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PLANNING AND MANAGEMENT MODELING FOR  
TREATED WASTEWATER USAGE

by

Leila Ahmadi

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Irrigation Engineering

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UTAH STATE UNIVERSITY  
Logan, Utah

2011

## ABSTRACT

Planning and Management Modeling for  
Treated Wastewater Usage

by

Leila Ahmadi, Doctor of Philosophy

Utah State University, 2011

Major Professor: Dr. Gary P. Merkle  
Department: Civil and Environmental Engineering

Two computational models, including several calculation and analysis sub-models, were developed to create a tool for assessing the impact of different treated wastewater reuse options on irrigated agriculture. The models consider various aspects of treated wastewater availability (past, present, and future), wastewater quality, agricultural water demand, and the economics of conveying wastewater from treatment plants to farms. The two models were implemented using Visual BASIC.NET in a GIS environment to facilitate visualization of some of the features of an area under study, and to provide a convenient interface for user application. One of the models is for treated wastewater availability calculations, and the other is for wastewater reuse.

The water availability model has sub-models including urban population predictions, agricultural land use changes, residential water demand, agricultural water demand (evapotranspiration) for over 40 crop types, and treated wastewater analysis. The water reuse model is composed of three sub-models, including soil water and salt

balance calculations, nutrient calculations, and pumping and conveyance costs calculations. The nutrient calculation sub-model is based on an existing model, but was completely rewritten and modified in some parts to accommodate the needs and features of the water reuse model presented herein.

A sample application of the models is presented for Cache Valley, Utah. The results show a comparison of treated wastewater reuse schemes for the study area, highlighting how irrigated agriculture would best benefit from the total or partial use of treated wastewater. Two wastewater reuse scenarios were considered. The water availability model shows good agreement with other sources of information in terms of population forecast and calculation of future residential and agricultural water demand. However, according to the results from the model, the rate of increase of the urban area was much higher than the rate of decrease of the agricultural areas between the years 1992 and 2001. The future population growth and water demand increases for urban areas was calculated and validated for Logan City. Also, in the case study the model was shown to be a good tool for wastewater influent analysis for Logan City.

(230 pages)

## PUBLIC ABSTRACT

Planning and Management Modeling for  
Treated Wastewater Usage

Population growth, urbanization and water scarcity in many parts of the world has resulted in transfer of agricultural water to municipal and industrial users on one hand and excessive production of wastewater on the other hand. Due to importance of agriculture in food production and in the economy of many regions around the world, water resources management and considering new water resources (such as treated wastewater) is critical. This study focused on analyzing the effects of population and urban growth on water demand for various users and municipal wastewater quantity changes; as well as investigating the feasibility of wastewater reuse projects.

This study focuses on development of two new mathematical models using VB.NET:

1. Water Availability Model which is a suitable tool that can assist decision makers in the appropriate and judicious allocation of water resources. Forecast of future population of an urban area, analysis of urbanization on the area of various land covers, forecast of future water demand for municipal, industrial and agricultural users and also analyzes the excessive quantity of wastewater production are some of the calculations considered in this model.
2. Water Reuse Model assists the decision makers in choosing the appropriate water reuse project, with proper crop types, and suitable water management with the least undesirable environmental effects on ground water and surface water. The Water Reuse Model was developed to allow the user define up to three scenarios

after providing the following parameters: land data; soil data; crop data; climate data; and water resources data. The Water Reuse Model is responsible for comparing the scenarios defined by the user in various aspects, such as: Crop yield; changes of soil salinity; environmental effects (nitrogen and phosphorus leached to ground water and lost to runoff); and pumping and conveyance requirements and costs of water delivery to farmland.

Both of the models were successfully developed, tested, and validated (for a case study in Utah) as part of this research.

To my parents: Aliasghar and Zohreh

and

To my sisters: Azita, Rozita and Aida

## ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the people without whom finishing this research would have not been possible.

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Leila Ahmadi



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## CHAPTER 1

### INTRODUCTION

“Urbanization is one of the most evident global changes” (Leao et al. 2004). Large amounts of area covered by farms, deserts, forests and wetlands in 1900s in the United States have changed to human settlements over the course of a single century (USGS 1999). According to Fulton et al. (2001), during a period of 15 years, from 1982 to 1997, the amount of urbanized land area in United States increased by about 47%, while the population growth was only 17%. Urban growth and the increase of population in urban areas are causing social problems throughout the world. In the last 200 years, the world population has increased six times, while the urban population has increased 100 times, which means less land area per person (USGS 1999). Also, the world population is estimated to grow from 6.1 billion in 2000 to 8.9 billion in 2050 (a 46% increase) (United Nations 2004).

Urbanization and attraction of urban areas has drawn more people to cities in recent years. In 1800 only 3% of population of the world lived in urban areas, but in 1900, 14% lived in cities and urban areas. In 1950 this amount increased to 30%, and in 2000 the population that lived in urban areas increased to 47%. According to the U.S. EPA (2004), by 2020 more than half the total population of Asia, Africa, and Latin America will be living in cities (Fig. 1.1). It is estimated that around 60% of the population of the world will be living in cities by 2020 (Balasubramanian and Choi 2010).

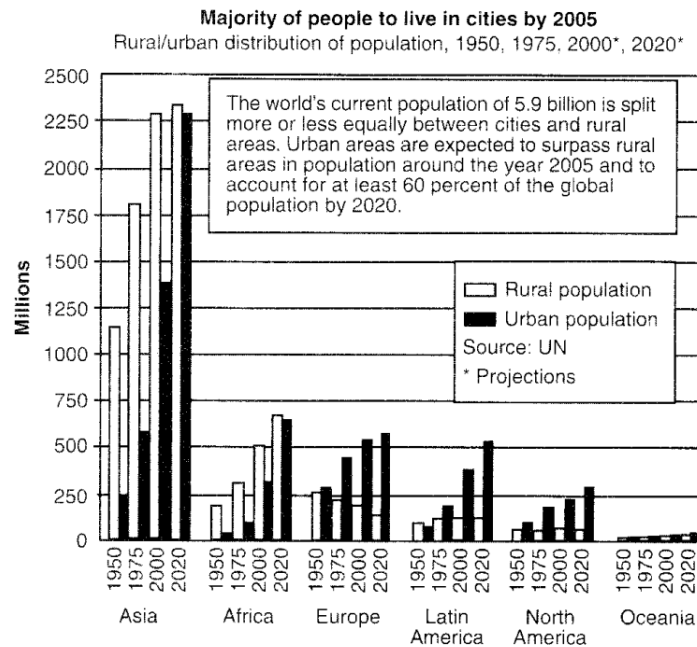


Figure 1.1. World population in cities in different continents during the 1950-2020 period (U.S. EPA 2004).

The rapid growth of the world's cities has put pressure on land and other resources (Leao et al. 2004). According to the Population and Habitat Program (2000), every year population growth adds about 78 million people to the world, while 27 million tons of topsoil is lost. In the United States of America (USA) more than 3 million acres of the best farmland is lost annually. Urbanization has decreased the area of agricultural lands in the USA in the last 50 years and is accelerating. Some of the best farmlands in the USA are around major cities, and are in danger of being lost due to population and urban growth. Also, since irrigated lands are more productive compared to rain-fed lands, and also due to population growth and more demand for food production every year, irrigation water demand has risen. In 1970 49,795,795 acres were irrigated, while in 2000 63,091,256 acres of land were irrigated in the USA (Irrigation at

K-State Research and Extension 2011). Therefore, population and urban growth have put pressure on natural resources around the world.

One of the most important natural resources that is under a crisis situation in the beginning of the twenty-first century is water. Limited water resources, uneven distribution of water resources, and continuing population growth have made the scarcity of water an important challenge throughout the world, especially in arid and semi-arid regions. According to hydrologists, if all the water in the world (fresh water, rivers, oceans, glaciers, and so on) is spread on the Earth, the whole Earth would be flooded with 3 km of water depth (Vigneswaran and Sundaravadivel 2004). Only 2.53% of the total water on Earth is fresh water; all the rest is salty or brackish water. Around two thirds of the fresh water is in glaciers and permanent snow and ice covers and is not currently usable by humans.

The distribution of water resources and population is not equivalent in different parts of the world. North America has about 8% of the total population of the world and 11% of the total available fresh water resources of the world (United Nations 2003). The Western USA is known for its low precipitation and arid and semi-arid climate. On the other hand, Western USA has the fastest population growth in the United States. According to U.S. Census Bureau, in 2000 around one third of the population of the US resides in 17 western states, and 7 of the 10 fastest growing states in USA are in the west; this trend is expected to continue in future years. According to Anderson and Woosley (2005), Utah is ranked number four in growth among all the USA states, with a population growth of 29.6% from 1900 to 2000. In 1995, 86% of the total water used for irrigation in USA was applied in the Western USA (Anderson and Woosley 2005). Therefore, water

availability has become a serious and critical issue in the Western US. Considering the large amounts of water demand in the USA, the pressure on water resources, and future problems from shortage of water will continue to rise (Anderson and Woosley 2005). Water use in the USA is around 150 gallon per person per day, compare to 0.5 gallons per person per day that is needed for humans to survive. One thousand and three hundred gallons per person per day is the total amount of water that agricultural and industrial users consume in the USA (Anderson and Woosley 2005). Agriculture is the world's largest water user (United Nations 2003) (Fig. 1.2).

However, due to population and urban growth and scarcity of water, water resources are being transferred from agricultural users to municipal and industrial (M&I) users. In many countries around the world, agriculture has a very important role in the economy. Therefore, ignoring or decreasing agricultural practices weakens the economy, and may make the country dependent on other countries.

According to Rosegrant et al. (2009), agriculture will remain the largest water

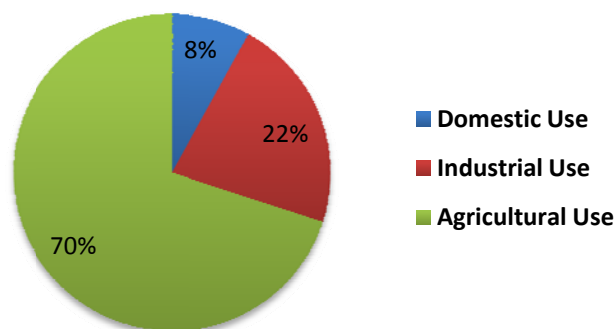


Figure1.2. Percentage of water use for different water users, worldwide (after United Nations 2003).

user and has to compete for the water with M&I users. Therefore, because of:

1. Scarcity of water manifested in many areas;
2. Population growth (and an increase in the amount of wastewater produced);
3. Urban growth (more need for water in industry and cities) and
4. Global climate change

other options should be considered to secure the agriculture and food production for the growing population. Wastewater is being produced and is increasing with growing population and urban area development. Dealing with wastewater is an important environmental issue in many parts of the world.

Efficient on-farm water management practices, water conservation methods, desalinization and water reuse are some of the methods to deal with the shortage of water. In many arid and semi-arid countries replacing of good-quality water resources with unconventional water sources, including wastewater effluents, as a new water resource for different uses has been seriously considered. Treated wastewater could be a more reliable water resource and is produced through the whole year, while fresh water sources are limited and are highly related to climatic conditions. Therefore, reuse of treated wastewater can be a win-win solution to regain some of the water transferred from agriculture to M&I for agriculture.

Although due to different and special characteristics of this resource, compared to fresh water resources, using wastewater has regulated in many related questions and problems. Kretschmer et al. (2011) have summarized the advantages and disadvantages and risks of reuse of treated wastewater for irrigation, as shown in Table 1.1.

Table 1.1. Advantages and disadvantages and risks of wastewater reuse (Kretschmer et al. 2011)

Advantages	Disadvantages	Risks
<p>Improvement of the economic efficiency of investments in wastewater disposal and irrigation</p> <p>Conservation of freshwater sources</p> <p>Recharge of aquifers through infiltration water (natural treatment)</p>	<p>Wastewater is produced continuously throughout the year where as wastewater irrigation is limited to the growing season</p>	<p>Potential harm to ground water due to heavy metal, nitrate and organic matter</p>
<p>Use of the nutrients of the wastewater (e.g. nitrogen and phosphate) ⇒ reduction of the use of synthetic fertilizer ⇒ improvement of soil properties (soil fertility; higher yields)</p>	<p>Some substances that can be present in wastewater in such concentrations that they are toxic for plants or lead to environmental damage</p>	<p>Potential harm to human health by spreading pathogens</p>
<p>Reduction of treatment costs: Soil treatment of the pre-treated wastewater via irrigation (no tertiary treatment necessary, highly dependent on the source of wastewater)</p>		<p>Potential harm to the soil due to heavy metal accumulation and acidification</p>
<p>Beneficial influence of a small natural water cycle</p>		
<p>Reduction of environmental impacts (e.g. eutrophication and minimum discharge requirements)</p>		

Due to the importance of the role of wastewater reuse as a new resource in many parts of the world in the present and in the near future, many studies have been done and are in progress to understand and analyze aspects of its use. Some of the challenges that were mentioned in the “Opportunities and Challenges in Agricultural Water Reuse” Conference in Santa Rosa, California, in October 2006, are summarized below:

- Wastewater treatment methods;
- Water quality problems and health aspects of use of reclaimed water for agricultural irrigation;
- Public perception of reuse of treated wastewater for agricultural irrigation; and
- Short term and long-term effects of reuse of reclaimed water for irrigation. These effects might be on soil characteristics (salinity problems), on crops, on surface water, on groundwater, on human health, on economy, and on the environment in general.

Although numerous researchers have worked on these challenges, there are still many unanswered questions on reuse of wastewater for agricultural irrigation, and there is still a long way to go in this area of research.

Table 1.2 shows the historical development of water reuse in the USA and other parts of the world (Tchobanoglous et al. 2003). Van Rooijen et al. (2005) stated that “irrigating with wastewater can compensate for the decrease in the amount of existing irrigated areas due to transfers to urban areas.” In addition to preserving scarce water sources while providing sustainable agriculture, the use of treated wastewater for irrigation may decrease the level of treatment required and treatment costs (because of



the bio-filter role of soil and crops), and also may decrease or diminish the use of fertilizers (Haruvy 1998).

Decision-making related to wastewater reuse should consider both aspects of benefits and hazards. Hazards can be decreased by improving effluent quality and/or conveying effluents to distant locations away from human populations, both of which involve increased costs. The proper reuse of wastewater in agriculture depends on various factors including water quality, the best irrigation method for that water, and the effects (short- and long-term) of reuse of treated wastewater on crops, soil, groundwater, surface water, economy, human health, and the environment.

Due to water shortage and to meet the water demand for various users, in some regions at the present time, and in other regions in the near future, it will be necessary to use treated wastewater for some purposes, especially for agricultural irrigation. Good planning and management are essential prerequisites for successful and optimum use of any water resource in irrigation. Accordingly, irrigation water planning and management has been practiced for a long time around the world.

Due to the specific characteristics of water resources and other dynamic conditions, irrigation planning and management will necessarily change. Treated wastewater is a different water resource with different characteristics than other sources (e.g., surface water and groundwater) that have primarily been used for agricultural irrigation.

The amount of treated wastewater is related to the population of an urban area, and this resource is generally available wherever there is an urban area. According to

Table 1.2. Historic development of wastewater reuse in the U.S. and other parts of the world (Tchobanoglous et al. 2003 and Asano 2001)

<b>Year</b>	<b>Location</b>	<b>Water Use Example</b>
1912-1985	Golden Gate Park, San Francisco, California, US	Watering lawns and supplying ornamental lakes
1926	Grand Canyon National Park, Arizona, US	Toilet flushing, lawn sprinkling, cooling water, and boiler feed water
1929	City of Pomona, California, US	Irrigation of lawns and gardens
1942	City of Baltimore, Maryland, US	Metals cooling and steel processing at the Bethlehem Steel Company
1960	City of Colorado Springs, Colorado, US	Landscape irrigation for golf courses, parks, cemeteries, and freeways
1961	Irvine Ranch Water District, California, US	Irrigation, industrial and domestic uses, later including toilet flushing in high-rise buildings
1962	County Sanitation Districts of Los Angeles County, California, US	Ground water recharge using spreading basins at the Montebello Forebay
1962	La Soukra, Tunisia	Irrigation with reclaimed water for citrus plants and to reduce saltwater intrusion into ground water
1968	City of Windhoek, Namibia	Advanced direct wastewater reclamation system to augment potable water supplies
1969	City of WaggaWagga, Australia	Landscape irrigation of sporting fields, lawns, and cemeteries
1970	Sappi Pulp and Paper Group, Enstra, South Africa	Industrial use of reclaimed municipal wastewater for pulp and paper processes
1976	Orange County Water District, California, US	Ground water recharge by direct injection into the aquifers at Water Factory 21
1977	Dan Region Project, Tel-Aviv, Israel	Ground water recharge via basins, pumped ground water is transferred via a 100 km-long conveyance system to southern Israel for unrestricted crop irrigation

Table 1.2. (Continued) Historic development of wastewater reuse in the U.S. and other parts of the world (Tchobanoglous et al. 2003 and Asano 2001)

<b>Year</b>	<b>Location</b>	<b>Water Use Example</b>
1977	City of St. Petersburg, Florida, US	Irrigation of parks, golf courses, schoolyards, residential lawns, and cooling tower make-up water
1984	Tokyo Metropolitan Government, Japan	Water recycling project in Shinjuku District of Tokyo providing reclaimed water for toilet flushing in 19 high-rise buildings in highly congested metropolitan area
1985	City of El Paso, Texas, US	Ground water recharge by direct injection into the Hueco Bolson aquifers, and power plant cooling water
1987	Monterey Regional Water Pollution Control Agency, California, US	Monterey Wastewater Reclamation Study for Agriculture--agricultural irrigation of food crops eaten uncooked including artichoke, celery, broccoli, lettuce, and cauliflower
1989	Shoalhaven Heads, Australia	Irrigation of gardens and toilet flushing in private residential dwellings
1989	Consorti de la Costa Brava, Girona, Spain	Golf course irrigation

water usage in most urban areas, there is a more constant outflow of this resource than surface flow from natural streams. Therefore, so many special characteristics of this water resource (such as water quality, availability, and others) make irrigation water planning and management with this resource significantly different compared to other sources.

In this study, treated wastewater planning and management is considered, taking into account the effects of urbanization, population growth, and transfer of fresh water resources from agriculture to M&I. Planning of the treated wastewater will create a

mutually beneficial situation for both agriculture and M&I. That is, the additional treated wastewater produced by growing M&I areas must be discharged to receiver environment destination. In many cases treated wastewater can be used for irrigated agriculture, which may have had some of its fresh water sources, transferred to M&I users. There are many aspects and issues that need to be considered for reuse of treated wastewater for irrigation but not all of these issues can be addressed in one research. In the study presented herein, some aspects of reuse of treated wastewater such as environmental effects on surface and ground water and economic estimations of water pumping and conveyance are considered.

## CHAPTER 2

### LITERATURE REVIEW

As mentioned in Chapter 1, population and urban growth has generally resulted in the following outcomes:

- An increased water demand;
- Increased amount of wastewater production;
- Transformation of agricultural lands to urban areas; and
- Transfer of water from agricultural to municipal users.

Due to the growing pressure on the freshwater resources and population and urban growth, water resources with lower quality have been considered as potential reliable sources for agricultural irrigation.

There have been many studies done throughout the world on the effects of population and urban growth on agriculture, reuse of treated wastewater, and effects of reuse of treated wastewater on crop, soil, and groundwater and surface water quality, but some of these studies are described below.

#### 2.1. Population Growth Methods

The population of a society is related to the rate of birth and death and the rate of net immigration. These factors cause the population of the society to increase or decrease. The British economist, Thomas Malthus (1798), published a famous book named *An Essay on the Principle of Population*. According to his book, population grows exponentially while other resources such as food increase linearly. He believed that

ignoring this trend of population growth will cause starvation, war, disease, and other calamities.

The exponential trend of population growth is shown as:

$$\frac{dP}{dt} = rP \quad (2.1)$$

$$P = P_0 e^{rt} \quad (2.2)$$

In which P is the population in the future,  $P_0$  is the starting population, t is the duration of time, and r is the rate of natural population increase. The parameter r is related to the amount of births and deaths, and also the amount of migration to or from an area.

In 1838, the Belgian Pierre-Francois Verhulst suggested a revised model which eliminates the undesirable effect of unlimited growth. Verhulst (1838) modified the model as follows:

$$\frac{dP}{dt} = rP - \mu P^2 \quad (2.3)$$

He assumed that when the population increases compared to resources, the rate of death will increase due to wars for limited amount of resources and food. Therefore, he put a new parameter as “mortality,” or  $\mu$ , in his equation. Defining:

$$K = \frac{\mu}{r} \quad (2.4)$$

as the Carrying Capacity (maximum sustainable population) of the environment, the equation will be:

$$\frac{dP}{dt} = rP \left( \frac{K-P}{K} \right) \quad (2.5)$$

This kind of model is called logistic model or S-curved model. The solution of the logistic differential equation is:

$$P = \frac{K}{1 + \exp(-r(t - P_0))} \quad (2.6)$$

## 2.2. Land Use Change Models

According to Clarke et al. (1997), “the most striking human-induced land transformation of the current era is urbanization.” Urbanization is the transformation of natural land cover to artificial land cover or human settlements and workplaces. This rapid trend of urbanization has had many effects on human life (Clarke et al. 1997).

In order to obtain a better understanding of urban growth and its effects and to develop better planning and management programs, urban growth modeling has often been considered (Leao et al. 2004). Large-scale urban growth models began to be used in the early 1960s, but they mostly failed around one decade later. Lee (1973) criticized these kinds of models in his “Requiem for Large Scale Models.” He mentioned seven “sins” for these models: (1) hyper-comprehensiveness; (2) grossness (the level of details was too coarse for policy makers to apply themodels); (3) hungriness (enormous data requirements); (4) wrong headedness (lack of a theoretical structure); (5) complicatedness; (6) mechanicalness; and (7) expensiveness.

Many urban growth and land use change models have been developed after Lee’s “requiem,” and there are still many research centers in the world that are working on these kinds of models (Wegener 1994). Continued development of these models has

been possible because of progress in computer technology, theory concepts, and data availability due to new tools such as geographic information systems (GIS).

There are numerous other urban growth and land-use changes models. These include the following: BOYCE, HUDS,ITLUP, KIM,LILT, MEPLAN, METROPILUS, POLIS,RURBAN, TRANSUS, What if?, and 5-LUT (Wegener 1994). Sietchiping (2004), made a simple comparison of some of these models. This comparison is shown in Table 2.1.

Table 2.1. GIS-based models and the purpose of their development according to U.S. EPA (2004)

<b>Model</b>	<b>Developer</b>	<b>Purpose</b>
Growth Simulation Model (GSM)	Maryland Department of Planning, Baltimore, Maryland. Contact: Joe Tassone	Projects population growth and new development effects on land use/land cover under alternative land management.
INDEX	Criterion Planners/Engineers, Inc.	Measures the characteristics and performance of land-use plans and urban designs with "indicators" derived from community goals and policies.
Land Transformation Model (LTM)	Dr. Bryan C. Pijanowski, Michigan State University	Integrates a variety of land use change driving variables to project impact on land use on a watershed level.
Land-Use Change Analysis System (LUCAS)	Michael W. Berry, et al., Department of Computer Sciences, University of Tennessee	Examines the impact of human activities on land use and the subsequent impacts on environmental and natural resource sustainability.
Sub-Area Allocation Model-Improved Method (SAM-IM)	Planning Technologies, LLC	Creates new land use scenarios that reflect alternative development concepts for the future.



Table 2.1.(Continued) GIS-based models and the purpose of their development according to U.S. EPA (2004)

<b>Model</b>	<b>Developer</b>	<b>Purpose</b>
Smart Growth INDEX	Criterion Planners/Engineers, Inc. (with Fehr & Peers Associates, Inc.)	Evaluates transportation and land-use alternatives and assesses their impact on travel demand, land consumption, housing and employment density, and pollution emissions.
Smart Places	Electric Power Research Institute (EPRI). Contact: Paul Radcliffe	Assists communities in the simulation and evaluation of land-use development and transportation alternatives using indicators of environmental performance.
TRANSUS	Modelistica	Analyzes the effects of land-use and transportation policies or combinations of policies on the location of various activities and the land market.
UPLAN	Robert Johnston, Department of Environmental Science and Policy, University of California at Davis	Creates alternative development patterns in response to changes in development and fiscal scenarios.
UrbanSim	Paul Waddell, Daniel J. Evans School of Public Affairs, University of Washington	Explores how the interactions between land use, transportation, and public policy shape a community's development trends and affect the natural environment.
What if?	Dr. Richard E. Klosterman (As Community Analysis and Planning Systems, Inc.)	Supports comprehensive community land-use planning in regard to determining land suitability for development, projecting future land-use demand, and providing the capability to allocate the demand to the most suitable locations.

SLEUTH is another GIS-based land use change model developed by Clarke et al. (1997). SLEUTH is an acronym for the input data needed to run the model: Slope, Land cover, Exclusion, Urbanization, Transportation and Hill shade. SLEUTH is a cellular, raster-based automaton model. It has two sub-models: The Urban Growth Model (UGM), and the Deltatron Land Use/Land Cover Model (DLM). This model considers four different types of urban growth: spontaneous, diffusive, organic, and road-influenced. Five factors control the behavior of the system: (1) diffusion; (2) breed; (3) spread; (4) slope resistance; and (5) "road gravity" (road-influenced growth) (Jantz et al. 2003; Clarke et al. 1997).

CUFM, the California Urban Futures Model, is a raster-based, GIS-based model developed by John D. Landis (Landis 1994). This model is the first model to incorporate GIS. UPLAN is a rule- and raster-based urban growth model, developed in ArcView® GIS by Johnston and Shabazian (2002). This model was developed for joint land-use and transportation planning. UPLAN uses any year as a base and then allocates the land use changes for the future. UPLAN allows the user to define demographic and land use density factors that can be converted to land area for each type of land use. The required data for this model can be found in most regions. These data are: 1. Attraction Grids (Freeway ramps; Highways; Major arterials; Minor arterials; Cities; Passenger rail stations; Airports; and Seaports); and 2. Exclusion Grids (areas where development cannot occur) (land use plans; rivers; lakes; vernal pools (seasonal wetlands); floodplains; slope; public Lands; existing urban; permanent open space; and farmlands) (Johnston and Shabazian 2002).

NAUTILUS (Northeast Applications of Usable Technology in Land Planning for Urban Sprawl), which is a NASA based center, has developed a model that quantifies and characterizes urban growth while maintaining the spatial detail of the source satellite imagery. This model is based on two dates of satellite-derived land cover and produces an output map identifying five types of urban growth: in-fill, expansion, isolated, linear branching and clustered branching. This model, like other models, has some limitations. The results are as good as the input land cover data, and there is always some error associated with land cover and other input data. Using two land cover definitions as input data can compound the error and cause inaccuracy in output data. Furthermore, the date of image capture in conjunction with the date of development can influence the type of growth. This model can be used to assist local decision-making process (Wilson et al. 2002).

The Salt River Project (SRP) is an irrigation water project developed approximately 100 years ago to supply water to 100,000 hectares of land in South Central Arizona. About 85% of the farmland served by SRP changed to urban area, and this change affected the operation and maintenance of the irrigation systems. SRP developed a series of four models called Water System Delivery Capacity (WSDC) (Gooch and Siewert 2006), all of which are currently under continued improvement:

1. Land Use Forecast Model
2. Water Demand Forecast Model: This model projects water demands for agricultural and municipal uses.
3. Trace Model, use GIS data on the facilities, and using the flow direction, calculates the water being demanded or supplied by delivery structures.

4. Canal Hydraulic Model: When the flow in the canal from Trace Model is greater than the nominal capacity of the canal, the HEC-RAS model is used to determine the free board and perform weir calculations in order to check if the canal cross-regulating structures can control the flow effectively and safely.

### 2.3. Wastewater

Wastewater is the water that has been used in different applications in a community. According to its source of generation, wastewater can be divided into industrial, residential, and institutional (Tchobanoglous et al. 2003).

Physical, chemical, and biological characteristics of the wastewater are summarized in Table 2.2, by Muttamara (1996). Important contaminants in wastewater treatment are shown in Table 2.3 (Mattumara 1996).

According to Tchobanoglous et al. (2003), wastewater produced by a community has to be returned to the receiving waters or reused. However, the important concern is the protection of the public health and the environment, which is achieved by treatment of wastewater.

Several treatment levels can be considered for wastewater (Pescod 1992):

- Preliminary
- Primary
- Secondary
- Tertiary

Table 2.2. Physical, chemical, and biological characteristics of the wastewater (Muttamara 1996)

Characteristic	Sources
<b>Physical Properties:</b>	
Color	Domestic and industrial wastes, natural decay of organic materials
Odor	Decomposing wastewater, industrial wastes
Solids	Domestic water supply, domestic and industrial wastes, soil erosion, inflow-infiltration
Temperature	Domestic and industrial wastes
<b>Chemical Constituents:</b>	
<b>Organic:</b>	
Carbohydrates	Domestic, commercial and industrial wastes
Fats, oils and grease	Domestic, commercial and industrial wastes
Pesticides	Agricultural wastes
Phenols	Industrial wastes
Proteins	Domestic and commercial wastes
Surfactants	Natural decay of organic materials
Others	
<b>Inorganic:</b>	
Alkalinity	Domestic wastes, domestic water supply, groundwater infiltration
Chlorides	Domestic water supply, domestic wastes, groundwater infiltration, water softeners
Heavy metals	Industrial wastes
Nitrogen	Domestic and agricultural wastes
pH	Industrial wastes
Phosphorus	Domestic and industrial wastes, natural runoff
Sulfur	Domestic water supply, domestic and industrial wastes
Toxic compounds	Industrial wastes
<b>Gases:</b>	
Hydrogen sulfide	Decomposition of domestic wastes
Methane	Decomposition of domestic wastes
Oxygen	Domestic water supply, surface-water infiltration
<b>Biological Constituents:</b>	
Animals	Open watercourses and treatment plants
Plants	Open watercourses and treatment plants
Protista	Domestic wastes, treatment plants
Viruses	Domestic wastes

Table 2.3. Important contaminants in wastewater treatment (Muttamara1996)

<b>Contaminants</b>	<b>Reason for Importance</b>
Suspended solids	Suspended solids can lead to the development of sludge deposits anaerobic conditions when untreated wastewater is discharged in the aquatic environment.
Biodegradable organics	Composed principally of proteins, carbohydrates, and fats, biodegradable organics are measured most commonly in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand). If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and to the development of septic conditions.
Pathogens	Communicable diseases can be transmitted by the pathogenic organisms in wastewater.
Nutrients	Both nitrogen and phosphorus, along with carbon, are essential nutrients for growth. When discharged to the aquatic environment, these nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of groundwater.
Refractory organics	These organics tend to resist conventional methods of wastewater treatment. Typical examples include surfactants, phenols, and agricultural pesticides.
Heavy metals	Heavy metals are usually added to wastewater from commercial and industrial activities and may have to be removed if the wastewater is to be reused.
Dissolved inorganic solids	Inorganic constituents such as calcium, sodium, and sulfate are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused.

Coarse solids and large particles are removed from the raw wastewater during the preliminary treatment method. During primary treatment method settleable organic and inorganic solids and the floating materials are removed. Removal of organic residuals and suspended solids are done during a secondary treatment procedure. Tertiary (advanced) wastewater treatment method removes some constituents that were not eliminated during

the secondary treatment. Removal of some nutrients and heavy metals are the purpose of tertiary treatment (Tchobanoglous et al. 2003; Pescod 1992).

Sometimes, a disinfection method for removal of pathogens is used as the last step of wastewater treatment procedure. This is done by injection of a chlorine solution at the head of a chlorine basin (Pescod 1992).

Due to population and urban growth and water shortage in many parts of the world reuse of water is considered. Major reuse applications are (U.S. EPA 2004):

- Urban;
- Industrial;
- Agricultural;
- Environmental and recreational;
- Groundwater recharge; and
- Augmentation of potable supplies.

Urban reuse considers various non-potable applications such as irrigation of the public parks, school yards, golf courses, athletic fields, and landscaped areas surrounding the residential area or the commercial developments. Industrial reuse applications include cooling water and boiler make-up water. Irrigation of the agricultural fields is the agricultural application of water reuse. Wetland enhancement and restoration, wetland creation for wildlife habitats and refuges, and stream augmentation are some of the environmental reuse applications. Augmentation of potable supplies is composed of direct potable reuse and indirect potable reuse via surface water augmentation and groundwater recharge (U.S. EPA 2004).

In the next section some case studies around the world that agricultural water reuse projects were practiced, are described.

#### 2.4. Case Studies for Reuse of Treated Wastewater for Agricultural Irrigation

A high rate of population growth, pollution of surface water and groundwater, uneven distribution of water resources, and periodic droughts have made the reuse of treated wastewater a viable water supply option. Agricultural irrigation is the largest current user of reclaimed water (Tchobanoglous et al. 2003). It is estimated that up to one-tenth of the world's population eats food produced using wastewater. As populations continue to grow and more freshwater is diverted to cities for domestic use (70% of which later returns as treated or untreated wastewater), the use of wastewater is certain to increase, both in terms of the areas irrigated and in terms of volumes applied.

Reuse of wastewater has been practiced since historical times but planned reuse has been considered mostly since two to three decades ago due to water resource deficiencies due to population and urban growth. Reuse of wastewater for agricultural irrigation in Greece was practiced 5000 years ago in Minoan civilization, and in Germany and the United Kingdom (UK) its use goes back to the 16<sup>th</sup> and 18<sup>th</sup> centuries. Reuse of wastewater in India and China has a long history as well (Vigneswaran and Sundaravadivel 2004). Before the introduction of treatment technologies, in many European and North American cities wastewater was used on agricultural lands for the prevention of pollution of water bodies. In developing countries such as China, Mexico, Morocco, Lebanon, Egypt, Peru, India and Vietnam, wastewater has been used as a good



source for crop nutrients for several decades (Drechsel et al. 2010). However, many issues such as environmental pollution and health were not clear at that time.

Wastewater reuse has been practiced indirectly in Egypt for centuries; however, formal wastewater reuse initiated in 1911 at a location called El-Gabal El-Afsar farm, Northeast of Cairo. The primary treated effluent was used for irrigation of 3,000 feddan (2.4 feddan is approximately equal to 1 ha) land for producing citrus, date palm, and pecan crops (Selim 2006; Misheloff 2010).

In Argentina, only 35% of the population is connected to sewer systems, and only a small percentage of the collected sewage undergoes appropriate treatment. Since the beginning of the 20<sup>th</sup> century, in densely populated areas in western parts (arid regions), there has been large-scale reuse of untreated wastewater for agricultural irrigation. The largest water reuse system in Argentina is located in Mendoza in the western part of the country, near the Andes Mountains. Treated wastewater in this region is an important water resource for irrigating over 3,640 ha of forests, vine yards, olives, alfalfa, fruit trees and other crops. Over 160,000 cubic meters per day of urban wastewater is treated by one the largest “lagooning” systems in the world at the Campo Espejo wastewater treatment plant, with a total area of 290 ha to meet WHO standards for unrestricted irrigation uses (U.S. EPA 2004).

Peru is another Latin American country that has water shortage problems. Only 5% of the sewage in Peru is treated before discharge. The reuse of mostly raw sewage has been practiced for agricultural irrigation of vegetables, fodder, forest trees, cotton, and other crops. Outside Lima, the capital city, about 5,000 ha of land is irrigated with

raw (untreated) wastewater. And at Tacna, in southern Peru, effluent treated in lagoons is used for the irrigation of 210 ha of land (U.S. EPA 2004).

In some parts of Italy, especially the southern parts, water availability does not match water demand. Therefore, farmers have been using wastewater in irrigation without any control. In northern and central Italy, available water matches the water demand. In these parts, wastewater reuse could be useful for controlling the pollution of water bodies (Barbagallo et al. 2001). According to Barbagallo et al. (2001), many wastewater reuse projects have been implemented in water scarce parts of Italy such as Sicily for irrigation of citrus orchards.

The Virginia Pipeline Project in Australia has been operating since 2000 and transports over 5,284 million gallons of reclaimed water (about 20% of the wastewater produced in the Adelaide area) from the Bolivar Treatment Plant, north of Adelaide, to the Virginia area in southern Australia. After secondary treatment of the wastewater at the plant, further treatment processes are utilized to reach the Australian standard for irrigation of those crops that are consumed uncooked. This system serves more than 220 farmers who produce root and salad crops, *bassicas*, wine grapes and olives (U.S. EPA 2004). Also, in Canberra, the Australian capital city, wastewater reuse is being tried (Neal 1995).

Sweden has a relatively large amount of freshwater. The highest water demand is for industry (55%), while the municipal and agricultural demands are 36% and 6%, respectively. However, in the southeast parts of Sweden the agricultural demand is greater and precipitation is less. More than 40 irrigation projects with treated wastewater have been constructed in that part of the country. The wastewater is stored in large

reservoirs for up to nine months before being used for irrigation, with or without blending with surface water. Two main benefits have been reported for these projects: first, an efficient, safe and cost-effective method of wastewater treatment and for recycling nutrients and second, a new water resource for agricultural irrigation, which saves groundwater resources for other purposes (U.S. EPA 2004).

In Sardinia, as in most Mediterranean countries, water scarcity is a concern. Recurrent droughts have increased the problems due to water shortage and made the agricultural sector suffer the water deficit. Therefore, the reuse of water in agricultural irrigation is considered as a desirable source to replace the insufficient amount of water supply. For this purpose, the water released from the “Is Arenas” treatment plant, which serves the city of Cagliari and its suburbs was considered as a source of irrigation water. Development of a tertiary treatment plant downstream of the “Is Arenas” plant in order to decrease the amount of phosphorus and bacteria, before the effluent is released in the Simbirizzi Reservoir, was part of the project. The water in the reservoir irrigates around 7,900 ha of area inside the irrigation district of Southern Sardinia. The tertiary treatment plant has been operating since 2002. This project appears to have been a good solution to the water scarcity problems and environmental protection issues (Botti et al. 2009).

Reuse of untreated wastewater for agricultural irrigation is common in most parts of Pakistan. The main crops cultivated in these areas are vegetables, fodder, and wheat. In Faisalabad, the third largest city in Pakistan, more than 2,000 ha of agricultural lands are irrigated with untreated wastewater. In Faisalabad farmers prefer to use untreated wastewater rather than treated wastewater because it is considered to be more nutrient-rich and less saline than treated wastewater. There are two main sites in Faisalabad:

(1)the Narwala Road Site; and (2) the Channel 4 Site. Farmers combine the wastewater with brackish groundwater at the Channel 4 site because of the toxicity of the wastewater (U.S. EPA 2004).

In Oman, another dry country, 90% of the treated effluent in the capital area since 1987 has been reused for agricultural irrigation of tree plantations by drip irrigation. It is noted that there are regulations for reuse of treated wastewater for irrigation in Oman. According to these rules, wastewater is classified into two categories: (1)Standard A (200Fecal Coliforms/100ml, less nematode ova/l) for irrigation of vegetable and fruit and landscape areas with public access and(2) Standard B (1000Fecal Coliforms/100ml, less nematode ova/l), for irrigation of cooked vegetables, fodder, cereals and area with no public access (U.S. EPA 2004).

Israel is another semi-arid country that is facing water shortage problems. Water reuse represents about 10% of the total national water use and almost 20% of the total water supply for irrigation. Almost 65% to 70% of the municipal wastewater is treated and reused for irrigation (Tal et al. 2003). The two largest reuse projects in Israel are the Dan Region Scheme and Kishon Scheme. In the KishonScheme 8450 mg/yr of wastewater from the Haifa metropolitan area is treated by conventional activated sludge systems. After treatment this water is transported to Yisre'el Valley, mixed with local waste and storm water, and then stored in a reservoir for summer irrigation of 15,000 ha of cotton and other non-edible crops. The facilities of the Dan Region reuse system that serves the Tel Aviv metropolitan area include a mechanical biological plant. After this treatment the water is discharged for storage in aquifer recharge basins. Then the treated water is pumped from recovery wells and transported to irrigated areas in the southern

coastal plains and the northern Negev area. There are also three other important water reuse projects in Jeezrael Valley, Gedera, and Getaot Kibbutz, which produce reclaimed water for irrigation of more than 40,000 ha of agricultural lands (U.S. EPA 2004).

Haruvy (1998) has said that by the year 2040, treated wastewater will be the main source of water for irrigation in Israel and the Palestinian autonomous regions.

Wastewater reuse in Turkey has been practiced by withdrawing of water from downstream end of treatment plants. Due to the lack of water quality control, these practices have caused the deterioration of surface water resources. Nevertheless, it should be noted that conscious and planned reuse activities in agriculture have recently improved by the operation of urban wastewater treatment plants (Tanik et al. 2005).

Agriculture in Kuwait had been very limited due to shortage of suitable water resources until the late 1970s, which made the country dependent on other countries for food importation. In 1975, a 900-ha tract of land was developed to produce forage crops (mostly alfalfa) using tertiary-treated wastewater. Side-roll sprinklers were used in this project. In 1985, 700 ha of land were added to the previous farm (Arar 2006).

Various cities in Mexico produce wastewater that is reused in agriculture. Mexico City is one important example. Almost all collected raw (untreated) wastewater is reused for irrigation on more than 85,000 ha of land for cultivating different crops. One of the largest wastewater reuse systems in the world is in central Mexico in Mezquital Valley, where the wastewater is used for agricultural purposes. Financial problems, water scarcity and population growth were the reasons to develop a wastewater reuse system in that area (U.S. EPA 2004; Cifuentes et al. 2000).

Water is an extremely valuable resource in Saudi Arabia. Most of the water used is supplied by non-renewable groundwater and desalination of sea water. In 1985, Saudi Arabia started to focus on ways to economize and regulate the use of water through a National Water Plan, as a result, this country is committed to a policy of complete water reuse. The largest water reuse scheme is in Riyadh.

Jordan is another country that has problems matching water demands and available water supply, due to very limited water resources and Jordan. About 12% of all water used for irrigation is from treated wastewater resources, which irrigates about 10,665 ha of land, under restricted or unrestricted agricultural practices. The water of one of the treatment plants called As-Samra is used for irrigating about 19,000 trees. Also, planting of about 500,000 apple, olive, poplar, eucalyptus, and acacia trees has been done with about 2% of the available effluent by Water Authority (Nazzal 2005; Arar 2006).

Because water scarcity in various parts of Iran treated and untreated wastewater have always been used for agricultural irrigation (Massoudinejad et al. 2006). In southern Tehran, the source of agricultural water is Firooz-Abad stream. This stream contains wastewater from many treatment plants and factories (Daie 1995; Massoudinejad et al. 2006). In Shiraz, industrial and domestic wastewater is discharged into the Khoshk River and in south-east Shiraz this water is used for agricultural irrigation (Massoudinejad 1994; Massoudinejad et al. 2006).

Due to frequent and severe droughts in Japan, and insufficient water for fast growing cities and populations, reuse of treated wastewater in large areas of cities has been considered since the early 1960s. Treated wastewater has been used for recreational

impoundments, agricultural irrigation, toilet flushing, melting snow, and industrial usages (Suzuki et al. 2011).

The first pioneer of water reuse in United States was the State of California in early 1900s. Fields of corn, cotton, barley, alfalfa, and pasture were irrigated with reclaimed water in 1912 in Bakersfield City. Later, reuse of reclaimed water was considered in more locations in California and Arizona in the late 1920s. In the 1960s Florida and Colorado developed projects to use treated wastewater for urban irrigation systems.

The first regulations on reuse of reclaimed water were made in California in 1918, and in the 1970s and 1980s more research was done on treatment methods and health risks of reuse of treated water. Reuse projects are increasing in different parts of the USA due to population growth and urbanization and water shortage (Utah Division of Water Resources 2005).

In summary, the patterns of water reuse in various countries around the world and the USA confirms the concerns and problems with water shortage due to population growth, climatic region, global climate change and urbanization. This reuse shows the important role of considering other water supplies besides freshwater supplies in order to meet increasing water demands.

## 2.5. Challenges of Reuse of Treated Wastewater for Agricultural Irrigation

Important factors and challenges that should be considered for wastewater reuse projects are:

- Legal issues and water rights issues;
- Health issues;
- Public perception;and
- Short term and long term water reuse effects on soil salinity, crop yield, crop quality, and environment. Environmental effects include the pollution of ground water and surface water.

Each of the above issues is explained briefly here.

#### 2.5.1. Legal issues and water rights issues

A water right is a right to use water. In the USA, the natural or public waters within the boundaries of a state are owned by the states and follow the rules and regulations of each state. According to the U.S. EPA (2004), “a “water right” allows water to be diverted at one or more particular points and a portion of the water to be used for one or more particular purposes.” Water rights allocations are based on two types of rights by state laws. These rights are:

- Appropriative rights and
- Riparian rights (U.S. EPA 2004).

Appropriative rights system is mostly common in western states and water-limited locations. The water is allocated based on a first in time, first in right method. Therefore, the last to get water rights, may get water only if enough water is available. Riparian rights system is more common in eastern states and water-abundant locations. The water right is based on the proximity to the water and can be maintained by purchasing the land.



These water rights affect the water reuse projects. They either promote water reuse projects or act as an obstacle for water reuse projects. However, in specific cases (when multiple states are involved in water allocations), federal water laws are considered for planning a water reuse project. In western USA, the reclaimed water can be more reliable, especially for the users obtaining their water rights last. For water reuse planning one important issue is to understand who is in control of the treated wastewater (U.S. EPA 2004). This issue is out of the boundaries of this study.

### 2.5.2. Public health

As was mentioned before, wastewater has various constituents that can cause health problems for humans such as pathogens, some nutrients, and heavy metals. One of the most important considerations in any reuse project is the protection of public health by (U.S. EPA 2004):

- restricting the concentrations of pathogenic bacteria, parasites, and viruses in the treated wastewater;
- controlling chemical levels in the treated wastewater; and
- limiting public exposure to treated wastewater.

Based on the location for use of treated wastewater, specific limits are defined for various constituents. The rules and regulations vary depending on the State and the type of water reuse (U.S. EPA 2004).

### 2.5.3.Public perception

Another important issue that should be considered for wastewater reuse is public acceptance. For agricultural wastewater reuse, this means how people feel about consuming these types of products or how the farmers feel about having contact with treated wastewater for irrigation. These change due to people's knowledge of wastewater and treatment technologies.

If people trust that treated wastewater resources will not threaten their health, and also if they understand the positive role that wastewater reuse has on the environment, they might be more open to wastewater reuse projects. According to Rock et al. (2012), the value of risk and organizational trust held by people has a very big impact on their opinion about the reuse of reclaimed water.

### 2.5.4.Effects of reuse of wastewater for agricultural irrigation

Another important issue that needs to be considered in water reuse projects is the long-and short-term effects of reuse of treated wastewater on crops, soils, and the environment. Due to lower quality of wastewater compared to fresh water sources, reuse of wastewater in irrigation could result in salinity of soil, or pollution of groundwater and surface water. The effects of treated wastewater reuse on crop yield, soil salinity, surface water pollution (nitrogen and phosphorus), and groundwater pollution (nitrogen and phosphorus) is described in the following sections.

#### 2.5.4.1. Effects of reuse of treated wastewater on crop yield and soil salinity

Reuse of treated wastewater can have both good and undesirable effects on crop yield. High nutrient concentrations in treated wastewater can be used by plants as a supplemental source of fertilizers and therefore, result in yield increase. However, high salinity levels in treated wastewater sources can cause the decrease in crop yield (Hussain et al. 2002).

In a study in Saudi Arabia the effects of reuse of treated wastewater compared to use of fresh water was studied on alfalfa and wheat for silty clay soil. This study showed that nutrients in treated wastewater increased the crop yield and dry matter content compare to fresh water resource and saved 45% and 94% in the costs of fertilizers for wheat and alfalfa, respectively. Alfalfa yield increased 23% and wheat yield increased 11%. Soil salinity did not show significant changes with time. Plant chemical compositions of copper (Cu), lead (Pb), cobalt (Co), and nickel (Ni) did not reach harmful levels. However, the amounts of iron (Fe) and zinc (Zn) significantly increased for wheat when irrigated by treated wastewater compare to freshwater. Similar results showed increase of iron levels in alfalfa. The amount of soil nitrogen was much lower when irrigated with fresh water compared to treated wastewater. No significant change in the amount of soil phosphorus and potassium was observed for two irrigation sources. Soil chemical compositions did not reach harmful levels, due to irrigation with treated wastewater (Aljaloud 2010).

EL-Aila and AbouSeeda (2011) studied the effects of water resources type on crop yield and grain quality. In a field experiment they used untreated wastewater, and

secondary treated wastewater compared to irrigation with well water for wheat production. An average increase of grain and straw yield for untreated wastewater, primary and secondary wastewater, due from this study is shown in Table 2.4. As shown in Table 2.3, untreated wastewater resulted in higher grain/straw ratio compared to treated wastewater and well water. The amount of crop nitrogen, phosphorus and potassium was higher in water with lower levels of treatment. However, the treatment of the wastewater decreased the amount of heavy metals stored in the grain and straw compared to an untreated wastewater source.

Currently, in the city of Alexandria in Egypt, about 1.5 millionm<sup>3</sup> of wastewater are produced per day, with the expected amount for year 2020 being 2.5 millionm<sup>3</sup>/day. Due to water scarcity problems in Egypt, reuse of treated wastewater for irrigation has gained the attention. A study was done on management of treated wastewater by Selim (2006) in Western Delta Region (El-Noubaria), 40 km south of Alexandria, for a three-year time period (2000 to 2003). In this research the use of treated wastewater delivering to the field in special tankers, compared to fresh water from the irrigation canals, was studied. The soil type was calcareous sandy soil, irrigation method was surface flow irrigation, and the crops were sunflower and sesame. The analysis showed that irrigation with secondary treated wastewater resulted in more crop yield compared to irrigation

Table 2.4. Average increase in the yield of grain and straw irrigated with different water types (El- Aila and AbouSeeda 2011)

	<b>Untreated Wastewater</b>	<b>Primary Wastewater</b>	<b>Secondary Wastewater</b>
Grain	298%	186%	85%
Straw	177%	127%	66%

with canal water. The yield of sunflower seeds increased by 14.77% ,using secondary wastewater. Also, in sesame, crop height, number of branches, and dry matter accumulation were increased when plants were irrigated with secondary treated wastewater. This could have been due to an increase of nutrients in treated wastewater, compared to canal water (Selim 2006).

Ahmadi Aghtape et al. (2011) studied the effects of reuse of treated wastewater on production of millet in the Agricultural Research Center of Zabol University in Iran. The soil was sandy loam soil and the climate was warm and dry. In this study three types of irrigation water were considered: tap water only, tap water and treated wastewater alternately and treated wastewater for all growth stages for three main plots. Each plot was divided into three sub-plots sprayed with three levels of complete fertilizer (non-sprayed, sprayed 600g of complete fertilizer per hectare, and sprayed with 1200g of fertilizer per hectare). The results showed significant increases in dry forage, grain yield, and forage quality when the crop was irrigated with treated wastewater and sprayed with a complete fertilizer treatment.

The effects of reuse of treated municipal wastewater on the income from corn and cotton for a three-year period (1995-1997) for the city of Larissa in central Greece was investigated by Tsadilas and Vakalis (2003). For this study, five types of water resources were considered: (1) Irrigation with fresh water; (2) Irrigation with wastewater and no mineral fertilization; (3) Irrigation with fresh water and complete mineral fertilization; (4) Irrigation with wastewater and reduced mineral fertilization; and (5) Irrigation with wastewater and complete mineral fertilization. It should be noted that the water released from the treatment plants undergoes both primary and secondary treatment. For this

purpose the net profit was calculated, subtracting the production expenditures from the gross output.

The results showed that for corn, irrigation with treated wastewater, in addition to all of the environmental benefits of reuse of treated wastewater, has caused an increase in income. Use of treated wastewater with complete mineral fertilization resulted in a 14% increase in yield compared to irrigation with fresh water with complete fertilization. Corn is a crop with high nitrogen demand and therefore, the yield and the income were lower when irrigation was done with wastewater without mineral fertilization compared to when irrigation was done with fresh water and complete mineral fertilization. For cotton, irrigation with wastewater with complete mineral fertilization, irrigation with wastewater and reduced mineral fertilization and irrigation with wastewater and no mineral fertilization resulted in similar yield amounts. For cotton, the income does not change significantly by replacing the fresh water with treated wastewater but it can replace the nutrients needed for the plant to grow.

In Jordan the effects of irrigation of cut flowers (roses) with treated wastewater were studied by Rusan et al. (2008). The plants were grown in a plastic house and were irrigated with fresh water or treated wastewater with different irrigation frequencies. The results of this study showed better rose quality and higher yield of the cut flowers for the cases in which the plant was irrigated with treated wastewater. Treated wastewater application frequencies did not affect the soil pH, but they increased the soil EC (electrical conductivity) and SAR (sodium adsorption ratio) in the soil. Therefore, according to Rusan et al. (2008), treated wastewater for irrigation of cut flowers can be

used but should be properly managed in order to avoid the accumulation of excessive amounts of salts and nutrients in the soil.

Cyprus is the third largest Mediterranean island with a population of 700,000, and like other Mediterranean countries, it is dealing with water shortage problems. Cyprus has a semi-arid climate, and about 80% of the average annual rainfall of 500mm is lost due to evaporation. There are no permanent surface water streams, and the fresh water resource is from groundwater resources. Therefore, in order to meet the demands of urban areas, and agricultural and industrial users, reuse of wastewater for agriculture and industry has been considered. About 25 active treatment plants are in Cyprus, and the water released from these plants is used for watering parks, hotel gardens, football fields and most importantly for irrigation of crops. There are specific and restricting water quality criteria for water reuse, although some factors have not been considered in these criteria. For instance, crop water demand can be met with fresh water, rainfall and also saline water and therefore, the effect of salinity on the soil is not as estimated while irrigating with saline water. Also, winter rain in the region of the case study leaches into the soil and decreased the effects of salinity, especially for the first growth stages of the crop, which is the most sensitive stage to soil salts. Reuse of wastewater can cause problems that can be solved with good management practices. In this study, it was shown that reuse of wastewater had increased the amount of organic matter of the soil, which caused structural improvement of the soil. Finally, reuse practices were found to be a good method of water conservation in this region (Nicholas 2010).

Shiraz located in southwest Iran is a growing city with widespread vegetables and wheat farms in its suburban area. Untreated wastewater released into the river is used for

irrigation of these fields along the Khoshk River banks. Shiraz Health Organization does not allow the usage of untreated wastewater for irrigation of vegetables, but the farmers continue to use this water (Qishlaqi et al. 2008). Research was conducted to investigate the effects of reuse of untreated wastewater on soil and crops by Qishlaqi et al. (2008). Two farms were considered for this study: Site A, where wheat is grown and irrigated by untreated wastewater and site B, where vegetables are grown and irrigated by wastewater and tube well water. Site C is the control site, where soil is irrigated with tube well water. Soil and crop sampling were done for mid-growing season and various depths of soil layer. The results from this study show that the concentration of most heavy metals in sites A and B are higher than the control site, and higher amounts of heavy metals in site A compared to site B were observed. Zn (Zinc) and Cr (Chromium) do not show any significant difference in various sites. Ni (Nickel), Pb (Lead), and Cd (Cadmium) increased 4.5%, 7%, and 4%, respectively, in the soil in site A.

Comparing the amount of heavy metals in the soil layer indicates that Ni and Pb are less mobile and therefore, accumulate in the topsoil. The amount of heavy metals in the crops is measured in this study. The results show that wheat is the most contaminated crop due to high amounts of Ni and Pb. Spinach and lettuce (from site B) follow, with high contaminations of Cd. Various factors affect the amount of heavy metal uptake by the plant; crop physiological properties and physical and chemical properties of the soil are some of those factors (Qishlaqi et al. 2008).

A study was carried in Central Iran in Borkhar, in Isfahan province. Two sources of water (wastewater and ground water) and two irrigation systems (sprinkler and surface) were considered in irrigation of sugar beet, corn and sunflower. The secondary



treated municipal wastewater from Shahinshahr near Isfahan was used for this study. During the growth season, water samples were collected and analyzed to determine physical and chemical properties. Soil samples were collected to a depth of 1.20m in order to investigate the concentration of lead (Pb), manganese (Mn), iron (Fe), cadmium (Cd), nickel (Ni), cobalt (Co), copper (Cu), and zinc (Zn). The results showed the decrease of Pb, Mn, Ni, Co, Cu, and Zn with soil depth. The accumulation of Pb, Mn, Ni, and Co increased in the soil irrigated with treated wastewater. The irrigation systems had no significant effect on the amount of heavy metal accumulated in the soil. However, soil physical properties were affected by the irrigation system. The infiltration rate increased for sprinkler system (Abedi-Koupai et al. 2006).

A study was conducted in Tehran, Iran to consider the effects of reuse of treated wastewater on yield and fiber of cotton plants. Eight experimental blocks were considered for this study. The amount of irrigation water for all plots was the same, and the method of irrigation was surface irrigation. However, various intervals and mixtures of treated wastewater and fresh water were used for these blocks. The results showed that the crop yield, number of bolls per square meter, leaf area index (LAI) and plant height increased significantly for plots irrigated with treated municipal wastewater compared to the ones irrigated with fresh water. However, no detrimental effect was observed in the quality of the fiber (Baniania et al. 2011).

In summary, in many regions in the world with arid and semi-arid climatic conditions, and due to urbanization and population growth, reuse of treated wastewater as a water resource for irrigation is an important (or the only) source for agriculture, and is sometimes the only way to produce the food supplies needed by a growing population. It

was also seen that in many regions around the world, reuse of treated wastewater has beneficial environmental effects, and can be a good alternative to releasing the low quality water directly in the fresh water resources. Finally, the nutrients in treated wastewater are good sources that can satisfy the crop demands and increase crop yields in many cases, compared to when the crop is irrigated with fresh water.

#### 2.5.4.2. Environmental effects of reuse of treated wastewater on ground water and surface water

Two important constituents in the wastewater that can have detrimental 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. Phosphate and nitrate transported by irrigation runoff can pollute the surface water and increase the growth of algae (Nathanson 2007; Feigin et al. 1991). In order to better understand these procedures, nitrogen and phosphorus constituents and their importance and effects and transformations in the soil are described below.

Nitrogen is one of the most important nutrients that plants need to grow. Plants can use nitrogen in two forms: (1) nitrate and (2) ammonium. Other forms of nitrogen are not usable by the plant. Some plants such as legumes have *Rhizobium* bacteria living on their roots and using the sugar from the plant as source of energy, they convert nitrogen gas to forms that can be utilized by the plant. This is called nitrogen fixation. Other plants must obtain the nitrogen they need from the soil (Dorn 2011). Animal waste, fertilizers, crop residue and also nitrogen in the rainfall are some sources of nitrogen in the soil. Nitrogen exists in soil in various forms and transforms from one form to another due to

biological, chemical, and physical processes. The nitrogen cycle is shown in Fig. 2.1, which shows different nitrogen transformations in the soil.

Nitrogen transformations include:

- Mineralization
- Denitrification
- Immobilization
- Volatilization

Mineralization is the process in which organic nitrogen transforms to inorganic nitrogen forms that are available to the crops. Mineralization occurs in two stages:

- Ammonification

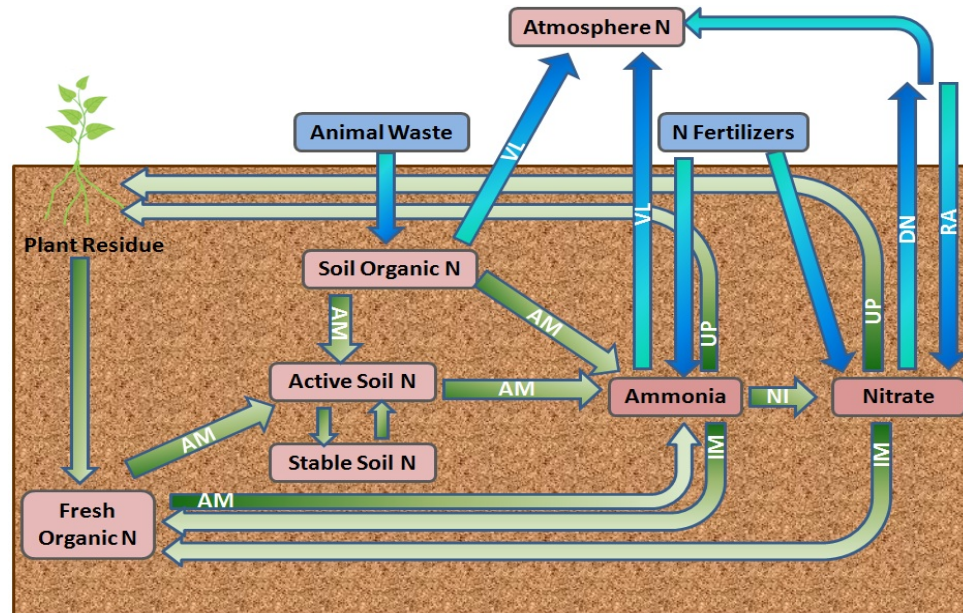


Figure 2.1. The nitrogen cycle. It should be noted that AM is ammonification, VL is volatilization, IM is immobilization, DN is denitrification, UP is uptake, and NI is nitrification (after Knisel et al. 1993).

- Nitrification

Ammonification is the transformation of organic nitrogen (such as active soil nitrogen, organic nitrogen from roots and crop residue, and organic nitrogen in animal waste), to ammonium ( $\text{NH}_4^+$ ). Nitrification changes the ammonium forms of nitrogen to nitrite ( $\text{NO}_2^-$ ) and then to nitrate ( $\text{NO}_3^-$ ). These processes occur through activity of soil organisms. Higher soil pH and better soil aeration increase the rate of mineralization. The ratio of C:N also affects the mineralization rate; if the C:N ratio is less than 25:1, mineralization occurs. The C:N ratio describes the relative amount of total carbon to total amount of nitrogen in soil. The microorganisms living in the soil need both carbon and nitrogen sources (University of Hawai'i 2012).

Immobilization is the reverse of mineralization and occurs for C:N ratios more than 25:1. During the process of immobilization, nitrate and ammonium transform to organic nitrogen. In soils with high pH and high temperature, losses of nitrogen to ammonia gases occur that is called volatilization.

Transformation of soil nitrate to nitrogen gases due to anaerobic bacteria under conditions when soil water content is higher than field capacity is called denitrification. The bacteria responsible for denitrification, need carbon source is essential for denitrification.

Nitrogen losses in the soil can occur due to these processes (Barbarick 2006):

- Plant removal
- Volatilization
- Denitrification
- Leaching

- Runoff and erosion

Nitrogen loss due to leaching and runoff and erosion is undesirable. Nitrogen lost in the runoff can cause pollution to the rivers and streams and nitrate lost below the root zone causes the loss of nutrients beneficial to plants and also can cause pollution of groundwater. Human activities are a major source of ground water pollution.

Agricultural chemicals are one of the sources of ground water pollution. The most common agricultural pollutant is nitrate, which is one the most soluble forms of nitrogen. High nitrate amounts in the ground water can cause very serious human diseases, such as blue-baby disease in infants and gastric cancer in adults (Johnson et al. 1991).

Phosphorus is another important nutrient in crop growth. Since phosphorus is largely immobile in the soil (especially the inorganic form of it), there are no phosphorus standards in ground water or drinking water. Phosphorus exists in the soil as organic and inorganic forms. The availability of phosphorus to plants is related to phosphorus solubility, which is related to soil pH. When the soil pH below 6 (acidic soils), phosphorus becomes fixed in iron phosphate and for high pH values, phosphorus becomes fixed in calcium phosphates and in both conditions, phosphorus is unavailable for plant use (Mississippi Agricultural and Forestry Experiment Station 2010). Unless there are specific circumstances such as low soil attenuation (soil with low concentrations of iron, aluminum and manganese), or preferential transport of phosphorus-containing wastes through the soil to ground water, phosphorus will not affect the ground water. Preferential flow is rapid and uneven movement of water and solutes in porous media such as soil; this reduces the potential for nutrient adsorption (Cornell University 2012). The major issue with phosphorus is its discharge into the surface water systems, which

results in algae growth in the streams and eutrophication (Minnesota Pollution Control Agency 1999). Sources of phosphorus are animal waste, crop residue, and fertilizers. The phosphorus cycle, showing different forms of phosphorus is seen in Fig. 2.2. Some of the transformations of phosphorus are:

- Mineralization
- Immobilization

Phosphorus mineralization is the transformation of organic phosphorus to labile phosphorus, which is available to the crop. High C:P ratios of crop residue cause the transformation of phosphorus available for the plant (labile phosphorus) to organic phosphorus. Labile phosphorus is the phosphorus that is loosely bound to and easily released from inorganic or organic soil constituents.

Labile phosphorus moves most readily among plants, their residues, soil microbes, the soil solution, and pools of phosphorus. Labile phosphorus remains in equilibrium with soluble phosphorus (Wiederholt and Johnson 2005; Johnson et al. 2003).

Phosphorus can be lost from the soil from runoff and erosion and also leaching. Although, it should be noted that usually leaching of phosphorus is small and most phosphorus losses occur due to erosion and runoff. Surface water quality and eutrophication are concerns due to phosphorus losses from runoff and erosion.

#### 2.5.4.2.1. Environmental effects of reuse of treated wastewater on ground water

Groundwater quality is one of the most important environmental factors that should be considered, especially in the Midwestern USA, where groundwater supplies

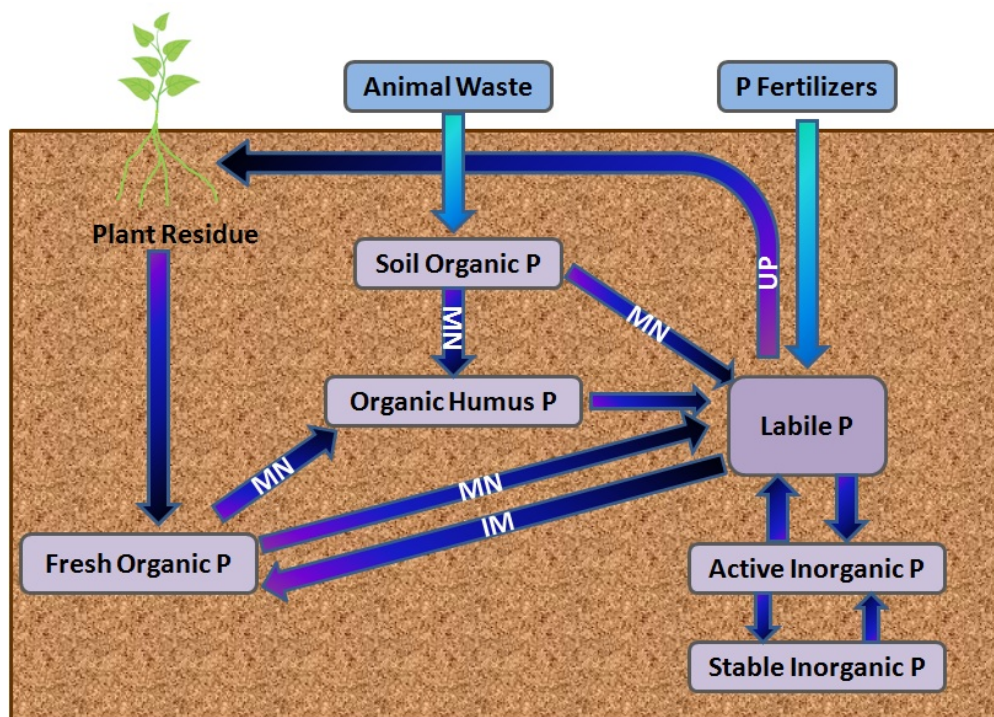


Figure 2.2. The phosphorus cycle (after Knisel et al. 1993).

drinking water to about 95% of rural and 50% of urban population (Loague and Corwin 2005; Engel et al. 1996). Groundwater pollution is a significant threat to many valuable water resources around the world. There are many different sources of groundwater pollution, some of which are point sources and others are non-point sources.

Non-point sources that include irrigation with wastewater and pesticide or fertilizer uses for farmland, has caused the pollution of groundwater resources in many parts of the world. Groundwater contamination due to non-point sources mostly occurs by leaching some amount of fertilizer, pesticide or wastewater through the vadose zone to the groundwater.

A study by the EPA in 1992 showed that more than half of the wells in the USA have high amounts of nitrate, and about 5% of them have high amounts of pesticides

(Engel et al. 1996). Studying groundwater quality and protecting the groundwater resources are possible by estimating the changes in the amount of a specific constituent with time. There are two methods for investigating these changes:

1. Real time measurements.
2. Water quality modeling.

In the first method the data for changes of a specific constituent with time are available through measurements (real data); while in the second method a mathematical model is used to simulate the data.

Nowadays, many different models are used in order to investigate groundwater vulnerability. Some of these models are for large scales (watershed) and some are field-based. Some are more complex and some are simpler. 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 examples. Also, there are many models that can investigate the effects of nutrients on surface runoff from irrigation such as HYDRUS-2D, and GLEAMS (Leonard et al. 1987). Some of the models are described briefly in the following paragraphs.

DRASTIC was developed by the U.S.EPA in order to investigate the potential of groundwater pollution in large scales. DRASTIC uses the hydrological settings of a region to predict the vulnerability of groundwater. The hydrological factors that are considered in this model are depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C).



Different weights are considered for each of these factors, according to their effect on groundwater vulnerability. The DRASTIC Index is calculated as (Babiker et al. 2005):

$$\text{DRASTIC(INDEX)} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (2.7)$$

in which D, R, A, S, T, I and C are the seven hydrological factors listed above and r and w subscripts account for ratings and weights. Higher values of the DRASTIC Index show higher groundwater vulnerability potential (Babiker et al. 2005).

SEEPAGE (System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments) was developed to evaluate the potential of groundwater contamination due to point or non-point sources using hydrogeology factors of a region. This model, similar to DRASTIC, uses hydrogeology data in order to classify the potential vulnerability of the groundwater contamination in an area, using GIS data. SEEPAGE considers factors such as: land slope, groundwater table depth, vadose zone material, aquifer material, soil depth and attenuation potential. This model also considers these factors: soil surface and subsoil textures, pH and organic matter of the surface layer, soil drainage class and soil permeability. Classifications are done by calculating a factor called SEEPAGE Index Number (SIN). Then, according to the SIN values, the areas are reclassified as low, medium, high or very high categories for contamination potential of the groundwater (Navulur and Engel 1998).

PRZM or Pesticide Root Zone Model was developed for U.S. EPA and is a one-dimensional finite-difference model that calculates the pesticide transport in the root zone. This model has two major components: hydrology and chemical transport. The model can be used with or without site-specific calibration.

HYDRUS-1D is a one-dimensional model that investigates the transport of heat and solute in the soil. There are also two-dimensional and three-dimensional versions of this model. This model numerically solves the Richard's equation for flow rate and convection-dispersion equation for heat and solute transport. A sink term is added to flow equation in order to account for plant uptake. The solute transport equation considers the convective-dispersion in the liquid phase and diffusion in the gaseous phase.

PELMO models the chemical transport through the unsaturated soil within and below the root zone at a field scale (Klein et al. 2000). This model is a German modification of PRZM, which is capable of more processes than PRZM. It has two sub-models: hydrology and chemical transport. Some of the PELMO's input data include: daily precipitation, daily mean temperature, relative humidity in the air at 2:00pm, soil bulk density, organic carbon content of the soil, ratios for biodegradation and pesticide parameters such as half life, temperature during degradation study, rate and date of chemical application and application depth (Cohen et al. 1995).

LEACHM (Leaching Estimation And Chemistry Model) is a one dimensional MS-DOS-based (Microsoft dist operating system) model that calculates water and solute flux in horizontally layered soils under transient condition. This model has various component models for different class of chemicals. LEACHP is for pesticide transport. LEACHP models water flow using the one dimensional Richard's equation, which is combined with convection-dispersion equation (Dust et al. 2000).

RZWQM (Root Zone Water Quality Model) is a complex one-dimensional field-scale model that predicts water and solute transport within the root zone. This model was

developed for agricultural management needs. RZWQM requires a large amount of input data, making it difficult for many to use (Cohen et al. 1995).

CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) is a physically based model that estimates runoff, erosion/sediment transport, plant nutrient, and pesticide yield for a field. CREAMS is composed of three components: hydrology, erosion/sedimentation, and chemistry (Knisel 1980).

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) is a physically-based mathematical model based on CREAMS. GLEAMS is a field-based simulation model that studies surface and subsurface flow and non-point pollution by pesticides and nutrients due to different agricultural management systems (Leonard et al. 1987). GLEAMS simulates both leaching and runoff. The GLEAMS model is composed of four editors: (1) Hydrology; (2) Erosion; (3) Pesticide; and (4) Nutrients. The GLEAMS model requires a large amount of input data. Daily rainfall, daily mean or monthly average max/min temperature, monthly average solar radiation, field geometry and slope, soil SCS curve number and hydrologic group, initial soil moisture, soil texture, maximum crop rooting depth, leaf area index as a function of time and depth, porosity and percentage of organic matter, field capacity, and wilting point for each soil layer are some of the input data needed by this model (Cohen et al. 1995). Due to lack of graphical interface, using this model is hard and time consuming.

Besides the models mentioned above there are many other models that have been used in different parts of the world.

There are many reports of water use to simulate groundwater quality due to non-point sources of pollution. In Goshen County, Wyoming, the groundwater supply for

Torrington City is polluted by nitrate, due to intensive crop production and agricultural fertilizer use in the county. A geographic information system (GIS) with the DRASTIC model was used by Zhang et al. (1996) to study the potential contamination of the groundwater in this region and to understand which areas are more likely to become polluted considering the human activities on the land surface. The most sensitive locations were the areas near the streams, rivers and lakes. Also, the locations with shallow water tables and deep saturated layers of soil and soils with very high porosity were classified as highly sensitive. Upland areas with very low hydraulic conductivities, very deep water tables and steep slopes were classified as low sensitive areas (Zhang et al. 1996).

In the next part of the study, the numerical modeling of 130 random locations in Goshen County was done using HYDRUS. For these locations the simulations of water flow and soluble transport in the soil towards groundwater was modeled. The input data included hydraulic conductivity, water recharge, groundwater depth and soil texture. The output data from this modeling were the cumulative water flux recharge to groundwater table since the start time of simulation, total amount of water in the soil, cumulative amount of solute leached to the groundwater since the start time of the simulation and the start time of groundwater pollution. The calculations showed that the contamination reached its maximum level in sandy soils much sooner than in clay soils (Zhang et al. 1996).

Onsite wastewater systems (OWS) are being used in many parts of US, Canada, Europe and Australia, in order to treat and dispose of domestic wastewater. Usually wastewater passes a pre-treatment process in the septic tank before being discharged on the surface of the soil treatment unit (STU). If the wastewater does not receive enough

treatment before reaching the groundwater, groundwater contamination will occur (Heatwole and McCray 2007).

Due to lowered water tables in major aquifers of the Denver Basin in Colorado, some aquifers that were not considered as drinking water sources are considered now. On the other hand, many regions in the Denver metropolitan area with OWS and shallow water table and highly permeable soils have high potential of groundwater contamination with nitrate. Therefore, before using this water as drinking water resource, careful investigations should be done. In a study by Heatwole and McCray(2007), in a specific region in Denver metropolitan area, flow and nutrient transport was modeled. The Todd Creek site in northwestern margin of Denver Basin was selected for this study. This region had been occupied by agricultural farms, although population and urban growth has changed the land use to residential developments in some parts. Using 25 local well logs obtained from the Colorado State Engineer's Office and data collection from five wells in the study area and analyzing them with geographic information system (GIS), a nitrogen transport model was created for Todd Creek.

Most of the municipal water in this region is taken from Laramie-Foxhills aquifer, although some residents by private wells draw water from Arapahoe aquifer. However, Arapahoe aquifer will probably be considered for more uses in the next years. A model using HYDRUS-1D was made for Arapahoe aquifer to investigate how the OWS in the Todd Creek area will affect this aquifer (Heatwole and McCray 2007). The input data included soil physical characteristics such as hydraulic conductivity, bulk density and dispersivity and others, effluent loading rate and its nitrogen concentrations, and also nitrification and denitrification rate coefficient parameters. The most important output

data are the ammonium and nitrate concentration changes with soil depth. Modeling the best-estimate input parameter values resulted in complete removal of nitrogen in soil profile in Todd Creek. However, according to this study, denitrification rate coefficient has both high sensitivity in the model and high uncertainty. This uncertainty, plus the uncertainty for other parameters, results in some amount of risk in modeling results. Therefore, regulators should agree on the acceptable level of risk (Heatwole and McCray 2007).

Pesticide fertilizer leaching due to agricultural activities is one of the major factors of groundwater resources pollution in many parts of the world and also in the USA. Therefore, in a study done by Nolan et al. (2005) seven solute transport models were evaluated for agricultural chemical transports based on ease of use compared to their capabilities. These models include: HYDRUS-2D, LEACHP, RZWQM, VS2DT (complex models) and GLEAMS, CALF and PRZM (simple models). Two sets of data were used for this purpose, one from a bromide tracer test near Merced, California, and one from an atrazine study in the White River Basin, Indiana. The Merced site is located in a semi-arid region with relatively homogeneous soil while the White River Basin site is located in a humid region with highly structured soil exhibiting preferential flow (Nolan et al. 2005). Due to time and money limitations the simulations were done for one lysimeter location and depth in White River Basin and a single concentration profile for a specific date for the Merced site.

The modeling was done with all seven models for both data sets. The compounds simulated by the models were: bromide for Merced site and atrazine (ATR), desethylatrazine (DEA), hydroxyatrazine (HYA), and didealkylatrazine (DDA) for the

White River Basin site. The results from the different models are not the same. It should be mentioned that these models were not calibrated. The results of this study showed that, among complex models, RZWQM and HYDRUS-2D are more user-friendly due to more documented information available for them. RZWQM is more appropriate for structured soils, because it can explicitly simulate water and solute flux in the macro pores. For sites near streams or drains, two-dimensional models like HYDRUS-2D and VS2DT are more appropriate. LEACHP does not have a graphical user interface, but it is relatively easy to use. However, the Richard's equation does not consider preferential flow. CALF is simple to use and has preferential flow capabilities. GLEAMS is easy to use and is appropriate for considering the agricultural effects but it cannot be used for depths greater than 1.5m. PRZM does not have any depth limitations and it can be used to evaluate many different processes such as microbial population growth, plant uptake and agricultural management practices. However, PRZM is hard to use and is sensitive to numerical grid-cell thickness (which determines the dispersivity) (Nolan et al. 2005).

In eastern Spain in the regions with agricultural activity, groundwater contamination with nitrate has been observed and even in some locations the groundwater concentration of nitrate exceeds the allowable levels (50 mg/l). Valencia is one of these regions. An area of 230 km<sup>2</sup> near Valencia with a population of about one million was selected for this study. This area is almost flat with an altitude of 60m and a shallow aquifer of 2-60m. Sixty percent of this area is occupied for agricultural purposes and growing vegetables and citrus in sandy-loam to clay soils. This region has dry summers and rainy autumns. Many wells for irrigation and domestic uses are located in this region. In this study, two sub-models of GLEAMS were used: (1)hydrologic; and (2)nutrient

sub-models. In this study a graphical user interface was made in the GIS system in order to make it easier to use. The input data for running GLEAMS were divided into five layers: soils, climate, land use, nitrate concentrations in irrigation water, and agricultural management practices. The results showed that the area cultivated in vegetables had the highest risk for nitrogen leaching. This is because of the high amounts of fertilizers used by the farmers for growing vegetables, shallow root depths of vegetables, and low irrigation and nitrogen uptake efficiencies. However, potato and artichoke had the highest risk of nitrogen leaching because they received the highest amount of nitrogen, and their uptake efficiency was the lowest (De Paz and Ramos 2002).

At the Indian Agricultural Research Institute Farm, New Delhi, a study was conducted in order to investigate the pattern of nitrogen leaching from onion fields under drip fertigation. Therefore, the two-dimensional HYDRUS model was used. Soil data were collected by taking soil samples at different depths and analyzing them for physical and chemical properties. Daily onion water requirements were estimated, using pan evaporation data and crop coefficient. Using HYDRUS-2D, the amount of nitrogen leaching from onion fields under drip fertigation was calculated. This model uses a finite-element solution of the flow equations (Richard's two-dimensional equation). Solute transport is modeled using the advection-dispersion equation, which is added to the nutrient uptake parameter. In this case solute transport is mainly physical transport and is mostly related to soil properties and emitter discharge rates. It should be noted that mineralization gains and denitrification losses were neglected (Ajdary et al. 2007).

After modeling the flow and solute transport, the model was calibrated for hydraulic conductivity and dispersivity, with the values of water and nitrogen at various



points at different time. This was done so the observed data were close enough to predicted data from the model. In the next step, for a whole crop season of 125 days, the model was run in order to predict the water flow and nitrogen leaching. This was done in order to validate the model (Ajdary et al. 2007).

The results from this model showed that HYDRUS-2D was appropriate for calculating flow and nitrogen leaching for this case study. The emitter flow rate did not affect nitrogen distribution in sandy clay loam and loam soils, while it affected nitrogen distribution in sandy loam, silt clay loam and silt soils. Nitrogen movement in coarse soils was downward, while in fine textured soils, it moved outward in top two layers. Seasonal nitrogen leaching was highest in coarse textured soils and almost zero in fine textured soils. Fertigation strategies, especially in fine textured soils, did not significantly affect nitrogen leaching (Ajdary et al. 2007).

According to the literature review, there are many different models available for prediction of groundwater quality or for comparison of groundwater contamination potential. These models are made in different levels of complexity and with different assumptions and restrictions and each have their own advantages and disadvantages. Also, each of them has been used in many different case studies all around the world. However, results from these literature reviews show that the best groundwater quality model for different case studies and various conditions is different. Therefore, not just one or few of these models could be determined as the best model.

Therefore, it is recommended that for different case studies, an appropriate groundwater quality model should be selected in order to get reasonable results. Some of the factors that should be considered for selecting the appropriate model are: (1) the goal

and objectives of the study; (2) amount of data available compared to the amount of input data needed by the model; (3) type of output data from the model compare to what exactly is needed to be simulated; (4) complexity of the model according to the knowledge of the model user; and (5) limitations of the model should be studied and compared to the case study carefully.

#### 2.5.4.2.2. Environmental effects of reuse of treated wastewater on surface water

Many human activities affect surface water quality. Agriculture is one of the biggest non-point sources of surface water pollution. Fertilizers and wastewater usage for agricultural area can release phosphorus into the surface water sources.

Eutrophication causes the growth of algae and aquatic weeds and shortage of oxygen due to their death and decomposition. Phosphorus accelerates the biological productivity of surface water and therefore eutrophication. Eutrophication is not desirable for various water users such as fisheries, recreation, and industry. Therefore, controlling the amount of phosphorus is an important factor to control eutrophication (Sharpley et al. 2003).

In order to better understand the relation between the land use activities and surface water quality, water quality modeling is used in watershed scale. There are many different models that can be used for this purpose. Some of these models are AGNPS (Agricultural Non-Point Source)(NRCS 2011), GWLF (Generalized Watershed Loading Function Model) (Haith and Shoemaker, 1987), HSPF (Bicknell et al. 1996) and SWAT (Im et al. 2003), PolFlow (De Wit 2001; Andersson et al. 2005), MONERIS (Modeling Nutrient Emission in River Systems) (Behrendt and Bachor. 1998; Andersson et al. 2005).

HSPF (Hydrologic Simulation Program-Fortran) is an EPA watershed-based model that can simulate the hydrology and water quality of the watershed of conventional and toxic organic pollutants. This model is composed of various sub-modules and can simulate the fate and transport of nutrients in one-dimensional streams (Bicknell et al. 1996).

SWAT(Soil and Water Assessment Tool) is a physically based watershed model that simulates the effects of management practices on water hydrology, sediment and water quality (Arnold et al.1994; Im et al. 2003).

HBV-NP is a newly developed model that simulates the nutrients (phosphorus and nitrogen) transformation and transport in a catchment scale (1 to 1,000,000 km<sup>2</sup>). This model has a hydrological core (HBV model) that has been improved by adding N and P routines (Swedish Meteorological and Hydrological Institute 2006).

AGNPS is a tool to study the effects of management decisions on watershed systems. AGNPS was developed in early 1980s by ARS (Agricultural Research Service) and Minnesota Pollution Agency and NRCS. This model was developed in order to analyze runoff water quality from agricultural watershed (a few hectares up to 20,000 ha). At first, this model was based on a single event, which made it less desirable to use but in early 1990's ARC and NRCS researchers made this model to a continuous annual model (AnnAGNPS) (Bosch et al. 1998).

GWLFis a watershed based model and can simulate runoff, sediment, nutrient loadings (N and P) from a watershed with different sources such as agriculture, forest or developed land. It can simulate non-point and point sources of pollution. It should be

noted that a GIS version of GWLF is developed in Pennsylvania State University (AVGWLF) (University of California Davis 2011).

NL-CAT is composed of different models such as: SWAP (soil water flow), ANIMO (soil water-nutrient flow), SWQN (Surface water quantity), and NuswaLite (surface water quality). Therefore, NL-CAT models the soil and surface water system in details (Schoumans et al. 2009).

PolFlow (Pollutant Flow) is a non-physical model and it is designed to operate at a river basin scale. “Spatial functions are used to route nutrients through the river network and dynamic functions are used to account for the delay of nutrient transport in the soil and the groundwater.” This model uses GIS datasets and five-year time steps (De Wit 2001).

There are many other models for the simulation of nutrient transport and fate and into the water resources.

## CHAPTER 3

### METHODOLOGY

The pressure that population growth and urban growth has on limited water resources, especially in arid and semi arid regions, is increasing all over the world. Among all the water users, people and municipalities have the priority. In order to satisfy all of the various human needs for water, the share of water for agriculture is decreasing with time in many regions. On the other hand, agriculture is a major source of food for a growing world population. Therefore, a decrease in agricultural water and land resources will have negative impacts on different countries, in terms of producing food for their growing population and also on the economy of many regions. The motivation of this study was the consideration of a method to prevent the diminishing or disappearance of agriculture in some areas by returning some of the water taken away from agricultural users. For this reason, the reuse of treated wastewater released from municipal areas for agricultural irrigation was considered in this study. Due to its nature and characteristics, treated wastewater usage cannot be accomplished without considering different aspects as mentioned in the previous two chapters. The study described herein considered:

- Effects of population growth and urban growth on water demand and agricultural lands;
- Securing the food production for a growing world by reuse of treated wastewater as a reliable water resource for agricultural irrigation;
- Effects of reuse of treated wastewater for irrigation, on groundwater and surface water;

- Economic feasibility of reuse of treated wastewater; and
- Effects of reuse of treated wastewater on soil salinity.

For this reason a GIS-based plug-in was developed in VB.NET which includes the following models:

1. Water Availability; and
2. Water Reuse.

A brief description of the objectives of these models is given in the following sections.

### 3.1. Water Availability Model

The Water Availability Model is a MapWindow plug-in developed using VISUAL BASIC .NET. This model was developed in order to better understand the effects of urban spatial growth and population growth on agricultural areas, as well as on water demand for different water users such as municipal, industrial, and agricultural users. This model with its graphic interface is user friendly and it includes the following procedures:

- Forecast of population growth based on historical trends, using regression analysis;
- Calculation of the changes in agricultural and urban area for a given time period;
- Calculation of water demand for various water users;
- Analysis of water released from treatment plants; and
- Analysis of differences in the quantity of water demand and water released from treatment plants.

This model can be used as a tool for better understanding the changes of population growth and urbanization and water demand over a period of time. Also, the comparison between water demand for different users and water released from a treatment plant shows if the water released can potentially match any of the demands.

### 3.2. Water Reuse Model

This part of the research focused on the development of a new GIS-based mathematical model (“Water Reuse Model”), which is in the form of a MapWindow plug-in. The model has been implemented using Microsoft VB .NET. The graphical interface of the model makes it very user-friendly.

The model is designed to help in the decision-making process for allocations of water resources (especially treated wastewater) to agricultural areas, considering factors such as crop types, water salinity, soil characteristics, pumping and conveyance costs, and also by comparing different management scenarios.

Since the issues of reuse of treated wastewater are vast, not all the concerns and aspects can be considered in this study, so this model focuses on only some of the issues, such as: crop yield; soil salinity; nitrogen, and phosphorus in the groundwater and surface water, and costs for water conveyance and pumping. The calculations for this model can be summarized as given below:

- Daily evapotranspiration calculations;
- Groundwater contribution calculations;
- Effective rainfall calculations;
- Daily water requirement calculations;

- Daily water balance calculations in the root zone;
- Crop yield calculations;
- Daily salt balance calculations in the root zone;
- Daily nitrogen balance calculations in the root zone;
- Daily phosphorus balance calculations in the root zone;
- Calculations of the water delivery systems and their capacity if needed;
- Calculations of pumping requirements if needed; and
- Calculations of the price of pumping and conveyance of water.

The model can be used as a tool for better understanding different scenarios of water resources management project, especially the reuse of treated wastewater for agricultural irrigation and its effects. This new model makes it possible for the user to define up to three scenarios with different soil, land, climate, crop, and water resources and irrigation data. The model can operate with or without GIS data. The input data for this model are summarized below:

1. Land Data
2. Soil Data
3. Crop Data
4. Water Resources Data
5. Climate Data
6. Energy Data

The scenarios defined will be compared based on crop yield, water conveyance and pumping costs, and soil salinity and environmental effects (pollution of the surface and groundwater due to nitrogen and phosphorus). This can give the user a better point



of view to make decisions about various water management methods, crop types, soil types, water conveyance system, and etc.

The details of the technical section of the model will be described in the next two chapters. Chapter 4 describes the Water Availability Model, while Chapter 5 describes the Water Reuse Model. In each of these chapters, one section is dedicated to technical details and theory of the model, and another section is dedicated to explaining how the user can enter the input data, apply the model, and check the results.

## CHAPTER 4

### WATER AVAILABILITY MODEL

#### 4.1. Methodology and Procedure

In this section of the chapter, a description of all the parts of the model is given.

The Water Availability Model has various sub-models, including:

1. Population Calculations;
2. Land Use Change Calculations;
3. Water Demand Calculations; and
4. Treated Wastewater Analysis;

all of which are described in more detail below.

##### 4.1.1. Population calculations

In this study the model predicts the future population of a specific study area. For this purpose two methods of population forecast are considered:

1. Exponential Method (which was described in Eq. 2.2);
2. Extrapolation Method.

For exponential method the following input data should be entered by the user:

- Beginning population of the study area;
- Time period for which the predictions are estimated; and
- Rate of natural increase of the population.

The extrapolation method estimates the future population based on the past population growth trend in an urban area and the best-fitting curve to the historic

data. The disadvantage of this method is that it only considers the previous trend of population growth in prediction of future population; in other words, the future population forecast is estimated assuming that the population growth trends will be similar to past growth trends. The advantage of this method is that it has low input data requirement. For this method the user must enter:

- Data set of population versus year for the study area; and
- The year for which the population should be estimated.

With this method, the model will generate five different functions to the data set entered by the user:

- Linear;
- Parabolic;
- Third-degree polynomial;
- Exponential; and
- Power.

Least squares method was used to fit the curves mentioned to the historic data which was set up in matrix format. Each of the curves mentioned, assumes a specific trend of population change in a study area. The linear method assumes that the change of population in every year in future is equal, and therefore the population is increasing or decreasing in a linear form:

$$Y = a + bX \quad (4.1)$$

in which Y is population and X is year.

The parabolic method is described using the following equation:

$$Y = a + bX + cX^2 \quad (4.2)$$

The third-degree polynomial method fits the following curve to the historic data:

$$Y = a + bX + cX^2 + dX^3 \quad (4.3)$$

The parabolic or polynomial methods can be used for cases that the population changes are not linear.

The regression for the exponential and power functions is done iteratively to determine a vertical shift, thereby providing a better fit to the sample data, in general.

The exponential method assumes that the population is changing exponentially:

$$Y = ae^{bX} + c \quad (4.4)$$

The “power curve” is:

$$Y = aX^b + c \quad (4.5)$$

The population forecast will be performed based on the selected regression function. When the data are loaded, the model performs regression analysis on the five functions shown above, then sorts the results according to the coefficient of determination, and finally displays the results on the computer screen. The coefficient of determination shows how well the curve fits the original data. This coefficient ranges between zero and one. The coefficient of determinations closer to one show better fit. For polynomials, the coefficient of determination ( $r^2$ ) can be calculated as follows:

$$r^2 = \frac{\Sigma(\hat{Y}-\bar{Y})^2}{\Sigma(Y-\bar{Y})^2} \quad (4.6)$$

where  $\hat{Y}$  are the predicted Y values (from the regression equation); and  $\bar{Y}$  is the average of the Y values.

For the exponential and power functions shown above, the coefficient is defined using logarithmic values, as follows:

$$r^2 = \frac{\sum(\ln \hat{Y} - \overline{\ln Y})^2}{\sum(\ln Y - \overline{\ln Y})^2} \quad (4.7)$$

where  $\overline{\ln Y}$  is the average of the logarithms of the Y values. Any logarithm base may be used, but it must be the same base for all the calculations.

The user can choose the desired equation from the list, and see the curve plotted against the sample data, then predict future values based on the selected function. For this method, it is better to have more data available.

As mentioned above, the extrapolation method needs more input data than the exponential method. If the historical population data of the case study is available, the extrapolation can be used. However, the best forecast method changes based on the population growth trend of the case study and could vary for different case studies.

#### 4.1.2. Land use change calculations

Due to complexity of many of the land use change models and also large amounts of data needed for them, and since the focus of this study was to investigate the effects of urbanization on agricultural area and water resources, not methods and details of land use change predictions, prediction of future land use changes was not considered. This sub-model is responsible for comparing the land use change maps of the study area at two different points of time and to investigate the changes of agricultural and urban area.

In this sub-model, two land cover maps for the beginning and ending simulation years are needed. The input data for this part of the Water Availability Model are:

- Land use layer of the study area (grid layer) for the beginning year of the simulation;
- Land use layer of the study area (grid layer) for the ending year of the simulation; and
- Boundary layer of the study area (polygon shape file).

The model will calculate the area of various land covers from beginning year of the simulation and ending year of simulation in the boundary defined by the user.

Therefore, the effects of land use change in terms of area of urban and agricultural area in a specific time period will be determined. For calculation of the area of agricultural and urban lands, the number of grids responsible for each land use cover type that are located inside the boundary is counted and multiplied by the area of each grid.

These calculations give the user a better understanding of the effects of land use change trends in the study area and they show the potential amount of decrease in agricultural land areas and the amount of increase in the municipal and industrial land areas.

#### 4.1.3. Water demand calculations

The Water Demand sub-model is responsible for investigation of the amount of water demand changes for various water users in a study area. The Water Demand sub-model calculates the water demand for agricultural, municipal, and commercial areas for the study area for the beginning and ending years of the simulation. This is done based on

a per capita method for municipal, industrial and unaccounted-for users. According to Logan City (2011) unaccounted-for water use is the water that is used but not billed. Fire flows and water lost in the water supply system are categorized under the unaccounted-for water use. Due to the results from the population sub-model, the population of the study area at the beginning and end of the simulation period is defined. Knowing the amount of water use per capita for various water users of the study area, the total amount of water demand for different users (residential, industrial and unaccounted-for water users) can be estimated. The amount of water use per capita for various water users is defined by the Utah Division of Water Rights and Resources for each county in Utah and is defined by the city offices for different municipalities.

It should be mentioned that the user can choose an option to calculate the future water demand for municipal, industrial and unaccounted-for users, with some specific amount of water conservation.

The user can choose an option to calculate the water demand for agricultural area, based on acre-ft per acre method or based on crop type and land area for each crop. For the acre-ft per acre method, the total water demand is calculated based on the water share that farmlands have per season. This amount can be defined from Utah Division of Water Rights. The total water demand per season can be estimated considering the irrigated agricultural area and the water acre-ft per acre of the land. The area of the agricultural area is taken from the calculations done by the model in the Land Use sub-model.

For the second method, the user will calculate the reference evapotranspiration for a typical year of the simulation, and based on the crop type, the model will calculate the crop water demand. The typical year data is the climate data of a year that can represent

the average condition of a region. The volumes of water demand for the agricultural areas are calculated based on the area of farmland and crop evapotranspiration. The model will plot the amount of water demand for the beginning and ending years of the simulation for various water users versus the day of the year.

The assumptions considered in this sub-model are summarized below:

- It should be mentioned that the agricultural area of the study area can be divided into the maximum number of ten farmlands and for each land the user can add five crop types.
- The water demand of various water users should be entered in the model on either a monthly or yearly basis. For either of those, the user can choose to make the water use trends stay the same, or they can change towards conserving some amount of water. The amount of conserved water can be defined by the user as a percentage.

#### 4.1.4. Treated wastewater analysis

In this sub-model, the wastewater resource is analyzed. This sub-model allows the user to enter the water supply on a yearly basis. The water supply being considered in this model is assumed to be treated wastewater. In this sub-model future wastewater being produced in a specific area is estimated based on the previous pattern of population growth and its relation to wastewater being produced. The population data for these estimations will be taken from the population sub-model. However, it should be considered that the portion of the wastewater influent that is from industrial users will be



subtracted by the model before relating the population to the total wastewater influent to the treatment plant.

The model will forecast the future wastewater produced by applying a user-selected regression equation to the data set of population versus summation of wastewater influent. The model will fit five types of curves to the data and based on the chosen curve, the future wastewater will be estimated:

- Linear;
- Parabolic;
- Polynomial (3<sup>rd</sup> degree);
- Exponential; and
- Power.

It is noted that many factors affect the amount of wastewater produced, such as weather conditions, and time of the year, but in this study only the population growth is considered in estimating the future wastewater quantity. Of course, the more data available for this part, the better the results will be. Also, it is important to choose the best curve to fit the data. Even though a better coefficient of determination shows a better fit for the historic data, the past trend of data would not necessarily be consistent in the future, and other factors can change the trend of wastewater productions in the future. Therefore, the best curve is not necessarily the curve with the best coefficient of determination.

This sub-model also forecasts the future daily average wastewater influent reaching the treatment plant. For this purpose, the residential portion of the average daily wastewater influent (entered by the user) will be calculated by the model. Then, the per

capita wastewater influent will be estimated by dividing the average wastewater influent to the population of the study area for the years that the data were entered. After calculating the average per capita wastewater for the study area, multiplying the future population estimated from the Population sub-model by the average per capita wastewater influent will result in the average daily future wastewater influent for the study area. Appendix A is a user manual for the Water Availability Model.

## CHAPTER 5

### WATER REUSE MODEL DEVELOPMENT

#### 5.1. Methodology and Procedure

As was mentioned in Chapter 3, Water Reuse Model compares various scenarios defined by the user, in different aspects such as crop yield, environmental effects (changes of nitrogen and phosphorus in the surface and groundwater), and conveyance costs of water delivery. This model will allow the user investigate various options of water resource, crop type, farm land location, and management decisions and their effects. The water reuse model is composed of three parts:

1. Soil water and salt balance calculations;
2. Nutrient calculations; and
3. Pumping and conveyance costs calculations

Each of these parts is described in detail in the following sections.

#### 5.1.1. Water and salt balance calculations

##### 5.1.1.1. Water balance calculations

Calculation of daily soil water balance in the root zone area of the crop is a part of the model. Figure 5.1 shows all the included water balance components in the crop root zone.

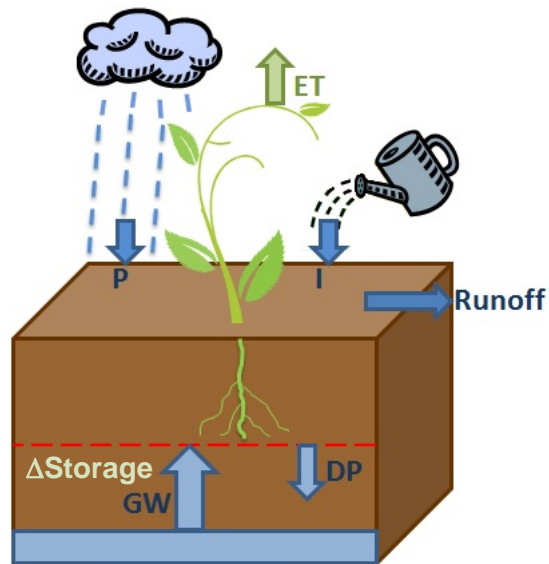


Figure 5.1. The mass-balance components included in the water balance model.

Various parameters that affect the daily water and salt balance are considered in the model, such as: depth of applied irrigation water, depth of precipitation, groundwater contribution, evapotranspiration, deep percolation, and surface runoff. Calculations of water balance are based on the following equation (Allen et al. 1998):

$$D_r(J) = D_r(J - 1) - P_{\text{net}}(J) - I_{\text{net}}(J) - GW_{\text{net}}(J) + ET_a(J) + DP_a(J) \quad (5.1)$$

in which  $J$  is the day of the year;  $D_r(J)$  is the depth of water depletion in the root zone at the end of day  $J$  (mm);  $P_{\text{net}}(J)$  is the actual amount of precipitation that enters the root zone during day  $J$  (mm);  $I_{\text{net}}(J)$  is the amount of irrigation water that infiltrates into the soil during day  $J$  (mm);  $GW_{\text{net}}(J)$  is the amount of groundwater contribution in the root zone area during day  $J$  (mm);  $ET_a(J)$  is the actual depth of crop evapotranspiration during day  $J$  (mm); and  $DP_a(J)$  is the actual depth of water deep-percolated below the root zone during day  $J$  (mm).

Accordingly, other factors that affect the above parameters are discussed and explained below. In order to be able to perform daily water balance calculations, all parts of the equation above must be calculated. Reference evapotranspiration for water balance calculations is calculated using the Penman-Monteith method (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (5.2)$$

in which  $ET_o$  is the reference evapotranspiration (mm/day);  $R_n$  is the net radiation at the crop surface ( $MJm^{-2}day^{-1}$ );  $G$  is the soil heat flux, positive downward ( $MJm^{-2}day^{-1}$ );  $T$  is the average daily air temperature ( $^{\circ}C$ );  $u_2$  is the wind speed at 2-m height above the ground (m/s);  $e_s$  is the saturation vapor pressure (kPa);  $e_a$  is the actual vapor pressure (kPa);  $\Delta$  is the slope of the saturation vapor pressure curve ( $kPa/^{\circ}C$ ); and  $\gamma$  is a psychrometric constant ( $kPa/^{\circ}C$ ).

The input data for calculating reference evapotranspiration are: maximum mean daily temperature,  $T_{max}(^{\circ}C)$ , minimum mean daily temperature,  $T_{min}(^{\circ}C)$ , relative humidity, RH (%), wind speed,  $u_2$  (m/s), solar radiation,  $R_s$  ( $MJm^{-2}day^{-1}$ ), and elevation and latitude of the site. Accordingly, potential crop evapotranspiration ( $ET_c$ ) is calculated using the following equation (Allen et al. 1998):

$$ET_c = ET_o K_c \quad (5.3)$$

where  $K_c$  is the crop coefficient, and is defined based on the crop type and the crop growth stage (Allen et al. 1998).

Actual evapotranspiration ( $ET_a$ ) is related to water availability and soil salinity.

Water or salt stress decreases the amount of evapotranspiration by the coefficient  $K_s$ :

$$ET_a = ET_c K_s \quad (5.4)$$

$K_s$  can be calculated using the following equations (Allen et al. 1998):

$$\text{If } D_r \leq RAW \text{ and } EC_e \leq EC_{\text{threshold}} \text{ then: } K_s = 1.0 \quad (5.5)$$

$$\text{If } D_r \leq RAW \text{ and } EC_e > EC_{\text{threshold}} \text{ then: } K_s = 1 - \frac{b}{100K_y} (EC_e - EC_{\text{threshold}}) \quad (5.6)$$

$$\text{If } D_r > RAW \text{ and } EC_e \leq EC_{\text{threshold}} \text{ then: } K_s = \frac{TAW - D_r}{TAW - RAW} \quad (5.7)$$

If  $D_r > RAW$  and  $EC_e > EC_{\text{threshold}}$  then:

$$K_s = 1 - \frac{b}{100K_y} (EC_e - EC_{\text{threshold}}) \left( \frac{TAW - D_r}{TAW - RAW} \right) \quad (5.8)$$

in which  $b$  is the reduction in yield per increase in  $EC_e$  ( $\%/dSm^{-1}$ );  $EC_{\text{threshold}}$  is the electrical conductivity of the saturation extract at the threshold of  $EC_e$  when crop yield first reduces below potential crop yield ( $dSm^{-1}$ ); and  $K_y$  is a yield response factor.

The water balance model has a daily time step, so the crop root zone depth is calculated each day using the following equation (Prajamwong 1994):

$$R_z(J) = R_z(J - 1) + \frac{(R_z)_{\text{max}} - R_z(J - 1)}{J_{\text{planting}} + L_1 + L_2 - J + 1} \quad (5.9)$$

where  $J_{\text{planting}}$  is the day of the year that the crop is planted;  $(R_z)_{\text{max}}$  is the maximum root depth for a specific crop;  $L_1$  is the length of the initial crop growth stage (days); and  $L_2$  is the length of the crop development stage (days).

In the calculation of the daily crop root zone depth, additional factors such as the crop growth stage, and location of the groundwater table are considered. If the bottom of the root zone coincides with the water table, there will be no root growth during that day. Likewise, there will not be any root growth if the water table is inside the root zone. It is assumed that if groundwater fluctuates and if the root zone stays within groundwater table for more than 3 days, the portion of the roots found below the water table will die due to lack of oxygen, and it will not grow back if the crop is already at the end of the development stage (i.e. has reached full cover).

The groundwater contribution is the up-flux due to capillarity from the water table that can be used by the crop. The groundwater contribution is calculated by the model on a daily basis. If the water table is not inside the root zone or at the root zone, the groundwater contribution can affect the plant only if capillary rise from the groundwater table reaches the bottom of the root zone. The amount of capillary rise for various soil textures is given in Table 5.1.

An average of the above values is considered. If the groundwater table is below the values given in Table 5.1, the groundwater contribution is assumed to be negligible; otherwise the amount of the groundwater contribution will be calculated based on Darcy's law for unsaturated soil condition (Eching et al. 1994):

$$GW = -K(\theta)\left(\frac{\partial h(\theta)}{\partial z} + 1\right) = -K(\theta)\left(\frac{h(\theta)}{GWT} + 1\right) \quad (5.10)$$

in which  $K(\theta)$  is the unsaturated hydraulic conductivity (m/s); GWT is the depth to the water table from the ground surface (m); and  $h$  is the soil water head (m). Unsaturated hydraulic conductivity is calculated as follows (Eching et al. 1994):

Table 5.1. Capillary rise values for various soil types (FAO 2010)

Soil Texture	Capillary Rise (cm)
Coarse	20 to 50 cm
Medium	50 to 80 cm
Fine	more than 80 cm, up to several meters

$$K(\theta) = K_{\text{Sat}} \left[ \frac{\theta(\text{J}) - \theta_r}{\theta_s - \theta_r} \right]^{0.5} \left[ 1 - \left( 1 - \left[ \frac{\theta(\text{J}) - \theta_r}{\theta_s - \theta_r} \right]^{1/m} \right)^m \right]^2 \quad (5.11)$$

in which  $\theta_r$  is residual soil moisture content;  $K_{\text{Sat}}$  is the saturated hydraulic conductivity; and  $m$  is defined as:

$$m = 1 - \frac{1}{n} \quad (5.12)$$

where  $n$  is an empirical parameter defined by Van Genuchten, and is defined in Table 5.2.

Finally,  $h$  is the soil water head and is calculated as follows (Raes 2009):

$$h(\theta) = \left( \frac{1}{\alpha} \left[ \frac{\theta_s - \theta_r}{\theta(\text{J}) - \theta_r} - 1 \right]^{1/m} \right)^{1/n} \quad (5.13)$$

The amount of runoff is estimated based on: (1) the amount of precipitation; (2) the amount of water that can be stored inside the root zone area; and (3) the irrigation method.

In the water and salt balance calculations, considering the soil water content, root zone depth and amount of water that can be stored in the root zone area, the amount of



Table 5.2. Values of Van Genuchten water retention parameters (Schaap et al. 1999)

Soil Type	n	$\alpha$ (cm <sup>-1</sup> )	$\theta_s$ (cm <sup>3</sup> /cm <sup>3</sup> )	$\theta_r$ (cm <sup>3</sup> /cm <sup>3</sup> )
Sand	3.18	0.0350	0.375	0.053
Loamy Sand	1.76	0.0320	0.391	0.049
Sandy Loam	1.45	0.0260	0.388	0.039
Loam	1.48	0.0098	0.400	0.062
Silt Loam	1.48	0.0098	0.400	0.062
Silt	1.68	0.0066	0.489	0.050
Silt Clay Loam	1.53	0.0076	0.484	0.090
Silt Clay	1.33	0.0140	0.476	0.115
Clay	1.27	0.0110	0.457	0.100

water deep percolation and runoff can be calculated. For this purpose, both irrigation water and precipitation are considered for each day of calculation. The amount of runoff due to irrigation water is estimated as a fraction of the total irrigation water. The amount of soil water storage, deep percolation and the amount of water ponded on the land is calculated thereafter.

The amount of runoff and deep percolation due to daily precipitation is calculated based on the effective rainfall amount. Effective rainfall is the amount of rainfall that can be used by the plant, which is the amount of total precipitation subtracted by the amount of runoff and deep percolation. Effective precipitation can be calculated using various methods, such as:

- FAO-AGLW method;

- USBR method (Smith 1988); and
- USDA-SCS method (Dastane 1978).

The method used in this model is FAO-AGLW, applied on a daily basis (Smith 1998):

$$P_{\text{eff}} = 0.6P_{\text{total}} - \frac{10}{30}; P_{\text{total}} \leq \frac{70}{30} \text{ mm} \quad (5.14)$$

$$P_{\text{eff}} = 0.8P_{\text{total}} - \frac{25}{30}; P_{\text{total}} > \frac{70}{30} \text{ mm} \quad (5.15)$$

in which  $P_{\text{eff}}$  is effective precipitation, which is the amount of precipitation that infiltrates at the soil at the surface; and  $P_{\text{total}}$  is the total precipitation.

The amount of deep percolation is calculated daily. Deep percolation quantity is related to the amount of water that can be stored in the root zone area. According to FAO (2010), the soil water content above field capacity cannot be held against the forces of gravity and will drain. Field capacity is the soil water content after the gravitational water has drained, and which is available to the plants. Field capacity is assumed to be reached when the water potential in the soil is at -33 kPa (-1/3 bar). The field capacity is reached in one to three days based on the soil texture. At the end of the day, if the soil moisture content of the root zone area is more than field capacity, the amount of deep percolated water estimated by model will be modified, according to the soil texture and hydraulic saturated conductivity.

The amount of ponded water on the soil also is being considered in the daily calculations of the model. Ponded water is affected by the irrigation method. For instance, if the irrigation system is basin, there will be no runoff from the land and the extra water will be considered as ponded water.

The amount of soil water content of the soil in the root zone area is assumed to be at field capacity at the beginning of the simulation and is updated several times each day of a simulation, considering the amount of evapotranspiration, groundwater contribution, precipitation, runoff, ponded water, and deep percolation.

The details of water balance calculations for a specific day of the year are shown in the flow charts presented in Appendix B. Also, it should be noted that the user manual for this model is shown in Appendix C.

#### 5.1.1.2. Salt balance calculations

In order to investigate the effects of water reuse on soil salinity, salt balance calculations are considered in this model, on a daily basis. Root-zone salt balance calculations are based on the following equations:

$$S_{\text{today}} = S_{\text{yesterday}} + \Delta S \quad (5.16)$$

where  $\Delta S$  ( $\text{kg}/\text{m}^2$ ) is the amount of salt entering the root zone, minus the amount of salt leaving the root zone. In other words:

$$\Delta S(J) = 6.4(10^{-4})[I_{\text{net}}(J)EC_i(J) + GW_{\text{net}}(J)EC_{\text{gw}}(J) - DP_a(J)EC_{\text{dp}}(J)] \quad (5.17)$$

For daily salt balance calculations, all parameters on the right side of the above equation should be determined. For the first day of calculations, an initial value for soil water salinity ( $EC_{\text{sw}}$ ) should be known. The average soil saturated extract salinity ( $EC_e$ ) will be calculated based on soil water salinity, using the following equation:

$$EC_e(J) = EC_{sw}(J) \frac{\theta(J)}{\theta_s} \quad (5.18)$$

where EC is in units of dS/m. Therefore, the salt content in the soil in root zone (S) can be calculated as:

$$S(J) = 0.64EC_e(J)R_z(J) \quad (5.19)$$

in which S is in kg/m<sup>2</sup>; and EC is in dS/m. The constant 0.64 is a conversion factor.

The amount of drainage water salinity is calculated, as follows (Ayers and Westcot 1994):

$$EC_{dp}(J) = 2EC_e(J) \quad (5.20)$$

If the calculations are done for a day other than planting day, according to a salt mass balance:

$$S(J) = S(J - 1) + \Delta S(J - 1) \quad (5.21)$$

in which  $\Delta S$  is the change in salt mass in the root zone. In other words:

$$S(J) = (S(J - 1) + \Delta S(J - 1)) \frac{R_z(J)}{R_z(J-1)} \quad (5.22)$$

Since the calculations are performed on a daily basis, the root depth is potentially (for annual and immature perennial crops) changing every day. Therefore, the change in root depth must be considered in the salt mass balance equation. This is done by adding the term  $\frac{R_z(J)}{R_z(J-1)}$ . Therefore, the average soil saturated extract salinity will be:

$$EC_e(J) = \frac{S(J)}{0.64R_z(J)} \quad (5.23)$$

The effects of salinity are being considered in two ways: (1) the effect of salinity on crop yield; and (2) the changes of salinity in soil saturated extract at the beginning and end of asimulation. More details aboutthe daily salt balance calculations are shown in the flow charts in Appendix B.

#### 5.1.1.3. Crop yield calculation

Maximum yield of a crop is related to its genetics and its adaptability to environmental factors. The environmental requirements for a crop to reach its maximum yield are different based on the crop type (Doorenbos et al. 1986). Several factors affect the crop yield. Water availability, soil nutrients, and soil salinity are some of those factors.

The effects of soil salinity and water stress are considered in the new model. Salts in the soil create high osmotic pressure in the root zone, which makes the water less available for the plants.This causes the decrease of the crop evapotranspiration and crop yield (Eq.5.6).Yield calculations were done using the following equation (Allen et al.1998):

$$K_S = 1 - \frac{1}{K_y} \left( 1 - \frac{Y_a}{Y_m} \right) \quad (5.24)$$

in which  $Y_m$  is the potential crop yield and  $Y_a$  is the actual crop yield.

#### 5.1.1.4. Parameters and assumptions

- The model uses a daily time step.

- Changes in water table depth due to deep percolation and groundwater contributions to the root zone are not considered. Instead, the depth to the water table is taken to be independent of internal variables.
- The soil column in the root zone is homogeneous (in both texture and structure) and soil water content and salt concentration is uniform throughout the depth of the root zone for each 24-h simulation interval.
- Lateral flow of soil water between adjacent fields and lands is considered to be negligible.
- It is assumed that there is only one soil layer.
- If irrigation, precipitation, and groundwater contributions all enter the crop root zone in any given day of a simulation, it is assumed that the groundwater contribution occurs first, followed by irrigation, and finally by precipitation.
- One or both of the following variables must be zero in each day of a simulation: net deep percolation from the root zone, and net groundwater contribution to the root zone.

#### 5.1.2. Nutrient calculations

Investigation of the effects of various scenarios on nitrogen and phosphorus pollution of groundwater and surface water cannot be done without a nutrient balance simulation in the root zone area. For this purpose the effects of water reuse on nitrogen and phosphorus leaching and runoff are evaluated on a daily basis. This part of the model is based on the method used in GLEAMS (Groundwater Loading Effects of Agricultural Management System) model, but with a simpler approach.

In order to perform the nutrient balance calculations in the root zone area, the results from the water balance simulation in the root zone should be used. However, due to many details considered in the water and salt balance described in the previous sections, another water balance procedure was used. This method is similar to the water balance method described above. The differences are:

- It is assumed that there are two soil layers: (1) a surface soil layer (1 cm); and (2) a soil layer that goes to the bottom of the root zone.
- Groundwater contributions are not considered.
- Water uptake by the plant is estimated based on the 10-20-30-40 pattern of water use as shown in Fig. 5.2 (Ayers and Westcot 1994). Therefore, based on the depth of the soil layer and actual evapotranspiration by the plant, water uptake for each soil layer is calculated.
- Runoff from the land is calculated based on the SCS curve number method.

According to this method, runoff can be calculated as:

$$Q = \frac{(P-0.2S)^2}{P+0.8S}, \text{ For } P > 0.2S \quad (5.25)$$

in which Q is the depth of runoff (mm); P is rainfall depth (mm); and S is potential maximum retention (mm), and can be estimated as follows:

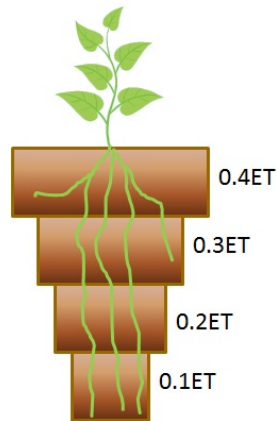


Figure 5.2. Water use pattern in the soil root zone (Ayers and Westcot 1994).

$$S = \frac{1000}{CN} - 10 \quad (5.26)$$

in which CN is the SCS curve number, which ranges from 30 to 100.

- Pondered water is not considered in these calculations.

The results from the water balance calculations are used to do the daily nitrogen and phosphorus mass balance in the root zone area. Similar to salt balance calculations, the nitrogen and phosphorus entering and leaving the root zone area should be considered. Rainfall, irrigation water, wastewater and nitrogen fixation in the root zone are the sources considered in this model that can add nitrogen to the soil. Runoff, deep percolation, volatilization, denitrification, and nitrogen in the crop yield are the sources that remove nitrogen from the soil. Sources considered for adding phosphorus to the soil are irrigation water and wastewater. Phosphorus can be lost from the root zone area by the amount stored in the crop yield, runoff, and deep percolation. It should be mentioned that some of nitrogen and phosphorus sources can be lost from the soil due to sedimentation, which was not considered in this study.



However, due to various forms and transformations of nitrogen and phosphorus in the soil, as mentioned in Chapter 2, the nutrient balance calculations are more complex. The addition of nitrate and phosphorus to the soil due to rainfall and irrigation is calculated. Nitrate addition to the soil due to rainfall is calculated as:

$$RN = 0.01(CN_R)(\text{Rainfall}) \quad (5.27)$$

in which RN is the rainfall nitrate added to the soil layer one (kg/ha);  $CN_R$  is the concentration of nitrate in the rainfall (mg/L); and Rainfall is the depth of rainfall in cm.

Nitrate added to the soil layer one due to rainfall is added to the amount of nitrate in the soil layer one. Nitrate added to the soil due to irrigation is estimated as (Knisel et al. 1993):

$$RCNI = 0.01(CN_I)(I) \quad (5.28)$$

in which RCNI is the nitrate added to the soil layer one due to irrigation (kg/ha),  $CN_I$  is the concentration of nitrate in the irrigation water (mg/L), and I is the irrigation water depth (cm). The amount of nitrate added to the soil due to irrigation should be added to the soil nitrate mass in soil layer one.

Phosphorus added to the soil layer one due to irrigation is calculated using the following equation (Knisel et al. 1993):

$$RCPI = 0.01(CP_I)(I) \quad (5.29)$$

in which RCPI is the phosphorus added to the soil layer one due to irrigation (kg/ha);  $CP_I$  is the concentration of phosphorus in the irrigation water (mg/L); and I is the irrigation

water depth (cm). The mass of phosphorus added to the soil due to irrigation should be added to the labile phosphorus mass inside soil layer one.

Daily nitrogen and phosphorus leaving the root zone area should be considered for nutrient balance calculation. Nutrients leaching below the root zone area, nutrients in the runoff and nutrients taken by the crop are some of the procedures during which nitrogen and phosphorus leave the root zone area. The uptake of ammonia (kg/ha) is calculated as (Knisel et al. 1993):

$$UPNH_i = 0.1(CNH4W_i)(WUP_i) \quad (5.30)$$

The uptake of nitrate (kg/ha) is calculated as:

$$UPNO_i = 0.1(CNO3W_i)(WUP_i) \quad (5.31)$$

in which  $CNH4W_i$  is the concentration of ammonia in water in soil layer  $i$ ; and  $CNO3W_i$  is the concentration of nitrate in water in soil layer  $i$ .

Large amounts of nitrogen in the soil do not result in uptake of nutrients more than the crop needs. Therefore, the crop demand of nitrogen should be calculated as (Knisel et al. 1993):

$$DEM N_d = TDM N_d - TDM N_{d-1} \quad (5.32)$$

in which  $DEM N_d$  is the nitrogen demand at day  $d$  (kg/ha); and  $TDM N_d$  is the total dry matter nitrogen (kg/ha), which can be estimated as follows (Knisel et al. 1993):

$$TDM N = 0.01(CN)(TDM) \quad (5.33)$$

in which, TMD is total dry matter (kg/ha) and CN is the concentration of nitrogen as percent of crop biomass. TMD and CN can be estimated as (Knisel et al. 1993):

$$CN = C_1(GRT)^{C_2} \quad (5.34)$$

$$TDM = (GRT)(PY)(DMY) \quad (5.35)$$

in which PY is the potential yield (kg/ha); DMY is the dry matter ratio; GRT is the growth ratio; and  $C_1$  and  $C_2$  are empirical coefficients.

In this model nitrogen losses due to runoff and deep percolation are estimated, for two layers of the soil: (1) surface layer (1 cm); and (2) the second soil layer.

Calculation of nitrogen loss due to runoff is described in the following paragraphs. Runoff nitrate (kg/ha) can be calculated as follows (Knisel et al. 1993):

$$RONO3 = 0.1(CNO3W_1)Q \quad (5.36)$$

in which, RONO3 is the runoff nitrate, Q is runoff in cm, and  $CNO3W_1$  is the concentration of nitrate in water in soil layer one (mg/L)(Knisel et al. 1993):

$$CNO3W_1 = 0.5 \frac{(SNO3_1)10^3}{(Soil\ Mass)_1} \quad (5.37)$$

in which,  $(Soil\ Mass)_1$  is soil mass in first soil layer (Mg/ha), and  $SNO3_1$  is the mass of nitrate-nitrogen in soil layer one in kg/ha.

Runoff ammonia (kg/ha) can be calculated using the following equation (Knisel et al. 1993):

$$RONH4 = 0.1(CNH4W_1)Q \quad (5.38)$$

in which  $RONH_4$  is the runoff ammonia, and  $CNH_4W_1$  is the concentration of ammonia in water in soil layer one (mg/L)(Knisel et al. 1993):

$$C_{NH_4W_1} = \left[ \frac{AMON_1 10^3}{(SoilMass)_1} \right] \exp \left[ \frac{-(F-ABST)}{CNHKD_1 \left( \frac{1-POR_1}{2.65} \right) + POR_1} \right] \left[ \frac{\beta_{nh}}{(1+\beta_{nh}CNHKD_1)} \right] \quad (5.39)$$

in which  $AMON_1$  is the ammonia in soil layer one (kg/ha);  $POR_1$  is porosity of soil layer 1; and  $ABST$  is the initial abstraction from rainfall (cm), and can be calculated as follows(Knisel et al. 1993):

$$ABST = 0.2(SAT_1 - SW_1) \quad (5.40)$$

in which  $SW_1$  is the volumetric water content for soil layer one; and  $SAT_1$  is the volumetric water content at saturation.  $CNHKD_1$  is the partitioning coefficient for ammonia in first soil layer ( $K_d$ ) and is defined as follows(Knisel et al. 1993):

$$CNHKD_i = 1.34 + 0.083CL_i \quad (5.41)$$

in which  $CL_i$  is the clay content (%) in soil layer i.

$\beta_{nh}$  is the extraction coefficient of ammonia and can be estimated as follows(Knisel et al. 1993):

$$\beta_{nh} = \begin{cases} 0.5, & CNHKD \leq 1.0 \\ 0.598 \exp(-0.179 CNHKD), & 1.0 < CNHKD < 10 \\ 0.1, & CNHKD \geq 10 \end{cases} \quad (5.42)$$

Therefore, total runoff losses of nitrogen (TotRON), in kg/ha will be(Knisel et al. 1993):

$$\text{TotRON} = \text{RONO}_3 + \text{RONH}_4 \quad (5.43)$$

Calculation of nitrogen loss due to percolation is described in the following paragraphs. Average percolated concentration of nitrate from soil layer one ( $\text{PERCNO}_1$ ) in mg/L is calculated using the following equation (Knisel et al. 1993):

$$\text{PERCNO}_1 = \frac{0.1(\text{MassPercNO})}{\text{PERC}_1} \quad (5.44)$$

in which  $\text{PERC}_1$  is the depth of percolation from soil layer one in cm; and  $\text{MassPercNO}$  is the percolation component of the total available nitrate mass and can be calculated as follows (Knisel et al. 1993):

$$\text{MassPercNO} = \text{AVNOMS} - [(\text{C}_{\text{av}})_{\text{NO}}(\text{SoilMass})_1] \quad (5.45)$$

in which  $\text{AVNOMS}$  is the initial mass of nitrate available for runoff and leaching (kg/ha); and  $(\text{C}_{\text{av}})_{\text{NO}}$  is nitrate concentration in soil layer one for runoff and leaching.

$$\text{AVNOMS} = (\text{CNO}_3)_1(\text{SoilMass})_1 \quad (5.46)$$

Percolated concentration of ammonia from soil layer one ( $\text{PERCNH}_1$ ) in mg/L is calculated as (Knisel et al. 1993):

$$\text{PERCNH}_1 = \frac{0.1(\text{MassPercNH})}{\text{PERC}_1} \quad (5.47)$$

in which  $\text{PERC}_1$  is the depth of percolation from soil layer one (cm); and  $\text{MassPercNH}$  is the percolation component of the total available ammonia mass and can be calculated using the following equation (Knisel et al. 1993):

$$\text{MassPercNO} = \text{AVNHMS} - [(\text{C}_{\text{av}})_{\text{NH}}(\text{SoilMass})_1] \quad (5.48)$$

in which AVNHMS is the initial mass of ammonia available for runoff and leaching (kg/ha); and  $(\text{C}_{\text{av}})_{\text{NH}}$  is ammonia concentration in soil layer one for runoff and leaching.

$$\text{AVNHMS} = (\text{CNH4})_1(\text{SoilMass})_1 \quad (5.49)$$

Percolation masses of nitrate and ammonia and also percolation mass of water from soil layer one, must be added to soil layer 2, and the calculations for soil layer 2 will be the same as in the first soil layer.

Calculation of phosphorus in runoff is described in the following paragraphs.

Labile phosphorus mass in runoff is (Knisel et al. 1993):

$$\text{ROLP} = 0.1(\text{CPLABW}_1)Q \quad (5.50)$$

in which ROLP is in kg/ha, and  $\text{CPLABW}_1$  is the concentration of labile phosphorus in soil water in soil layer one (mg/L) and can be estimated from the following equation (Knisel et al. 1993):

$$\text{CPLABW}_1 = \frac{(\text{C}_{\text{av}})_{\text{P}}\beta_{\text{P}}}{1+(\text{CPKD}_1)\beta_{\text{P}}} \quad (5.51)$$

in which  $\beta_{\text{P}}$  is extraction coefficient for phosphorus, CPKD is the partitioning coefficient of phosphorus, and  $(\text{C}_{\text{av}})_{\text{P}}$  is the concentration of phosphorus in the surface layer of the soil available for runoff and percolation in layer 2, and can be estimated as (Knisel et al. 1993):

$$(C_{av})_P = (CPLAB_i) \exp \left[ \frac{-(F-ABST)}{CPKD_1 \left( \frac{1-POR_1}{2.65} \right) + POR_1} \right] \quad (5.52)$$

In which CPLAB is the concentration of labile phosphorus ( $\mu\text{g/g}$ ).

$$CPKD_i = 100 + 2.5CL_i \quad (5.53)$$

in which,  $CL_i$  is the percentage of clay in the soil layer  $i$ .

It should be mentioned that phosphorus loss due to erosion is not considered in this model and therefore is not described in this study.

Mineralization of nitrogen for each soil layer ( $\text{kg/ha/day}$ ) can be estimated from the following equation (Knisel et al. 1993):

$$MN_i = (CMN)(POTMN_i)[(SWFA_i)(TFA_i)]^{0.5} \quad (5.54)$$

in which  $MN_i$  is the mass of nitrogen mineralization in soil layer  $i$ ;  $CMN$  is a mineralization constant ( $0.0003 \text{ kg/ha/day}$ );  $POTMN$  is the active N pool (potentially mineralizable) in  $\text{kg/ha}$ ;  $SWFA$  is the soil water factor for ammonification; and  $TFA$  is the temperature factor for ammonification.

$$SWFA_i = \frac{(SW_i - WP_i)}{(FC_i - WP_i)} \text{ for } SW \leq FC \quad (5.55)$$

$$TFA_i = \frac{T_i}{T_i + \exp(9.93 - 0.312T_i)} \text{ for } T_i > 0 \quad (5.56)$$

in which  $T$  is the soil temperature in degrees centigrade.

In the next part, nitrification ( $\text{kg/ha/day}$ ) is calculated as (Knisel et al. 1993):

$$NIT_i = \frac{(TFN_i)(SWFN_i)}{(SoilMass)_i} \quad (5.57)$$

in which TFN is the temperature factor for nitrification; and SWFN is the soil water factor for nitrification (Knisel et al. 1993).

$$TFN_i = \begin{cases} 0, & T_i \leq 0 \\ 0.496T_i, & 0 < T_i \leq 10 \\ \exp\left(22.64 - \frac{5956.4}{(T_i+273)}\right), & T_i > 10 \end{cases} \quad (5.58)$$

$$SWFN_i = \begin{cases} 0, & SW_i \leq WP_i \\ \frac{SW_i - WP_i}{FC_i - WP_i}, & WP_i < SW_i \leq FC_i \\ 1 - \left(\frac{SW_i - FC_i}{SAT_i - FC_i}\right), & FC_i < SW_i < SAT_i \\ 0, & SW_i \geq SAT_i \end{cases} \quad (5.59)$$

Mineralization from fresh organic phosphorus is estimated as:

$$RMP_i = (DCR_i)(FOP_i) \quad (5.60)$$

where RMP is in kg/ha. FOP is the fresh organic phosphorus (kg/ha).

Immobilization rate of nitrogen can be estimated from the following equation:

$$WIMN_i = (DCR_i)(FRES_i)(0.016 - C_{nfr}) \quad (5.61)$$

in which WIMN<sub>i</sub> is the nitrogen immobilization rate (kg/ha/day); and C<sub>nfr</sub> is the concentration of nitrogen in fresh residue (kg/ha) (Knisel et al. 1993):

$$(C_{nfr})_i = \frac{FON_i}{FRES_i} \quad (5.62)$$

where FON is the nitrogen in the fresh residue (kg/ha).

The immobilized phosphorus in kg/ha is (Knisel et al. 1993):



$$WIMP_i = (DCR_i)(FRES_i)[0.16PLI_i - (C_{pfr})_i] \quad (5.63)$$

where DCR is the decomposition of crop residue; and;  $C_{pfr}$  is the concentration of phosphorus in the fresh residue (kg/ha), which can be calculated as follows:

$$(C_{pfr})_i = \frac{FOP_i}{FRES_i} \quad (5.64)$$

PLI is labile phosphorus immobilization factor and is estimated as follows (Knisel et al. 1993):

$$PLI_i = 0.01 + 0.001CPLAB_i, \text{ For } CPLAB \leq 10 \quad (5.65)$$

$$PLI_i = 0.02, \text{ For } CPLAB > 10 \quad (5.66)$$

in which CPLAB is the concentration of labile phosphorus ( $\mu\text{g/g}$ ).

Volatilization of ammonia is estimated as (Knisel et al. 1993):

$$VOLN = (AWNH)[1 - \exp(-k_v t)] \quad (5.67)$$

in which VOLN is in kg/ha; AWNH is the ammonia in animal waste (kg/ha);  $k_v$  is a volatilization rate constant; and t is time (days). Volatilization rate constant can be estimated as follows (Knisel et al. 1993):

$$k_v = 0.409(1.08)^{T-20} \quad (5.68)$$

in which T is the mean daily air temperature (degrees Celsius).

The following assumptions were made for the nutrient calculations:

- It is assumed that there are two soil layers for calculations of nutrients; one surface soil layer with 1cm depth and the other one is the rest of the root zone depth.
- The root zone depth is calculated for each day.
- Nutrient loss effects on crop yield are not considered in this model.
- The effects of fertilizers are not considered. Only wastewater effects are considered in this model.
- Erosion of the land and nutrient amounts in sedimentation is not considered.

#### 5.1.3. Pumping and conveyance costs calculations

One of the important factors in treated wastewater reuse management is the location of treatment plants with regard to agricultural lands, and whether pumping will be needed to deliver water. In the Water Reuse Model, the water conveyance and pumping costs for different scenarios are calculated and compared. In the following sections the details of these calculations are described.

For conveyance and pumping costs calculations in the Water Reuse Model, the user can add up to three connections between the agricultural land and the water resource in order to define the topography of the land. Each of these connections has specific characteristics that must be defined by the user:

- Elevation (m);
- Distance (to the previous connection) (m);
- Connection efficiency; and

- Type of connection (if the connection is already existing or not)

For three connections, based on their relative elevations, 27 different cases can be considered, two of which are shown in Fig. 5.3. Based on the topography of the land between agricultural area and water resource, annual pumping cost, and annual water conveyance costs are calculated in the Water Reuse Model. Therefore, based on the calculations of water demand for each day (calculated in water and salt and salt balance calculation method), the efficiency of the delivery method and the characteristics of each connection, factors such as those given below are estimated for each connection:

- Whether the capacity is sufficient;
- If there is a need to install more pipe, or to expand the canals; and
- If there is need for water pumping and the beginning and ending locations, between which pumping is needed.

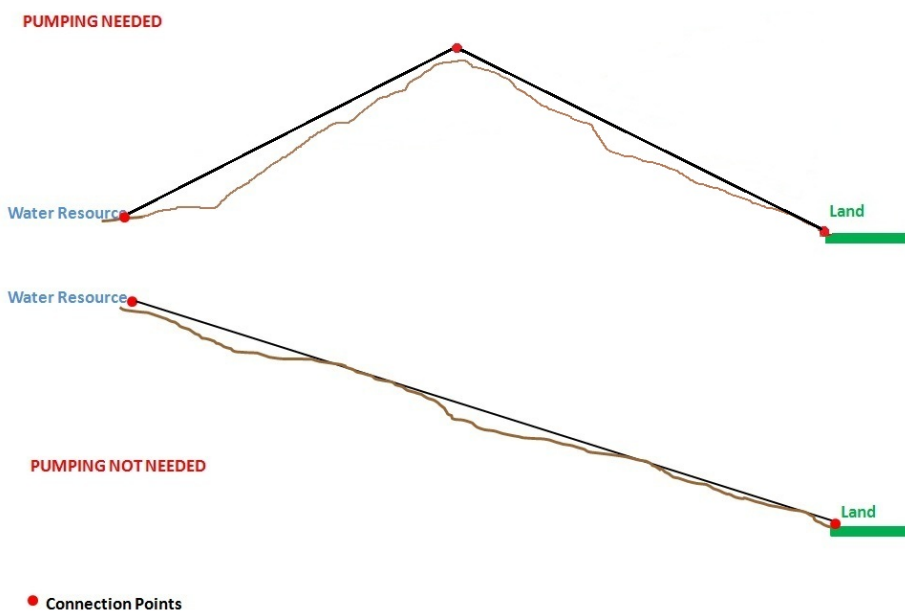


Figure 5.3. Two cases that can occur for calculations of pumping and conveyance costs.

The model calculates the amount of gross annual water demand for each scenario. The water demand for each crop is calculated in water balance calculation section. For each crop, based on the irrigation system efficiency and the percentage of the land area that the crop is grown on, the volume of gross water demand per day is calculated:

$$\text{Gross Water Demand Volume} = \frac{(\text{Kc ETc})(\text{Land Area})}{\text{Irrigation Efficiency}} \quad (5.69)$$

Then, the total gross water demand per day for each scenario will be calculated. The maximum daily water requirement will be considered for calculations of conveyance needs.

The model will investigate if pumping is needed in order to deliver the water. For this purpose, the model will compare the elevations of water resource, land and the connections added by the user and if the water is supposed to be delivered to a higher elevation, the model will assume that pumping will be needed. The locations from where to where the water should be pumped is defined by the model; therefore, the pumping capacity can be calculated by dividing the gross water demand at the land entrance to the efficiency of the conveyance system. In order to be able to calculate the pumping price for each year, water horsepower of the pump is calculated:

$$\text{WHP} = \frac{Q \text{ TDH}}{102} \quad (5.70)$$

in which WHP is water horsepower of the pump in kW; Q is the peak daily water requirement converted to flow rate in L/s, considering the total number of irrigation

hours; and TDH is the total dynamic head, in m. The total dynamic head can be calculated from the following equation:

$$\text{TDH} = \text{Static Head} + \frac{V^2}{2g} + \text{Friction Loss} \quad (5.71)$$

where the gauge pressure head at the outlet is assumed to be zero. Friction loss is calculated using the Darcy-Weisbach method:

$$\text{Friction Loss} = f \frac{L}{D} \cdot \frac{V^2}{2g} \quad (5.72)$$

in which friction loss is in head of water (m); L is length of the pipe (m); D is the inside diameter of the pipe (m); V is flow velocity inside the pipe; and f is the Darcy-Weisbach friction coefficient, which can be estimated from the equation for laminar flow ( $R_e < 2000$ ), or otherwise from the Blasius equation:

$$f = \frac{64}{R_e}, \text{ for } R_e < 2000 \quad (5.73)$$

$$f = \frac{0.3164}{R_e^{0.25}}, \text{ for } R_e \geq 2000 \quad (5.74)$$

in which  $R_e$  is the Reynolds number. However, laminar flow is almost never found in irrigation pumping systems.

Water horsepower of the pump is converted to kWh in order to calculate the annual pumping price:

$$\text{kWh} = \text{WHP} \times (\text{Operating hrs per day})(\text{Operating days per year}) \quad (5.75)$$

The annual pumping cost is calculated by the model based on the fuel used for pumping.

The conveyance cost is calculated by the model. The model will consider the first connection defined by the user. Depending on the elevation of the connection compare to the elevation of the previous connection (or the land), the model will automatically consider either a pipe or a canal. Then, depending on the connection built or not built, the model will calculate the capacity of the existing pipe or canal and compare it to the required capacity. The capacity of the pipe will be calculated based on the maximum allowable water velocity inside the pipe:

$$Q = AV_{\max} \quad (5.76)$$

in which,  $Q$  is the pipe capacity ( $\text{m}^3/\text{s}$ );  $V_{\max}$  is the maximum allowable flow velocity inside the pipe, and is assumed to be equal to 1.5 m/s; and  $A$  is the area ( $\text{m}^2$ ) of the pipe cross section, and is calculated using the following equation:

$$A = \pi D^2/4 \quad (5.77)$$

in which  $D$  is the pipe diameter (m). The pipe capacity is compared with the system capacity, which is assumed to be the peak flow rate. If the existing pipe is not capable to convey the water requirements, the appropriate diameter of the pipe is calculated.

If a canal exists for the connection, the capacity of the canal can be calculated using the Manning equation:

$$Q = \frac{1}{n} AR^{2/3} S^{0.5} \quad (5.78)$$

in which Q is the flow rate (m<sup>3</sup>/s); n is the Manning roughness coefficient (s/m<sup>1/3</sup>); R is the hydraulic radius (m); and S is the canal longitudinal bed slope(m/m). If the channel capacity is less than the capacity needed for delivering the water to the land, the canal expansion will be considered. The suitable canal capacity for the scenario is calculated by the model. In order to design the dimensions of the canal, if no canal exists, the model will assume that the canal is rectangular; if a canal already exists, the model will assume that the shape of the new canal is the same as the canal existing (either rectangular or trapezoidal). For any of those cases the following term should be calculated:

$$AR^{2/3} = \frac{nQ}{S^{0.5}} \quad (5.79)$$

in which Q is the canal design capacity (m<sup>3</sup>/s).

Calculation of the canal dimension is based on the assumption of designing a hydraulically efficient canal. The conveyance of a canal increases with increase in the canal hydraulic radius or with decrease in the canal wetted perimeter. Therefore, a canal having the least wetted perimeter for a specific area has the maximum conveyance capacity (all else being equal), and it is called a hydraulically efficient canal (Thandaveswara 2011). The characteristics of the hydraulically efficient cross section, is summarized in Table 5.3, for rectangular and trapezoidal channel shapes. Combing Eq. 5.79 and Table 5.3, the cross section dimensions of the channel are calculated as described below. For rectangular channels:

$$\frac{nQ}{S^{0.5}} = (2y^2)(0.5y)^{2/3} = 1.2599y^{8/3} \quad (5.80)$$

Therefore, channel depth (m) is estimated using:

$$y = \left[ \frac{nQ}{(1.2599)S^{0.5}} \right]^{3/8} \quad (5.81)$$

According to Table 5.3, channel width is:

$$b = 2y \quad (5.82)$$

In the next step, the flow velocity will be calculated:

$$V = \frac{Q}{by} \quad (5.83)$$

The channel flow velocity should not be too low to allow sedimentation and vegetation growth in the canal. A value of 0.75 m/s is assumed as the lowest velocity allowed in the channel design (Thandaveswara 2011).

Also, the average flow velocity should be less than maximum allowable velocity, which is defined based on the channel material (Table 5.4). Froude number should be calculated and checked. Froude number should be less than 1, which means that the flow

Table 5.3. Characteristics of hydraulically efficient channel cross sections (Thandaveswara 2011)

<b>Cross Section</b>	<b>Rectangular</b>	<b>Trapezoidal</b>
Area (A)	$2y^2$	$1.732y^2$
Perimeter (P)	$4y$	$3.464y$
Hydraulic Radius (R)	$0.5y$	$0.5y$
Hydraulic Depth (D)	$y$	$0.75y$



in the canal should be subcritical. Froude number can be calculated using the following equation:

$$Fr = \frac{v}{\sqrt{gD}} \quad (5.84)$$

in which, D is the hydraulic depth of the canal, which is the area of the canal cross section divided by canal top width. If the Froude number is equal or more than one, the model designs the canal assuming that the Froude number is equal to 0.8.

The same steps that were described for rectangular channel design are also applied to trapezoidal channels: (1) the flow velocity should not be less than minimum allowable velocity (0.75 m/s); (2) flow velocity should be less than the maximum allowable velocity; and (3) flow should be subcritical (Froude number should be less than 1).

For trapezoidal cross section, channel depth (m) is defined as:

$$y = \left[ \frac{nQ}{(1.091092)S^{0.5}} \right]^{3/8} \quad (5.85)$$

Table 5.4. Maximum allowable flow velocity for various channel linings (Village of Canal Wenchester 2010)

<b>Channel Lining Material</b>	<b>Maximum Allowable Velocity (m/s)</b>
Sand	0.61
Silt	1.07
Firm Loam	1.07
Fine Gravel	1.52
Stiff Clay	1.52
Coarse Gravel	1.83
Concrete	5.49

According to Table 5.3, channel width is estimated using:

$$b = 2.3094y \quad (5.86)$$

Therefore, the channel side slope is:

$$m = \frac{A-b}{y} \quad (5.87)$$

Free board is considered in estimation of canal dimensions. Free board suggested by the USBR is summarized in Table 5.5 (Thandaveswara 2011). Therefore:

$$y = y + \text{Free board} \quad (5.88)$$

Based on the prices entered by the user for expansion of a canal to a certain cross section, the price of the expansion will be calculated. Calculation of the dimensions of a canal is done by using the cross section corresponding to the most hydraulically efficient channel.

Finally, the total annual costs for pumping and conveyance of water are calculated.

Therefore, the price for building a pipe or canal is converted to an equivalent annual cost using the following equation (Newnan 1980):

Table 5.5. Free board recommended by the USBR (Thandaveswara 2011)

<b>Q (m<sup>3</sup>/s)</b>	<b>Free Board (m)</b>
< 0.75	0.45
0.75-1.5	0.60
1.5-85	0.75
> 85	0.90

$$A = P \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (5.89)$$

in which  $i$  is the annual interest rate;  $n$  is the useful life for each infrastructure component (different useful lives for various infrastructure components can be defined);  $P$  is present sum of money; and  $A$  is the equivalent uniform cost (Fig. 5.4). Therefore, the total annual costs for pumping and conveyance costs will be equal to the annual pumping cost, plus the equivalent annual cost of conveyance. Finally, for conveyance costs, 2% of total costs are added to annual costs. It should be considered that the cost calculations are only estimates and do not consider all the details of costs.

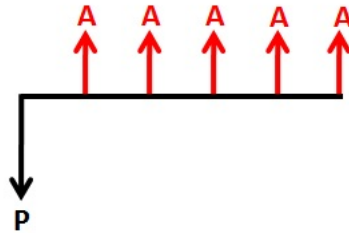


Figure 5.4. Conversion of total present cost to an equivalent annual cost for a specific period of time.

## CHAPTER 6

## SAMPLE APPLICATION AND RESULTS

## 6.1. State of Utah

Utah is an arid western state of the USA with an area of 82,170 square miles and a population of 2,817,222 (U.S. Census Bureau 2011). According to the estimates, in 2005 compared to 2000, a population growth of about 10.6% has been observed. Utah is the second driest state of the nation, and population growth and urbanization represent important impacts on the state's scarce water resources, and also on the agricultural lands. However, Utah is ranked 26<sup>th</sup> in terms of the amount of land being used for agriculture. According to the National Resources Inventory, from 1982 to 1997, around 105,000 acres of farmland have been developed to urban area in the state of Utah (UACD, UDAF, and NRCS2005).

Currently, there are about 12 million acres of farmland in Utah, 1.3 million (about 11 %) of which is irrigated. Agriculture has a large effect on the economy of the state of Utah. However, due to the location and climate of Utah, drought problems have occurred. In 2004, Utah State farmers faced a drought disaster that caused \$133 Million negative impact on the agricultural economy.

Considering the characteristics of this state, it is apparent that reclaimed water can be an appropriate and vital resource to prevent the disappearance of agricultural lands. In some parts of the state, such as in the Weber Basin area, farms have almost disappeared because of housing developments. In this region, treatment plants route water back into the streams, because water reuse within the service area causes the decrease of the return

flow back to the stream and affects the water rights. However, wastewater reuse as a secondary water supply in M&I (mostly landscape irrigation) is becoming more important, thereby reducing the availability of treated wastewater for application to irrigated agriculture (Anderson 2006).

In other areas, such as the City of Logan, the reclaimed water (with secondary treatment) is used by farmers from the middle of June to the middle of September each year. During the rest of the year, it will be discharged from the wetlands to the Swift Slough that drains into the Cutler Reservoir. It is up to the Division of Water Quality to determine how much water and with what quality can be released. Once the water is released, the Utah Division of Water Rights is responsible for regulating its use. Even though the water is not used by farmers during this period, storing such a large amount of treated wastewater could allow them to supply a larger area of land with water and expand irrigated agriculture. However, a very large area of land and therefore large amounts of funding, will also be needed to store the reclaimed water in the winter (Houser 2006).

## 6.2. Cache County

In order to test the model that was developed as part of this research, Cache County is considered. Cache County is one of the northwestern counties of Utah, with a total area of 3,038 km<sup>2</sup> (Figure 6.1). The Wasatch Mountains are located on its east edge and the Wellsville Mountains are located on its west edge, and the Bear River flows through the valley.

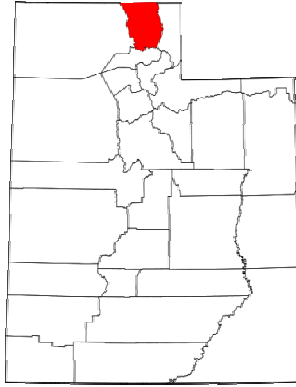


Figure 6.1. Utah counties and Cache County highlighted in red.

Cache County has 112,656 residents from 19 municipalities such as Logan, North Logan, Nibley, Smithfield, Hyde Park, Providence, Hyrum, and Richmond. Cache County has an important role in the agriculture of the state (U.S. Census Bureau 2011).

According to the Census Bureau (2011), the population in Cache County increased from 70,460 in 1990 to 111,873 in 2008; which is a 58.77% increase (Fig. 6.2). Therefore, the demand for water in municipalities has also increased.

Agriculture plays an important role in Cache County's economy. According to Cache County (2003), 26% of all gross economic output in Cache County is from agriculture. Cache County has about 1,195 farm fields (251,550 acres). Barley, winter wheat, spring wheat, dry beans, corn for silage, alfalfa hay and apples are important crops of Cache County (Utah State University-Economic Department 2006). Since 1986, around 14 square miles of prime and statewide important farmlands has changed to urban area. With the same rate of development, Cache County loses about 600 acres of prime and statewide important farmland to urban development annually (Cache County

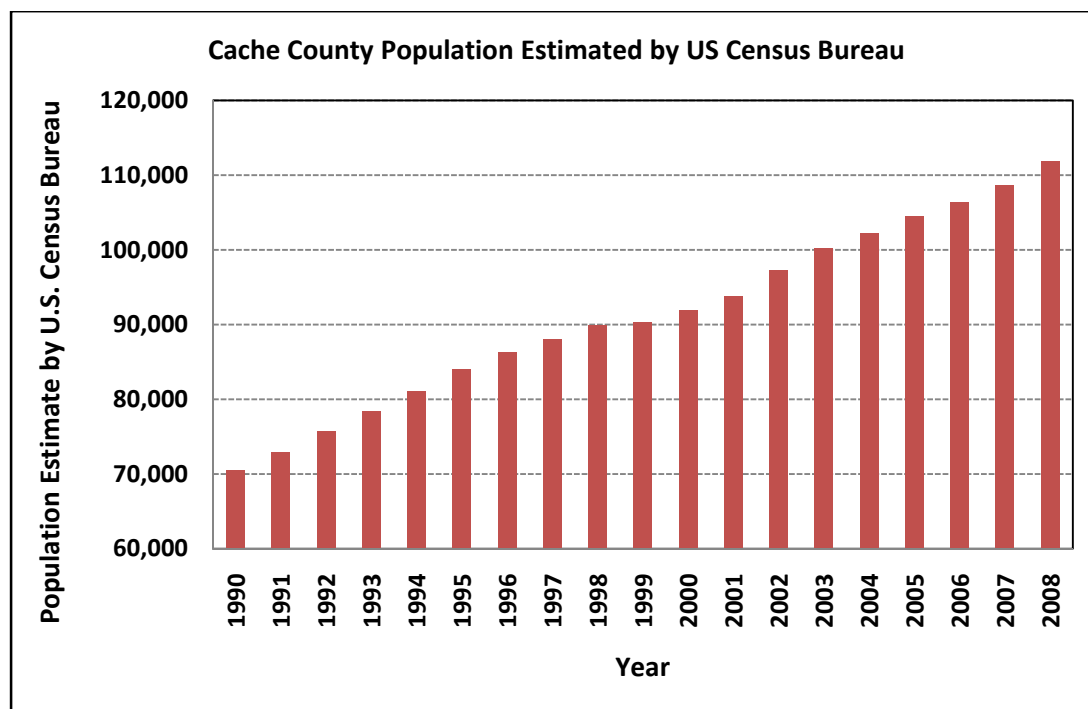


Figure 6.2. Cache County's population as estimated by the US Census Bureau.

2003). In Cache County, a reduction of 6.2% in the irrigated cropland was seen from 1986 to 2003; this is due to population growth and urbanization of irrigated agricultural lands (Division of Water Resources 2004).

Cache County receives most of its water from spring runoff (snowpack). The county's water is primarily used for irrigation purposes (Zhang et al. 2009). About 75% of water used for irrigation in Cache County is from rivers (Cub, Logan, and Blacksmith Fork) and runoff, 15% is from reservoirs and 10% is from deep wells (Utah State University-Economic Department 2006).

The new mathematical models developed in this study (Water Availability Model and Water Reuse Model) were tested for parts of Cache County and the case study results are described in the following sections.

### 6.3. Testing the Water Availability Model

The Water Availability Model was tested for one of the northern cities of Utah. Logan City, with an area of 16 square miles and an average elevation of 4,534 ft, is the home of the main campus of Utah State University and is located in Cache County at 41° 44' 08" N latitude and 111° 50' 04" W longitude (Logan Library 2011). Population growth, land use changes, water demand, and wastewater production analysis were performed for Logan City using the Water Availability Model. The following sections show the results for various parts of this model in detail.

#### 6.3.1. Population

As of 2010, the population of Logan was estimated to be 48,174 (U.S. Census Bureau 2011). Figure 6.3 shows the population of Logan from 2000 to 2009.

The future population of Logan was estimated using the new model, which allows

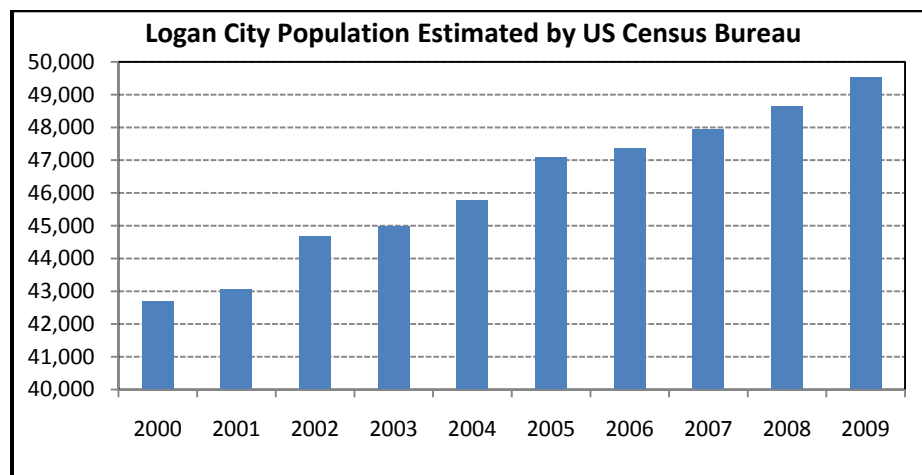


Figure 6.3. Population of Logan City from 2000 to 2009.



the user to apply two different methods (exponential and extrapolation) for future population forecast in the study area. In order to test the model, both methods were applied.

#### 6.3.1.1. Exponential method

According to U.S.Census (2011), the population of Logan City in 2000 was 42,670 and the population growth from 2000 to 2006 was around 2% per year. Therefore, using the population in year 2000 as the base population, and a growth rate of 2% per year, the future population of Logan was predicted. According to the results from the new model, the population of Logan for future years was estimated and is summarized in Table 6.1. The population forecast was compared with the population estimations by the Governor's Office of Planning and Budget (Logan Library 2011). The results indicate that the estimated populations by the new model are about 5.28% less than the values forecasted by the Governor's Office of Planning and Budget.

Table 6.1. Population estimated by the new model using the exponential method

<b>Year</b>	<b>Population Estimated by the New Model</b>	<b>Population Estimated by Governor's Office of Planning and Budget</b>	<b>Difference (%)</b>
2020	63,656	67,122	-5.16
2030	77,750	81,530	-4.64
2040	94,964	101,238	-6.20
2050	115,989	122,253	-5.12

### 6.3.1.2. Extrapolation method

The Extrapolation method for future population forecast was also tested. The population data available for past years was used to predict the future population. The model fits five curves types to the available data and assumes that the population will increase with the same trend, and the future population of Logan was predicted from the best-fit curve. The data shown in Table 6.2 were entered as the historic data. According to the results from the model, the exponential and power curves fit the data very well, with coefficients of determination ( $r^2$ ) equal to 0.9950 and 0.9949, respectively. The equations for these curves are:

$$Y = 1.040(10)^{-13}e^{(2.029(10)^{-2}X)} + 3.1479(10)^2 \quad (6.1)$$

$$Y = 2.236(10)^{-129}X^{4.038(10)} + 3.1479(10)^2 \quad (6.2)$$

in which Y is the population; and X is the year.

The future populations predicted in this method were summarized and compared to the population projections by the Utah Governor's Office of Planning and Budget (Tables 6.3 and 6.4). As seen in the tables, the predicted population is closer to the method mentioned above. However, it should be considered that the larger the data set entered by the user, the better the expected results.

### 6.3.2. Land use change

In the next part of the model, the changes of land use cover in the study area were investigated. The GIS layers of Logan City for years 1992 and 2001 were used together

Table 6.2. The population projection for Logan by the US Census Bureau and the Governor's Office of Planning and Budget as input data for the new model

<b>Year</b>	<b>Population</b>
1970	22333
1980	26844
1990	32762
2000	42713
2001	43082
2002	44701
2003	44994
2004	45795
2005	47088
2006	47359
2007	47965
2008	48656
2009	49549

Table 6.3. The population forecast by the new model, extrapolation method, exponential curve

<b>Year</b>	<b>Population Estimated by the New Model</b>	<b>Population Estimated by Governor's Office of Planning and Budget</b>	<b>Difference (%)</b>
2020	65,575	67,122	-2.30
2030	80,253	81,530	-1.57
2040	98,232	101,238	-2.97
2050	120,255	122,253	-1.63

Table 6.4. Population forecast by the new model, extrapolation method, power curve

<b>Year</b>	<b>Population Estimated by the New Model</b>	<b>Population Estimated by Governor's Office of Planning and Budget</b>	<b>Difference (%)</b>
2020	65,352	67,122	-2.64
2030	79,704	81,530	-2.24
2040	97,127	101,238	-4.06
2050	118,260	122,253	-3.27

with a boundary shape file (polygon type) that included Logan City. The input data for this part was gathered from Logan City GIS specialists and also through the Utah GISPortal (<http://gis.utah.gov/>). One of these layers and the study area are shown in Fig. 6.4.

The model calculates the area of various land covers for both map layers. These calculations for the case study data were done by the model and are shown in Table 6.5. As shown in the model results, the urban area inside the boundary layer increased approximately 49.3% from 1992 to 2001, while the agricultural area decreased approximately 3.4% in 9 years. However, it should be noted that the results are as accurate as the map layers are. Missing data in the maps will cause errors in the calculated area. This sub-model shows the effects of urbanization on agricultural area for the study area. Similar to Logan City, in many parts of the world, agriculture has a significant role in the economy and independence of countries and unfortunately, it has been ignored due to population and urban growth and increasing the demand rate of land and water resources.

According to the land cover maps gathered from the Logan City, GIS Department(2011c), the area of the city has changed from 5.57 square miles in 1950 to 14.46 square miles in 1990. The changes of the area of the Logan City are summarized in Table 6.6.

### 6.3.3. Water use

Water use is distinguished by two different categories (Logan City 2011a):

- Billed water use; and

- Unaccounted-water use (such as fire-hydrant flows and water lost due to leakage in water supply system).

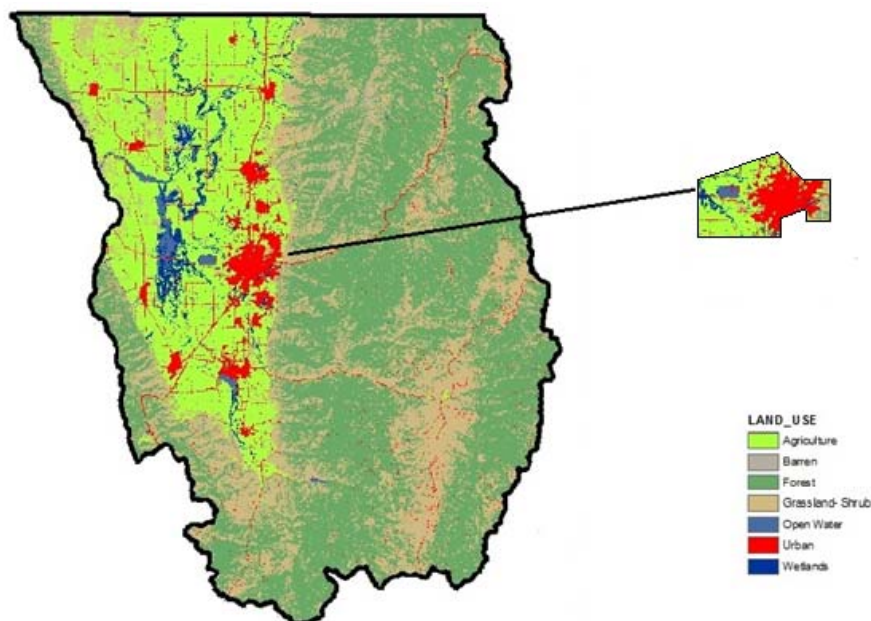


Figure 6.4. Land Use layer of Cache County for the year 2001, and the approximate study area for testing the Water Availability Model.

Table 6.5. The results calculated by Water Availability Model, Land Use Change sub-model

Land Cover	Area in 1992(ha)	Area in 2001 (ha)
Open Water	211.3	185.1
Urban	2,271.8	4,481.9
Barren	1.9	1.0
Forest	201.2	154.9
Grassland-Shrub	3,036.4	899.0
Agriculture	7,691.7	7,427.2
Wetland	307.0	572.3
<b>Totals</b>	<b>13,721.6</b>	<b>13,721.6</b>

Table 6.6. Changes of the area of Logan City, according to the data gathered from the Logan City, GIS Department (2011c)

<b>Year</b>	<b>Area (ha)</b>	<b>Area (square miles)</b>
1950	1441.7	5.5
1970	1908.3	7.3
1983	3303.7	12.7
1990	3745.0	14.4

Logan's billed water use is divided into two parts: (1) residential water consumption; and (2) commercial water consumption, which includes industrial, institutional, and irrigation of parks. Logan City has the records of water use per capita for various consumers mentioned above. The changes of water use per capita are shown in Fig. 6.5.

According to the graph, the average water demand per capita for residential area is approximately 95 gpcd (gallons per capita per day) for a period of 18 years (1992-2010). The average commercial water consumed through this period was about 75 gpcd. According to Logan City (2011a), commercial billed water use (including USU) accounts for 47% of the total billed water consumption.

The unaccounted-for water use in Logan City has decreased due to the city's flow measurement efforts over the past several years. The per capita use for unaccounted-for water use was more than 180gpcd in the 1900's, and decreased to 59 gpcd in the year 2010 (Logan City 2011a).

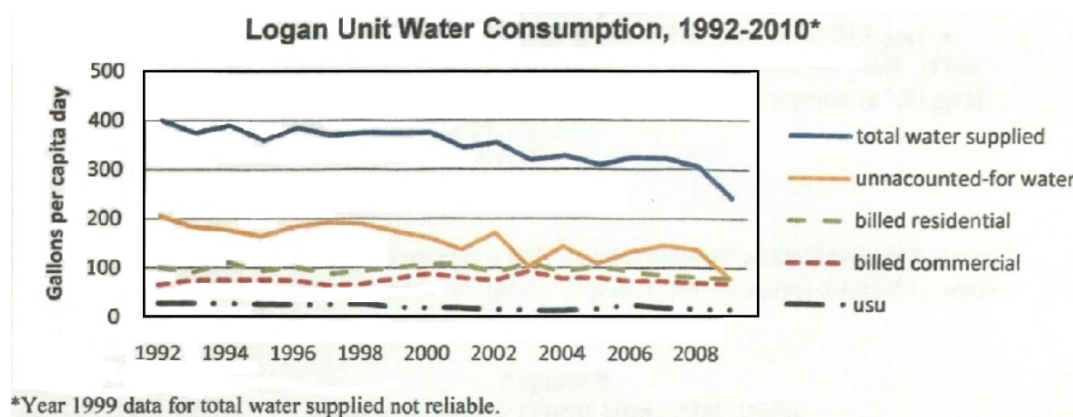


Figure 6.5. Changes of water use per capita for Logan City during 1992-2010 (Logan City 2011a).

An estimation of the water demand for Logan City using Water Availability Model was done based on a per capita method for residential and industrial users and water demand calculations for agricultural area. Water demand forecasts for the future in the study area can be estimated:

- Assuming the rate of water use stays the same; or,
- Assuming that the rate of use does not stay the same and water conservation methods are used.

In order to test the model, both of these methods were used and the results are discussed below. The data gathered from Logan City (2011a) indicates an average water usage of 95 gpcd for residential area and 88 gpcd for commercial users (75 gpcd for commercial and 13 gpcd for USU). Unaccounted-for water usages account for 59 gpcd in Logan City. Therefore, a total water demand of 242 gpcd for Logan City was used for the year 2011 (Logan City 2011a).

The average water usage is not equal for all months of the year. These values are higher in warmer months of the year and are lower during colder seasons. The model

allows the user to enter different values for various months and seasons of the year, but since there was not enough data for different parts of the year in Logan City, the calculations for this case study were done assuming that water usage rate is constant throughout the whole year. The results of this sub-model, for the total water demand, in the future years are summarized in Table 6.7. It is noted that the results were estimated by assuming that the water demand trend does not change. The results show a total water demand of 45.03 cfs for the study area, which is very close to the 45cfs water demand estimated by Logan City (2011a). Therefore, the model shows excellent agreement in terms of water demand calculations.

Agricultural water demand calculations can be performed using two methods:

- Per acre foot method; and
- Evapotranspiration calculations.

The first method was tested herein. According to the Utah Division of Water Rights (2011) the duty of water for the agricultural area around Logan varies from 3 to 5 acre-ft per acre. It should be noted that the amount of water that the farmlands receive depends on the weather conditions, including the amount of rainfall and snow pack. The farmers receive their total water share amount only if there is enough water available. According to the results from the Land Use sub-model, the agricultural area within the boundary defined for this study has changed from 7691.76 ha in 1992 to 7427.25 ha in 2001. According to the per acre-ft method, the water demand for agricultural area in the study area decreased approximately 3.4% from 1992 to 2001, assuming the 4 acre-ft/acre water use (Table 6.8).



Table 6.7. Water demand calculations for future by the Water Availability Model

<b>Year</b>	<b>Population Estimated by the New Model</b>	<b>Total Water Demand Estimated by the New Model (gpd)</b>	<b>Total Water Demand Estimated by the New Model (cfs)</b>
2020	65,575	15,869,150	24.55
2030	80,253	19,421,226	30.05
2040	98,232	23,772,144	36.78
2050	120,255	29,101,710	45.03

However, more accurate water demand calculations for agricultural area can be made by knowing the crop types grown in the lands and the fraction of the area for each crop. The Water Availability Model has the capability to calculate the water demand for farmland based on evapotranspiration calculations.

#### 6.3.4. Wastewater

In this model the water supply is assumed to be treated wastewater. The Logan wastewater treatment plant is the Logan Lagoon, which is operated by the Logan City Environmental Department. The Logan treatment plant consists of 460 acres of lagoon, 240 acres of wetlands and two storage ponds of 400 million gallons volume (combined) (Logan City 2011b; Utah Department of Environmental Quality 2009). This treatment plant receives its influent from Logan, Smithfield, Hyde Park, North Logan, River Heights, Providence, Nibley, and Utah State University.

The water released from the Logan treatment plant is used for agricultural irrigation from April 15<sup>th</sup> to October 1<sup>st</sup> according to the contract between the City of Logan and the Logan Cow Pasture Water Company Corporation (Utah Department of Environmental Quality 2009).

Table 6.8. Calculation of water use changes for agricultural lands in the study area by the Water Availability Model

Year	Agricultural Area in Study Area		Water Use (M.G.)
	ha	Acres	
1992	7,691	19,006	24,771.1
2001	7,427	18,353	23,920.8

The data for the influent to the treatment plant and the effluent from the plant was gathered from the Logan City Environmental Department. Total wastewater influent for different months of year for 2006- 2010 is shown in Fig. 6.6. It is seen that the quantity of water usage by all the users is at its highest during the summer season and at its peak in July. The influent entering the wastewater plant is at its lowest during the cold season of the year. On the other hand, the demand for irrigation water for agricultural area is mostly during the warm season of the year. This shows that wastewater can be considered as a reliable water supply for agricultural areas, especially in arid and semi-arid regions.

In this part of the model the amount of wastewater influent to the treatment plant is analyzed and the future water supply is forecasted. The annual maximum, minimum and average and total wastewater influent quantities to the Logan treatment plant for the period of 2006 to 2010 were the input data for the new model (Table 6.9). It should be mentioned that the retention time at the Logan treatment plant is 90 days.

According to Table 6.9, average water influent reaching the Logan treatment plant is approximately 12.30 million gallons per day, with a maximum of 24 million gallons

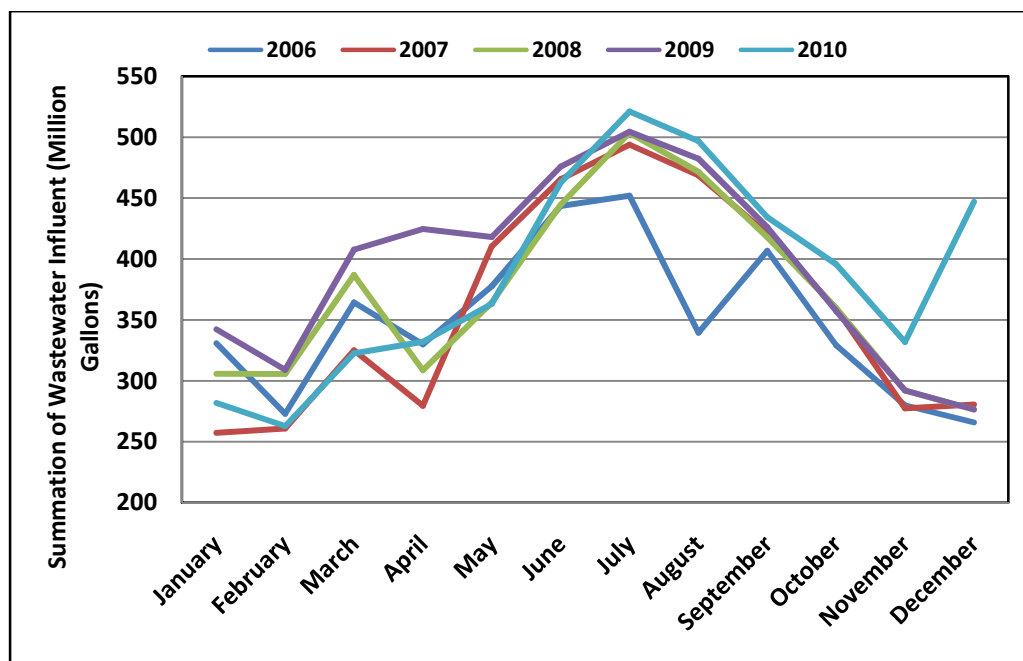


Figure 6.6. Total wastewater influent to the Logan Lagoon treatment plant during the year for various years (Logan City 2011b).

per day and a minimum value of 7 million gallons per day. Figure 6.7 shows the changes of these values for the years from 2006 to 2010.

According to the City of Logan, 11.6% of the influent was due to industrial users in 2010. Therefore, this amount should first be subtracted from the total wastewater influent in order to determine the part that is residential. This percentage might be different for the previous years, but it was assumed that for years of 2006 to 2010, 11.6% of the influent is from industrial sources. Also, it should be considered that the influent for Logan treatment plant comes from various cities, but in this study only the part related to Logan City was analyzed. The study area was Logan City, so the part of the influent that is related to other municipalities was subtracted from the data.

Table 6.9. Summary of the wastewater influent reaching the Logan treatment plant for various years, collected from Logan City (2011b)

Year	Average (M.G./day)	Maximum (M.G./day)	Minimum (M.G./day)	Summation (M.G./year)
2006	11.83	18.8	7.09	4,192.51
2007	11.76	17.82	7.51	4,298.9
2008	12.11	17.38	7.92	4,436.81
2009	12.91	19.36	7.26	4,716.51
2010	12.72	24.81	8.22	4,651.75

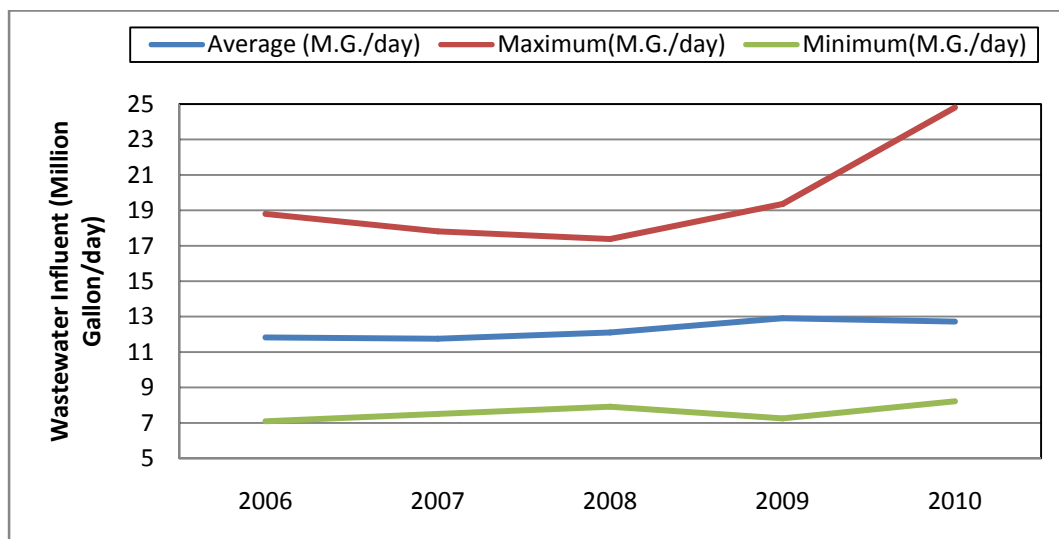


Figure 6.7. Monthly average, maximum and minimum of wastewater influent for Logan Lagoon treatment plant for various years (Logan City 2011b).

The population for the residential service area of the Logan treatment plant is summarized by the city (Logan City 2007), and is shown in Table 6.10. Logan City accounts for 60.8% of the total population of the service area of the treatment plant. Assuming that this portion does not change for future years, 39.2% of the wastewater influent was subtracted in order to investigate the wastewater influent that reaches the Logan Lagoon from Logan City (Table 6.11).

The model relates the population data to the total wastewater quantity reaching the treatment plant. After fitting five different curves to population and total wastewater influent, the model predicts the future wastewater influent based on the future population, which was calculated above. The five functions are: linear, parabolic, 3<sup>rd</sup> degree polynomial, power, and exponential. Also, the coefficient of determination for each curve is calculated by the model (more available data can result in better results for

Table 6.10. Population projection for Logan treatment plant (Logan City 2007)

City	Population (2010)	Percentage of Total Population of the Service Area of the Logan Treatment Plant
Hyde Park	3,354	4.31
Logan	47,276	60.81
Nibley	2,403	3.09
North Logan	7,171	9.22
Providence	4,950	6.37
River Heights	1,672	2.15
Smithfield	9,185	11.81
Millville	1,739	2.24
Total	77,750	100.00

Table 6.11. Average, maximum, minimum influent from Logan City, after subtracting the industrial portion and the part related to other municipalities

Year	Average (M.G./day)	Maximum (M.G./day)	Minimum (M.G./day)	Summation (M.G./year)
2006	6.36	10.11	3.81	2253.73
2007	6.32	9.58	4.04	2310.92
2008	6.51	9.34	4.26	2385.05
2009	6.94	10.41	3.90	2535.41
2010	6.84	13.34	4.42	2500.60

curve fitting). According to the results from this sub-model, linear and power curves fit the data best, with coefficients of determination of 0.887 and 0.895, respectively. It should be considered that some curves might have very high coefficient of determination, but are not appropriate for the future forecasts. Comparing of the results with the wastewater projections by CorallaEngineers and Hansen, Allen & Luce show that in this case the exponential curve has a relatively high coefficient of determination, like the other curves, but seems to overestimate the future wastewater influent. The linear and power equations are as follows:

$$Y = 0.0678X - 1159 \quad (6.3)$$

$$Y = 0.0002X^{1.4906} \quad (6.4)$$

in which X is population and Y is total wastewater influent in million gallons.

The exponential curve fitted to the data is shown in Fig. 6.8. However, since the data available are only for a period of five years, the results calculated by the model might not be very accurate.

The forecast of future wastewater influent reaching the treatment for Logan City (residential area), is summarized in Table 6.12.

Also, the model calculates the average wastewater for future years. After subtracting the industrial portion of the influent and the part coming from other cities, the model calculates the per capita wastewater influent and based on the future population of

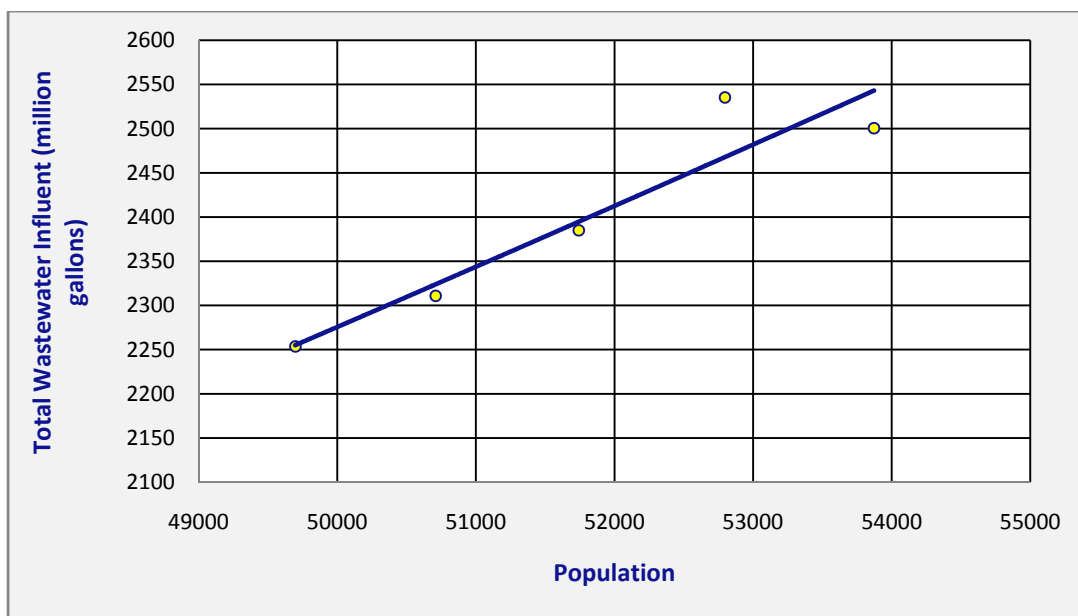


Figure 6.8. The linear curve fitted to the data by Water Availability Model.

the Logan City, the model predicts the future average wastewater influent, assuming that the trend of wastewater producing would not change. The per capita average wastewater influent is shown in Table 6.13.

According to Table 6.13, the average per capita wastewater influent for Logan City, based on the calculations of the Water Availability Model, is approximately 127.36 gpcd. According to this average, and based on the calculations of future population of Logan City in the Population sub-model, the average wastewater influent for the residential part of Logan City was estimated by the Water Availability Model and is summarized in Table 6.14.

As seen in Table 6.14, the average wastewater influent for Logan City (residential portion), is predicted to increase to more than double its quantity from 2010 to 2050.

Table 6.12. Estimation of future total wastewater for Logan City, calculated by the Water Availability Model using a linear extrapolation

<b>Year</b>	<b>Population</b>	<b>Summation of Influent for Logan City (M.G.)-Linear Curve</b>
2006	49697	2255.21
2007	50710	2324.75
2008	51743	2395.72
2009	52797	2468.14
2010	53872	2542.04
2020	65920	3369.72
2030	80678	4383.59
2050	120900	7146.85

Table 6.13. The average calculated wastewater influent from Logan City on a per capita basis

<b>Year</b>	<b>Population Estimated by the Model (Exponential Curve)</b>	<b>Average Influent (MG/day)</b>	<b>Average Influent per Capita (gpcd)</b>
2006	49697	6.36	127.96
2007	50710	6.32	124.66
2008	51743	6.51	125.81
2009	52797	6.94	131.45
2010	53872	6.84	126.93

Table 6.14. Results of average wastewater influent for residential part of Logan City, calculated by the Water Availability Model

<b>Year</b>	<b>Population Estimated by the Model (Exponential Curve)</b>	<b>Average Influent (MG/day)</b>
2020	65,920	8.40
2030	80,678	10.28
2050	120,900	15.40



The wastewater projections for Logan City have been done by Hansen, Allen & Luce Inc. and Carollo Engineers (Hansen, Allen & Luce Inc. 2007). The results from this sub-model were compared with the future projections of wastewater for Logan City done by Hansen, Allen & Luce (2007). Hansen, Allen & Luce estimated the Logan City wastewater for 2025 to be 8.4 million gallons per day. Carollo Engineers estimated an annual average daily wastewater flow of 9.1 million gallons per day for 2025 from Logan City (Hansen, Allen & Luce Inc. 2007). Those results are without considering the infiltration part of wastewater flow.

The results from this new model show an annual average daily wastewater flow of 9.24 million gallons per day for 2025. This is 1.54% more than the estimation by Carollo Engineers and 10% less than the estimation by Hansen, Allen & Luce.

The calculations for the future wastewater influent for both the linear fit and the per capita method were compared. This was done by dividing the annual wastewater flow rates estimated by linear method to the number of days in a year. The results show that the estimations from the linear curve method were approximately 12% different than the per capita method estimations for 2025, and in 2050 the wastewater influent forecast using a linear curve were approximately 28% higher than the per capita wastewater influent forecast method. This shows that the curve fitting method for future annual wastewater influent prediction don't show suitable results for Logan City. This could be due to limited input data. However, the per capita average daily wastewater predictions showed suitable results that were very close to the predictions by Carollo Engineers. It should be considered that testing of the Water Availability Model was done based on the available data. Different simulation periods for each sub-model are due to a lack of data.

## 6.4. Testing the Water Reuse Model

Three scenarios were defined in Northern Cache County, Utah to test different aspects that are included in the Water Reuse Model. Each of these scenarios is described in detail below.

### 6.4.1. Case one

This scenario considers farmland with an area of 80 ha (197.68 acre) located west of Logan Lagoon and the North Cow Pasture ditch. The lands in this area have shallow soils and are not leveled. These farms are under cultivation of grass and pasture (mostly fescue grass and reed canary grass). The irrigation method is flood irrigation with irrigation efficiency of 35%. Therefore, most of the irrigation water returns to the irrigation canal and drains into Cutler Reservoir. Cutler Reservoir is located west of Logan and has an average elevation of 4,407 ft. Due to a contract between Logan City and the Logan Cow Pasture Water Company Corporation, the treated wastewater is released into the North Cow Pasture canal in order to be used by the farmers during the summer irrigation season. This contract allows the release of 19 cfs of water for irrigation purposes (Utah Department of Environmental Quality 2009). The water diverted by the farmers is taken from 11 locations along the North Cow Pasture canal. The rest of the wastewater is discharged into the South Ditch. Five other locations along the South Ditch are available for farmers to take water. The effluent hydrograph data for several years (2004 to 2010) was collected from the Logan City Environmental Department.

The soil data for the study area were obtained from the Web Soil Survey, Natural Resources Conservation Service (NRCS) website ([websoilsurvey.nrcs.usda.gov/app/](http://websoilsurvey.nrcs.usda.gov/app/)). The soil map for this scenario is shown in Fig. 6.9 and the soil data are summarized in Table 6.15.

As shown in Table 6.15, according to NRCS data, the water table in this scenario is very shallow. However, according to a study by Stevens et al. (2011), the water table at that area is not as high as mentioned; therefore, the water table was assumed to be 1.5m below the soil surface. The climate data were obtained from the Utah State University Extension website (<http://extension.usu.edu/agweather/###>). The station considered for this study is the Drainage Farm, which is located at 41° 50' N and 111° 52.5' W, with an average elevation of 4,430 ft (Fig. 6.10).

Table 6.15. Summary of soil data for scenario one and three, collected from Web Soil Survey, NRCS site

Map Unit Symbol	Cd	TtA
Map Unit Name	CarbonSilty Clay	Trenton Silty Clay Loam, Moderately Deep Water Table, 0-2 % Slopes
Depth to Water Table (cm)	92	77
EC (dS/m)	1	7.9
Hydrologic Soil Group	D	D
Organic Matter (%)	0.97	0.7
Clay (%)	55	47.7
Sand (%)	2.5	7.2
Silt (%)	42.5	45.1
Soil pH	8.1	8.8
K <sub>sat</sub> (m/d)	0.018	0.0266
Wilting Point Soil Moisture	0.289	0.244
Field Capacity Soil Moisture	0.342	0.327
Carbonate Calcium (%)	25	25

For this scenario it was assumed that the crop for the farm is alfalfa hay and the planting day is April 15<sup>th</sup>. There were three cuttings during the plant growth season. The irrigation frequency was 8 to 10 days, depending on the month of the irrigation. The irrigation water source was treated wastewater from the Logan treatment plant, and the effluent data for the Logan treatment plant for the year 2010 was used for this scenario. Also, the water quality data for the effluent released from the treatment plant was obtained from the Logan City Environmental Department. Figures 6.11 and 6.12 show the concentrations of total phosphorus and ammonia, respectively, in the effluent released from the Logan Lagoon. The Logan treatment plant has a UPDES permit to discharge its water to Cutler Reservoir (Utah Department of Environmental Quality 2009). A threshold

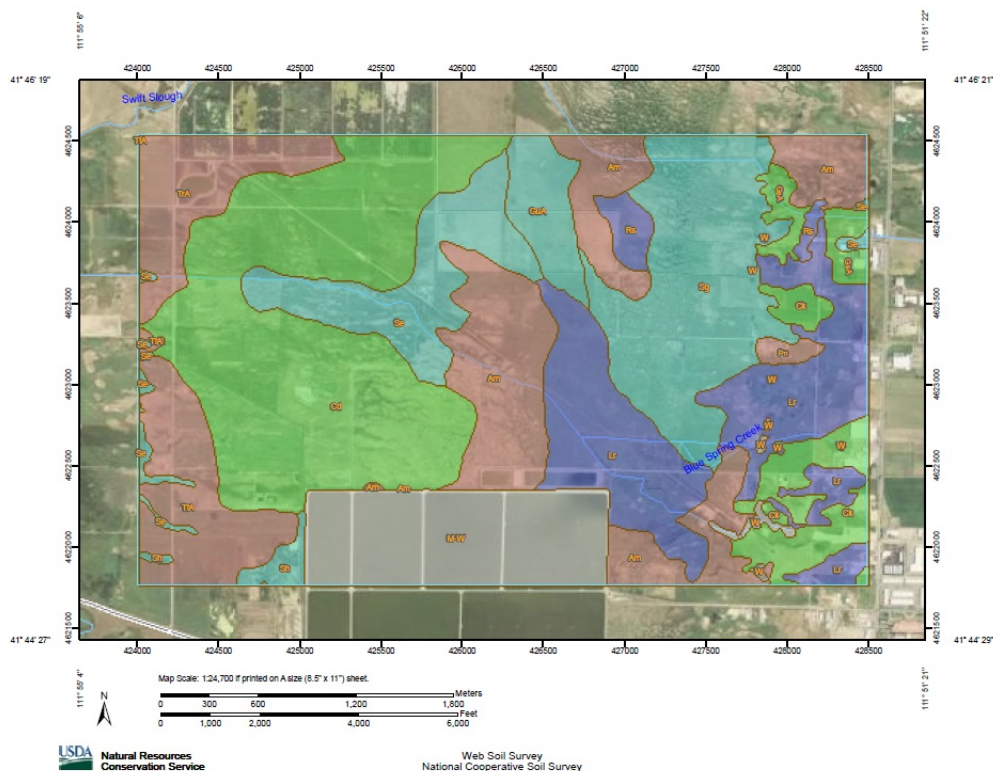


Figure 6.9. Soil map units for scenarios one and three from NRCS, Web Soil Survey website (2011).

value of 0.025 mg/L total phosphorus concentration in lakes, and reservoirs and 0.05 mg/L for rivers, was established in the State of Utah. According to the Utah Department of Environmental Quality (2009), the concentration of phosphorus in Cutler Reservoir is more than the allowable threshold value, and values as high as 1.0 mg/L have been observed in this reservoir. However, the Logan treatment plant does not have a phosphorus limit in their permit. As seen in Fig. 6.11, an average concentration of 3.311 mg/L total phosphorus has been observed in the effluent in the year 2010, which is much higher than the allowed values. The maximum and minimum concentrations observed for total phosphorus were 6.2 and 2.1 mg/L. Also, an average concentration of 9.136

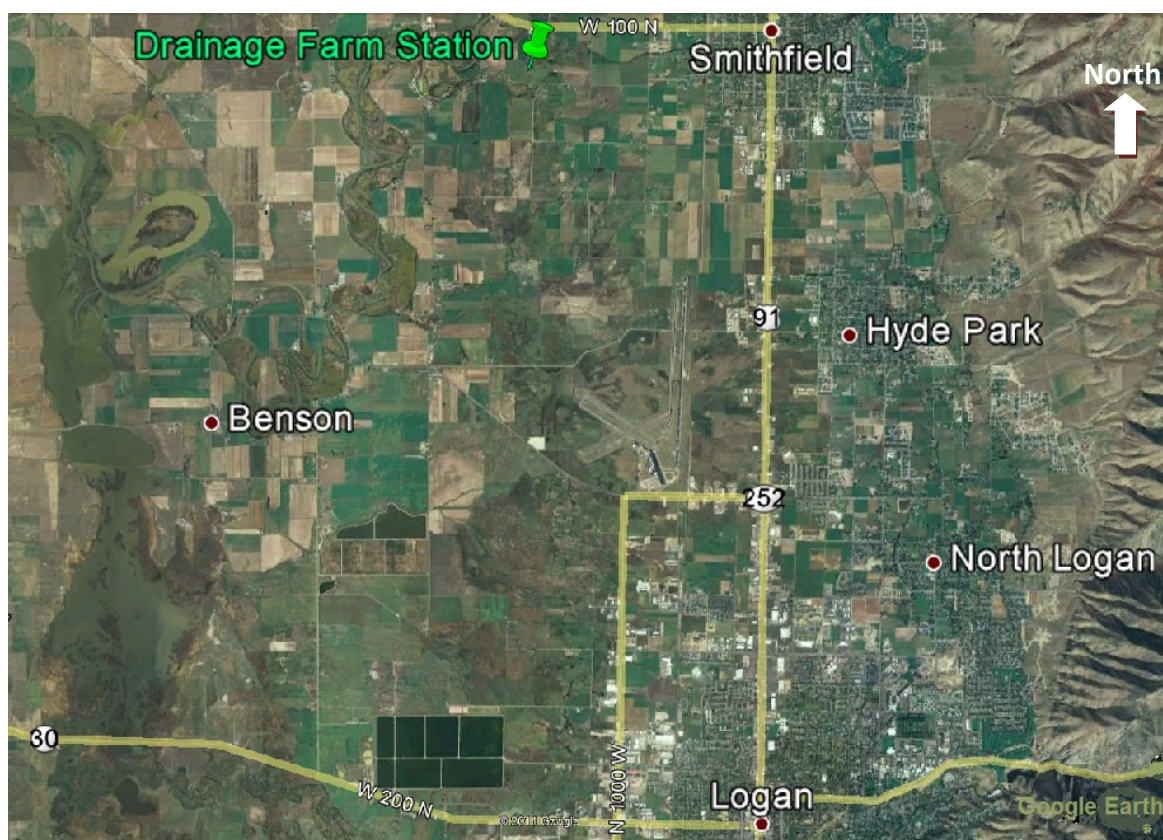


Figure 6.10. Drainage Farm Climate Station (Google Earth 2011).

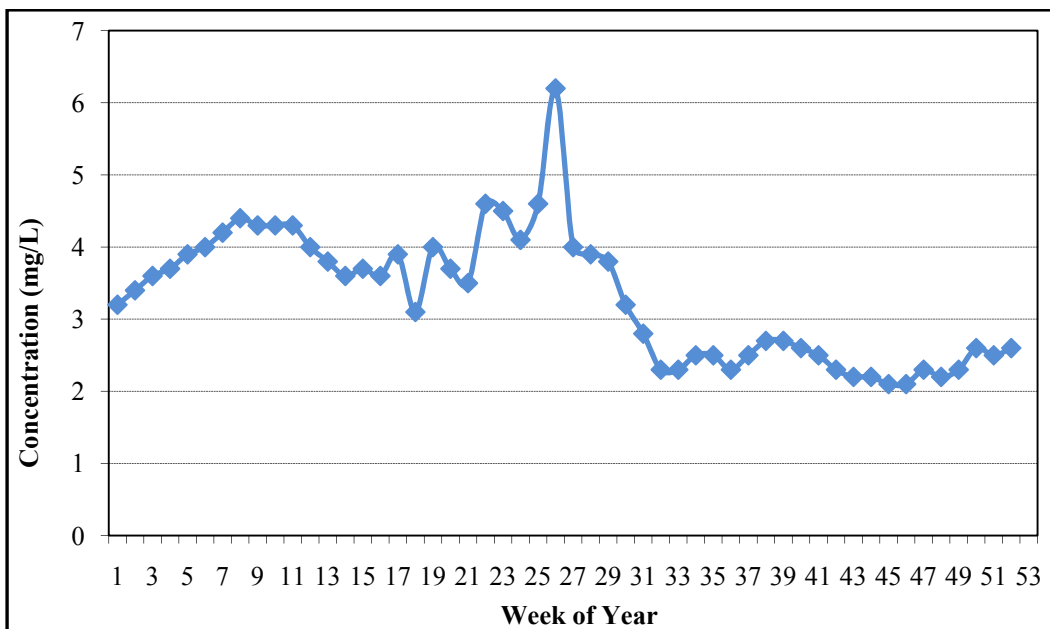


Figure 6.11. Total phosphorus concentrations of the treated wastewater effluent from Logan lagoon in 2010 (Logan City2011b).

mg/L of ammonia was measured in the effluent released from the Logan lagoon by Logan City (Fig. 6.12). The maximum and minimum concentrations of ammonia in the effluent in the year 2010 were 21.1 and 0.2 mg/L. For this scenario, the concentration of ammonia and phosphorus was assumed 9.136 mg/L and 2.1 mg/L, respectively.

#### 6.4.2. Case two

The second scenario considers 80 ha of farmland which is located north side of the Logan wetlands. These farms irrigate using water that is pumped from the Swift Slough. However, since the purpose of this study was to investigate the reuse of treated wastewater, it was assumed that these lands take their water from the wetland.

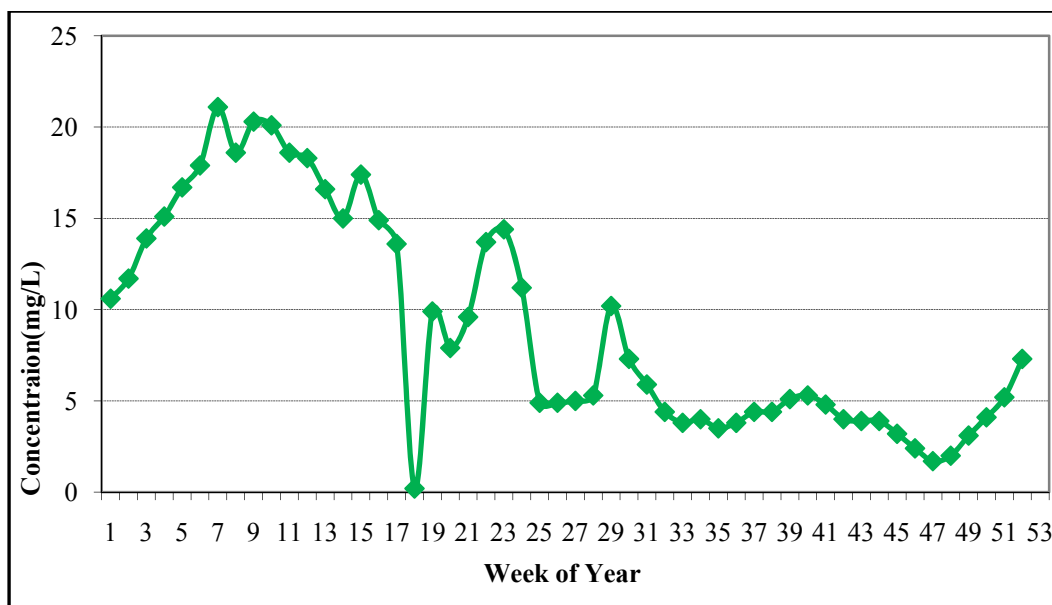


Figure 6.12. Ammonia concentrations of the treated wastewater effluent from Logan lagoon in 2010 (Logan City 2011b).

The Logan wetlands release the water into the Swift Slough at “point 002,” through a 36-inch HDPE pipe (State of Utah Division of Water Quality 2006). The Swift Slough drains its water into the Cutler Reservoir. In this scenario, it was assumed that the farmlands in the second scenario irrigate from the wetlands. However, it was assumed that the water quality was the same as the water quality in the first scenario.

It is assumed that the crop planted is corn and the irrigation system is sprinkler irrigation with 70% efficiency. The farmlands in this area have better quality compared to the land in scenario one. The water table is deeper compared to scenario one and the soil salinity is lower.

The soil map for land in the second scenario is shown in Fig. 6.13 and the data are summarized in Table 6.16. The data were collected from the NRCS, Web Soil Survey site. The location of all scenarios is shown in Fig. 6.14.

### 6.4.3. Case three

The third scenario is similar to the first scenario. However, in this scenario it is assumed that the concentration of nitrogen and phosphorus is at their peak. An ammonia concentration of 9.136 mg/L and a phosphorus concentration of 6.2 mg/L were assumed in this case. This scenario was considered in order to investigate the effect of water quality changes on ground water and surface water.

### 6.4.4. Results

These scenarios were run in the Water Reuse Model and the result is described in detail in the following sections. The results from running the scenarios described previously are shown in Table 6.17. This table shows how these scenarios are ranked for different

Table 6.16. Summary of soil data for scenarios two gathered from NRCS, Web Soil Survey web site

<b>Map Unit Symbol</b>	Jo
<b>Map Unit Name</b>	Jordan Silty Clay Loam
<b>Depth to Water Table (cm)</b>	99
<b>EC (dS/m)</b>	2
<b>Hydrologic Soil Group</b>	D
<b>Organic Matter (%)</b>	0.4
<b>Clay (%)</b>	39
<b>Sand (%)</b>	12.8
<b>Silt (%)</b>	48.2
<b>Soil pH</b>	8.5
<b>K<sub>Sat</sub> (m/d)</b>	0.0835
<b>Wilting Point Soil Moisture</b>	0.205
<b>Field Capacity Soil Moisture</b>	0.312
<b>Carbonate Calcium (%)</b>	25



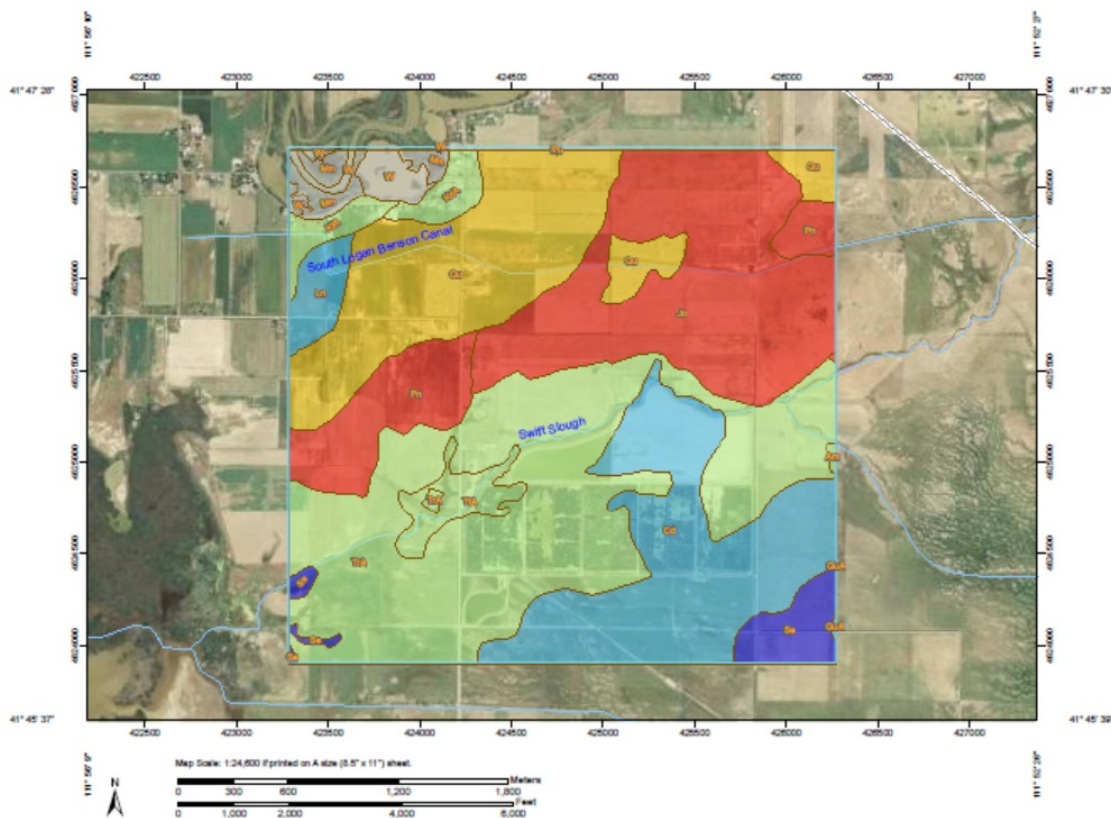


Figure 6.13. Soil map for scenarios two, gathered from the NRCS Web Soil Survey web site.

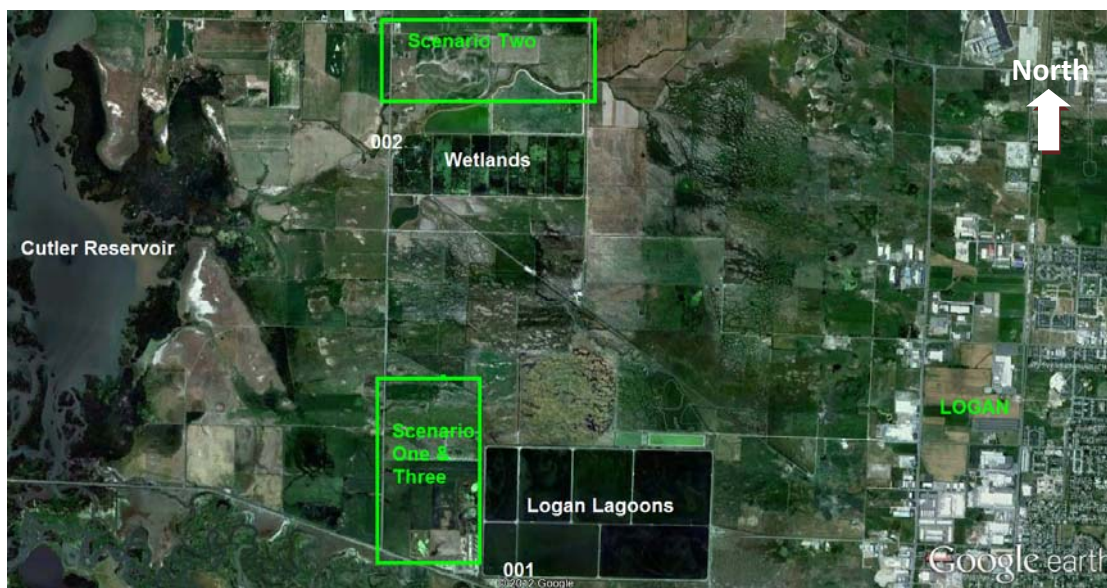


Figure 6.14. Approximate location of the scenarios (Google Earth 2011).

Table 6.17. Ranking the scenarios for different aspects

Aspect	Scenario Number	
	Better	Worse
Yield	1-2	3
Soil Salinity	3	1-2
Surface Water Pollution	2	3
Groundwater Pollution	2	3
Pumping and Conveyance Costs	1-2	3

aspects mentioned above. These rankings are based on a relative comparison of the output results from scenarios defined.

The water and salt balance calculations for the first scenario show larger runoff quantities (Fig. 6.15) compared to the amount of deep percolation. Flood irrigation, low irrigation system efficiency, unlevel land, and very low saturated hydraulic conductivity (around 2 cm/day) are some of the reasons for these results. Site investigations in that area, and also the study done by Stevens et al. (2011), confirm this. In this scenario, low irrigation water efficiency leads to the need for large amount of water demand for irrigation of the crop. The gross water demand for scenario one is shown in Fig. 6.16. The amount of groundwater contribution, which can fulfill some water demand, is also shown in Fig. 6.16. Some factors affecting the amount of groundwater contribution are the soil type, groundwater table, and soil water content.

The soil in scenario one is very saline (Table 6.15). A salinity of 3.5 dS/m was assumed for soil water in this case. It should be noted that the salinity of the treated wastewater effluent was not available. Therefore, for testing the Water Reuse Model the salinity of the water resource was assumed. The wastewater and groundwater salinity was

assumed to be 1.5 dS/m and 2.0 dS/m, respectively. The change of soil water extract salinity is estimated for the growth season and is shown in Fig. 6.17. As seen in Fig. 6.17, the salinity of the soil water extract decreases in the beginning of the season, due to some deep percolation, which caused the leaching of some of the salt available in the root zone. At the beginning of the crop growth season, the root zone depth is small and therefore, the water with lower salinity than the soil water washes some of the salt down. However, in the next stages of simulation, an increase of root zone depth, and no leaching water below the root zone, results in accumulation of salts in the soil and therefore, increase of the soil water extract salinity (Fig. 6.17). Unleveled land in this scenario and therefore, the loss of most of the excessive irrigation water to runoff does not help decrease the soil salinity levels.

Yield calculation in this model considers the effects of water and salt stress. The effects of both of these stress factors are seen in the calculations of the Water Reuse Model. The effects of salts on the crop yield were investigated in this scenario and shown in the model results. Alfalfa hay is moderately sensitive to salts, with a threshold salinity value of 2 dS/m (Allen et al. 1998). This means that if the salinity of the soilwater increases to values more than the threshold value, the high salt amounts prevent the crop from absorbing the water needed by the plant; therefore, lower crop yields result.

As seen in Fig. 6.18, the relative crop yield decreases at the beginning of the growing season due to high salinity levels, but later in the season the salinity of the soil decreases; therefore, the crop yield would not be expected to change during that period.

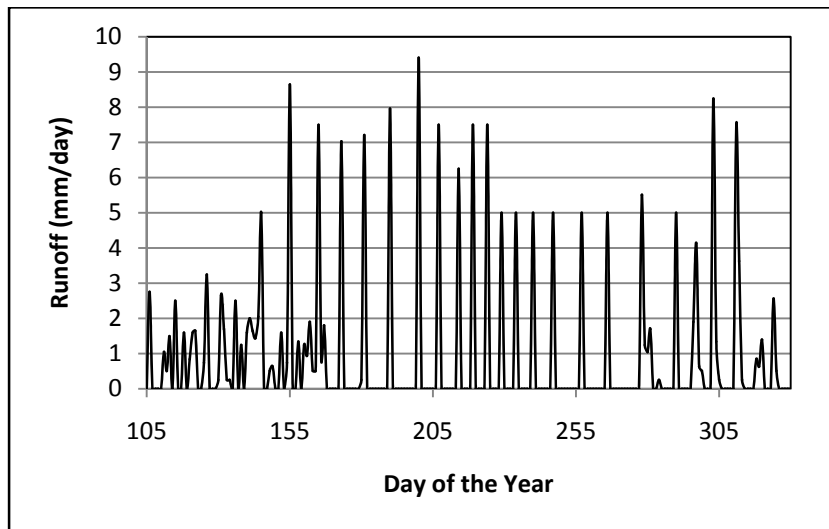


Figure 6.15. Calculated daily runoff amounts for scenario one.

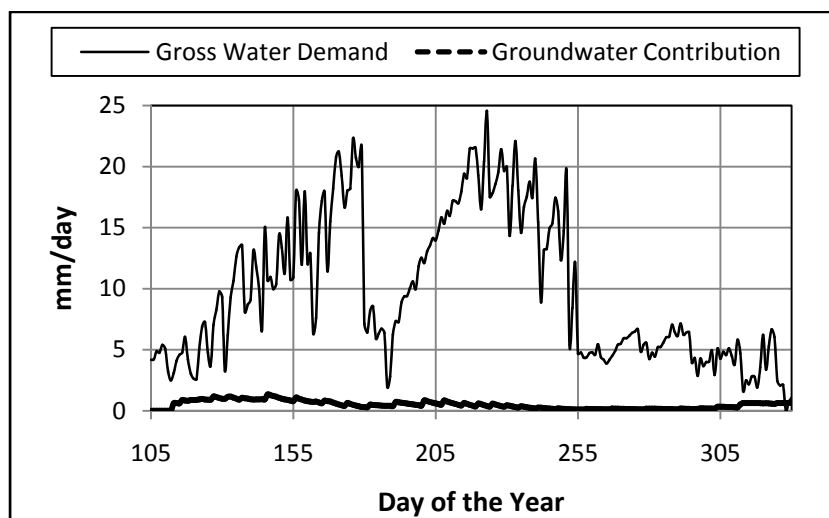


Figure 6.16. Gross water demand and groundwater contribution for scenario one.

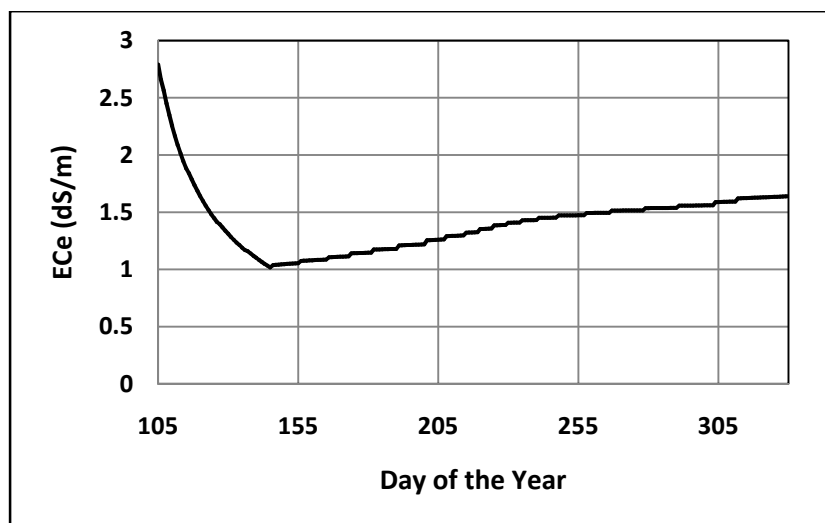


Figure 6.17. Calculated soil water extract salinity for the crop season growth in scenario one.

As mentioned in the previous chapters, considering the treated wastewater as a reliable source for irrigation purposes is necessary in many parts of the world and is becoming more important in other parts. One of the challenges for reuse of treated wastewater is its effect on pollution of ground and surface water sources. Therefore, nitrogen and phosphorus balance in the root zone area is achieved by the model and the amounts of nitrogen and phosphorus in the runoff and leaching water are estimated. The nutrient component of the model was validated with GLEAMS model results.

According to the results from the model, the runoff and small amount of deep percolation results in loss of some nutrients. The nitrate and phosphorus in the runoff during the growth period are loaded into the Cutler reservoir. There were some nutrients, mostly nitrate in the leaching water. According to the results from the model, leaching of

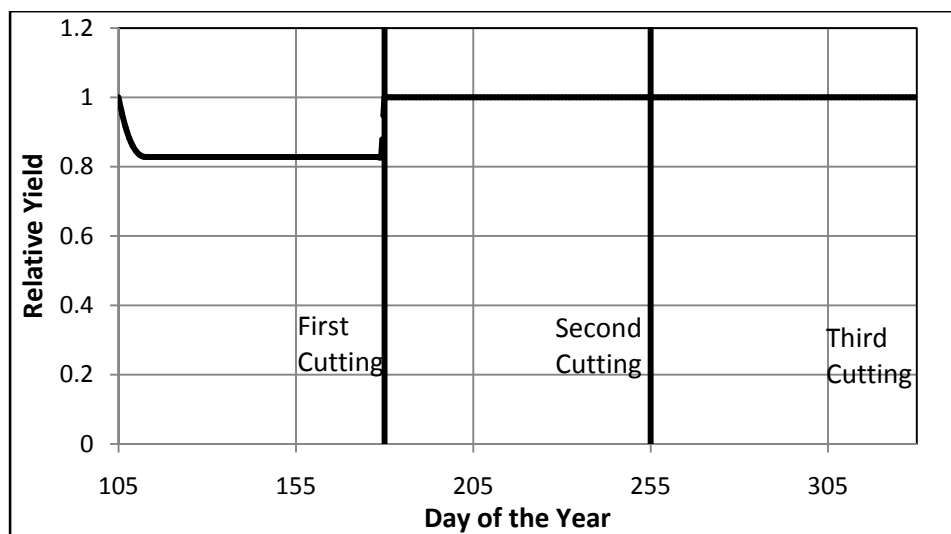


Figure 6.18. Relative yield calculations for scenario one.

nitrogen, especially nitrate is much higher than phosphorus and other forms of nitrogen. The amount of nitrogen and phosphorus leached and lost due to runoff in this scenario are summarized in Table 6.18. However, it should be noted that phosphorus amounts in the sediment load are not considered in this model. With the assumptions of the first scenario, the reuse of treated wastewater added about 18 kg/ha of phosphorus and 111 kg/ha of nitrogen to the land.

Alfalfa hay roots can grow very deep (1.5 to 2 m). Alfalfa hay can uptake nutrients from deeper soil layers, which are not available to plants with shallower root depths. Since alfalfa hay is a legume, it can satisfy its own nitrogen demand by fixation. Therefore, alfalfa hay does not necessarily need nitrogen fertilizers. However, it is important to mention that the amount of nutrient uptake is also related to other factors such as the availability of nutrients in the soil, and the water uptake by the crop. If there is enough nitrogen available in the soil and water for the crop growth, alfalfa hay would not

use its ability to fixate nitrogen. The results of the model show around 311 kg/ha of nitrogen and around 55 kg/ha of phosphorus uptake in alfalfa hay. According to Stark et al. (2002), alfalfa hay needs around 270 lbs/acre (303 kg/ha) of nitrogen and 36 lbs/acre (40 kg/ha) of phosphorus for 4.5 tons of yield. Mikkelsen (2006) mentions the need for 252 kg of nitrogen and 65 kg of phosphorus for 4.5 tons of alfalfa hay. These were confirmed by the results from the model. The results from the model showed 126 kg of nitrogen and 22.5 kg of phosphorus for 4.5 tons of crop yield.

For the first scenario the costs of pumping and conveyance of water resources were less than the second scenario. This is because the study area in this case is located very close to treated wastewater, (which is the water resource) and because the farmland is located at a lower level compared to the water resource. Also, since the treated wastewater is being released into the North Cow Pasture Ditch, which passes from the east side of the case study, and the farmers can divert the water from various locations along the canal, the construction of any type of conveyance systems or pumping is not necessary in this scenario. However, it should be considered that the canal is an earthen canal and there is some amount of water loss due to seepage in the conveyance system. Large amounts of water are lost while irrigating due to runoff. This is because the land in

Table 6.18. Summarized results for nitrogen and phosphorus runoff and leached for all scenarios

Scenario Number	Runoff (kg/ha)		Leached (kg/ha)	
	N	P	N	P
1	3.23	0.242	2.229	0.004
2	0.59	0.103	0.417	0.001

3	5.30	0.700	2.425	0.004
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this area is not leveled and also because the flood irrigation method is used with very low efficiency, which causes large amount of water loss due to runoff to Cutler reservoir.

According to the soil data, it is shown that the soil for the second scenario is better than the first scenario in terms of soil salinity. The soil in the second scenario is not as salty as in scenario one, and has a higher saturated hydraulic conductivity. However, it should be noted that the saturated hydraulic conductivity for both soils are very low. Therefore, the land in the third scenario seems to be a better environment for crop growth. For scenario three, the soil salinity was assumed to be 2dS/m. Since the farm is irrigated with a sprinkler system with a relatively small amount of water leaching below the root zone, the salts from the treated wastewater (assumed to be 1.5dS/m for this scenario), are added to the salts in the soil and therefore, an increase in the salinity of the soil is observed(Fig. 6.19). In this scenario the amount of water runoff is less than the previous scenarios and the water leaching is negligible (Fig. 6.20).

As shown in the model results, the effects of the reuse of treated wastewater on soil salinity is highly affected by two factors: (1) the salinity of the treated wastewater; and (2) the amount of water leaching below the root zone.

The changes of relative crop yield for corn in scenario three is shown in Fig.6.21. In this scenario, since the salinity of the soil water extract remains below the threshold values for corn, the increase in the salinity levels of soil water extract does not affect the relative crop yield. Corn is moderately sensitive to salts; the threshold salinity for corn is



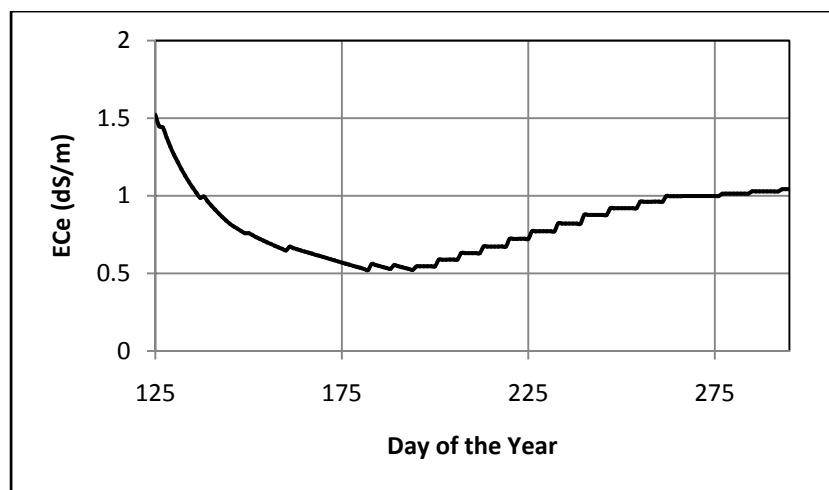


Figure 6.19. Calculated soil water extract salinity for the crop season growth in scenario two.

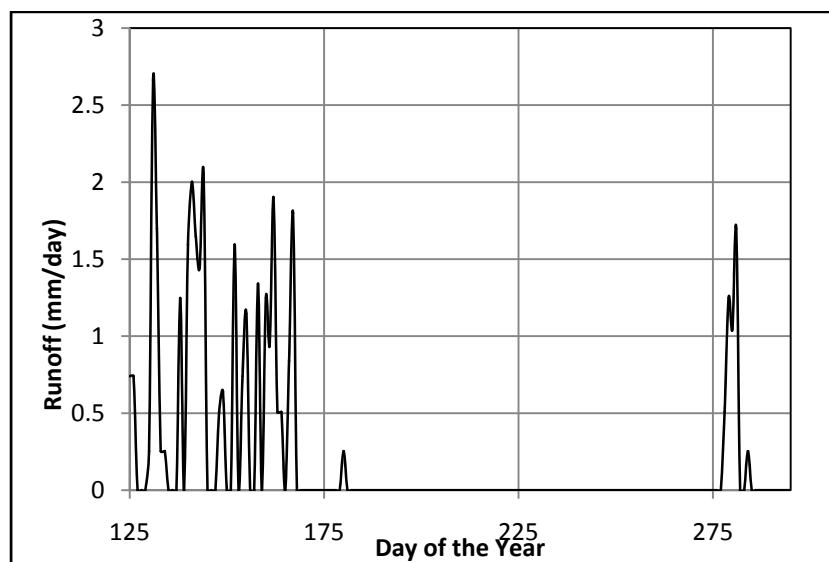


Figure 6.20. Runoff from the land in scenario two during the crop growing season.

1.7 dS/m (Allen et al. 1998). Water stress, especially during the middle and last parts of the crop grown season, affects the relative crop yield and causes a decrease in the crop

yield. Figure 6.22 shows the changes of daily soil moisture content during the crop growing season.

Irrigation of crops that need high amounts of nitrogen and phosphorus during their growth period (such as corn), with treated wastewater seems to be preferred by the farmers. The nutrient amounts in the treated wastewater substitutes some amount of nitrogen and phosphorus and potassium that is needed for crop growth. Also, since a large amount of nitrogen is taken up by the plant, less nutrients will leach below the root zone. However, irrigation with treated wastewater must be done under careful management practices in order to minimize the pollution of ground water and surface water resources.

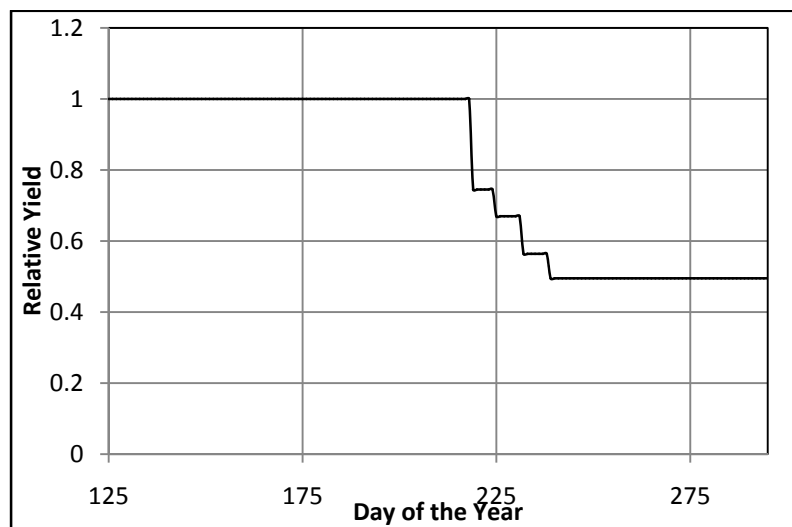


Figure 6.21. Relative crop yield changes during the crop growth season for the second scenario.

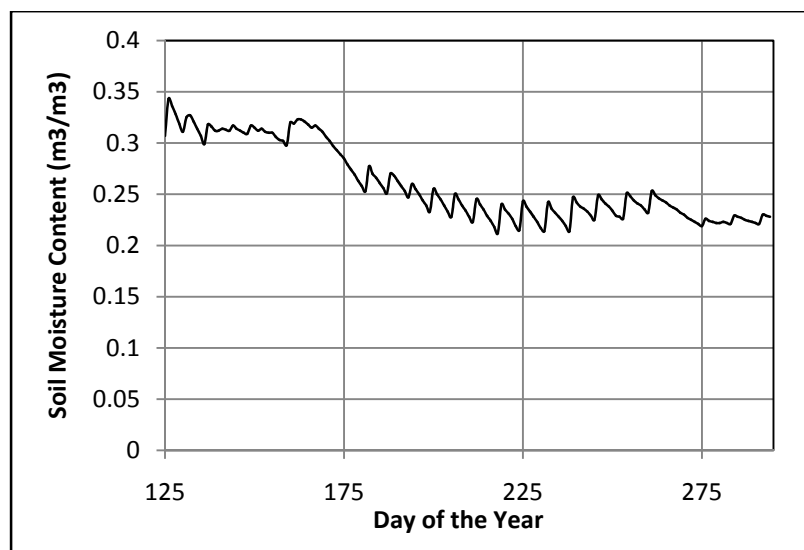


Figure 6.22. Soil water content changes during the crop growth season for scenario two.

In the second scenario about 104 kg/ha of nitrogen and 16.5 kg/ha of phosphorus is added to the land during irrigation. Scenario two is shown to be better in terms of environmental effects. In this scenario, lower amounts of water are lost due to runoff compared to the first scenario and deep percolation, results in lower nutrients affecting surface water and ground water. The amount of nitrogen and phosphorus lost from the root zone area in the second scenario is shown in Table 6.18.

For the second scenario, the land is located at a higher elevation compared to the water resource elevation and therefore, the water pumping and conveyance costs are higher than in the first scenario. This is due to the pumping needs for water to the farm. In these scenarios, similar to the previous scenario, there will not be any need for pipe or canal construction. Therefore, the costs are mostly due to the pumping needs. However, the Water Reuse Model does not consider the pumping needs due to the irrigation method. Therefore, in this scenario the pumping costs are underestimated.

The third scenario was developed in order to investigate the environmental effects of various irrigated water quality on ground water and surface water. The results of nitrogen and phosphorus lost due to runoff and leaching are shown in Table 6.18. According to the results from the model the amount of nutrient loss due to runoff increased for third scenario compared to first scenario. However, the increase in the amount of nutrient leaching was smaller. This could be due to low saturated hydraulic conductivity and therefore, smaller deep percolation loss of water with respect to runoff loss of water. It should be mentioned that in this scenario during irrigation season 185 kg/ha of nitrogen and 46 kg/ha of phosphorus is added to the farm.

The nutrient sub-model was tested and validated. This was achieved by:

- Running the Water Reuse Model for a specific scenario;
- The GLEAMS input data files for the same scenario were developed;
- The GLEAMS model was run;
- The results from both models were compared.
- The amount of nitrogen and phosphorus lost due to runoff and deep percolation were compared for both models.

Scenario one defined previously was considered for testing and validation of the Water Reuse Model. In order to run GLEAMS model, five data files were defined: Precipitation data, daily temperature data, hydrology data, erosion data, and nutrient data. Some of the results from these models were summarized in Table 6.19. As shown in the table, the amount of nutrient leaching for both models is very close. However, the nutrient lost due to runoff is higher for Water Reuse Model. This is due to different assumptions for these models. Some of these differences are:

- Water Reuse Model considers one soil horizon and two soil layers, while GLEAMS considers up to five soil horizons and many soil layers;
- The methods of water uptake calculations are different for these models;
- Soil temperature is calculated in GLEAMS model, while it is an input data in Water Reuse Model;
- Sedimentation is considered in GLEAMS, but estimated in Water Reuse Model;
- The effect of nutrient deficiency on crop yield is not considered in Water Reuse Model.

It should be mentioned that both models achieve nitrogen and phosphorus mass balance on a daily basis.

Table 6.19. Comparison of results of nutrient leaching and runoff for a scenario with Water Reuse Model and GLEAMS Model

		Water Reuse Model	GLEAMS Model
Runoff (kg/ha)	N	3.23	3.79
	P	0.242	0.02
Deep Percolation (kg/ha)	N	2.23	1.99
	P	0.004	0

## CHAPTER 7

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Population growth and urban growth around the world has resulted in more pressure on water resources. Uneven distribution of water resources emphasizes this problem in arid and semi-arid regions. On the other hand, increasing quantity of wastewater production and dealing with this excessive amount of wastewater in an environmentally safe method is another challenge in urban areas. Agricultural users as one of the biggest water users are mostly the ones affected by this, through transfers of water resources from agricultural users to municipal and industrial users. Due to importance of agriculture in food production and in the economy of many regions around the world, water resources management and considering new water resources (such as treated wastewater), in order to benefit both M&I and agricultural users is critical. This study focused on analyzing the effects of population and urban growth on water demand for various users and municipal wastewater quantity changes; as well as investigating the feasibility of wastewater reuse projects.

In order to fulfill the objectives of this project two new mathematical models were developed:

- A Water Availability Model; and
- A Water Reuse Model.

The Water Availability Model is used to analyze changes in the population and urban growth, and their effects on future water demand and future quantity of wastewater production. This model predicts the future water demand for different users and the

excessive amount of water needed to fulfill the demand of the M&I and agricultural sectors. Also, an increase of municipal wastewater production was forecasted in the case study presented in Chapter 6. This is a suitable tool that can assist decision makers in the appropriate and judicious allocation of water resources. The Water Availability Model has a graphical interface, and it includes four sub-models:

- Population sub-model;
- Land use change sub-model;
- Water demand sub-model; and
- Water supply sub-model.

The population sub-model is responsible for future population forecasting. Future population predictions are done based on one of two methods: (1) an exponential method; and (2) an extrapolation method. In the extrapolation method, the model fits five function types to historical population data for a study area. These include: linear, parabolic, 3<sup>rd</sup>-degree polynomial, power and exponential functions. The regression for the exponential and power functions is done iteratively to determine an optimal vertical shift, thereby providing a better fit to the sample data, in general.

The land use change sub-model is responsible for analyzing the changes of urban and agricultural area for a study area in the course of time. In this sub-model, the area of various land cover types is calculated for grid map layers of two specific years in order to investigate the changes of the agricultural area in that period of time. This sub-model helps the user understand how urbanization can affect the agricultural area.

The water demand sub-model is responsible for prediction of future residential and industrial water demand for the study area based on a per capita method. This sub-

model also calculates the water demand for an agricultural area using either: (1) an acre-ft per acre method; or, (2) the Penman-Monteith reference evapotranspiration equation.

This sub-model shows the effects of population growth and urbanization on the water demand of the study area over the course of time.

The wastewater sub-model is used to analyze the water supply, which is assumed to be treated wastewater. In this sub-model, the future average wastewater influent is predicted based on a per capita method. Also, the future total yearly wastewater influent reaching the treatment plant is forecasted by a regression method. Since the municipal wastewater is considered in this study, the average wastewater influent and the total wastewater influent portion that is related to residential areas are extracted from the total wastewater influent before the estimations. Total wastewater influent is related to the population the wastewater treatment plant is servicing. The linear, parabolic, 3<sup>rd</sup>-degree polynomial, power, and exponential are the functions that the model can fit to the data for regression method.

All the sub-models are put together to make the Water Availability Model easy to use, with a graphical interface to analyze the effects of population and urban growth on future water demand and wastewater.

The second model (Water Reuse Model) focuses on other aspects of reuse of treated wastewater. Proper management of wastewater reuse projects cannot be done without considering various factors. Water quality, groundwater and surface water pollution, salinity effects on soil and costs of water delivery to the farmlands are among some of those. Various sub-models of the second model assist the decision makers in choosing the appropriate water reuse project, with proper crop types, and suitable water



management with the least undesirable environmental effects on ground water and surface water.

The Water Reuse Model was developed to allow the user define up to three scenarios after providing the following parameters: land data; soil data; crop data; climate data; and water resources data. The Water Reuse Model is responsible for comparing the scenarios defined by the user in various aspects, such as:

- Crop yield;
- Changes of soil salinity;
- Environmental effects (nitrogen and phosphorus leached to ground water and lost to runoff); and
- Pumping and conveyance requirements and costs of water delivery to farmland.

For each scenario, the model calculates the crop evapotranspiration for up to three crops. Evapotranspiration is calculated based on the Penman-Monteith method. The water requirement for each scenario is estimated in this model. The daily water and salt balance calculations for each scenario is performed considering various components such as groundwater contribution, ponded water, deep percolation, and runoff. The relative crop yield calculations are made based on the effects of water and salt stress in the root zone. Daily nitrogen and phosphorus calculations in water leached below the root zone and water lost as runoff, are estimated considering their transformations such as nitrification, mineralization, and volatilization of the various types that are being considered. Daily nitrogen and phosphorus balance is achieved in the root zone area.

And last, but not least, an estimate of pumping and conveyance requirements and costs of delivering water to the land for each scenario is given in this model. For estimations of the pumping and conveyance costs, the model allows the user to add up to three connections between the land and the water resource in order to better model the topography of the land. These estimations include calculation of the pumping requirements, pipe and canal water capacity calculations, and design of a canal or pipe, if necessary. The result is the total estimated costs of pumping and construction of pipes or canals (if needed), which are changed to annual equivalent costs for pumping and conveyance for each scenario.

These models were developed in VB .NET, in the form of a MapWindow GIS Plug-in. The two models are easy to use and user friendly.

In order to test the developed models, a case study was performed for Cache County, Utah. For this purpose, a significant amount of time was dedicated to gathering information and data for this region. Cache County Office, Logan City Office, Logan City Environmental Department, and the Utah NRCS office were contacted several times. Lance Houser, Logan City assistant city engineer, IssaHamud, environmental director of Logan City, James Harps, environmental permits and analysis, Eric Dodson, Lyle Shakespeare, Logan City GIS specialist, Nathan Daus, UACD of Utah NRCS, and Bob Fotheringham, Cache County water manager, are among the many people who were contacted to assist with some of the data and information used in this research.

## 7.1. Conclusions

Both of the models were successfully developed, tested, and validated as part of this research. The Water Availability Model with a graphical and user-friendly interface is a suitable tool for analysis of the effects of population growth and urbanization on agricultural area, residential and agricultural water demand and wastewater supply. The analysis from the Water Availability Model shows the amount of increase in water demand for various users over the course of time, and also shows the amount of increase in the municipal wastewater production that can be potentially considered as a reliable water resource for agricultural areas. These estimations can help decision makers better allocate the water resources to satisfy the needs for the residential area and also benefit the agricultural users, while successfully dealing with the increasing amount of wastewater production.

The Water Reuse Model is shown to be a useful tool to compare the feasibility of various treated wastewater reuse projects in aspects such as: effects of water salinity and water management on crop yield; effects of wastewater reuse on groundwater and surface water pollution (due to nitrogen and phosphorus); effects of water management on soil moisture content changes, and the amount of water loss due to runoff and deep percolation, and others. These are predicted by various sub-models developed in the Water Reuse Model.

The new model is very easy to use, with various help files for the user. Also, a reasonable amount of input data are needed for this model. The input data can be entered directly to the model and no specific time consuming format for data entry is needed.

This model gives the user the ability to relatively compare various scenarios of water use, based on the priorities or factors that are important for each case study. For instance, if the project is used for a crop type with high price value, then the amount of crop yield and the amount of decrease in the relative yield would be very important. If the environmental effects are critical in a case study, the user can base his or her decision on the amount of nitrogen and phosphorus leached below the root zone or lost due to runoff. For cases where the budget is limited, the priority for decision-making will be the annual pumping and conveyance requirement and costs for the selected scenarios. The water reuse model showed good results for the case study in Cache County, Utah.

The amount of crop nitrogen and phosphorus uptake by the crop was also calculated by this model. This can be used in order to decide which crop is better for various water quality water resources. In other words, some crops have higher nitrogen and phosphorus uptake, which make them better crops to be grown when treated wastewater, or any lower quality water, is being used for irrigation. The more the uptake of nutrients by the crop, the less nitrogen and phosphorus is left in the soil to affect the environment. However, it should be considered that the nutrient uptake of a crop is also related to the amount of crop water uptake, crop nutrient demand, and the availability of nutrients in the soil.

Similar to any other model, the accuracy of the output data is dependent (in part) on the accuracy of the input data.

## 7.2. Recommendations

As in all engineering research, the work described herein encompasses only a portion of what could potentially be done in the subject area. And as with all models, those developed in this research are not complete, and they never will be. The models can be endlessly expanded, improved, and refined. Thus, the following recommendations are made for those who might be interested in pursuing the topic further.

1. The results from this model were used for a relative comparison of various scenarios. However, for more accurate results, real-time data for the case study would be desirable;
2. In this model some aspects of reuse of treated wastewater were considered, but some aspects such as water rights aspect of reuse of treated wastewater, public perception and environmental effects of other nutrients and pharmaceuticals were beyond the scope of this study. Each of these aspects could be studied in future work;
3. In these models the effects of nutrient loss in crop yield is not considered, but that could be included in the future model development;
4. The nutrient loss due to sedimentation was not estimated in this model, but it would be useful to include this feature, especially for phosphorus; and
5. The models do the analysis and comparisons based on a crop season, which can be improved in order to compare scenarios in a long-term period of time.

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APPENDICES

Appendix A. Users Manual for the Water Availability Model

In order to be able to use this model on any computer, Map Window should be installed. Map Window is a free, open-source geographic information system (GIS), developed by Daniel P. Ames at Utah State University (USU), and then was improved by him and his team at Idaho State University (ISU) and Idaho National Laboratory (INL). The first version of the Map Window MapWinGIS ActiveX control was released in 2002 and has been further improved since then. Map Window has attracted a large group of users in a short time (Ames 2006). Map window can be downloaded from the eponymous website: (Map Window 2011).

After Map Window is installed on the computer, the model developed in this research can be used. Running the model's executable file starts the plug-in for the Water Availability Model and automatically brings up Map Window and a page similar to Fig. 4.1 will be shown. In order to add the model to the toolbar, the user should click on the Plug-ins menu item, shown in Fig. A.1, and choose "LA". "LA" is the name of the plug-in that was developed.

When this Plug-in is selected by the user, the models developed as part of this study will be added to the toolbar area, as a button. However, it should be noted that the button will not be activated unless a shape file layer or grid map layer is added to the project. In that case, the button for Water Availability Model will be activated, as shown in Fig. A.2.

If the user clicks on the Water Availability Model button shown in Fig. A.2, a window as shown in Fig.A.3 will be opened. In this window, the simulation period must

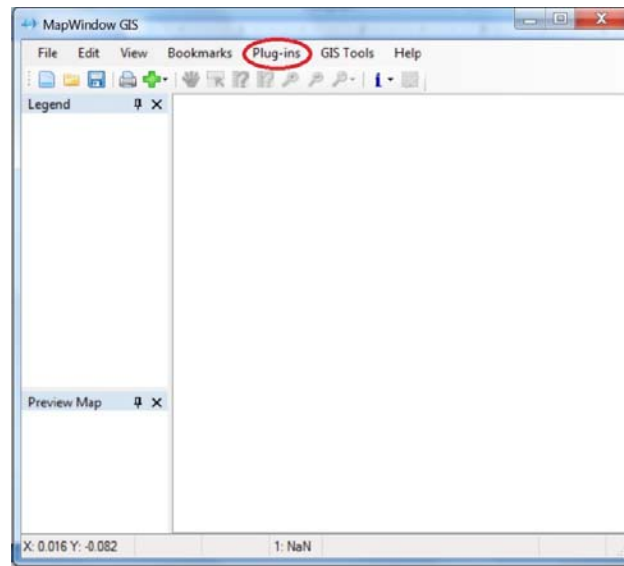


Figure A.1. The main window of the Map Window GIS.

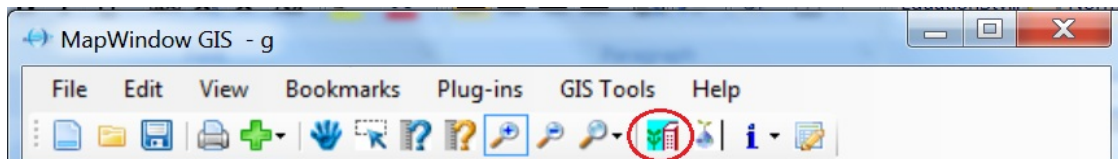


Figure A.2. The button for the Water Availability Model in the Map Window tool bar (circled in red).

be defined by the user. Also, options for calculations of population and water demand should be defined by the user in this window.

As it can be seen in Fig.A.3, there are various tabs in this window:

- Project Data
- Population
- Land Use Change
- Water Demand
- Water Supply

Figure A.3. The water availability model.

- Results Tab


**Population Tab:** Population forecasts are done in the Population Tab. This tab includes the following sub-tabs:

- Exponential Method
- Extrapolation Method

Depending on the method chosen by the user, one or both of the tabs will be inactive. The tab for the exponential method is shown in Fig. A.4. For a forecast of the population of the study area using the exponential method, the following input data are to be defined by the user:

Base Population: The population of the study area at the beginning of the simulation.

Population Growth Rate: Average annual change in the population of a study area.


If the user clicks the Calculation Button () , the model will calculate the population of the study area for the simulation ending year, using the exponential method, described before. The calculations will be shown for at least 20 years in a table in the same window and also a graph for population versus year will be shown after the calculations are performed by the model.

The Extrapolation Method Tab is shown in Fig. A.5. The input data for this method include the following:

Excel File for Population Data: Input Excel file of data set for population versus year.

The Excel file should have two columns with the following titles: Year, and Population.

If the user chooses an Excel file with the format described, the model will read the data in the excel file and will load them in a table and will draw the graph (points) with data in the same window. At the same time, the model will fit five different curves to the data set entered by the user and show the curves and their coefficient of determination and their curve in the same window. These curves are: Linear, Exponential, Power, Parabolic, and 3<sup>rd</sup>-degree Polynomial curves

The model also allows the user to choose any of the curves fitted to the data from a list and calculate the population of various years if desired by clicking on the Calculation button  .

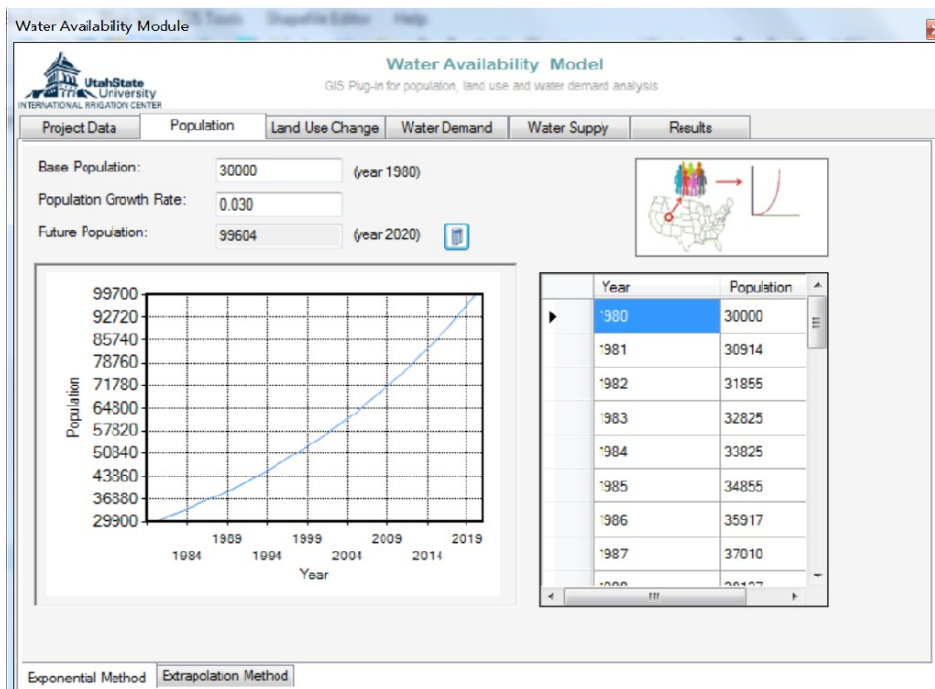


Figure A.4. Population tab with the exponential method of population forecast.

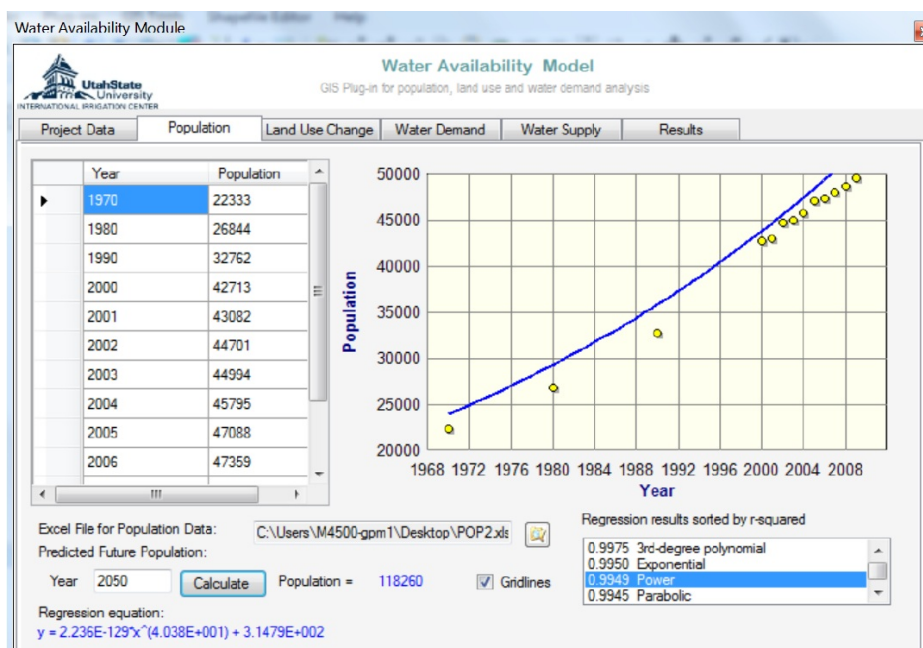


Figure A.5. Population tab with the extrapolation method of population forecast.

**Land Use Change Tab:** In this tab (Fig. A.6), changes of the area of various land covers over the period of simulation can be estimated. For this purpose the user must enter the following input data:

Land Cover Layer: Land cover layers (grid data) should be entered for the beginning and ending years of the simulation.

Boundary Layer: A boundary layer, which defines the study area, should be defined by the user.

If the user clicks on the Estimate button, the model will calculate the area of various land cover for both maps for two different years. Nevertheless, it is noted that the number of missing data in the layers is a source of error in these estimations.

**Water Availability Model**  
 GIS Plug-in for population, land use and water demand analysis  
 Developed by: Laila Ahmed and Gary P. Hartley

Project Data | Population | **Land Use Change** | Water Demand | Water Supply | Results

Land Cover Data  
 Land Use Layer 1: LU\_2001  
 Land Use Layer 2: utm\_53631  
 Boundary Layer: Test\_Boundary

Land Use 1  
 DX = 30  
 DY = 30  
 Area = 2674.03422817505

Land Use 2  
 DX = 30  
 DY = 30  
 Area = 2674.03422817505

LU ID	Area 1	Area 1 (ha)	Area 2	Area 2 (ha)
Open water	4373	39.357	13263	119.367
Urban	27245	245.205	4678	42.102
Barren	362	3.258	112	1.008
Forest	12294	110.646	2392	21.528
Grassland-Shrub	37323	335.907	37421	336.789
Agriculture	192206	1729.854	82861	745.749
Wetland	23313	209.817	13541	121.869
Ice Snow	153950	1385.55	153950	1385.55

Land Use Data | Criteria for Land Use 1 | Criteria for Land Use 2

Figure A.6. Land use change tab.



**Water Demand Tab:** In this tab (Fig. A.7), water demand for residential, commercial and agricultural area for beginning of simulation and end of simulation period will be calculated. The required parameters for calculation of future water demand for residential and industrial users are:

1. Per Capita Residential Demand (gallon/day)
2. Per Capita Industrial Demand (gallon/day)
3. Per Capita Unaccounted-for Demand (gallon/day)

The water demand can be entered for various months of the year, and if the user has the data in a yearly basis, he/she can check the box at the top of the window shown in Fig. A.7 and the model will automatically set the data to the same value for all months. If the user chooses to calculate the water demand for agricultural area based on the evapotranspiration calculation method, the following data should be defined instead of the per capita quantity for agricultural users:

1. Number of Agricultural Lands: The model can divide the total agricultural area into maximum of 10 farms. The user should define the number of farmlands in the study area.
2. Land Latitude: For each farm, the user should define the latitude.
3. Land Altitude: The altitude of each farm should be defined by the user in metric units.

Number of Crops: The user can define up to five crops for each farm.

Crop Type: The crop type is defined from a list of crops in the model. The data for 24 crops are included in the model and the user can load the data related to those crops as the

default values. If the user adds a crop that is not included in the list, he/she should choose “Other” from the crop list, and must enter the data related to that crop.

Planting Day: Day of crop planting should be chosen from the list of days.

Planting Month: The month crop is being planted in should be chosen by the user.

Planted Area: The percentage of the area of the farmland that is cultivated by each crop.

Crop Coefficient: Crop coefficient for each crop for three crop growth stages must be defined by the user. As mentioned above, these values are saved for 24 crop types in the model.

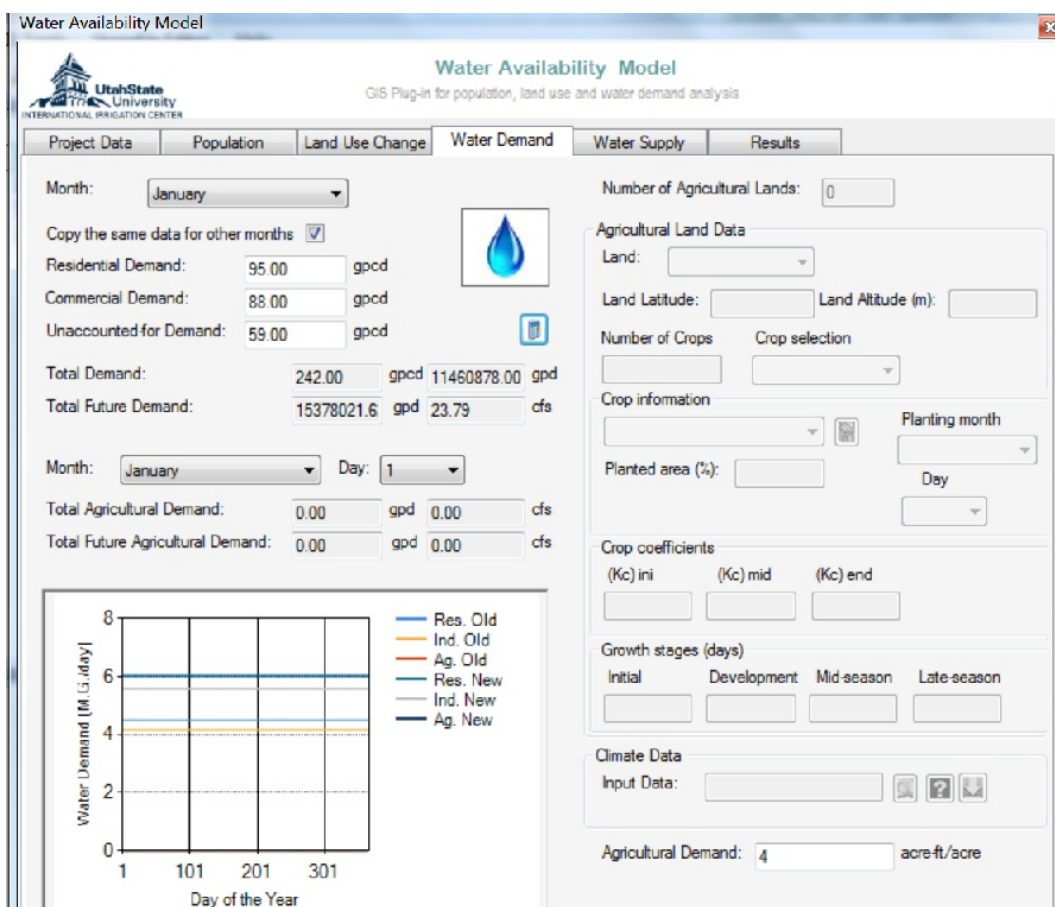



Figure A.7. Water demand tab.

Growth Stages: Crop growth stages for each crop must be defined by the user.

Climate Data Input: The climate data must be entered by the user, and only one set of climate data are to be specified for the whole study area.

- Climate data include: A text file for the whole year in a daily basis format. The order of the tab-delimited data should be: (1) maximum daily temperature ( $^{\circ}\text{C}$ ); (2) minimum daily temperature ( $^{\circ}\text{C}$ ); (3) mean daily relative humidity (%); (4) wind speed at a height of 2 m (m/s); and (5) solar radiation ( $\text{MJ m}^{-2}\text{day}^{-1}$ ).
- An MS Excel file that stores the data in sheet1 of the spreadsheet file. Maximum daily temperature ( $^{\circ}\text{C}$ ), minimum daily temperature ( $^{\circ}\text{C}$ ), mean daily relative humidity (%), wind speed at 2 m height (m/s), and solar radiation ( $\text{MJ m}^{-2}\text{day}^{-1}$ ) for a whole year should be stored in columns with the following names as the column titles: tmax, tmin, RH, wind, radiation, and precipitation.

After choosing the weather data, the user must click on the “Read Data” button (  ), in order for the model to read the climate data. If the Estimate button is clicked by the user, the calculations of water demand will be performed and shown in a graph in the same window, as shown in Fig.A.7.

**Wastewater Quantity Tab:** In this tab (Fig. A.8) the model will analyze the treated wastewater resource. The influent reaching the wastewater treatment plant is the input data of this part of the model. The data are presented on a yearly basis.

Input File: An Excel file with five columns, entitled “Year”, “Average”, “Maximum”, “Minimum”, and “Summation” should be entered by the user. The beginning year of the table should be the beginning year of the simulation. All the data except the summation

of influent, is in million gallons per day. Figure A.9 shows an example input file for treated wastewater influent.

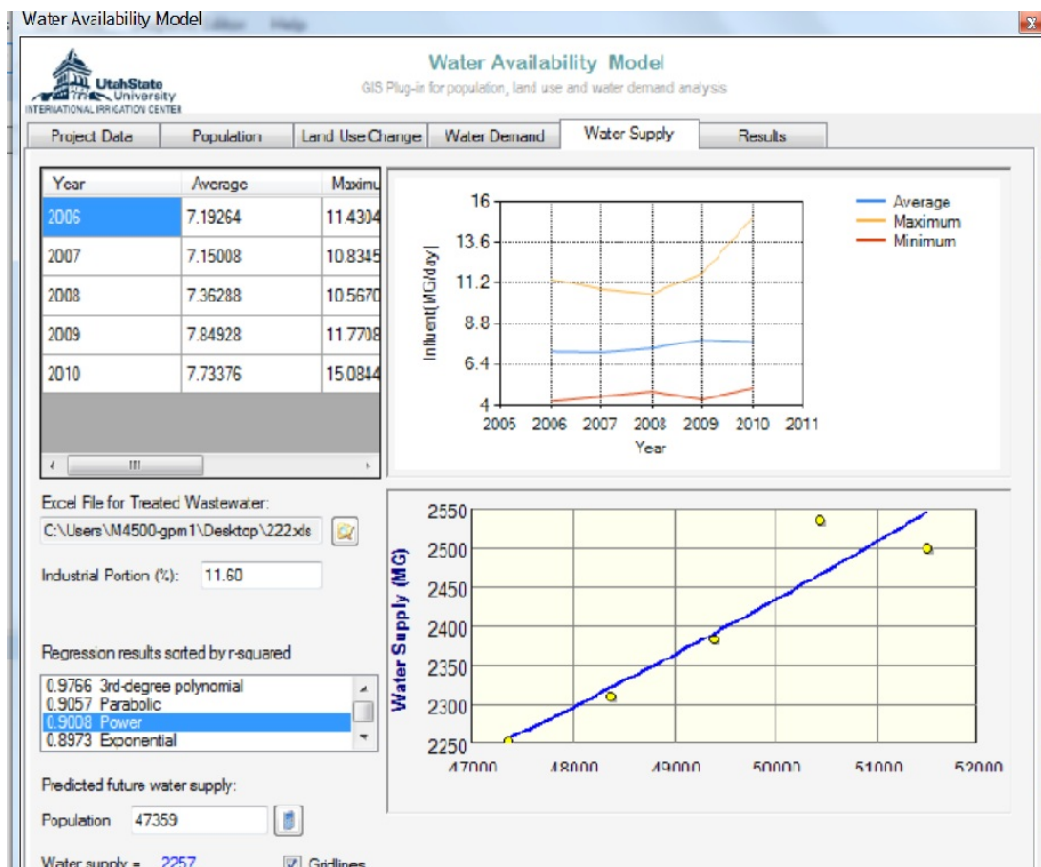


Figure A.8. Water supply tab of the Water Availability Model.

Year	Average	Maximum	Minimum	Summation
2006	11.83	18.8	7.09	4192.51
2007	11.76	17.82	7.51	4298.9
2008	12.11	17.38	7.92	4436.81
2009	12.91	19.36	7.26	4716.51
2010	12.72	24.81	8.22	4651.75

Figure A.9. Input Excel file format for water supply.

If the user chooses an Excel file for water supply, the data will be loaded in a table inside the window and also graphs of the data will be shown in the window in order to give the user a better sense of wastewater produced in the study area through the years.

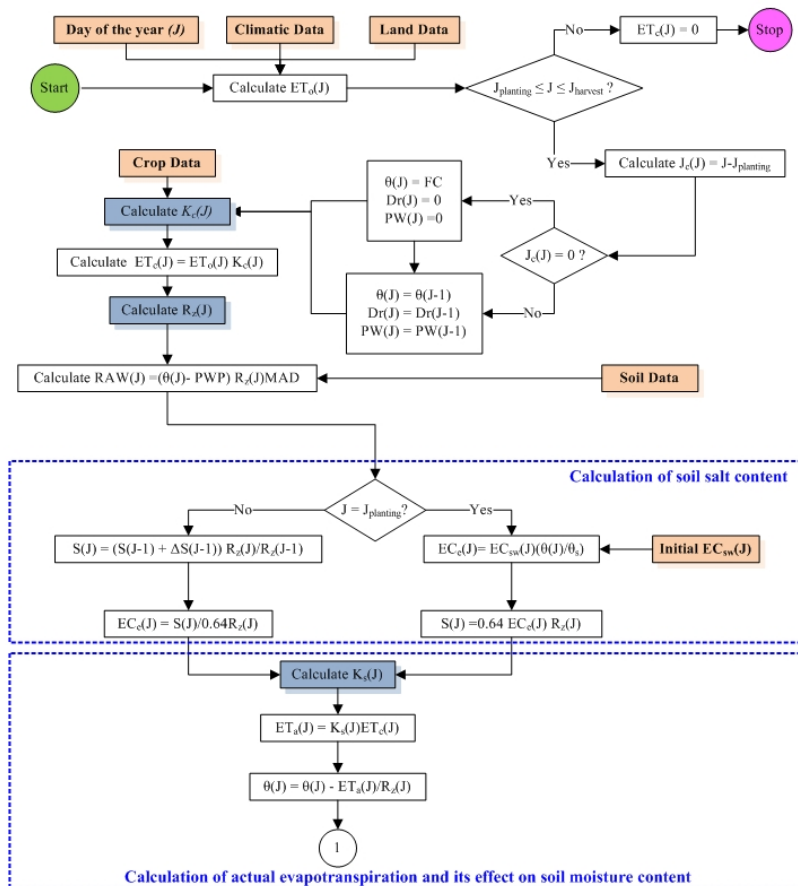
Also the model will fit various curves (as described above), to the data set of summation of wastewater produced per year to the population of the study area.

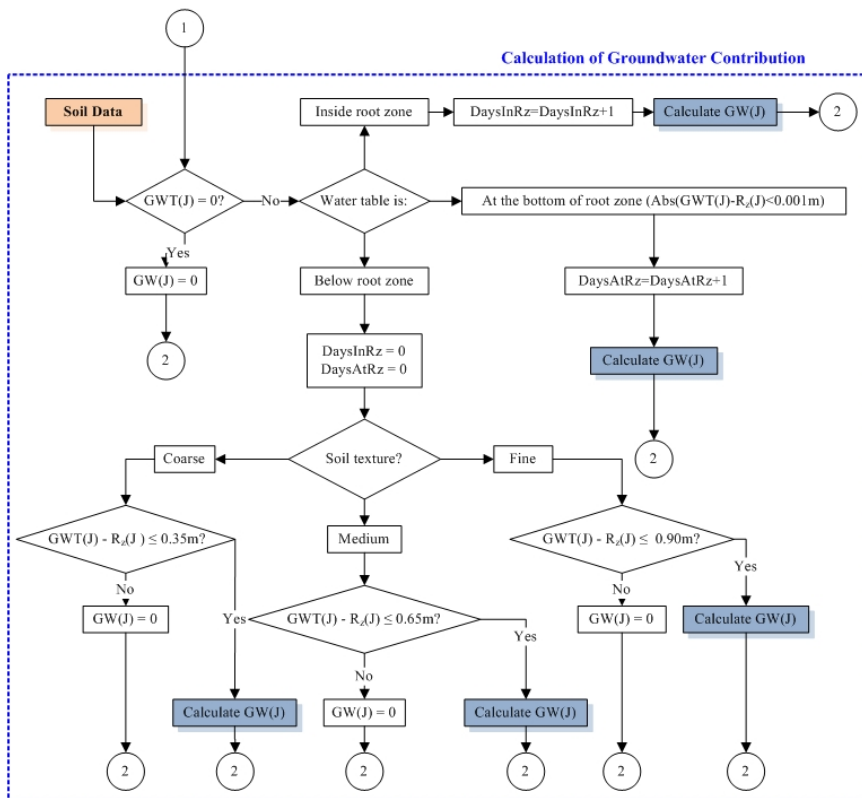
According to the calculations, the best-fit curve (with the best coefficient of determination) will be chosen automatically by the model as the default, and wastewater production for the ending year of simulation will be estimated based on its population.

**Results Tab:** This tab summarizes all the calculations done in all the tabs of this window, in various graphs. This will allow the user better understand and analyze:

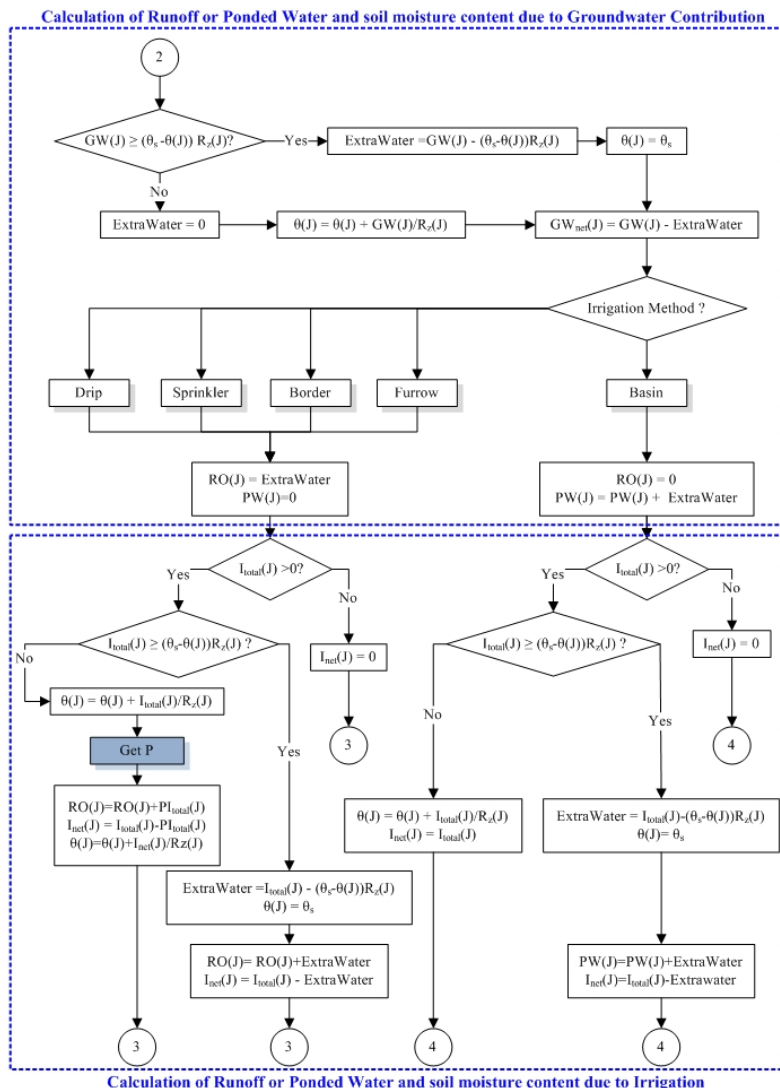
- The population changes in a study area;
- The land use changes and its effects on the agricultural area;
- The effects of population growth and land use changes on water demand; and
- The effects of population on wastewater production.

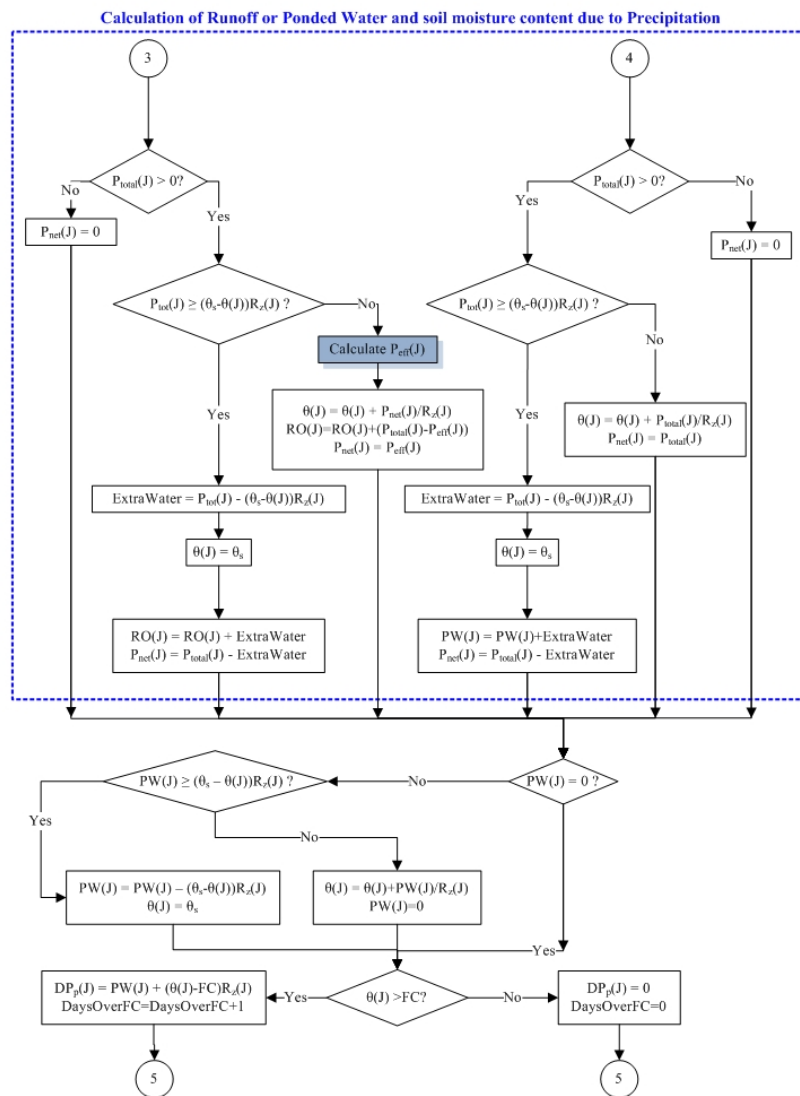
Appendix B. Water and Salt Balance Flow Charts

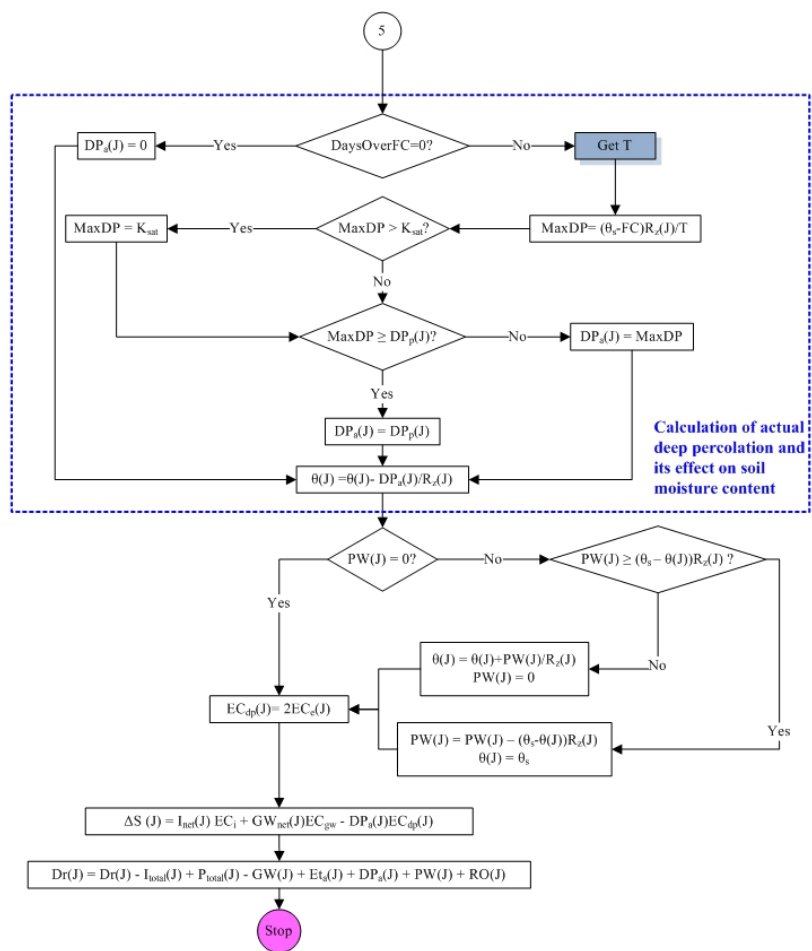






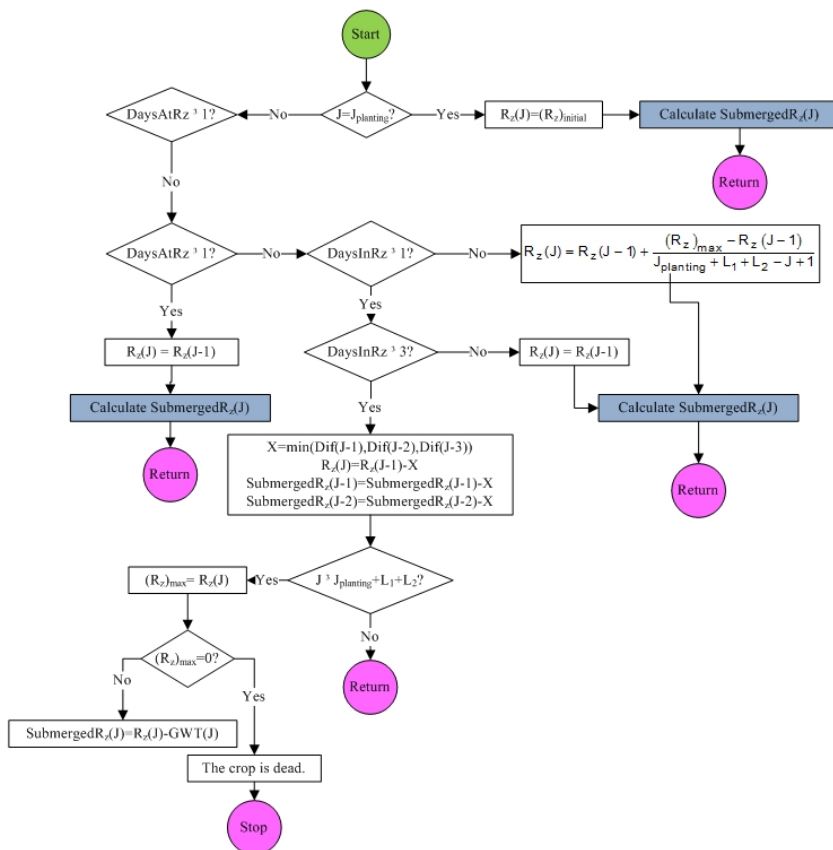




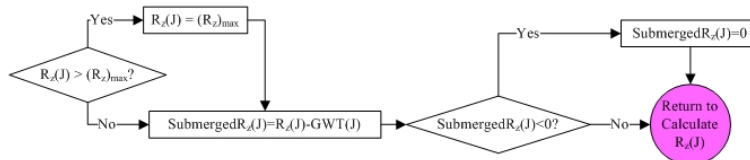


Note: Calculation of  $K_s$  and  $K_c$ ,  $GW$  and  $P_{eff}$  is based on the methods described in Chapter 5.  $T$  is the time that will take for the soil moisture content to reach the field capacity, and  $P$  is the percentage of irrigation water runoff that is related to soil type and irrigation method.

### CALCULATE $R_z(J)$



### CALCULATE Submerged $R_z(J)$



Appendix C. Users Manual for the Water Reuse Model

The Water Reuse Model is a MapWindow Plugin that can operate as a GIS-based model or can execute independently without the GIS data. In order to use the model, the user should activate the plug-in named “LU”. When the “LU” plug-in is activated by the user, the button for Water Reuse Model will be added to the Map Window, as shown in Fig. C.1.

This button will be activated even if no shape file or grid layers are added in the Map Window. When the Water Reuse Model is clicked by the user, the main page of the model is shown (Fig. C.2).

Similar to the Water Availability Model, this model has a graphical, user-friendly interface that makes it easy for the user to enter the input data and define various scenarios and compare them. Figure C.2 shows the model interface, which will appear after the user presses the “Start” button. If the mouse is on any of the buttons in this page, their name will be shown, such as: Input data, Calculation Options, and so forth. This window is composed of four buttons that help the user define up to three scenarios and compare them. In the following sections all the buttons and their functions are described in more details.

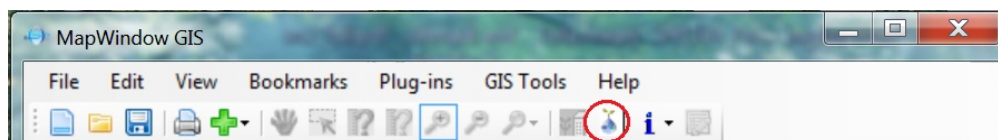


Figure C.1. The button for the Water Reuse Model in the toolbar of MapWindow.

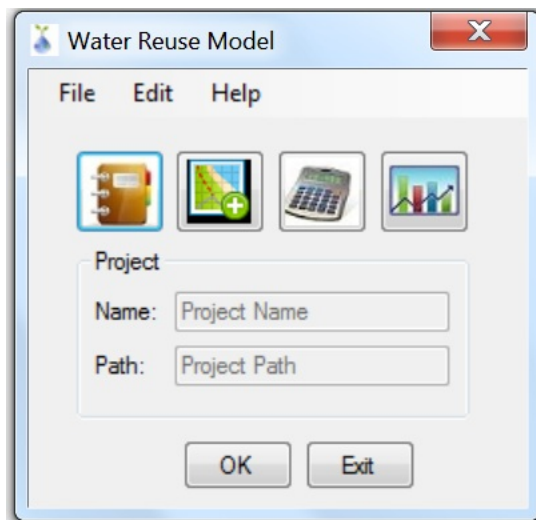


Figure C.2. The main window of the Water Reuse Model.

### New Project

The first step is to define a new project. For this purpose, the user should click on the File button on the menu, and then click on “New Project,” as shown in Fig. C.3.

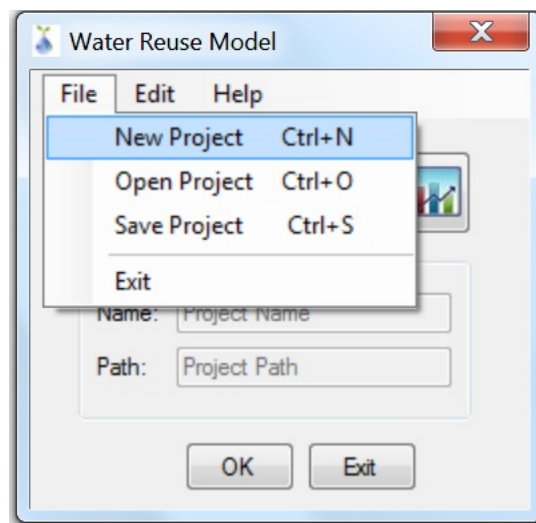


Figure C.3. The procedure for adding a new project.

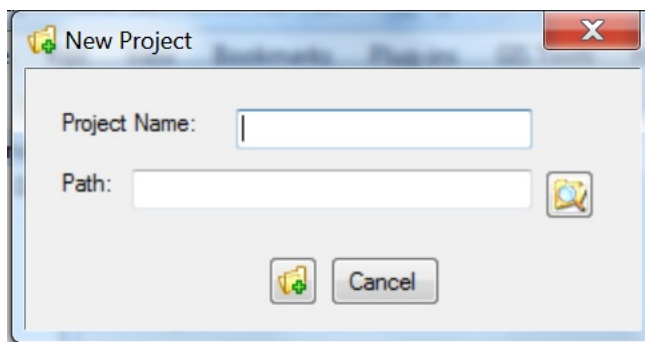


Figure C.4. The window for adding a new project in Water Reuse Model.

This will result in the appearance of the window shown in Fig. C.4, in which the location and the name of the project can be defined by the user and therefore, a new project can be created. Upon the creation of a project a main folder under the name of the project defined by the user will be created in the location desired by the user and inside the main folder, two folders named “Input” and “Output” will be created automatically. The input data and output data are saved under binary files in Input and Output folders created by the model. The project files for this model have .mprj extensions. If the project is defined and its name and path are specified by the user, then in the main page of the model their name and path will be shown in the boxes in Fig. C.2, and if not the terms “Project Name” and “Project Path” will be shown.

### **Input Data**

In the next step the user should define the input data for different scenarios. The first button from left in Fig.C.2 is the “Input Data” button. If the user clicks this button, a window as shown in Fig.C.5 will appear, allowing the user to enter the data.



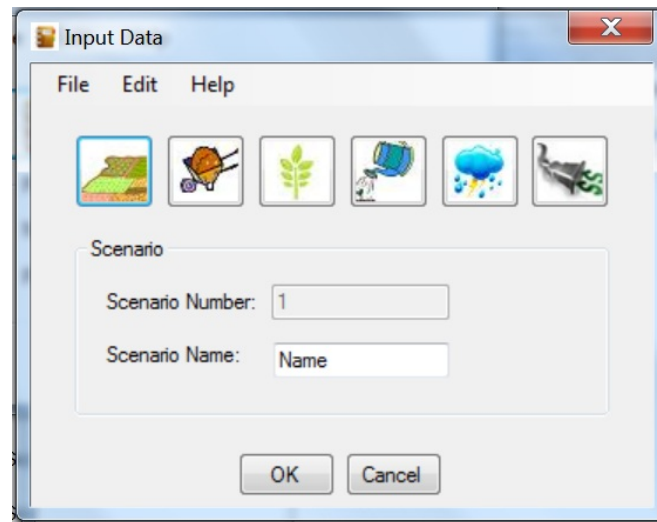


Figure C.5. The window for input data for the Water Reuse Model.

Input data include:

1. Land Data
2. Soil Data
3. Crop Data
4. Water Resources Data
5. Climate Data
6. Energy Data

For each scenario the user can choose a name. The user can define scenarios by changing the input data mentioned above. However, the area of the land for all the scenarios in a project should be equal (each scenario should have the same area). In order to define other scenarios, the user should click on the “Edit” in the toolbar as shown in Fig. C.6. The user can define up to three scenarios.

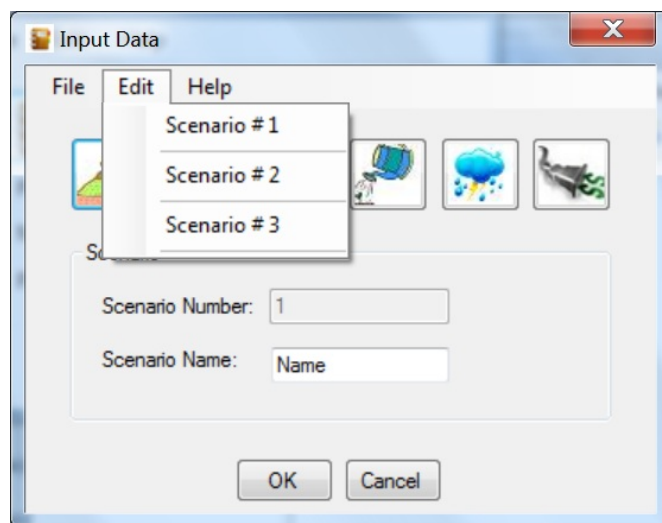


Figure C.6. The procedure to define or edit data for different scenarios.

### Land Data

When the Land button in the Input Data window is clicked by the user, a page (as shown in Fig.C.7) will appear. Land data include:

1. Land Area, which is the area of the land in hectares.
2. The latitude of the land (Degrees).

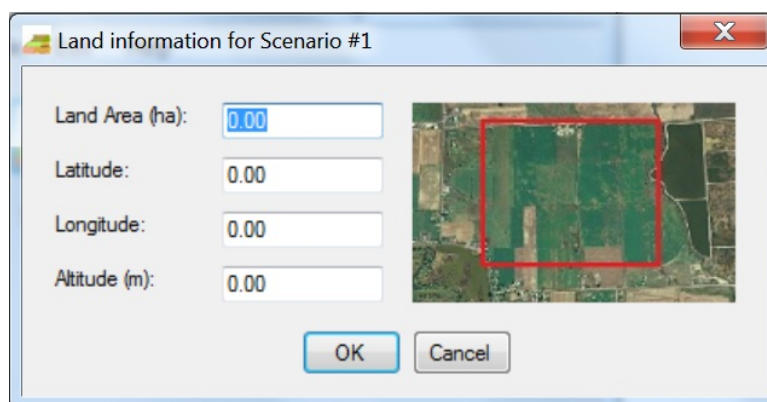


Figure C.7. Land input data window for the Water Reuse Model.

3. The longitude of the land (Degrees).
4. Altitude, meaning the average elevation of the land (m).

### Soil Data

When the soil data button is clicked by the user, the soil data window will appear as shown in Fig. C.8. The soil parameters are:

1. Soil type, meaning the USDA soil texture, which can be chosen from a list of soil textures included in the model. There is a help file in the model for the user to correctly define the soil texture.
2. Clay (%). This is the percentage of clay (particle size equal to or less than 0.002 mm) in the soil.
3. Silt (%). This is the percentage of silt (particle size greater than 0.002 mm and smaller than 0.05 mm) in the soil.
4. Soil characteristics. One of the following options should be selected by the user: calcareous, slightly weathered, or highly weathered. Calcareous soils have high amounts of calcium carbonate, and they mostly occur in arid and semi-arid regions.
5. Base saturation (%) of the soil. The base saturation is a measurement that indicates the relative amounts of base cations in the soil. By definition, it is the percentage of calcium, magnesium, potassium and sodium cations that make up the total cation exchange capacity ([www.ctahr.hawaii.edu/mauisoil/](http://www.ctahr.hawaii.edu/mauisoil/) 2011).
6. Soil pH, indicating the acidity or alkalinity of the soil.

Figure C.8. The soil input data window for the Water Reuse Model.

7. Calcium carbonate content (%).

Phosphorus sorption coefficient is related to soil characteristics. Based on soil characteristics, factors such as base saturation, calcium carbonate content, or soil pH will be used for calculation of phosphorus sorption coefficient (Knisel et al. 1993).

8. Saturated hydraulic conductivity (m/day).

9. Porosity ( $\text{m}^3/\text{m}^3$ ).

10. Field-capacity water content ( $\text{m}^3/\text{m}^3$ ). This is the volumetric soil water content at field capacity.


11. Wilting-point water content ( $\text{m}^3/\text{m}^3$ ). This is the volumetric soil water content at the permanent wilting point. The soil moisture content at wilting

point is not available for the plant and it is the soil moisture corresponding to pressure of -15 bars.

12. Initial crop residue on the ground surface (kg/ha).
13. SCS curve number, which can be defined based on the hydrologic group to which the soil belongs.
14. Organic matter content (%) of the soil.
15. Total nitrogen (%) in the soil horizon.
16. Nitrate-nitrogen concentration (Mg/g) in the soil horizon.
17. Potentially mineralizable nitrogen (kg/ha) in the soil horizon.
18. Organic nitrogen from animal waste in the plow horizon (%).
19. Total Phosphorus (%). This is the total phosphorus in the soil horizon.
20. Labile Phosphorus Concentration (Mg/g).
21. Organic Phosphorus from Animal Waste in Plow Horizon (%).
22. Soil Salinity (dS/m).

It should be mentioned that if the user does not define the nutrient amounts in the soil (variables 15 to 21), the model will define some default values for them.

### **Crop Data**

When the crop data button is clicked by the user, the crop data window will appear as shown in Fig. C.9. For each scenario the user can define up to three crops. The user can choose the crops from a list that is already saved in the model. The data for crops can be loaded (using the  button) from the default values saved in the model, or

they can be defined by the user. As shown in Fig. C.9, the graph for crop coefficient and root zone depth is drawn by the model when the user enters these values.

The crop parameters are:

1. Crop Name: A list of crop names is saved in this part of the model and the user can choose one.
2. Planted Area (%): Planted area shows the percentage of the land for the crop defined by the user.
3. MAD: Maximum allowable depletion that can be defined based on drop type and management practices.
4. Planting Day: The day of the month that the crop is cultivated
5. Planting Month: The month of the year that the crop is cultivated
6. Initial Root Depth

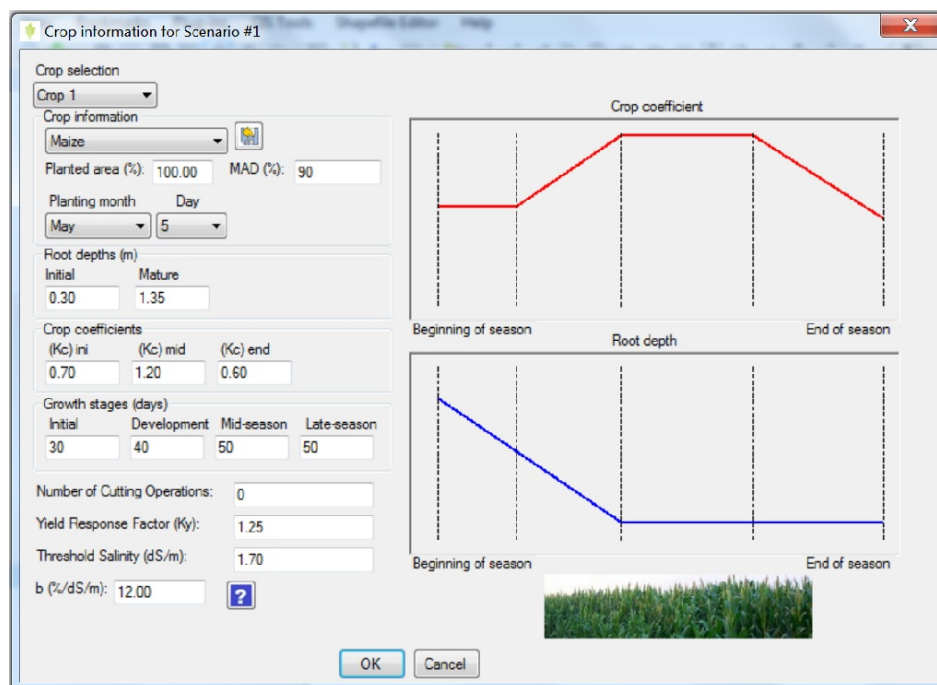



Figure C.9. The crop input data window for the Water Reuse Model.

7. Mature Root Depth: The maximum root depth (m) of a crop defined by the user
8.  $(Kc)_{ini}$ : Crop coefficient for the initial crop growth stage.
9.  $(Kc)_{mid}$ : Crop coefficient for the mid-season growth stage.
10.  $(Kc)_{end}$ : Crop coefficient at the end of the late season stage. This value reflects crop and water management practices.
11. Initial Growth Stage: Initial stage of crop growth runs from planting date to about 10% ground cover. The length of this stage is related to the crop type.
12. Development Growth Stage: Development crop growth stage runs from 10% ground cover to effective full cover.
13. Mid-Season Growth Stage: Mid-season stage runs from full cover to the start of crop maturity.
14. Late-Season Growth Stage: Late season growth season runs from the start of the maturity to the harvest.
15. Number of Cutting Operations: If the crop selected for the scenario should be cut before harvest, the number of cutting operations should be entered.
16. Yield Response Factor ( $K_y$ ): The response of the crop yield to water and salt stress is quantified with yield response factor.
17. Threshold Salinity ( $EC_{threshold}$ ): Electrical conductivity of the saturation extract at the threshold, when crop yield first reduces below maximum yield ( $dSm^{-1}$ ) (Allen et al. 1998).
18.  $b$  : Reduction in yield per increase in  $EC_e$  ( $\% / (dSm^{-1})$ ).

The data for crop coefficients, crop growth stages, yield response factor, threshold salinity and b are saved in the model for 23 crop types, including alfalfa, cabbage, cotton, maize, onion, pea, pepper, potato, sorghum, soybean, sugar beet, sugar cane, tomato, and others.

### **Water Resources Data**

This part of the model is composed of various tabs for entering the input data for surface water, groundwater, treated wastewater and irrigation water. The user can add up to two types of water resource for each scenario. The input data needed for each water resource are described below.

Treated Wastewater: Treated Wastewater Hydrograph: In this part the user can add the data for the treated wastewater hydrograph released by a treatment plant for a whole year. These data can be entered either as a text file or an Excel file. For the Excel file, the user should enter the data for treated wastewater effluent released for a whole year (starting from January first) in m<sup>3</sup>/day. The data should be entered in a column with the title “effluent” and in sheet1 of the file. For the text file, the data should be entered for the whole year in m<sup>3</sup>/day, starting from January first. Each data should be in a line. After the user has selected a file for treated wastewater data, he/she should click on the load button ; this will load all the data in table shown in Fig. C.10.

1. Water Resource Elevation: The elevation of the location the treated wastewater is released in meter.
2. Distance to Land: The distance between the water resource and the land in meters.



3. Treated Wastewater EC: The salinity of the treated wastewater in dS/m.
4. Total Nitrogen: Total amount of nitrogen in treated wastewater released in %.
5. Organic Nitrogen: Organic nitrogen in treated wastewater released in %.
6. Ammonia: Ammonia amount of treated wastewater released in %.
7. Total Phosphorus: Total amount of phosphorus in treated wastewater released in %.
8. Organic Phosphorus: Amount of organic phosphorus in %.
9. Organic Matter: Amount of organic matter in % in released treated wastewater.

Surface Water: Surface water input data tab is shown in Fig. C.11. Surface water data can be either of the following methods:

1. On-demand method
2. Rotation method

For the On-demand method, these are the data that the user should define:

1. Total Quantity Available ( $m^3$ ): Total volume of water available for the user.
2. Flow Rate ( $m^3/hr$ ): Flow rate of the surface water.

Water Resources Data for Scenario #1

Treated Wastewater | Surface Water | Ground Water | Available Water | Irrigation Water | Fertilizer

Wastewater Availability  
Treated Wastewater Hydrograph File: [Browse] [Open]

Wastewater Quality  
Total Nitrogen (%): 0.00  
Organic Nitrogen (%): 0.00  
Ammonia (%): 0.00  
Total Phosphorus (%): 0.00  
Organic Phosphorus (%): 0.00  
Organic Matter (%): 0.00

Wastewater Salinity  
Treated Wastewater EC (dS/m): 0.00

Wastewater Source Information  
Water Resource Elevation (m): 0.00  
Distance to Land (m): 0.00

Month	Day	Treated Wastewater (m3)
January	1	0.00
January	2	0.00
January	3	0.00
January	4	0.00
January	5	0.00
January	6	0.00

OK Cancel

Figure C.10. The treated wastewater window.

Water Resources Data for Scenario #1

Treated Wastewater | Surface Water | Ground Water | Available Water | Irrigation Water | Fertilizer

Surface Water Delivery Method  
 On Demand Method  
Total Quantity Available (m3): 0.00  
Flow Rate (m3/hr): 0.00  
 Rotation Method  
Rotation Intervals: [ ]  
Flow Rate (m3/hr): [ ]  
First Date Available: January 1  
Irrigation Hours per Day: 0

Surface Water Information  
Surface Water Elevation (m): 0.00  
Distance to Land (m): 0.00

Surface Water Quality  
Surface Water EC (ds/m): 0.00

Month	Day	Irrigation Hrs	Surface Water (m3)
January	1	0.00	0.00
January	2	0.00	0.00
January	3	0.00	0.00
January	4	0.00	0.00
January	5	0.00	0.00
January	6	0.00	0.00
January	7	0.00	0.00

OK Cancel

Figure C.11. The surface water input data tab in the water resources window.

For this method, the table in Fig.C.11 should be completed by the user. The user should define the irrigation hours and based on the surface water flow rate and availability of the water, the column for “Surface Water” will be filled in. For the rotation method the following input data must be entered by the user:

1. Rotation Intervals: Irrigation intervals in days.
2. Flow Rate ( $\text{m}^3/\text{hr}$ ): Surface water discharge.

3. First Date Available: Month and day that surface water will be available to the user.
4. Irrigation hours per Day: Number of hours per day that water will be available to the user.

For this method, the table in Fig.C.11 will be filled based on the input data the user has entered automatically. Three other parameters should be defined by the user for either type of surface water:

1. Surface Water Elevation (m): The average elevation of surface water is delivered to the user.
2. Distance to Land (m): Distance of surface water source to the location of the land in the selected scenario.
3. Surface Water EC: Salinity of the surface water resource (dS/m).

Ground Water:Ground water data that should be entered by user are listed below:

1. Total Quantity Available ( $m^3$ ): Total volume of ground water that can be extracted for the season.
2. Flow Rate ( $m^3/hr$ ): Flow rate of ground water extraction.
3. Ground Water Elevation (m): Elevation of the water table.
4. Distance to Land (m): Distance of ground water resource to the location of the land being studied.
5. Groundwater EC (dS/m): Salinity of the groundwater.

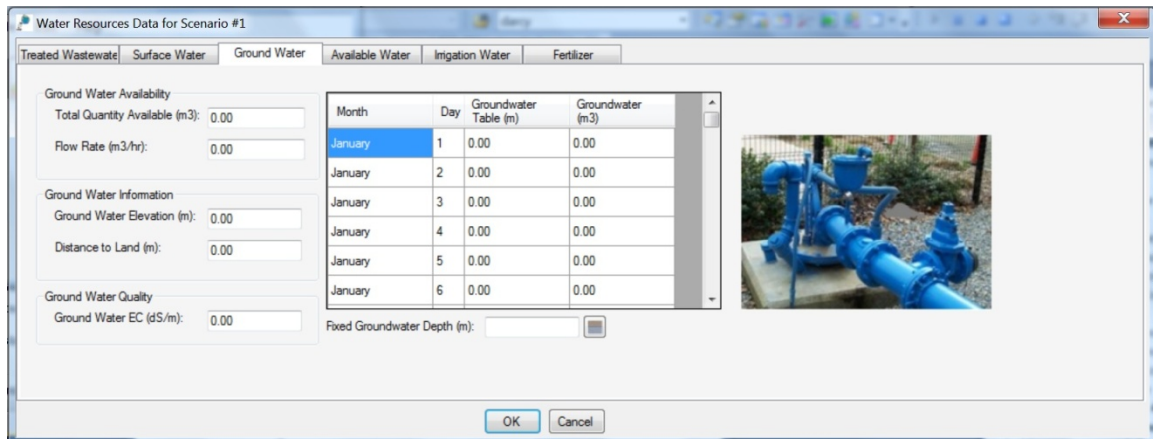


Figure C.12. The groundwater tab in the water resources window.

The user enters the groundwater extraction for each day during the simulation season. The model will check for the available ground water volume and will not allow the user to exceed the limits defined by the user for ground water extraction. The user should also define the depth to the ground water table during the entire simulation period. If the user decides to assume a specific ground water depth for the whole year, he/she should define the “Fixed Ground Water Depth (m)” and if he/she clicks on the button next to it as shown in Fig. C.12, the table will automatically be filled in.

Available Water: In the available water tab (Fig. C.13), the user must choose up to two water resources for each scenario. The available water for irrigation can be chosen for two methods:

1. Alternative: In alternative method, the model will use the source#1 as the main water resource and if the water was not enough, the model will use the second water resource.
2. Mixing: In mixing method, the model will mix water resource #1 and water resource #2, based on the amounts the user defines in the input data.

Based on the input data defined by the user in the available water tab, the table in Fig.C.13 will be automatically completed. In this tab some data for possible pumping of water should be entered by the user. Fuel type should be selected from a fuel types saved in the model. Operational hours per day and operating days per year also must be defined by the user.

Irrigation Water: In the irrigation water tab (Fig. C.14), the user should define the irrigation system that being used in the study area and the efficiency of that irrigation system. It should be mentioned that if the user puts zero for the efficiency of an irrigation system, the model will assume some default values (0.7 for surface irrigation systems, 0.8 for sprinkler irrigation system, and 0.9 for drip irrigation system).

The table shown in Fig.C.14 should be completed by the user. Based on the number of crops defined for a scenario and the planting date and harvest date, the user can irrigate the crops. In other words, the user can enter the amount of irrigation water for the specific dates between the crop planting date and its harvest date.

The screenshot shows the 'Water Resources Data for Scenario #1' window with the 'Irrigation Water' tab selected. The window is divided into several sections:

- Irrigation Water Source:**
  - Alternative: Source #1: TreatedWastewater, Source #2: TreatedWastewater
  - Mixing: Source #1: TreatedWastewater, Amount (%): [ ], Source #2: TreatedWastewater, Amount (%): [ ]
- Pumping:**
  - Fuel Type: Electricity
  - Operation Hours per Day: 8.00
  - Operation Days per Year: 0.00
- Table:**

Month	Day	Water Source #1 (m3)	Water Source #2 (m3)	Total Water Available (m3)
January	1	0.00	0.00	0.00
January	2	0.00	0.00	0.00
January	3	0.00	0.00	0.00
January	4	0.00	0.00	0.00
January	5	0.00	0.00	0.00
January	6	0.00	0.00	0.00
January	7	0.00	0.00	0.00
January	8	0.00	0.00	0.00
January	9	0.00	0.00	0.00

Figure C.13. The available water tab in the water resources window.

## Climate Data

If the user clicks on the climate data button in Fig.C.2, the climate data window (Fig.C.15) will appear. This window allows the user to define a specific path for an existing text file or MS Excel file, including the daily climate data for a year. The model will open the file and read the climate data from that file. Climate data should be stored in either of the following formats, for a whole year, beginning January first:

- A text file for the whole year in a daily basis format. The order of the tab-delimited data should be: (1) maximum daily temperature (C); (2) minimum daily temperature (°C); (3) mean daily relative humidity (%); (4) wind speed at a height of 2 m (m/s); (5) solar radiation (MJ m<sup>-2</sup>day<sup>-1</sup>); (6) total daily precipitation (mm); and (7) soil temperature (°C).
- An MS Excel file that stores the data in sheet1 of the spreadsheet file. Maximum daily temperature (°C), minimum daily temperature (°C), mean daily relative

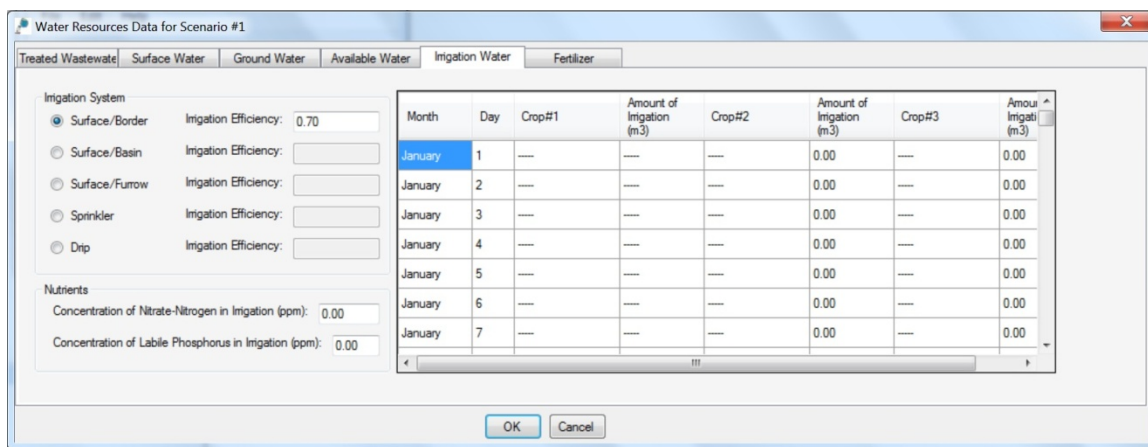


Figure C.14. The irrigation water tab in the water resources window.

- humidity (%), wind speed at 2 m height (m/s), solar radiation ( $\text{MJm}^{-2}\text{day}^{-1}$ ), total daily precipitation (mm) and soil temperature ( $^{\circ}\text{C}$ ) for a whole year should be stored in columns with the following names as the column titles:  $t_{\max}$ ,  $t_{\min}$ , RH, wind, radiation, and precipitation.

### Energy Data

If the energy data button of the window (shown in Fig.C.2) is clicked by the user, the energy data window will appear (Fig. C.16). This window allows the user to add the land and the water resources (up to two water resources) and up to three connections between the land and each of the water resources. The buttons at the top of the window are the tools for this purpose.

From left to right the buttons at the top of the energy window are for: (1) Adding a land to the schematic; (2) Adding a water resource to the schematic; (3) Adding a connection to the existing schematic; (4) Adding a connection to a new schematic; (5) Edit the connection data; and (6) Price data.

It should be considered that:

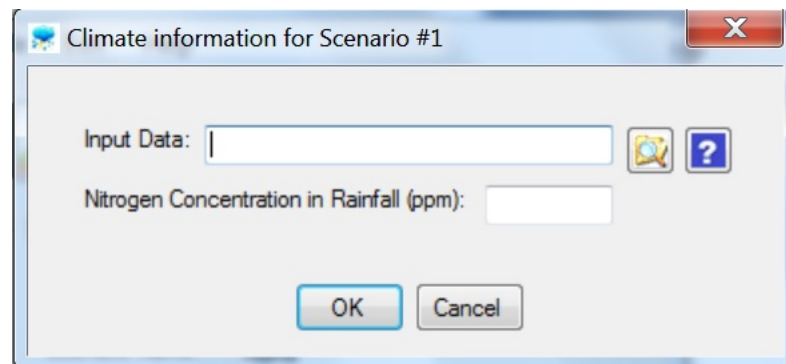


Figure C.15. The climate data window.

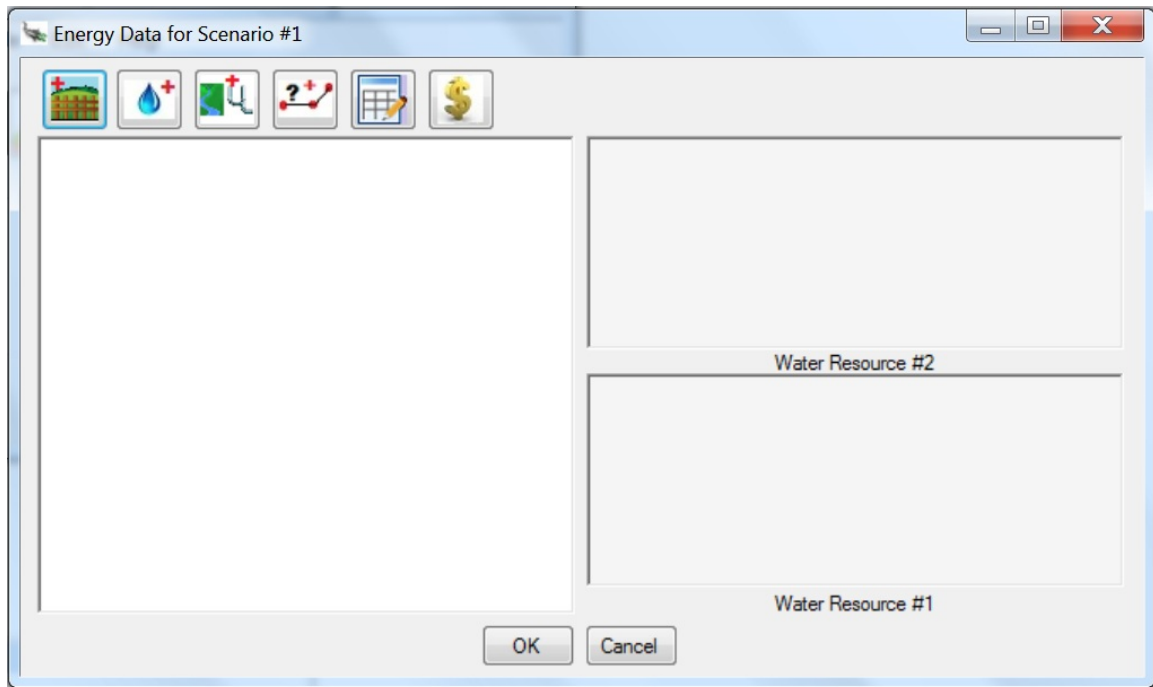




Figure C.16. Energy input data window.

- Based on the number of water resources defined for the scenario, the model will allow the user to add either one or two water resources to the schematic.
- If the user adds a built connection that has an elevation lower than the previous connection (downstream), the model will automatically assume a pipe; otherwise the model will assume a canal for that connection.
- The user can move the locations of the land, water resources and connections, after the drawing is finished, by dragging and dropping them.
- For the last connection (the closest one to the water resource), the model will assume the same elevation as the water resource.
- The user can add up to three connections.



- For water resource one and two, after the schematic is drawn by the user, the model will draw the topography of the ground between the land and the water resource, in the boxes on the right hand side of the energy window.
- After the user finished drawing the schematic of land and water resource and the connections, he/she can edit the data by clicking the  button.

If the user clicks on the  button, a window (Fig.C.17) will open. For each connection the user should enter the elevation, the distance to the previous connection, and also the efficiency of the conveyance system. If the connection is already built, depending on having a canal or a pipe the following data should be defined by the user:

1. Canal: Width of the canal, height of the canal, side slope of the canal and the Manning number (roughness) of the canal. The Manning roughness of the canal can be defined based on its material and vegetation in the bed and side slopes of the canal.
2. Pipe: The pipe diameter and pipe material can be selected from a list of data that is already saved in the model.

If the price data button is clicked by the user, the price information window (Fig.C.18) will open. In this window the user should enter the data for prices of pipes and canal expansions and fuel for pumping.

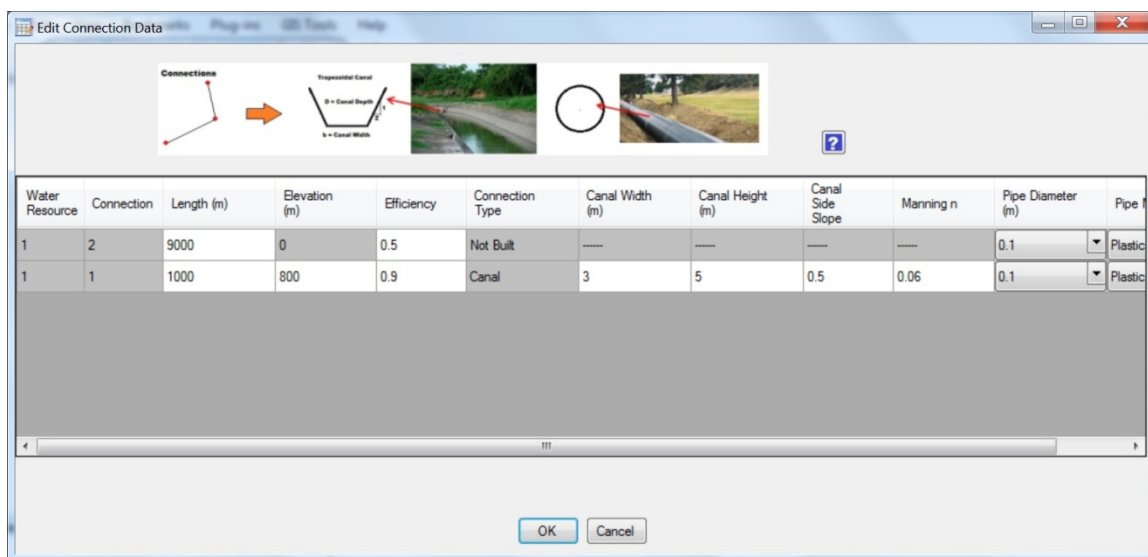


Figure C.17. The edit connection data window.

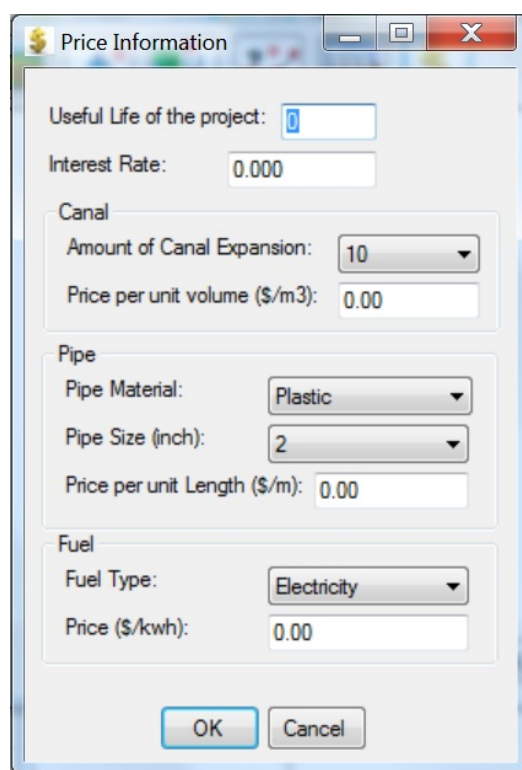


Figure C.18. The price information window.

### **Define the GIS Layers**

When the user clicks the Define GIS Layers button, the window shown in Fig.C.19 will appear. In this window, all the GIS layers added by the user in Map Window project will be added to the land layers list (Fig. C.19) if they are grid or polygon shape files, or added to water resources layers list (Fig. C.19) if they are point shape files. In the GIS layers data window, the user can choose the GIS layers for the project. However, it should be noted that this is an optional choice for the user to decide whether to define GIS layers or not. For the convenience of the user, the model was developed so that it can be executed either as a GIS-based model or without defining GIS data for the project. The area of the land and the location of the land for each scenario are taken automatically from the data user has entered in the previous steps. When the model is running, the location of the land in each scenario, and the water resources locations for each scenario, will be specified by squares that show the size and location of each scenario. The GIS tools give the option of presenting the location of the water resources and scenarios in a visual way. Thus the user will have a better understanding of the scenarios and their locations with respect to each other and to the water resources. This will allow the user to overlap soil or topography maps of the study area for the locations of the scenarios and investigate them in various aspects.

### **Run**

When the Run Button is clicked by the user, the model will start running a simulation, calculating the water and salt balance, nutrient calculations and pumping and conveyance costs calculations on a daily basis for the year of simulation, and will write

the results and output of the calculations in a binary file in the output folder (which was created while creating a new project by the user).

## Results

The Result button opens the results of the calculations in one table that ranks the scenarios defined by the user according to three factors:

- Crop yield
- Environmental effects
- Pumping and conveyance costs
- Soil water salinity

Detailed results for all the scenarios for water and salt balance and nutrient balance calculations, and calculations of pumping and conveyance costs are also saved in tables in the results part of the model. There are graphic results available for the user to

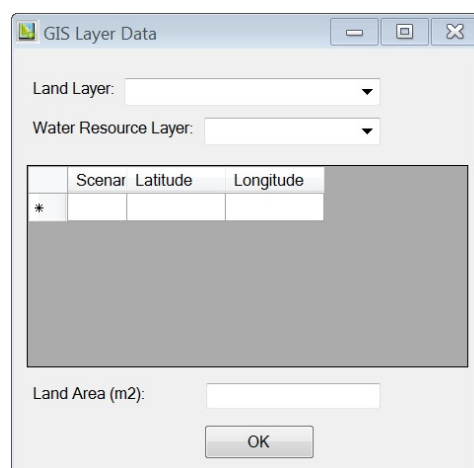


Figure C.19. GIS layer data window.

see the changes of various parameters calculated (such as soil moisture content, reference ET (mm), crop ET (mm), actual ET (mm), water demand for each scenario (mm), root depth (m), soil water salinity (dS/m) and so on, on a daily basis.

## VITA

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- PhD, Civil and Environmental Engineering
- GPA 3.91
- PhD Thesis to be defended Oct. 2011, title: “*Planning and Management Modeling for Treated Wastewater Usage in Agricultural Irrigation.*”

**Shiraz University**, Shiraz, Iran

- Masters, Irrigation and Drainage Engineering
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- Bachelors of Science, Irrigation Engineering
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**EXPERIENCE:****Civil and Environmental Engineering Dept., Utah State University**, Logan, Utah - 2005-2011**Graduate Research Assistant**

- Developed a new model to investigate the effects of population growth and urbanization on agricultural area, and future water demand and also to analyze the future quantity of wastewater producing.
- Developed a new mathematical model to assist in planning and management of reuse of treated wastewater for agricultural irrigation (**VB.NET and as a Plug-in in Map Window**), which includes daily water balance and salt balance, evapotranspiration and yield calculations and nutrient balance and also conveyance and pumping costs of water delivery.

**Haseb Consulting Engineers Company**, Shiraz, Iran  
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- Conducted river training and flood control projects on different rivers in Southern Iran.

- Investigating erosion and sedimentation in some rivers in Southern Iran.
- Conducted water depth simulations in rivers and canals, using Hec-Ras model.
- Conducted some hydrological modeling using HEC-HMS model.
- Prepared many technical reports.

**Water Engineering Dept., Shiraz University, Shiraz, Iran**  
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- Taught lab on design of irrigation systems to senior-level undergraduate students.

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- *Planning and Management Modeling for Treated Wastewater Usage*, Journal of Irrigation and Drainage Systems, Special Issue, Springer Netherlands, Ahmadi, L. and G. Merkley (2009) 23:97-107 (DOI: 10.1007/s10795-009-9062-1).
- *Planning and Management Modeling for Treated Wastewater Usage*, USCID Conference on Urbanization of Irrigated Land and Water Transfers, Scottsdale, Arizona, Ahmadi, L. and G. Merkley (2008).
- *Investigation of Hydraulic Behavior of Khoshk River Using Unsteady MIKE11 and HEC-RAS Models*, DHI Water and Environmental Software User Conference, Florida, Ahmadi, L. and M. Javan (2005).

#### **ACTIVITIES & HONORS:**

- Member of USU Water Fellow Initiatives (since 2007)
- Member of Golden Key International Honor Society (since 2007)
- Scholarship recipient of Utah State University International Student & Scholars (2006)
- Member of AGU (American Geophysical Union)(since January 2011)

#### **SOFTWARE APPLICATION:**

- VB.NET (Programming)
- Map Window
- Arc-GIS
- HEC-RAS
- MIKE11 (Hydrodynamics module and non-cohesive sediment transport module)
- HEC-HMS
- AUTO-CAD

#### **LANGUAGES:**

- Farsi (fluent)
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