MODELING AND REMOTE SENSING OF WATER STORAGE CHANGE IN LAKE URMIA BASIN, IRAN

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ABSTRACT

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Lake Urmia, the second largest saline lake in the world, is on the verge of drying up completely and creating a massive environmental disaster in the region. Several studies have suggested that the intensive irrigation activities and prolonged droughts are the main causes for the depletion, but none of them have simulated the anthropogenic activity in the watershed. In this study, streamflow simulated from a land surface model with anthropogenic impact assessment capabilities (HiGW-MAT) is used, along with a high resolution land use land cover change map, to investigate the natural and human-induced changes in the hydrology of Lake Urmia basin. The overall goal of the study is to attribute the observed changes in lake volume to natural and anthropogenic factors. Analysis of the Standardized Precipitation Index (SPI) over the Lake Urmia region suggests that the on-going depletion of the lake is not solely due to prolonged droughts alone. Anthropogenic activities have also caused a significant change in land use, streamflow, and water storage within the watershed. There has been a 98% and 180% increase in the total area of agricultural land and urban areas, respectively, from 1987 to 2016, with a corresponding shrinkage of 86% in the lake area. The linear trend of the lake volume and Terrestrial Water Storage (TWS) from HiGW-MAT model suggest that the watershed is gaining water from the lake at a rate of 0.28 km$^3$/year, which could be because of the numerous water resources projects in operation in the watershed. Furthermore, the comparison of streamflow output of HiGW-MAT model with and without human impact showed an average reduction of 2.66 km$^3$/year from 1998 to 2010, further suggesting the significant role of human activities on the depletion of the lake volume.
ACKNOWLEDGEMENTS

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Chapter 1.

INTRODUCTION

1.1. Introduction

Water is one of the basic needs of human beings. The growing scarcity of fresh and clean water is among the most important issues of civilization in the 21st century. With population on a constant rising trend, most of the countries in the world are caught between the growing food and water demand for drinking and other purposes such as irrigation, industrial and domestic. To cope up with this growing demand, the need for increment in food production and water resources management is essential. The most common water management technique used is construction of other water retaining structures such as weirs, dikes and dams. The main purpose of these retaining structures is to store large amounts of water, so that it can be used later for a variety of functions, including land irrigation, power generation, water supply and flood control. Although there are numerous advantages of this technique, disadvantages are quite extensive through an environmental point of view. The wetlands and surface water bodies lying downstream of these structures dry up due to less availability of water, causing the loss of many habitats. An increase in food production can only come from four sources: capturing local rain, horizontal expansion of agriculture, food imports, or lower calories diets (Rockström & Barron, 2007). Out of these, the most commonly adopted source is horizontal expansion of agricultural land.

This condition is reported by numerous studies regarding Lake Urmia region in northwest part of Iran (Abbaspour & Nazaridoust, 2007; AghaKouchak et al., 2015; Alesheikh, Ghorbanali, & Talebzadeh, 2004; Delju, Ceylan, Piguet, & Rebetez, 2013; Eimanifar & Mohebbi, 2007; Ghaeri,
Lake Urmia, known as one of the largest saltwater water bodies in northwestern Iran, has been shrinking with a catastrophic 88% depletion in lake area in the last 2 decades (AghaKouchak et al., 2015). The dramatic shrinkage of the lake area in recent decades has resulted in an unprecedented scale of environmental catastrophe. While most of the studies are crediting this depletion to causes such as climate change and anthropogenic activities, a profound understanding of the processes occurring in the watershed is obligatory. As both the causes mentioned above are interdependent on each other, evaluating and correlating them together becomes indispensable.

1.2. Research Motivation

Lake Urmia is one of the most saline water bodies in the world with a very high salt concentration with long-term average of 150 to 170 g/L of NaCl. Several studies in recent years have mentioned the significant water level drawdown that endanger the whole ecosystem in that area (Abbaspour & Nazaridoust, 2007; AghaKouchak et al., 2015; Ahmadzadeh Kokya, Pejman, Mahin Abdollahzadeh, Ahmadzadeh Kokya, & Nazariha, 2011; Hassanzadeh, Zarghami, & Hassanzadeh, 2012; Sima & Tajrishy, 2013).

In the ever growing debate on the main reasons of Lake Urmia’s shrinkage, some have provided evidence about the extended drought periods and climate change (Madani, 2014), whereas others debated it with intensive agricultural activities and anthropogenic changes as the main reason (AghaKouchak et al., 2015; Hassanzadeh et al., 2012; Zeinoddini, Bakhtiari, & Ehteshami, 2015). There are also some other studies that attributes the depletion of Lake Urmia mostly to anthropogenic impacts rather than natural change. Ahmadzadeh, Morid, Delavar, & Srinivasan,
2015 assessed the impacts on water productivity and wastage of water from the biggest feeding river of Lake Urmia by changing irrigation method from surface to pressurized systems. The coastline changes of the Lake Urmia derived from Landsat imagery indicate a 1000 sq.km lake area reduction from year 1998 to 2001.

A more thorough understanding of anthropogenic influences, mainly land cover change patterns, and knowledge of the environmental, hydrologic, and socioeconomic effects that promote such changes is critical for the study of Lake Urmia. Unfortunately, the investigations regarding land use land cover (LULC) change in Lake Urmia watershed are hindered by the lack of accurate data. The use of remote sensing, such as Landsat imagery, enables us to overcome this drawback by providing us with high resolution land cover map. All the previous studies on Lake Urmia have focused on limited types of land use, mostly agriculture. This study provides a detailed change of trend for six main land types including agricultural land. Also, previous studies have not much concentrated on climate variables, except those with focus on temperature and precipitation. Streamflow, as the most important data used in planning and designing water resources projects, has received less attention. Thus, there is an obvious need for more research in this area to provide an integrated prospective about status of streamflow, and no study has yet exclusively modelled streamflow trend in Iran, especially in the Lake Urmia basin. This study contributes to the debate of anthropogenic impact on Lake Urmia by interpreting the scale of impact from a global Land Surface Model (LSM) which accounts for human water resources management activities. It provides a comparative study of Lake Urmia basin with and without human activities. Specifically, this report presents how the anthropogenic exploitation of land and water resources in the watershed contributed to the desiccation of Lake Urmia over the period of 1980 to 2010, through climate change, land cover mapping, and land surface modeling with and without human impacts.
1.3. Research Objectives

The overall goal of this thesis is to identify, evaluate and analyze the anthropogenic influence on LULC change in Lake Urmia Basin and attribute the lake depletion to climatic and anthropogenic changes using a global land surface model HiGW-MAT.

The specific objectives are:

- Analysis of climate variable of Lake Urmia basin to examine the trend of climate change or climate variability,
- Creation of historical land use maps using historical aerial imagery and modeling of LULC change over time to identify, evaluate and analyze the human impact on Lake Urmia basin,
- Interpretation of the terrestrial water storage change and other hydrological parameters such as streamflow indicating the extent of anthropogenic activity in the Lake Urmia basin using a global land surface model, and
- Evaluation and attribution the Urmia lake depletion to climatic and anthropogenic changes

The direct outcomes of this research will provide insight as to what caused the massive depletion in Lake Urmia. This research is necessary as anthropogenic activity is increasing and/or continuously changing in the watershed, thereby causing higher rates of depletion in Lake Urmia. Increased understanding of the effects of LULC and anthropogenic activity in Lake Urmia basin is also needed in order to come up with a restoration plan to avoid an environmental disaster such as that of Aral Sea.
1.4. Organization of Thesis

The thesis has seven chapters including the Introduction. Given the rationale and the purpose of the thesis, the chapters are designed to contribute to fulfilling the three objectives. In Chapter 2, a review of the relevant literature on the major methodological and empirical issues pertaining to the objectives of the thesis is provided. Chapter 3 gives a detailed description of the Lake Urmia watershed in terms of geography and water resources. Chapter 4 studies and interprets the climate change or variability occurring over Lake Urmia region. Chapter 5 assesses the land use and land cover change in the Lake Urmia basin. Chapter 6 addresses the methods used for hydrological modeling of terrestrial water storage in the watershed and describes the results obtained from it. The thesis ends with a Conclusion in Chapter 7.
Chapter 2.

LITERATURE REVIEW

2.1. Water Scarcity

The population has been on an exponential rise since the 20th century, yet the amount of water available for human use is the same, which results in to a water stress (Alcamo, Döll, Henrichs, Kaspar, Rösch, et al., 2003; Arnell, 2008; Oki & Kanae, 2006; Vorosmarty, Green, Salisbury, & Lammers, 2000). As both the population and water resources are unevenly distributed over the globe, water stress varies from place to place. Some places face physical water scarcity whereas some face the social water scarcity which is induced by socio-economic relations, politics, etc. (Ohlsson & Turton, 1998). The physical water scarcity can further be categorized into two concepts – Demand Driven and Population Driven (Falkenmark et al., 2007). Demand driven scarcity is the amount of water withdrawn from the sources such as rivers, lakes and aquifers. Demands can be of various types such as domestic, industrial and irrigation. The population driven scarcity depends on the number of people sharing a water resource, which is also termed as water shortage. This can be measured by an index introduced by Falkenmark et al., 2007, as the water crowding index. Van Loon & Van Lanen, 2013 considered that water scarcity represents the overexploitation of water resources when demand for water is higher than water availability.

To date there have been many studies related to global water scarcity (Alcamo, Döll, Henrichs, Kaspar, Lehner, et al., 2003; Alcamo, Döll, Henrichs, Kaspar, Rösch, et al., 2003; Arnell, 2008; M. Falkenmark et al., 2007; M. Falkenmark, Lundqvist, & Widstrand, 1989; M. A. Falkenmark, 2013; Haddeland et al., 2014; N. Hanasaki et al., 2013; Hoekstra & Mekonnen, 2011; Islam et al.,
2007; Matti et al., 2010; Oki & Kanae, 2006; Smakhtin, Revenga, & Doll, 2004; Vorosmarty et al., 2000). Most of these studies have projected the water scarcity in the near future. Some of these studies have also studied the evolution of trend of the water scarcity over the past few decades. Matti et al., (2010) used historical History Database of the Global Environment (HYDE) data and model results from WaterGAP and STREAM to show that the water scarcity started from as early as 1900. It had risen to 9% in 1960 and then rapidly increased to 35% in 2005. According to Falkenmark, 2013, over 46% of the world’s population could be facing both green (infiltrated rain) and blue water (runoff and surface water) shortage for food production in 2050. The country level water stress projections in Luo, Young, & Reig, 2015 provides a lot information of potential outcome under different scenarios. The scenarios considered in their study area are business-as-usual, optimistic and pessimistic used in Luck, Landis, & Gassert, 2015. The business-as-usual scenario projects on the basis of an assumption that the historical trend of water use continues in the future. Whereas, optimistic scenario assumes that the historical trend shows some positive change and the pessimistic scenario assumes the trend shows a negative change. Figure 1, Figure 2 and Figure 3 shows the country wise water stress indices projected for the year of 2020, 2030 and 2040 respectively (Luo et al., 2015).
Figure 1 – The map shows country-wise ratio of total water withdrawals to total renewable water supply for year 2020. The projections are based on a business-as-usual scenario described in Luo et al., 2015.

Figure 2 - The map shows country-wise ratio of total water withdrawals to total renewable water supply for year 2030. The projections are based on a business-as-usual scenario described in Luo et al., 2015.
Even in places where water is available abundantly, the problem of over-exploitation is very common. In fact, some places have already exhausted their water sources and are categorized as high water stress areas. Table 1 lists some places where the water sources are already exhausted or are on the verge of exhaustion as given in Richter, 2014. The exploitation of water resources can be categorized using an index called Water Exploitation Index, which is the ratio of mean annual total freshwater demand to long term mean annual total fresh water availability. A water exploitation index of 0.4 and higher indicates extreme water stressed watersheds.
Table 1 – World’s most depleted fresh water sources as given in Richter, 2014

<table>
<thead>
<tr>
<th>World’s Most Depleted Fresh Water Sources</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Aral Sea, Kazakhstan/Uzbekistan</td>
<td>Persian Aquifer, Iran</td>
</tr>
<tr>
<td>Krishna River, India</td>
<td>Dead Sea, Jordan/Israel</td>
</tr>
<tr>
<td>Armeria River, Mexico</td>
<td>Rio Grande / Rio Bravo, USA/Mexico</td>
</tr>
<tr>
<td>Loa River, Chile</td>
<td>Doring River, South Africa</td>
</tr>
<tr>
<td>Brazos River, USA</td>
<td>Sacramento River, USA</td>
</tr>
<tr>
<td>Lower Indus Aquifer, India/Pakistan</td>
<td>Fuerte River, Mexico</td>
</tr>
<tr>
<td>Cauvery River, India</td>
<td>San Joaquin River, USA</td>
</tr>
<tr>
<td>Mahi River, India</td>
<td>Ganges River, India/Bangladesh</td>
</tr>
<tr>
<td>Central Valley Aquifer, USA</td>
<td>Santiago River, Mexico</td>
</tr>
<tr>
<td>Murray-Darling Basin, Australia</td>
<td>Godavari River, India</td>
</tr>
<tr>
<td>Chao Phraya, Thailand</td>
<td>Shebelle River, Ethiopia/Somalia</td>
</tr>
<tr>
<td>Narmada River, India</td>
<td>Great Salt Lake, USA</td>
</tr>
<tr>
<td>Chira River, Ecuador &amp; Peru</td>
<td>Tapti River, India</td>
</tr>
<tr>
<td>Nile Delta Aquifer, Egypt</td>
<td>High Plains Aquifer, USA</td>
</tr>
<tr>
<td>Colorado River, USA</td>
<td>Huasco River, Chile</td>
</tr>
<tr>
<td>North Arabian Aquifer, Saudi Arabia</td>
<td>Western Mexico Aquifer, Mexico</td>
</tr>
<tr>
<td>North China Plain Aquifer, China</td>
<td>Yonding River, China</td>
</tr>
<tr>
<td>Penner River, India</td>
<td>Conception River, Mexico</td>
</tr>
</tbody>
</table>

To avoid the increase in water stress, concepts of water management, water governance, water policy, environmental integrity, and water’s role in societal and economic development plays an important role (Matti et al., 2010). Research related to water cycles and the hydrological water budget will provide a scientific way of managing the water usage efficiently. Understanding of the interdependence of various components of a hydrologic cycle and the effect of climate change and other factors, mainly anthropogenic impact on them is necessary. The anthropogenic impact on a certain area is best measured in terms of land use and land cover change. Increase in population
causes an increase in infrastructure development which in turn causes deforestation, increased agricultural activities, urbanization, etc. To provide food for large population, intensive agricultural activities are adopted which requires large scale irrigation projects to complement soil moisture deficits. The Green Revolution is a perfect example of this kind of human impact. Post World War II, the Green Revolution had a tremendous success while causing a lot of unintended ill effects to the water cycle (Falcon, 1970). Intensive irrigation activities dramatically altered river flows (Y. N. Pokhrel, Felfelani, Shin, Yamada, & Satoh, 2017), depleted the ground water table (Y. Pokhrel et al., 2015) and caused massive water pollution due to fertilizers. It also expanded the total agricultural area causing deforestation and hence a huge change in land cover.

Although, infrastructure development such as construction of dams and aquifer mining, benefits the human being, it is catastrophe for the water bodies downstream of the construction. The wetlands, lakes and other water bodies dry up due to the water trapped by dams, hence destroying the habitat for several endangered species. The Aral Sea is one the major catastrophe recorded to date caused by over consumption of the river flows. The surface area of the Aral Sea decreased from ~64000 km$^2$ to 44000 km$^2$ in the period of 1925-1985 (Micklin, 1988). Due to this depletion of fresh water inflow in the sea, the salinity increased tremendously, causing a complete habitat loss. The world’s net area under cultivation has seen a substantial growth by 12 percent over the last 5 decades, at the expense of forest, wetland and grassland habitats, while doubling the total area under irrigation. (FAO, 2011). Changes in land use occur as the direct and indirect consequence of human actions (Briassoulis, 2008; Erle & Robert, 2010). Industrialization since the 18th century has motivated the increase in the concentration of human populations within urban areas and the intensification of agriculture in the most productive lands (Briassoulis, 2008; Erle & Robert, 2010; Turner & Meyer, 1994).
2.2. Anthropogenic impact on land cover change and climate change

The best known impact of human activity on climate change is presence of high amounts of greenhouse gases in the atmosphere, but variations in land use and land cover may be of equal importance which can also be result of intensive anthropogenic activity. For many years, concerns about land-use or land cover change have become an important issue for global climate change. It has been shown by many studies that land-cover change affects surface albedo and thus surface-atmosphere energy exchanges which have an impact on regional climate and water cycle (Fu, 2003; Jule Charney, Peter H. Stone, 1975; Otterman, 1974; Sagan, Toon, & Pollack, 1979). Evapotranspiration is also an important contributor to the water cycle which is dependent on land cover type. Other surface dynamic parameters of the hydrologic cycle are surface roughness, fraction of vegetation coverage, soil water content, leaf area index, etc. Land cover change can impact the regional/global climate in two ways namely through, biogeochemical and biogeophysical processes (Feddema et al., 2005). Biogeochemical changes affects climate by changing the chemical composition of the atmosphere, whereas the bio-geophysical changes directly alters the physical parameters of the Earth’s surface, hence affecting the water cycle and energy balance. The effect of the bio-geophysical changes can be faster and were severe than that of biogeochemical changes. The alteration of landscape, mostly the transition of natural vegetation for example, forests to agricultural land, changes the partitioning of solar radiation into its sensible and latent turbulent heat forms namely the Bowen ratio (Lawton, Nair, Pielke, & Welch, 2001; Pielke et al., 2002). Due to this, transpiration decreases resulting less precipitation activity over the landscape.
2.3. Importance of Remote Sensing and other datasets

Not only anthropogenic factors, but climatological factors also cause widespread changes in the Earth’s land cover. Most land cover changes take place at a very slow pace and the regional patterns develop over long time scales (Lambin, Geist, & Lepers, 2003; Townshend & Justice, 1988). Policymakers and scientists faced major problems of lack of comprehensive data on the land cover and land use types (Loveland et al., 2000). In the past, governmental and private agencies produced maps using the information from ground surveys involving censuses and observation (Anderson, Hardy, Roach, & Witmer, 1976). Remote sensing technology has proven itself beneficial against this drawback by allowing us to use the spectral signatures to classify the land cover types by means of satellite sensors (Loveland et al., 2000; Prince, Justice, & Los, 1990). Land use or land cover mapping using remote sensing is more complex because the spectral signatures of different land use types are not entirely distinct. They are usually a combination of satellite observation, and field observations known as ground-truth data (Lambin et al., 2003; Sohl et al., 2012). Not only land cover data but several climatological components can also be obtained through remote sensing.

Due to a veil of political conservatism in Iran, the local ground data related to climate and other hydrological parameters is not freely available. Lack of reliable data on water demand and irrigation in the region prevent direct water budget assessment on the Lake Urmia basin. Due to all these factors, satellite data is the best option to study the changes occurring in the Lake Urmia basin. As far as the hydrological parameters are concerned, numerous satellite missions provide reliable data of some parameters such as precipitation, evaporation, surface temperature, soil moisture, etc. Precipitation data can be obtained from Global Precipitation Climatology Center.
(GPCC), Global Precipitation Climatology Project (GPCP), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), etc. GPCC data is a compilation of rain gauge from all over the world, whereas GPCP data is an integrated dataset of satellite data and GPCC data. Land surface temperature can be derived from the historical Landsat imagery. The recently launched Soil Moisture Active Passive (SMAP) satellite measures the amount of water in the top 5cm of soil column. The top layer of soil is a major contributor of the water and carbon cycle. The dynamics of the soil moisture change will not only help us better understand the process of circulation of carbon and water, but will also serve as an early warning systems for droughts.

2.4. Land Surface Models

Another useful application of remote sensing in the field of hydrology is the Land Surface Model (LSM). Atmospheric turbulent heat fluxes have been recognized since the 1920s as an important process in the energy and water balance in the hydrosphere, atmosphere and biosphere (Bowen, 1926; Chowdhury, Tarboton, & Bowles, 1992; Dingman, 2001; Famiglietti & Wood, 1994; Monteith, 1965; Morton, 1983; Penman, 1948; Priestley & Taylor, 1972; Seller et al., 1996). Using remote sensing one can provide relative measurements of physical parameters such as albedo and emissivity, required for the computation of turbulent heat fluxes. Remote sensing allows us to study these fluxes on regional or continental scales, but conventional techniques of lumping everything to a single point proves very effective at a local scale. Current generation Land Surface Models have a very sophisticated methods of estimating these heat fluxes using remote sensing data. Numerous schemes and parameters are derived and proposed by different studies to estimate each and every component of heat fluxes such as latent heat, sensible heat, ground heat flux and
snow processes (Chowdhury et al., 1992; Jiang & Islam, 1999; Priestley & Taylor, 1972; Tarboton, 1994). In-depth understanding of these parameters and processes of the turbulent heat fluxes is critical for studying the interaction between land surface and atmosphere and for many water resources management over a range of space and time scale.

Anthropogenic activities such as irrigation can severely alter the energy and water balance of a region (Boucher, Myhre, & Myhre, 2004; Haddeland, Lettenmaier, & Skaugen, 2006; Haddeland, Skaugen, & Lettenmaier, 2006; Kueppers, Snyder, & Sloan, 2007; Lobell et al., 2009; Ozdogan, Rodell, Beaudoin, & Toll, 2010; Puma & Cook, 2010; Sacks, Cook, Buenning, Levis, & Helkowski, 2009; Tang, Oki, Kanae, & Hu, 2007). Due to the ever increasing demand for irrigation, the studies related to the quantification and modeling of the impact of anthropogenic activities on the terrestrial water cycle are emphasized a lot. Recent attempts of land surface modeling show considerable success in application of anthropogenic disturbance to water resources at a global scale assessment (Alcamo, Döll, Henrichs, Kaspar, Rösch, et al., 2003; De Rosnay, Polcher, Laval, & Sabre, 2003; Haddeland et al., 2014; N Hanasaki et al., 2008; Y. Pokhrel et al., 2015; Rost et al., 2008; Wisser, Fekete, Vörösmarty, & Schumann, 2010; Wood et al., 2011).

This study uses the land surface model named HiGW-MAT (Y. Pokhrel et al., 2012, 2015; Y. N. Pokhrel et al., 2012) which incorporates the human impact (Hi) and a groundwater pumping scheme (GW) in to the well-known process based LSM, Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) (Takata, Emori, & Watanabe, 2003). MATSIRO is the LSM part of the global climate model (GCM) known as MIROC (Model for Interdisciplinary Research on Climate) which computes the biophysical changes. It is mainly a compilation of several other models such as a multilayer canopy model to compute the vegetation effects developed by Watanabe, 1994, stomatal conductance model by Collatz, Ball, Grivet, & Berry, 1991, vertical soil
moisture movement model by Richards, 1931 and runoff processes model namely TOPMODEL developed by Beven & Kirkby, 1979. The detailed description of the HiGW-MAT model is given in Chapter 6.
Chapter 3.

WATERSHED DESCRIPTION

3.1. Location and Description

Lake Urmia is the second most hypersaline lake and 20th largest lake in the world. It has become one of the wonders of today’s world because of the changes in its water level over the past 4-5 decades. In the past decades, the lake’s water level has been significantly decreasing, endangering its unique ecosystem (Abbaspour & Nazaridoust, 2007; AghaKouchak et al., 2015; Ahmadzadeh Kokya et al., 2011; Arkian, Nicholson, & Ziaie, 2016; Fathian, Morid, & Kahya, 2014; Hassanzadeh et al., 2012; Sima & Tajrishy, 2013; Tourian et al., 2015; Zeinoddini et al., 2015). AghaKouchak et al. (2015) reports that the lake area has shrunk by around 88% in the past decade. Lake Urmia is located in the northwestern region of Iran, between latitude 37°N to 38.5°N and longitude 45°E to 46°E. The entire Lake Urmia watershed spans over an area of 52000 km² comprising of parts of three states, East Azerbaijan, West Azerbaijan and Kurdistan. Out of this watershed, the lake spanned over an average area of 5,900 km² in the 1970s and is currently around 708 km² (AghaKouchak et al., 2015).

Iran is a semi-arid area with mean annual temperature of 11.2°C and average evaporation and precipitation of 1200 and 341 mm/year (Djamali et al., 2008). Climate in the lake’s catchment is mainly controlled and affected by the mountains surrounding the lake. There is considerable seasonal variation in the air temperatures in the semi-arid climate. The data from the weather station in Tehran, the capital of Iran shows that the months May, June, July, August and September
cover the dry period. The wet season lasts for 7 months with a peak in precipitation in November and December as snowfall and in March-May as spring rainfall.

Figure 4 – Figure showing the location of Lake Urmia Basin (red border) in Iran, Central Asia (top) and the location and extent of Lake Urmia in the Lake Urmia watershed (bottom).
Urmia lake is also known as a major habitat of brine shrimp (*Artemia*) a very important genus of aquatic crustaceans (Barigozzi, Varotto, Baratelli, & Giarrizzo, 1987; Vahed et al., 2011). Brine shrimp, known as Artemia, are the dominant macro zooplankton present in many hypersaline environments (Wurtsbaugh & Maciej Gliwicz, 2001). Due to this shrimp habitat, the lake hosts huge herds of Flamingos (*Phoenicopterus*) and White Pelicans (*Pelecanus*) every winter.

*Figure 5 – A sample of Lake Urmia water consisting of brine shrimp (left) and the close up picture of the Artemia species of brine shrimp found in Lake Urmia.*

Due to the big size of the lake, the temperature and humidity are moderated in the surrounding regions, making them suitable for agricultural activities. Huge agricultural lands and farms can be seen around the lake in the Landsat imagery as well. The major crops grown in this area are wheat and barley. As the agricultural industry boomed in the region, more and more urban areas such as Miandoab, Maragheh, Tabriz and Urmia developed in the last few decades. This rapid development is having adverse effects on the water level of Urmia Lake. Sahand Mountain (Kuh-e-Sahand), the third of the great volcanoes in the volcano province of Eastern Anatolia and Northwestern Iran with an elevation of 3710 m is also a part of the Lake Urmia watershed.
Lake Urmia occupies 3.15% of Iran area, and also about 7% of the total surface water resources of the country belong to the lake. From the total area of the watershed, mountain areas covered about 35,150 km² area. Whereas plains and foothills, about 9,000 km² and finally the lake and marshy lands around it, about 7,310 km² (Ghajarnia, Liaghat, & Daneshkar Arasteh, 2015). The overall physiography is that of an almost circular geological basin structure with the lake in its central part. As such, it receives a number of tributaries of different lengths and water-carrying intensities. A total of 21 permanent or seasonal rivers as well as 39 periodic ones discharge into the lake (Ghaheri et al., 1999). The thirteen major rivers emptying into the lake consists of Barandozchay, Shahrchay and Nazlo Abajaio in the west, Zolachay in north-west, Mahabadchay and Godarchay in south-west, Zarrinerud and Seminerud-pole in south and Ajichay in the east. The longest of these is the Zarrinerud with a length of approximately 230 km, entering the lake from the south. The second largest is the Ajichay with a length of approximately 140 km. Out of these rivers, Zarrinerud River is the main contributor of surface water to Lake Urmia comprising of 42% of total intake (Alipour, 2006). Figure 6 shows the surface water contribution of the major rivers to Lake Urmia in the watershed.

Table 2 – Major features of rivers flowing in Lake Urmia

<table>
<thead>
<tr>
<th>Name</th>
<th>Length (km)</th>
<th>Flow Catchment Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zarrinerud</td>
<td>230</td>
<td>11897</td>
</tr>
<tr>
<td>Simminehrud</td>
<td>150</td>
<td>3656</td>
</tr>
<tr>
<td>Mahabadchay</td>
<td>80</td>
<td>1528</td>
</tr>
<tr>
<td>Godarchay</td>
<td>100</td>
<td>2123</td>
</tr>
<tr>
<td>Barandozchay</td>
<td>70</td>
<td>1318</td>
</tr>
<tr>
<td>Shahrchay</td>
<td>70</td>
<td>720</td>
</tr>
<tr>
<td>Rozechay</td>
<td>50</td>
<td>453</td>
</tr>
<tr>
<td>Nazlochay</td>
<td>85</td>
<td>2267</td>
</tr>
<tr>
<td>Zolachay</td>
<td>84</td>
<td>2090</td>
</tr>
</tbody>
</table>
Due to the increasing population, there has been a steady increase in the agricultural activities in the Lake Urmia Watershed. To cope up with the irrigation water demand, a lot of dams and diversion projects regulating the water in rivers were constructed and are currently in operation in the Lake Urmia watershed. For increased water resource management, the number of projects are also increasing. Out of 275 projects under study, 231 are future projects consisting of 71 reservoir dams, 124 weirs, 17 pumping stations and 10 flood controlling and artificial feeding (Hassanzadeh et al., 2012). As of 2006, the total capacity of all the regulating water projects in Urmia Lake basin was 1712 Million cubic meters (MCM) and including the future projects, the capacity will be close to 3869 MCM in year 2026.
3.2. Lake Urmia Data

The biggest constraint about studying Lake Urmia watershed is data availability. Most of the data used in this study is remote sensing data. The land cover maps are derived from Landsat imagery, the precipitation data used is from Global Precipitation Climatology Center (GPCC), etc. Other data specifically related to Lake Urmia were obtained from research papers. For example lake level, lake area and lake volume were obtained from Arkian, Nicholson, & Ziaie, 2016, whereas the lake area and lake volume trend was acquired from Sima & Tajrishy, 2013. As Lake Urmia is a terminal water body, the outflows from the lake are limited to seepage and evaporation. The report of Water Research Institute (2003) states there is no considerable amount of groundwater flow from the lake to neighboring aquifers. Using this data Hassanzadeh et al., 2012 calculated the total surface water inflow to Lake Urmia using an annual water balance. This inflow data is used in this study to validate the streamflow obtained from the LSM simulation.

![Figure 7 – Water level fluctuations in Lake Urmia from the year 1979 to 2010 (Arkian et al., 2016)](image-url)
Figure 8 – Lake Urmia area fluctuations (top) and volume fluctuations (bottom) (Sima & Tajrishy, 2013)
Figure 9 – Surface water inflow to Lake Urmia as estimated by Hassanzadeh et al., 2012
Chapter 4.

CLIMATE CHANGE OR VARIABILITY

4.1. Introduction

Evidence related to anthropogenic contribution to climatic changes during the past century is accumulating rapidly. The increase in concentration of anthropogenic greenhouse gases, such as CO$_2$ and CFCs, has been one of the main hypothesized anthropogenic forcing that influence climate change. The study of atmospheric CO$_2$ concentration indicates that CO$_2$ concentration has been increased exponentially to 367 ppm in 1999 and to 379 ppm in 2005 (Le Treut et al., 2007), from about 280 ppm in the pre-industrial era (AD 1000-1750). Due to this increase in greenhouse gas concentrations, Earth’s efficiency to radiate heat back to the space is reduced, thereby intensifying the Earth’s greenhouse effect. Not only that, many greenhouse gases tend to be long-lived and have a long-term effect on the climate system. There are also other anthropogenic forcings that influence the evolution of the climate system, such as aerosols. Aerosols are small airborne particles that result mainly from fossil fuel and biomass burning. They affect the climate by changing the energy balance of the Earth’s atmosphere through the reflection of incoming solar radiation. Not only anthropogenic forcing, but natural forcing also play a role in influencing the climate system, such as those that arise from solar changes and explosive volcanic eruptions. Solar energy directly heats the climate system and thus variation in solar output will thereby change the climate system. Explosive volcanic activity can inject large amounts of short-lived (2-3 years) aerosols into the stratosphere. These aerosols have been shown to have a cooling effect on the climate system. Natural forcing on its own probably would have cooled the climate system during the latter half of the 20th century (IPCC, 2007).
These changes in the climatic system can be analyzed and predicted using historical direct observations of climatic factors such as precipitation and temperature. The direct observations for precipitation are usually obtained using rain gauges for placed in watersheds of interest. Many core concepts of hydrology are based on statistical extrapolation of observation data. The sites where the rain gauges are not applied, one can make use of remote sensing data to study the trend of change of the climatic parameters. Observation data in many watersheds around the world are only available at coarser temporal resolution such as monthly. If insights are to be derived about extreme changes in precipitation or temperature at the watershed-scale, monthly-scale data is good enough for to perform a meaningful analysis. The quality of precipitation observation data is also suspect. Rain gauge stations are also often placed at low elevations in their watersheds, a practice which contributes to a known systematic underestimation of precipitation due to a phenomenon known as the orographic effect.

Trend insights derived from precipitation observation have been developed in a variety of different studies.

4.2. Data Acquisition and Methodology

A number of papers have evaluated meteorological circumstances (Arkian et al., 2016; Delju et al., 2013; Fathian et al., 2014). One of these studies investigated the climate of the Urmia Lake region by using data from four meteorological stations in the watershed (Fathian et al., 2014). The paper shows a correlation of 0.69 between change in annual rainfall and lake level over the period 1965 to 2010, suggesting that precipitation has played an important role in the documented decline of the lake.
4.2.1. Precipitation

This study uses Global Precipitation Climatology Center (GPCC) precipitation data obtained from rain gauges for analysis of climate change. The hydrological model explained in Chapter 5, uses the same precipitation dataset for the simulation of hydrological parameters. GPCC mainly consists of the three global precipitation products, the monitoring product, the full data product (V7) and the first guess with various spatial resolutions. This study uses the Full Data Product (V7) of the GPCC dataset for the Lake Urmia region for the study period of 1980 to 2010 with spatial resolution of 0.5° x 0.5°. The GPCC precipitation data was preferred over the weather station data mainly because of its spatial distribution. The weather station data obtained from the Iran Meteorological Organization consisted data from merely 4 weather stations. Figure 10 shows the average precipitation data of Lake Urmia region obtained by GPCC for years 1980 to 2010.

4.2.2. Temperature

The temperature data used in this analysis is from 4 weather stations in the Lake Urmia watershed, namely Tabriz, Urmia, Maragheh and Sarab for the period of 1980 to 2007. This data was provided by Iran Meteorological Organization. The station records extend much further back in time, but most of those we were able to obtain extend only to 2007.
Figure 10 - The seasonal cycle of mean precipitation (mm/month) from 1980 to 2010 (top) and annual precipitation (mm/year) time series (bottom) over Lake Urmia’s catchment, as estimated from GPCC data.
4.2.3. Drought Analysis

The precipitation and temperature data is analyzed for any significant change in its long term trend. Drought analysis is done using Standardized Precipitation Index (SPI) (Mckee, Doesken, & Kleist, 1993). The SPI is based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of timescales. The ability to examine different timescales also allows droughts to be readily identified and monitored for the duration of the drought. Calculation of the SPI for a specific time period at any location requires a long-term monthly precipitation database with 30 years or more of data. The probability distribution function is determined from the long-term record by fitting a function to the data. The cumulative distribution is then transformed using equal probability to a normal distribution with a mean of zero and standard deviation of one, so the values of the SPI are really in standard deviations. These time scales reflect different water resources. In this study the SPI was calculated 12-month time scales, which correspond to the past 12 months (i.e. annual) of observed precipitation totals respectively. The SPI is defined for each of the above time scales as follows:

\[ SPI = \frac{x_i - \bar{x}}{s} \]

Where \( x_i \) is the monthly rainfall amount, \( \bar{x} \) is the mean of rainfall and \( s \) is the standard deviation of rainfall calculated from the whole time series of monthly values.

4.3. Results and Discussion

Figure 10 (top) shows seasonal cycle of mean precipitation (mm/month) from 1980 to 2010, as obtained from GPCC data for the Lake Urmia region. Maximum precipitation over the region occurs in April, and the region is nearly rainless from June to September. Figure 10 (bottom) shows
annual precipitation (mm/year) time series from 1980 to 2010 over Lake Urmia’s catchment, as obtained from GPCC data. The overall trend line indicates a decreasing trend for annual precipitation during the study period. The maximum annual precipitation over the region occurred in 1993 and 1994 of about 612 mm and 605mm respectively. It was followed with a severe reduction up to 303mm in the year 1999. The region has received a spell of low rainfall in the range of 300 – 400 mm/year during the study period, with the major ones in 1983, 1989, 1999 and 2008.

The SPI on the other hand shows severity of these low rainfall events compared to the long term average rainfall over the Lake Urmia region. Figure 11 shows the SPI computed for the 12 month time scale for this region. The SPI values indicate that the rainfall event during the period from 2008 to 2009 was the most severe drought event of the entire study period with an index of -2.6. The second most severe drought event occurred during the year 1999 and lasted for 4 years till the end of 2002.

To compare the changes in the climate with the depletion of Lake Urmia, the parameters were normalized and plotted as a time series. Figure 12 shows the comparison of time series normalized Lake Urmia level and climatic parameters such as average precipitation and temperature of the watershed. One can conclude from Figure 12 that lake level is sensitive to the climatic factors to quite an extent till 2000. Similar trend change is observed in the lake level and precipitation till the one of the major drought of the region in year 2000. After year 2000, the trend of lake level keeps of declining even after a significant increase in precipitation. This suggests that Lake Urmia water level was governed by the climate over the region only till the year 2000 and later it mzy have shifted to some other factors, for example, anthropogenic activities.
Figure 11 - SPI values calculated for the 12-month time scale plotted with annual precipitation for Lake Urmia Region.

Figure 12 – Annual Normalized time series of average precipitation and temperature of Lake Urmia watershed and Urmia Lake level with shaded area highlighting the major droughts during the period of 1980 to 2010.
Overall, the results indicate that Lake Urmia region has been suffered a number of drought events during the study period of 1980 to 2010. Even though there is no significant trend in these drought events, their severity combined with the less annual precipitation in the latter years seems to be enough to create a water scarcity problem in the Lake Urmia region. The lake level appears to be governed by the precipitation over the region only till year 2000 and after that it shows very less correlation with rainfall trend indicating the dominance of other governing factors. This water scarcity problem apparently introduced by the droughts, will build up if there is a corresponding increment in the water demand, causing major depletion in the surface water resources in the region. The increase in water demand in terms of agricultural demand is studied in the next chapter using the land use land cover change approach.

If significant land use land cover change is observed in the region, then it can explain the sudden intensification of droughts in the Lake Urmia region. Due to the radiative effect of addition of CO\textsubscript{2} in the atmosphere, the increase in temperature and the corresponding drought can be explained. But to exactly quantify the cause of this climate change, intensive climate modeling is required.
Chapter 5.

LAND USE / LAND COVER CHANGE

A limited amount of global historical land use data over long time periods is available due to the lack of historical data sources. To fully understand the development of anthropogenic activities in the Lake Urmia watershed, a land use land cover map of the watershed is essential. Historical trends in LULC change can be linked to a variety of physical (e.g. urban areas) and socioeconomic (e.g. population) indicators. In this study, Landsat imagery is used to create historical land use maps, from which impacts on hydrologic response and changes in anthropogenic activity over the study period can be inferred. Depending on data availability, images dating back to the 1980s were desired in order to correspond to the time period considered in the hydrological model explained in Chapter 4 (i.e. 1979-2010). This final LULC data can also serve as a basis for predicting future LULC change, and to understand associated implications on the environment.

5.1. Data Acquisition

Historical land use change is generally strongminded by the use of remote sensing and then GIS is employed for further spatial analysis (Hudak & Wessman, 1998). Many studies have utilized the Landsat data to generate historical land use maps and study the environmental consequences of LULC change (Alves et al., 1996; Comber, Fisher, Brunsdon, & Khmag, 2012; Congalton, Oderwald, & Mead, 1983; Rhemtulla, Mladenoff, & Clayton, 2007; Valeriano et al., 2004; James E Vogelmann et al., 2001). The earliest Landsat data available is for the year 1972. There have been a total of eight Landsat satellite missions, out of which only seven were functioning.
Figure 13 – Landsat Mission timelines

The land use change analysis in this study is done on the Imagery obtained from Landsat 5 TM and Landsat 8 OLI. All the imagery used in this project were downloaded from the Earth Explorer tool of United State Geological Survey. In all, eight images were required for each year to cover the entire Lake Urmia watershed. The path and row details of the Landsat imagery used in this study is given in Figure 14. Due to limited data availability and high number of images per year, LULC maps for the years of 1987, 1998, 2006, 2011 and 2016 were produced. Landsat 5 TM imagery was used for the years 1987, 1998, 2006 and 2011, and Landsat 8 OLI for 2016. As this study is more focused on the agricultural land cover in Lake Urmia basin, the cropping pattern becomes an important factor in terms of accuracy. To accommodate the cropping pattern changes, the Landsat imagery was obtained only for the month of September, which is the start of the harvesting season of the Urmia region. As the extents of the historical images do not align with watershed boundary, preprocessing of the imagery was required.
Figure 14 – Path and row details of the Landsat Imagery used in this study along with the Lake Urmia Watershed boundary (black line)

5.2. Data Processing

The Landsat data acquired from the Earth Explorer were raw images which contained the data of intensity of electromagnetic radiation (ER) from each spot viewed on the Earth’s surface as a Digital Number (DN) for each spectral band. The range of DN’s for Landsat TM is 0 to 255. Preprocessing of the raw imagery is required before doing any kind of analysis based on it. To make the DN data comparable with each other, they are converted to Radiance. In order to make a meaningful measure of radiance at the Earth’s surface, the atmospheric interferences must be
removed from the data using the process called “atmospheric correction”. The spectral radiance of features on the ground are usually converted to reflectance, because spectral radiance depends on the degree of illumination of the object. Thus spectral radiances will depend on factors such as time of day, season, latitude, etc. Since reflectance represents the ratio of radiance to irradiance, it provides a standardized measure which is directly comparable between images. This entire process of converting digital number data to ground reflectance is called Radiometric Correction or Radiometric Calibration.

Digital Numbers can be converted to radiance using the gain and bias values provided in the metadata file of the Landsat imagery. The data required for the conversion of radiance to surface reflectance are mean solar exo-atmospheric irradiances, solar zenith angle and earth-sun distance on the day the image was captured.

Although the images were now atmospherically corrected, converted to surface reflectance and are spatially connected, a physical permanent join of the rectified images has not yet occurred. This can be done by mosaicking them together. As each image is unique in its own way, unsupervised classification of the pixels were done prior to mosaicking them. The images containing the major parts of the watershed were given the first preference. Once all the images were mosaicked, they were clipped using the watershed boundary of Lake Urmia. This was completed in ArcMap. The example of this process is shown in Figure 15.
Figure 15 – Mosaic of Landsat Imagery of year 1987 of the Lake Urmia region (top), clipped to Lake Urmia Watershed (bottom)
5.3. Methodology

The pixels in the Landsat imagery can be classified using its spectral signature. Every land cover type has its unique spectral signature in terms of reflectance. There are two main classification strategies, supervised classification and unsupervised classification. Supervised classification involves creating classes based on the user knowledge of the study area, and creating training data consisting of certain spectral combinations, or signatures, associated with each desired class. Every pixel in the image is then compared to the training data and assigned to the appropriate class (Lillesand & Kiefer, 1994). Whereas, in the unsupervised classification is suitable for areas where user is not so familiar with the study area. The image pixels are clustered into a set number of classes according to their similarity in terms of their spectral signature (Lillesand & Kiefer, 1994). Each cluster then can be assigned to a specific land cover type depending on their reflectance values. Both of these methods can be applied using different algorithms. Commonly used algorithms for supervised classification are Parallelepiped, Minimum distance to means, Maximum likelihood and Spectral angle mapping. Examples of unsupervised classification algorithms are ISODATA and K means.

The ISODATA algorithm evenly places centroids for the specified number of clusters and then pixels in the image are assigned to the cluster for which the mean vector is closest. Mean vectors are then recalculated for each of the clusters. These revised means are used to reclassify the data and the process repeats itself until there is no significant change in the location of the class mean vectors. K means algorithm uses the same process, but initial placing of the centroids of the specified number of clusters is random. Due to this, the clusters resulted from K means algorithm differ a little, every time one runs it.
The primary advantage of the unsupervised method is removal of bias associated with forcing the classification into predetermined classes, thereby allowing an increased opportunity to identify all spectrally distinct classes. Therefore, this study was conducted using unsupervised classification with the ISODATA algorithm. For each Landsat scene, the ISODATA algorithm was run initially with 250 clusters. These clusters were then merged together to form 7 classes of water, shallow water, natural vegetation, clouds, cropland, bare soil and urban areas. The classified Landsat scenes of each study year were then mosaicked together and finally clipped with the watershed boundary to get the final classified images of Lake Urmia watershed.

Due to the lack of field data for the accuracy analysis of the above performed classification, reference data was obtained from Google Earth. Random points were created and assigned to the 7 classes using the high resolution imagery in Google Earth. The number of sites in each class does have an effect on how well accuracy can be determined. To avoid this bias, each class of the reference data comprised 0.001% number of points as that of the original classified class. Accuracy was measured for each classification using a statistical analysis software package in ENVI that performs a pixel-by-pixel comparison of the classified data with the reference data. The result is a confusion matrix, which identifies percentage correct, errors of commission (pixels assigned to a specific class to which they do not belong) and errors of omission (pixels that should have been assigned into a specific class and were not). In addition to a standard pixel-by-pixel accuracy assessment, the KHAT, or Kappa, statistic was also calculated which is proven to be a strong estimator of classification accuracy (Conese, Maracchi, & Maselli, 1993; Stehman, 1996; J E Vogelmann, Sohl, & Howard, 1998).
5.4. Results

In this study, historical land use and land cover of the Lake Urmia basin was mapped employing Landsat digital satellite data. A total of eight Landsat scenes per study year were classified using the unsupervised approach by ISODATA algorithm. The methodologies employed have resulted in the production of LULC maps of Lake Urmia watershed with a resolution of 30m for the years of 1987, 1998, 2006, 2011 and 2016. The results of each image classification indicate that the Lake Urmia watershed is composed of the six major land cover types namely water, shallow water, natural vegetation, cropland, bare soil and urban region. Figure 18 shows the final classified imagery of the Lake Urmia basin for each study year.

To determine the accuracy of the above mentioned land use land cover classification results, a confusion matrix with pixel-by-pixel comparison of reference data was adopted. In addition to this comparison, the Kappa co-efficient was also calculated to add further confidence in the classification results. The overall accuracy of the classification performed for the study year of 2016 was found to be about 82% with a kappa co-efficient of 0.76. Table 4 shows the confusion matrix derived from the reference data obtained from Google Earth. The accuracy assessment was only done for one year due to data constraints. As the same classification technique was used for the study areas, the accuracy for the rest of the years is likely to be somewhat similar to that of 2016.
Table 3 – Confusion matrix for the Landsat classification of Lake Urmia watershed for the year 2016

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
<td>Soil</td>
</tr>
<tr>
<td>Water</td>
<td>184</td>
<td>0</td>
</tr>
<tr>
<td>Soil</td>
<td>36</td>
<td>312</td>
</tr>
<tr>
<td>N. Veg</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Farms</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Urban</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>248</td>
<td>354</td>
</tr>
<tr>
<td>Producer's Accuracy</td>
<td>74.19%</td>
<td>88.14%</td>
</tr>
</tbody>
</table>

The final classified maps were used to get the transition of land cover into different classes. As this study is more focused on the change in cropland and water class, the transition and change only in these classes was studied. The main transition in Lake Urmia basin was water to bare soil, i.e. the drying up of Lake Urmia. Almost 86% of the lake area transitioned to bare soil from the year 1998 to 2016. The lake area was at peak in 1998 due to high rainfall activity in the region. Figure 17 shows the trend of change of Lake Urmia during the study period. The transition of natural vegetation to cropland and bare soil to cropland was second to the water class. Table 4 shows the quantification of each LULC class in terms of sq. km in Lake Urmia basin. The area occupied by the clouds is not included in Table 4. The cloud cover was more in the images of 1987 and 1998 compared to the latter years. Figure 16 provides a graphical representation of the changes in each LULC class from 1987 to 2016.
Table 4 - Area in sq. km covered by each generalized LULC type over historical period in Lake Urmia Basin.

<table>
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<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4990</td>
<td>5545</td>
<td>4139</td>
<td>2623</td>
<td>1233</td>
</tr>
<tr>
<td>Vegetation</td>
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<td>1660</td>
<td>1458</td>
<td>1820</td>
<td>1807</td>
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<tr>
<td>Agricultural Land</td>
<td>1565</td>
<td>1919</td>
<td>2283</td>
<td>2458</td>
<td>3102</td>
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<tr>
<td>Bare Soil</td>
<td>43537</td>
<td>42511</td>
<td>43680</td>
<td>44589</td>
<td>45295</td>
</tr>
<tr>
<td>Urban</td>
<td>133</td>
<td>186</td>
<td>260</td>
<td>321</td>
<td>372</td>
</tr>
</tbody>
</table>

Figure 16 – Graphical representation of land cover change in Lake Urmia basin from 1987 to 2016
Figure 17 - Graphical representation of the changes in Lake Urmia area derived using Landsat classification from 1987 to 2016
Figure 18 - Landsat land cover classifications of Lake Urmia watershed for each study year
As seen in Table 4 (Section 3.4), the both Cropland and Urban class shows a steep positive trends in the period of 1987 to 2016. This change is directly connected to the anthropogenic activities in the Lake Urmia watershed. Urban developed land in Lake Urmia watershed has transitioned from the lowest LULC type within the watershed at 132 sq. km in 1987, with an increment of approximately 180%, to 372 sq. km at present. This drastic conversion of LULC caused a similar increment of 98% in the agricultural land in the watershed.

5.5. Validation with other available LULC datasets

The main advantage of the land cover dataset obtained from this study is the resolution. The region under study is a part of a number of global land cover datasets. But most of them are of coarse resolutions in the range of 500m to 2.5 degrees. For example, MODIS land cover dataset (MCD12Q1) provided on https://lpdaac.usgs.gov has a resolution of 500m. The scheme used in this product uses 17 LULC types introduced by International Geosphere Biosphere Program (IGBP). These 17 land cover types consists of 11 natural vegetation classes, 3 mosaicked land classes, and three non-vegetated land classes. Specifically, the cropland class data from the MODIS dataset was used for the following analysis. Another widely used LULC map is the Global Map of Irrigated Areas, the first raster dataset showing the percentage area equipped for irrigation in 0.5°x 0.5° cell area (Döll & Siebert, 1999). This map was later improved with a higher resolution of 5’ x 5’ for 2000. The Global Irrigated Area Map (GIAM) (Thenkabail et al., 2009) produced by the International Water Management Institute (IMWI) using a multi-resolution blend of satellite observations, climate and topography data. It used unsupervised classification technique with some post-classification refinement to obtain the final map of fractional irrigated areas for each cell.
Another similar global cropland dataset is HYDE 3.1 (Klein Goldewijk, Beusen, Van Drecht, & De Vos, 2011). HYDE stands for History Database of the Global Environment. HYDE is not a remote sensing dataset. The land cover is populated using the country statistics and population distribution. HYDE 3.1 provides estimates of agriculture area, livestock numbers, and fertilizer use and food consumption for the period of 10,000 BC to 2000 AD at a resolution of 5’.

A few of the global land cover datasets namely, MODIS land cover product, Global Irrigated Area Map and HYDE 3.1 is used to validate the land cover classification of Lake Urmia watershed done in this study. As the temporal span of all these datasets vary from the study years used in this study, the results are validated using the data of the closest year available. The classification results of the year 1987 are compared with HYDE 3.1 dataset of 1990, whereas to validate the results of 2006, MODIS land cover product of 2006 is used. Similarly the classification of 2011 is validated using the dataset of IMWI-GIAM.

Visual comparison of the Figure 19, Figure 20 and Figure 21, one can conclude that the unsupervised classification results displayed in the Figure 18 is fairly accurate. The cropland class from the classification fairly coincides with the above mentioned land cover datasets. The actual values of the class area may differ to a great extent though. This primarily is because of the difference in the resolution of these datasets. Also, the irrigated area land cover type from IMWI GIAM exactly coincides with the cropland class of the Landsat classification. Using this similarity as a base, it should be safe to conclude that almost all the croplands in the Lake Urmia watershed are irrigated.
Figure 19 – Validation of Landsat classification of year 1987 using HYDE 3.1 dataset of year 1990 showing the irrigated area in each grid cell
Figure 20 - Validation of Landsat classification of year 2006 using MODIS Land cover dataset of year 2006
Figure 21 - Validation of Landsat classification of year 2011 using IMWI GIAM dataset of year 2010.
5.6. Discussion

The Landsat classification results explained earlier shows a major decline in the class of water comprising of all the surface water in the Lake Urmia watershed and a steady increase in the classes of agricultural land and urban areas. The decline in surface water in Lake Urmia basin is found to be about 77% with a corresponding decline of 86% in Lake Urmia itself between the years of 1987 and 2016. This declination rate is found to consistent with rate reported through other studies (AghaKouchak et al., 2015). As far as agricultural land is concerned, it shows an increment of about 98% with corresponding increase of 180% in urban areas. These statistics definitely suggests a considerable amount of anthropogenic activity in Lake Urmia basin during the study period.

This increase in agricultural areas and the need to satisfy the water demand, lead to the development of many water resources management projects consisting of dams and diversion structures in the watershed. As reported by Hassanzadeh et al., 2012, they studied in all 275 projects in the year 2012, out of which 231 were to be constructed in the near future. These projects consisted of 71 reservoir dams, 124 weirs and conduction facilities, 17 pumping stations and 10 flood controlling and artificial feeding. Until 2006, these water management projects had a capacity of 1712 MCM, which would increase to 3869 MCM in the next 20 years, in return affecting the major source of water to Lake Urmia.

Given the quantity of water stored in dams and reservoirs, the streamflow in the watershed is bound to show a dramatic alteration. The change in streamflow and the terrestrial water storage in Lake Urmia watershed is modelled and presented in Chapter 6.
Chapter 6.

HYDROLOGICAL MODELING USING HiGW-MAT MODEL

6.1. Introduction

Terrestrial water storage (TWS), is the sum of soil moisture, groundwater, snow and ice, water in biomass, and surface water in lakes, reservoirs, wetlands and river channels, in short measure of all the water in the grid cell. It plays a significant role in the climate system, primarily through the water and energy processes at the land surface, by controlling the partitioning of precipitation. The Gravity Recovery and Climate Experiment (GRACE) mission (Tapley, Bettadpur, Ries, Thompson, & Watkins, 2004) has provided us with the data of global TWS changes. As GRACE only measures TWS and not individual TWS components, hydrological modeling becomes a valuable tool for partitioning TWS into individual storage components. More recently, detailed evaluations of simulated river discharge and TWS variations over large global river basins were conducted using the human impacts and GW scheme in the MATSIRO model and demonstrated that HiGW-MAT simulates river discharge reasonably well in the selected global river basins (Koirala, Yeh, Hirabayashi, Kanae, & Oki, 2014; Y. Pokhrel et al., 2012, 2015). Using the same model and approach, in this study, we investigate the temporal variations of TWS and its streamflow component by using the hydrologic modeling approach through HiGW-MAT model over Lake Urmia region. The simulated TWS is compared to GRACE data from 2002 to 2010. The river flow component of TWS variations is compared to using streamflow data from Hassanzadeh et al., 2012.
6.2. Model Introduction

HiGW-MAT (Y. Pokhrel et al., 2015) incorporates the human impact (Hi) and a groundwater pumping scheme (GW) into the well-known process based LSM, Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) (Takata et al., 2003). MATSIRO is the LSM part of the global climate model (GCM) MIROC (Model for Interdisciplinary Research on Climate) which computes biophysical changes. MATSIRO is a compilation of models developed by Watanabe, 1994; Collatz, Ball, Grivet, & Berry, 1991; Richards, 1931 and Beven & Kirkby, 1979. The model also uses the river routing model Total Runoff Integrating Pathways (TRIP) (Oki & Sud, 1998).

Initially, the H08 model developed by Hanasaki et al. (2008) simulated both natural and human impacted flows of water globally, with the use of a simple bucket model to simulate the land surface components. HiGW-MAT is derived using a similar approach as that of H08. It replaces the simple bucket model with a process based LSM (MATSIRO) and also overcomes some drawbacks of both the H08 and MATSIRO models by adding the TRIP model for river routing along with a new irrigation scheme. The four anthropogenic water regulation modules derived from H08 model are also incorporated in the framework of MATSIRO-TRIP. The four modules included in the human impact module are namely, crop growth module, reservoir operation module, water withdrawal module and environmental flow module. Each of these modules are described in detail in the following sections.
6.3. Module Description

Human impacts and groundwater in MATSIRO model (HiGW-MAT), as the name suggests, it mainly consists of two modules, the Human Impact module and Groundwater pumping scheme.

6.3.1. Human Impact

The main human impact module represents the various water related human activities. It is divided in four sub-modules according to the activities that affect the water cycle in a considerable way. These are namely, crop growth and irrigation, reservoir operation, water withdrawal, and environmental flow requirements. The crop growth module is derived using the vegetation formulations and parameters from the Soil and Water Integrated Model (SWIM) (Krysanova,
Müller-Wohlfeil, & Becker, 1998). Irrigated area data from Döll & Siebert, 1999 developed Global Map of Irrigated Areas is used for the estimates of cropping period through SWIM. Further the crop growth module also simulates the crop calendar using climate parameters such as down welling shortwave radiation, air temperature, and the actual and potential evapotranspiration. Evapotranspiration and other energy balance terms are calculated through MATSIRO, and all these components along with the climate parameters are used to calculate potential evapotranspiration externally using FAO Penman Monteith method (Penman, 1948) which is not a part of original MATSIRO model. Every grid cell is divided into two sections, irrigated and non-irrigated. For the irrigated region, the model estimates the irrigation water demand using the soil moisture deficit, i.e. the difference between the target soil moisture content (TSMC) and the actual soil moisture content. Irrigation demand is calculated in each time step as,

\[ I = \frac{\rho_w}{\Delta t} \sum_{k=1}^{3} (\max[(TSMC - \theta_k), 0]D_k) \]

Where \( I \) (kg m\(^{-2}\) s\(^{-1}\)) is the irrigation demand, \( TSMC = \alpha X \theta_s \), \( \rho_w \) (kg m\(^{-3}\)) is the density of water; \( \Delta t \) is the model time step; \( \theta_s \) and \( \theta_k \) (unit less) are the soil porosity and simulated actual soil moisture content, respectively; and \( D_k \) (m) is the thickness of kth soil layer from the land surface.

The \( \alpha \) is set at 1 for rice and 0.75 for the other crops.

The other three sub-modules of reservoir operation, water withdrawal, and environmental flow requirements are a part of the river routing scheme. The water withdrawal which is a sum of all the demands including agricultural, domestic and industrial, runs for every grid cell. The agricultural water demand is basically the simulated irrigation demand whereas, the domestic and industrial demands are used from Hanasaki et al., 2008. The reservoir operation module is adopted
from Naota Hanasaki, Kanae, & Oki, 2006. This module uses global water withdrawal information to set the three monthly reservoir operating rules viz. the annual total release for the following year is provisionally targeted to reproduce inter-annual fluctuations in release; for each month, the release is provisionally targeted, accounting for storage, inflow, and water demand along the lower reaches, to reproduce monthly fluctuations in release; and the targeted annual total and monthly releases were combined to determine each monthly release. The environmental flow requirement is estimated using the algorithm from Shirakawa, 2004.

6.3.2. **Groundwater pumping scheme**

The groundwater pumping scheme is basically a water balance performed at each grid. It estimates the total amount of water withdrawn from the aquifer based on the surface water deficit, which is the difference between the total water demand and the surface water available in the grid cell. The GW pumpage/withdrawal is estimated as,

\[
GW_{pt} = CWU_d + CWU_i - WS_{riv} - WS_{Mres}
\]

Where \(GW_{pt}\) is the total groundwater pumpage, \(CWU\) is the consumptive water use for agriculture, domestic and industrial and \(WS\) is the water supplied by rivers and medium reservoirs respectively. Consumptive water uses domestic and industrial are set to 10% and 15% of total water use, respectively. Using this GW pumping, one can easily derive the dynamics of groundwater table using a water balance.

6.4. **Model Inputs and Forcing Data**

The newly developed model in the fully integrated mode (a schematic is shown in Figure 22) simulates surface and subsurface water flows by taking into account the processes of runoff
routing, reservoir operation, irrigation, water withdrawals, environmental flow requirements, ground water table dynamics, and well pumping. The simulation is conducted at 1° x 1° spatial resolution and at hourly time step. The model was run for 31 years from 1979 to 2010 with a sufficient amount of years for spin up (>100) with repetitive forcing data and no human impact scheme. First 1 year of simulation results are discarded to allow the adjustment of state variables in the model. Thus, the results from 1980 to 2010 are used for the analysis of Lake Urmia.

The climate forcing data used to run the model is based on six hourly data from Kim, Yeh, Oki, & Kanae, 2009, which is based on atmospheric reanalysis data provided by Japanese Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS). The gridded irrigated areas of 1° x 1° spatial resolution are adopted from Global Map of Irrigated Areas (GMIA) (Siebert, Döll, Feick, Hoogeveen, & Frenken, 2007).

The GRACE data is used to validate model simulated long-term trend of TWS change as well as the seasonal cycle of TWS variations. We used spherical harmonic GRACE solutions of equivalent water height thickness from JPL (which are available for download from JPL website; http://grace.jpl.nasa.gov/data/get-data/) for model evaluation and to characterize the uncertainty within the three GRACE products. Corrections and adjustments are needed to reduce noise and isolate the TWS changes from GRACE signals. The GRACE data from aforementioned sources was already corrected including atmospheric mass changes removal, glacial isostatic adjustment (GIA), truncation of spherical harmonic coefficients, and application of de-striping filter alongside with a 300-km Gaussian smoother. Since the data are in 1 degree resolution with varying grid cell area, an area-weighted arithmetic mean was calculated as:

\[ H(x, t) = \frac{\sum_{i=1}^{n} S_i(x, t)}{A}, \quad S_i = \begin{cases} 1 & x a_i x s, \quad \text{inside the basin} \\ 0, \quad \text{outside the basin} \end{cases} \]
Where $s$ is the LSM or GRACE estimate, $a_i$ is the cell area, $S_i$ is the weighted estimate for each cell inside the basin, $n$ is the number of cells in a basin, $A$ is the total area of the basin, and $H(x, t)$ represents the estimate of water storage for basin at time.

### 6.5. Model Results & Discussion

The LULC classification results from Chapter 4 shows considerable amount of anthropogenic activity. This anthropogenic activity in Lake Urmia basin is mostly in terms of agricultural activities and water resource management activities like construction of water retaining structures to satisfy the increasing irrigation demand. For the attribution of the depletion in Lake Urmia to anthropogenic activities, we use the hydrological modeling approach by studying the result of land surface model with a capability of assessing anthropogenic activities, called Human impact and Groundwater in MATSIRO (HiGW-MAT).

The HiGW-MAT model estimates Terrestrial water storage (TWS) at a $1^\circ \times 1^\circ$ spatial resolution along with the individual storage components of TWS. The model results, specifically TWS changes over Lake Urmia watershed, are validated using the GRACE data from JPL. According to the spatial resolution of the model and watershed area of Lake Urmia, the results of a total 16 grids are used in this study. Figure 23 shows these grids comprising of Lake Urmia watershed.
Even though, Lake Urmia watershed can be fitted in 14 grids, we used 16 grids to capture the TWS variations over the region surrounding region as well to get a better validation with GRACE data. Figure 24 shows the comparison of anomalies of GRACE data obtained from JPL and the simulated TWS variations from HiGW-MAT. As you can see from the figure GRACE data had some gaps in the years of 2002 and 2003.
Figure 24 – Validation of simulated TWS anomalies from HiGW-MAT with TWS anomalies obtained from GRACE for the period of 2002 – 2010

Figure 25 – Comparison of seasonal dynamics of TWS from HiGW-MAT model and GRACE data

It is evident from the figure that the model captures the long-term trend of TWS fairly well with good agreement for most years with certain underestimations and overestimations during a few
years. The results for the preceding years could not be validated due to the lack of TWS data or any other data before the year 2002. Figure 25 shows a pretty accurate comparison of seasonal TWS variations from GRACE and the model simulations. The underestimations and overestimations observed in Figure 24 could be because of the GRACE footprint. The GRACE footprint is of about 200000 sq.km to obtain fairly accurate of TWS variations. As the area under study is of about 158000 sq.km, it could have introduced underestimations and overestimations observed in Figure 24.

The TWS variations in the entire study period (Figure 26) show an increase till year 1990, then a sudden decrement in the year of 1991 due to reduced precipitation. In 1995, the trend shows the highest amount of TWS over Lake Urmia watershed, which corresponds to the highest precipitation during the study period. In the later years, the TWS over the region keeps on
decreasing, except for a small increment in the year 2003 corresponding to increased precipitation. Overall, for the entire study period the TWS shows a decreasing trend of 0.32 km$^3$/year.

To further add confidence in the model results, we compare the river flow obtained from model to the streamflow obtained from Hassanzadeh et al., 2012. This research paper quantifies inflow to the Lake Urmia using a simple lake water balance. Figure 27 shows the comparison of simulated river flow and the streamflow data. The model simulates river flow in Lake Urmia basin accurately for the study period of 1979-2010. The primary objective of this comparison is to ensure that model simulates the river flow within the plausible limits for the Lake Urmia watershed. It should be noted that the streamflow is not actually measured, but the results of a water balance done by Hassanzadeh et al., 2012.

![Figure 27 – Validation of simulated river flow using the streamflow data from Hassanzadeh et al., 2012 with shaded area highlighting the major droughts.](image-url)
From Figure 8 (bottom), we know that during the study period the lake has lost water on an average rate of 0.6 km$^3$/year, whereas the simulated rate of water loss of the entire basin is much less, namely 0.32 km$^3$/year. As Lake Urmia is a major body of the watershed, these results indicate that the lake is somehow losing water to the watershed at a rate of about 0.28 km$^3$/year. In other words, the watershed is storing 0.28 km$^3$ of water somewhere other than the lake every year. The possible reasons for this trend behavior might be because of an increased leakage of lake water to the underlying aquifer or the ongoing water resources management activities in the watershed, namely dams and reservoirs. The increased leakage to the aquifer occurs as the groundwater level becomes lower than its normal level, increasing the hydraulic head difference between the lake and the groundwater table and corresponding groundwater flow. If this is the case, then groundwater table should show a slight and steady positive trend. However, as we do not have any groundwater data, we cannot validate this scenario. On the other hand, any water management activity like dam construction or diversion of surface water for irrigation purposes would prevent a normal inflow into the lake, causing lake depletion. This seems to be the most probable case given the rate of depletion and the increase in agricultural activity in the watershed. Storing water behind dams can explain the water surplus outside the lake and also can describe the extra acceleration of water loss inside the lake due to a reduction of lake inflow. The water scarcity problem caused by the recent droughts over this region may have amplified the depletion rate. To test this hypothesis, the streamflow data with and without human impact from the HiGW-MAT is used to examine the difference in streamflow caused by anthropogenic activity.

After getting assurance that the model simulates river flow for the Lake Urmia region in the plausible limits, to interpret the anthropogenic impact on Lake Urmia, we compared the river flow obtained from model simulations with no human impact and with human impact. In other words,
river flow under natural condition is compared with human impacted condition. Figure 28 shows the comparison. As surface water inflow is one of the major water source of Lake Urmia, the difference in inflow between the natural and human impacted condition can be used to quantify the anthropogenic impact on the lake. The figure shows considerably less river flow from the human impacted condition than under natural condition.

Figure 28 – Comparison of simulated river flow in Lake Urmia watershed under natural condition and human impacted condition

The difference in streamflow with and without human impact is found to be higher in the years after 1998, corresponding to the increased anthropogenic activity in the watershed. The streamflow appears to be governed by the changes in rainfall in the first two decades and later mostly by anthropogenic activities. In the early years, the difference is found to be minimal indicating less anthropogenic activities compared to current year in the Lake Urmia area. The average difference between the streamflow with and without human impact is found to about 2.66 km³/year after the year of major drought, 1998.
This difference in streamflow can be connected to the increase in water resource management activities in the watershed. The increasing number of water retaining structures in the watershed are storing more water every day, hence decreasing the inflow to Lake Urmia. The capacity of all the water retaining structures under operation in 2006 was about 1712 MCM (Hassanzadeh et al., 2012) which can explain the surplus water outside the lake, the extra acceleration of water loss inside the lake and also describes the decrease in streamflow in the watershed.
Chapter 7.

CONCLUSIONS

The thesis investigates the possible causes of Lake Urmia depletion by examining the climatic and anthropogenic factors in its watershed. The investigation is done using a variety of approaches such as climate change, land use land cover change and hydrological modeling with human impact capabilities, namely HiGW-MAT. We have combined, for the first time, the results from land surface model with human impact capabilities and high resolution land use land cover change map together with in situ and satellite monitored hydrological fluxes to investigate and attribute the causes of Lake Urmia depletion due to anthropogenic and climatic factors for the period of 1980 to 2010.

Our results show that the Lake Urmia region has been hit by severe droughts during the study period. One of the major drought of the region during the study period had a Standardized Precipitation index of -2.6 occurred recently in 2008. Even though the droughts do not have a significant trend, their severity alone was enough to create a water scarcity problem in the region. Droughts combined with the increase in agricultural land and urban areas in the watershed, the scarcity problem was amplified, creating a need for water resource management projects in the area. The increasing demand for food is achieved by the horizontal development of agricultural areas in the region as discussed earlier. The land use land cover analysis shows an increase of 98% in the area of cropland and 180% in the urban areas, indicating a rise of anthropogenic activities in the watershed.
Our results from the hydrological modeling reveal that, the water storage in the entire basin has a decreasing trend of an average of 0.32 km$^3$/year, whereas the lake, a major water body in the basin, shows a declining trend of 0.6 km$^3$/year, which indicates that the watershed is gaining water from the lake. We have discussed two possible scenarios for this result, namely leakage into the underlying aquifer and reduction in the streamflow in the lake due to water retaining structures. Both of these scenarios with anthropogenic influence explains the role of humans in the desiccation of Lake Urmia. Due to the lack of sufficient groundwater data, the validation of the first hypothesis was not done, but for the later one, the output of the hydrological model was used. The simulated streamflow with and without human impact showed an average of difference of 2.66 km$^3$/year after the year of one of the major drought, 1998.

We conclude, that the desiccation of Lake Urmia has been occurring due to a chain of reasons, which are highly influenced by anthropogenic activities. One can imagine that the rate of groundwater extraction and storing water behind the dams correlate with water availability over the region, which has been considerably high compared to the amount of rainfall received by the region. According to the results obtained from this study, the drought in 1998 was the turning point, causing an increased extraction of groundwater and led to keeping water behind the dams, which led to streamflow leading to a negative balance in the hydrological input, which, in the end, caused a negative trend in the storage of Lake Urmia.
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