Fax: (435) 797-1248, leila.ahm@aggiemail.usu.edu.
[2] Professor, BIE Dept., Utah State Univ., Logan, UT 84321. Voice: (435) 797-1139. Fax: (435) 797-1248, gary.merkley@usu.edu.

5- Planning and Project Comparison Module

The first four modules are related to each other and GIS-based, while the last module optionally uses GIS data from the first four modules, or another data source. The details of all these modules are discussed in this paper.

AGRICULTURAL LAND SUITABILITY MODULE

The Agricultural Land Suitability Module can help planners in making better decisions for the locations of future agricultural areas. Agriculture is not possible without two important resources: appropriate lands (soil) and water. In this module, preferred lands for agriculture will be determined and ranked according to these two resources. First, it is considered that appropriate land for agriculture should have proper soil texture and land slope. Second, it should not be too far from water resources. In this study, the water resources considered are treatment plants. Therefore, to determine the appropriate locations for agricultural lands the transportation and conveyance of the water to the land should also be considered in terms of pumping and conveyance costs. Conveyance costs are related to the size of the lands and also to the distance between the land and the water resource. On the other hand, pumping cost is related to the elevation difference between land and the treatment plant, as well as the flow rate, which is related to the land area and crop water requirements.

In this study, according to the distance and the elevation difference between the treatment plant and the agricultural land, and also according to the land area, land slope, and soil texture (if available), the lands are ranked into three different levels of suitability for agriculture. Therefore the input data include:

- A current GIS map of the urban area, including land-use layer and topography layers.
- A GIS layer with the location of the water treatment plants.
- Soil characteristics, including soil texture, infiltration rate, and water-holding capacity.

The output data will include a GIS map of the area in which the available lands are ranked by three levels of suitability for agriculture.

AGRICULTURAL LAND AVAILABILITY MODULE

Through the years, due to population growth and urban growth, a lot of agricultural lands have changed and transformed to residential, municipal and industrial developments. Many studies have shown that after a few years there will not be any agricultural lands left in or near some urban area.

The Agricultural Land Availability Module helps the user determine how much time it will take for all of the agricultural area to disappear due to population and urban growth. This module is composed of two sub-modules: 1- Population Sub-module; and, 2- Land-Use Change Sub-module.

Population Sub-Module

This sub-module is responsible for the prediction of the population of an urban area in the future. The population of a society is related to the rates of birth and immigration, and to the rates of death and emigration. These factors cause the population of that society to increase or decrease.

There are many different methods for calculation and estimation of population growth of an urban area, such as the exponential method, the logistic method, and others. In this model, one of the simplest methods of estimation of population growth is used: the exponential method.

The exponential trend of population growth is shown as Malthus (1798):

$$P = P_0 e^{rt} \tag{1}$$

in which P is the future population; P_0 is the starting population; t is the duration of time; and, r is the natural rate of population increase; and, r is related to the amount of births and deaths, and also the amount of migration to or from an urban area. Therefore, the needed input data include:

- Base population of the Urban Area
- Time Duration (years)
- Growth Rate

The output from this module will simply be the population of an urban area after *t* years.

Land-Use Change Sub-Module

This module predicts the land use changes (especially for agricultural lands and green areas) in an urban area due to population and urban growth. For this sub-module, an appropriate land-use change model is used. There are many urban growth models such as GSM, INDEX, UPLAN, TRANSUS and etc. (EPA, 2004). According to the goals of this study, a Land Transformation Model (LTM) developed by Pijanowski et al.(2002) is used as a sub-module. LTM uses GIS and Artificial Neural Network (ANN) in order to forecast the land use changes.

LTM can consider many different socioeconomic, political and environmental factors that affect land use changes. These factors can be determined by the user for different case studies.

These sub-modules and especially LTM helps us to forecast after how long the agricultural area in the region of the study will disappear.

WATER AVAILABILITY MODULE

This module is composed of four different sub-modules and it calculates the amount of water demand and water supply in an urban area, comparing the results with changes in land use and population. These calculations are done in order to estimate when there will not be enough fresh water resources to support agricultural irrigation.

The sub-modules are:

1- Population Sub-Module
2- Land-Use Change Sub-Module (LTM)
3- Water Supply Sub-Module
4- Water Demand Sub-Module: 1- Municipal and industrial water use; 2- Agricultural water use.

The first two sub-modules were explained in the previous sections of this paper.

Water Supply Sub-Module

This sub-module is responsible for gathering the information about water supplies and analyzing them. Water supplies for an urban area can be divided into two parts: 1- Treated wastewater; 2- Fresh water (Surface water, ground water, and imported water). This study emphasizes on treated wastewater. The locations and capacities of the water treatment plants, the quality of the released water from different treatment plants and the time series of released water from treatment plants are some of the important input data for this module. The information for freshwater supplies is some other input data for this part of the model.

Water Demand Sub-Module

Water demand is divided into two parts:

Municipal and Industrial Water Use: In this module, M&I water use is predicted for the future of an urban area.

M&I water use is the daily per capita use, which includes (Bhave, 2003):

- Domestic water use, that is the water use for residential areas (like houses), such as water for drinking, showering, air conditioning and for watering the gardens. Domestic water demand, related to the population and economic level of users, is about 30-50% of the total water use.
- Public water use, is about 5-10% of total water use and is the water needed for public buildings such as schools, hospitals and etc.
- Commercial and Industrial water use, is the water demand for commercial and industrial purposes such as factories, shopping centers, offices and etc.(about 10-30% of total water use).

- Loss and Waste use, is about 10-20% of water that gets lost from pipes and valves, also the unauthorized usages of water and error in water-meter readings.

Therefore, the amount of municipal and industrial water use is related to many different factors, including population, city size, users' income, climate, and many other factors. According to these factors, there are different methods for forecasting the water demand in an urban area. Some of the methods are very simple and others are quite complex. The per capita method is one of the simplest methods used for water demand forecasting. This method simply multiplies the per capita use of water in an urban area by the population of that urban area for the future. The disadvantage of this model is that it ignores all other factors affecting water demand –it only considers the population. There are also some other multi-variate models, such as IWR-MAIN, that use a lot of different factors to forecast the water demand (Hillyer et al., 1998). In this study the simplest method, which is per capita, is used.

Agricultural Water Use**:** Agricultural water demand is the amount of water needed for irrigation of an agricultural land and is related to crop types, crop pattern, and climatic parameters. In this module, the amount of water needed to irrigate the remained agricultural area is calculated on yearly and monthly bases. This calculation can be done using the following equation:

$$ET_C = K_C ET_0 \tag{2}$$

in which ET_C is the evapotranspiration of a specific crop; K_C is the crop coefficient, which is different for various crops and in different growth stages. ET_0 is the reference crop evapotranspiration (FAO, 1998).

Using the above equation, the amount of water required for the irrigation of a specific crop will be calculated in mm/month. ET_0 could be calculated according to different estimation methods. In this model two methods are considered for calculation of water demand: 1) FAO Penman-Monteith equation; and, 2) Hargreaves equation.

FAO Penman-Monteith Method (FAO, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

In which:

ET_0- Reference evapotranspiration [mm day^{-1}],
R_n-Net radiation at the crop surface [MJ m^{-2} day^{-1}],
G- Soil heat flux density [MJ m^{-2} day^{-1}],
T- Mean daily air temperature at 2 m height [°C].

Hargreaves Method

This equation is more practical, due to very few data that it needs. Hargreaves equation is (FAO, 1998):

$$ET_0 = 0.0023(T + 17.78)T_D^{0.5} R_s \quad (4)$$

Where:
ET_0- Potential daily evapotranspiration (mm/day),
T- Mean temperature (°C), and;
R_s- Incident solar radiation converted to depth of water, mm/day; and;

The model also has the information of crop coefficient for different crops, saved. Crop coefficient changes the reference evapotranspiration to crop evapotranspiration. The crop coefficient is different for different crop growth stages. FAO has determined the crop coefficient for different crop types in different growth stages, which will be used in this model. Therefore, the model would be capable of estimating the water demand in agricultural area according to the crop types and crop pattern determined by the user.

Other than crop demand, for different types of water supply an extra amount of water is used for leaching in order to protect the soil from getting salty and inappropriate for agriculture. In the next part the calculation method of this excessive amount of water for leaching is shown (Feigin et al., 1990).

Leaching ratio can be calculated as follows (FAO, 1994):

$$LR = \frac{EC_W}{5EC_e - EC_W} \quad (5)$$

In which:

LR- Leaching ratio.
EC_W - Irrigation water salinity (dS/m).
EC_e - Saturated soil extract salinity for 90% yield potential.

Therefore, the calculations of water demand and water supply for the future of an urban area with more population, and comparing them can show if there will be enough water available for agricultural irrigation or not and if there is not, after how long there wont be enough water left. This calculation will also be done assuming higher water use efficiencies for municipal users.

According to the calculations of water demand for agricultural and green lands, water demand for each month can be plotted. Also, the released water data from treatment plants in different locations as input data can be plotted as water supply for each month of a year. Using these data, different analysis could be done for matching the supply and demand, such as:

1- Plotting the variation of wastewater supply and agricultural water demand during a year for different time intervals chosen by the user.
2- Comparing the changes of wastewater supply and agricultural water demand during a year and for different season, for specific time intervals defined by the user.

STORAGE MODULE

In an urban area the production of wastewater is continuously along the year, while the agricultural water demand is limited just for a short period of time in the agricultural season. Therefore, storing the treated wastewater at the season of low demand could make a reliable water resource for when it is needed especially for arid and semi arid regions. In this model, the possibilities of storing treated wastewater also will be investigated. According to the previous part, the changes of treated wastewater supplies and agricultural water demand will be available and therefore, the amount of water that can be stored can be calculated.

According to Juanico and Dor (1999) and Mancini et al.(2007), the case studies in Israel and Italy have shown besides other benefits, the wastewater reservoirs also have improved the water quality to large extents.

Storing the wastewater could be in two ways: 1- Surface reservoirs; 2- Groundwater Basins (Guymon et al., 1990). In this study just surface reservoirs will be considered.

Comparing the changes of water supply and water demand in agricultural area for specific time intervals, this module will determine if there is need for storing wastewater or not. Also the amount of water that needs to be stored will be determined by the model. Considering the pumping and conveyance costs, the open spaces near the urban area will be ranked due to suitability for building the reservoir.

It should be noted that this module is related to Water Availability Module and it can not be run without that. In other words, this module uses the output data from that module and uses them as an input module.

PLANNING AND PROJECT COMPARISON MODULE

The purpose behind making this module was to make it possible for users and decision makers to be able to check some planning options and scenarios without the need of having the GIS maps of an area. This module makes it possible for the users to check and compare different planning scenarios that they have in mind for reuse of treated wastewater for agricultural irrigation, with changing many different factors and parameters and finally to make better choices and decisions in this matter. The scenarios are compared considering the crop yield produced, environmental effects in terms of the effects of nitrate and phosphate and pumping costs.

This module is composed of two different sub-modules:

Input Sub-Module

In this part the user can define different scenarios for the model by changing various factors mentioned below.

a) Land Characteristics Sub-Module, in which the agricultural land area and locations and the distance between them and their elevation and slope would be determined by symbolic shapes such as rectangles for agricultural lands and lines for the distance between them.

b) Crop Sub-Module in which the crop types and pattern for each agricultural land could be determined.

c) Soil Sub-Module in which soil characteristics for different agricultural area if available could be determined.

d) Wastewater Sub-Module, in which the locations, time series and characteristics of water released from treatment plants would be determined.

Output Sub-Module

It should be noted that the user chooses the crop types and crop pattern for each agricultural land. Then, according to the standard quality of water for irrigation of agricultural area, the water resources (treatment plants) that are appropriate will be chosen by the model and others will be eliminated. In the next step, it will be checked if the salinity of the water resources is appropriate for the crops chosen and if it is not, how much fresh water should be added in order to be able to use that specific treatment plant as water resource. This is done by the model using the mass balance equation.

For all the water resources or scenarios these calculations are done:

1- Crop yield is calculated.

Salts in the soil water can reduce the crop yield by decreasing the ability of crop roots to take the soil water. The amount of salt till a specific threshold won't have any effect on the crop yield, but after that threshold, increase in the salt amount would decrease the yield with a linear relation (Maas and Hoffman, 1977) or S-shaped curve (Van Genuchten and Gupta, 1993).

Maas and Hoffman suggested the following equation for calculation of the crop yield under salinity stress (FAO, 1994):

$$Y = 100 - b(EC_e - EC_{eThreshold}) \tag{6}$$

in which Y is relative crop yield (percent); EC_e is salinity of the soil saturation extract (dS/m); $EC_{eThreshold}$ is the salinity of the soil saturation extract at the threshold (dS/m), which can be determined from Table 5; and b is the reduction in crop yield per unit increase in salinity, which is (FAO, 1994):

$$b = \frac{100}{EC_{e(0\%)} - EC_{e(100\%)}} \tag{7}$$

Usually, EC_e is defined as:

$$EC_e = 1.5 EC_W \tag{8}$$

where EC_w is the irrigation water salinity (dS/m).

It should be noted that the model uses this equation in order to calculate the relative crop yield reduction according to soil water salinity.

2- Each water resource is ranked according to pumping and conveyance costs (or distance between the land and the plant), and elevation changes between the plant and the land.
3- Using another model as sub-module, the effects of nitrate and phosphate are investigated on ground water and surface water. In other words, the environmental effects of nitrate and phosphate are assessed.

Two important constituents in the wastewater that have adverse effects on the environment are nitrate and phosphate. Although, they are essential nutrients for crop growth, nitrate can leach to lower levels of the soil and pollute the groundwater, which can cause health problems and phosphate and nitrate transported by irrigation runoff can pollute the surface water and increase the growth of algae (Nathanson, 2007; Feigin et al., 1990).

There are many different models that can predict the amount of nitrogen leaching to deeper layers of soil considering different factors, such as crop uptake, nitrate transport in the soil and others. Nleap (Shaffer et al, 1991), RZWQM2 (Ahuja et al., 1999), WHNSIM, HYDRUS (Simunek et al., 1998) and GLEAMS (Leonard et al., 1987) are some of these. Also, there are many models that can investigate the effects of nutrients on surface runoff from irrigation such as HYDRUS-2D, GLEAMS (Leonard et al., 1987).

In this study, considering the effects of nitrate and phosphate was important. Therefore, a model that could model the effects of water quality both on surface water and groundwater due to irrigation management practices should be chosen. GLEAMS (Leonard et al., 1987) is the model that was chosen to be used in this study as a sub-module. GLEAMS, or Groundwater Loading Effects of Agricultural Management Systems, is a field-scale mathematical model that considers the effects of non-pointsource pollution on ground water and surface runoff from a field with different agricultural management systems (Leonard et al., 1987).

All these are summarized in a table as output data and could be used by the user to decide and choose the better option and scenario.

SUMMARY AND CONCLUSIONS

Using Microsoft© Visual Basic .NET, a new model is being developed to:

- Investigate the effects of population growth and urban growth on agricultural lands and food production in terms of land (soil) and water resources availability.
- Compare different scenarios for water resources allocations for agricultural area (with the emphasis on water treatment plants as water resources), in various ways, such as: crop yield, conveyance and pumping costs and environmental impacts (in terms of the effects of nitrate and phosphate on surface and groundwater).

The model is composed of five different modules and various sub-modules, including a GIS-based urban growth model, LTM (which relies on ANN) (Pijanowski et al., 2002), and a model for investigating the effects of nutrients on groundwater and surface water, GLEAMS (Leonard et al., 1987). The main modules of this model are:

1- Agricultural Land Suitability Module.
2- Agricultural Land Availability Module.
3- Water Availability Module.
4- Water Storage Module.
5- Planning and Project Comparison Module.

The results of this model include:

- A GIS map of suitable that ranks the area for agricultural purposes, considering the soil characteristics, soil slope, water resources available and pumping and conveyance costs.
- A prediction of the time that all the agricultural area in or near an urban area will be disappeared.
- A prediction of the time when the fresh water resources won't match the demand in an urban area, assuming: 1- the current trend of water use for municipal users and; 2- higher municipal water use efficiencies.
- Prediction of the time that water resources will be limiting factors for agriculture.
- The plots of water supply (treated wastewater) and agricultural and green area water demand along a year for specific time intervals and checking if there would be a need for water storage facilities.
- Comparison of different scenarios defined by user (by changing water resources (water treatment plants) characteristics, land characteristics, crop types and pattern and etc.), in terms of crop production, conveyance and pumping costs, some environmental effects.

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