CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Tropical AgriSciences

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Lake Urmia - mitigation of water loss impact

BACHELOR THESIS

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BACHELOR THESIS ASSIGNMENT

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Thesis title

Lake Urmia – mitigation of water loss impact

Objectives of thesis

The Aim of this bachelor thesis is to describe issues occurring in and around hypersaline Lake Urmia, that are caused by loss of water in the Lake. And consequently the main aim is to design appropriate technology or strategy ,which should solve or at least reduce impact of the water loss in the lake, according to the local environmental conditions and also to give a brief summary of already proposed solutions and preventive measures for this lake and nearby area which should be used mainly for the benefit of the population.

Methodology

The information in this bachelor thesis rests upon the analysis of the available data from scientific databases, mainly in the form of scientific periodicals and papers in English. The used databases: Web of Science, Science direct and Google scholar. A systematic literature review is also performed using relevant textbooks and bibliographies.

The proposed extent of the thesis

30-40 pages

Keywords

Lake Urmia, environment, water treatment

Recommended information sources

Jalili, S., Hamidi, S. A., & Ghanbari, R. N. 2015. Climate variability and anthropogenic effects on Lake Urmia water level fluctuations, northwestern Iran. Hydrological Sciences Journal:1–11. DOI: https://doi.org/10.1080/02626667.2015.1036757

Mardi A.H., Khaghani A., MacDonald A.B., Nguyen P., Karimi N., Heidary P., Karimi N., Saemian P., Sehatkashani S., Tajrishy M., Sorooshian A. 2018.The Lake Urmia environmental disaster in Iran: A look at aerosol pollution. Science of The Total Environment 633: 42-49. DOI: https://doi.org/10.1016/j.scitotenv.2018.03.148.

Shadkam S., Ludwig F., van Vliet M.T.H., Pastor A., Kabat P. 2016. Preserving the world second largest hypersaline lake under future irrigation and climate change. Science of The Total Environment 559: 317-325. DOI: https://doi.org/10.1016/j.scitotenv.2016.03.190.

2012. The Drying of Iran's Lake Urmia and its Environmental Consequences. Environmental Development 2:128-137. DOI: https://doi.org/10.1016/j.envdev.2012.03.011.

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Declaration

I hereby declare that I have done this thesis entitled “Lake Urmia - mitigation of water loss impact” independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague 11.04.2019

Vladimír Šindler

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Abstract

Lake Urmia, located in the Northwest of Iran, used to be one of the largest saline lakes in the world. But since 1995 the lake has been drying up mostly due to poor management of water resources, excessive use of water in agriculture and climate change. Water loss in the lake presents major threats for humans and wildlife within the lake´s basin in the form of increasing salinity of the lake and groundwater and exposed lakebed with thick layer of salts being eroded by wind and carried across the lake basin. In the similar case of Aral Sea, the saline dust from the lakebed was increasing salinity of the soils and causing respiratory, eye, heart and other kinds of illness to humans and animals around the area. This bachelor thesis presents major causes and consequences of the desiccation of Lake Urmia, together with a brief overview of proposed solutions and strategies to the situation, including a proposal of prevention against saline dust spreading beyond edges of the lake in the form of windbreakers consisting of salt resistant plants (halophytes). And brief overview of water desalination technologies that may be implemented in areas with high levels of groundwater salinity.

Key words: Lake Urmia, environment, water treatment

Contents

List of figures

List of the abbreviations used in the thesis

EC - electrical conductivity

LU - Lake Urmia

RO - Reverse osmosis

MSF - multi-stage flash

MED - multi-effect distillation

°C - degrees Celsius

μm - micrometre (1×10^{-6} m)

mS/cm - millisiemens per centimetre

μS/cm - microsiemens per centimetre

g/L - grams per litre

UN - United Nations

ET - Evapotranspiration

1. Introduction

Recently water resources have become more and more discussed topic and general public is becoming more aware of the potential threats of water loss in the world. This awareness is spread most efficiently by case studies of situations where the loss of water caused damage of unimaginable volume. The perfect example here would be Aral Sea, where the combination of semi-arid climate together with inappropriately planned high-consumption agriculture led to a desiccation on monumental scale. This in turn has caused a collapse of an entire ecosystem that has played a vital role in social, ecological and economical activities in the area.

And just as Aral Sea, lake Urmia, the largest lake in Iran and one of the biggest hypersaline lakes in the world, is under threat of desiccation. Lake Urmia, just as Aral Sea, plays a vital role in the local ecosystem, greatly contributing to the well-being of both the wildlife and people the regulation of local climate, provision of nutrition and, of course, attracting tourism.

2. Aims of the Thesis

The Aim of this bachelor thesis is to describe issues occurring in and around the hypersaline Lake Urmia that are caused by the loss of water in the Lake. Consequently, the main aim is to design appropriate technology or strategy, which should solve or at least reduce impact of the water loss in the lake, according to the local environmental conditions and also to give a brief summary of already proposed solutions and preventive measures for this lake and nearby area which should be used mainly for the benefit of the population.

3. Methods

The information in this bachelor thesis rests upon the analysis of the available data from scientific databases, mainly in the form of scientific periodicals and papers in English language. The used databases include: Web of Science, Science direct and Google scholar. A systematic literature review is also performed using relevant textbooks and bibliographies.

4. Literature Review

4.1. Background of Lake Urmia

Lake Urmia (LU) is one of the largest permanent hyper-saline lakes in the world with its maximum surface area of 6100 km2 and maximum depth of 16 m (Eimanifar & Mohebbi 2007). Salinity of the lake ranges between 120 g/L and more than 300 g/L and is caused by the fact that Urmia is a terminal lake. The lake plays a vital role in the North-western region of Iran from many points of view; economic, environmental and social for over 6 million (2011) people living in the lake basin (UN science division 2017). In the area of the lake has been recorded 102 islands from which only Shahi Island (peninsula) is inhabited (Asem et al. 2014). LU and its islands have been designated a National Park, Ramsar Convention Site since 1971, and comprise UNESCO Biosphere Reserve since 1976 (Jalili et al. 2016).

4.1.1. Location and geography

LU is situated in north-western Iran in latitude 37°03'N to 38°17'N and longitude 44°59'E to 45°56'E, in between the East and West Azerbaijan Provinces. Due to seasonal variation the surface water level moves between 1272 m above mean sea level. and 1278 m above mean sea level. Maximum length is 146 km and maximum width is 58 km. The lake is surrounded by mountains (Jalili et al. 2016; Hosseini-Moghari et al. 2018).

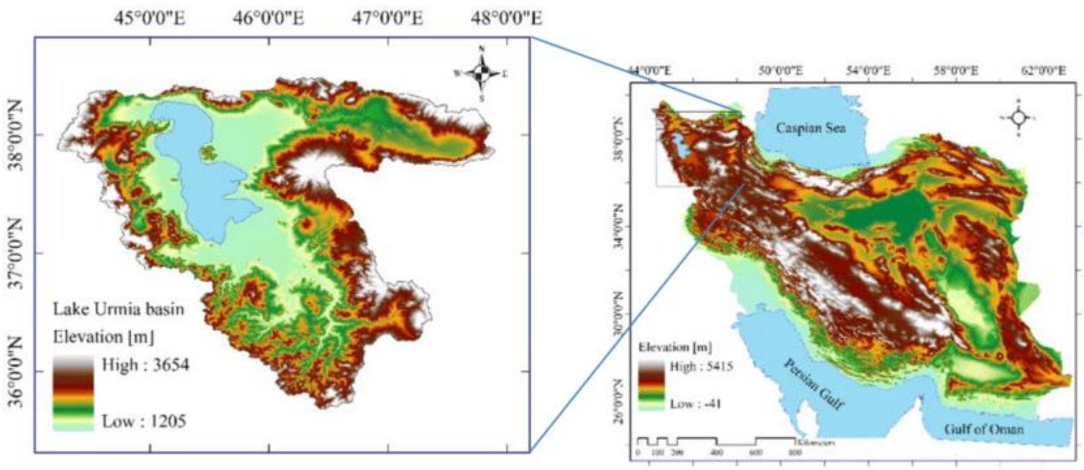

Figure 1: Topographic map of Urmia lake basin (Hosseini-Moghari et al. 2018).

4.1.2. Climate

Climate in LU basin is prevalently continental and supports Irano-Turanian steppe vegetation. Winters in the area around the lake are cold and summers are temperate. Mountains stretching around the lake are covered by snow during winters, receiving around 380 mm of precipitation annually, whereas the lake and nearby plains receive 316 mm of precipitation per year. Winter (November to April) is considered as wet and humid season while summer (May to October) is dry with rainfall being fairly rare. Average annual temperature in the basin and on the lake is around 11°C. Based on latitude temperatures in the basin vary and oscillate between 6.5°C in higher latitudes to 13°C in lower latitudes. The coldest month is January while the hottest is July. Maximal temperature ranges up to 40°C meanwhile winter temperatures range between 0°C down to a minimum of -20°C; however, the water in the lake moderates these extreme

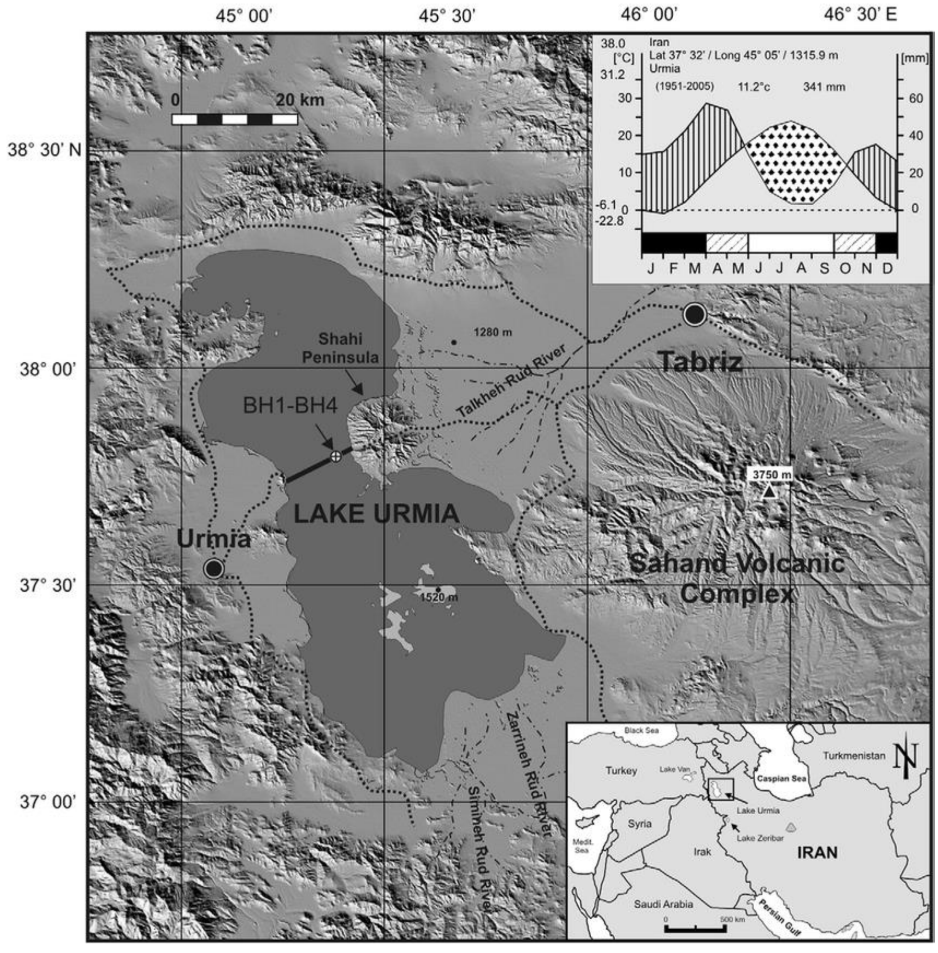

Figure 2: Relief map of LU. Upper right inset shows the climate diagram of the Urmia meteorological station (1951–2005). Dotted area of the climate diagram represents the period of relative drought and vertically hatched areas indicate the wet period (Djamali et al. 2008).

temperatures and humidity in the lake basin (Heidari et al. 2010). Evaporation in the lake basin varies between 1050 mm in the northeast to 1550 mm in the southwest. Mountain ranges like Zagros Mountains to the southwest and the Ararat Mountains in the far north of the lake have slight effect on the climate in basin (Fazel et al. 2018).

4.1.3. Hydrology and water supply

Besides the rainfall and groundwater the main source of water in LU are 9 main rivers depicted on figure 3, where you can see: Zola-chay in northwest; Nazlou-chay, Shahar-chay and Barandouz-chay on the west side of lake; Gadar-chayr and Mahabad-chay in the south; Simineh-roud and Zarrineh-roud located also in the south, as the largest rivers supply more than 50% of total inflow to the lake; Aji-chay (Talkhe-roud) inflowing from the eastern side. There are more in flowing rivers but their contribution to total inflow are almost insignificant (considering scale of the lake itself). But among the larger ones are Rozeh-chay, Leylan-chay, Ghaleh-chay and some seasonal rivers such as Sofe-chay and Mardog-chay. Majority of the rivers bring fresh water to the lake except Aji-Chay and also several smaller seasonal creeks that run through salt domes in area of Khoy city (marked with yellow point on figure 3) that carry saline water (Alipour 2006).

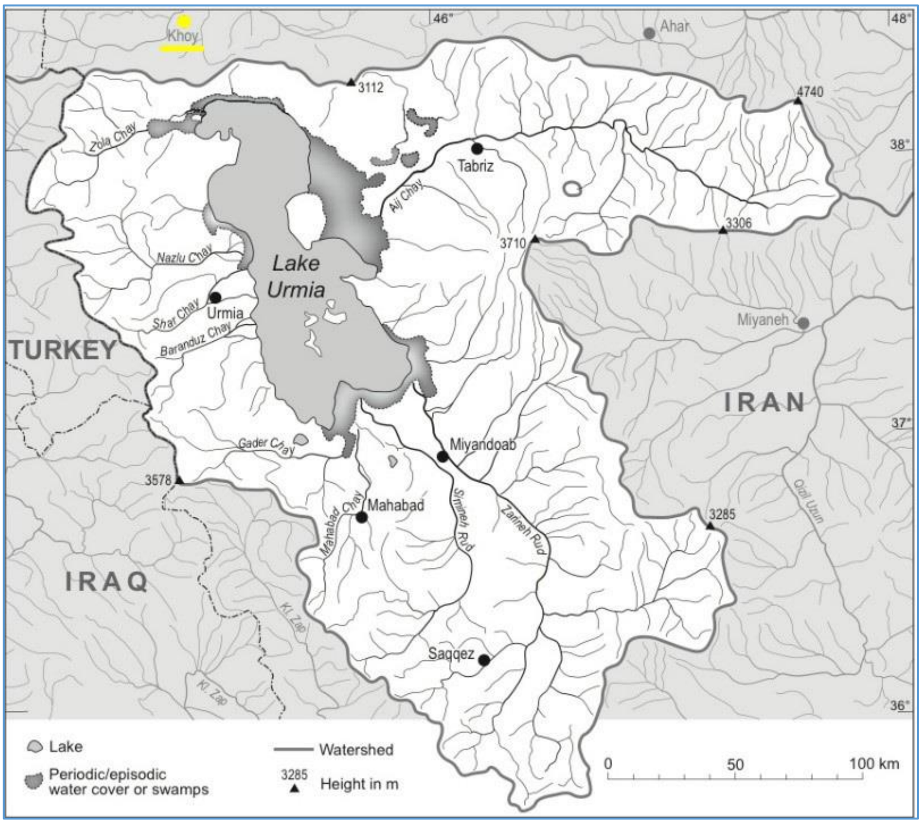

Figure 3: Hydrography and catchment area of Lake Urmia (Ehlers 2013).

These seasonal rivers mostly conduct water only for a short period of time following precipitation or snowmelt (Vaheddoost & Aksoy 2018). The inflow to the lake from the rivers occurs mostly with delay from groundwater or snowmelt. And therefore, highest discharge occurs during May (figure 5) when based on climate diagram in figure 2 the precipitation starts decreasing. Meanwhile in August during dry season the discharge is lowest and most probably sourced from groundwater (Vaheddoost & Aksoy 2018).

LU is a terminal or an endorheic lake, meaning it has no outflowing rivers, and so the water leaves the lake through evaporation. This causes mineral build up, which causes high salinity of the water (Pengra 2012).

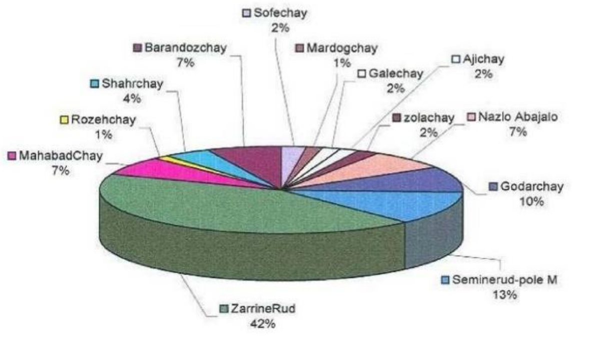

Figure 4: Comparison of river debits flowing into Urmia Lake during 1991–2000 (Alipour, 2006).

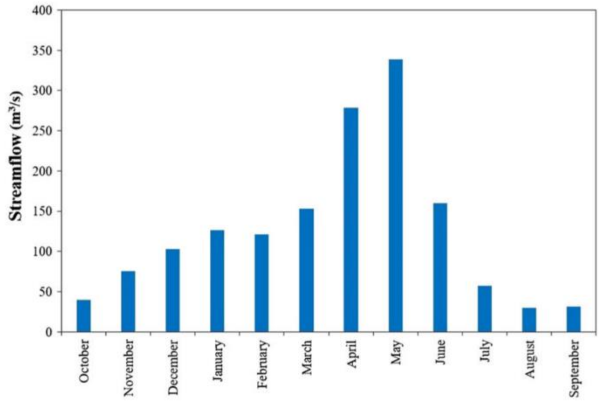

Figure 5: Monthly streamflow discharge coming into Lake Urmia (Vaheddoost & Aksoy 2018).

4.2. Decline in the water level

LU has started losing water around 1995 and has been losing more water ever since. Between 1992 and approximately 1995 water levels rose dramatically and caused floods and several other problems. But before 1992 there were relatively stable seasonal and decadal fluctuations in water level (figure 7) ranging from 0,6 m to 2,7 m caused most probably by climate variability (Fazel et al. 2018). But after 1995 its clearly visible on figure 6 that water level started to dramatically decline resulting in almost 8 m drop (up to 2019). Because of the socioecological importance of the LU in the region, a vast amount of research was done to address shrinkage of the lake and different aspects of it like biodiversity, climate, hydrology and water resources, and environmental management (Asem et al. 2014).

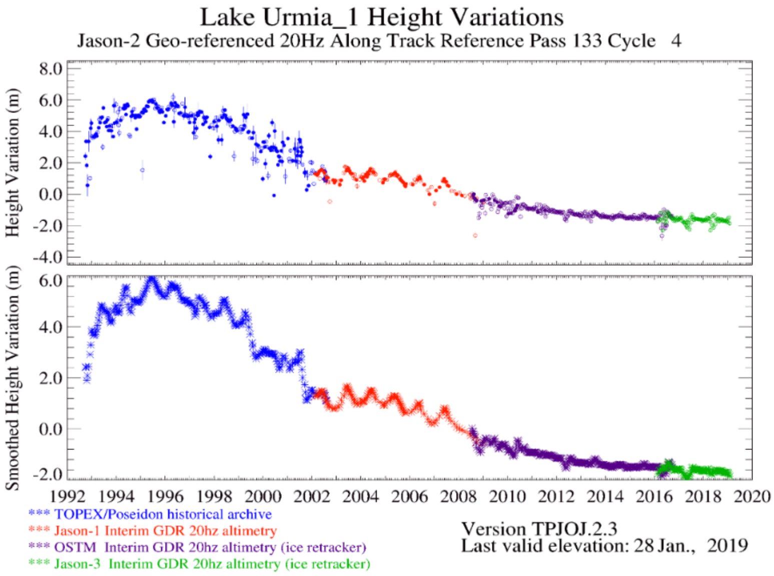

Figure 6 : Height variation of LU 1992-2019 (United States Department of Agriculture 2019).

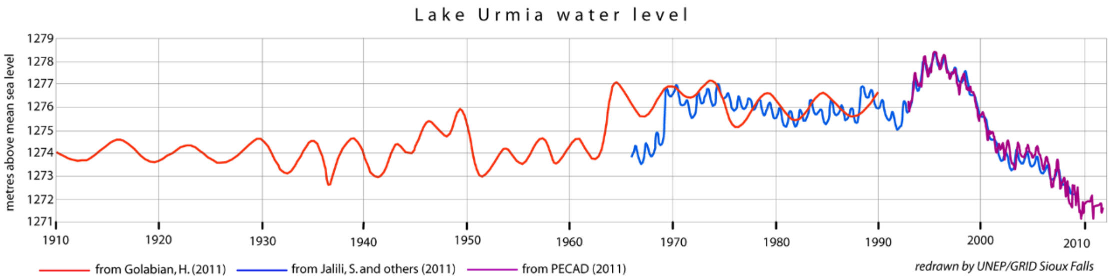

Figure 7: Overlaying multiple records of the lake's surface elevation 1910 – 2010 (United States Department of Agriculture 2019).

4.2.1. Causes of water loss

Several authors, such as Hassanzadeh et al. (2012), Jalili et al. (2016), Shadkam et al. (2016), Ahmadaali et al. (2018), Pengra (2012) and Amini (2019) have been trying to find the cause of water loss in this lake with the use of different approaches and implementation of different methods. And despite the slightly different results, all of them agreed that the water loss is caused mainly by 2 aspects: climate change and human factors, such as building of dams and agricultural development. However, when they tried to pinpoint relative contribution to water loss their results were slightly different. Amini (2019) wrote that over 30 years annual inflow to LU has dropped down by 48% from which 60 % were caused by climate change and 40% by water resource development as misconduct in human activities. Results of Hassanzadeh et al. (2012) were that: *"Inflows* *due to the climate change and overuse of surface water resources is the main factor for 65% of the effect, constructing four dams is responsible for 25% of the problem, and less precipitation on lake has 10% effect on decreasing the lake's level in the recent years."* Ahmadaali et al. (2018) claims that decrease in water level is caused mostly by human impact rather than climate change. Pengra (2012) suggest a similar idea, claiming that the diversion of water was one of the most, if not the most significant cause of water loss in LU and that the other causes are reduced precipitation, warmer temperatures and groundwater abstraction. And Jalili et al. (2016) supports the idea that most contributing factors to water loss in the lake are climate change and overuse of surface water resources, new dams and decrease in rainfall. Additionally, decades of poor water management, agricultural policies, population pressure, climate related drought, and water diversions affected the water level of LU and consequently its ecosystem quite dramatically.

4.2.1.1. Climate change

One of the major suspects causing the water loss is climate change, which has already proved in the past that it has enough influence to dry the lake completely on its own. Based on a sample retrieved from up to 100 m deep under the lake bed indicate that LU has gone through enormous water level fluctuations in the lake for the last 200,000 years. For example, approximately 30 000 years ago during the last glacial period, water level in the lake reached tens of meters higher than present water level. But during interval of 22 000 to 18 000 years ago the lake most probably dried out completely. Despite the large time scale these results present that climate itself is capable of causing water level fluctuations like we see today (Jalili et al. 2016). Another more recent exhibition of climate change influence on the lake level could have been seen during a period of extreme drought in 1800, when, according to historical records, the lake almost dried out and was in fact left only with maximum depth of 75 cm. But later the lake's water level managed to recover again (Fazel et al. 2018).

Some of the latest evidence for climate change in the area may be the fact that in the period of 1966 to1990 the average annual rainfall was 382 mm and dropped to average annual rainfall between 1991 and 2015 to 315 mm. On contrary the temperature rose from average 11.6°C during period of 1966 to 1990, to average 12°C in period of 1991 to 2015 (Taravat et al. 2016).

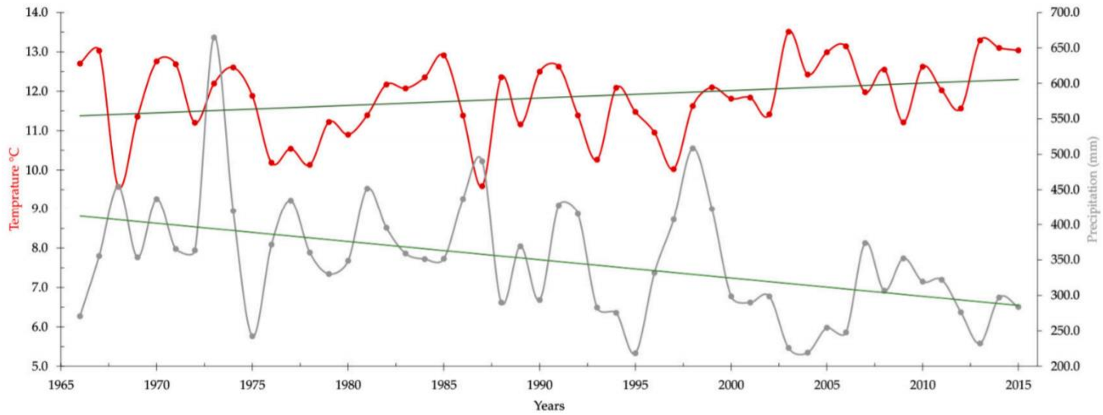

Figure 8: Annual precipitation variations over the Lake Basin and annual temperatures variations on Urmia lake (Taravat et al. 2016).

4.2.1.2. Dams

Almost all major rivers flowing to LU have dams or diversion projects, regulating inflow of water to the lake, not allowing surface water to inlet the lake. In figure 9 we can observe intensification in diversion of surface water through the increasing number of larger projects under construction, especially south of the lake. Speaking of all considered projects in 2010 there were 275 projects under study of which 231 were discerned to be constructed in near future. Among the projects were 71 reservoir dams, 124 weirs, 17 pumping stations and 10 flood controlling projects (Hassanzadeh et al. 2012). These water resource development projects are diverting massive quantities of fresh water and preventing a replenishment of lake water. In 2014 according to Asem et al. (2014) reservoirs of dams have hold up to 3.568 billion m3.

The reasons for construction of so many projects that are now causing the drop of water level in the lake are most probably inappropriate decision-makers decision in water management sector (Amini 2019). Especially following the floods in 1995. As indicated on figure 7 during 1995 the water level in the lake reached the highest point since 1910 (oldest available measurement data) elevated water level caused floods resulting in damage of houses, infrastructure and agricultural lands. Additionally, risen saline water from the lake started to leak to the surrounding aquifers and contaminated fresh water stored there. This has caused problems in terms of usage of groundwater for municipal and agricultural purposes. In order to resolve the situation policy makers and water system managers started implementing projects and strategies targeted at lowering the water inflow to the lake (Amini 2019). Their strategy was mostly based around construction of new dams and diversions, which should have lowered the inflow from river to lake. And as can be seen on figure 7 the implemented projects and strategies most probably caused water level to drop as was predicted at the beginning. But it is suspected that in the following years the water inflow reduction strategy together with unexpected years of droughts and lesser precipitation caused the water level to drop far more than was projected (Jalili et al. 2016).

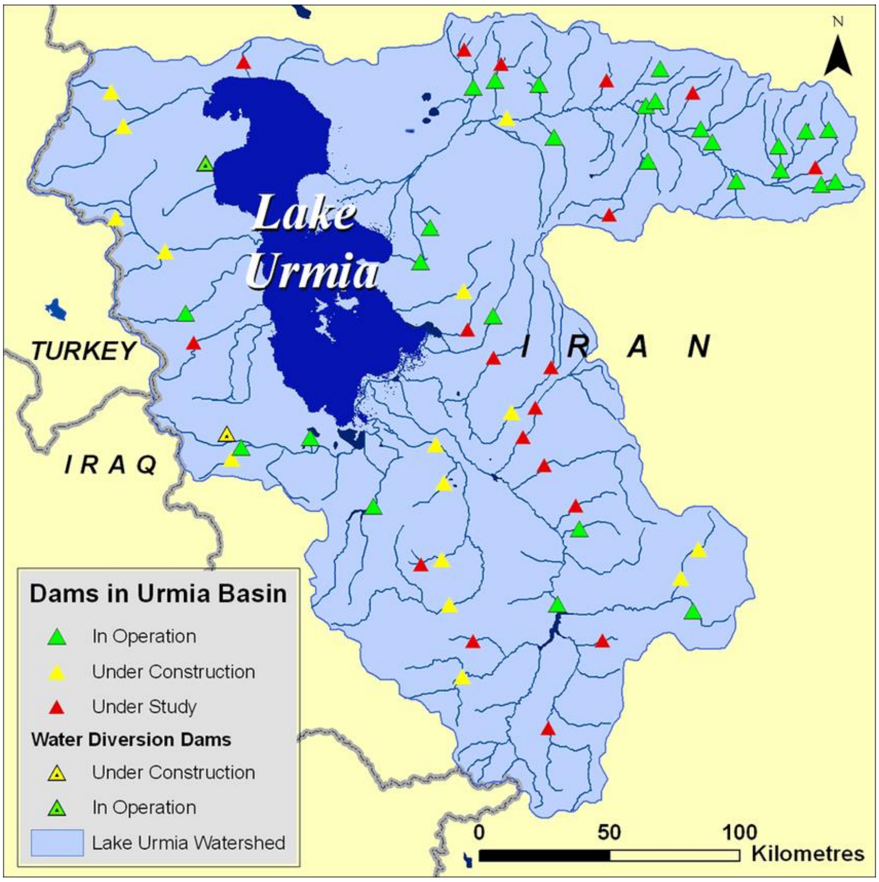

Figure 9: Dam construction in the LU basin 2012 (Pengra 2012).

4.2.1.3. Agriculture

Agricultural production in LU basin consists mostly of crops like wheat (mostly in the west), barley, sugar beet, alfalfa, and in particular grapes and apples which are mostly exported to foreign countries (Hassanzadeh et al. 2012). Major causes for water loss are intensive development of agriculture which is resulting in over-exploitation of surface and groundwater resources (Asem et al. 2014). According to Urmia Lake Restoration Program (2015) agriculture consumes 90% of total water consumption. Beside using surface water as a source of water for agriculture there were at least 90 000 wells in the basin in 2015, from which approximately 50% were illegally constructed,

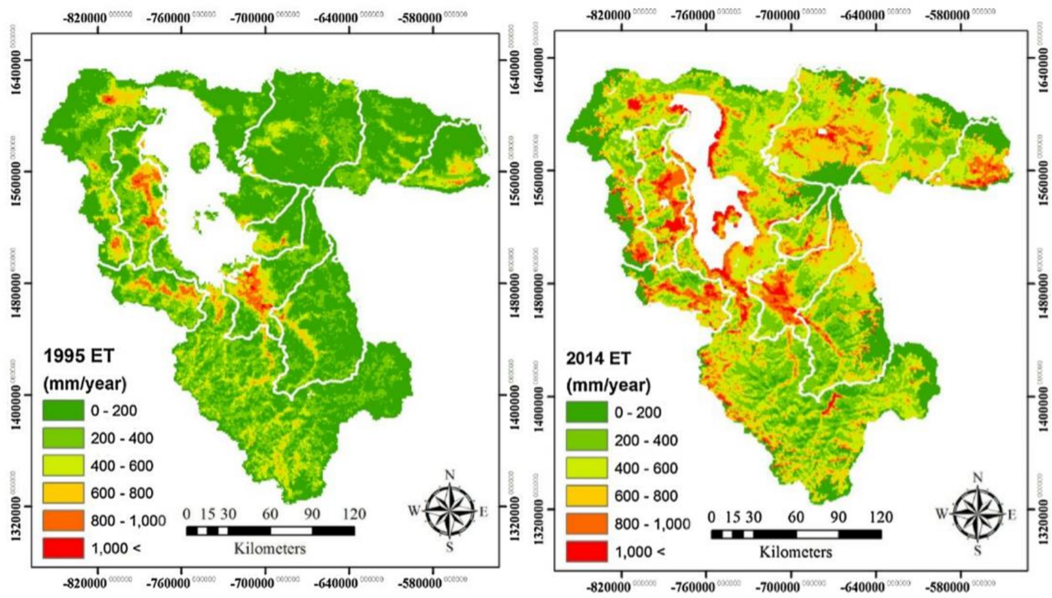

Figure 10: Comparison between 1995 and 2014 of annual evapotranspiration (mm/year) over Lake Urmia (Taheri et al. 2019).

leading to uncontrollable withdrawal of groundwater causing further problems as increasing salinity of the groundwater sources. Another issue in the form of increasing evapotranspiration was the slowly rising consumption of water for agriculture. Together with farmers choosing crop patterns with water-based crops such as sugar beet and orchards, evapotranspiration was kept on increasing. Average evapotranspiration values of irrigated agricultural lands rose from 555 to 736 mm between the years 1995 and 2014, as you can observe in figure 10, where evapotranspiration values are elevated across the whole basin compared to 1995. And cultivation area of farms and orchids rose from 387 500 to 419 500 hectares in between years 1995 and 2014.

4.2.2. Effects of water loss

In figure 11 is clearly visible the difference between LU in 1995 and 2014 when water level has dropped by at least 7 meters since then. White outline of the lake is lake bed with thick layer of salt creating vast salt deserts on the edges of the lake. The lake’s tendency to continue in declining in water levels is a threat for hydrology and ecology of the lake, therefore a potential problem for the whole region (Fazel et al. 2018).

Figure 11: Comparison of satellite captured images of Lake Urmia 1998 (on the left) and 2014 (on the right) (NASA 1998, 2014).

4.2.2.1. Salinity

Since LU is a terminal lake, naturally occurring salt in water cannot flow further into the sea, and therefore is deposited in the lake during the evaporation of water. And since the decrease in water level the amount of diluted salt in the water has been increasing, causing several problems. One of them may be combination of lowering of groundwater level and hypersaline water in the lake manifesting into saline water intrusion into groundwater aquifers. Vaheddoost and Aksoy (2018) suggest that in some places groundwater level in close proximity to LU dropped up to 16 m and 15 out of 27 studied aquifers in LU were depleted. This was most likely caused by overusing of groundwater for irrigation by a large number of illegal wells. With such drastically low groundwater level the direction of flow towards the lake may be reversed and the hypersaline lake may drain into aquifers. Which will not only speed up the desiccation of the lake but may irreversibly contaminate the aquifers on which the agricultural land surrounding the lake relies.

Beside the natural effect of rising concentration of salt in the lake due to evaporation of water, there may be yet another cause contributing to this problem. In 1980s the construction of a causeway (figure 12) started and took almost 25 years until in 2006 the last part of the project – the multi-span arch bridge – was completed (Karimzadeh et al. 2018). Environmentalists have been predicting that the causeway is too long and may disrupt natural hydrological process in the lake and affecting climate in the region. Apparently 1276 m wide gap (in figure 2 is the gap with the bridge marked as BH1 – BH4) is not spacious enough to allow adequate flow in between the divided lake parts (Mohebbi et al. 2011). Another effect of this causeway may be uneven spreading of inflowing water into the lake, intensifying water level decrease in low height areas and therefore causing faster evaporation, thus increasing salinity (Pesyan et al. 2017; Ghadimi & Nezammahalleh 2015). Similar case supporting this idea happened in Great Salt Lake, USA, where a railroad causeway divided the lake into southern and northern section. After some time, the norther section has experienced significant rise in salinity while the southern section has been diluted and was losing salinity (Mohebbi et al. 2011). Additionally, water mineral composition survey shows that northern part of Great Salt Lake has lower concentration of calcium than its southern neighbour. This is caused by calcium rich rivers flowing into the southern part of the lake but not distributing calcium evenly because of the separation brought by the causeway (Alipour 2006).

Interesting phenomena concerning salinity has occurred in the LU several times in the past years. As on figure 13 it can be seen that lake is completely red. Briefly, when light intensity and salinity in the lake reached higher levels, micro-algae *Dunaliella salina* that thrives in conditions much like in LU, turns its colour from green to red because of production of protective carotenoids in its cells (Mohebbi et al. 2011).

Figure 12: Causeway on Lake Urmia (Ghale 2014).

Figure 13: Lake Urmia coloured red by *Dunaliella salina* (Halsnes 2018).

4.2.2.2. Biodiversity

Despite LU being a hypersaline lake, it possesses relatively rich fauna and flora compared to, for example, the notorious Dead Sea. LU does not support any fish or mullusk species and no other plants beside phytoplankton within the lake and a variety of salt tolerant plant species (halophytes) growing around the lake in its wetlands. But the most important aquatic fauna in LU is a macro-zooplankton, *Artemia urmiana*. This brine shrimp species is critical in the lake's food chain feeding itself by algae and being consumed by diverse migratory bird population occurring in the lake area (Pengra 2012).

Evaporation of the water in LU was causing rise in salinity reaching 300g/L in 2012 and it believed that levels of sodium chloride above 320 g/L are fatal for brine shrimp. At that time reduction of reproduction rate was observed together with rising salinity in the lake. Since the brine shrimp is a vital part of the lake's food chain, its loss will most probably cause also the loss of LU´s migratory bird population for which LU is a major rest place for one of the most important flight corridors of migratory birds in the world. It is safe to say that the loss of the brine shrimp will eventually impact the entirety of the local and surrounding ecosystem (Asem et al. 2014).

4.2.2.3. Dust

As indicated in figure 14, insufficient inflow to the lake, continuous evaporation of water and draining of groundwater around the lake caused rapid decline in water level, exposing the lakebed with thick layer of salts (mostly sodium chloride). In 2015 it was approximated that there was about eight billion tons of salt in the exposed layer of the lakebed (Hossein Mardi et al. 2018). If we take a look at a similar case of Aral Sea where exactly same problem with exposed lakebed occurred, wind erosion of salt layer caused significant increase in airborne particulate matter, consisting predominantly of salts. This had major negative impacts on vegetation growth, crop yields and vegetation mortality. Apart from vegetation salt pollution was affecting also the domestic animals and was causing respiratory illnesses, eye problems and throat and esophageal cancer (Pengra 2012).

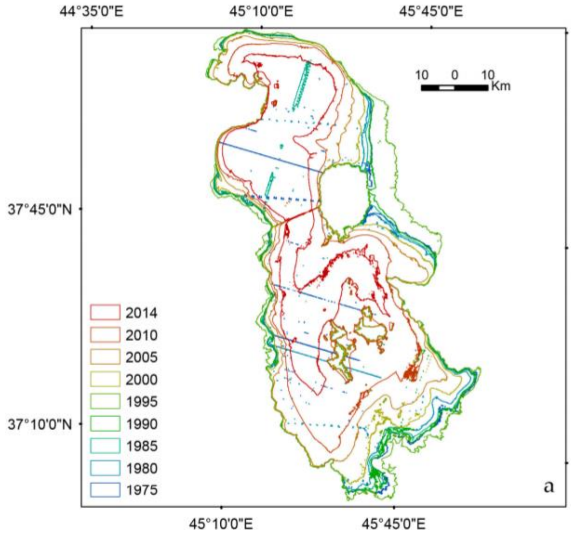

Figure 14: Temporal surface area changes between 1975 and 2014 (Taravat et al. 2016).

According to Gholampour et al. (2015) under common wind strength condition dust and salt grains with diameter under 10 μm can be transported by wind for thousands of kilometres and bigger particles up to 20 μm can be carried for hundreds of kilometres under wind speeds above 15 m/s. So, during warm seasons and under particular wind conditions, the currents may transport saline dust across the whole lake basin and beyond, causing similar problems like the saline dust at Aral Sea.

Figure 15: Salt storm, Lake Urmia (July 2015) (South Azerbaijan 2015).

Combining wind erosion of salt layer and strong winds, saline dust storms (figure 15) may occur. In areas like LU dried lakebed magnitude of such storms is increased because of the absence of vegetation that would mitigate the strong winds and so wind erosion is increased, releasing more salts into the air. Under particularly strong wind condition this saline dust may be transported in large quantities for thousands of kilometres, beyond the lake basin area (Middleton & Kang 2017). Storms of such magnitude may potentially render agriculture land unusable because of the soil's high salinity from the saline dust (Pengra 2012). Consequently, these storms may alter the entire region's ecosystem and cause medical problems to people in the affected area (Hassanzadeh et al. 2012). In particular, long term exposure to saline dust may cause respiratory and eye related illnesses (Morman & Plumlee 2013). Beside salts according to Hassanzadeh et al. (2012) heavy metals, industrial pollutants and large quantities of pesticides have accumulated in groundwater and surface water that inflow to the lake. And so, these pollutants are likely present in exposed lakebed and due to wind erosion contributing to air pollution.

4.2.2.4. Groundwater salinity

According to Ghalibaf1 and Moussavi (2014) 41% of water used comes from groundwater sources. Out of this 87 % is used for agriculture and 13% as potable water and water for industrial purposes. Recently, overuse of groundwater together with construction of illegal wells caused significant drop of water level in aquifers. This in turn allowed saline water from the lake to intrude into underground aquifers. Available statistics claims that 1002 out of 9459 deep and semi-deep wells in those aquifers bordering with LU are contaminated with salts. Amiri et al. (2016) supports this claim through measuring electrical conductivity (EC) in samples obtained in western part of LU. Figure 16 presents sampling area divided on Norther par and Southern. Red areas on the map represent groundwater samples with higher EC, indicating higher amount of dissolved salts in the water. Which have occurred there through intrusion of saline groundwater that originated from diluted saline/saltwater into freshwater aquifers. Another evidence for intrusion of saline water into groundwater may be analysis of groundwater in the area of a city called Tabriz, on the eastern side of the lake and located further from the lake. Analysis shows continuous trend of increasing concentration of ions such as Na+ and CL- indicating infiltration

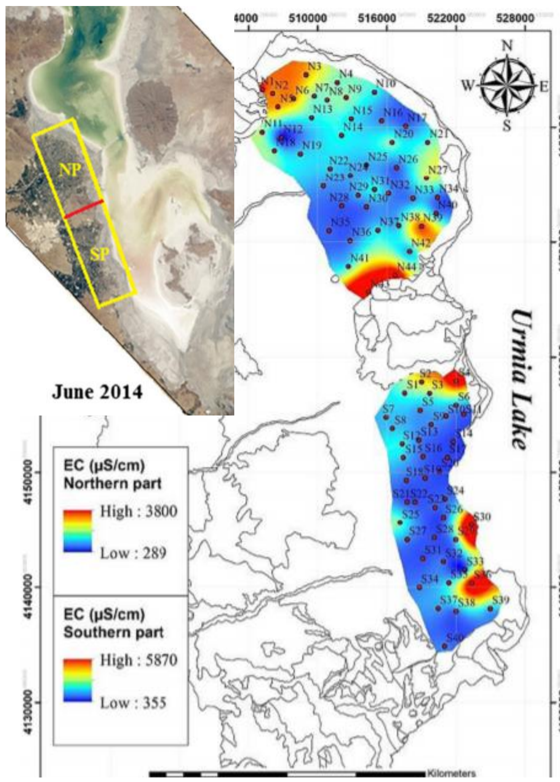

Figure 16: The EC values of groundwater samples in July 2014 (Amiri et al. 2016).

of saline water into aquifers. In figure 18 violet areas represent groundwater with lower EC of samples, thus lower salinity, meanwhile green areas represent higher EC of samples. Some of the water samples were reaching concentrations of ions that exceeded safety limits for drinking and domestic purposes, as you can see in figure 17, where vertical colour lines represent water samples reaching the highest EC. Water in these areas was even considered inappropriate for agricultural use (Dehghani et al. 2019).

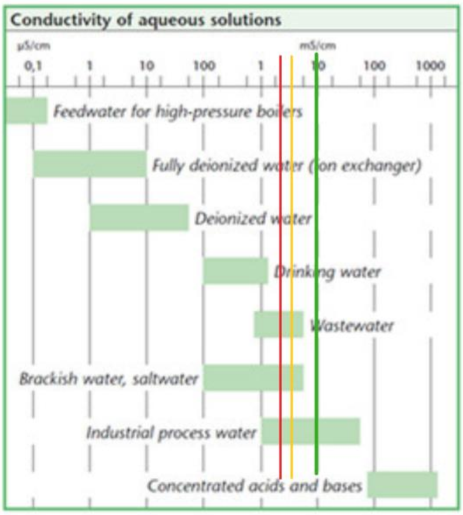

Figure 17: EC of various aqueous solutions with coloured lines representing water samples with highest EC results from: western part of LU (figure 16) – north (red), south(yellow); and Tabriz (figure 18) (green) (Xylem Inc. 2019).

Apart from intrusion of saline water from the lake there may be other sources of contamination of the freshwater aquifers. One of the sources may be saline dust blown on the surface above contaminated water from dried lakebed. These salts on surface are dissolving during precipitation or irrigation and then leaking into groundwater. Another source may be interaction of the water with the rock, like dissolution and leaching of minerals into the water (Barzegar & Asghari Moghaddam 2016).

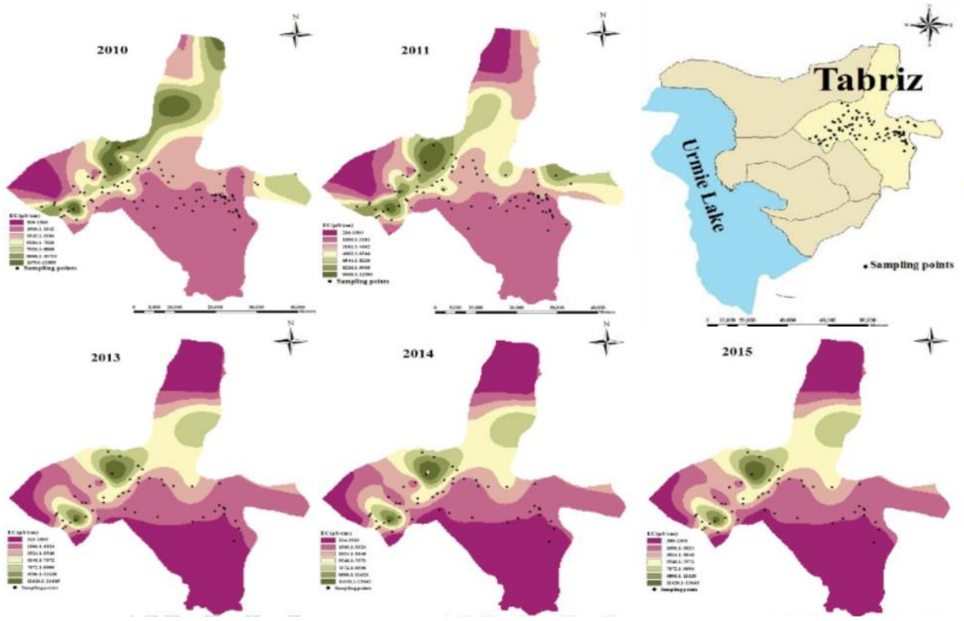

Figure 18: The EC of the groundwater samples studied in Tabriz from 2010 to 2015 (Dehghani et al. 2019).

Beside the higher salinity, which already presents a problem by itself, high levels of sodium and chloride are often associated with high concentrations of bio-accumulated elements such as selenium and arsenic (Amiri et al. 2016). In particular groundwater contaminated with arsenic used for human or animal consumption may during long-term exposure cause arsenic poisoning resulting in many health issues including heart disease and cancer (Sun et al. 2014).

4.3. Proposed solutions and preventive measures

Desiccation of the LU during the years brought a lot of attention and so solutions and strategies were developed to stop the water level dropping further consequently causing more damage to environment and population in close proximity of the lake. Most considerable strategies are targeted to adjustment of water allocation through the lake basin and water consumption reduction. This should achieve adequate water inflow to the lake and restore its former water level (Pengra 2012).

4.3.1. Water allocation

As presented in previous chapters one of the major reasons for water loss is increased consumption of water by mainly agricultural sector but also domestic and industrial sector caused by increasing population in LU basin. Potential solution is presented by Soudi (2017), who points out that traditional water management will most probably result in complete drying out of LU, and so proposes emergency plan where water allocated for agricultural uses should be reduced by 40%. Pengra (2012) also presents reducing the amount of diverted water for agricultural, domestic and industrial uses as potential solution, but claims that with growing population and recent trends in decreasing precipitation and increasing temperature this solution is inadequate and impractical.

Another solution is releasing of stored water from 13 large dams in the lake basin and potentially prevent construction of new dams. These decisions lay on water resource managers and policy makers whose mismanagement of water balance by decisions to build too many dams or reduce water flow to the lake by storing the water in the dams may possibly cause complete drying of LU. Resource managers and policy makers should also consider climate variability into account of water level in LU and compensate the water lost due to more intense evaporation and decreased precipitations (Jalili et al. 2016).

Another often mentioned solution may be diversion of water from other than interbrain sources. Some of the possible sources for inter-basin transfer would be the Zab River, Caspian Sea and Aras River. However, transfers of water from other river basins would allow to bring just limited amount of water to LU, considering that any change in donor river flow rate would probably negatively impact source rivers basin ecology. Also, there is the fact that Zab river basin is located in both Turkey and Iraq, which means that for creating the diversion from Zab river there would be needed international agreement and cooperation on this matter. Transfer from Caspian Sea would be more viable due its larger volume relatively to proposes rivers flow. But transfer route would be around 300km and the costs were estimated at around 5.5 billion US $, which is clearly economically not plausible. Beside that time necessary to complete the project was estimated to be around 5 years. This kind of solution is also not very eco-friendly, since, in the case of diversion of water from rivers, the water flowing through manmade canals would carry fresh water which presents no danger to environment as it flows through. But transferring saline water from Caspian Sea through manmade canals would cause saline water intrusion into aquifers and increased salinization of environment surrounding the canal (Pengra 2012; UN science division 2017).

4.3.2. Reduction of water consumption

More sustainable solution would be reduction of water use across the LU basin. Reduction should be targeted mainly on agriculture sector where 87% of all consumed water is being used, mainly for irrigation (Amiri et al. 2016). Especially considering that irrigation efficiency is relatively low. Comparing overall irrigation efficiency in Iran, which is around 35% to average for developing countries (45%) and developed countries (60%) (Amini 2019). Main causes of inefficiency of irrigation include poor maintenance and inadequate design of irrigation and water distribution systems, inadequate training of farmers and their careless operation with irrigation systems. Highest loses of water are caused by evaporation from surface irrigation canals, which are mainly used for growing wheat, barley and alfalfa (Jalili et al. 2016; Amini 2019).

And so, improvement of irrigation systems and their efficiency together with crop pattern change to less water demanding crops would not only help to lower consumption of water that would instead of crop fields reached the LU, but also increase sustainability of agriculture, especially considering the growing population (Ahmadaali et al. 2018).

Ideally the government should consider implementing economic instruments and legislation in order to encourage water conservation and sustainable agriculture; more particularly, it should consider improving water use rights and approval of new water development plans. This should help to prevent constructing of new illegal water uptakes from the basin (UN science division 2017). Apart from agriculture, domestic water use should be also taken into consideration for reduction strategy. With population over 6 million (data from 2011) (Urmia Lake Restoration Program 2015), even a small reduction in domestic water use will result in nonnegligible addition to conservation of the lake, due to the size of the population. For more sustainable water use public awareness about the matter should be raised in the LU basin´s population (Khatami & Berndtsson 2013).

4.4. Water purification and saline dust mitigation

Despite already ongoing projects targeted on restoration of the lake, it will probably take many years to fill LU to its desirable water level, where salinity would drop to former levels and the dry saline layers on the lakebed would be submerged and dissolved. And so, for many years to come LU basin is likely to be still endangered by saline dust storms and saline water intrusion into freshwater aquifers. Which will cause all kinds of problems that are described in previous chapters. And so, to mitigate these effects and protect LU basin against saline dust and water two complementary strategies are presented.

4.4.1. Saline dust mitigation using halophytes

In previous chapter about saline dust was presented how many problems are caused by these saline dust storms, as well as how far they can reach. Especially considering that flat open space lakebed covered with salt layer is perfect space for occurrence of fast-moving winds carrying the salt, that has no obstacles in its way that would bring its potency down. Solution would be planting a vegetation that would act as windbreaker; unfortunately, the salt flats are incapable to support most of the natural vegetation (Pengra 2012). A solution to this problem might be using salt-tolerant plant species (also known as halophytes), which are capable of surviving in 'harsher' environments such as salt marshes, salt deserts and coastal areas, where high salt concentration occurs (P Shah 2017).

This idea has already been executed in small scale next to Jabal Kandi village (figure 20). During the past few years several nearby villages were abandoned, and many farms and trees dried up as a consequence of LU water level drop and frequent dust storms (IFP Editorial Staff 2018).

Figure 20: Location of the Jabal Kandi village and sand dune fields in LU (Ahmady-Birgani et al. 2018).

Beside dust storms themselves another situation occurred from intense wind erosion of the lakebed. And that are emerging sand dunes in area next to Jabal Kandi village, where until LU water level drop in 1995 was lake surface. Since then these sand dunes covered approximately 2000 ha of lakebed and fraction of former coastline (Ahmady-Birgani et al. 2018).

Figure 19: Planting of halophytes on dried lakebed/sand dunes next to the Jabal Kandi village (IFP Editorial Staff 2018).

Because of this situation, working group tasked with reviving LU started in 2015 with planting of halophytes on dried lakebed/sand dunes next to the Jabal Kandi village (figure 19) to reduce the amount of salt and sand particles carried by wind. For creating a windbreaker barrier two species of halophytes were chosen. The *Nitraria* genus halophytes locally called Karadagh (figure 21) and *Tamarix* genus halophytes locally called Shoorgaz (figure 22) (IFP Editorial Staff 2018). Halophytes from genus Nitraria are drought-resistant shrubs or bushes that usually grow less than 1 m in height. Besides their potential as windbreakers capable of reducing wind erosion, they produce red fruit that can be consumed by humans or animals and most probably possess favourable therapeutic properties. They are also investigated as protentional fodder for livestock (Du et al. 2015). Halophytes from genus Tamarix are evergreen or deciduous dense shrubs or trees growing from 1 to18m in height. They have long tap roots allowing them to utilise deep groundwater sources. They are also used in antidesertification program in China indicating their potency for mitigation of LU problems (Cui et al. 2010).

Figure 21: Tamarix gallica L. (Meneerke Bloem 2010).

According to Motamedi et al. (2018) halophytes in LU basin may be used also for improvement of saline soil affected by saline water and dust. In his research he claims that in the soil samples (where halophytes were grown) in depths from 0 - 15cm, EC was reduced (salinity decreased) due to plant-root action that helped to absorb more salts from the soil and transportation of the salts to shoot parts. This process of continuous desalinisation can be applied on larger scale as cost effective and eco-friendly solution. Similar experiments were carried out by Wucherer et al. (2005) on the saline lands of Aral Lake region and, interestingly enough, in the north-eastern parts of Brazil. There he concluded that halophytes are suitable tools for rehabilitation of saline soil and that increasing vegetation cover using halophytes is a realistic way to reduce the salt dust output from the dry seafloor.

Figure 22: Nitraria retusa and its fruit in right-upper corner (Ferran J Lloret 2018).

Besides mitigation of the dust and rehabilitation of saline soils, halophytes may be potentially used as forage source for grazing animals due to capability of some species of halophytes to achieve high biomass production (Motamedi et al. 2018). Halophytes may also serve as shelters for wildlife and complementary as biodiversity enhancement (P Shah 2017).

4.4.2. Purification of well water

In chapter "Groundwater salinity" were presented issues causing elevated levels of salinity in groundwater and their potential solutions in chapter "Proposed solutions and preventive measures" which should be main objective, since it's more reasonable to fix the cause of the problem rather than the consequence. But just like in the case of saline dust, solving high salinity in groundwater sources will probably take many years and meanwhile there is present need for fresh water in places that are further away from rivers and thus rely on groundwater sources. Because of that, in this chapter will be presented appropriate water purification methods for desalinisation of contaminated groundwater.

There are two main water purification processes targeted at desalination: thermal-based and membrane-based. Thermal-based methods are based on heating of the saline water that evaporates while leaving salts behind, and then condense back into liquid state resulting in potable water. Since generally thermal based methods require rather high amounts of energy for evaporation, they are used in places where energy costs are low and salinity high, or in facilities which produce waste heat as a by-product. Few examples of the most widespread thermal-based methods are multi-stage flash (MSF) and multi-effect distillation (MED). Until the end of the last century thermal-based methods were preferred over membrane-based and used more commonly. But since the beginning of 21st century membrane-based methods were becoming more popular especially because their lower energy consumption in comparison with thermal-based methods. Among membrane-based technologies the most popular ones are ultrafiltration, electrodialysis, and in particular reverse osmosis (RO). In 2012 RO was the most commonly used desalination process worldwide accounting for 61% of the worldwide fresh water production by desalination, followed by MSF at 26% and MED at 8% (Likhachev & Li 2013; Darre & Toor 2018).

4.4.2.1. Multi-stage flash

MSF distillation method is based on distillation of water through several flash chambers. In these flash chambers the so-called flash evaporation occurs, caused by releasing heated water into environment with lower pressure, which causes the water to boil rapidly resulting in rapid (flash) evaporation. To present how MSF works figure 23 is used with number referencing individual stages in the text. First the saline water is pumped into the system (1) and then is conducted through individual flash chambers in pipes, where it accumulates heat from hot water vapour (2). Then the heated saline water enters the heater (3), where hot steam increases the temperature of the water up to maximum of 120°C. Then it is released in first flash chamber (4), where flash evaporation occurs due to lower pressure. Water vapour then ascends to the heat exchanger tubing (condenser) (2), through which the colder saline water flows, cooling the vapor and resulting in its condensation. The evaporation and condensation parts of the chamber are divided by demister (5), which captures brine droplets launched during flashing of water. The condensed (distilled) water is than collected (6) and conducted out of the system. The saline water that wasn't evaporated and condensed continues to next flash chamber (7) in sequence, where the exact same process occurs, only differing in lower pressure and temperature. And so, the saline water passes through several chambers until it is released from the system (8) in the form of brine with higher concentration of salts.

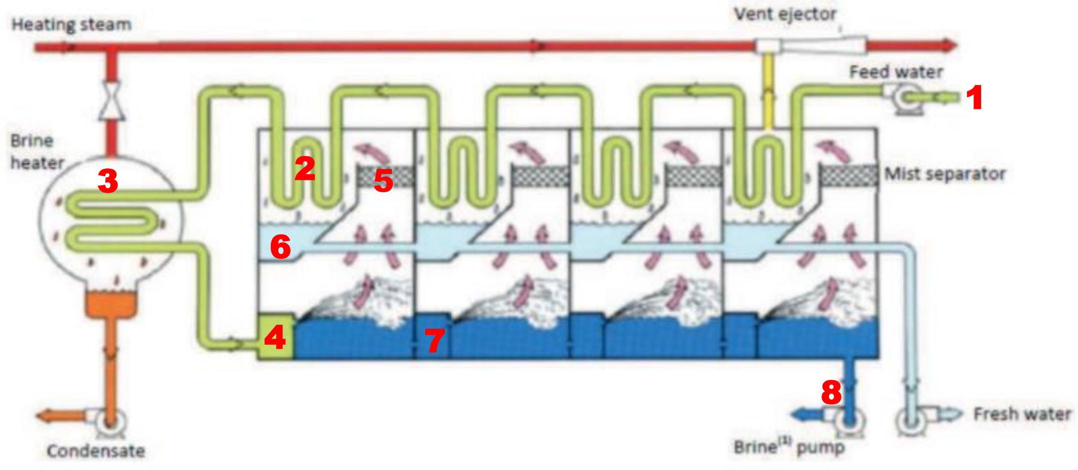

Figure 23: Multi-stage flash system diagram (Thimmaraju et al. 2018).

The reason for higher amount of flash chambers is that this design increases thermal efficiency of the system by recuperation of the heat. Recovery of the heat is illustrated in graph in figure 24, where green line represents saline water passing from the source to the heater, recovering heat from the condensers and finally being heated in heater to required temperature for proper flashing evaporation effect. Then following the orange line in the graph, we can see as with each following chamber temperature of the saline water drops, although due to the lower atmospheric pressure in each following chamber the boiling point of the water is lowered, and so sufficient evaporation still occurs across the whole sequence.

Efficiency of the MSF method reaches up to 15% of purified water out of total saline water intake depending on number of segments. This can be improved by operating at higher temperatures, but higher temperatures will also cause the salts such as calcium sulphate to precipitate on the tubes' surfaces, therefore causing thermal and mechanical problems like tube clogging. Some of the positives of MSF are relatively simple construction and operation of the system, high level of purification even though during the process most of the minerals are removed; thus, to render it fit for consumption it needs to be re-mineralized in post-treatment (Likhachev & Li 2013; Thimmaraju et al. 2018).

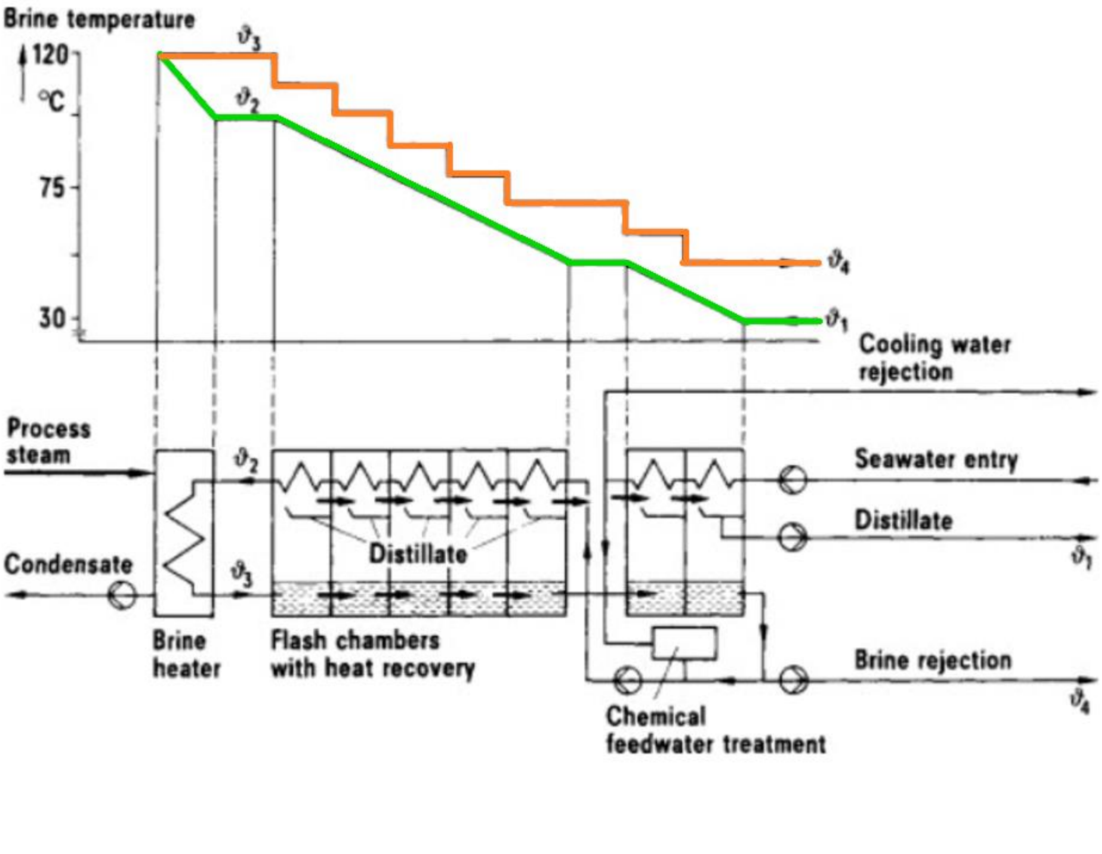

Figure 24: Multi-stage flash system diagram with graph of saline water temperature across the system (Kuenstle et al. 1984).

4.4.2.2. Multi-effect distillation

MED is similar to MSF, they share design of following stages (which are called effects in MED) with generation of water vapor from seawater, and recuperation of heat from the vapor to preheat the feed saline water via a heat exchanger. But design and utilisation of the evaporated water is different. Again, to present how MED works figure 25 is used with numbers referencing individual stages. First, the saline water is pumped through the heat exchanger (1), which preheats the water. This water is then sprayed on heat exchangers in individual effects (2). The first effect is heated by external source heat via steam in the heat exchanger (3). This steam from first effect will condensate and be collected together with rest of the distilled water (4). Water vapour from first effect is conducted into heat exchanger in the following effect (5) and after heat transfer, collected just as steam from the first effect. Saline water that hasn't evaporated at first is conducted into the following effect (6) where there is lower pressure than in the previous effect, which causes the same effect as in MSF. This process repeats in each effect until the last one, where fraction of the vapour is conducted to the condenser/heat exchanger (1), which preheats feed water. The other fraction of vapour is mixed with steam (7) from external heating source and conducted into the first effect.

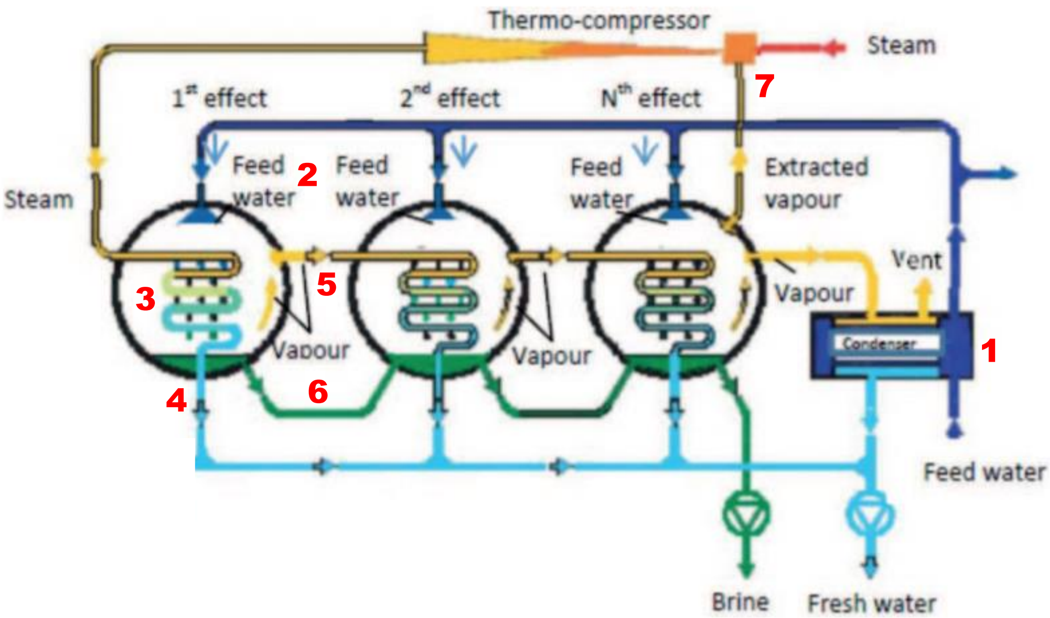

Figure 25: Multi-effect distillation system diagram (Thimmaraju et al. 2018).

Major characteristics of MED are high quality of purified water and high heat efficiency. Another positive is that MED power consumption is lower, and performance is higher than that of MSF. Therefore, MED method may be considered more cost effective and efficient than MSF method. On other hand MED systems are more complex and have higher need for maintenance than MSF (Warsinger et al. 2015; Thimmaraju et al. 2018).

4.4.2.3. Reverse osmosis

While in case of thermal based methods the salts are separated during evaporation, in case of membrane-based methods the salts are separated by filtration. RO membrane is capable of filtering out the smallest contaminants and ions, while other membranes used in nanofiltration, ultrafiltration, and microfiltration systems are designed to filter out materials of gradually increasing size, as presented in figure 26 (Aliku 2017).

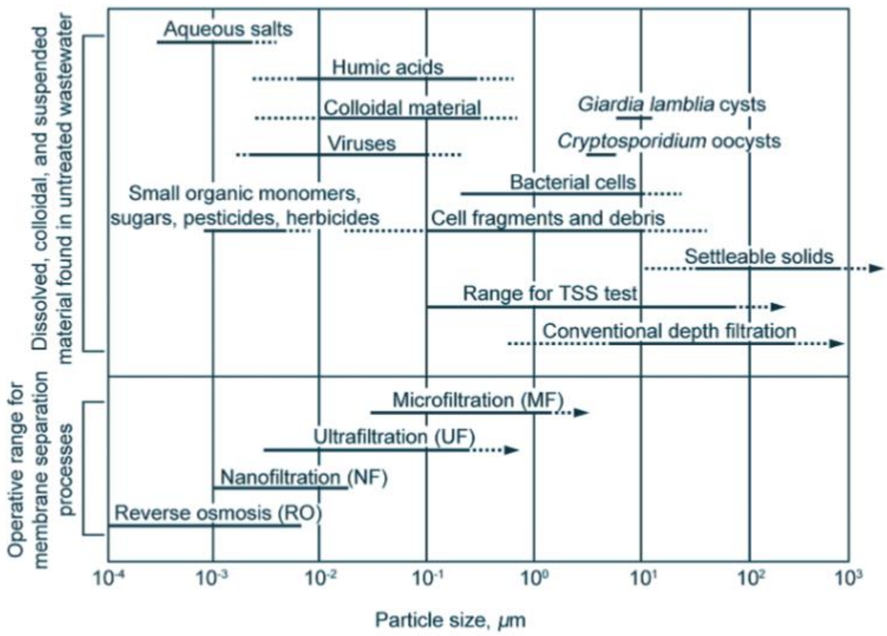

Figure 26: An illustration of the range of nominal membrane pore sizes for reverse osmosis, nanofiltration, ultrafiltration and microfiltration (Aliku 2017).

RO filtration is based on naturally occurring phenomenon called osmosis. Osmosis may be defined as a natural process in which water molecules spontaneously move from a solution of low saline concentration (low osmotic pressure) to a solution of high saline concentration (high osmotic pressure) across a semipermeable membrane, which filter out the solutes and allows only water molecules to pass (figure 27a). The process of osmosis continues until chemical potentials across the membrane become equal, which will result in higher amount of water on the saline side of the membrane under osmotic pressure (figure 27b). But if pressure is increased on the side with higher salinity to the point, where artificially applied pressure is higher that naturally occurring osmotic pressure, the process of osmosis will be reversed, and water molecules will move from a solution of high saline concentration to a solution of low saline concentration, leaving the solutes behind (figure 27c).

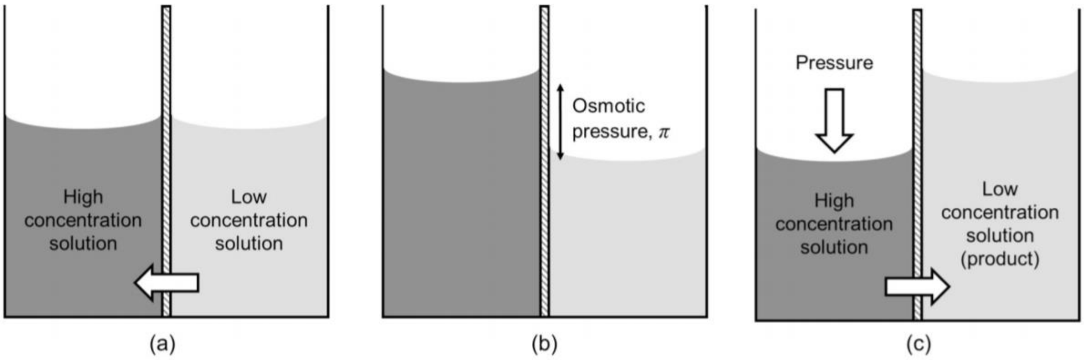

Figure 27: Diagram of (a) osmosis, (b) osmotic equilibrium and (c) reverse osmosis (Qasim et al. 2019)

In figure 28 is presented basic RO system, where saline water must first go through pre-treatment process. This step is crucial for consistent long-term process of filtration using RO, because the membrane is very susceptible to membrane fouling, which is a process during which solutions, particles or organisms are deposited on the surface of the membrane, causing its degradation. For that reason, pre-treatment is necessary to keep the membrane clean (Badruzzaman et al. 2019). After pre-treatment saline water is conducted to high-pressure water pump and further to the membrane module. In the module a part of the water is pushed under pressure through the membrane, while the rejected water with increased content of salts is being conducted through ventil securing high pressure in the module out of the system. Purified water then continues to the last stage: post-treatment.

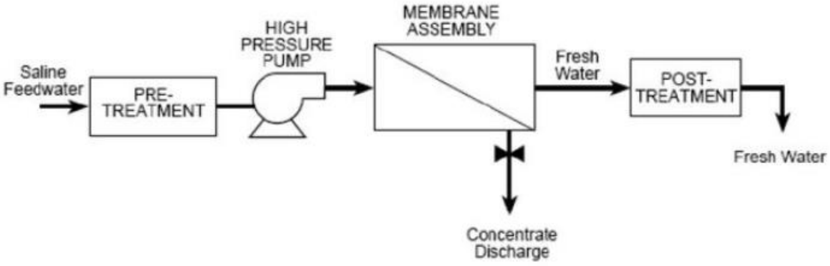

Figure 28 : Schematic basic RO system (Eltawil et al. 2008)

Core part of the RO system are membrane modules, which contain a membrane predominantly made from polymer material forming layered, web-like structure. There are nowadays 4 different types of modules: plate, frame, hollow fibre and spiral wound. Plate and frame modules were used initially, but recently they were replaced by hollow fibre and spiral wound modules. However, the hollow fibre modules are used less often because of their difficult cleaning and high susceptibility to fouling. And so spiral wound modules (figure 29) are currently the most used type in RO desalination. As the name suggests, the membrane is coiled in a spiral manner around the collector tube. More accurately, two membrane sheets are placed together with a permeate spacer in between them (for purified water flow) and another spacer on top and bottom (for saline water flow). The membrane sheets are glued from three sides with the fourth side left open and connected to a central perforated collector tube. The combination of membranes and spacers is wrapped around the permeate collector tube to create a spiral configuration and finally placed inside a housing. Feed water is introduced from one end of the module and travels along the length of the module. Water molecules are forced through the membrane and are collected through the perforated collector tube. The concentrated saline water leaves the module at the end opposite to the feed (Qasim et al. 2019).

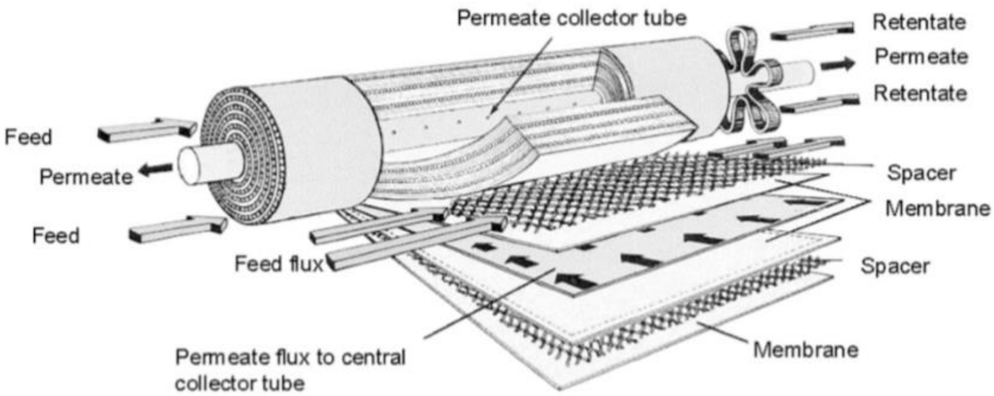

Figure 29: Spiral wound membrane module for RO system (Qasim et al. 2019).

Comparing the reverse osmosis method with thermal methods has an essential disadvantage: the need for proper water pre-treatment to prevent fouling. On the other hand, RO requires less power for continuous operation since there is no need for heating the water and there is also the possibility for instalment of recovery device, which would dramatically lower the power consumption. In most RO systems, recovery ranges from 50 to 85% and typically depends on the feed characteristics, feed salinity, pre-treatment, design configuration, and brine disposal considerations (Qasim et al. 2019).

5. Discussion

After the floods in 1995 the construction of the dams and diversions as preventive measure of future floods drastically decreased inflow of the water to the LU and was most probably the biggest contribution to desiccation of LU. After years of trend in water level decreasing, Ministry of Energy agreed upon allocation of 2 to 3 million m^3 of water to slow the desiccation, which resulted in noticeable decrease in the speed with which the water level in LU was dropping. This change is observable in figure 6 since 2010 (Jalili et al. 2016).

Beside the construction of dams and diversion of water, increasing water consumption of population in LU basin (especially in agriculture sector) is definitely another major cause for water losses in the lake and surrounding aquifers. This problem was addressed in the Iranian government fifth 5-year development plan (2010 – 2015) together with strategic policies and plans targeted at environmental issues as well as an ecosystem-based approach to the management of wetlands and biodiversity. The sixth 5-year development plan (2016 – 2021) continues to focus on reduction of water consumption of fresh water, setting the goal that consumption of potable water will be reduced by 30% by 2021. And also, to produce 30% of required water by the population of south Iran using desalination technologies (UN science division 2017).

Since 2005, the United Nations Development Programme, the Global Environment Facility and the Iranian Department of Environment have been working together to improve the management of Iran's wetlands (UN science division 2017).

In 2014 the Japanese government started providing grant for a project called "Contribution to restoration of LU via local community participation in sustainable agriculture and biodiversity conservation". The project was focused on implementing sustainable agricultural techniques in farming communities adjacent to the saltwater lake, resulting in 35% decrease in water consumption and drop in fertilizers and pesticides use by 40%. Thanks to the annual contribution of 1 million USD from the government of Japan, the project has covered 130 villages so far (UNDP Iran 2018).

In 2016 Food and Agriculture Organisation started collaboration with Iranian government on "Urmia Lake Restoration Programme" to ensure sustainable management of the water resources of the lake basin area (UN science division 2017).

6. Conclusions

Lake Urmia has been losing water since 1995, initial water drop was most probably caused by construction of dams and water diversions across the lake's basin with contribution of latter droughts and overall decreased precipitation. With increasing population in LU basin, domestic, industrial but most importantly agricultural water consumption was also increasing, causing further reduction of inflow water to the lake and overusing of groundwater sources. This resulted in increased salinity of the lake, which further caused loss of biodiversity in the lake basin, through mass reduction in brine shrimp population. Decreasing water level revealed lakebed with thick layer of salts that through wind erosion is capable to spread the salts throughout the whole lake basin and potentially even further causing more problems in areas that have no control over the source of the problem. Much like increasing of salinity of the soil, health problems and increased salinity of the groundwater by salts being transferred by precipitation into lower layers of soil.

To revive Lake Urania, water reduction strategies must be adopted throughout the whole lake basin to increase available water for lake inflow. Together with better water allocation management that would allow LU to refill while also satisfying the energy and water needs provided by dams. Resolving the source of the problem (low water level in the lake) should also resolve consequences of it (dust, groundwater salinity). But resolving the core problem will most likely take some time during which the consequences will only grow. And so at least temporary solution should be offered. To prevent increasing spread of salt particles through the wind, planting halophytes onto dried lakebed proved in small scale to be effective solution that should be applied in larger scale to prevent salinization of the soil and consequently groundwater. Although because of overuse of water from aquifers, the intrusion of saline water from the lake caused on several places around the lake increase in groundwater salinity. Which in some cases renders the water unfit for consumption by humans or animals. And using this kind of water for irrigation will cause inhibition of plant growth. For that reason, these affected areas should be equipped with water desalinisation unit to produce potable water.

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