INVESTIGATION ON THE IMPOUNDMENT EFFECTS OF THE CONSTRUCTED DAMS ON THE HYDRODYNAMIC AND DISTRIBUTION OF SALINITY IN URMIA LAKE (BY MIKE 3 FLOW MODEL FM)

Ph.D. Thesis
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Summary (In English)

The Urmia Lake is the second most saline lake in the world after the Dead Sea, located in Northwestern of Iran. The lake has been facing a serious environmental crisis, because of mismanagement in water uses. Natural flow patterns of the input rivers in the Urmia Lake basin have changed over the past two decades due to changes in water resources use, land use and climate. The reduction of the water level of the lake during the two last decades, evaluated both on a monthly and yearly scale, was more harsh than ever before and deeply different from changes in precipitation and temperature during the same period, leading to the conclusion that anthropogenic factors have been impacting far more than natural variability. Water resources development plans such as constructing of reservoir dams has environmental effects on rivers that change in the natural river regime and reduce in the natural river discharge in downstream of the dam is major effects of those. The main objective of this research is to regulating dams as the river has closest intra annual flow to natural regime of the river. This thesis investigates the effects of the constructed dams on the hydrodynamics and the salinity distribution inside the Urmia Lake, making use of the three-dimensional MIKE 3D flow Model FM solver. The thesis is structured in four main parts:

The first part deals with the correct water balance of the Urmia Lake. Being the lake a closed basin, its water level and salinity depends on the water balance. Therefore before any analysis it is necessary to model water level fluctuations with sufficient accuracy. Using the discharges measured at the last hydrometric stations of each tributary led to remarkable errors in water level simulation, as both significant water consumption for agricultural purposes and positive groundwater underflow contributions occur in the final river reaches. Indeed, between the last hydrometric station and the lake there is an area where losses and yields can affect the final amount of flow reaching the lake. This is called the buffer zone. In this study, two boundaries are defined for the buffer zones, through which two zones are created. An additional discharge term ($V_{Unmeasured}$) has been added to the water balance equation of the lake to account for the unmeasured positive and negative terms between the last hydrometric stations and the lake and also resultant of errors in the estimation of each term in the water balance equation. This term can be considered as losses, including agricultural and industrial uses in buffer zone 1, penetration and evaporation of water, or as inputs, including precipitation, runoff of seasonal rivers or groundwater that has reached the surface of the buffer zone. In the current study, the methods adopted to determine each of the terms in the water balance equation of the lake have been described. The unknown water volume $V_{Unmeasured}$ in the mentioned equation has been calculated and then equated to precipitation and evaporation height for negative and positive values of $V_{Unmeasured}$, respectively in all simulations of the water level of the lake. As a result of the corrections to the discharges at the hydrometric stations, the simulated water level agrees with the measured one in all the simulated periods. The water balance of the lake was calibrated by comparison between the measured surface water levels and those simulated by MIKE 3 Flow Model FM, between the volume measured by bathymetry of the lake and the volume calculated by the water balance equation of the lake and also between the surface area of the lake estimated by satellite images with the simulated one.

The contribution of each term of the water balance equation is different in producing the final value of $V_{Unmeasured}$. Results revealed that the evaporation term has the most uncertainty so it is very effective in estimating the final value of $V_{Unmeasured}$. The runoff to rivers flowing into the lake can also affect the value of $V_{Unmeasured}$ during wet months; this term has significant impact on the $V_{Unmeasured}$ values. The results revealed the value of $V_{Unmeasured}$ are 25.67, 11.55, 3.53 and

4.65 percent of the annual river inflow, respectively, for 1986-1987, 1991-1992, 2004-2005 and 2009-2010. The annual amount of $V_{Unmeasured}$ is not a good indicator of the monthly amount of this term, because it can be affected by high values occurring only in one or some months of the year. For example, it is possible that, even for most months the amount of this term is negative, few months of positive $V_{Unmeasured}$ lead to an annual positive value. In other words, if the annual scale is assumed to evaluate the amount of water required for release, then, depending on the release rate, not only a different value for $V_{Unmeasured}$ can be obtained, but also its sign will be changed. Therefore, the time scale is crucial in estimating the correct value for $V_{Unmeasured}$. It is recommended to employ smaller time scale to close the water balance, i.e. monthly or daily ones.

The second part of this thesis quantified the changes in the hydrology of surface waters in the Urmia Lake area due to river regulation, water use and climate changes. The changes are evident in rivers and lakes as shifts in flow regime characteristics (timing and magnitude of the flow and its distribution). To understand the impacts of the construction of dams in the dynamics of natural rivers, simple indicators can be used as management tools to quantify the various impacts caused by changes in water use. This knowledge is valuable for making decisions about the role of constructed and under construction reservoir dams, to achieve to water release patterns from dams that minimize the hydrological, morphological and biological impacts.

Flow release from reservoirs can be partly supplemented or compensated by natural runoff from downstream (residual) catchment areas. In a new hydrological approach (presented by Torabi Haghighi, 2014), optimal intra–annual flow regime of dams can be estimated by considering water inflow from the downstream residual sub-catchment. In this study the regulation rule of some major dams in the Urmia Lake basin for three different release policies (30, 50 and 80 percent of mean annual flow) have been calculated. By using the simple theorical approach basis on water balance and historical measured of hydrometric data, the monthly value of $Q_{Residual}$ (the water provided by the unregulated catchment downstream of the dam) has been calculated. Then, Q_{AAD} (the annual available water volume in the last hydrometric station) for each river has been calculated under the three mentioned dam operation policies. The results revealed that under scenario 3 with 80% of Mean Annual Flow (MAF), all of the rivers have possitive value for Q_{AAD}, so scenario 3 selected as an effective scenario for restoration of the lake. Finally, by using the monthly distribution of water volume in unit annual natural (unregulated) hydrograph, the monthly value of Q_{CAH} (the closest annual hydrograph to natural hydrograph of the river) in the last hydrometric station for each river and Q_{RW} (role curve of dam) for scenario 3 has been calculated.

In the third part of this thesis, the three-dimensional numerical model MIKE 3 Flow Model FM was employed to evaluate the lake response to the dam regulations and to investigate the hydrodynamic behavior of the lake. Model sensitivity analyses revealed that wind speed is effective input variable and wind friction coefficient and vertical eddy viscosity are effective parameters on flow velocities and on the salinity distribution. The lake bottom roughness height is less influenced and negligibly affects surface velocities. Using a very low vertical eddy viscosity improves flow velocities underestimation, but worsted the reproduction of salinity distribution. Use of the UNESCO equation for density implemented in MIKE 3 Flow Model FM for hypersaline the Urmia Lake leads to density overestimation, yet model accuracy in prediction of salinity of the lake is acceptable. The simulation results of the Urmia Lake revealed that the salinity differences between North and South basins significantly increased after the draining process and in intra annual scale peaking in May with the arriving of fresh waters from snow melting. This study indicate that the present model of the Urmia Lake could be run for any time

period in natural and drought conditions and can satisfactorily simulate the hydrodynamics and salinity distribution. The overall water flow was directed from the Southern to the Northern basin for the simulated periods of 1986-1987 and 2004-2005. The exchanged discharge strongly reduced because of the increased salinity difference due to lake draining. Results also revealed that there is a two ways opposed flows along the water depth due to wind and inflows.

As the ShahidKazemi Dam (Bukan Dam) is the largest dam in the Urmia Lake basin, in the last part of this thesis, it’s selected for investigation the effect of impoundment of dam on hydrodynamics and salinity distribution of the Urmia Lake. Results of evaluation for periods of 2009-2010 indicated that if the dam was not supply any volume of water since 23th September 2009 the lake water level will be increased about 11 cm until 23th September 2010 but base on measured data impoundment of 1310 Mm^3 of inflow by the dam for off stream diversion and storage purposes cause to 24 cm declining of the water level. Therefore, the ShahidKazemi Dam has remarkable effect on water level of the lake. Average salinity of the lake has been decrease about 40 PSU in mentioned condition.

The results of this thesis can be guidance for water resources managers in the Urmia Lake basin and experts of Urmia Lake Restoration Committee for operation of dams in the basin.

Keywords: Dam regulation, Hydrodynamic modeling, MIKE 3 Flow Model FM, Urmia Lake, Shallow hypersaline lakes, Salinity distribution.

Summary (In Persian)

دریاچه ارومیه بعد از دریای مرده به عنوان دومین دریاچه شور دنیا در شمال غرب ایران واقع شده است که به دلیل عدم مدیریت مصرف آب با بحران زیست محیطی جدی مواجه شده است. رژیم طبیعی جریان رودخانه های ورودی در حوضه آبریز دریاچه ارومیه در طی دو دهه گذشته به دلیل تغییر در استفاده از منابع آب، تغییر کاربری اراضی و تغییر اقلیم کاهش پیدا کرده است که این تغییرات در مقیاس ماهانه و سالانه بسیار شدیدتر و متفاوت تر از تغییرات بارش و دما است. بنابراین اثرات فاکتورهای انسانی نسبت به متغیرهای طبیعی بیشتر است. طرح های توسعه منابع آب نظیر احداث سد های مخزنی دارای اثرات زیست محیطی متعددی می باشند که تغییر رژیم طبیعی رودخانه و کاهش جریان طبیعی پایین دست از مهمترین آن هاست. مهمترین هدف این تحقیق تنظیم سدها بصورتی است که رودخانه با کمترین تغییر نسبت به رژیم طبیعی خود جریان داشته باشد. این تحقیق شامل چهار بخش مجزا می‌باشد:

در ابتدا، از آنجا که دریاچه ارومیه دارای یک حوضه آبریز بسته می‌باشد تراز سطح آب و شوری آن به بیلان آب آن وابسته است. بنابراین قبل از هر اقدامی ضروری است که نوسانات تراز سطح آب با دقت مناسبی شبیه‌سازی شود. از آنجا که مصرف قابل ملاحظه آب برای اهداف کشاورزی و ورود جریان آب زیرزمینی در بخش انتهایی رودخانه‌ها اتفاق می‌افتد استفاده از دبی اندازه‌گیری شده توسط آخرین ایستگاه هیدرومتری روی هر رودخانه منتهی به دریاچه منجر به خطای قابل ملاحظه‌ای در شبیه‌سازی تراز سطح آب دریاچه می‌شود. در فاصله بین آخرین ایستگاه هیدرومتری نزدیک دریاچه و پیکره آبی آن ناحیه‌ای وجود دارد که تلفات و آوردها در این ناحیه می‌تواند بر مقدار آب ورودی به دریاچه تاثیر بگذارد. $V_{Unmeasured}$ در معادله بیلان آب دریاچه یک مجموعه‌ای از ترم‌های مثبت و منفی حساب نشده بین آخرین ایستگاه آبسنجی تا پیکره آبی دریاچه و همچنین برآیند خطاهای برآورد هر یک از مولفه‌های بیلان آب دریاچه است. این مولفه‌ها می‌تواند بصورت افت شامل مصارف در بخش کشاورزی و صنعت در بافرزون ۱، نفوذ و تبخیر آب و یا بصورت ورودی شامل بارندگی روی سطح بافرزون‌ها، رواناب رودخانه‌های فصلی یا آب زیرزمینی که به سطح بافرزون رسیده است باشد. در این تحقیق روش تعیین هر یک از مولفه‌های معادله بیلان آب ذکر شده است. $V_{Unmeasured}$ بصورت مولفه‌ی نامعلوم در معادله مذکور محاسبه شده است و سپس به ارتفاع بارندگی و تبخیر به ازای مقادیر مثبت و منفی در تمامی شبیه‌سازی‌های دریاچه تبدیل شده است. نتیجتا اصلاح دبی ورودی از آخرین ایستگاه هیدرومتری نشان داد تراز سطح آب اندازه‌گیری شده با تراز سطح آب شبیه‌سازی شده در تمامی سال‌های مبنای مدل‌سازی مطابقت دارد. به عبارت دیگر برای کالیبره کردن بیلان آب دریاچه، مقایسه بین تراز سطح آب اندازه‌گیری شده و شبیه‌سازی شده توسط مدل MIKE 3 Flow Model FM، حجم اندازه‌گیری شده توسط نقشه بسیمتری دریاچه در مدل و محاسبه شده توسط معادله بیلان آب دریاچه و همچنین مقایسه بین مساحت پیکره آبی دریاچه در تصاویر ماهواره‌ای با مساحت شبیه‌سازی شده توسط مدل به کاربرده شده است.

سهم هر یک از مولفه‌های معادله بیلان آب در مقدار نهایی $V_{Unmeasured}$ متفاوت است. نتایج نشان داد که مولفه‌ی تبخیر بر مقدار نهایی $V_{Unmeasured}$ خیلی تاثیرگذار است همچنین مجموع دبی ورودی رودخانه‌ها به دریاچه می‌تواند مقدار $V_{Unmeasured}$ را در ماه‌های تر تحت تاثیر قرار دهد. نتایج نشان داد که مقدار $V_{Unmeasured}$ برابر با ۲۵/۶۷ ، ۱۱/۵۵ ، ۳/۵۳ و ۴/۶۵ درصد از مجموع دبی سالانه اندازه‌گیری شده رودخانه‌های ورودی به دریاچه به ترتیب در سال‌های ۱۹۸۷–۱۹۸۶، ۱۹۹۲–۱۹۹۱، ۲۰۰۵–۲۰۰۴ و ۲۰۱۰–۲۰۰۹ می‌باشد. مقدار سالانه $V_{Unmeasured}$ نماینده خوبی از مقدار ماهانه این مولفه

نمی‌باشد چرا که زیاد بودن مقادیر این ترم در یک یا چند ماه خاص از سال می‌تواند روی مقدار سالانه آن اثر بگذارد. به عنوان مثال این امکان وجود دارد که در اکثر ماه ها مقدار این ترم منفی باشد (یعنی درصدی از آب رسیده به بافر زون در داخل آن تلف شده باشد) در حالیکه $V_{Unmeasured}$ سالیانه مقدار مثبتی را نشان دهد. به عبارت دیگر در صورتیکه مقیاس سالانه، معیار تصمیم گیری برای مقدار آب مورد نیاز جهت رها سازی باشد، ممکن است با توجه به میزان رها سازی نه تنها مقدار متفاوتی برای $V_{Unmeasured}$ بدست آید بلکه علامت آن نیز عوض شود. بنابراین مقیاس زمانی نقش موثری را در مقدار برآورد شده برای $V_{Unmeasured}$ دارد. و با توجه به تغییرات این ترم در ماه های مختلف پیشنهاد می شود که مقیاس زمانی جهت بستن بیلان آب کوچکتر (ماهانه یا روزانه) انتخاب شود.

بخش دوم تحقیق حاضر شامل کمی کردن تغییر در هیدرولوژی رودخانه بعد از تغییر در تنظیم دبی رودخانه، مصرف آب و اقلیم است. تغییرات در رودخانه‌ها و دریاچه بصورت تغییر مشخصات رژیم جریان (زمان‌بندی، اندازه جریان و توزیع آن) است. برای فهمیدن اثرات ساخت سدها بر دینامیک رودخانه‌های طبیعی، شاخص‌های ساده‌ای بصورت ابزار مدیریتی برای کمی کردن اثرات مختلف ایجاد شده توسط تغییر الگوی مصرف آب می‌تواند مفید واقع شود. این آگاهی برای تصمیم‌گیری درباره منحنی فرمان سدهای مخزنی ساخته شده و در حال ساخت و همچنین رسیدن به الگوی رهاسازی آب از سدها که اثرات هیدرولوژیکی، مورفولوژیکی و بیولوژیکی را به حداقل می‌رساند ارزشمند است.

منحنی فرمان سدها و بهینه کردن توزیع آب آن برای سلامتی اکوسیستم دریاچه ضروری است. جریان آب رها شده از سدها می‌تواند توسط رواناب طبیعی حوضه آبریز پایین‌دست سد تقویت شود. در یک روش هیدرولوژیکی جدید (ارائه شده توسط ترابی حقیقی، ۲۰۱۴)، رژیم جریان بهینه سدها در طول سال با استفاده از جریان آب حوضه آبریز پایین‌دست می‌تواند تخمین زده شود. در این تحقیق منحنی فرمان چند سد مهم حوضه آبریز دریاچه ارومیه تحت سه سیاست متفاوت رهاسازی آب از سد (۳۰، ۵۰ و ۸۰ درصد میانگین جریان سالانه که از سال ۱۳۷۶ تا ۱۳۹۱ در نظر گرفته شده است) محاسبه شده است. با استفاده از روش تئوری ساده بر اساس بیلان آب و دیتای آبسنجی اندازه‌گیری شده، مقدار ماهانه $Q_{Residual}$ (مقدار آب فراهم شده توسط حوضه آبریز پایین‌دست سد) محاسبه شده است. سپس Q_{AAD} (مقدار حجم آب در دسترس سالانه در آخرین ایستگاه هیدرومتری هر رودخانه) برای هر سه سناریو بهره‌برداری از سد محاسبه شده است. نتایج نشان داد با بکاربردن سناریو ۳ با ۸۰ درصد از MAF همه رودخانه مقدار مثبتی برای Q_{AAD} خواهند داشت بنابراین سناریو ۳ بعنوان سناریو موثر بر احیای دریاچه انتخاب شد. در نهایت با استفاده از توزیع ماهانه حجم جریان در هیدروگراف واحد سالانه طبیعی، مقدار ماهانه Q_{CAH} (نزدیک‌ترین هیدروگراف سالانه به هیدروگراف طبیعی رودخانه) در آخرین ایستگاه آبسنجی هر رودخانه و Q_{RW} (منحنی فرمان سد) برای سناریو ۳ محاسبه شد.

در قسمت سوم از تحقیق برای ارزیابی واکنش دریاچه به تنظیم سدها و برای بررسی رفتار هیدرودینامیکی دریاچه، مدل عددی سه بعدی MIKE 3 Flow Model FM به کار برده شد. آنالیز حساسیت مدل نشان داد که سرعت باد متغیر ورودی و ضریب اصطکاک باد و لزجت گردابی عمودی پارامترهای موثر بر سرعت جریان و توزیع شوری هستند. ارتفاع زبری بستر کمتر تاثیرگذار بوده و به میزان ناچیزی بر سرعت جریان در سطح اثر می‌گذارد. استفاده از لزجت گردابه‌ای خیلی کم، سرعت جریان را بهبود می‌بخشد ولی توزیع شوری را بدتر می‌کند. استفاده از معادله یونسکو برای چگالی در مدل برای دریاچه فوق اشباع از نمک ارومیه منجر به بیش برآورد چگالی دریاچه می‌شود. دقت مدل در برآورد شوری قابل قبول می‌باشد. نتایج شبیه‌سازی دریاچه ارومیه نشان داد اختلاف شوری بین شمال و جنوب دریاچه به طور قابل ملاحظه‌ای بعد از فرآیند خشک شدن دریاچه افزایش یافته و در یک طول سال نیز در ماه می (اردیبهشت ماه) به دلیل ورود جریانات آب

شیرین ناشی از ذوب شدن برف‌ها به اوج خود رسیده است. این تحقیق ثابت کرد که مدل ارائه شده دریاچه ارومیه می‌تواند برای هر دوره زمانی در شرایط خشکی و شرایط طبیعی مورد استفاده قرار گیرد و بطور رضایت بخشی می‌تواند هیدرودینامیک و توزیع شوری دریاچه را شبیه‌سازی کند. جهت برآیند جریان آب از جنوب به شمال برای سال‌های ۱۳۶۶–۱۳۶۵ و ۱۳۸۴–۱۳۸۳ بوده است. کاهش شدید دبی تبادلی با خشک شدن شدن دریاچه دلیل افزایش اختلاف شوری دریاچه است. همچنین نتایج تحقیق نشان داد که جریانات دو سویه ناشی از وزش باد وجود دارد که به دلیل کم عمق بودن دریاچه اختلاط کامل جریان توسط نیروی باد صورت می‌گیرد.

با توجه به این که سد شهید کاظمی بزرگترین سد مخزنی در حال بهره‌برداری حوضه آبریز دریاچه است جهت بررسی اثر آبگیری از سدها بر هیدرودینامیک و پراکنش شوری دریاچه انتخاب شد. نتایج بررسی برای سال ۲۰۰۹–۲۰۱۰ نشان داد که در صورت عدم آبگیری از سد مذکور تراز سطح آب دریاچه ۱۱ سانتی‌متر در انتهای سال آبی افزایش خواهد داشت در حالیکه به دلیل ذخیره ۱۳۱۰ میلیون متر مکعب آب در پشت سد طی سال ۲۰۰۹–۲۰۱۰ در ۲۳ سپتامبر ۲۰۱۰ شاهد ۲۴ سانتی‌متر کاهش تراز سطح آب دریاچه بوده ایم. این بدین معنی است که سد شهید کاظمی اثر قابل ملاحظه ای بر تراز سطح آب دریاچه ارومیه داشته است. همچنین نتایج بررسی شوری آب دریاچه نشان داد که شوری متوسط دریاچه به ازای ورود ۱۳۱۰ میلیون متر مکعب آب بیشتر در اثر عدم آبگیری سد به میزان ۴۰ PSU کاهش یافته است.

نتایج تحقیق حاضر می‌تواند بصورت یک راهنما برای مدیران منابع آب حوضه آبریز دریاچه ارومیه و کارشناسان ستاد احیای دریاچه ارومیه در جهت بهره‌برداری سدهای حوضه مورد استفاده قرار گیرد.

کلمات کلیدی: تنظیم سد، مدلسازی هیدرودینامیکی، MIKE 3 Flow Model FM، دریاچه ارومیه، دریاچه‌های فوق اشباع از نمک کم‌عمق، توزیع شوری.

CHAPTER 1: INTRODUCTION

1.1. Introduction to the Urmia Lake

The Urmia Lake is the second most saline lake in the world after the Dead Sea (Karbasi et al., 2010). It is located in Northwestern Iran, between the provinces of West and East Azerbaijan. The Urmia Lake is an endorheic closed basin, so that water leaves only by evaporation, hence explaining hypersalinity. Inlets consist of precipitation, rivers, runoff and groundwater (Ghaheri, 1999). Some general information and qualitative and quantitate ecological index of the Urmia Lake have been shown in Table 1.1 and 1.2, respectively. In Table 1.3 and 1.4 differences of land use area and population growth during last decades in the whole lake basin has been shown.

Table 1.1. General information on the Urmia Lake

Location of the lake	Latitude : 35°40’N - 38°30’N Longitude : 44°13’E - 47°54’E
Basin Area	51,876 km^2
Mean Surface Elevation (average from 1969 up to 2016)	1274.94 m a.s.l.
Surface Area (average from 1969 up to 2016)	4619.52 km^2
Length (North to South)	130-146 km
Width (West to East)	15-58 km
Depth	6-13 m
Volume (average from 1969 up to 2016)	18.34 106 m^3
Topographical Distribution*1	Mountainous: 33,736 km^2 (63.3%) Plain: 12,664 km^2 (23%) Lake: 5,362 km^2 (13.7%) (as of Dec, 2013)
Administration*1	East Azerbaijan Province (24,888 km^2, 48%) West Azerbaijan Province (20,832 km^2, 40%) Kurdistan Province (6,042 km^2. 12%)
Population (as of 2011) *2	East Azerbaijan Province (2,143 thousand people, 57.6%) West Azerbaijan Province (1,437 thousand people, 38.6%) Kurdistan Province (142 thousand people, 3.8%)
Season*1	Spring: March – May Summer: June – August Autumn: September – November Winter: December – February
Air Temperature*3	-6 – 31.2°C (Urmia)
Average Air Temperature*3	10.9°C
Average Annual Precipitation*1	401 mm
Potential Annual Evapotranspiration*1	530～680mm
Climate*1	Cold Semi-Arid, Steppe Climate (Köppen: BSk)

*1: Source: JICA et al., (2016)
*2: Source: “Statistical Centre of Iran” (http://www.amar.org.ir/Default.aspx?tabid=133)
*3: Source: “World Weather Service” (http://worldweather.wmo.int/en/city.html?cityId=1454)

Table 1.2. Qualitative and quantitate ecological index of the Urmia Lake (Source: http://urmialake.urmia.ac.ir/sites/urmialake.urmia.ac.ir/files/last-rep-urmialake.pdf))

Index	Value	Unit
Threshold of salinity tolerance	240	mgr/lit
Ecological water level of the lake	1274.1	m a.s.l
Ecological surface area	4652.2	km^2
Evaporation from the lake surface	4467.9	Mm^3/Year
Precipitation on the lake surface	1381.2	Mm^3/Year
Required volume of inflow rivers to maintenance on the ecological water level	3086	Mm^3/Year

Table 1.3. Summary of differences of land use area in the whole lake basin (JICA et al., 2016)

	Bare Soil	Dry Farming	Irrigated Wheat	Orchard	Rangeland	Residential	Summer crops	Water	Total
In 1987 (km^2)	2,116	6,900	982	351	33,153	201	2,968	5,112	51,783
(Percentage in the basin)	4%	13%	2%	1%	64%	0.39%	6%	10%	-
In 2007 (km^2)	2,604	8,507	1,792	1,312	30,333	332	2,564	4,338	51,783
(Percentage in the basin)	5%	16%	3%	3%	59%	0.6%	5%	8%	-

Table 1.4. Summary of population growth in the whole lake basin (Statistical Centre of Iran: http://www.amar.org.ir/Default.aspx?tabid=133)

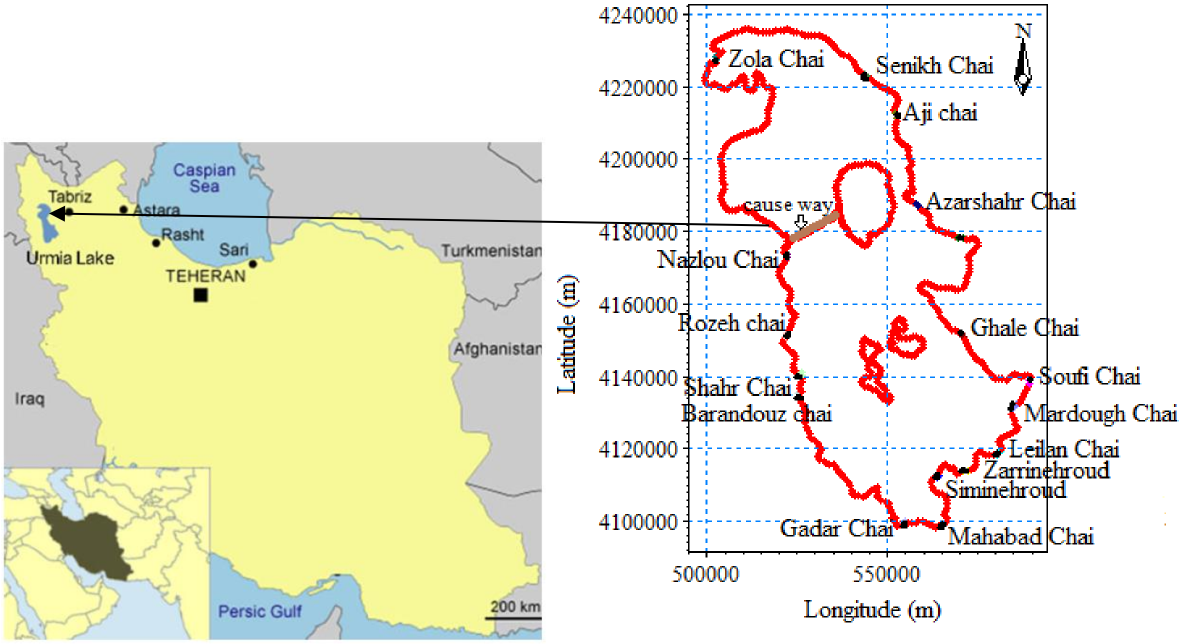
Population Growth Ratio						Population			
1996-2006			1986-1996						
Rural	Urban	Total	Rural	Urban	Total	2011	2006	1996	1986
-0.1	1.9	1.2	0.5	2.7	1.8	3722213	4113227	4312114	3151534

Because of its unique natural and ecological features, such as the existence of an exclusive parthenogenetic species of Artemia (Urmiana Artemiana) (Barigozzi et al., 1987), this hypersaline lake was declared a wetland of international importance by the Ramsar Convention in 1971 (Ramsar Site) and in 1976 was designated a UNESCO (UNESCO Site) Biosphere Reserve (ULRC, 2015a).

A dike-type causeway crossing the whole lake was gradually built in the middle of the lake from 1979 to 2009 to connect the cities of Urmia (West Azerbaijan Province) and Tabriz (East Azerbaijan Province). The causeway divides the lake in Northern and Southern basins, limiting the exchange of water to a 1.25-km long opening in correspondence of a bridge (Teimouri, 1998).

During the last two decades, because of climate change and anthropogenic reasons, the water level of the Urmia Lake has been strongly declining, with the Southern part of the lake drying up completely. This fact has caused salinity to rise sharply. According to the latest sampling taken in November 2016 by the Fisheries and Aquaculture Department of Urmia University, salinity was between 408 to 432 PSU. Results of hydrodynamic numerical modeling of the Urmia Lake reveal that the flow field is affected by wind, while river discharge, evaporation and rainfall were the main input variables of numerical simulation that affecting the salinity distribution. The influence of the causeway on salinity difference between northern and southern parts as well as on flow exchange between these two basins is unquestionable, and needs additional hydrodynamic studies to those already performed to gain a better knowledge about it.

The location of the Urmia Lake and of the causeway, as well as of the mouths of the major input rivers, is shown in Figure 1.1. The Urmia Lake has 22 tributaries, the most important being Zarrinehroud, Siminehroud, AjiChai, GadarChai, NazlouChai and MahabadChai. All main inflows to the Urmia Lake discharge into the South basin.



(a) (b)

Figure 1.1. Location of the Urmia Lake in Iran (a) and outline of the Urmia Lake with the causeway and the final reaches of the major input rivers (b)

1.2. Causes and consequence of drying

During the last two decades (since 1995) the water level of the Urmia Lake has been declining. Based on precipitation measurement stations in the lake basin, the annual precipitation in the basin from 1995 up to 2013 decreased by about 18%, i.e. by about 68 millimeters (ULRC, 2015 a). Ecosystem of the Urmia Lake has been deranged by operating 35 dams with storage volume of about 1707 Mm^3 (Yasi, 2017). Results of investigations by Hassanzadeh et al., (2011) revealed that four dams (Alaviyan, ShahidKazemi Dam (Bukan Dam), Mahabad and Nahand) have been responsible for 25% of the lake water level reduction, while climate change and overuse of surface water is the cause of 65% of the same reduction. The remaining 10% is caused by the lower precipitation.

Nonetheless, the reduction of the water level of the lake through the two last decades, evaluated both on a monthly or yearly scale, was more harsh than ever before and different from the changes in precipitation and temperature in the same period, leading to blame anthropogenic factors (Jalili et al., 2016 a; Jalili et al., 2016 b; Zoljoodi and Didevarasl, 2014).

Furthermore, last assessment of water demand in the Urmia Lake basin revealed that 70% consumption of renewable water resources of the basin, whereas according to the Stable Development Index of the United Nations Commission the amount of secure and acceptable consumption of renewable water resources should be between 20% and 40%. Therefore, the 30% overuse from the Urmia Lake basin because of the development of agriculture has affected the stability of the water resources of the basin (ULRC, 2015 a).

In the Urmia Lake basin, the population growth leads to an increasing need for food as well as water demand (Khatami and Berndtsson, 2013). Agriculture in the basin consumes about 90% of water and more than 60% of the renewable one. Based on recently published data by the Ministry of Energy (MOE), in 2011 the annual water volume consumption for agriculture purpose was 4.3 Mm^3. In spite of that, agriculture consists of 30% of whole basin incomes (ULRC, 2015 a). It seems that developing industrial activities in the Urmia Lake basin can decrease, depending on the economy of the region to agriculture, thus decreasing water demand.

The drop in the lake water level has increased the salinity of the lake. Artemia Urmiana tolerates a salinity range of 40 to 250 gr/lit (Csavas, 1996), so continuation of this trend in recent years threatens the life of Artemia with extinction danger. Since Artemia is the main food resource for birds, especially flamingos, which spawn in the basin, a severe decrease in the number of birds has also occurred (Abbaspour et al., 2012).

Furthermore, drying of the Urmia Lake has left the majority of the lake area covered by salt, especially in the southern part. Based on experience from the Aral Sea, this change leads to many problems for the ecosystem and the climate of the area, such as salt storms and subsequent refractory diseases for children and other health hazards (Zetterstrom, 1999).

In Figure 1.2, some examples of the consequences of dropped water level in the Urmia Lake are shown. Other strong environmental impacts consist in the rising the lake bed level and in its flattening because of settling salts. Based on satellite images and other remote sensing observations, the bed level of the lake has increased by 4 up to 108 cm from 2013 to 2015 (WRI, 2015).


(a) (b) (c)

Figure 1.2. Examples of the consequence of the drying of the Urmia Lake; a: desertification in Jabal Kandi region (south -western part of the Urmia Lake, in January 2014); b: salt storm; c: death of birds.

1.3. Administrative action plans of the Urmia Lake Restoration National Committee

The Urmia Lake Restoration National Committee (ULRC) has proposed management and structural policies for the restoration of the lake. As the programs have pros and cons, an accurate investigations of cost to benefit ratios of the different projects is essential. Proposed plans consist in the actions listed below (ULRC, 2015 b):

I. enhancement of inflow volume in rivers flowing into the Urmia Lake, through;
- the connection of two major rivers, Zarrinehroud and Siminehroud, to ease water delivery to the lake;
- the dredging of Siminehroud, GadarChai, MahabadChai and AjiChai Rivers;

II. increase in input water volume to the lake by the release of stored water from the constructed dams;
III. inspection of illegal overuse of surface and ground waters;
IV. protection actions to decrease salt storm disasters;
V. Inter basin water transfer plans;
- from Zaab River Subbasin;
- from the Silve Dam to the Southern part of the lake;

VI. increase of the efficiency of irrigation by using new methods.

Some of the mentioned action plans have high costs such as the dredging of major rivers and cross basin water transfers plans. Those restoration plans so far have had huge expenses for the government, but their implementation process has been slow and their efficiency in restoring the lake water level has been questionable (Khatami and Berndtsson, 2013).

Transferring water from other basins to the Urmia Lake, because of the long distance, would be much more expensive and would cause problems for the water balance and ecosystem of the other basins. Thus, inter basin water transfer plans would be expensive, time-consuming and environmentally impacting cannot be considered as a short-term solution.

1.4. Objectives, scope and key assumptions

A multi-purpose project has been here developed using a numerical model to study the hydrodynamic behavior of the lake under the natural drivers as well as different dam operation policies, to analyze the effectiveness of these efforts and predict the future of this precious natural body of water. The output of this research will be useful to improve our understanding about the future plans and also the effective operations of dams and management of water resources.

As was mentioned above, most past numerical modeling researches on the Urmia Lake indeed used MIKE 3 Flow Model FM, so that it is possible to compare the results of this research with the previous ones. The current study has tried to correct many of the shortcomings of these past works and has also attempted to calibrate and validate the model against the most accurate available field measurements.

The secondary aim of the work was to assess the river regime before and after the construction of dams. A starting assumption for the thesis was that river discharge is an important and effective variable which is altered by the construction of reservoir dams and whose changes affect the lake ecology. For this purposes, river discharges were assessed before and after the construction of dams. The focus being the assessment impacts of some major dams on river flow in the Urmia Lake basin.

In brief, this research intends to answer three major questions within the main objective of estimating the Urmia Lake water level in the future under different dam operation policies:

Research question 1: which is the pattern of the monthly circulations between the North and South basins of the Urmia Lake and what is the main reason of the salinity difference between them?

Research question 2: How can the impact of dams on river regimes be quantified and, in particular, how can dam operation policies affect river’s flow regime?

Research question 3: Which is the response of the Urmia Lake to river regime alteration under different dam operation policies?

CHAPTER 2: STATE OF THE ART OF THE RESEARCH ON THE URMIA LAKE

2.1. Main findings and implications

Processes such as turbulence, salinity and heat advection and dispersion and wind stress transmission in shallow lakes are actually three-dimensional (3D) (Martin and McCutcheon, 1999). Three-dimensional hydrodynamic numerical models therefore result in better estimations than two-dimensional (2D) depth-integrated ones (Fenocchi et al., 2016; Fenocchi and Sibilla, 2016), as also indicated for the Urmia Lake by the higher correlations with field data for 3D models compared to 2D ones (Abrari, 2003; Tarhe Noandishan, 2004; Zeinoddini et al., 2009).

Sadra (2003), Fallah (2004), Abrari (2003), Tarhe Noandishan (2004), Zeinoddini et al., (2009), Damanafshan, (2011), Pirani (2017) are some numerical modeling efforts on the Urmia Lake. Most of the mentioned numerical modeling efforts dealt with the effect of the causeway on salinity and flow circulation.

Tarhe Noandishan (2004) and Zeinodini et al. (2009) evaluated different possible numerical approaches for simulating the hydrodynamics of the Urmia Lake, finally selecting the three-dimensional MIKE 3 Flow Model FM from the Danish Hydraulic Institute (DHI). Based on their results and on the problem requirements, such model was also employed in the current numerical investigation, also enabling comparisons of the present results with previous one. In these studies, the effective parameters of MIKE 3 Flow Model FM for 3D simulations of shallow hypersaline lakes such as the Urmia Lake were assessed through sensitivity analyses.

The results of these sensitivity analyses showed that the lake water level is highly sensitive to riverine input, so that further water abstraction projects in the Urmia Lake basin would disturb the lake ecosystem (Abbaspour et al., 2012). The Japan International Cooperation Agency (JICA et al., 2016), in collaboration with the Water Resources Management Company (WRMC) and the MOE modelled the effects of such projects and the hydrological cycle of the Urmia Lake basin with the MIKE-SHE and GETFLOWS numerical models, respectively. Based on the result of the MIKE-SHE model, the water level of the Urmia Lake was simulated for the condition where a selected hydrological situation will continuously occur every year from the beginning to the end of a sequential simulation. The results of some relevant sequential simulations are summarized in Figure 2.1. As a result, it can be seen that only the P3 restoration project (i.e. interruption of the whole water withdrawal from tributaries) can achieve the target water level (1,274.1 m), even though all scenarios except P1 (maintenance of the *status quo*) have the possibility to recover the lake water level to some extent (JICA et al., 2016). It is then essential to design an appropriate regulation rule schedule for dams. From the result of the simulations, it became clear that river inflow volumes of approximately 2,050 Mm^3/year were necessary for around 10 years to reach the target water level. However, in case of more than 2,100 Mm^3/year, the water level would also rise higher than the target water level of 1,274.1 m in the future. Other studies estimate inflow volumes as 3085 Mm^3/year for the restoration of the lake (Abbaspour and Nazaridoust, 2007). Thus, after the achievement of the target water level, the total river inflow volume should be maintained to approximately 2,100 Mm^3/year (JICA et al., 2016).

In the case that all restoration projects are implemented simultaneously, the river inflow volume will increase to approximately 3,177 Mm^3/year and the lake water level is likely to rise to around 1,276.78 m (higher than the target water level). In this case, it would take around 6 years to reach the target water level (1,274.1 m) (JICA et al., 2016).

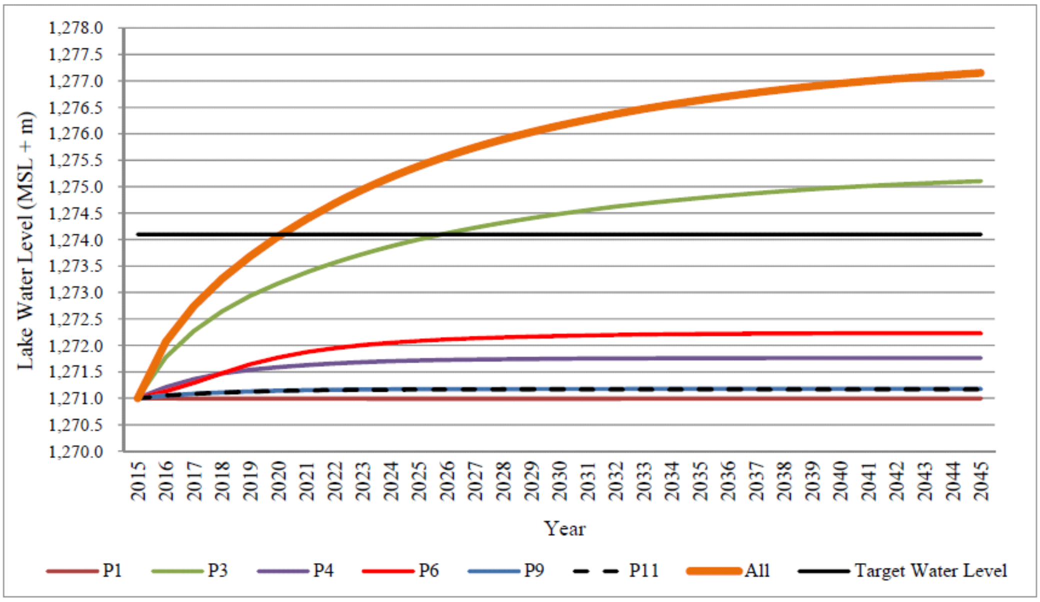


Figure 2.1. Effects of lake restoration projects (Change of Yearly Average Water Level).

P1: Prohibition against any increase of water use (maintenance of status quo). P3: Interruption of whole water supply. P4: Water transmission from the Zaab River to the Urmia Lake basin. P6: Control and reduction of water consumption in agriculture. P9: transfer of water from rivers into the lake. P11: Transfer of water from the Aras River in West Azerbaijan into the Urmia Lake. All: joint adoption of projects P3 (including P6 action), P4, P9 and P11 (JICA et al., 2016).

Beside modifications of the hydrological regime, one of the solutions proposed for reducing the salt content of the Urmia Lake is using desalination techniques, which are however extremely expensive when applied to hypersaline waters. It is better to allow higher riverine discharges to the lake for reducing salinity and increasing aquatic life rather than creating fresh water through reverse osmosis and distillation processes (Karbasi et al., 2010). Fortunately, authorities of the Ministry of Energy have agreed with this policy. During dry seasons, the Southern part of the Urmia Lake was dry in the last years (Figure 2.2). An emergency action was to release 136 Mm^3 water from three reservoir dams (Bukan, Sarough, and Hassanlou) to the lake during February and March 2015. In 2016, extra precipitation over the Urmia Lake basin resulted in the overflow of flood flows from most of the dams within the basin to the lake. So, the lake water level approached 1270.55 m on February 15, 2016. Figure 2.3 shows the effectiveness of natural water inflows to the lake. At the same time, other actions such as dredging of the rivers' mouths, connecting Zarinehroud and Siminehroud Rivers, and controlling the illegal overuse of surface waters facilitated the recovery of the lake.

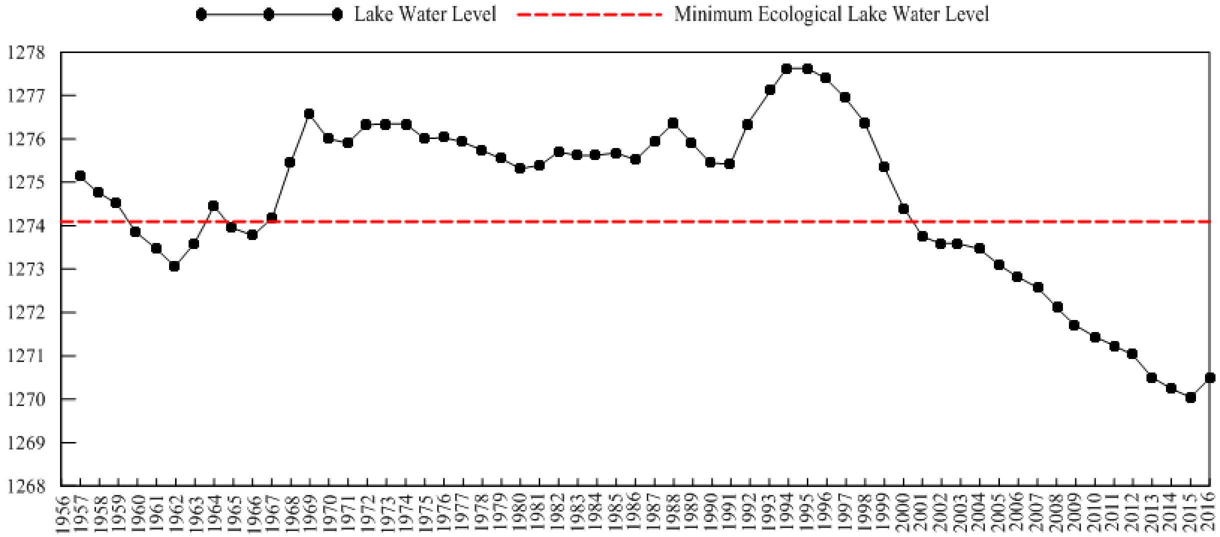


Figure 2.2. The Urmia Lake water level trend for last 60 years

(a) Before over flow; (b) after over flow

Figure 2.3. A satellite image of the water abstraction effects in the Urmia Lake, captured on (a) November 28, 2015; and (b) February 15, 2016. Note the extent of dry regions in the Southern part. Image Source: https://earthexplorer.usgs.gov/

The hydrology and the hydrodynamics of the lake and the effect of the causeway on the changes in the physical and chemical characteristics of the lake water in its northern and southern parts were studied by Ab-Nirou (1995). This research included the only available flow velocity measurements for the Urmia Lake, which were taken in 1991. As such, they were used for numerical hydrodynamic model calibration by various sources (Sadra, 2003; Zeinoddini et al., 2009; Pirani, 2017).

A relevant numerical modeling study by Abrari (2003), using a two-dimensional depth-averaged model, whose results were compared with the measured data on April, May and June 2002, stated that the flow pattern of the Urmia Lake is controlled by wind. Yet, the wind friction coefficient adopted in that study was much higher than the common range adopted in the scientific literature. So far, most numerical modeling efforts on the Urmia Lake dealt with simulating the effect of the causeway on salinity and flow circulation, planning scenarios to improve current conditions for the causeway. Examples of these studies are: Sadra (2003), Fallah (2004), Abrari (2003), Tarhe Noandishan (2004), Zeinoddini et al., (2009), Damanafshan, (2011), Pirani, (2017). Their main findings have been reported in the following numbered list. An exhaustive list of the numerical hydrodynamic modeling studies of the Urmia Lake is given in Table 2.1.

1. Numerical modeling of the Urmia Lake indicates that wind energy is the main environmental variable influencing water flow in the lake. River discharges, evaporation and rainfall have been found to be the key input variables effecting salinity in the lake (Zeinoddini et al., 2009; Pirani, 2017). The water level is also highly sensitive to river discharges (Abaspour et al., 2012).
2. Spatial salinity gradients over the lake area were found to have an insignificant impact on the water flow regime (Zeinoddini et al., 2009; Pirani, 2017). Results of 3D modeling showed that the velocity and the direction of flow change along the depth (Tofighi, 2006). This is consistent with the observations by Ab-Niroo (1995). 3D modeling also showed that variations in water density along the depth are insignificant (Tofighi, 2006), still consistently with observations (Sima and Tajrishi, 2015). Therefore, the observed changes in direction and magnitude of flow velocity along the vertical are not due to density differences (Pirani, 2017; Zeinoddini et al., 2009), rather being the product of other forces such as bathymetrical gradients, wind and river discharges (Tofighi, 2006). Results of 3D models (Zeinoddini et al., 2009; Tarhe Noandishan 2004) have been found to better correlate with field data than those from 2D models (Abrari 2003; Zeinoddini et al., 2009; Tarhe Noandishan, 2004).
3. The effects of adding an extra opening in the causeway have also been examined with 3D models. An insignificant variation of water salinity distribution in the lake compared to the current situation was obtained (Zeinoddini et al., 2009; Pirani, 2017, Marjani and Jamali, 2014). Compared to the conditions prior to the building of the causeway, salinity transport from the Southern to the Northern part decreased by 49%, vice versa from the Northern to the Southern basin by 49.4% (Pirani, 2017).
4. The North-to-South and South-to-North flows through the opening balance out during a year. However, northbound flow prevails in spring, due to the head difference between the two parts of the lake, caused by the discharges of the major rivers (Marjani and Jamali (2014); Pirani, (2017)). Owing to the causeway, the flow exchange between the North and South parts decreased (Ab-Niroo 1995; Sadra 2003; Pirani, 2017). Compared to natural conditions prior to the causeway, northbound and southbound flow dropped by 48% and 50% respectively (Pirani, 2017; Sadra 2003).
5. In case a new opening is built, it should be at least 500 m long and placed in the western arm of the causeway. This solution would allow a 40% increase in water exchange between the South and North basins (Sadra, 2003).
6. Salinity changes in the North and South basins of the lake do not have steady trends. Their change rather reflects the evolution of the environmental factors, as also evident from field observations (Tarhe Noandishan, 2004; Pirani, 2017). When river inputs are low, salinity is inversely proportional to water depth, so that the Northern part is less saline than the Southern one. Instead, during the wet periods, water discharges from rivers into the Southern basin cause salinity to decrease there. Such salinity drop is directly proportional to river discharges and inversely proportional to the distance from their mouths (Pirani, 2017). The Northern basin is deeper than the Southern one and has a larger water volume. Therefore, salinity impacts less this area than the shallower Southern part.
7. Researchers tried to simulate the exact conditions of the lake. However, modeling simplifications led to errors in the results. For example, in the two-dimensional results by Tarhe Noandishan (2004), the existence of layered flows is mentioned but not simulated due to the inherent assumptions of the model. In addition two dimensional modeling of Ab-Nirou (1995) eliminates the modeling of two-stream flows. Three-dimensional simulations (Pirani, 2017) have shown that a large volume of waters in the two northern and Southern parts of the lake, especially in the end of winter and spring are transmitted through two-way currents around the causeway, which ultimately have a positive effect on the mixing of the entire water of the lake and its general homogeneity

Some criticism can be made over the results of the studies introduced above, as specified in the following numbered list:

1. Numerical modeling usually employed hydrological data in mean or extreme conditions (studies by Ab-Nirou (1995), Tarhe NoAndishan (2004), Sadra (2003), Abbaspour et al. (2012)) instead of relying on real data time series for the analyzed period.
2. In the study by Pirani (2017), exhaustive model calibration and validation of salinity distribution could not be performed, as data were available for a single year only. In addition, the density and flow velocity were not investigated and the water level elevation was simulated for the 2003-2004 period only.
3. In the modeling study performed by Marjani (2007) with the COHERENCE model, river inflows were assumed as fresh water. Precipitation and evaporation for the Northern and Southern basins as input variables were also are assumed to be coincident and equal to an average value for both regions. According to measured data (JICA et al., 2016), evaporation from the surface of the lake is higher than direct precipitation, so both mentioned assumptions are far from reality and create some errors in modeling.
4. There are some farms between the last hydrometric stations and the lake. Because of the easy and low-cost access to surface water compared with groundwater, farmers prefer to pump directly riverine water. Due to water demand for agricultural purpose, the total discharges at the last stations cannot be the actual ones flowing into the lake, with remarkable differences between them. However, all previous studies numerically modeling the Urmia Lake (Pirani, 2017; Zeinoddini et al., 2009; Abaspour et al., 2012; Tofighi, 2006) disregarded this.

2.2. Conclusions

Traditional water management will soon result in the drying of the Urmia Lake, an internationally recognized hypersaline wetland in Iran. The highest priority is an action plan to deliver in-basin surface waters to the lake, in the order of 20% to 40% of the potential annual flows from the major rivers discharging into the lake. The revision of the current water allocation for agricultural uses, emergency plan to reduce 40% of irrigation water, to lease farmers' water rights, to prevent illegal water intakes from the rivers, to release 30 to 40% of reserved water from 13 large dams around the lake, and to perform river improvement works to facilitate water delivery are necessary for saving the Urmia Lake. The long-life and sustainable solution is to increase the environmental flow allocations from rivers, from the existing less than 13% to 20-40% of their potential annual flows. The change in the volume of water regulation in the 13 active dams, and the reduction of possible storage of water in the 11 under-construction dams are to be considered for the future restoration of the Urmia Lake.

In recent years, the southern part of the lake was completely dried out. This part of the lake is wide and shallow and, because of the drying, crystallized salt has been deposited on the lake bed. This is an opportunity for easy and low-cost extraction of the deposited salts. The salt of the Urmia Lake is well-known for its medicinal values, and extraction of the huge amount of salt at the Urmia Lake (about 8-10 billion tons) with environmental standards could play significant role in the economic development of the West Azerbaijan province, being a replacement of agriculture for the survival of native people.

The lake bed has risen and strategies such as allowing more discharge from dams may not be effective. By releasing stored fresh water in the dams to the southern part of the lake, large quantities of such water would flow on a crystallized salt bed, therefore wasting a large amount of water by evaporation. Therefore, it is important to develop models to study the effects of releases from dams to different parts of the lake.

This thesis aims at developing a numerical framework to study the hydrodynamic behavior of the lake under the natural drivers, as well as under different restoration strategies, to analyze the effectiveness of these efforts and predict the future of this precious natural body of water.

To reach this goal, the three-dimensional MIKE 3 Flow Model FM code from the Danish Hydraulic Institute (DHI) was widely employed, attempting to correct many of the shortcomings of past works and to calibrate and validate the model against the most accurate available field measurements.

Table 2.1. Summary of previous studies on the numerical hydrodynamic modeling of the Urmia Lake

Authors	Model Description			Calibration Data			
	Code	Mesh Size (m)	Mesh Type	Salinity	Current Speed	Density	Water Level
Ab-Niroo (1995)	MIKE 21 Flow Model	-			1991	-	
Sadra (2003)	HD and AD module of MIKE21	150 and 450		May and September 1987	1991	-	
Tarhe Noandishan (2004)	Model by Lawrence (1990)	-	Rectangular	-	-	-	
Zeinoddini et al. (2009)	MIKE 3 and MIKE 21 Flow Model FM	300, 450, 900		May and September 1987	1991	1987	1986-1987
Marjani (2007)	COHERENCE (3D) and POM (1D)	900				-	2001-2004 1993-1994
Abaspour et al., (2012)	FVCOM (3D)	500-1500	Unstructured triangular	May and September 1987			Average of 20 year (1967-1986)
Pirani (2017)	MIKE 3 Flow Model FM	200	Unstructured triangular	2003-2004	-	-	2003-2004
East Azerbaijan Department of Environment (2017)	MIKE 3 Flow Model FM	100-2100	Unstructured triangular	May and September 1987; July 2008	-	July 2008	1993 and 1996

CHAPTER 3: MATERIALS AND METHODS

3.1. Introduction

The water of inland terminal lakes has a different ionic composition to that of sea water, also displaying variations at inter-annual time scales (Anati, 1999). Since Urmia Lake is a closed basin, its salinity depends on the water balance. Therefore, it is necessary to model water level fluctuations with sufficient accuracy, verifying the outputs of the model by comparison with the water level fluctuations data in Urmia Lake, which have been recorded for the past 69 years at the Golmankhaneh Station. The location of the Golmankhaneh Station has been shown in the Figure 3.40.

Using the discharges measured at the last hydrometric stations of each tributary led to remarkable errors in water level simulation, as both significant water consumption for agricultural purposes and positive groundwater contributions occur in the final river reaches (Ministry of Energy, 2004).

Indeed, between the last hydrometric stations and the lake there is an area where losses and inflows can affect the final amount of flow reaching the lake. This zone will be referred in the following as the *buffer zone*, in this study two boundaries were defined, therefore subdividing the buffer zone into two regions:

1. the boundary that connects the last hydrometric stations of each river flowing into the lake: to determine this boundary in the GIS framework, the catchment areas from the last hydrometric stations to the lake were identified and joined one to another.
2. the boundary of the lake when it reached the maximum water level (1378 m a.s.l. in 1996).

The outer area between the two mentioned boundaries, *buffer zone 1*, while the inner one between the second boundary and the water body will be identified as *buffer zone 2*. In Figure 3.1, an illustration of these two boundaries is shown. The area of buffer zone 1 was estimated through the GIS framework, to be equal to 10060.101 km^2. The area of buffer zone 2 is a function of the lake water level. By increasing the lake water level, and consequently increasing the relative lake surface area, A_{lake} (z), the area of buffer zone 2 is decreases according to:

$$A_{\text{buffer zone 2}}(z) = 5955.318\ \text{km}^2 - A_{\text{lake}}(z) \qquad 3.1$$

The drying of a large part of the lake causes at present water to flow over long distances before reaching the lake, over salty and dry lands that were formerly part of the lake bottom, so the lake and rivers in dry season disconnect from each other. The flatness of that area causes rivers to widen, increasing the water loss due to evaporation and penetration in the buffer zone 2. Figure 3.2 shows an example of the water flow in the dried area of the lake and its distribution when river flows into the lake during wet seasons.

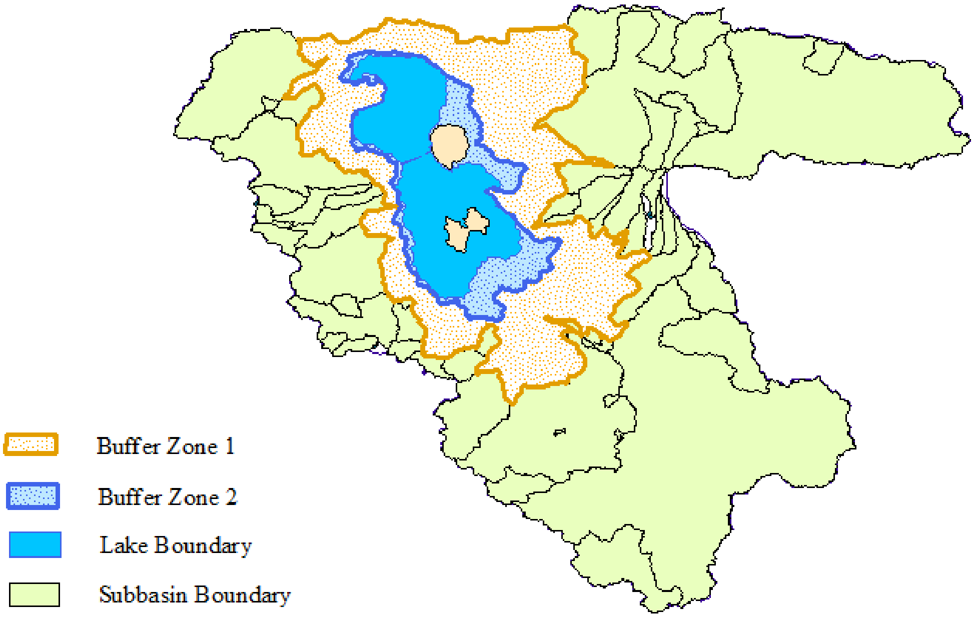


Figure 3.1. Boundaries defined for buffer zone 1 and 2

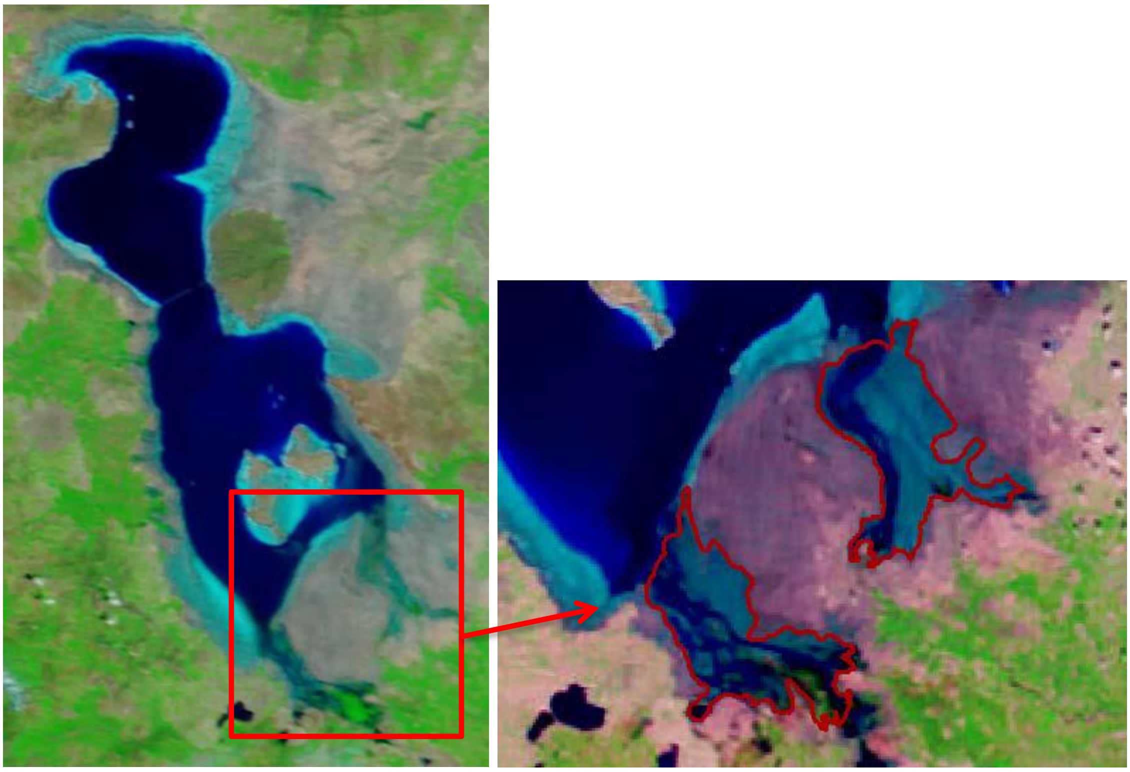


Figure 3.2. The water movement on the dry area of the lake and its distribution when river flows into the lake during wet seasons (RSRC, 2015).

3.2. Water balance of Urmia Lake

In the current study, the water balance of the lake has been defined as:

$$\Delta V = P_L + RD + V_{EL} + V_{Unmeasured} \qquad 3.2$$

in which ΔV is the volume variation, P_L is volume of the direct precipitation on the surface of the lake, RD is the inflow volume from tributaries, V_{EL} is the evaporated volume from the lake surface and $V_{Unmeasured}$ is the total water volume losses and incomes in the buffer zones. All the units are in Mm^3.

$V_{Unmeasured}$ in Equation 3.2 is a collection of unmeasured positive and negative terms between the last hydrometric stations and the lake water body. These terms can be losses, including agricultural and industrial uses in the buffer zone 1, penetration and evaporation of water in the buffer zones 1 and 2, or inputs, including precipitation in the buffer zones, runoff of seasonal rivers (just major river's discharge has been calculated in the RD and seasonal rivers have been eliminated) or groundwater reaching the surface.

In the following paragraphs, the methods adopted to determine each of the mentioned variables in Equation 3.2 will be described.

3.2.1. Estimation of Evaporation from the Urmia Lake Surface

Evaporation is an unknown and influential factor in the lake's water balance, as there is no method to directly measure the evaporation from the lake.

Due to the lack of sufficient measured data for the variables affecting evaporation, pan evaporation data were analyzed to determine the correct evaporation of the lake. Data recorded by the Ministry of Energy (Iran Water and Power Resources Development Company) indicates that the evaporation rate and precipitation in this area are somewhat different from one station to another, so the use of multi-station data near the lake can increase the accuracy of modeling (Ab-Nirou, 1995). Therefore, in this study, mean evaporation and precipitation data of the AbajalouSofla, BanisShanjan, Pol-e-SorkheMahabad and YalghouzAghaj stations have been considered for evaporation and direct precipitation in the modeling. Based on the monthly pan evaporation at these four stations adjacent to Urmia Lake, average evaporation from the lake surface was estimated with the Thiessen Polygons Method. Figure 3.3 shows the location of the mentioned stations and the Thiessen delineation of the lake surface calculated in the GIS framework, while Table 3.1 shows the calculated Thiessen coefficients.

It is worth noting that the criteria for selecting these stations were (i) the availability of data over the mentioned time periods (especially for 1986-1987 and 1991-1992) and (ii) their distance from the lake.

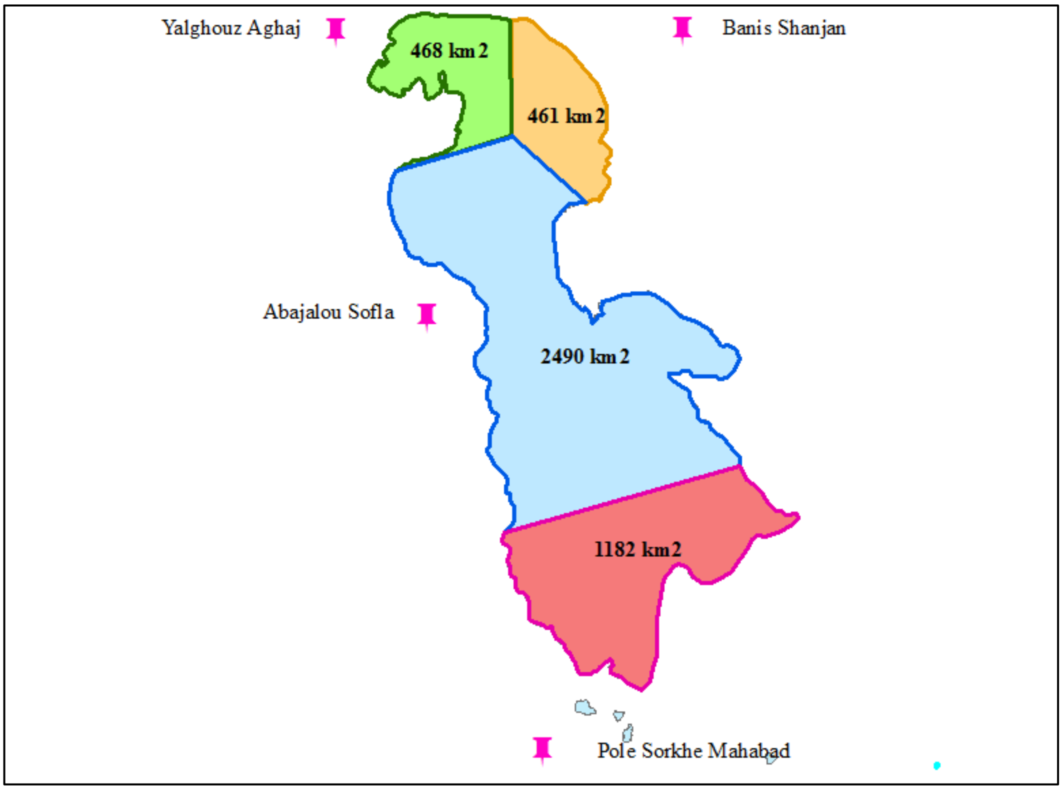


Figure 3.3. Thiessen delineation of the Urmia Lake surface

Table 3.1. The location of selected evaporation and precipitation monitoring stations and Thiessen network of the Urmia Lake surface.

Station Name	Longitude (degree)	Latitude (degree)	Area (km^2)	Thiessen Coefficient
Abajaulo Sofla	44-56-00	38-14-00	2490	0.54
Yalghouz Aghaj	48-02-00	37-32-00	468	0.1
BanisShanjan	45-54-00	38-21-00	461	0.1
Pol-e SorkheMahabad	45-23-00	36-58-00	1182	0.26

It must be underlined that the average evaporation considered as above has to be corrected by two correction coefficients:

1. Pan correction coefficient (C_p)
2. Saline water evaporation coefficient (C_s)

3.2.1.1. Pan correction coefficient:

One of the points that should be taken into account when calculating the amount of evaporation of Urmia Lake using pan evaporation data is the effect of the humidity of air over the lake surface in reducing the evaporation rate. This means that if a pan were filled with water with the same salinity and physical characteristics of the lake water, the evaporation rate in it would be still higher than that in the lake. One possible solution for converting the pan evaporation data into the evaporation from the surface of the lake is using Penman's formula; another is to use a correction coefficient of pan evaporation. The first method requires the solution of six equations and the calculation of these equations requires the knowledge of many data, including the humidity of air, the amount of heat transfer from the lake to the ground, etc. The reduced availability of some of these data makes it difficult to calculate the evaporation of the lake surface by using this method. The alternative is measuring the evaporation of water from the pan evaporation (E_{pan}), and then multiplying it by a correction coefficient. This coefficient is independent from the salinity of the lake water, and only depends on the humidity of air over the lake surface. This coefficient expresses the relationship between the evaporation from the pan to that from the lake surface, assuming the same physical and chemical conditions of water in both cases. This coefficient varies seasonally due to changes in the water temperature of the lake (Allen and Crow, 1971) and has a linear relation to the amount of air humidity (Eagleman, 1971). Pan evaporation coefficient values for the American A-class evaporation pan are listed in Table 3.2. Pan evaporation coefficients for different lakes are in the range of 0.70 to 0.82 (Mohammadi, 2004). Mohammadi (2004) proposes a value of 0.79 for the evaporation coefficient from the Urmia Lake surface. This value is at the upper limit of the range 0.62-0.80 proposed by Linsley, et al. (1988) for the evaporation coefficient from a lake surface. Therefore, in the current study a slightly lower value of 0.77 was used for the evaporation coefficient.

Table 3.2. Recommended literature values for the evaporation coefficient

References	Pan evaporation coefficient	References	Pan evaporation coefficient
Stanhill (1970)	0.7	Yang (1947)	0.77
Allen and Crow (1971)	0.75-0.78	Penman (1948)	0.78
Ficke (1972)	0.76	Kohler et al (1955)	0.6-0.82
Hounam (1973)	0.72-0.80	Harbeck (1958)	0.69
Neuwrich (1973)	0.72	Nordensen and Baker (1962)	0.74
Hoy (1977)	0.78	Nimmo (1964)	0.61-0.79
Garret and Hoy (1979)	0.63-0.94	Sellers (1965)	0.82
Linsley et al (1982)	0.71-0.73	Webb (1966)	0.7
Duru (1984)	0.79	Stanhill (1969)	0.67

3.2.1.2. Correction coefficient for saline water (Cs)

It should be noted that most evaporation stations measure evaporation by using fresh water. Evaporation from saline lakes, especially in oversaturated ones, does not conform to standard evaporation calculations (Asmar and Ergenzinger, 1999). Based on physics, evaporation from a saline water surface is less than evaporation from a fresh water one; therefore, to calculate the evaporation of Urmia Lake, the evaporation from the fresh water pan needs to be multiplied by a correction coefficient to calculate the evaporation in saline water. Increasing the salinity of water, the evaporation rate decreases (Mohammadi, 2004).

In the Golmankhaneh Station (with 1 km distance from the lake) there are two pan measured data since 1989, one of them measuring fresh water evaporation (GolmankhanehAbshirin) and another one measuring saline water evaporation (GolmankhanehAbshour). The correction coefficient C_s can therefore be estimated there as:

$$Cs = E_{Golmankhaneh\ Abshour} / E_{Golmankhaneh\ Abshirin} \qquad (3.3)$$

In Figure 3.4 changes in the annual ratio of saline water evaporation to the fresh water evaporation (C_s) with water salinity at the Golmankhaneh Station from 2006 to 2011 have been shown. The amount of Cs decreases with increasing salinity, meaning that the amount of evaporation from the surface of saline water decreases relative to surface evaporation of fresh water. For TDS values above 360 mg/lit, the evaporation coefficient distances from 1, the difference between the surface evaporation of saline and fresh water being negligible below such value ($C_s \approx 1$).

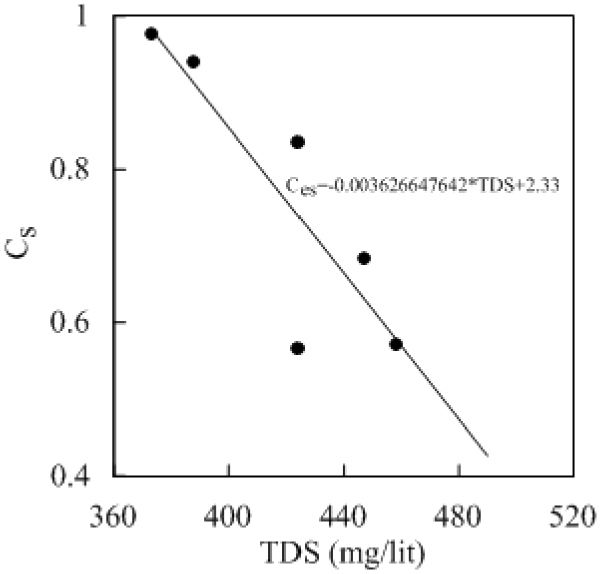


Figure 3.4. Dependence of the C_s evaporation coefficient from TDS (mg/lit)

3.2.2. Estimation of precipitation on the Urmia Lake surface

For estimating the amount of direct rainfall on the lake surface, the average daily rainfall data of the four considered stations (AbajalouSofla, Banisshanjan, Pol-e-SorkheMahabad and YalghouzAghaj) was applied to each of parts in which the lake was subdivided with the Thiessen method (Figure 3.3), consistency with the methodology adopted for evaporation.

3.2.3. Volume variation (ΔV)

The bathymetry of Urmia Lake and the hypsographic curve were prepared by WRI[1] using field data measured at 55 stations and remote sensing methods in April 2013, but due to the high salt precipitation rates a new bathymetry of the lake was prepared in 2015. As in the present the calibration of the model is based on data collected before 2013, the bathymetry realized in 2013 was assumed to be valid for the lake. In Figure 3.5 and 3.6, the hypsographic curves calculated with the two bathymetries are compared and show a significant difference for before 2013.

In Figure 3.5, only water levels below 1271 m (from 2013 onwards, the lake's water level was less than 1271 m a.s.l) are displayed. As shown in the figure, due to the rise of the lake's bed as well as the homogenization of it due to sedimentation, the volume hypsographic curve of the lake for the 2015 data compared to the 2013 one, displays (i) has a lower slope for low water levels and (ii) an inferior volume of water stored in the lake for the same lake water level. For increasing water level, the curves are parallel and have the same slope (WRI, 2015). This means that the rate of change in water level by changing the lake volume for the 2015 bathymetry is the same as for the 2013 one for levels above 1271 m, so the use of both bathymetries will provide the same values for ΔV.

In Figure 3.6, the lake surface area hypsographic diagram is shown for the bathymetries of 2013 and 2015. As expected, the lake surface area for levels above 1270 m shows very few changes before and after sedimentation. This is due to the very low sedimentation rates at higher altitudes of the lake bed and to the lack of water and the dryness of these areas in recent years. But at lower water levels, due to the significant rise of the lake bed on the one hand, and the development of salt dunes

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[1] Water Researches Institute

on the other hand, the surface area of the lake has decreased significantly. For example, at 1269.5 meters, the surface area of the lake before 2013 was about 856 km^2, but this amount was reduced to 496 km^2 in 2015 (WRI, 2015). The interpolating equation defining the volume hypsographic curve of Urmia Lake in 2015 which will be used in the following is:

$$\text{Water Level (m)} = -0.0042V2 + 0.383V + 1269.7 \qquad R^2 = 0.9904 \qquad 3.4$$

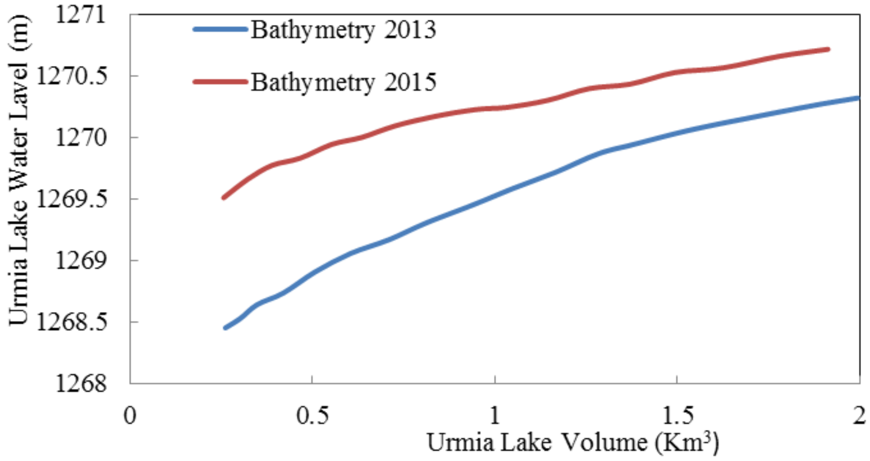


Figure 3.5. Volume hypsographic curves of Urmia Lake for the 2013 and 2015 bathymetries (Ministry of Energy, 2004).

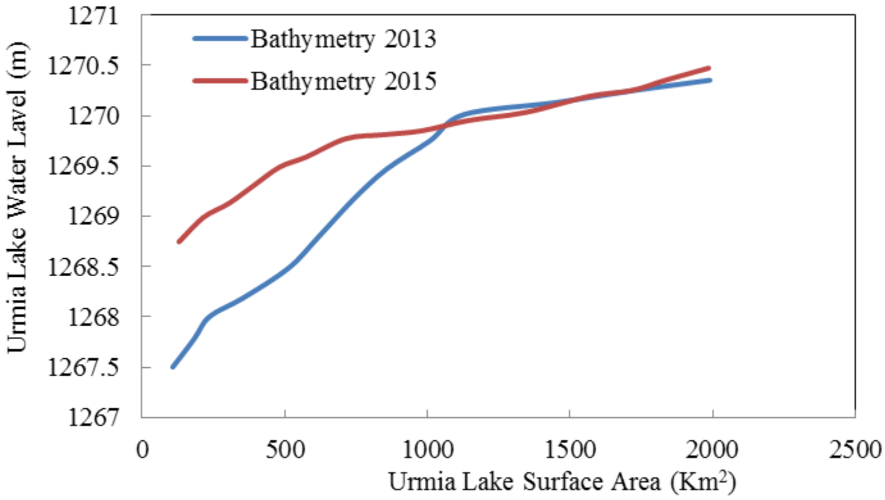


Figure 3.6. Surface area hypsographic curves of Urmia Lake for the 2013 and 2015 bathymetries (Ministry of Energy, 2004).

3.2.4. Rivers discharge (RD)

In a closed basin, such as Urmia Lake, the rivers discharging into the lake are very important in forming the ecologic and hydrodynamic processes of the lake. The rivers, while causing the water level variation of the lake, have a basic role in salinity pattern. Also, inflow of sediments may have an important role in establishing morphological situations in different parts of the lake. The salinity data of rivers are completely dependent on their inflow discharge and are usually defined as a function of it. In a research by Sadra (2003) the mean salinity equations for some major rivers flowing into the lake were determined.

Twenty-two rivers flow into the Urmia Lake, the most important of them being Zarrinehroud, Siminehroud, AjiChai, GadarChai, NazlouChai and MahabadChai. All main rivers of the Urmia Lake are discharging into the southern part of the lake.

The information obtained from existing hydrometric stations on the rivers is the most reliable information on their discharges. In these stations, the discharge of rivers is estimated by measuring the current velocity in the different parts of the rivers and recording water level. Based on the information given by the Water Resource Research Center (TAMAB) there are 117 hydrometric stations in the main and small branches of the rivers in the Urmia Lake basin. In addition to the discharges, sediment concentrations and chemical characteristics of water are measured in these stations. The oldest stations in the basin are over the NazlouChai, ShahrChai, BarandouzChai and AjiChai rivers, having recorded hydrological data since 1954.

The extraction of daily time series of the riverine discharges for analyzing the lake water level requires a careful consideration of indicators such as the proximity of the stations to the lake, the use of rivers' waters downstream of the stations and the availability of data. Table 3.3 shows the nearest hydrometric stations to the lake related to 17 important rivers discharging into the lake.

In most research on the Urmia Lake (Sadra, 2003; Zeinoddini et al., 2009; Pirani, 2017; Damanafshan, 2011), the assumption that, after the last hydrometric stations in the catchment area there is no water consumption was made. Yet, evidence in some stations indicates that there is water consumption by pumping from the rivers for agricultural purposes; moreover in some rivers there is an inflow of submarines after the last hydrometric station and groundwater. The effect of the mentioned hypothesis on the lake water level results have been assessed in the current study.

Table 3.3. Final hydrometric stations of rivers flowing into the Urmia Lake for calculating surface runoff

	Station Name	River Name		Station Name	River Name
1	Akhoula	AjiChai	10	Babaroud	BarandouzChai
2	Shishvan	GhaleChai	11	Keshtiban	ShahrChai
3	Gheshlagh-eAmir	MardoughChai	12	AbajalouSofla	NazlouChai
4	Miandoab	Siminehroud	13	YalghouzAghaj	ZolaChai
5	Nezamabad	Zarrinehroud	14	Daryan	DaryanChai
6	Gord e Yaghoub	MahabadChai	15	Shirinkandi	LeilanChai
7	Pol-e-Bahramlou	GadarChai	16	GoijaliAslan (PoleOzbak)	RozehChai
8	Bonab	SoufiChai			
9	Khormazard	ChwanChai	17	AzarShahr	AzarShahrChai

The detailed description of the hydrological characteristics and of the available discharge data of all the tributary watersheds of the Urmia Lake will be given in the following.

Table 3.4. Estimated distribution of monthly volume of water consumption after the last hydrometric stations in the Urmia Lake basin (Ministry of Energy, 2004).

River Name	Last Station	Agriculture Area (ha)	Consumed volume (Mm^3)												
			Mehr (Sep)	Aban (Oct)	Azar (Nov)	Dey (Dec)	Bahman (Jan)	Esfand (Feb)	Farvardin (Mar)	Ordibehesht (Apr)	Khordad (May)	Tir (Jun)	Mordad (Jul)	Shahrivar (Aug)	Total
Zarrinehroud	Nezamabad	5207	2.34	2.34	0	0	0	0	0.45	7.03	8.9	9.37	9.37	7.03	46.83
ShahrChai	Keshtiban	820	0	0	0	0	0	0	0.62	2.77	2.77	0	0	0	6.16
ZolaChai	Yalghouz Aghaj	1511	0.11	0	0	0	0	0	0.11	1.36	2.04	2.04	3.97	1.7	11.33
NazlouChai	AbajalouSofla	1445	0.11	0	0	0	0	0	0.11	1.3	1.95	1.95	3.79	1.63	10.84
GhaleChai	shishvan	445													1
SoufiChai	Bonab	1650	0.12	0	0	0	0	0	0.12	1.49	2.23	2.23	4.33	1.86	12.38
GadarChai	Pol-e-Bahramlou	200	0.02	0	0	0	0	0	0.02	0.18	0.27	0.27	0.53	0.23	1.5
MardoughChai	Malekkandi	6000	0.45	0	0	0	0	0	0.45	5.4	8.1	8.1	15.75	6.75	45
Siminehroud	Miandoab	9975	4.49	0	0	0	0	0	0.9	13.47	17.06	17.96	17.96	13.47	85.31
BarandouzChai	Babaroud	620	0.05	0	0	0	0	0	0.05	0.56	0.84	0.84	1.62	0.7	4.65
MahabadChai	Gord e Yaghoub	150	0.01	0	0	0	0	0	0.01	0.14	0.2	0.2	0.4	0.17	1.13
RozeChai	GoijaliAslan	2275	0.17	0	0	0	0	0	0.17	2.05	3.07	3.07	5.97	2.56	17.06
ChowanChai	Khormazard	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AjiChai	Akhoula	5300	0	0	0	0	0	1.296	16.07	17.41	8.035	0	0	0	42.81

3.2.4.1. SenikhChai River

The total length of the SenikhChai River is 52 km, its average slope is 0.7% and its catchment area is about 646 km^2 (Ministry of Energy, 2004). The last hydrometric station on the SenikhChai River is the Pol-e-Senikh Station. During visits to this area by the experts of the Ministry of Energy (2004), numerous channels have been observed which are used to irrigate the surrounding villages. According to interview with native farmers, from May to November, whenever there is a negligible flow in the SenikhChai River, all of the water downstream of the PoleSenikh Station is used for irrigation of the agricultural lands, the excess artificially recharging the groundwater in the surrounding lands. If there is a residual flow in winter downstream of the PoleSenikh Station, it enters the lake. It should be noted that in recent years, due to reduced rainfall, there was practically no relevant summer flow in the SenikhChai River after the PoleSenikh Station. In Figure 3.7, the SenikhChai River basin is shown.

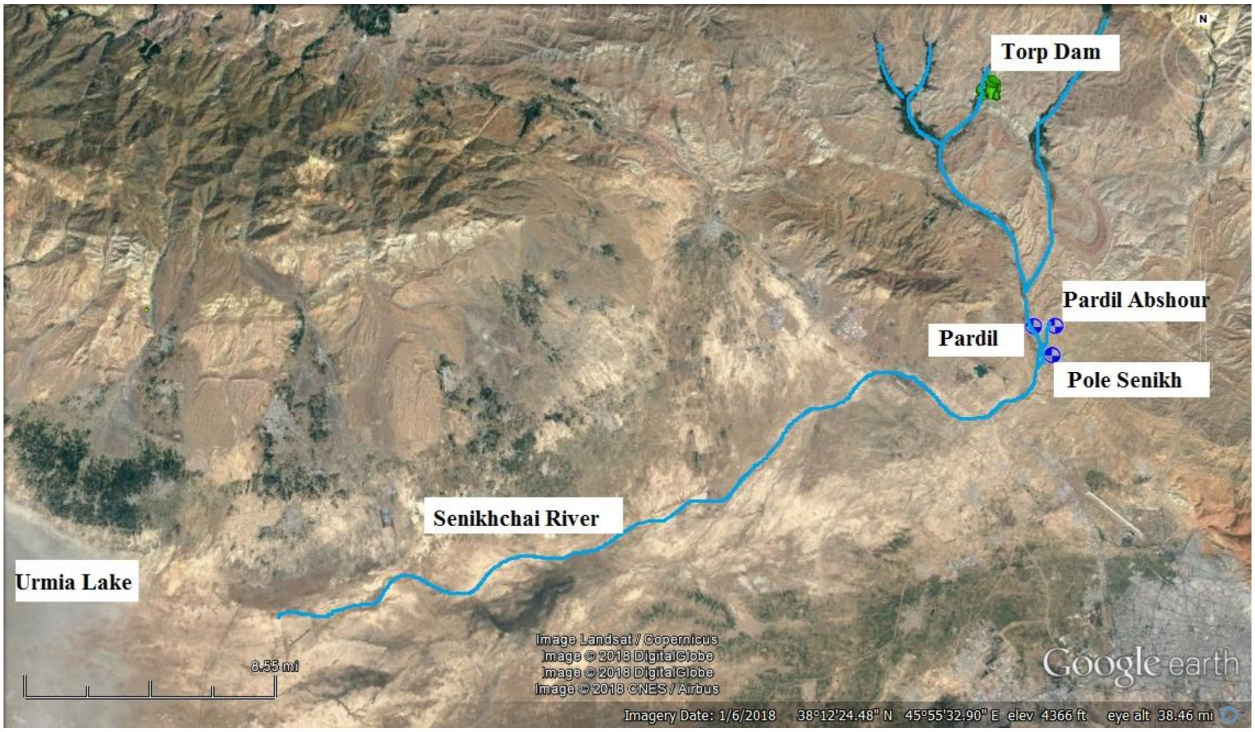


Figure 3.7. The hydrographic network, location of hydrometric stations and of the under preliminary evaluation Torp Dam in the SenikhChai River catchment.

3.2.4.2. AjiChai River

The length of the AjiChai River is 223 km (Ministry of Energy, 2004). The Akhoula Station has a relatively long-period data series. Discharges measured at this station can be used to calculate the inflow into the Urmia Lake after subtracting the agricultural demands.

Since 1996, downstream of the Akhoula Station, the SarinDizaj Station has been built. After the Sarin-Dizaj Station, due to the salinity of the land, there is no surface water consumption for agriculture. The comparison between the two mentioned stations (Akhoula and SarinDizaj) shows that 23.63 Mm^3 per year on average are consumed for agriculture. After the Akhoula Station, there are approximately 5,300 ha of arable lands used for agriculture in seasons when river water quality is appropriate for irrigation (Ministry of Energy, 2004).

Therefore, considering the quality of water of the AjiChai River and the water consumption months, the volume of water inflow into the lake from the AjiChai River mouth has been evaluated as follows:

- From 1996, the measured discharge at the SarinDizaj Station.
- Prior to 1996, the amount of water consumption of the AjiChai River, taking into account the water needed for grain, i.e. 10,000 m^3 per ha per year and 25% return water from drainage, according to Table 3.4.

It should also be noted that the most important limitation to water consumption after the Akhoula Station is the high salinity of water. In Figure 3.8, the AjiChai River basin is shown.

Figure 3.8. The hydrographic network and location of the hydrometric stations and of the Nahand and Venyar active Dams in the AjiChai River catchment.

3.2.4.3. AzarShahrChai River

The total length of the AzarShahr River is about 49 km, its average slope is 1.2% and the total area of the catchment is about 745 km^2 (Ministry of Energy, 2004). The last hydrometric station on the Azar-ShahrChai River, is the AzarShahr Station. The station has been inactivated since 1996, due to the lack of river flow in most days of the year. Since 1996, due to climate changes and the agricultural demand of the lands upstream of the AzarShahr Station, as well as the construction of the Yengije Reservoir Dam (Figure 3.9), no flows have been entering from the AzarShahrChai River into the lake (Ministry of Energy, 2004).

There are about 1254 ha of gardens and agricultural lands in the AzarShahr region. Due to lack of water during the crop season, a part of water requirements provide by groundwater so the amount of surface water abstraction from the river per ha is low, 1000 m^3, and the 25% of water demand is recyclable.

Figure 3.9. The hydrographic network and location of the hydrometric stations and of the active Yengije Dam in the AzarShahrChai River catchment.

3.2.4.4. GhaleChai River

The total length of the GhaleChai River is about 56 km, its average slope is 1.5% and the area of the basin is about 714 km^2. The Ajabshir Dam has been operating on the main river reach since 2006 (Ministry of Energy, 2004).

The nearest hydrometric station to the Urmia Lake in the basin of Ghalechai River is the Shishvan Station. Measured discharges at the Shishvan Station have been available since 1983. Prior to the establishment of the mentioned station, the last station on the GhaleChai River was the Ajbashir Station, which was activated in 1964 and was operated for 15 years. Due to the negligible distance between the two stations, a significant surface runoff does not flow into the river reach between the stations. Therefore, we can practically consider the measurements of the two stations to be equivalents and to rely on discharge data of the river since 1964 (Ministry of Energy, 2004).

According to the results of field surveys in 2001 by the Ministry of Energy (2004), there are 445 ha of arable lands downstream of the Shishvan Station; in the crop season, after the station, the river water is pumped from the natural stream for agricultural uses. The average water withdrawal from the Shishvan Station during time period of the 36 years is one Mm^3 per year. In Figure 3.10, the GhaleChai River basin is shown.

Figure 3.10. The hydrographic network and location of the hydrometric stations and of the active Ajabshir Dam in the GhaleChai River catchment.

3.2.4.5. ChwanChai River

The length of the ChwanChai River is more than 45 km, its average slope is 1.6% and its catchment area is 262 km^2 (Ministry of Energy, 2004). The Khormazard Station is the nearest station to the Urmia Lake in the basin of the mentioned river.

According to the Ministry of Energy (2004), there are no agricultural lands after the station, so that the amount of water entering into the Urmia Lake is equal to the measured discharge at the Khormazard Station. In Figure 3.11, the ChwanChai River basin is shown.

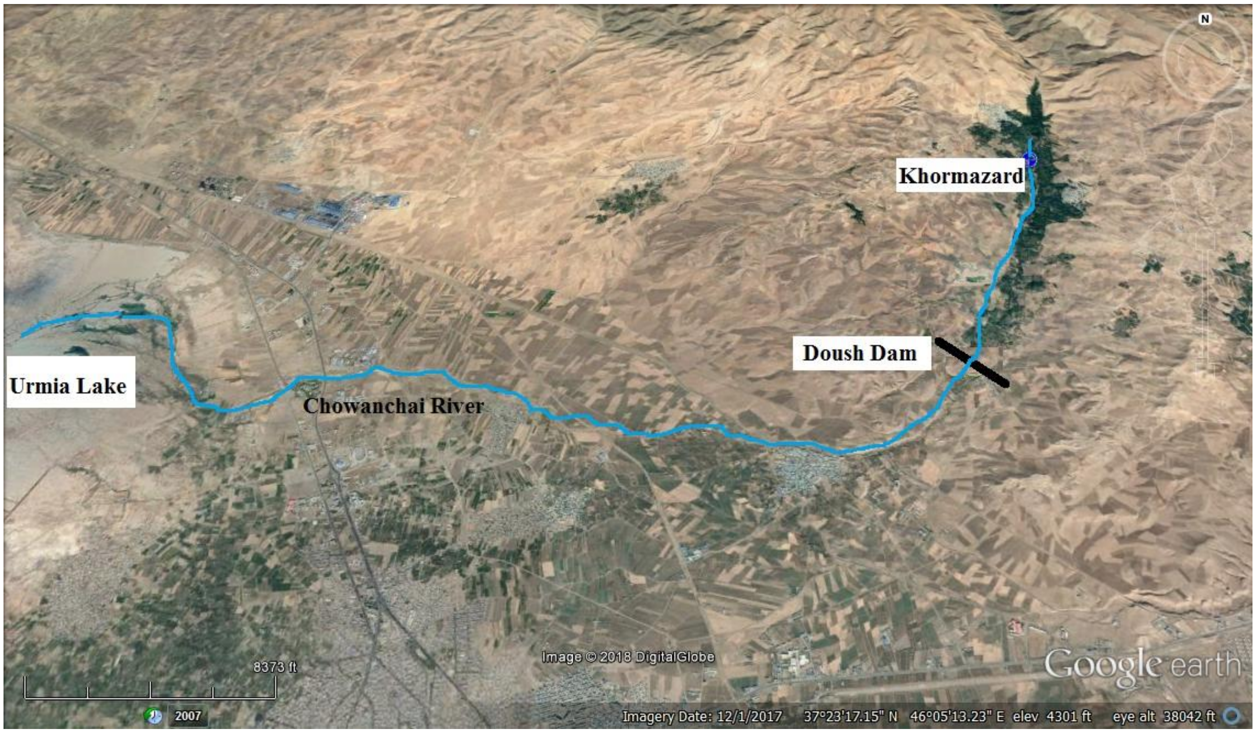


Figure 3.11. The hydrographic network and location of the hydrometric stations and of the under-evaluation Doush Dam in the ChowanChai River catchment.

3.2.4.6. SoufiChai River

The length of the SoufiChai River is 69 km, with an average slope of 1.3%, and its catchment area is about 561 km^2 (Ministry of Energy, 2004). The ChekanChai branch flows parallel to the main river and eventually joins it. The last hydrometric station on the SoufiChai River is Bonab. Due to lack of water flows for most of the year at the station, after 1996 the station has been inactivated.

In 1996, the Alavian Dam with a regulated volume of 314 Mm^3 was activated upstream of the Maragheh Station (Figure 3.12). There are about 1650 ha of arable lands after the Bonab Station, which is irrigated with the river water if any water inflows in it. According to the inhabitant near the Bonab Station, after the construction of the dam there was practically no water flow downstream of the dam, as far as the station (Ministry of Energy, 2004).

According to the report of the Center for Studies of East Azerbaijan and the Ardebil Regional Water Organization (1994), there are seven canals after the Bonab Station. The amount of water consumption from the river is 10,000 m^3 per ha and 25% of the water comes back to the river with drainage. The monthly distribution of water after the Bonab Station is in accordance with Table 3.4.

According to the mentioned table and the discharge at the Bonab Station, due to water consumption at the Alavian Dam after 1996, as well due to recent droughts, no flow from the SoufiChai River has been entering into the Urmia Lake.

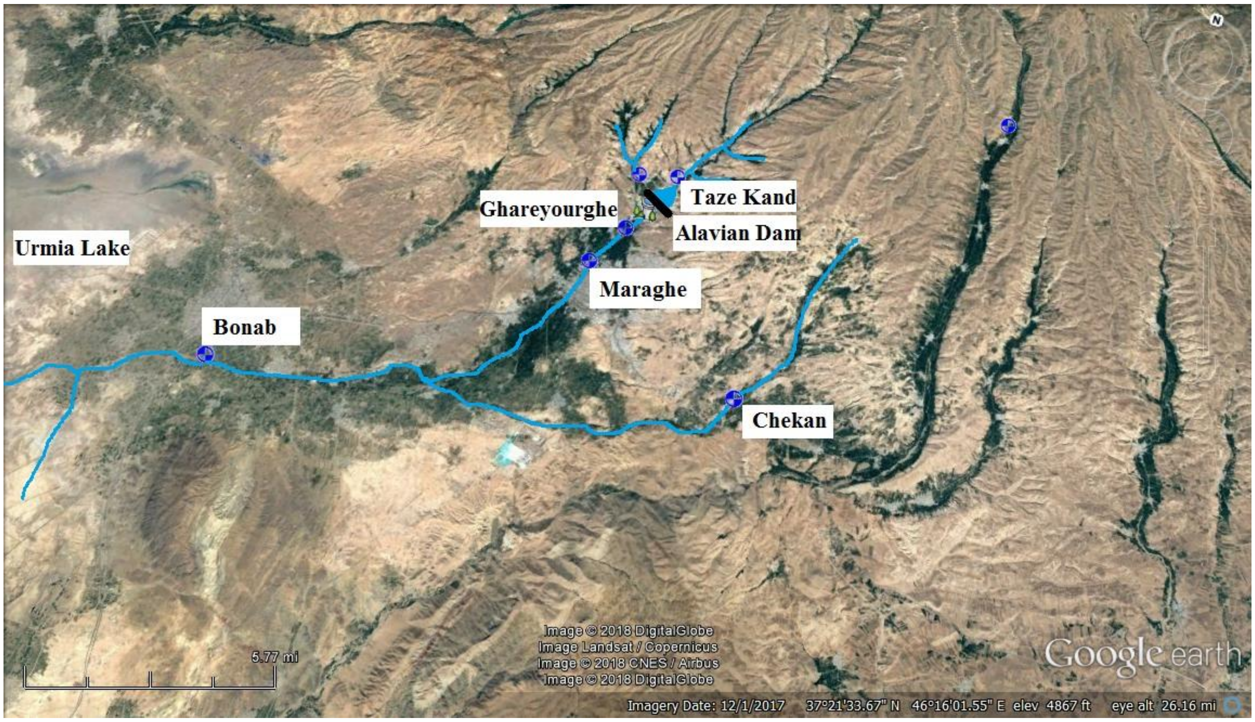


Figure 3.12. The hydrographic network and location of the hydrometric stations and of the Alavian active Dam in the Soufi-Chai River catchment.

3.2.4.7. MardoughChai

The river has a length of more than 94 km and an average slope of 1.2%, with a catchment area of 983 km^2 (Ministry of Energy, 2004). The last hydrometric station on the MardughChai River is the Malek Kandi Station. The station was inactivated in 1971 due to lack of flow after the mentioned station. Currently, the last active hydrometric station in the MardoughChai River reach is the Qheshlaq-e Amir Station. The station is upstream of the site where the new reservoir of GhareNaz Dam (Figure 3.13) has been designed, its construction being at present under evaluation.

In the recent years, due to the drought, flow discharge of the river at the Qheshlaq-e Amir Station has been decreasing.

There are plenty of agricultural lands downstream of the Qheshlaq-e Amir Station, which could be irrigated during the crop season with the presence of water in the river. The area of these lands is about 6000 ha (Ministry of Energy, 2004).

The amount of the MardughChai River discharge entering the Urmia Lake has been therefore evaluated as follows:

- After 1997, during winter and crop seasons, no water flows into the Urmia Lake from the MardoughChai River.
- Prior to 1997, according to the Table 3.4 and with the presence of water in the river, about 45 Mm^3 of water per year are subtracted for irrigation of agricultural lands.

Figure 3.13. The hydrographic network and location of the hydrometric stations and of the under-evaluation GhareNaz Dam in the MardoughChai River catchment.

3.2.4.8. Zarrinehroud River

The Zarrinehroud basin is the largest sub-basin of the Urmia Lake. It accounts for 23% of the total area of the lake basin and about 41% of the lake inflowing discharge comes from this sub-basin. The length of the Zarrinehroud River is about 320 km, its average slope is about 0.4% and its catchment area is about 12000 km^2 (Jamab Consulting Engineers, 2005). The general structure of the hydrographic network of this basin is shown in Figure 3.14 and the name of the stations has been listed in Table 3.5.

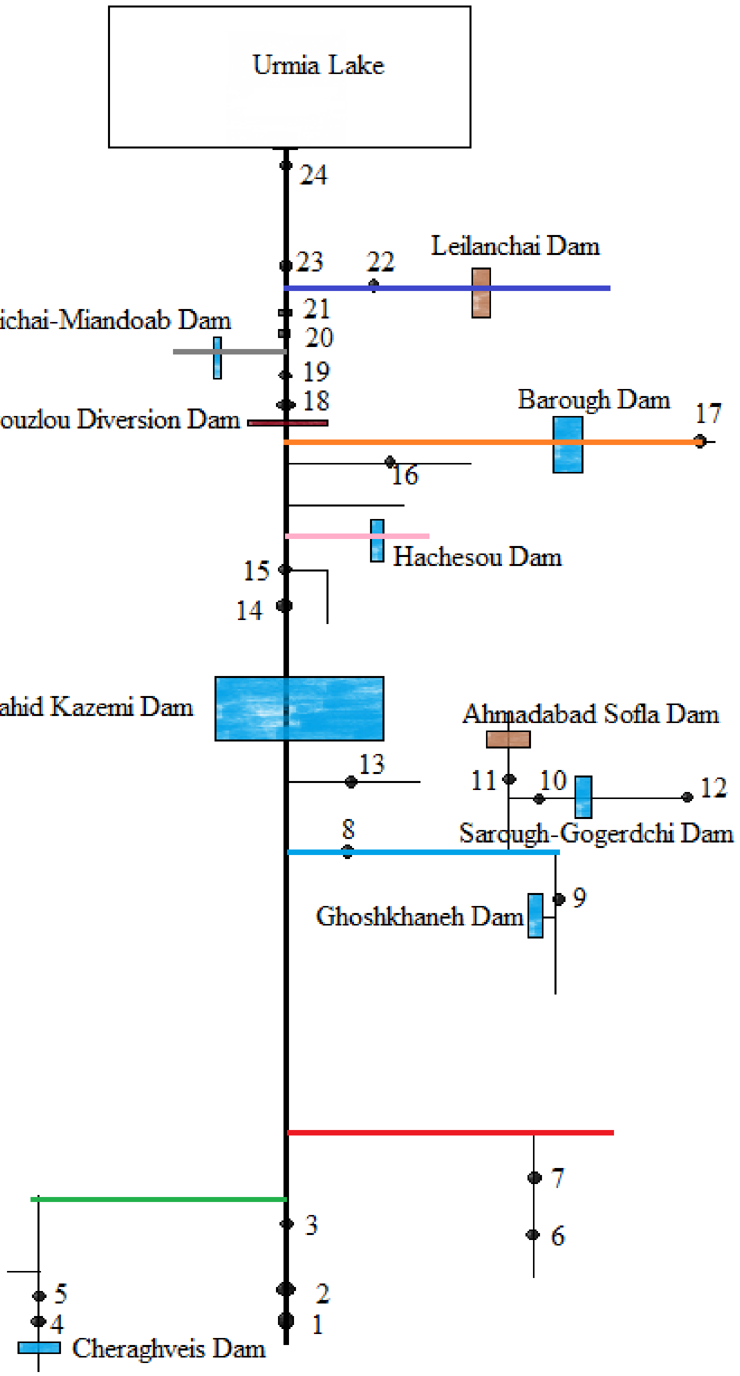


Figure 3.14. The hydrographic network and location of the hydrometric stations and of the active ShahidKazemi Dam and of the other dams in the Zarrinehroud River catchment.

Table 3.5. Hydrometric stations in the Zarrinehroud River basin

Station Name	Station Number	Station Name	Station Number
PoleHassan Salaran	1	-	13
PoleGheshlagh	2	Sarighamish	14
PoleAnian	3	Ghiz Kurpi	15
Ghabghablou	4		16
Darre Panbedan	5	Chalikhmaz	17
Sante	6	Gheshlagh	18
Karim Abad (Khor Khoreh)	7	Ghale	19
Saffakhaneh	8	Serahi Shahin Dejh	20
Ghoshkhaneh	9	Miandoab	21
Right Ala Saghal	10	Shirin Kandi	22
Left Ala Saghal	11	Nezamabad	23
Ghoshkhaneh Sofla	12	Ghare Papagh	24

There are about 5207 ha of agricultural lands after the Nezamabad Station, which consume water from the Zarrinehroud River during the crop season. Volume of water consumption is about 167.94 Mm^3 of water per year.

According to the experts (Ministry of Energy, 2004), and the dominant cultivation in the region (sugar beet), the water consumption per ha and per year is 12000 m^3 and 25% of the water that is used is recyclable. According to Table 3.4, the amount of water consumption after the Nezamabad Station is about 46.86 Mm^3 per year.

Since 1998, the Zarrinehroud River discharge has dropped sharply in the vicinity of the Nezamabad Station. The main reason for this decline is the lack of rainfalls in recent years.

3.2.4.9. LeilanChai River

The total length of the LeilanChai River is about 111 km, the average river slope is about 0.6%, and its catchment area is about 955 Km^2 (Ministry of Energy, 2004). The last hydrometric station on the LeilanChai River is the Shirinkandi Station (Figure 3.14). Since 1981, the river path has been changed and connected to the Zarrinehroud River with the construction of a channel after the Nezamabad Station. The agricultural lands downstream of the Shirin Kandi Station are about 6000 ha. Before the change of the river path, in the years when the river had water, all of it was taken from the river for irrigation.

3.2.4.10. Siminehroud River

This river is located south of the Urmia Lake and west of the Zarrinehroud basin. The Siminehroud River divides into two branches after the Miandoab Station; its average slope is 0.3% and its catchment area is approximately 353 km^2. On the branches of the Siminehroud River, there are the ZanjirAbad and the TazeKand Station. Due to inaccuracies in their data, the Miandoab Station data were selected. After the Miandoab Station, there are significant agricultural lands; water is being consumed during the crop seasons (Ministry of Energy, 2004). The water consumption is from April until November.

According to the experts (Ministry of Energy, 2004), the average water consumption for agricultural lands is 12,000 cubic meters per ha per year and 25% of the used water is recyclable. The percentage of water demand downstream of the Miandoab Station for 9975 ha of agriculture lands is in accordance with Table 3.4.

The Siminehroud Reservoir Dam with a capacity of 312 Mm^3 are constructing for DW, IW, AW, EL, FC, AR purposes, also the SardarAbad and Khorasane Dam in the catchment area of this river are under-evaluation in the Siminehroud River catchment. In Figure 3.15, the Siminehroud River basin is shown.

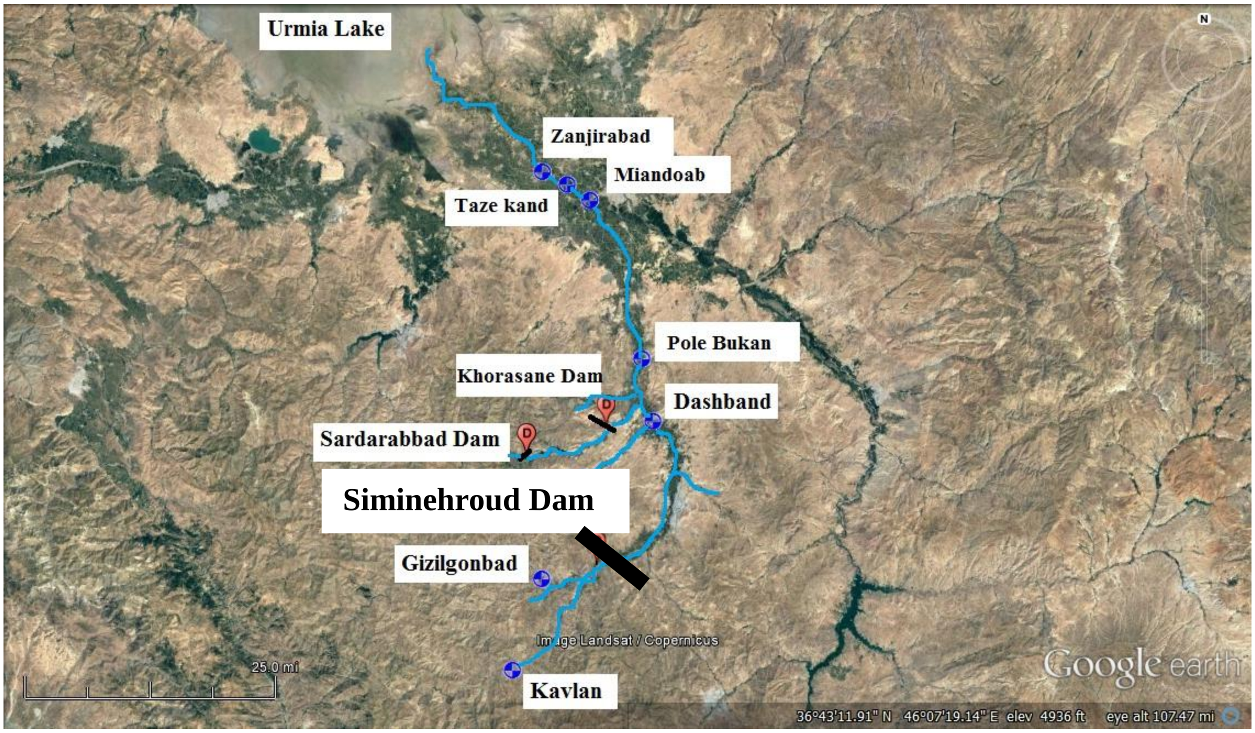


Figure 3.15. The hydrographic network and location of the hydrometric stations and the under evaluation Siminehroud Dam and the Khorasaneh and SardarAbad Dam under-evaluation in the Siminehroud River catchment.

3.2.4.11. MahabadChai River

The length of the MahabadChai River is more than 71 km with an average slope of 0.3% and its catchment area is about 1540 km^2. The MahabadChai River originates from the Mahabad Dam and then a part of the river discharge is diverted by another diversion dam downstream for irrigation of agricultural lands. The Mahabad Dam was built in 1970 and the capacity is about 230 Mm^3. Its regulatory volume is 190 Mm^3 per year. The last hydrometric station on the MahabadChai River is the GordeYaghoub Station. The location of the station is such that there are only 150 ha of land downstream (Ministry of Energy, 2004). The amount of water demand for those lands is 1.13 Mm^3 per year in accordance with Table 3.4. In Figure 3.16, the MahabadChai River basin is shown.

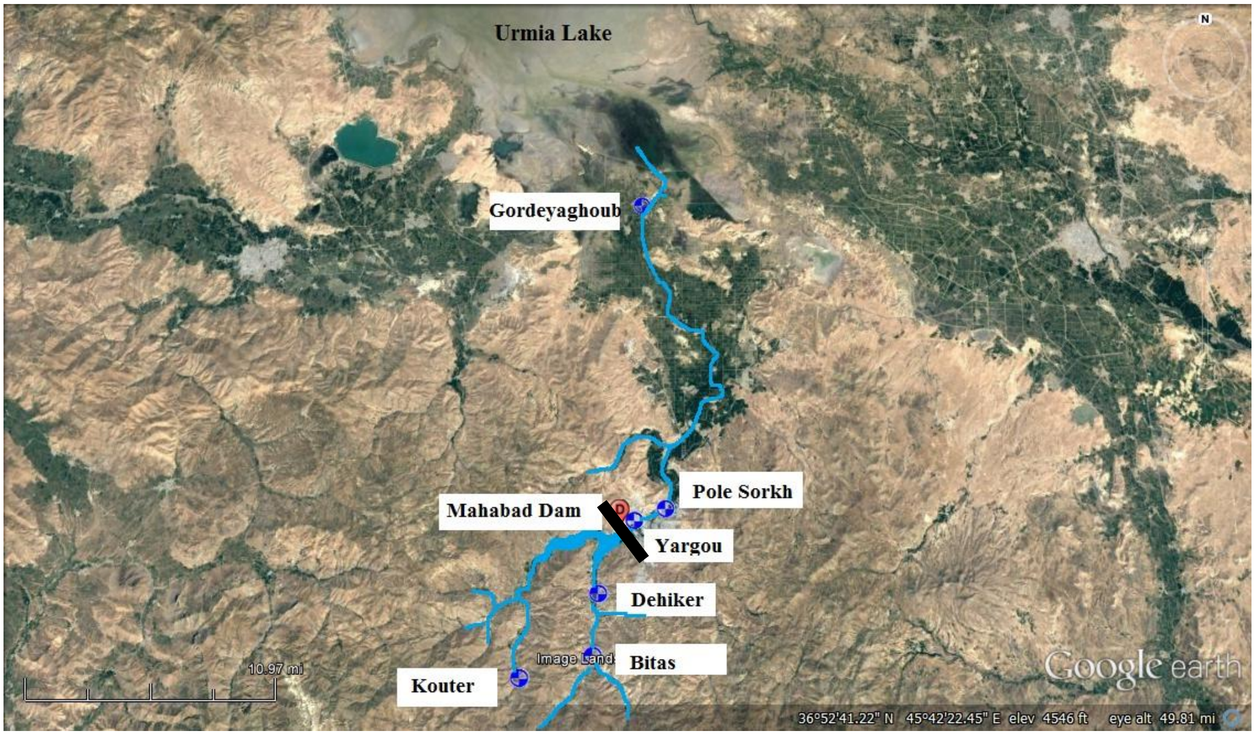


Figure 3.16. The hydrographic network and location of the hydrometric stations and the active Mahabad Dam and of the Yousefkandi diversion Dam in the MahabadChai River catchment.

3.2.4.12. GadarChai River

Approximately 8.2% of the total discharge into the Urmia Lake is provided by the GadarChai River. The total length of the GadarChai River is 95 km, its average slope is 0.5% and its catchment area is about 2108 km^2 (Ministry of Energy, 2004). The GadarChai River has 14 active hydrometric stations; the most important of them are Naghadeh and PoleBahramlou Stations, which are located on the main river. The Naghadeh Station indicates the total potential discharge of the river, being the use of the river discharge between this station and the Urmia Lake. Data at this station have been recorded since 1965. The PoleBahramlou Station is the nearest station to the lake and is important for assessing the discharge into the lake. The PoleBahramlou Station has been active since 1957. Its maximum yearly discharged volume was in 1968 and equal to 993.7 Mm^3 and its minimum discharged volumes occurred in recent years. Discharge reduced due to recent drought and the impoundment of the Hassanlou Dam with a regulated volume of 94 Mm^3 since 1999. About 200 ha of agricultural lands are located after the PoleBahramlou Station, in which water is consumed during the crop season from the river. In 1997, at the DashKhaneh Station, the Urmia Environmental Office has built a diversion dike on the main stream of the GadarChai River to provide water for the lagoon near the DashKhaneh Station. In the first years, all the river discharge flowed into the lagoon, 50% of it nowadays.

The distribution of water demand for irrigation of 200 ha of arable lands after the PoleBahramlou Station is in accordance with Table 3.4. In Figure 3.17, the GadarChai River basin is shown.

Figure 3.17. The hydrographic network and location of the hydrometric stations and of the active Hassanlou Dam and the under construction ChaparAbad Dam and the under evaluation Dehgorgi Dam in the GadarChai River catchment.

3.2.4.13. BarandouzChai River

This river is located west of the Urmia Lake. The total length of the BarandouzChai River is about 63 km, which flows with a 0.7% average slope into the Urmia Lake, the area of the catchment being 1588 km^2. BarandouzChai has four active hydrometric stations at Dizaj, Ghasemlou, Babaroud and Hashemabad (Ministry of Energy, 2004). The location of the hydrometric stations and under-evaluation dams is shown in Figure 3.18.

The last hydrometric station on the BarandouzChai River is the Babaroud Station, whose data are available since 1953. The maximum annual discharge at the station was recorded in 1969 and it was equal to 586.7 Mm^3, while the minimum yearly discharges occurred in recent years, such as in other rivers in the Urmia Lake basin. The land was closely monitored after the last station, which has about 620 ha of arable lands fed by a deviation dike in the main river reach. The percentage of distribution and quantity of water consumption in the crop season are listed in Table 3.4.

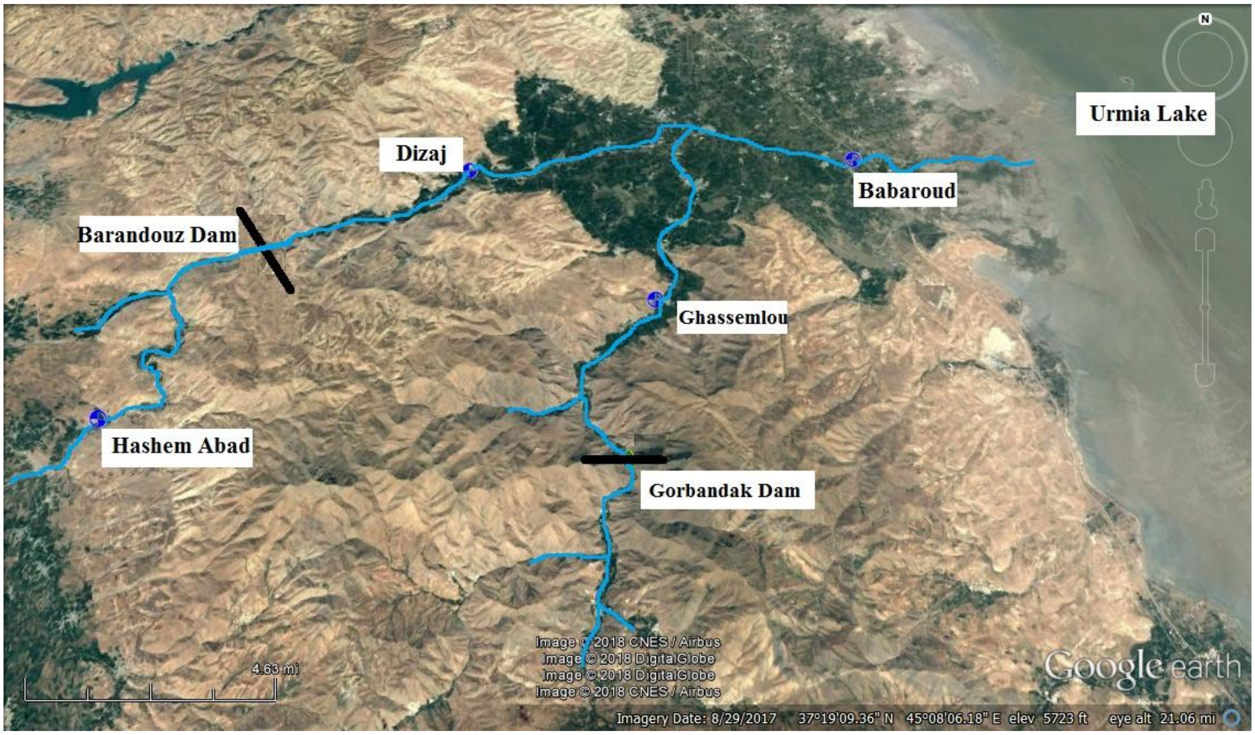


Figure 3.18. The hydrographic network and location of the hydrometric stations and the under- -evaluation Barandouz Dam in the BarandouzChai River catchment.

3.2.4.14. ShahrChai River

The total length of the ShaharChai River is about 69 km and its average slope is about 0.7%. The catchment area of this river is about 600 km^2. At the site of the Band Station, a diversionary dike deviate the entire discharge throughout the cropping season. As a result, only flood discharges in the ShaharChai River enter the Urmia Lake (Ministry of Energy, 2004). The ShahrChai River basin is shown in Figure 3.19.

The flow of this river from the MirAbad Station to the Keshtiban Station is diverted into irrigation channels. MirAbad, Band and Keshtiban Stations are active hydrometric stations within the basin; The ShahrChai Dam was built in 2005 at 10 km distance from the Band Station.

The last hydrometric station on the ShahrChai River is the Keshtiban Station, with a sub-basin area of 595 km^2. The station was inactivated after 13 years of operation in 1977 and in 2003 reactivated again. The average discharge at the station during the 13-years period was 110.2 Mm^3/year. The monthly distribution at the station has shown that more than 91% of the flows are during spring (Ministry of Energy, 2004).

The Band Station has more than 69 years of measured data and its sub-basin catchment area is 420 km^2. The discharge recorded at the station in recent years has been lower than the long-term average due to reduced precipitation and high water demand for agriculture. Downstream of the station, almost all of the river discharge is taken for irrigation by a diversionary dike during the cropping season. Due to lack of water during the crop season and according to the recommendations of the authorities of the West Azerbaijan Regional Water Organization (WARWO), in recent years all winter and autumn water is used only for the artificial recharging of groundwater in the region. Therefore, the flow of the river reaches the Keshtiban Station only in spring.

After the Keshtiban Station there are about 820 ha of arable lands in which water is consumed in spring (Ministry of Energy, 2004). The water demand takes place only in three months of the year, is about 6.16 Mm^3/year. Table 3.4 shows the distribution and the amount of water demand for agriculture after the Keshtiban Station.

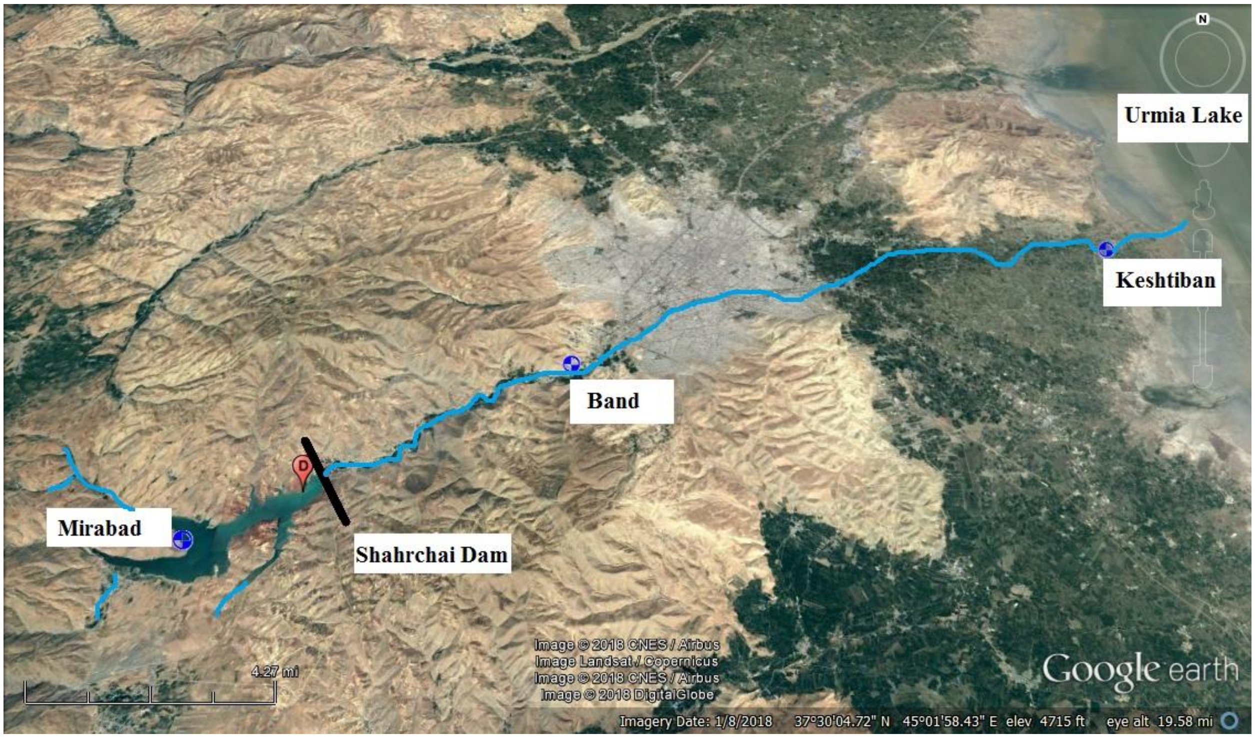


Figure 3.19. The hydrographic network and location of the hydrometric stations and of the active ShahrChai Dam in the ShahrChai River catchment.

3.2.4.15. RozehChai River

The total length of the RozehChai River is more than 63 km, with an average slope of about 1.1%, and its catchment area is about 528 km^2. The last hydrometric station on the RozehChai River is the Gojali-Aslan Station. About 60% of the station's discharged volume is during spring. Reduction of the discharge of the RozehChai River has been remarkable in the recent years. There are about 2,275 ha of lands irrigated with river water when there is a discharge in it (Ministry of Energy, 2004).

According to Table 3.4, percentage of distribution and water requirements for agricultural lands, about 17.06 Mm^3/year of water are required in the cropping season. In Figure 3.20, the RozehChai River basin is shown.

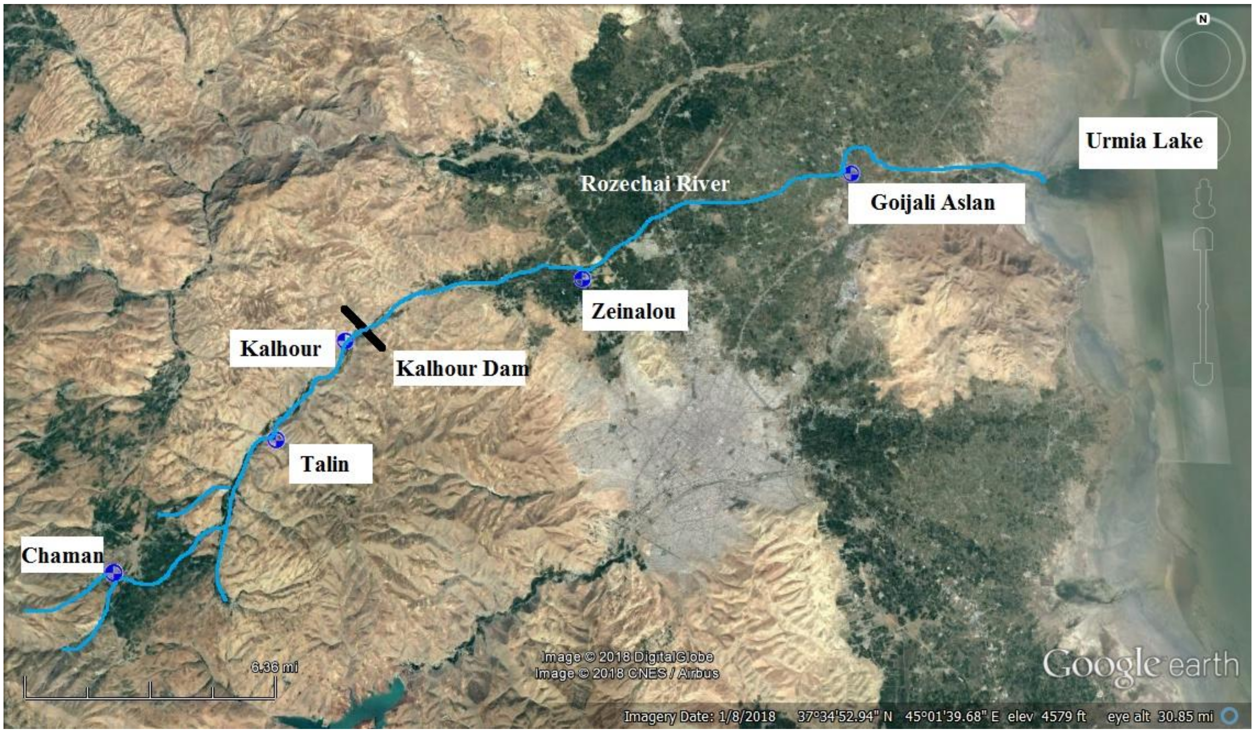


Figure 3.20. The hydrographic network and location of the hydrometric stations and of the under-evaluation Kalhour Dam in the RozehChai River catchment.

3.2.4.16. NazlouChai River

The total length of NazlouChai River is 70 km, its average slope is 0.3% and its catchment area is 2917 Km^2.

The last hydrometric station on the NazlouChai River is the Abajola Sofla Station. During the crop season, about 1445 ha of agricultural lands are irrigated using river water. The water used for irrigation according to Table 3.4 is 10.84 Mm^3/year, which is consumed if there is any flow in the river. The flow regime of the river is torrential, 76.76% of the yearly volume being discharged during spring (Ministry of Energy, 2004). Construction of Nazlou Dam in the NazlouChai basin is stopped because of the Urmia Lake restoration plans. In Figure 3.21, the NazlouChai River basin is shown.

Figure 3.21. The hydrographic network and location of the hydrometric stations and of the under evaluation Nazlou Dam in the NazlouChai River catchment.

3.2.4.17. ZolaChai River

The ZolaChai River flows the Northern part of the Urmia Lake, it has a length of 87 km, its average slope is 0.7%, and its catchment area is about 2,200 km^2 (Ministry of Energy, 2004). The hydrographic network and location of hydrometric stations in ZolaChai basin is shown in Figure 3.22. Important branches of ZolaChai include the DarehLiSu and Derik River.

The last hydrodynamic station in the ZolaChai River basin is the YalghouzAghaj Station; there are about 1511 ha of agricultural land after the station, in which water is consumed for irrigation of the lands during the cropping season.

The KhorkhorehChai River flows into the ZolaChai River downstream of the Yalghouz Aghaj Station. The last hydrometric station on the KhorkhorehChai River is the Tamr Station. According to the region's residents and the experts, when the discharge of the river is high, the river flows into the Zola-Chai River. During winter, the discharge of KhorkhorehChai River is used for irrigation of the lawns and during the crop season it is used for irrigation of the fields. As a result, 50% of the river's discharge flows into the ZolaChai River during spring and specially, in the middle of May, and the rest is used for irrigation of grasslands and agricultural lands.

A part of the ZolaChai River flow in winter has been used for irrigation of grasslands. This amount is about 50% of the river discharge. Due to the decrease of flow in the river during recent years, sediments have been packing at the entrance of the ZolaChai River in the lake, so that for low discharges the river does not enter the lake.

Important structures are being used to control the discharge in the ZolaChai River basin; these are:

-the Zola Reservoir Dam, which has been active sing 2010 and is located 42 km upstream of the Urmia Lake; the objectives of the dam include an annual adjustment of 132 Mm^3 of discharge for irrigation of

15,800 ha of lands and control the floods of the ZolaChai River to prevent flood damage and drinking water supply;

-the Derik Reservoir Dam, which has been built in 2007 on the DerikChai River, 50 km upstream of the Urmia Lake, with an annual water content of 34.14 Mm^3.

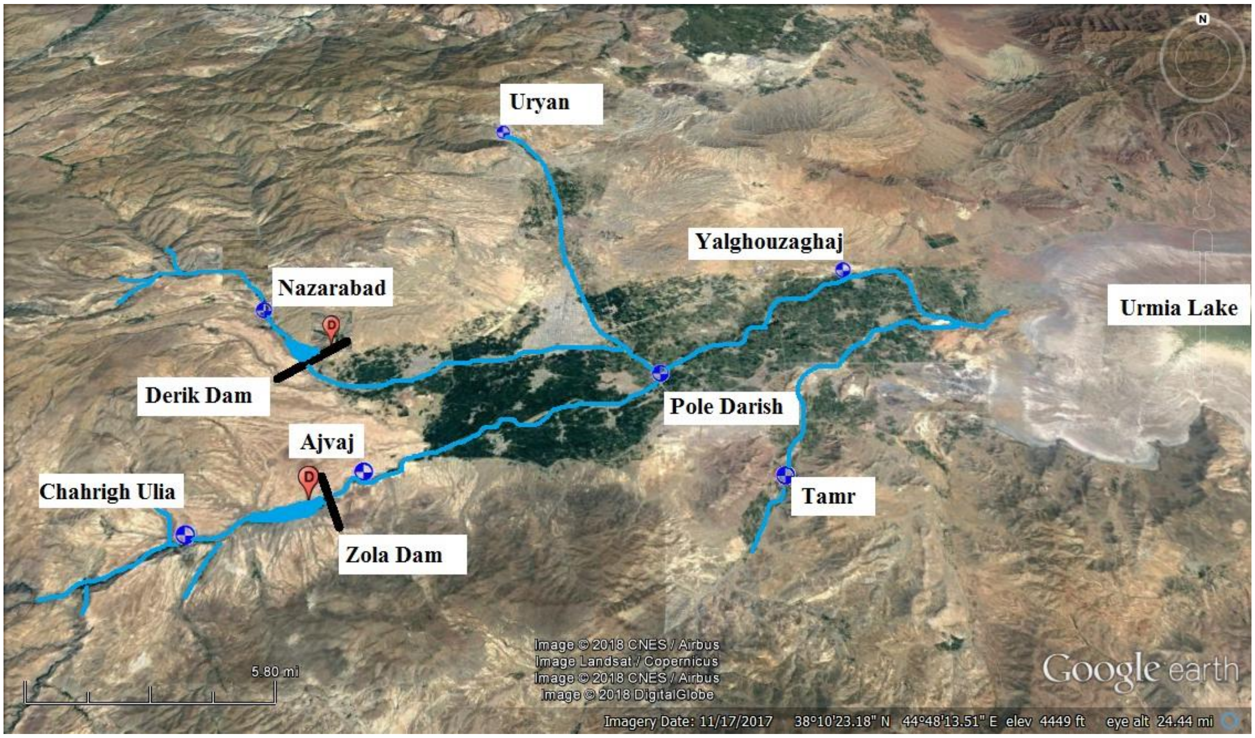


Figure 3.22. The hydrographic network and location of the hydrometric stations and of the active Zola and Derik Dams in the ZolaChai River catchment.

3.2.5. Estimation of the sum of water losses and inflows in the buffer zone ($V_{Unmeasured}$)

The evaluation of additional flow rate terms $V_{Unmeasured}$ to be subtracted from the measured flow rate at the last hydrometric station in the two buffer zones of each river basin requires the estimation of different terms:

- the precipitation over the flood region in the buffer zone 2 estimated from the monthly precipitation on the surface of this zone, to be subtracted from $V_{Unmeasured}$, the boundary of the first buffer zone must be specified precisely in order to obtain a better estimate of the precipitation on the buffer zone 2;
- the evaporation from the flood region in the buffer zone 2, estimated by hydraulic modeling or remote-sensing methods, through which flooded areas for each river under different discharges can be obtained.
- the discharges of seasonal tributaries entering each river in the reach between the last hydrometric stations and the Urmia Lake (the tributaries in buffer zone 1).
- the water consumption in river reaches between the last hydrometric stations and the Urmia Lake, owing to agricultural and industrial use within the buffer zone 1: this datum can provide more accurate information about the amount of flow entering the second buffer zone (in which, the major loss of evaporation, occurs due to the spread of water on a large area).

In a report published by the Ministry of Energy (2004), all factors that have contributed in reducing the discharge of permanent rivers to the lake have been identified and by taking those into account, the amount of the actual inflow into the lake can be calculated. In the report, the main factors that reduce the discharge of the rivers are listed as follows:

- water consumption for agriculture: in most permanent rivers within the Urmia Lake basin there is a considerable extension of agricultural lands after the last hydrometric station, water is withdrawn from the rivers either by gravity or pumping; most of the agricultural lands belong to the Siminehroud River sub-basin with about 10,000 ha, while the smallest is the MahabadChai River sub-basin with about 200 ha;
- artificial recharging of groundwater during the winter: in some river basins such as the Shahr-Chai and NazlouChai River, due to the lack of groundwater during summer, the farmers irrigate the lands downstream of the last hydrometric stations also during winter, this practice being called “Slush”;
- water consumption for lagoons in the vicinity of the lake: there are several natural lagoons in the vicinity of MahabadChai and GadarChai Rivers, which are supplied with natural streams for environmental protection reasons;
- diversion of some rivers: due to plans for the development and construction of hydraulic structures, the path of some rivers has been changed, such as for the LeilanChai River, which has been connected to the Zarrinehroud River after the last hydrometric station (Shishvan Station);
- accumulation of sediments at the river mouth: in recent years, due to drought, the decrease of the discharge of the rivers caused the accumulation of sediments at the mouths of the rivers, leading to increased water losses due to evaporation; one of these rivers is the ZolaChai River.

3.2.5.1. Estimation of the monthly distribution of consumed water volume after the last hydrometric stations in the Urmia Lake basin

Among the variables mentioned above, the most important one is water consumption for agriculture. After visits to the sub-basins of all rivers in the Urmia Lake basin by experts, the figures listed in Table 3.4 have been provided for the monthly water consumption after the last hydrometric station of each river (Ministry of Energy, 2004).

3.3. Evaluation of the lake response

The surface water level in the Urmia Lake is a function of different components of the water balance equation such as river discharge and net precipitation. To evaluation of the environmental impacts of river flow on the lake water levels, the concept of capacity inflow ratio has been defined by Rami Reddy (2005) as following:

$$CIR = MLC/MAF \quad 3.4$$

Where MLC is the maximum lake capacity or volume (m^3) and MAF is the mean annual river flow (m^3). The MLC term can be calculated by topographical maps and the lake hypsographic curves.

Also the degree of lake wetness (DLW) indicator has been defined by Torabi Haghighi (2014) to show the lake response to net precipitation and river flow as Equation 3.5. Based on the lake volume as a percentage of the maximum volume of the lake, it is classified in five categories as:

dry (<20%), semi–dry (20–40%); normal (40–60%), semi–wet (60–80%) and wet (>80%). By using the measured lake level fluctuation data on past, the percentage of time in months per total record that the lake was in dry (A_1), semi–dry (A_2), normal (A_3), semi–wet (A_4) and wet (A_5) conditions DLW can be calculated as:

$$DLW= (A_1\times10+A_2\times30+A_3\times50+A_4\times70+A_5\times90- 1000) / 8000 \quad 3.5$$

In the Urmia Lake, maximum recorded volume is equal to 36120340620 m^3 volume of the lake correspond to 1278.41 m water level.

In this study by using DLW index the response of the lake to changes in the water allocation has been quantified. As climate change and constructing the hydraulic structures such as reservoir dams in the lake basin can affect the lake regime. So in this study by using mentioned index the boundary between before and after drying of the Urmia Lake has been determined.

3.4. General view of dams in the Urmia Lake basin

The construction of dams in the Urmia Lake basin started with the construction of the Mahabad Dam over the Mahabad River in 1971. At present, a total of 44 dams have been built. The potential inflow of surface runoff is affected by 24 dams upstream of the lake (Yasi, 2017).

The biggest portion of intake and water supplied by these dams are used for irrigation. Water supply for drinking water and industrial use is also provided by these dams.

The dams are managed mainly by the Regional Water Corporation of each province under the Water Resources Management Company (WRMC) of the Ministry of Energy (MOE). There are also other dams managed by the electric companies and drinking water supply companies of the cities (Note: This is based on the information from WRMC, However, information from the management agencies of each dam could not be collected). Furthermore, about 30 new dams are being proposed or studied. In terms of storage volume, the ShahidKazemi Dam, the ShahrChai Dam and the Mahabad Dam have the 1st, 2nd and 3rd largest storage volume among the existing dams, respectively (JICA et al., 2016).

Among the existing dams, the ShahidKazemi Dam, located in the Zarrinehroud River basin has the largest storage volume of 762 Mm^3 and a wide catchment area of 6,890 km^2. The ShahrChai Dam in the ShahrChai River basin has the second biggest storage volume of 213 Mm^3 and a catchment area at the dam site of 330 km^2. The Mahabad Dam which is located in the MahabadChai River basin has the third largest storage volume of 190 Mm^3 and a catchment area of 806 km^2.

In the regulation rule schedule of dams in the Urmia Lake basin, the contribution of environmental flow of the downstream river is less than 13%. In other words, less than 13% of MAF estimated at diversion sections is currently release below the water intake structures. As of nowadays, about 90% of surface water flows toward the Urmia Lake are controlled and withdrawn. Currently, according to the order from the Urmia Lake Restoration Program, all the processes of dam construction are stopped (Yasi, 2017). Therefore, it is necessary to revise the allocation of the downstream environmental flow contribution in the regulation rule curve of dams in the Urmia Lake basin in the present and future.

In the following paragraphs first the largest dams of the basin will be described; then, the river flow regime and the effect of dams on it are evaluated. Then, using an optimal theory method, the discharges of rivers at the location of the last hydrometric station are obtained from the natural flow of rivers, and finally, based on that, a calendar of water release from dams is extracted.

3.4.1. ShahidKazemi Dam

Active, under-construction, and under-evaluation dams in the catchment of the Zarrinehroud River and their characteristics are shown in Table 3.6. One of the largest and oldest dams constructed on Zarrinehroud basin is the ShahidKazemi Dam. The dam was launched in 1971 with the aim of supplying agriculture, drinking water and producing electricity for the region. With the increase in reservoir volume in 2005, the total reservoir storage of the dam passed from 486 to 762 Mm^3. The total volume of the other dams built in the Zarrinehroud River basin (Ghoshkhaneh, Barough, Hachesou, Sarough-Gogerdchi, GhouriChai) is 135.49 Mm^3. Therefore, proper operation of the ShahidKazemi Dam, considering the environmental water requirement downstream of the dam, is of great importance in the process of restoring the Urmia Lake. Upstream of the ShahidKazemi Dam there are three permanent rivers, SaroughChai, SaghezChai and KhorkhoreChai, which are flow into the reservoir of the ShahidKazemi Dam. Mentioned rivers affect the volume of discharged water from the Shahid-Kazemi Dam.

According to Figures 3.14 and 3.23, the last station on the Zarrinehroud River is the Nezamabad Station. Discharge data at the mentioned station has been available since 1992. Before the establishment of this station, there was the PoleMiandoab Station as the last station on Zarrinehroud River. With the construction of the Zarrinehroud irrigation network, given the inappropriate location of the station, the PoleMiandoab Station was inactivated in 1992 and instead of it the Nezamabad Station was built. Due to the construction of the Zarrinehroud network, no runoff between the two mentioned stations can enter the river. Therefore, it is possible to estimate the hydrometric data of the Nezamabad Station since 1965 (since the establishment of the PoleMiandoab Station).

The Nezamabad Station is located on the main river and is the nearest active station to the lake (distance is less than 19 kilometers), 87 km downstream of the ShahidKazemi dam, which is important for assessing the amount of input flow to the lake.

The Sarighamish Station is the first station after the ShahidKazemi Dam and its measured data is important for evaluating the out flow from the ShahidKazemi Dam. This station has discharge data in the period before (1955-1971) and after (1971-2018) the construction of the dam. Regarding to the construction year of other dams of the Zarrinehroud River, in order to eliminate the effect of other dams in the catchment area on the discharge of the Sarigamish Station, the time period “1955-1971” was considered as the Preimpact period and “1986-2004” as a post impact period.

The Sarighamish Station is the first station after the ShahidKazemi Dam and its measured data is important for evaluating the flow of the ShahidKazemi Dam. This station has discharge data in the period Pre (1955-1971) and post (1971-2018) of construction of the dam. Regarding to the construction year of other dams of the Zarrinehroud River, in order to eliminate the effect of other dams in the catchment area on the discharge of the Sarigamish Station, the time period “1955-1971” was considered as the preimpact period and “1986-2004” as a post impact period.

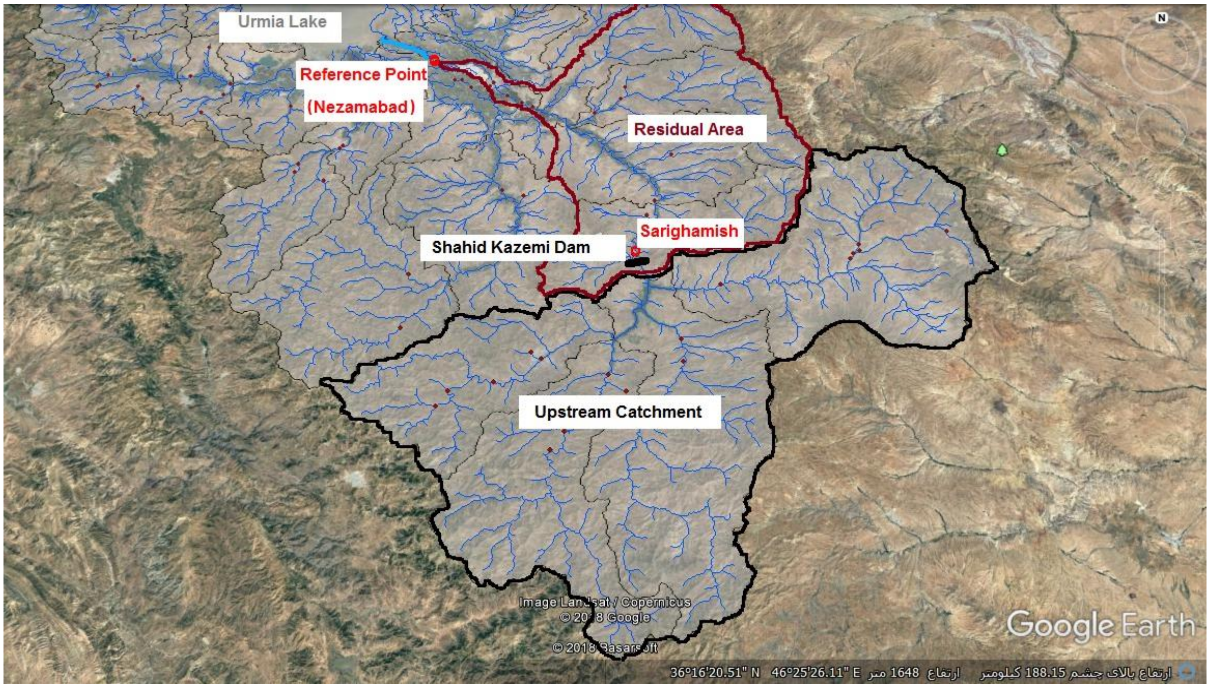


Figure 3.23. The location of the Zarrinehroud catchment, tributaries of the Zarrinehroud River, hydrometric stations and the ShahidKazemi Dam.

Table 3.6. Properties of dams in the Zarrinehroud catchment

Dam Name	Activation Year	Purpose	Storage Volume (Mm^3)	Catchment Area (Km^2)	Current Status
ShahidKazemi	1971	AW, EL	762	6890	OP
Goshkhaneh	2003	AW, DW	0.14		OP
Barough	2013		100		OP
Hachesou	1986		0.35		OP
Sarough-Gogerdchi	2009	DW, IW, AW	35	332	OP
LeilanChai	2012	AW, EL, FC, AR	35.5	571	UC
GhouriChai-Miandoab	2004				OP
Cheraghveis	2015	DW, IW, AW	68.6	363	UC
Ahmad Abad Sofla			1.8		UC
Sante		AW, EL, FC, AR, EN	67.08	884	ST
Ajorlou			93		ST
Khanoum guli			16		ST
Kordkand			11.5		ST
Markhaz		AW, FC, AR, EN	44.14	58	ST
Sayenjigh			18.5		ST

Data source: Ministry of Energy, Water Resources Management Company (WRMC)
Note: 1) Current Status: OP_active, UC_under construction and ST_under evaluation.
2) Purpose: DW_drinking water supply, IW_industrial water supply, AW_agricultural water supply, EL_electric power generation, AR_artificial recharge, FC_flood control and EN_environment.
4) It is not confirmed whether the under-construction dam with activation year before 2014 are already under-operation or not. So, they are written in the group of under-construction dams in the above table.

3.4.2. ShahrChai Dam

The ShahrChai Dam was built in 2005 on main reach of the ShahrChai River with a storage volume of 213 Mm^3 for drinking, industrial and agricultural purposes, and is located about 36 km from the Urmia Lake.

Figure 3.24 shows the location of the ShahrChai Dam and its upstream catchment area (black border) along with the hydrometric stations of the ShahrChai River basin (red circles) and the residual sub-basin (red border in the figure) to the Keshtiban Station.

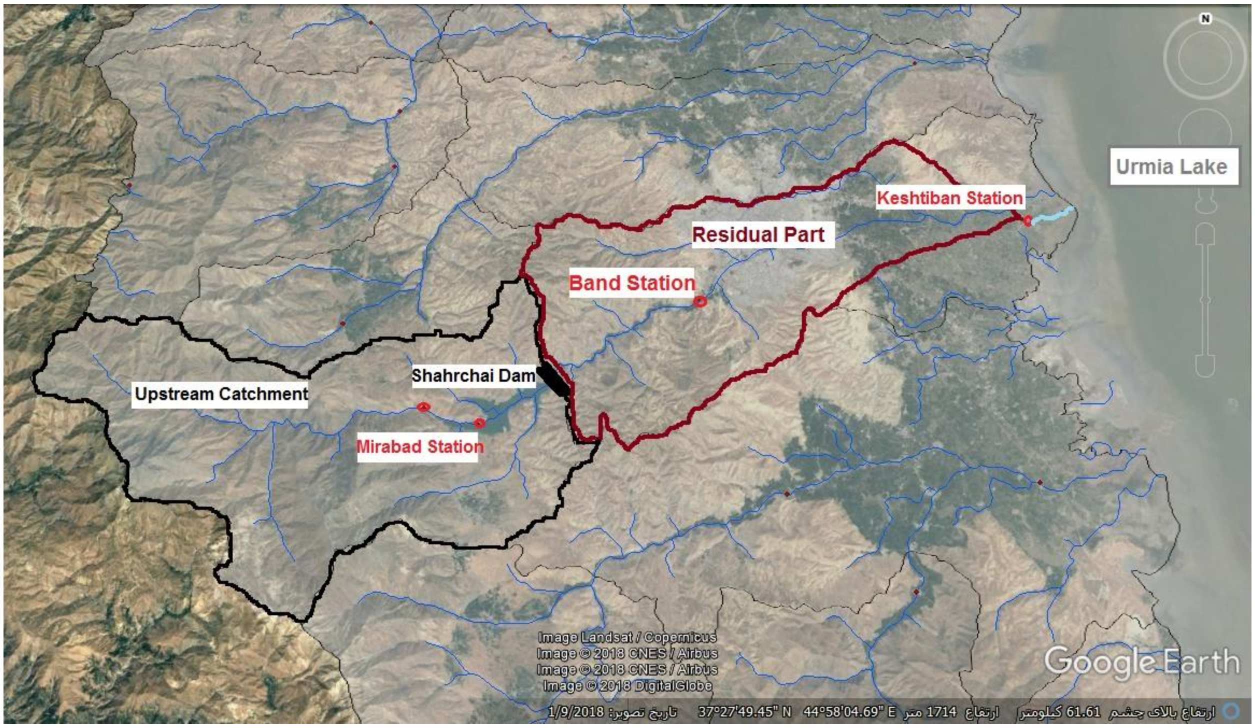


Figure 3.24. The location of the ShahrChai catchment, tributaries of the ShahrChai River, hydrometric stations and the ShahrChai Dam.

3.4.3. Mahabad Dam

The Mahabad Dam was built in 1970. The capacity of the reservoir is about 230 Mm^3. Its regulatory volume is 190 Mm^3 per year. The dam is built for drinking, industrial and agricultural purposes and power generation, at a distance of about 40 km from the Urmia Lake. In Figure 3.25 the location of the Mahabad Dam and its upstream catchment area (black border) along with the hydrometric stations of the MahabadChai River basin (red circles) and the residual sub-basin (red border in the figure) to the last station of the GordeYaghoub, are shown.

The PoleSorkhMaabad Station is located immediately downstream of the dam, at a distance of less than 1 km. The GordeYaghoub Station is the last station, at 11.5 km from the lake.

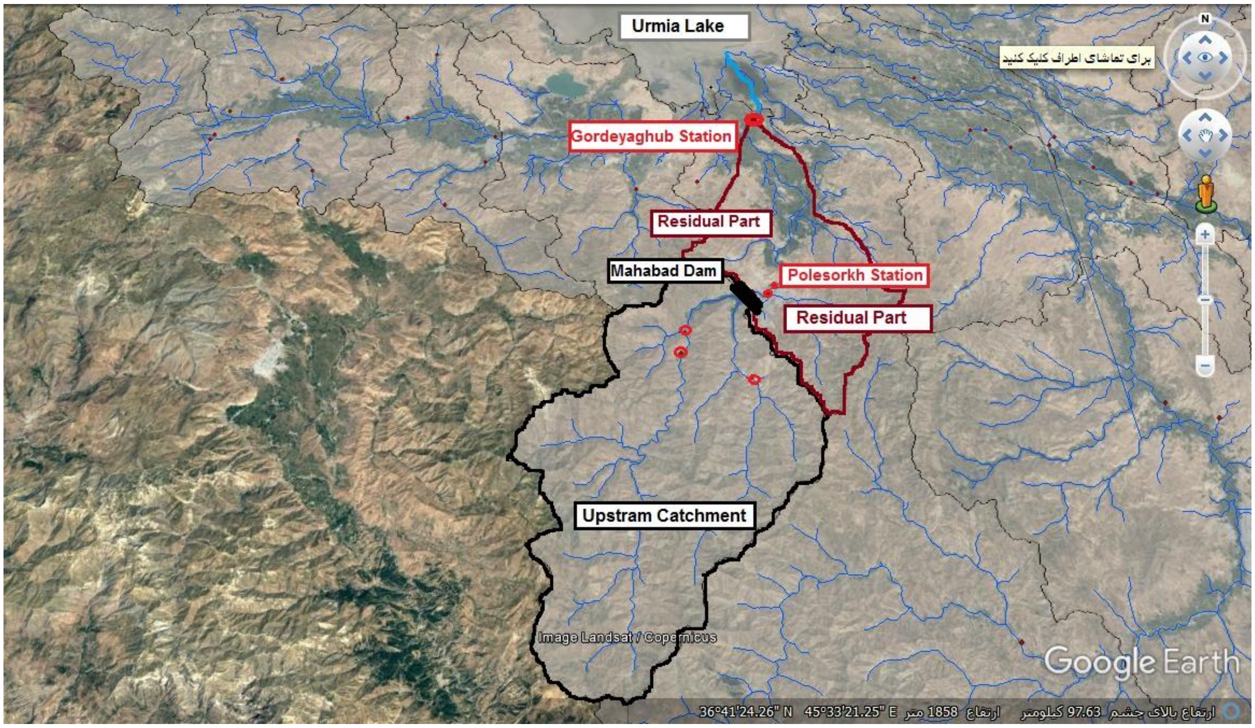


Figure 3.25. The location of the MahabadChai catchment, tributaries of the MahabadChai River, hydrometric stations and the Mahabad Dam.

3.4.4. Venyar Dam (ShahidMadani Dam)

There are about 26 active dams, 1 under construction and 9 under evaluations in the AjiChai River basin, whose properties are shown in Table 3.7.

In the main reach of the river, there is the Venyar Dam, which was activated in 2014. The dam is the largest along the AjiChai River, and its storage capacity is larger than the total storage capacity of all other dams in the AjiChai basin. So it has a very important role in annual inflows of the AjiChai River into the Urmia Lake. This dam is built for agricultural purposes. There is no reservoir dam in the distance between the Venyar Dam and the lake.

In Figure 3.26 the location of Venyar Dam and its upstream catchment area (black border) along with the hydrometric stations of the AjiChai River basin (red circles) and the residual sub-basin (red border in the figure) to the Akhoula Station (blue border in the figure), to the Sarin Dizaj Station, the last hydrometric station on the main reach of the AjiChai River and the nearest hydrometric station of the river to the Urmia Lake are shown. Furthermore, the distance that the AjiChai River passes after the last hydrometric station (Akhoula station) to the Urmia Lake (the distance that measured data from the river discharge not available) is demonstrated in blue.

In Table 3.8 the characteristics of three hydrometric stations in the AjiChai River catchment area are shown. The Venyar Station, located upstream of the Veanyar Dam, expresses the potential flow upstream of the dam. The Akhoula and Sarin Dizaj Stations are also important for checking the inflow of the river into the lake. The Akhoula Station, located 49 km far from the lake, is the last hydrometric station that has an extended series of measured discharges

Table 3.7. Properties of dams in the AjiChai Catchment

DAM_NAME	VOLUME (Mm^3)	BASIN (Km^2)	ACTIVATION YEAR	OBJECTIVE	Stage
Ghirikh Akhaj	3			AW, AR, FC	OP
Hassan Janlouh	0.3				OP
Abdolabad	0.25				OP
Mollayaghoub	3				OP
Vaneghulya	1				OP
Gavdoush	2.5		1999	AW	OP
Ughan	1				OP
Tajiar Sarab	3.5			AW	OP
Ghisragh	2.6	189	2006	AW	OP
Ardalan	4.5				OP
Barough Haris	0.15		1982	AW	OP
Khormalou	0.35		1979		OP
Param	3.3	82	1997	AW	OP
Maghsoudlou	1.4				OP
Manigh	0.4				OP
Arbatan	25				OP
Amand Tabriz	2.2				OP
Amand 1	0.25		1982	AW	OP
Amand 2	0.25		1985	AW	OP
Nahand	21.1	216	1996	DW, ID	OP
Sefidan Atigh	0.4	36	1997	AW	OP
Malek Kian	8.8		2000	AW	OP
Kord Kandi	5.18	105	2003	AW	OP
Choghan	2.5	45		AW	UC
Baftan	5.8				OP
Asgar Abad	16.5				US
Dash Asiran	1				OP
Venyar	280	7723	2014	AW	OP

Table 3.8. Properties of the hydrometric stations in the AjiChai River basin.

Station Name	Distance from the Urmia Lake	Distance from Venyar Dam	Data
Venyar	+77	-	Since 1949 to now
Akhoula	+44	-33	Since 1983 to now
Sarin Dizaj	+20	-57	Since 2001 to now

The sign (-): Upstream of the dam, the sign (+): Downstream of the dam.

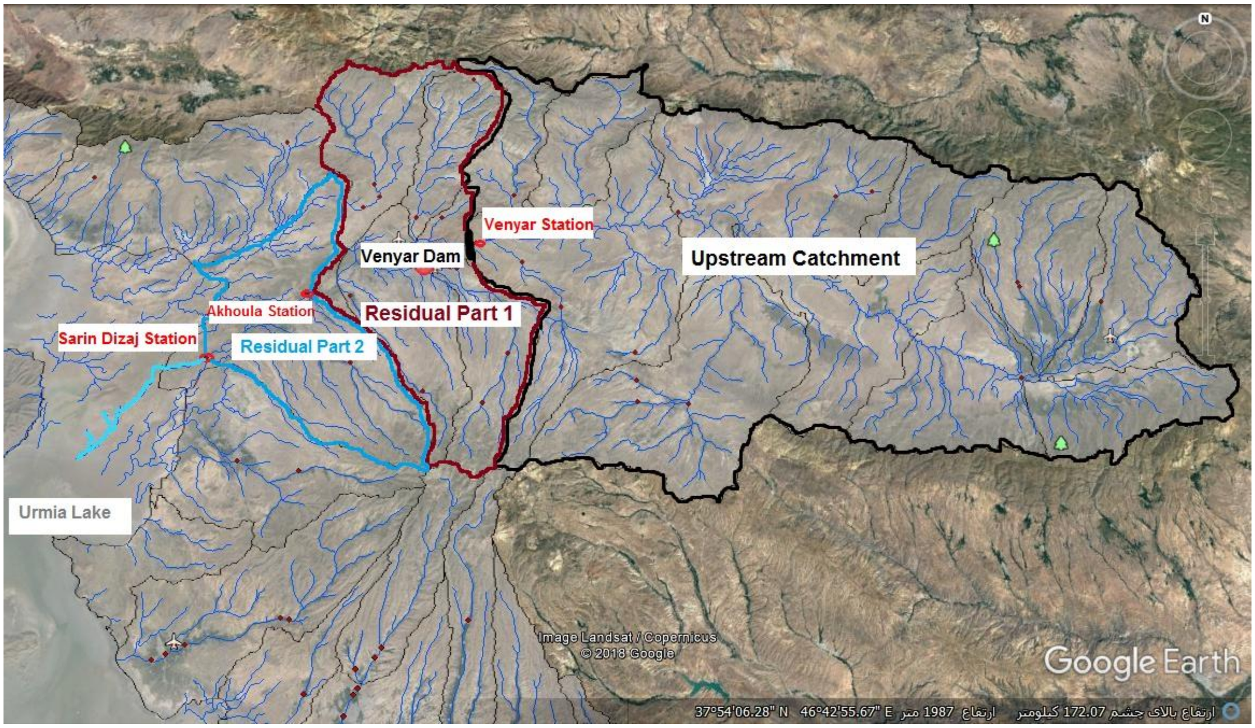


Figure 3.26. The location of the AjiChai catchment, tributaries of the AjiChai River, hydrometric stations and the Venyar Dam.

3.4.5. Ajabshir Dam

The Ajabshir Dam was built on the main reach of the QhaleChai River in 2006 with a storage volume of about 38.8 Mm^3 for drinking, industrial, agricultural and power generation purposes. In Figure 3.27, the location of the dam and its upstream sub-basin (black border), the hydrometric stations of the QhaleChai River basin (red circle) and residual part 1 (red border in the figure) are shown. Also the QhaleChai River sub-basin after the last hydrometric station (Shishvan Station) to the Urmia Lake, named residual part 2 (the distance that measured data from the river discharge are not available) is shown in the figure by blue border.

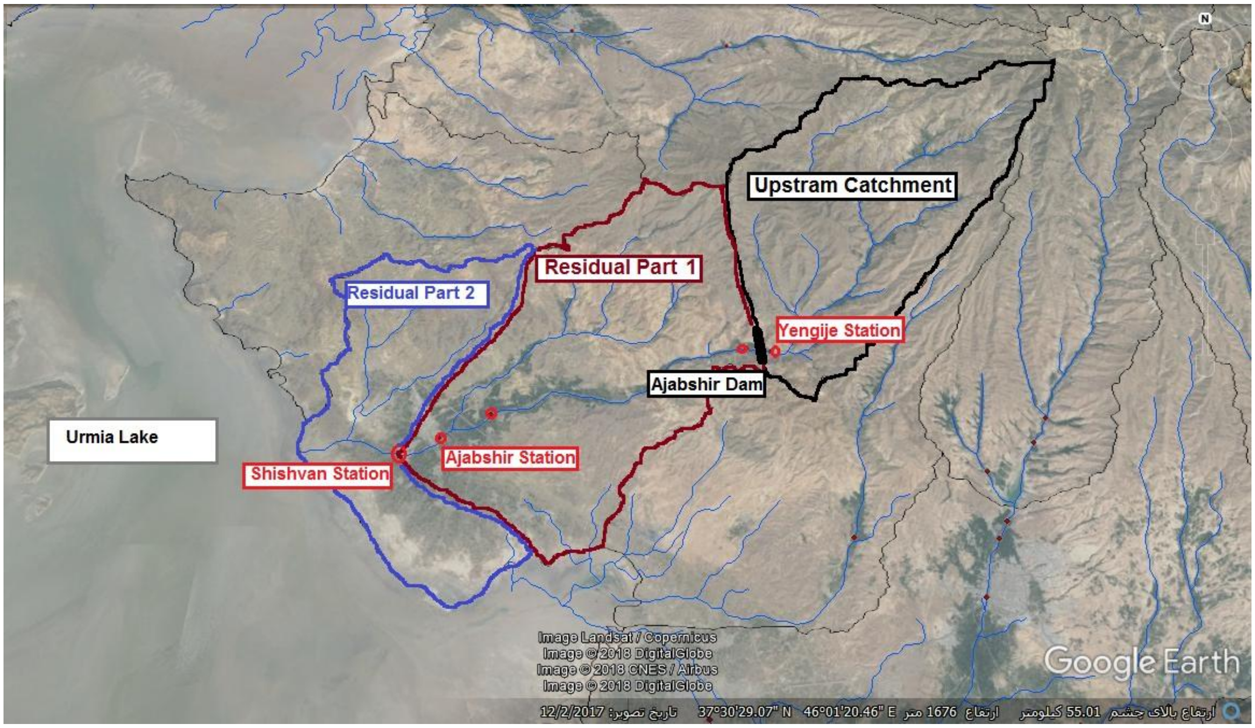


Figure 3.27. The location of the GhaleChai catchment, tributaries of the GhaleChai River, hydrometric stations and Ajabshir Dam.

3.4.6. Alavian Dam

The Alavian Dam was built on the main reach of the SoufiChai River in 1996 with a volume of 57 Mm^3 for drinking, industrial, agricultural and power generation purposes. In Figure 3.28, the location of the dam and its upstream sub-basin (black border), the hydrometric stations of the SoufiChai River basin (red circle) and the residual sub-basin (red border in the figure) to the Bonab Station are shown.

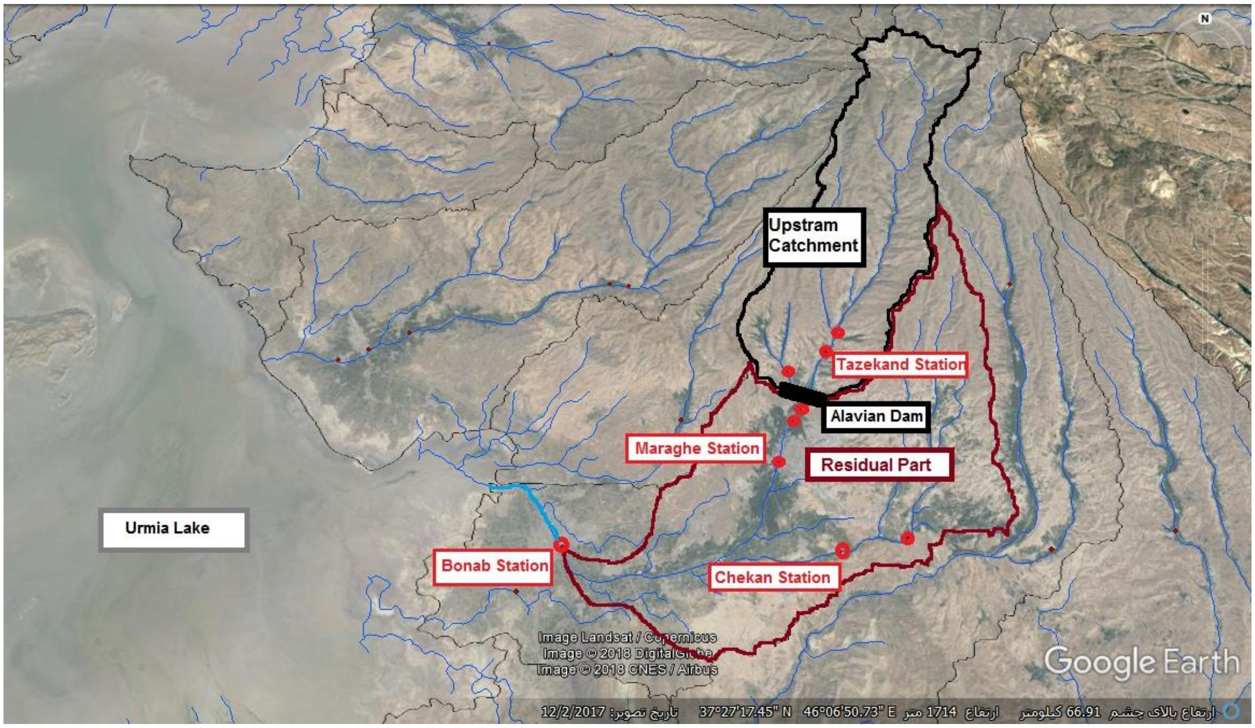


Figure 3.28. The location of the SoufiChai catchment, tributaries of the SoufiChai River, hydrometric stations and the Alavian Dam.

3.4.7. Siminehroud Dam

The Siminehroud under evaluation dam will be built on the main reach of the Siminehroud River with a volume of 312 Mm^3 for drinking, industrial, agricultural, power generation, flood controlling and artificial recharge purposes. Construction of the dam has been stopped because of the Urmia lake restoration policies. In Figure 3.29, the location of the dam and its upstream sub-basin (black border), the hydrometric stations of the Siminehroud River basin (red circle) and residual sub-basin 1 (red border in the figure) to the Miandoab Station are shown. Also the Siminehroud River sub-basin after the last hydrometric station (Miandoab Station) to Urmia Lake, named residual sub-basin 2 is shown in the blue border.

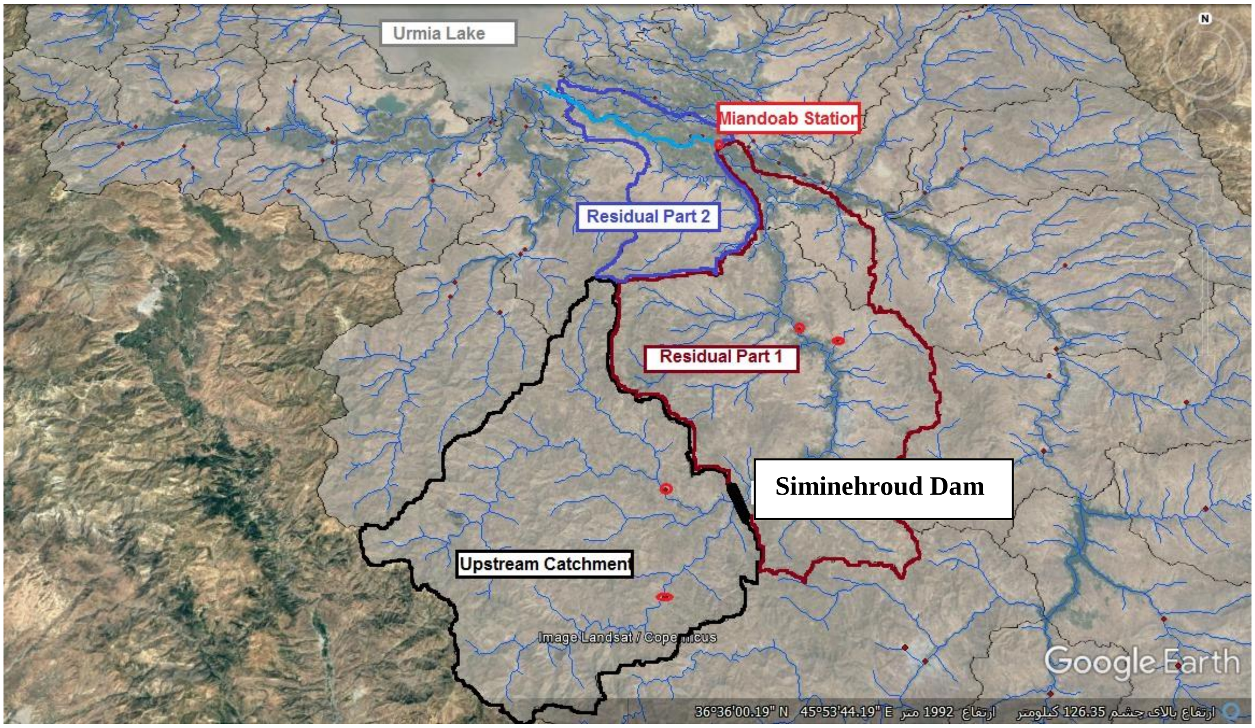


Figure 3.29. The location of the Siminehroud catchment, tributaries of the Siminehroud River, hydrometric stations and the Siminehroud Dam.

3.4.8. Barandouz Dam

The Barandouz Dam will be built on the main reach of the BarandouzChai River with a volume of 84 Mm^3 for drinking, industrial, agricultural, power generation, flood controlling and artificial recharge purposes. Because of the Urmia Lake restoration policies the construction of the dam has been stopped. In Figure 3.30, the location of the dam and its upstream catchment area (black border) with the hydrometric stations of the BarandouzChai River basin (red circle) and residual sub-basin (red border in the figure) to the Babaroud Station are shown. Also the BarandouzChai River catchment area after the last hydrometric station (Babaroud Station) to the Urmia Lake, named residual sub-basin 2 is shown in the blue border.

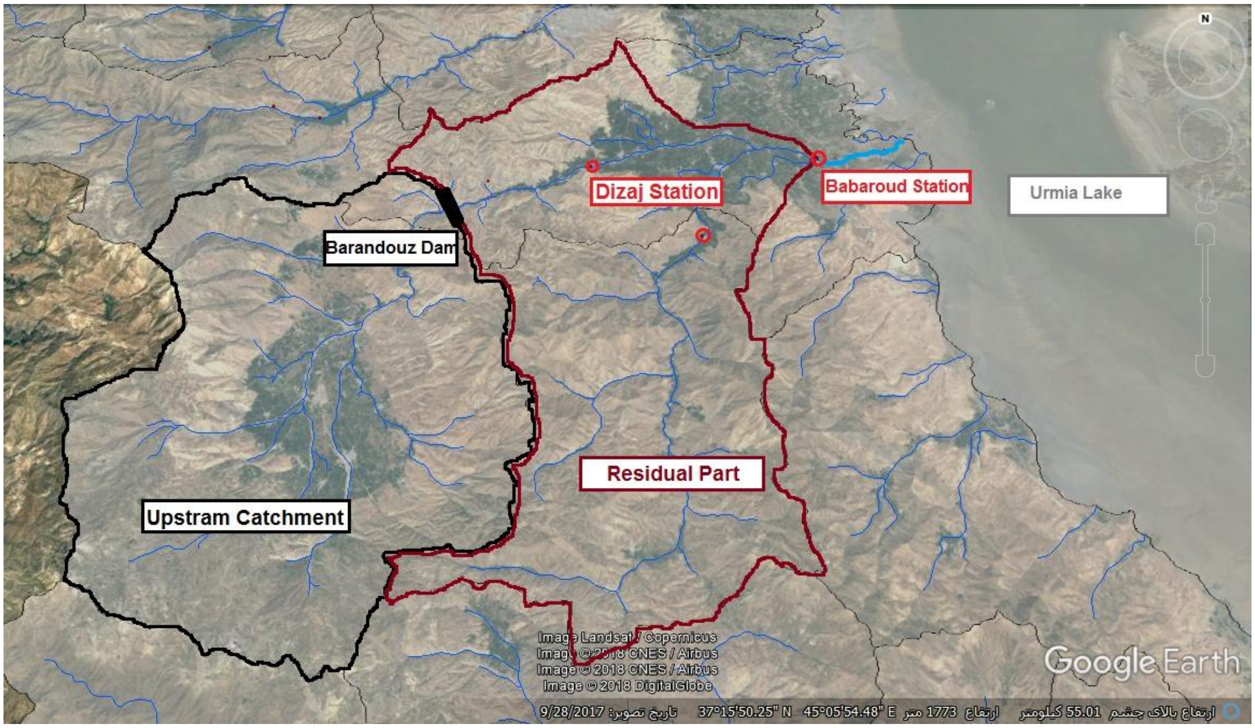


Figure 3.30. The location of the BarandouzChai catchment, tributaries of the BarandouzChai River, hydrometric stations and the Barandouz Dam.

3.4.9. Nazlou Dam

One of the important under-evaluation structures for controlling water on the NazlouChai River is the Nazlou Dam, which will be operated with a capacity of 145 Mm^3 for drinking, industrial, agricultural and power generation purposes.

In Figure 3.31, the location of the dam and its upstream catchment area (black border) with the hydrometric stations of the NazlouChai River basin (red circle) and the residual sub-basin (red border in the figure) to the Abajalou Sofla Station which is the last hydrometric stations near the Urmia Lake are shown.

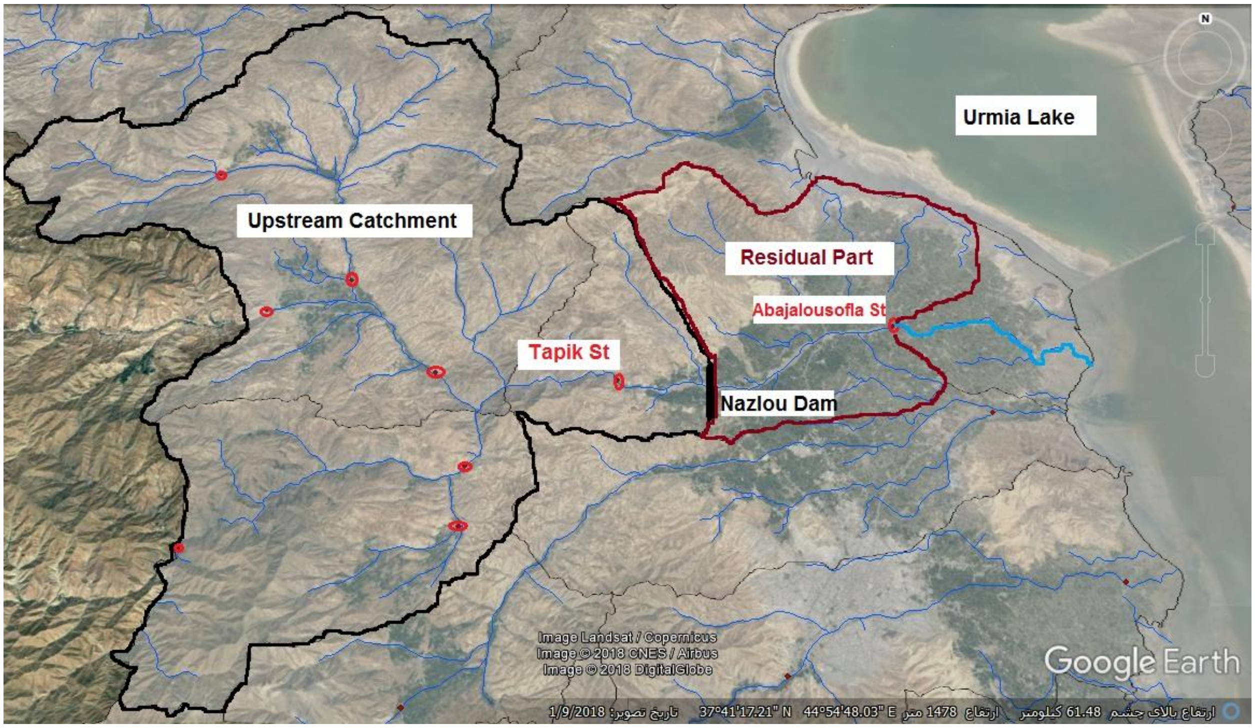


Figure 3.31. The location of the NazlouChai catchment, tributaries of the NazlouChai River, hydrometric stations and the Nazlou Dam.

3.4.10. Zola and Derik Dams

The Zola Dam is located 50 km from the main branch of the ZolaChai River. It has been operated since 2010 with a storage capacity of 72 Mm^3 and its distance to the Urmia Lake is 42 km. The objectives of the dam include an annual regulation of 132 Mm^3/year of the ZolaChai River for drinking and industrial uses, and irrigation of the 15.800 ha area, and electricity generation.

The Derik Dam has a storage volume of 22 Mm^3 on the DerikChai River, a branch of the ZolaChai River, is located 50 km from the Urmia Lake, and has been operated since 2007 for irrigation. The objectives of the dam include an annual regulation of 34.14 Mm^3 of water.

In Figure 3.32, the location of the dams and the upstream catchment area (black border for Zola and pink border for Derik) with hydrometric stations of the ZolaChai River basin (red circle) and the residual sub-basin (red border in the figure) to the YalghouzAgaj Station which is the last hydrometric stations near the Urmia Lake are shown.

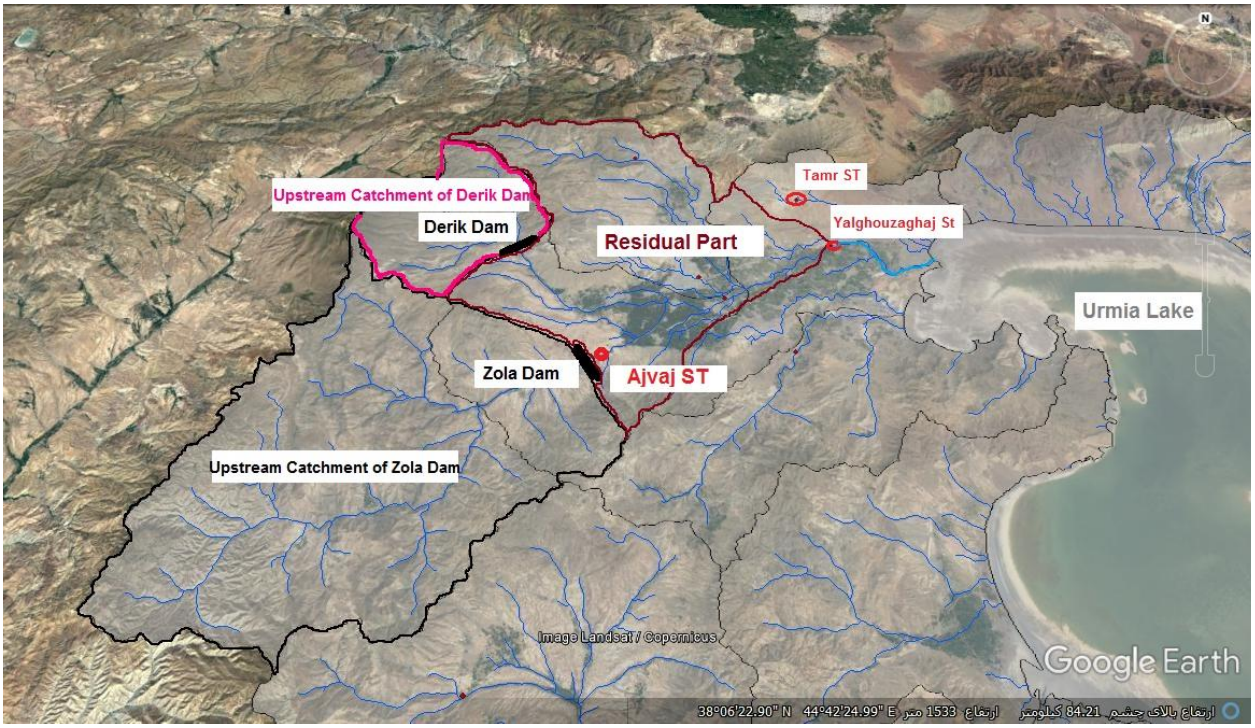


Figure 3.32. The location of the ZolaChai catchment, tributaries of the ZolaChai River, hydrometric stations and the Zola and Derik Dams.

Table 3.9. Properties of the catchment area of the rivers

River Name	Dam Name	Area of Upstream Catchment	Area of Residual Part 1
AjiChai	Venyar Dam	7692	2188
GhaleChai	Ajabshir Dam	283	232
SoufiChai	Alavian Dam	311	438
Zarrinehroud	ShahidKazemi Dam	6357	4575
Siminehroud	Siminehroud Dam	1439	1669
MahabadChai	Mahabad Dam	809	407
BarandouzChai	Barandouz Dam	534	266
ShahrChai	ShahrChai Dam	325	332
RozehChai	Kalhor Dam	169	101
NazlouChai	Nazlou Dam	1098	145
ZolaChai	Zola and Derik Dam	1047	757

3.5. Modifying irrigation supply dams

As the irrigation reservoirs dams always stored water throughout the year except during flood events, so for reoperation of those, it is necessary to avoid capturing of low flows during the dry season. The storage volume of the reservoirs can supply by capturing higher flow events during the wet season. Sometimes it is difficult to obtain more natural seasonal pattern during reoperation of dams (Richter and Thomas, 2007). For the management of irrigation dams there are many techniques in this study the technique is presented by Torabi Haghighi (2014) has been selected and described in the following.

3.6. Effect of active dams on river regime

As in evaluation of the impact of active dams on river regime, size and purpose of dam are important parameters. In the Urmia Lake basin, some dams are constructed to work for single purpose (such as the Venyar Dam on the AjiChai River) or for multipurpose (ShahidKazemi, ShahrChai and Alavian Dam). In the evaluation technique presented by Torabi Haghighi (2014) the three main characteristics of monthly hydrographs: i) magnitude, ii) variability and iii) timing of flow can affect by dams (Figure 3.33). Water supply dams for irrigation and domestic demands can change the magnitude and variability of flow as shown in Figure 3.33 (b) and (c) respectively. Hydropower or flood control dams can change the variability and timing of flow (Figures. 3.33 c, d); those also can have negligible effect on the magnitude of flow because of the increasing surface evaporation after converting the system from river to reservoir. As for restoration of the Urmia Lake Magnitude of input water volume is important in this study just the effect of dams on the magnitude of flow has been discussed.

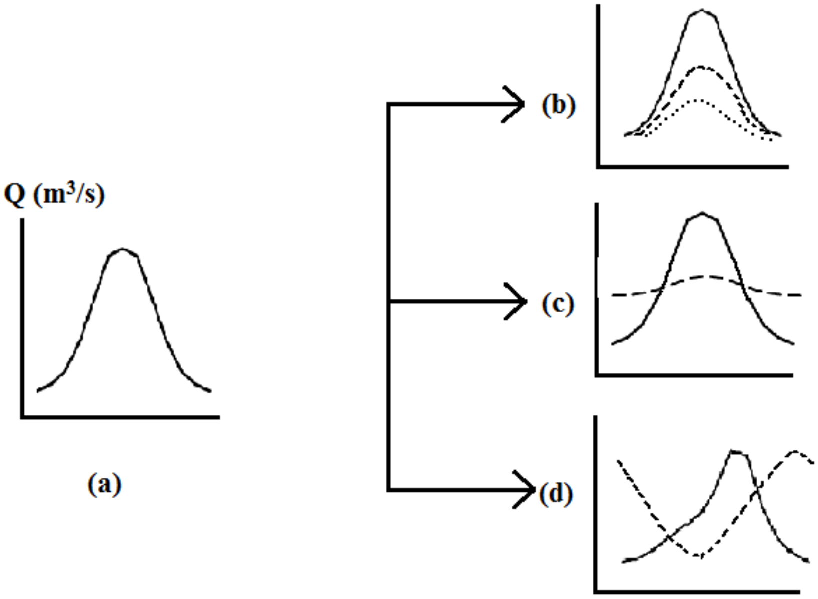


Figure 3.33. Natural flow regime (a) and regulated flow regime; b) effect of the flow magnitude function (MIF), c) effect of the flow regime alteration function (VIF), and d) the effect of the flow timing function (TIF) (Torabi Haghighi, 2014)

3.6.1. Magnitude impact factor (MIF)

There are two ways for calculation of the effect of dam on magnitude of river flow the first method is presented by Torabi Haghighi (2014) that flow magnitude impact factor (MIF) has been defined as:

$$\mathrm{MIF}_1=\frac{\mathrm{AOF}}{\mathrm{AIF}} \qquad 3.6$$

where AOF is annual outflow from the dam (m^3 or m^3/s), AIF is annual inflow to the dam (m^3 or m^3/s).

The second approach is called IHA[1] method because of it is used in IHA framework. It has been defined as:

$$\mathrm{MIF_2} = \frac{\mathrm{AF_{Post}}}{\mathrm{AF_{Pre}}} \qquad 3.7$$

$\mathrm{AF_{Post}}$ is annual outflow from the dam after dam construction and $\mathrm{AF_{Pre}}$ is annual flow rate before dam construction. This approach has some major weaknesses that are because of two different time periods that is used in the Equation 3.7. Sometimes there is climate change in the river basin before and after dam construction that can be effected on the magnitude of inflow to dam. By using the $\mathrm{MIF_1}$ factor in unstable climate the effect of climate can be eliminated. But in the stable climate MIF would be approximately the same value for both when a sufficient number of years are included in the pre– and post– construction periods.

3.6.2. Optimum flow regime

Fundamental revising in the operation policy of the active dams in the Urmia Lake basin is necessary (Yasi, 2017). The main objective of this thesis is to determine how much water are used in downstream of the dams and how much of the release water from dams have to reach the lake? For answering the mentioned questions by using one simple theorical approach that presented by Torabi Haghighi (2014), the optimum monthly release flow from dams for different operation policies has been determined. According to the mentioned approach, the magnitude of allocated flow, the natural flow regime at reference points, and dam location are three important parameters that determine the results of optimization.

Each river basin has been divided to three separated area consist of upstream catchment, residual part 1 and residual part 2 (in the figures from 3.23 to 3.32 for all major rivers in the Urmia Lake basin mentioned parts have been shown; according to figures residual part 1 is the catchment between the dam and selected reference point and the residual part 2 is the unmeasured area downstream of the reference point). The catchment area of mentioned parts depends on the location of dam and selected reference point. Reference point is nearest active station to the lake that measured received water from upstream catchment of the dam and residual part 1. In the approach have been attempt to regulate river as natural regime at the reference point so it is assumed that the hydrograph in the reference point before any regulation can be used as criteria for measuring of the ecological damage of regulation.

According the approach stages of calculation of optimum flow regime released from the dam has following steps (Figure 3.34):

i) determining of the natural annual hydrograph in the reference point (NAH): it can be obtained from monthly average discharge (Q) values at the reference point before any regulation as the following matrix:

$$[\mathrm{Q_{NAH}}] = [\mathrm{Q_1 Q_2} \ldots \mathrm{Q_i} \ldots \mathrm{Q_{11}}\ \mathrm{Q_{12}}] \qquad 3.8$$

Then the matrix of Equation 3.8 convert to the scaled annual hydrograph in the reference point to determine the percentage of contribution of each month in annual hydrograph as:

$$[\mathrm{PR_{SAH}}] = [\mathrm{PR_1 PR_2} \ldots \mathrm{PR_i} \ldots \mathrm{PR_{11}}\ \mathrm{PR_{12}}]$$

Where

$$\mathrm{PR_i} = \frac{\mathrm{Q_i}}{\sum_{i=1}^{i=12} \mathrm{Q_i}} \qquad 3.9$$

---

[1] Indicators of Hydrologic Alteration

with Q_i being monthly discharge in month i.

ii) determining of the residual hydrograph based on the reference points and dam location $[Q_{Residual}]$: based on real data and using Equation 3.10, the residual hydrograph for the reference point could be defined as

$$[Q_{Residual}] = [Q_{RAH}] - [Q_{VAR}] \qquad 3.10$$

where $[Q_{RAH}]$ is the annual flow hydrograph at the reference point after regulation and $[Q_{VAR}]$ is the annual flow hydrograph at the dam location. As the term $[Q_{Residual}]$ is resultant of input runoff and abstraction from rivers in the distance between the dam and reference point it can has both positive and negative values for each month.

iii) determining of the magnitude of available annual discharge (Q_{AAD}) at the reference point as:

$$Q_{AAD} = Q_{RW} + Q_{Residual} \qquad 3.11$$

in this study dams release policies was defined as 30%, 50% and 80% of MAF[1] in dams location being called Scenario 1, Scenario 2 and Scenario 3 respectively for these locations.

iv) Determining of the intra-annual regime of dam regulation$[Q_{RW}]$: after calculation the value of Q_{AAD} by multiplying it to PR_i in each month the closest annual flow to natural annual flow of the reference point for each scenario $[Q_{CAH}]$ and the intra-annual regime of dam regulation $[Q_{RW}]$ can determined as Equation 3.12 and 3.13 respectively.

$$[Q_{CAH}] = Q_{AAD}[PR_1 PR_2 \dots PR_i \dots PR_{11}\ PR_{12}] \qquad 3.12$$

$$[Q_{RW}] = [Q_{CAH}] - [Q_{Residual}] \qquad 3.13$$

---

[1] mean annual river flow

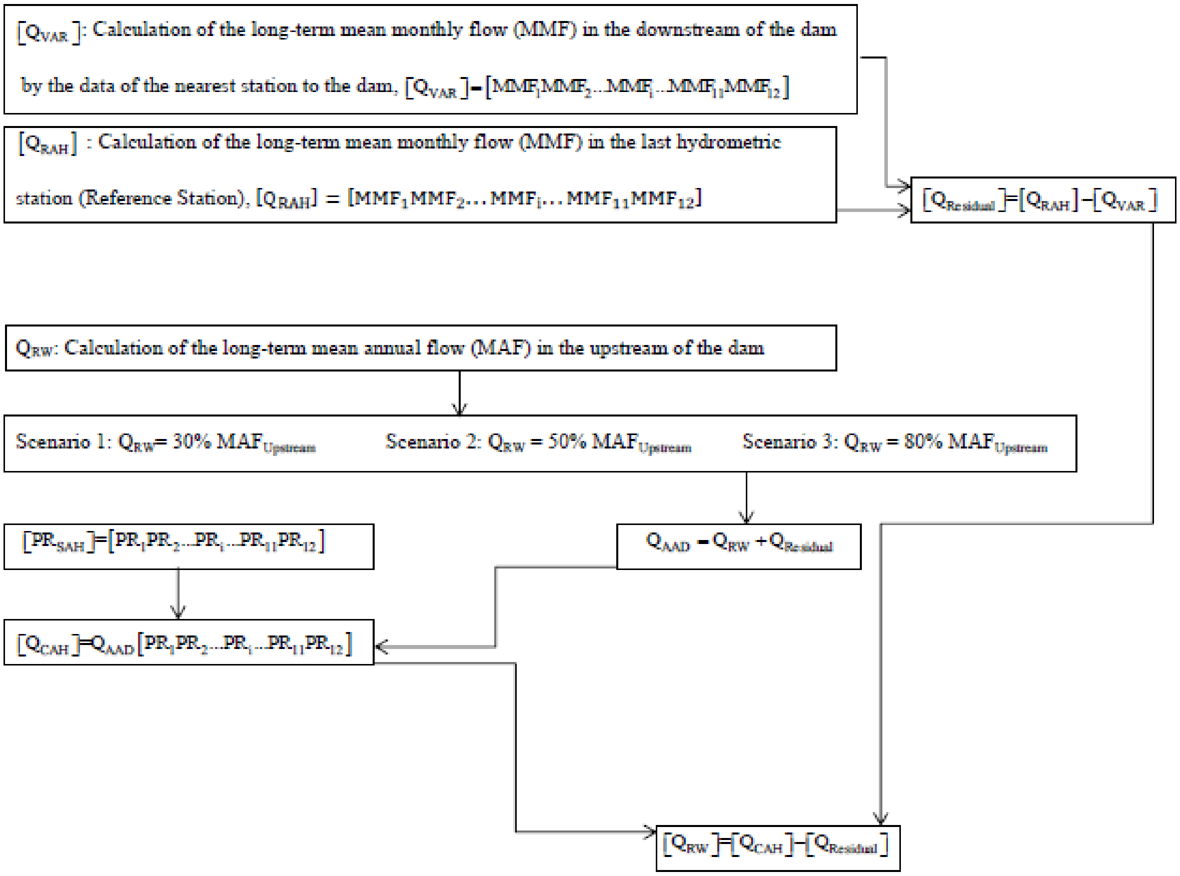


Figure 3.34. Flowchart of the calculation of the term of Q_{RW}

3.7. Numerical Modelling

Tarhe Noandishan (2004) and Zeinodini et al., (2009) evaluated different possible numerical approaches for simulating the Urmia Lake, finally selecting the three-dimensional MIKE 3 Flow Model FM from the Danish Hydraulic Institute (DHI). Based on their results and on the problem requirements, such model was also employed in the current numerical investigation, also enabling comparisons of present results with theirs. In this study, the effective parameters of MIKE 3 Flow Model FM for 3D simulations of shallow hypersaline lakes such as the Urmia Lake are assessed through sensitivity analyses.

Since the surface and bottom exchange is very important in water circulation process and the importance is generally more significant when depth of the lake is shallower, which would also change the water quality in the lake, 3D case is setup.

3.7.1. Model Description

The MIKE 3 Flow Model FM integrates the governing equations of the relevant fluid flow processes (such as continuity and momentum balance, as well as convection-diffusion-dispersion of transported quantities such as contaminants or salt) over an array (or mesh) of cells, using the finite-volume method. The discretization of the spatial domain is accomplished over triangular and rectangular flexible elements. Flexible meshes are non-structured and allow the highest degree of compactness of the solution domain.

In the mentioned model, the hydrodynamic module is based on the numerical solution of the Reynolds-Averaged Navier-Stokes equations for the turbulent flow of an incompressible liquid, under the a Boussinesq hypothesis and the assumption of hydrostatic pressure.

The MIKE 3 Flow Model FM is based on a flexible mesh approach and it has been developed by DHI for applications in ocean, coastal and estuarine environments. The model solves the continuity, momentum, temperature, salinity and density equations and can be closed by a variety of different turbulent closure schemes. Density depends on temperature and salinity. In this study an unstructured mesh is used in the horizontal plane while a structured mesh is used in the vertical domain of the 3D model (Figure 3.35).

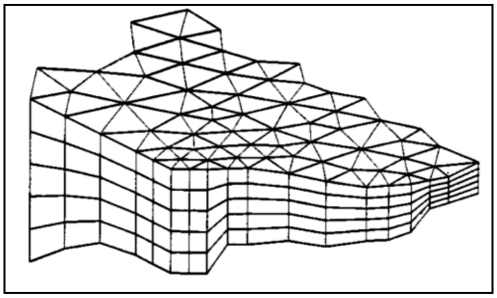


Figure 3.35. Principle of meshing for the three-dimensional case

3.7.2. Governing equations

The governing equations are presented here using Cartesian coordinates.
The local continuity equation is written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \qquad 3.14$$

And the two horizontal momentum equations for the x- and y-components are respectively:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}= fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial P_a}{\partial x}-\frac{g}{\rho}\int_z^\eta \frac{\partial \rho}{\partial x}dz \qquad 3.15$$

$$-\frac{1}{\rho_0 h}(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y})+F_u+\frac{\partial}{\partial z}(v_t\frac{\partial u}{\partial z})+u_s S$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}= fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial P_a}{\partial x}-\frac{g}{\rho}\int_z^\eta \frac{\partial \rho}{\partial x}dz \qquad 3.16$$

$$-\frac{1}{\rho_0 h}(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y})+F_u+\frac{\partial}{\partial z}(v_t\frac{\partial u}{\partial z})+u_s S$$

Where x, y and z are the Cartesian coordinates; u, v, and w are the velocity components in the x, y and z directions; t is time; η is the surface elevation; d is the water depth; h= η+d is the surface water elevation; f= 2Ωsinϕ is the Coriolis parameter (Ω is the angular rate of revolution and ϕ the geographic latitude); g is the gravitational acceleration; ρ is the density of water; S_{xx} , S_{xy} and S_{yy} are the components of the stress tensor; v_t is the vertical turbulent (or eddy) viscosity; p_a is the atmospheric pressure; ρ_o is the reference density of water; S is the magnitude of the discharge due to point source and (u_s, v_s) is the velocity by which the water is discharged into the ambient water.

Turbulence is modelled using an eddy viscosity concept. Several turbulence models can be applied: a constant viscosity, a vertically-variable viscosity with parabolic distribution and a standard k-ε model (DHI, 2011). Different eddy viscosities can be used to model turbulent diffusion on the horizontal plane or in the vertical direction.

In detail, the vertical eddy viscosity can be derived from the log-law is calculated as:

$$\upsilon_t = U_\tau h\left(c_1 \frac{z+d}{h} + c_2 \left(\frac{z+d}{h} \right)^2 \right) \tag{3.17}$$

Where $U_\tau = \max\left(U_{\tau s}, U_{\tau b}\right)$ and c_1 and c_2 are two constants. $U_{\tau s}$ And $U_{\tau b}$ are friction velocities associated with the surface and bottom stresses, coefficients $c_1 = 0.41$ and $c_2 = -0.41$ give the standard parabolic profile.

In many applications a constant eddy viscosity can be used for the horizontal eddy viscosity. Alternatively, Smagorinsky (1963) proposed to express sub-grid scale transport by an effective eddy viscosity related to a characteristic length scale. The sub-grid scale eddy viscosity is given by

$$A = c_S^2 l^2 \sqrt{2 S_{ij} S_{ij}} \tag{3.18}$$

Where c_s is the constant Smagorinsky coefficient, l is a characteristic length and the deformation rate is given by

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (i, j=1,2) \tag{3.19}$$

3.7.3. Mesh

The dimensions of the mesh were selected so that the results are independent from the dimensions of the grid and the computational time is minimized. Triangular mesh elements with variable dimensions were herein used, increasing the resolution near the causeway to increase accuracy where needed (Figure 3.36). The maximum area of the elements was generally set to 3.10^6 m^2, dropping down to 5.10^4 m^2 in the proximity of the causeway (i.e an approximate planar size ranging from 340 m to 2.6 km). The resulting mesh has 7073 elements for each of the 10 vertical layers.

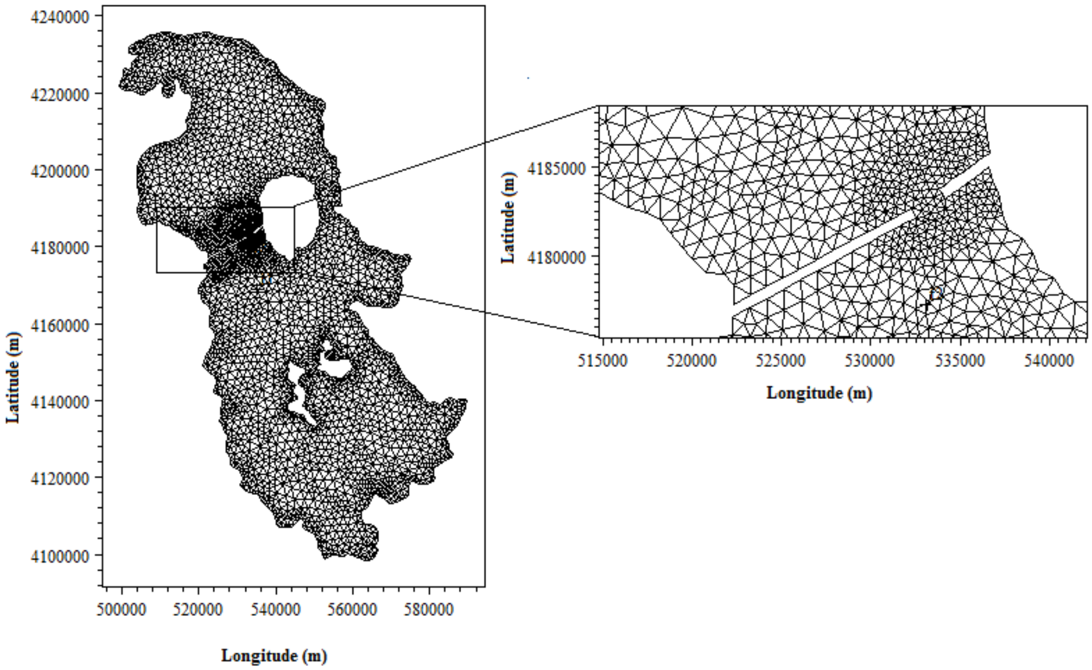


Figure 3.36. Non-structured mesh for each of the vertical layers.

3.7.4. Time step

Different time steps were tested to optimize the computational time, also ensuring the independence of results from time discretization. The resulting optimal time step was Δt = 120 s. For such value, a CFL= $v \Delta t / d < 1$ condition for the Courant-Friedrichs-Lewy parameter (based on the local flow velocity v and the cell size d) is met everywhere in the flow field for stability, given the explicit scheme adopted by the model.

3.7.5. Coriolis force

The Coriolis force was considered unimportant for circulations in the Urmia Lake due to its shallow depth by Tofighi (2006). However, while the Coriolis force is actually negligible for shallow lakes of small size (Fenocchi and Sibilla, 2016), this does not hold on a theoretical standpoint for the Urmia Lake, its large surface area leading to $Ro << 1$ values for the Rossby number, highlighting the relevance of geostrophic currents. Actually, if an average width $L \approx 20$ km and a characteristic velocity $U \approx 0.1$ m/s are considered, the Rossby number for the Urmia Lake is $Ro = U / (2L\ \Omega \sin \varphi) = 0.06$, where $\Omega = 7.2921\ 10^{-5}$ rad/s is the Earth rotation rate and $\varphi \approx 37°\ 30'$ is the average latitude of the Urmia Lake. In light of this, we included the Coriolis force in the present model.

3.7.6. Threshold value for dry-cell conditions

Due to fluctuations in the surface level at the boundaries of the lake, the outer model cells vary between wet and dry conditions, causing possible instability of the numerical model. For this purpose, by defining the minimum depth of the flood, the depth of wetting and the depth of the drought are prevented from the fluctuations in the boundaries. Therefore, if the water depth is less than the wet depth, the model changes the equation and uses the equation for the flood and dry depth, but if the depth of water is less than the depth of the drought, that area (finite volume) is not simulated and the depth should be greater than the depth of the flood.

The depth at each element/cell is monitored and the elements are classified as dry, partially dry or wet. Also, the element faces are monitored to identify flooded boundaries. Elements are classified according to the following principles:

- An element face is defined as flooded if the following two criteria are satisfied. Firstly, the water depth at one side of face must be less than a tolerance depth, h_{dry} and the water depth at the other side of the face larger than a tolerance depth, h_{flood}. Secondly, the sum of the still water depth at the side for which the water depth is less than h_{dry} and the surface elevation at the other side must be larger than zero.
- An element is dry if the water depth is less than a tolerance depth, h_{dry} and no of the element faces are flooded boundaries. The element is removed from the calculation.
- An element is partially dry if the water depth is larger than h_{dry} and less than a tolerance depth, h_{wet} or when the depth is less than the h_{dry} and one of the element faces is a flooded boundary. The momentum fluxes are set to zero and only the mass fluxes are calculated.
- An element is wet if the water depth is greater than h_{wet} both the mass fluxes and the momentum fluxes are calculated.

$$h_{dry} < h_{flood} < h_{wet} \qquad 3.20$$

When an element is removed from the calculation, water is removed from the computational domain. However, the water depths at the elements, which are dried out, are saved and then reused when the element becomes flooded again.

In the present study, the default values of the model, 5 cm and 10 cm for flood and wet condition respectively, were used. By comparing the surface area of the lake in the model to Landsat images in GIS software according to Figure 3.37, h_{dry} equal to 3 cm was employed and calculations were done only for regions where the depth of water was more than the drying depth (3 cm).

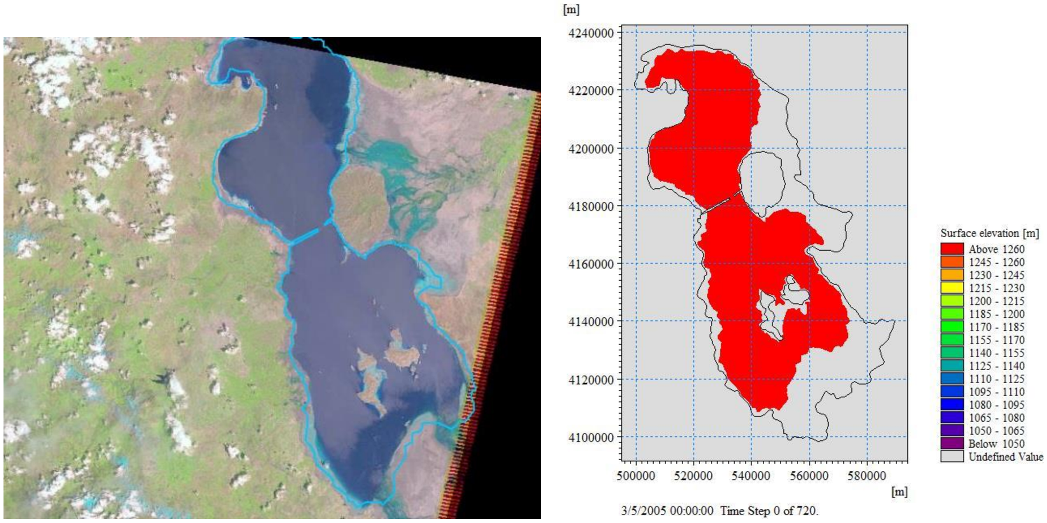


Figure 3.37. Comparison of the Urmia Lake boundary in MIKE 3 Flow Model FM and the Landsat image taken on 22th October 2010 for 1272.15 m surface elevation

Also, according to results of previous studies such as Pirani (2017) and Zeinoddini et al., (2009), the horizontal eddy viscosity and the dispersion coefficient, the orders of accuracy of time integration and space discretization techniques have negligible effects on the results of water level, flow velocities and salinity distribution of the lake water. All four mentioned parameters after investigation and confirmation of previous research were considered in all simulations as constant and equal to the recommended values by DHI.

In the present study, a h_{dry} = 0.03 m threshold value was selected for distinguishing wet and dry cells to avoid computational instability.

3.7.7. Wind friction coefficient

One of the important parameters in hydrodynamic analysis in models with shallow water equations is the coefficient of friction between water and wind.

The wind friction coefficient for high wind speeds is given as constant value of 0.0026. Therefore, according to DHI recommendation, main parameters for calibration in HD module consist of bed resistance and eddy viscosity.

Surface stresses with respect to wind speed at 10-m height, along x and y, are obtained by the following equation:

$$\frac{\tau_b}{\rho_a} = c_d u_w |u_w| \qquad 3.21$$

In the above equation ρ_a is the air density, $C_{d\ ,10}$ is the drag coefficient of air, $\tau_b = (\tau_{bx}, \tau_{by})$, $u_w = (u_w, v_w)$ are the shear stress and wind speed 10 meters above the water level, which are expressed along x and y respectively. The drag coefficient is function of the wind velocity.

By changing the wind friction coefficient, the shear stress of wind on the water surface is changed and therefore the flow velocity changes. This can be particularly effective for high wind speeds that cause high flow velocities. The value of this coefficient can be considered constant or variable (a function of the wind speed in accordance with Figure 3.38).

To calculate the friction coefficient of wind in the present study, Equations 3.22 (Wüest and Lorke, 2003) were used to approximate the real variation of the wind friction coefficient. In previous studies, the wind friction coefficient has been considered as one of the calibration coefficients of the model, because of its influence on flow velocity.

$$C_{10} = \begin{cases} 6.5 \cdot 10^{-5}\, U_{10} + 0.0008 & \text{for } U_{10} > 7\ \text{m/s} \\ 0.0044\, U_{10}^{-1.15} & \text{for } U_{10} \leq 7\ \text{m/s} \end{cases} \qquad (3.22)$$

where U_{10} is the wind speed at 10-m height.

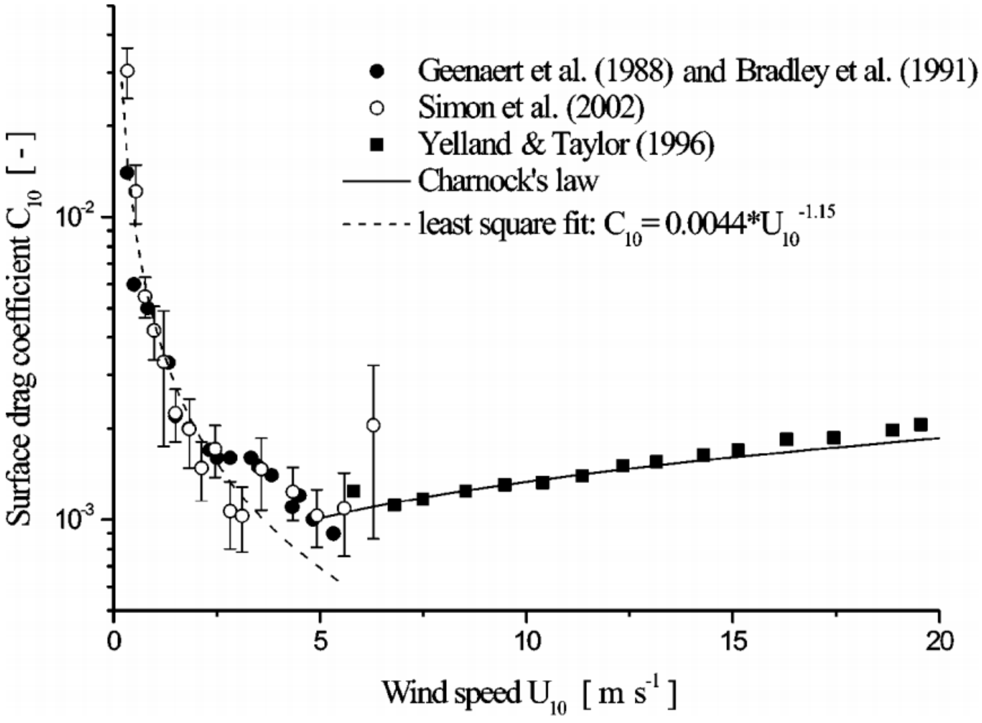


Figure 3.38. Variation in the friction coefficient of wind as a function of wind speed 10 m above the lake water surface (U_{10}) (Wuest and Lorke, 2003)

3.7.8. Bed roughness height

The bed sediments of the Urmia Lake consist mainly of clay. Based on previous studies (Sadra, 2003; Zeinoddini et al., 2009, 2015), the bed roughness height in the 3D model was set to k_s = 0.07 m, being equal to a Manning's coefficient n = 0.025 according to the usual $n = k_s^{1/6} / 26$ relation. According to previous research on the Urmia Lake indicated that the bed roughness height affects the flow velocities in the model less than the wind friction coefficient (Zeinoddini et al., 2009).

3.7.9. Solution Technique

Model runtime and the accuracy of the results depend on the order of accuracy of numerical methods. The low-order (1nd order) method has a fast rate of computation, but the precision of the results is low, and vice versa, the high-order (2nd order) method takes a longer time to perform calculations, but provides more precise results, hence, depending on the type of process involved, one of the two options is selected. In the processes in which the advection processes is dominant, it is better to use the high-order method due to the high speed of the flow, and vice versa, in the dispersion processes, the low-order method is suitable for providing the exact answer (results). Time discretization of the shallow water equation and the advection - dispersion equation are carried out in a semi-implicit method, the horizontal terms being explicit and the vertical terms implicit. To guarantee the stability of the explicit method, the time interval must be chosen such that the value of the Courant-Friedrichs-Lewy (CFL) number is less than one. In this study, the value of the CFL number was considered equal to 0.8 s.

$$CFL=\left(\sqrt{gh}+|u|\right)\frac{\Delta t}{\Delta x}+\left(\sqrt{gh}+|v|\right)\frac{\Delta t}{\Delta y} \qquad 3.23$$

CFL : Courant-Friedrichs-Lewy number in hydrodynamic flows, h : water depth, Δt : time interval, Δx and Δy :size of the smallest mesh elements in the x and y directions, u and v : velocity components in the x and y directions.

3.7.10. Molecular and eddy viscosity

Growing water salinity brings about increasing molecular viscosity of water. According to measurements performed in April-June 2002 (Mirzaee Seviri, 2003), the molecular viscosity of the Urmia Lake water with ~220 ppm salinity and 9 °C temperature is approximately 2.02 times the viscosity of ocean water with 35 ppm salinity and the same temperature, i.e. it is equal to $\sim 2 * 10^{-6}$ m^2/s.

Regarding the eddy viscosity adopted in the model due to the Boussinesq hypothesis for the Reynolds stresses in the RANS equations, a constant $1 \cdot 10^{-5} m^2/s$ value was adopted for its horizontal component, the relative model sensitivity being negligible (Pirani, 2017), whereas k-epsilon, log law and constant eddy formulation approaches were tested to optimize the value of the vertical component.

3.7.11. Density

Due to the incompressible assumption, water density is herein assumed as a function of temperature and salinity only. Density influences the flow structure and velocity and the advection and diffusion of temperature and salinity. Density in the MIKE 3 Flow Model FM is calculated with the UNESCO standard equation (UNESCO, 1981).

In this study, heat diffusion was not considered due to lack of extended measurements for the temperatures of the Urmia Lake and its tributaries. Temperature effects on density are also negligible compared to those of salinity, especially considering the hypersaline nature of the basin. In the model, therefore, density was simulated as a function of salinity only, assuming a constant temperature of 10° C, equal to the average annual temperature of the Urmia Lake water.

3.8. Field data

Due to the lack of simultaneous density, salinity and flow velocity measurements, model calibration and validation were performed over different years for the various model variables. The period 2009-2010 was selected for water density distribution, for which the data from Sima and Tajrishi (2014) were available at several stations for September 2009 and May and July 2010. The location of their sampling points is shown in Figure 3.39. The years 2009-2010 are also representative of drought conditions in the Urmia Lake, defined as whenever the water level is below the prescribed one for good ecological status (1274.1 m a.s.l). The period 1987-1988 was adopted for the salinity, for which field data were reported by Daneshvar and Ashassi (1994). These years were also selected as reference for simulating the Urmia Lake natural conditions and were also modelled by Sadra (2003), Zeinoddini et al., (2009) and Pirani (2017). The year 1991 was further simulated, since flow velocity measurement campaign was performed by Ab Nirou (1995) in November 1991. The velocity sampling points in the latter study are shown in Figure 3.38.

Wind data from the Urmia Airport Station (Figure 3.40) have been employed in the present study. Such station has been providing wind direction and speed data at 3-hour resolution since 1961, which have been used in most studies (Pirani, 2017; Tofighi, 2006).

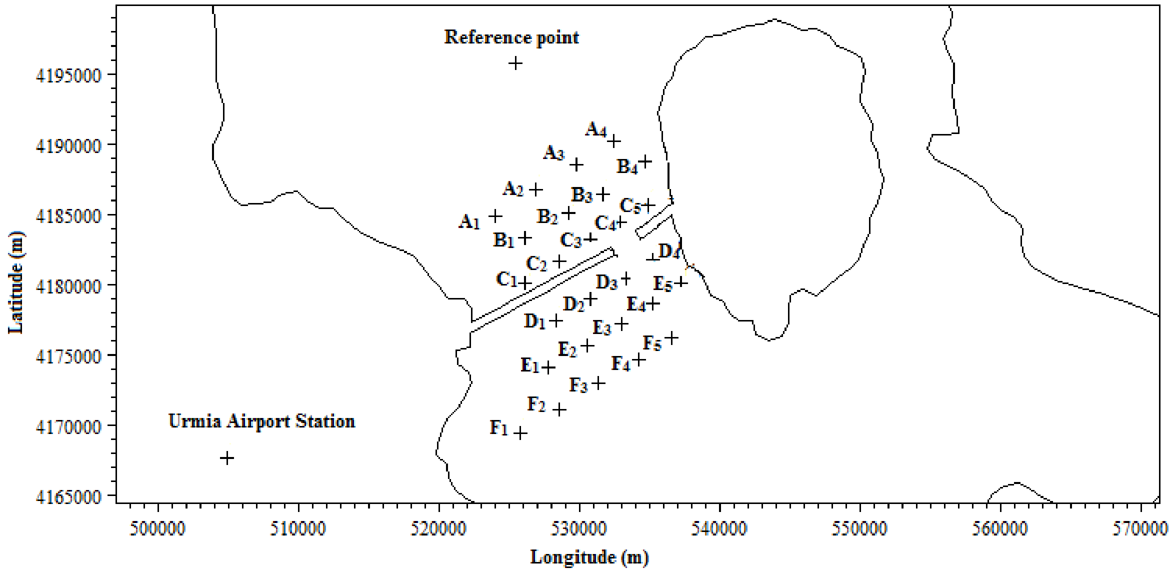


Figure 3.39. Location of the flow velocity measurement points considered by Ab Nirou (1995)

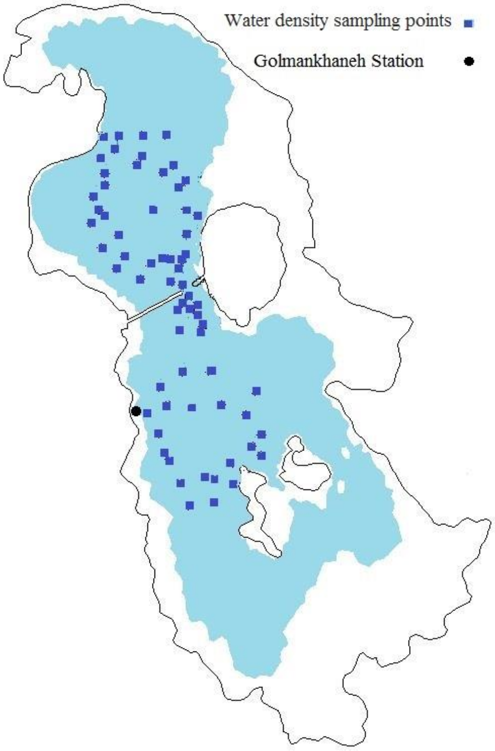


Figure 3.40. Location of the water density sampling points in the Urmia Lake considered by Sima and Tajrishi (2014)

The periods of 1987-1988 has been selected for wet conditions, salinity and density data having been measured by Daneshvar and Ashaasi (1994) according to Table 3.10. Mentioned data has been employed for numerical modeling in many previous studies such as Sadra (2003), Zeinoddini et al. (2009), Pirani (2017). Lake salinity data from May 2004 until March 2006 (Table 3.11) measured by the Fisheries and Aquaculture Studies Department of the Urmia University at the surface and bottom layers, and lake density data for October 2009, May and July 2010 measured by Sima and Tajrishi (2014) were available. The 2004-2005 and 2009-2010 periods have been selected as indication of dry condition (water level is less than the ecological water level), salinity and density data for lake water being available at several stations.

The ecological water level is the minimum level for which the biological and non-natural features of the lake are secured and its salt concentration is tolerable for the organisms in the catchment area, which is set at 1,274.1 meters a.s.l. for the Urmia Lake (Abbaspour and Nazaridoust 2007). During dry years, the rainfall and runoffs of rivers are low, which leads to a decrease in the level of the lake to less than the ecological water level.

In general, due to the lack of density, salinity and flow velocities data at the same time duration, calibration and validation of the parameters were carried out for different years. This method has more accurate and assurance of the model calibration for all possible conditions in the lake. Summary of available data is:

A) Natural Condition
  - Salinity and density data 1987-1988 (Ashasi et al., 1994)
  - Flow velocities data 1991-1992 (Ab-Nirou, 1995)

B) Dry Condition
  - Salinity data 2004-2005 (Fisheries and Aquaculture Studies Department of the Urmia University)
  - Density data 2009-2010 (Sima and Tajrishi, 2014).

Table 3.10. Measured density and salinity Data in the Urmia Lake (Daneshvar and Ashassi, 1994)

Month in 1991	Region	Density(kg/m^3)	Salinity(gr/lit)
April	North	1146±2	235±3
	South–West	1140±2	225±4
	Center & East	1138±4	211±16
September	All	1159±1	251±2.5

Table 3.11. Properties of samples collected by the Fisheries and Aquaculture Studies Department of the Urmia University

Date	stations	Geographic coordinate	Temperature at the Surface (˚C)	Temperature at the Bottom (˚C)	Salinity at the Surface (PPT)	Salinity at the Bottom (PPT)
04/05/2004	North	37˚48’-45˚15’	20	19	242	265
	North	37˚55’-45˚10’	21	20	250	270
	South	37˚32’-45˚29’	21	20	255	265
05/06/2004	North	37˚48’-45˚15’	26.8	25.9	260	268
	North	37˚55’-45˚10’	25.5	25.1	240	258
	South	37˚23’-45˚36’	27	21.3	260	280
	South	37˚32’-45˚29’	28.6	25.9	260	272
04/08/2004	North	37˚48’-45˚15’	27.3	27.5	280	280
	North	37˚55’-45˚10’	29.5	28.2	275	285
	South	37˚23’-45˚36’	29.5	28.2	275	285
	South	37˚32’-45˚29’	30.5	29.5	282	285
5/03/2005	North	37˚48’-45˚15’	11.2	11.4	260	270
	North	37˚55’-45˚10’	13.3	12.8	255	270
	South	37˚23’-45˚36’	14.1	12	250	270
	South	37˚32’-45˚29’	12.6	13.2	260	270
10/5/2005	North	37˚48’-45˚15’	20.1	19.3	265	280
	North	37˚55’-45˚10’	21.2	20.4	245	289
	South	37˚32’-45˚29’	21.3	20.2	263	285
08/06/2005	North	37˚48’-45˚15’	27.1	26.2	260	268
	North	37˚55’-45˚10’	25.5	25.1	240	258
	South	37˚23’-45˚36’	27	21.3	260	280
	South	37˚32’-45˚29’	29	26.5	269	287
11/08/2005	North	37˚48’-45˚15’	28.2	27.5	284	290
	North	37˚55’-45˚10’	29.8	28.6	281	291
	South	37˚23’-45˚36’	29.7	28.5	285	295
	South	37˚32’-45˚29’	31	30	290	296
01/03/2006	North	37˚48’-45˚15’	10.2	11	266	277
	North	37˚55’-45˚10’	12.6	11.9	266	280
	South	37˚23’-45˚36’	13	11.8	257	278
	South	37˚32’-45˚29’	12	13.5	268	280

3.9. Wind Data

Accurate simulation of flow circulation in the lake requires wind information with proper spatial and temporal precision. Satellite wind data is not available in the systematic temporal and spatial networking in the Urmia Lake region. But there are several meteorological stations around the lake (Figure 3.41). These stations record different meteorological data every three hours, including wind speed and direction, air pressure and temperature, relative humidity, precipitation, evaporation extra.

But according to Table 3.12 wind data for all simulation periods aren't available so in the current study just the data of one synoptic station (Urmia Airport Station) have been used due to following facts (Pirani, 2017; Tofighi, 2006)

- the Urmia Airport Station is the nearest station to the lake.
- the station level is very close to the lake level.
- the wind records in this station include wind data from 1961 to now.

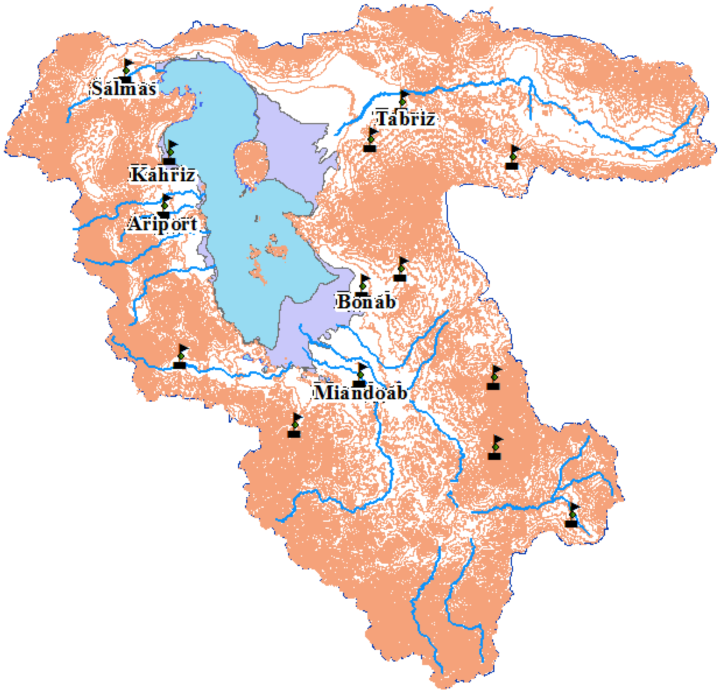


Figure 3.41. The location of stations and elevation curves in the Urmia Lake basin.

Table 3.12. Properties of selected synoptic stations.

Station Properties				Existence of Wind Data			
Name	Longitude (m)	Latitude (m)	Elevation (m)	1986 to 1987	1991 to 1992	2004 to 2005	2009 to 2010
Airport	504409.662	4168833.205	1328	×	×	×	×
Bonab	594493.359	4132384.622	1290			×	×
Miandoab	593467.099	4091689.657	1300			×	×
Tabriz	612547.891	4215838.604	1361	×	×	×	×
Salmas	486869.239	4229865.714	1337			×	×
Kahriz	507361.437	4192883.829	1325				×

3.9.1. Correction of Wind Data

In MIKE 3 Flow Model FM the direction of the wind is given as that towards which it blows, in degrees relative to the true North (see Figure 3.42), so it is necessary to correct the measured wind direction by adding 180°.

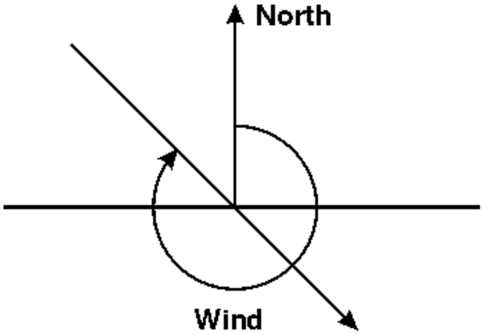


Figure 3.42. Definition of wind direction in MIKE 3 Flow Model FM

In this study overwater wind data are not available, so we had to use wind data measured at the synoptic station in the Urmia Airport Station, but some correction on data have been implied. For estimation of overwater wind speed from the observation in the station, three main steps presented by Resio and Vincent (1976) have been used as the Urmia Airport Station (X=504409.662 m , Y=4168833.205, Elevation= 1328) is nearest station to the lake that measured wind data are available for all simulation periods, so by assuming that wind is variable in time but constant in domain.

3.10. Numerical performance measure

Calibrated parameters were bottom roughness, wind friction coefficient and vertical eddy viscosity. Flow velocities and salinity distribution were adopted as target variables through comparison with field measurements. Mentioned parameters were objects of a sensitivity analysis.

Commonly applied numerical performance measures based on comparing time series of the simulated values and observed equivalents are given in Table 3.13 and have been employed to estimate model accuracy in this study. The ME (Mean Error), MAE (Mean Absolute Error), RMSE (Root Mean Square Error), STD (Standard Deviation of Residuals), R^2 (Coefficient of Determination) and d (Willmott’s Index of Agreement) are goodness-of-fit metrics were employed to estimate model accuracy. OBS_i is the observed value and SIM_i is the simulated equivalent. OBS and SIM are the average of the observed and simulated values, respectively. The statistics are evaluated over the period with observations i=1,..., n.

The ME is a measure of the general offset between measurements and simulations (bias), whereas STD is a measure of the dynamical correspondence. The RMSE is an aggregate measure that includes both bias and dynamical behavior. The RMSE is often used as an overall measure of comparison. The ME, MAE, RMSE and STD statistics are all dimensional measures with units of the variable considered. The coefficient of determination R^2 and the coefficient of efficiency or Nash-Sutcliffe coefficient E (Nash and Sutcliffe, 1970) are dimensionless.

Table 3.13. Employed goodness-of-fit metrics for assessing model accuracy

Performance measure	Equation
Mean Error	$\mathrm{ME} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{OBS_i} - \mathrm{SIM_i}) = \overline{\mathrm{OBS}} - \overline{\mathrm{SIM}}$
Mean Absolute Error	$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\lvert \mathrm{OBS_i} - \mathrm{SIM_i}\rvert$
Root Mean Squared Error	$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{OBS_i} - \mathrm{SIM_i})^2}$
Standard Deviation of Residuals	$\mathrm{STD} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\mathrm{OBS_i} - \mathrm{SIM_i} - (\overline{\mathrm{OBS_i}} - \overline{\mathrm{SIM_i}})\right)^2}$
Coefficient of Determination	$\mathrm{R}^2 = \frac{[\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{OBS_i} - \overline{\mathrm{OBS_i}})(\mathrm{SIM_i} - \overline{\mathrm{SIM_i}})]^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{OBS_i} - \overline{\mathrm{OBS_i}})^2 \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{SIM_i} - \overline{\mathrm{SIM_i}})^2}$
Willmott's Index of Agreement	$\mathrm{d} = 1 - \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{OBS_i} - \mathrm{SIM_i})^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\lvert \mathrm{SIM_i} - \overline{\mathrm{OBS_i}}\rvert + \lvert \mathrm{OBS_i} - \overline{\mathrm{OBS_i}}\rvert)^2}$

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Introduction

The main goals of this thesis are the quantification of the effect of the construction of dams on rivers and on the Urmia Lake, the analysis of the possible modifications of the usage programs of dams and of dam operation policies, based on water balance in the lake and the simulation of the lake responses to changes in the discharges of rivers under different dam operation policies. The MIKE 3 Flow Model FM, described in Chapter 3, was used to analyze the hydrodynamic regime of the lake, particularly the flow and salinity distribution within the lake. For these purposes, at first the water level of the lake was simulated based on the water balance equation of the lake by the model, and then the hydrodynamic behavior of the lake were discussed. Finally, the response of the lake to non-impoundment of dam has been investigated.

The approach presented here is a method for determining the monthly release of dams in an optimal way. The method considers the water provided by the unregulated catchment downstream of the dam, being referred to in this thesis as the 'residual hydrograph'.

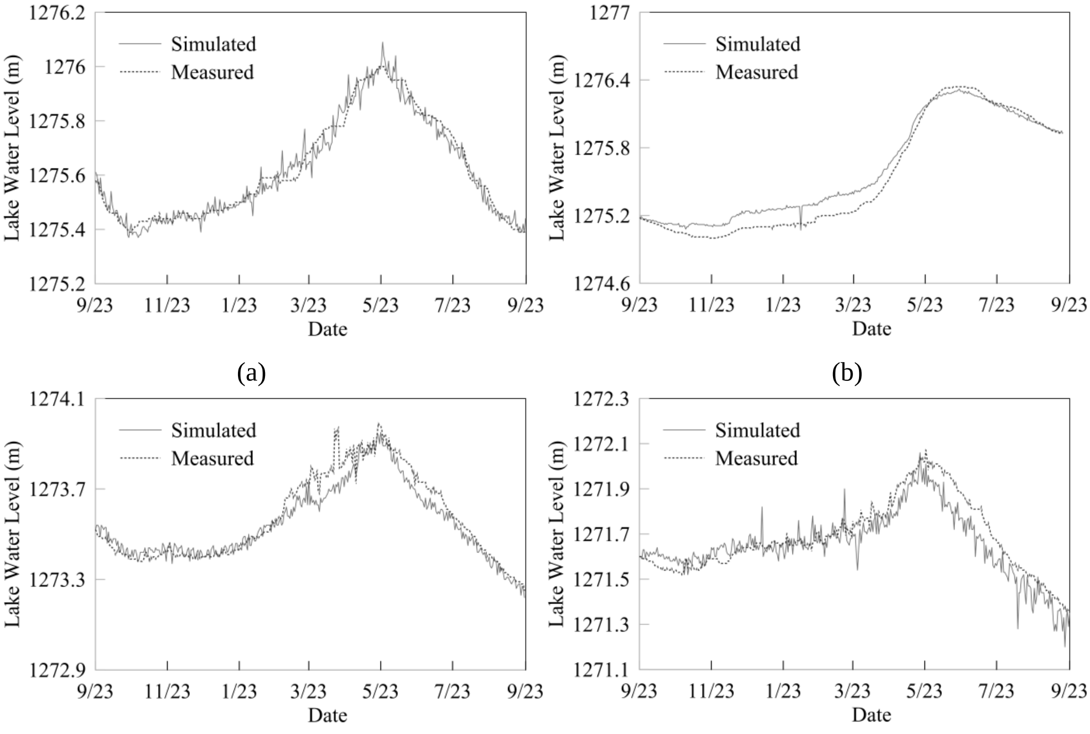
4.2. Water Balance of the Urmia Lake

Figure 4.1 displays the simulated and measured water levels at the Golmankhaneh Station in the Urmia Lake in four separate simulation years. By using Equation 3.2, $V_{Unmeasured}$ as an unknown term in the mentioned equation has been calculated and then equated to precipitation and evaporation height for negative and positive values of $V_{Unmeasured}$, respectively. As a result of the corrections to the discharges at the hydrometric stations, the simulated water level agrees with the measured one all over the simulation periods. In order to calibrate the water balance of the lake, three conditions were compared: (i) the surface water level measured in the Golmankhaneh Station with those simulated by the model; (ii) measured volume using the bathymetry map with the volume calculated by Equation 3.2; (iii) the surface area of the lake derived from the analysis of satellite images with the simulated one.

Commonly applied numerical performance measures based on comparing time series of simulated and observed water level at the Golmankhaneh Station are given in Table 4.1, to estimate the model accuracy in the simulation of water level. The results of the comparison between measured and simulated time series have been shown in Table 4.1. The results revealed that the simulated water level using the water balance components presented in Figure 4.1 is in agreement with the measured water level.

Table 4.1. Goodness of the numerical simulations as regards water level

Performance Measure	Unit	2009-2010	2004-2005	1991-1992	1986-1987
Mean Error	[m]	-0.0325	-0.0356	-0.0680	-0.0046
Mean Absolute Error	[m]	0.0529	0.0496	0.0859	0.0272
Root Mean Squared Error	[m]	0.0662	0.0617	0.1027	0.0353
Standard Deviation of Residuals	[m]	0.0577	0.0504	0.0770	0.0350
Coefficient of Determination	[-]	0.9299	0.9279	0.9895	0.9653
Coefficient of efficiency (Nash-Sutcliffe coefficient)	[-]	0.8791	0.8838	0.9457	0.9646
Index of Agreement	[-]	0.9632	0.9719	0.9881	0.9910



(a) (b)

(c) (d)

Figure 4.1. Simulated and measured water level of the Urmia Lake at the Golmankhaneh Station for: (a) September 1986-September 1987, (b) September 1991-September 1992, (c) September 2004 -September 2005, (d) September 2009 -September 2010

The contribution of each term of the water balance equation is different in producing the final value of $V_{Unmeasured}$. As shown in Table 4.2, Because of the uncertainties in the estimation of the precipitation, evaporation and river inflow volume have been accumulated in the $V_{Unmeasured}$ amount; the accuracy of the estimation of each variable can be effective in estimating the final value of $V_{Unmeasured}$. The value of evaporation volume has highest uncertainty so this term has the highest effect on the final value of $V_{Unmeasured}$ among other variables on the monthly and annual scale. The accumulation input discharge of rivers into the lake can also affect the $V_{Unmeasured}$ amount during wet months. Furthermore, this term has the highest effect on the $V_{Unmeasured}$ value after the evaporation on an annual scale.

In Table 4.2 to 4.6, the monthly water balance of the Urmia Lake for periods of 1986-1987, 1991-1992, 2004-2005 and 2009-2010 has been shown. According to tables the annual amount of $V_{Unmeasured}$ is not a good indicator of the monthly amount of this term, because the high amount of this term in one or several months of the year can affect the annual amount. For example, it is possible that for most months the amount of this term is negative (some percentage of water volume in the buffer zone has been lost), while $V_{Unmeasured}$ annually displays a positive amount. In other words, if the annual scale is the decisive criterion for the amount of water required to be released from dams, depending on the release time, not only a different value for $V_{Unmeasured}$ can be obtained, but also its sign will be changed. Therefore, the time scale has an effective role in the estimated value for $V_{Unmeasured}$ and due to changes in this term in different months; it is recommended that a smaller time scale (monthly or daily) is selected to close the water balance.

Because of the lack of data for AjiChai and Zarrinehroud Rivers at the SarinDizaj and Nezamabad Stations in 1986-1987 and 1991-1992, measured data of the Venyar and Miandoab Stations have been used respectively instead of data of the mentioned stations, so according to Table 4.3 and 4.4 the value of $V_{Unmeasured}$ for mentioned periods are remarkable.

Table 4.2. The Urmia Lake annual water balance contributions in selected periods.

Date	Average Water Level	Area (km^2)	ΔV(Mm^3)	Precipitation Volume (Mm^3)	Surface Evaporation Volume (Mm^3)	River Inflow Volume at the Hydrometric Station (Mm^3)	$V_{Unmeasured}$ (Mm^3)
Sep 1986- Sep 1987	1275.61	5114.721	-775.3806	1253.7677	5279.5365	4396.040655	-1128.3307
Sep 1991- Sep 1992	1275.535	5024.869	3502.97239	1669.3211	4266.764583	6899.42897	-796.749
Sep 2004- Sep 2005	1273.54	4360.9	-1074.29523	1151.283479	4650.110319	2486.288995	-87.7048
Sep 2009- Sep 2010	1271.67	3404.783	-687.956933	1369.86222	3586.9443	1603.671062	-74.54

Table 4.3. The Urmia Lake monthly water balance contributions in 1986-1987.

Date	Average Water Level	Area (km^2)	ΔV(Mm^3)	Precipitation Volume (Mm^3)	Surface Evaporation Volume (Mm^3)	River Inflow Volume at the Hydrometric Station (Mm^3)	$V_{Unmeasured}$ (Mm^3)
Mehr (Oct)	1275.58	5072.3711	-919.6757	153.9870	465.5078	88.7440	696.8989
Aban (Nov)	1275.39	5032.6163	241.2176	324.8755	164.6924	202.0740	121.0395
Azar (Dec)	1275.44	5035.1271	48.4613	125.1028	25.4645	215.1852	266.3623
Dey (Jan)	1275.45	5037.6379	242.3064	65.2475	0	292.6567	115.5977
Bahman (Feb)	1275.5	5043.4966	436.1516	132.4927	0	387.9524	84.2935
Esfand (Mar)	1275.59	5069.4586	436.1516	201.6225	116.5658	490.8859	139.7910
Farvardin (Apr)	1275.68	5104.3021	581.5354	166.3390	266.5774	1052.9283	371.1545
Ordibehesht (May)	1275.8	5187.5036	969.2257	60.4759	696.6035	1108.2255	-497.1278
Khordad (Jun)	1276	5240.6217	-726.9193	19.8096	819.7669	299.7769	226.7389
Tir (Jul)	1275.85	5042.0453	-581.5354	1.7647	1024.2481	95.8264	-345.1216
Mordad (Aug)	1275.73	5072.0162	-1114.6096	0.7912	974.7931	54.7158	195.3235
Shahrivar (Sep)	1275.5	5037.2195	-387.6903	1.2593	725.3170	89.7477	-246.6197

Table 4.4. The Urmia Lake monthly water balance contributions in 1991-1992.

Date	Average Water Level	Average Area (km^2)	$\Delta V(Mm^3)$	Precipitation Volume (Mm^3)	Surface Evaporation Volume (Mm^3)	River Inflow Volume at the Hydrometric Station (Mm^3)	$V_{Unmeasured}$ (Mm^3)
Mehr (Oct)	1275.18	4897.9239	-632.4811	71.2877	394.5178	36.4703	345.7213
Aban (Nov)	1275.05	4851.4873	-243.2620	151.3396	237.7090	69.8164	226.7089
Azar (Dec)	1275	4833.6271	437.8715	348.4801	48.1123	200.4212	62.9175
Dey (Jan)	1275.09	4865.7755	97.3048	74.3257	0	161.5006	138.5215
Bahman (Feb)	1275.11	4872.9196	389.2192	17.0466	0	166.8894	-205.2832
Esfand (Mar)	1275.19	4901.4959	194.6096	162.7901	0	318.0669	286.2475
Farvardin (Apr)	1275.23	4915.7841	1313.6146	207.2257	245.9029	1337.5938	-14.6980
Ordibehesht (May)	1275.5	5012.2293	3065.1008	517.2716	440.6246	2897.4568	-90.9969
Khordad (Jun)	1276.13	5237.2680	1021.7003	88.7217	585.0701	1386.9343	-131.1144
Tir (Jul)	1276.34	5312.2809	-729.7859	0.0000	827.8599	215.0358	116.9617
Mordad (Aug)	1276.19	5258.7003	-681.1335	28.2620	815.1130	66.9237	-38.7938
Shahrivar (Sep)	1276.05	5208.6917	-729.7859	2.5702	671.8550	40.0559	100.5571

Table 4.5. The Urmia Lake monthly water balance contributions in 2003-2004

Date	Average Water Level	Average Area (km^2)	ΔV(Mm^3)	Precipitation Volume (Mm^3)	Surface Evaporation Volume (Mm^3)	River Inflow Volume at the Hydrometric Station (Mm^3)	$V_{\text{Unmeasured}}$ (Mm^3)
Mehr (Oct)	1273.52	4360.899641	-482.22337	14.13804	425.9554	17.6010	88.0070
Aban (Nov)	1273.4	4294.732105	84.33624778	298.53542	188.3371	61.1469	87.0090
Azar (Dec)	1273.42	4305.760028	-84.33624778	70.97615	11.8958	102.2257	245.6423
Dey (Jan)	1273.4	4294.732105	119.95653	53.84735	0	83.1620	17.0528
Bahman (Feb)	1273.43	4311.273989	362.26684	180.56478	0	189.6661	7.9641
Esfand (Mar)	1273.52	4360.899641	776.98053	50.79576	0	835.9481	109.7633
Farvardin (Apr)	1273.71	4465.664905	373.6367	148.22435	312.7922	561.8415	23.6369
Ordibehesht (May)	1273.8	4515.290556	799.6438	276.16420	488.7718	434.1988	-578.0526
Khordad (Jun)	1273.99	4620.05582	-1131.97063	10.03476	774.2490	88.2003	455.9567
Tir (Jul)	1273.72	4471.178866	-533.7837	7.60100	922.9204	25.9200	-355.6156
Mordad (Aug)	1273.59	4399.497369	-726.81112	29.01029	896.0507	17.1984	-123.0310
Shahrivar (Sep)	1273.41	4300.246066	-631.99081	6.03755	717.7003	13.3523	-66.3197

Table 4.6. The Urmia Lake monthly water balance contributions in 2009-2010.

Date	Average Water Level	Average Area (km^2)	ΔV(Mm^3)	Precipitation Volume (Mm^3)	Surface Evaporation Volume (Mm^3)	River Inflow Volume at The Last Hydrometric Station (Mm^3)	$V_{Unmeasured}$ (Mm^3)
Mehr (Oct)	1271.6	3329.539	-171.98923	1.64253	281.39437	8.4265	99.3361
Aban (Nov)	1271.54	3325.776	143.32436	322.65399	160.18153	53.3465	-72.4946
Azar (Dec)	1271.59	3363.399	143.32436	55.88806	28.18959	57.0199	58.6060
Dey (Jan)	1271.64	3385.972	28.66487	30.27078	32.70482	63.4907	-32.3918
Bahman (Feb)	1271.65	3408.545	143.32436	45.53091	5.90404	64.4876	39.2099
Esfand (Mar)	1271.7	3434.881	57.32974	160.25632	0.00000	192.8102	-295.7367
Farvardin (Apr)	1271.72	3468.740	200.65411	184.38898	205.78070	234.1943	-12.1485
Ordibehesht (May)	1271.79	3581.607	659.29206	466.15225	274.35793	792.0218	-324.5241
Khordad (Jun)	1272.02	3619.229	-372.64334	62.98926	558.68501	79.6163	43.4361
Tir (Jul)	1271.89	3487.551	-630.62719	1.60664	742.40151	25.1401	85.0276
Mordad (Aug)	1271.67	3348.350	-429.97308	0.00000	714.98008	16.9808	268.0262
Shahrivar (Sep)	1271.52	3231.721	-458.63796	38.48250	582.36472	16.1364	69.1079

4.3. Analysis of the alteration of the flow regime in the Urmia Lake and its tributary rivers to assess the impact of major constructed dams

Natural flow patterns have changed over the past century due to changes in water resources use, land use and climate (Nilsson & Berggren, 2000).

In the Urmia Lake basin, the reduction of the water level of the lake through the two last decades, whether at monthly or yearly scales was more harsh and different than the changes of precipitation and temperature, so anthropogenic factors have impacted more than the natural variability (Jalili et al., 2016 a; Jalili et al., 2016 b; Zoljoodi and Didevarasl, 2014).

To understand the impacts of anthropogenic changes in the dynamics of the natural rivers, simple indicators can be useful as management tools to quantify the various impacts caused by changes in water and land use.

Different methods can be used to quantify changes in the hydrology of surface waters after river regulation, water use and climate change. The changes are evident in rivers and lakes as shifts in regime characteristics (timing and magnitude of flow and its distribution). The impacts of regulation can be modified using different methods applying environmental flow principles. In this study, the effect of climate, of regulation and of water use has been investigated by using DLW and MIF indexes before and after regulation and the decline of precipitation. In the following paragraphs the mentioned indexes are discussed.

4.3.1. Degree of Lake Wetness (DLW) of the Urmia Lake

In the past, using water level fluctuations within each year and between different years has been considered a key factor in lake and wetland management. However, using water level data alone does not summarize the lake state. By using the concept of DLW (described in Chapter 3) the lake historical state has been classified in Figure 4.2. According to the figure, since 1997 the lake condition has changed sharply. The detail of DLW index calculation before and after 1997 is reported in Table 4.7. According to the table, DLW was 0.531 since 1966 to 2014, but its values before and after 1997 have significant difference.

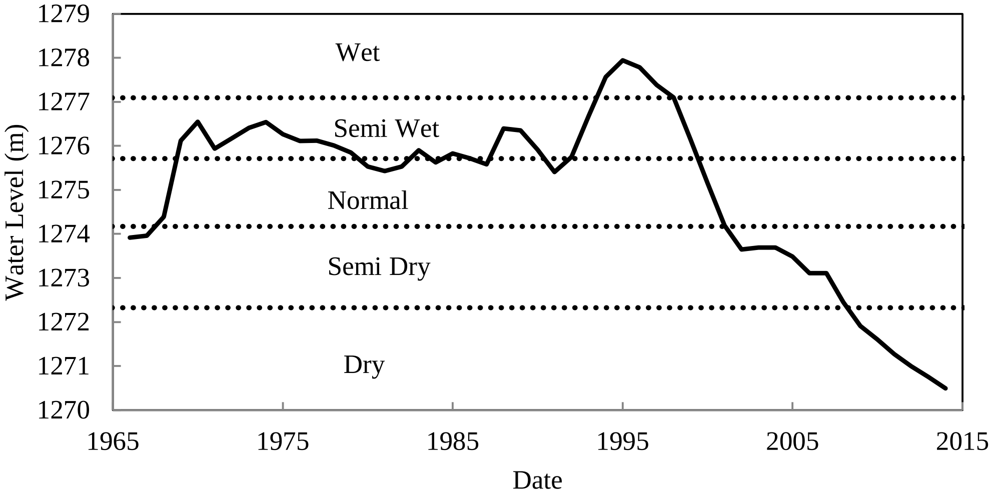


Figure 4.2. The Urmia Lake classification based on the second definition of Degree of Lake Wetness (DLW)

Table 4.7. Degree of Lake Wetness (DLW) in different time periods

Time Period	Lake Volume (%)	Lake Volume (Mm^3)	Water Level (m)	Number of Months	Percent of Month	State
(1966-2014)	0-20	0-7224	1272.328	76	A_1=13.01	Dry
	20-40	7224-14448	1274.17	107	A_2=18.23	Semi Dry
	40-60	14448-21672	1275.71	128	A_3=21.75	Normal
	60-80	21672-28896	1277.09	223	A_4=37.95	Semi Wet
	80-100	28896-36120	1278.41	54	A_5=9.06	Wet
	DLW= 0.531					
(1966-1997)	0-20	0-7224	1272.328	0	A_1=0	Dry
	20-40	7224-14448	1274.17	23	A_2=5.85	Semi Dry
	40-60	14448-21672	1275.71	106	A_3=26.97	Normal
	60-80	21672-28896	1277.09	210	A_4=53.44	Semi Wet
	80-100	28896-36120	1278.41	54	A_5=13.74	Wet
	DLW= 0.688					
(1997-2014)	0-20	0-7224	1272.328	76	A_1=37.81	Dry
	20-40	7224-14448	1274.17	84	A_2=41.79	Semi Dry
	40-60	14448-21672	1275.71	22	A_3=10.94	Normal
	60-80	21672-28896	1277.09	13	A_4=6.47	Semi Wet
	80-100	28896-36120	1278.41	6	A_5=2.99	Wet
	DLW= 0.238					

4.3.2. Separation of the effect of the constructed dams from other effective Parameters

The index MIF_2 can be used to assess the impacts of land use and climate change. In Figure 4.3 the flow regime of the tributaries to the Urmia Lake at the last hydrometric stations is shown. According to the figure, because of the reduction in precipitation and the change in the land use in the river catchments, there is the significant difference between the annual hydrographs of all rivers before and after 1997, therefore the IHA method (which uses data from before and after construction) may be not be suitable for assessing the effects of the regulation of rivers in the Urmia Lake basin with high natural climate variability.

In Table 4.8, the Magnitude Impact Factor (MIF_2) of all the major rivers at the last stations before and after 1997 has been calculated. To eliminate the effect of dams, both of the selected periods in the table are before any regulation on rivers. According to the table, after 1997 the annual inflow volume of rivers has been reduced because of increasing water demand and decreasing precipitation. Maximum and minimum MIF_2 is 0.689 and 0.409 for ChwanChai and RozehChai River, respectively, implying a respective reduction of the annual volumes of the river discharges by 31% to 59%. However, according to most references, the decline in precipitation on the lake basin can be estimated to be 18%, so that the remaining part of the reduction can be ascribed change in land use and to the increase of surface water abstraction. Therefore it is important to reduce overall demand before any modification in operation of active dams.

Table 4.8. Magnitude Impact factor (MIF_2) of climate change

River Name	Station Name	Before 1997	After 1997	$MIF_2 = \frac{AF_{Post}}{AF_{Pre}}$
ChwanChai	Khormazard	1976-1996	1997-2012	0.689
MardoughChai	Gheshlagh e Amir	1974-1996	1997-2012	0.586
RozehChai	Goijali Aslan	1982-1996	1997-2014	0.409
LeilanChai	Shirin Kandi	1973-1996	1997-2012	0.550
Siminehroud	Miandoab	1966-1996	1997-2005	0.584
SenikhChai	PoleSenikh	1965-1996	1997-2012	0.539
GhaleChai	Shishvan	1982-1996	1997-2005	0.433
BarandouzChai	Babaroud	1971-1996	1997-2012	0.557
NazlouChai	Tapik	1965-1996	1997-2014	0.536
NazlouChai	Abajalou Sofla	1963-1996	1997-2014	0.444
ShahrChai	Keshtiban	1964-1976	2003-2005	0.56
DerikChai	Nazar Abad	1985-1997	1997-2007	0.442
ZolaChai	Yalghouz Aghaj	1974-1996	1997-2007	0.562

4.3.3. Quantification of the impacts of dams on the regime of rivers

In Figure 4.3, the average annual hydrograph at the last hydrometric stations of rivers flowing into the Urmia Lake are shown. According to Figure 4.3, the average annual hydrograph of hydrometric stations have a significant difference for different periods of time. In addition the increase of surface water consumption in recent years and a decrease in precipitation and climate change leads to a reduction in the volume of the annual inflow. Also according the results of last study on time series of 65 hydrometric stations on the Urmia Lake basin by Hesari and Zeinalzadeh (2019) the average volume of surface waters inflowing the Urmia Lake have decreasing trend from 4654 Mm^3 in years before 1995 (the starting year of drying) to 2134 Mm^3 in years after 1995 and the different between average discharges of the mentioned periods was significant at 95% confidence level on the basis of t-student method. Therefore, in the present study, available hydrometric data since 1997 (two years after starting year of drying) are considered as the base period and in the regulation curve of large operating dams have been revised based on the average annual hydrograph since 1997. For example, by comparing the graphs of discharge for the periods of 1983-1996, 1997-2005 and 2005-2012 at the Shishvan Station in Figure 4.3, it can be concluded that in the periods of 1997-2005 due to the reduction of precipitation and climate change, as well as surface water withdrawal, the discharge flow rate of the station has decreased considerably when compared to the periods of 1983-1996. However, due to the construction of the Ajabshir Dam, since 2005 the flow rate of the station was more decreased.

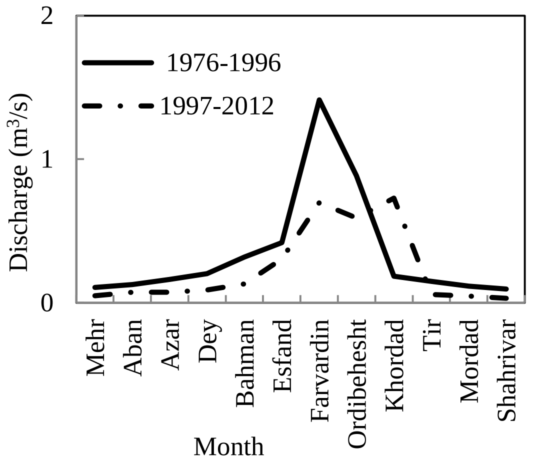
In Figure 4.4 the mean annual hydrographs of the GhaleChai, ZolaChai, Zarrinehroud, ShahrChai and GadarChai River for the time periods before and after the construction of Ajabshir, Zola and Derik, ShahidKazemi, ShahrChai and Hassanlou dams on the river reach have been shown, respectively. Also, in Table 4.9 the values of MIF for dams that have adequate measured data have been calculated.

In many cases, the crop season can be totally different from the rainy season or the high discharge season. In hot, dry climates such as in the Urmia Lake basin in particular, dams used for irrigation purposes and store water in some wet months (Farvardin and Ordibehesht) and release water in other months (Tir and Mordad). For example, in Figure 4.4 Zola, ShahrChai and ShahidKazemi Dams affect the timing of discharges.

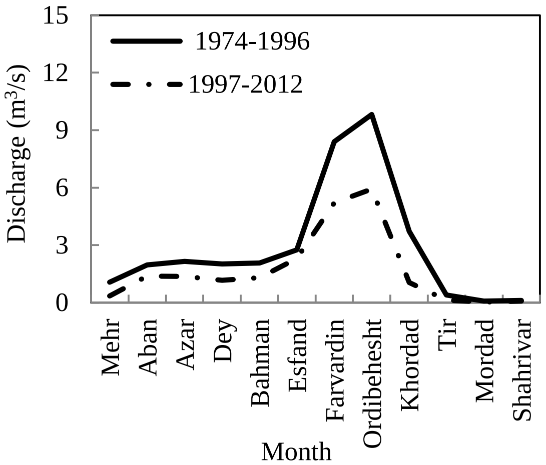
The Ghoshkhaneh Dam and the Sarough Dam were activated in 2003 and 2009, respectively, on the main tributaries that inflow to ShahidKazemi Dam, so to eliminate the effect of mentioned dams, the 1985-1997 and 2003-2009 have been chosen as pre- and post-impact periods.

In Figure 4.5 the annual hydrograph of the Zarrinehroud River in the Sarigamish Station (nearest station to the dam that located in downstream of dam) has been compared with annual inflow to the ShahidKazemi Dam. Comparing the Scaled Annual Hydrograph (SAH) in Figure 4.5 (a) for pre and post modification periods (i.e. after the increase of the storage capacity and the height of the ShahidKazemi Dam in 2005), 2003-2005 and 2005-2009 respectively, it appears that modification of the ShahidKazemi Dam changed the normal distribution of the annual hydrograph at the Sarigamish Station and shifted the maximum value in the annual hydrograph from Farvardin to Ordibehesht. It also increased the discharge of the Zarrinehroud River at Khordad, Tir and Mordad by releasing water in the irrigation periods.

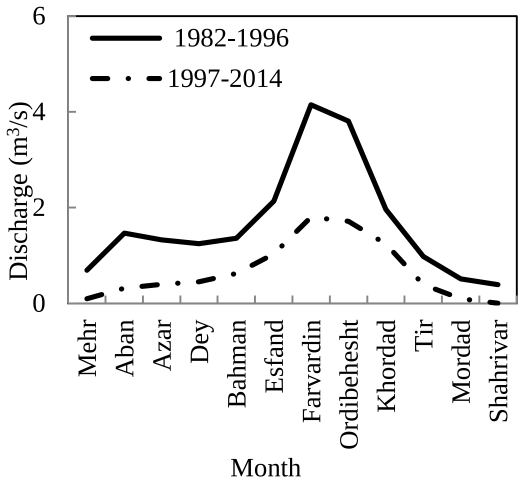
According to Figure 4.5 (b) there are a few differences between the cumulative input water volume of the PoleAnian, Sante, DarePanbedan and Saffakhaneh Stations and the output volume of water from the Sarigamish Station. This is due to some ignored tributaries and the distance between the input stations and the Sarigamish Station. After the construction of the ShahidKazemi Dam in 1971 according to Figure 4.5 (c), the mentioned difference became more predominant. In Table 4.9, the value of MIF_1 for the Zarrinehroud River has been calculated for three different time periods (i.e. before the construction of the ShahidKazemi Dam, after its construction, and after its modification). Also the MIF values for other built dams have been calculated and are shown in Table 4.9. The MIF index shows the high impact of the Ajabshir Dam construction on the GhaleChai River, while the Derik Dam has a low effect on the river regime (less than 20%) since it is a single purpose dam with low storage capacity (22 Mm^3).



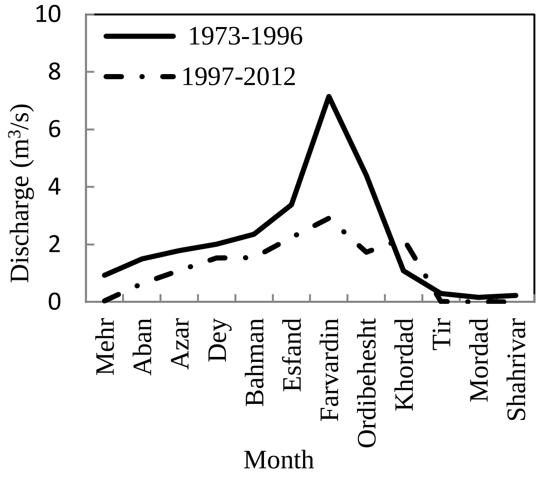
Khormazard



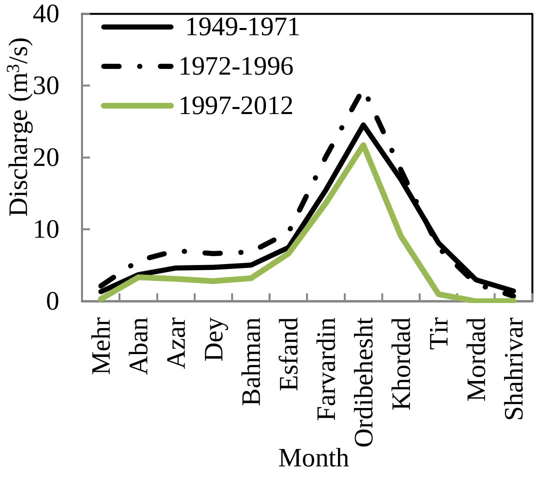
Gheshlagh e Amir



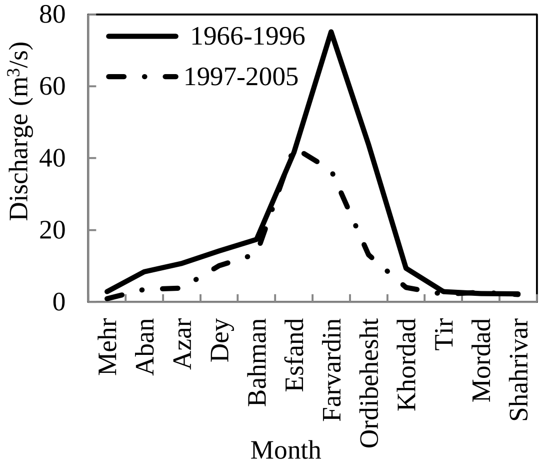
Goijali Aslan



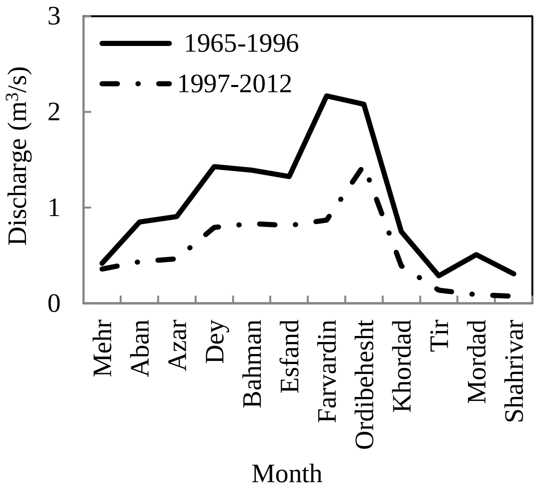
Shirin Kandi

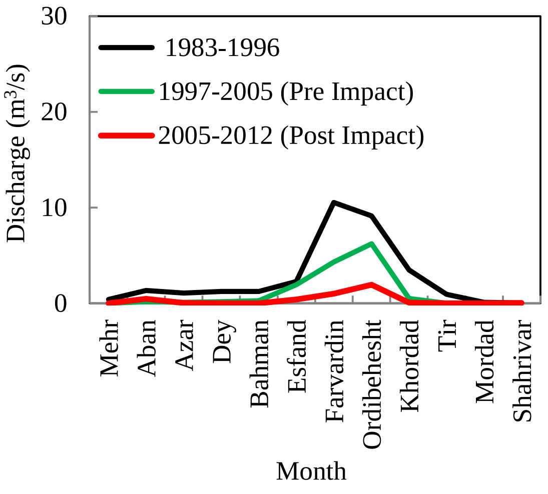


Babaroud



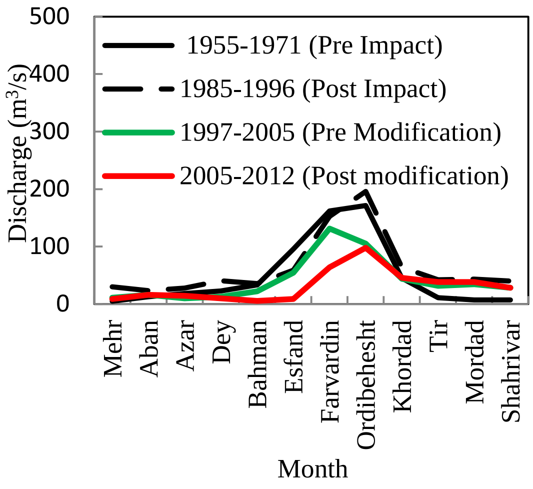
Miandoab

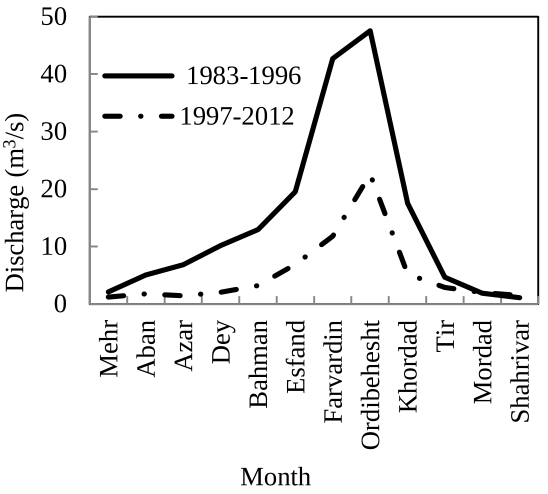




Pol-e- Senikh

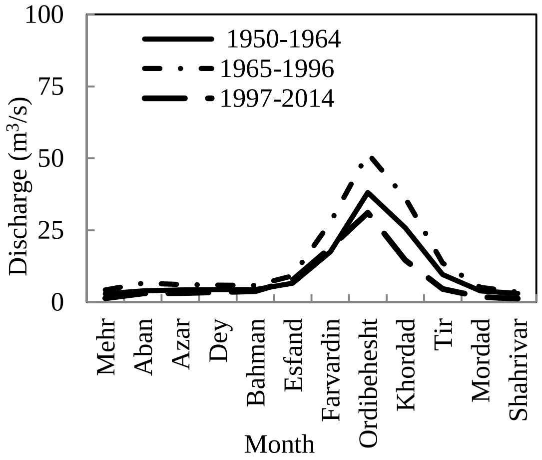
Shishvan

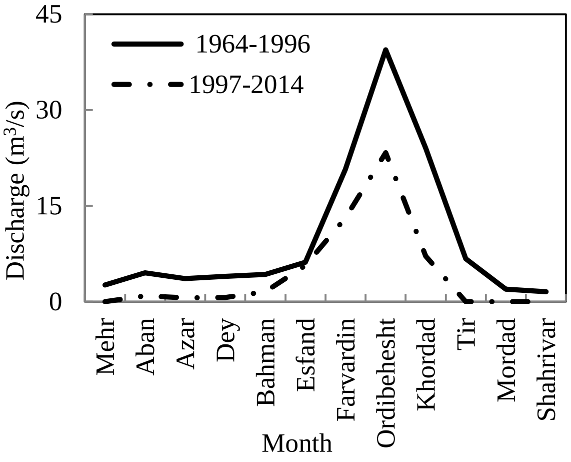




Sarighamish

Akhoula





Tapik

Abajalou Sofla

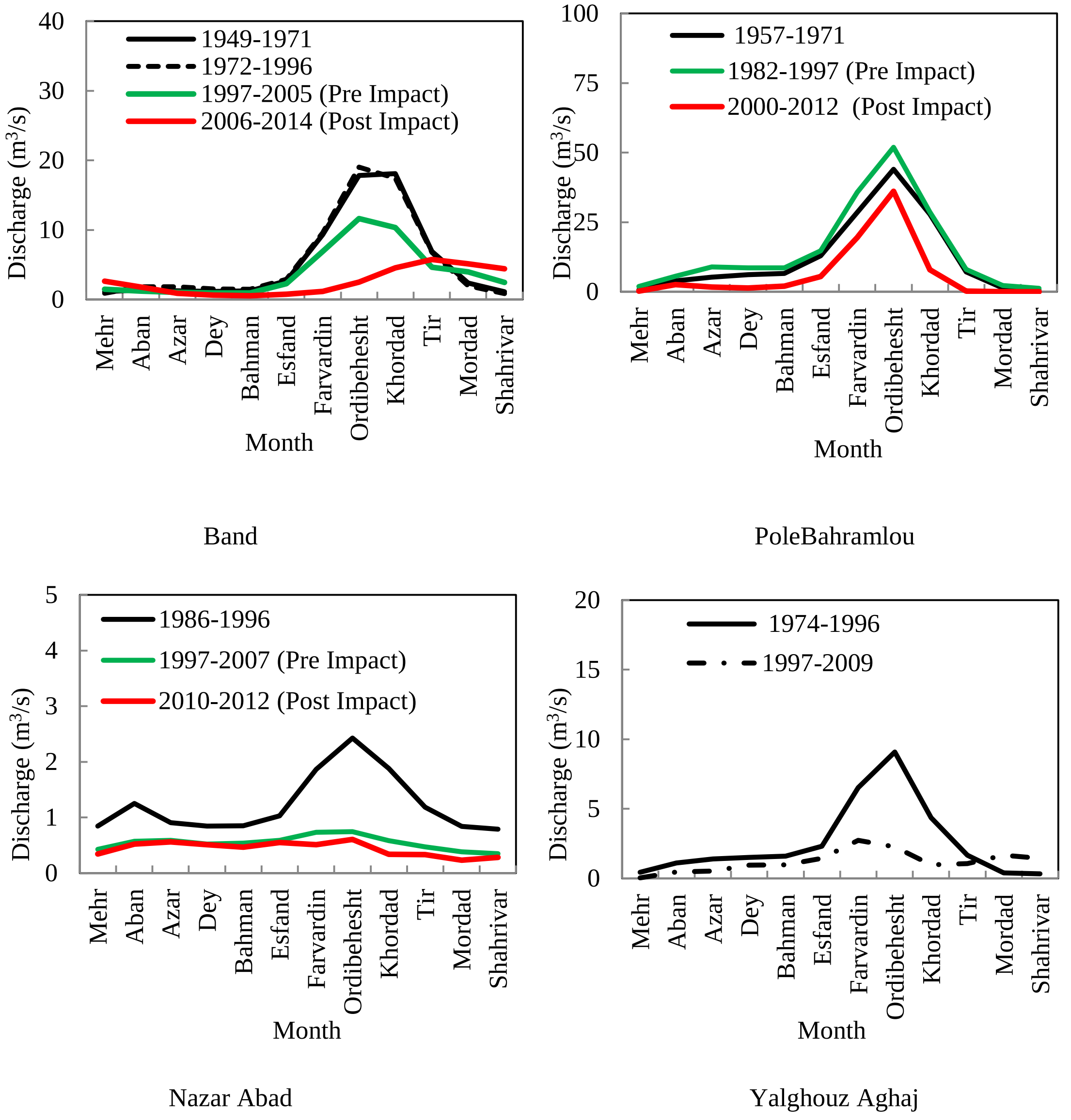
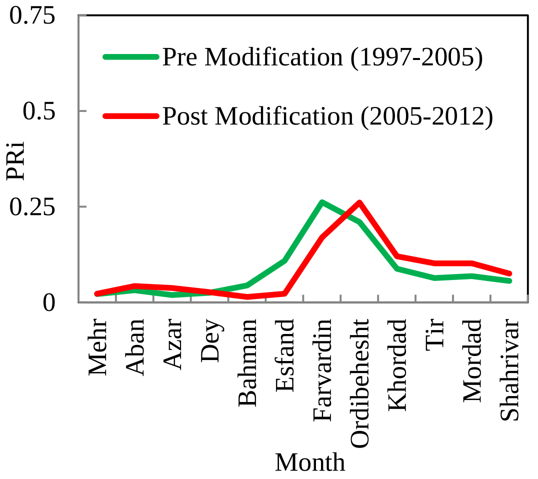
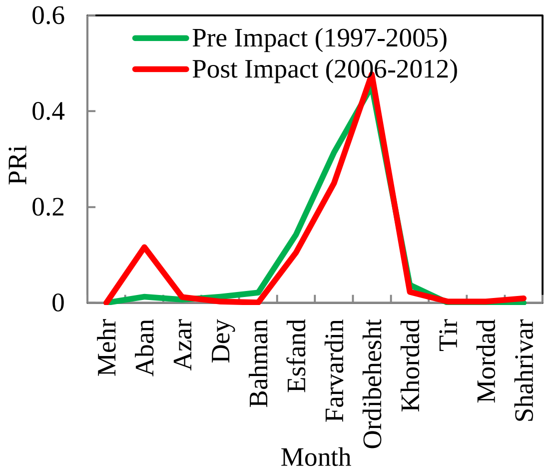


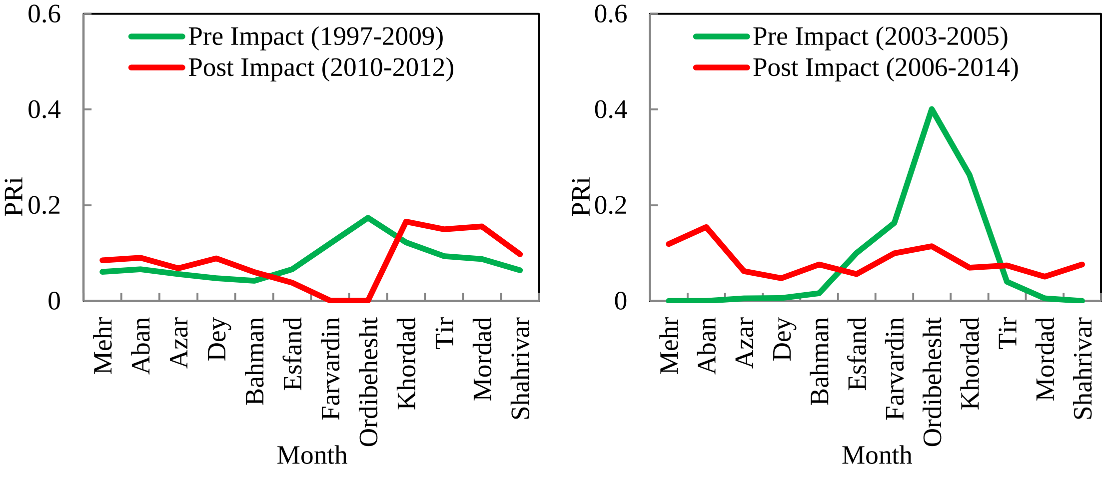
Figure 4.3. Mean annual flow (MAF) at Hydrometric stations for different time periods



(a) Effect of the modification of the Shahid-Kazemi Dam on the Zarrinehroud River regime at the Sarighamish Station

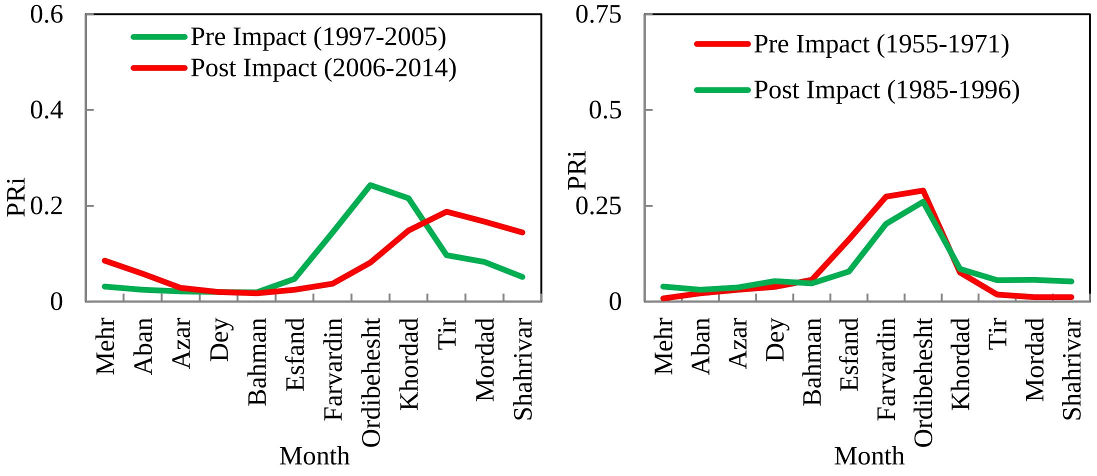


(b) Effect of the Ajabshir Dam on the Ghale-Chai River regime at the Shishvan Station



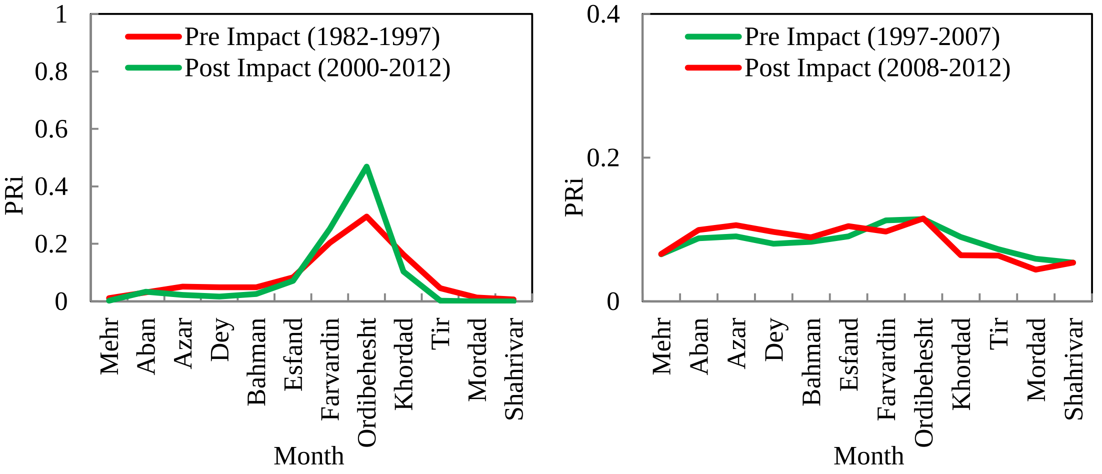
(c) Effect of the Zola Dam on the ZolaChai River regime at the Ajvaj Station

(d) Effect of the ShahrChai Dam on the ShahrChai River regime at the Keshtiban Station



(e) Effect of the ShahrChai Dam on the ShahrChai River regime at the Band Station

(f) Effect of the ShahidKazemi Dam on the Zarrinehroud River regime at the Sarighamish Station



(g) Effect of the Hassanlou Dam on the GadarChai River regime at the PoleBahramlou Station

(h) Effect of the Derik Dam on the ZolaChai River regime at the Nazar Abad Station

Figure 4.4. Changes in distribution of rivers scaled mean monthly discharges following the construction of dams

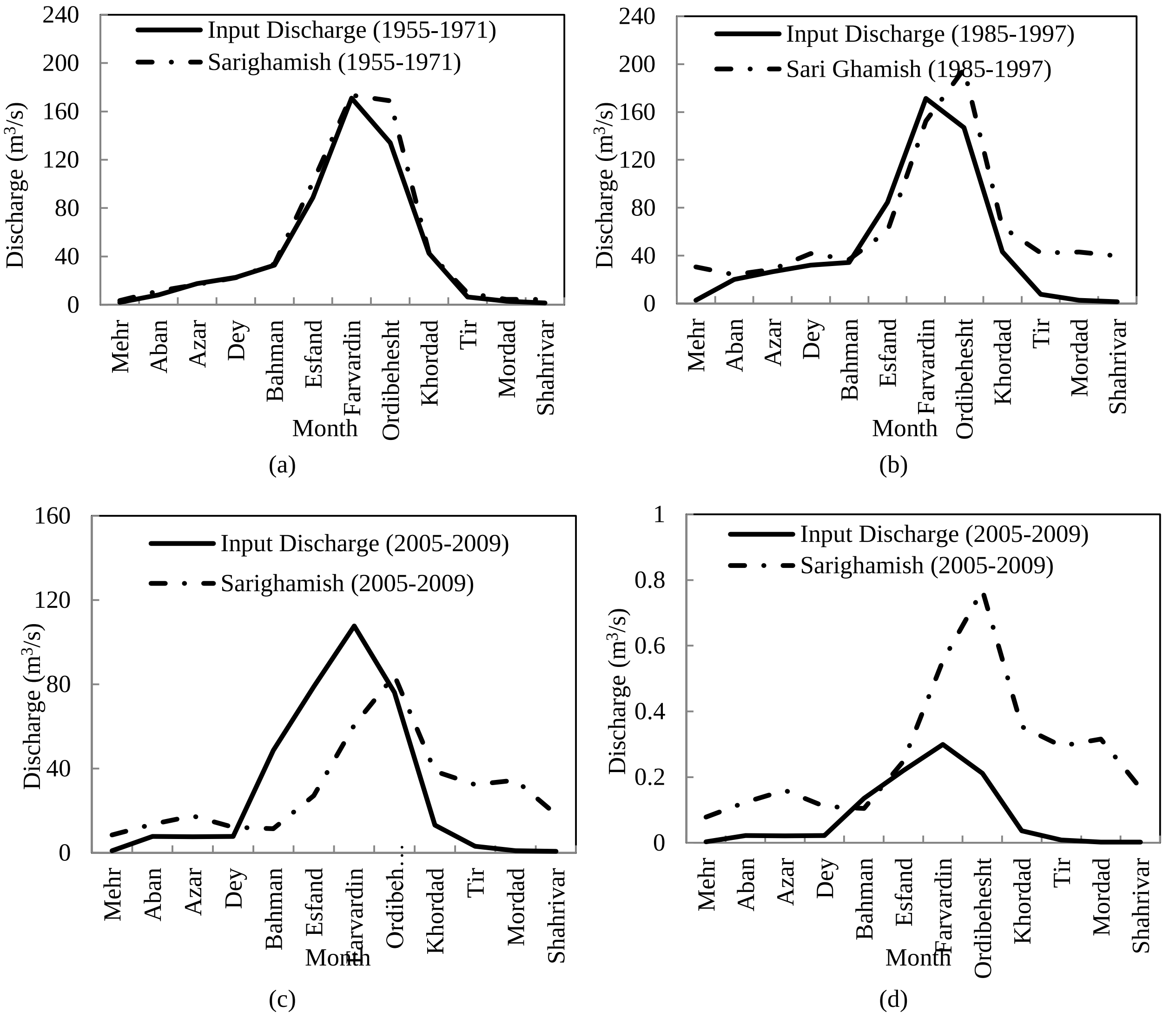


Figure 4.5. Comparison between input and output mean annual hydrographs at the Sarigamish Station: a) before the dam construction (1955-1971); b) after the dam construction (1985-1997); c) after the dam construction (2005-2009); d) scaled annual hydrograph for after the dam construction (2005-2009).

Table 4.9. Magnitude Impact factor (MIF) of dam construction

River Name	Dam Name	Activation Year	Inflow	Outflow	Time Period	$\mathrm{MIF}_1 = \frac{\mathrm{AOF}}{\mathrm{AIF}}$	Pre-Impact Time Period	Post-Impact Time Period	Station Name	$\mathrm{MIF}_2 = \frac{\mathrm{AF}_{\mathrm{Post}}}{\mathrm{AF}_{\mathrm{Pre}}}$
Zarrinehroud	ShahidKazemi Dam	1971	Cumulative discharge of input tributaries	Measured discharge in Sarighamish Station	1955-1971	1.12	1955-1971	1985-1996	Sarighamish	1.27
					1985-1997	0.743	1997-2005	2005-2012	Sarighamish	0.75
		Modificated in 2005			2005-2009	0.91				
ShahrChai	ShahrChai Dam	2005					1997-2005	2006-2014	Band	0.64
ZolaChai	Zola Dam	2009					1997-2009	2010-2012	Ajvaj	0.746
DerikChai	Derik Dam	2008					1997-2007	2010-2012	Nazarabad	0.81
GhaleChai	Ajabshir Dam	2006					1997-2005	2005-2012	Shishvan	0.295
GadarChai	Hassanlou Dam	2000					1972-1997	2000-2012	PoleBahramlou	0.437

4.4. Optimum flow regime of input rivers and regulation rules for active dams

For some major dams for which adequate data are available, the optimum release volume of water has been calculated through the following parameters:

I. Scaled Annual Hydrograph (SAH)

In order to establish the lake's goods and services, the water allocation for lakes must be close to the natural regime (Dyson et al., 2003). The natural regime is defined by a natural annual hydrograph with the average monthly discharges (Q) at the gauging stations, used as reference points in natural conditions before any regulation.

In this study, the data before 1997, if available, have been used to eliminate the effect of the decline in precipitation on natural discharges. To eliminate the effect of the regulation by dams, the data before dam construction has been used. By using available historical data Scaled Annual Hydrograph of the last stations before regulation has been calculated in Table 4.10. According to Figure 4.6 maximum discharges occur in March (Farvardin) and April (Ordibehesht).

II. Mean Annual River Flow (MAF)

The optimal monthly distribution of the regulation rules of dams depends on how much water is allocated, on the location in the catchment and on the target for allocating. In most regions the regulation rules of active dams are based on the Mean Annual Flow (MAF) of rivers. In this study three scenarios with different allocation flows have been defined consist: 1) low (30% of MAF); 2) mean (50% of MAF); 3) high (80% of MAF). According to Table 4.11 to calculate the effect of the reduction in precipitation on the discharges of rivers, the mean annual flow after 1997 has been selected for MAF.

III. Loss and yields in residual parts between dam and the reference point ($Q_{Residual}$)

$Q_{Residual}$ is the residual discharge between the target points and water release point (Dam) location. Based on real data and using Equation 3.10, the residual discharge for the reference points has been defined. Because of changes in land use and water consumption in recent years, the time period after 1997 was selected for calculations in Table 4.12. In some stations such as the Gord e Yaghoub and Pol-eSorkh Station in the MahabadChai River basin, because of non-overlapping of available data in the mentioned stations, it isn't possible to calculate $Q_{Residual}$.

IV. Available annual discharge at reference point (magnitude of flow) (Q_{AAD})

By using Equation 3.11 by three scenarios for releasing policy according to Table 4.13, available annual discharges at reference points have been calculated. Under Scenario 1 in some of the rivers (ShahrChai, ZolaChai, NazlouChai, GhaleChai, Zarrinehroud and AjiChai) because of the large amount of water consumption at the residual parts, Q_{AAD} is negative. This means that if %30 of MAF is used as dam release policy in the mentioned rivers catchment, no water can reach the lake by the rivers. Under Scenario 2, the ShahrChai River has a negative value of Q_{AAD}, due to the remarkable water consumption in the ShahrChi River catchment after the ShahrChai Dam.

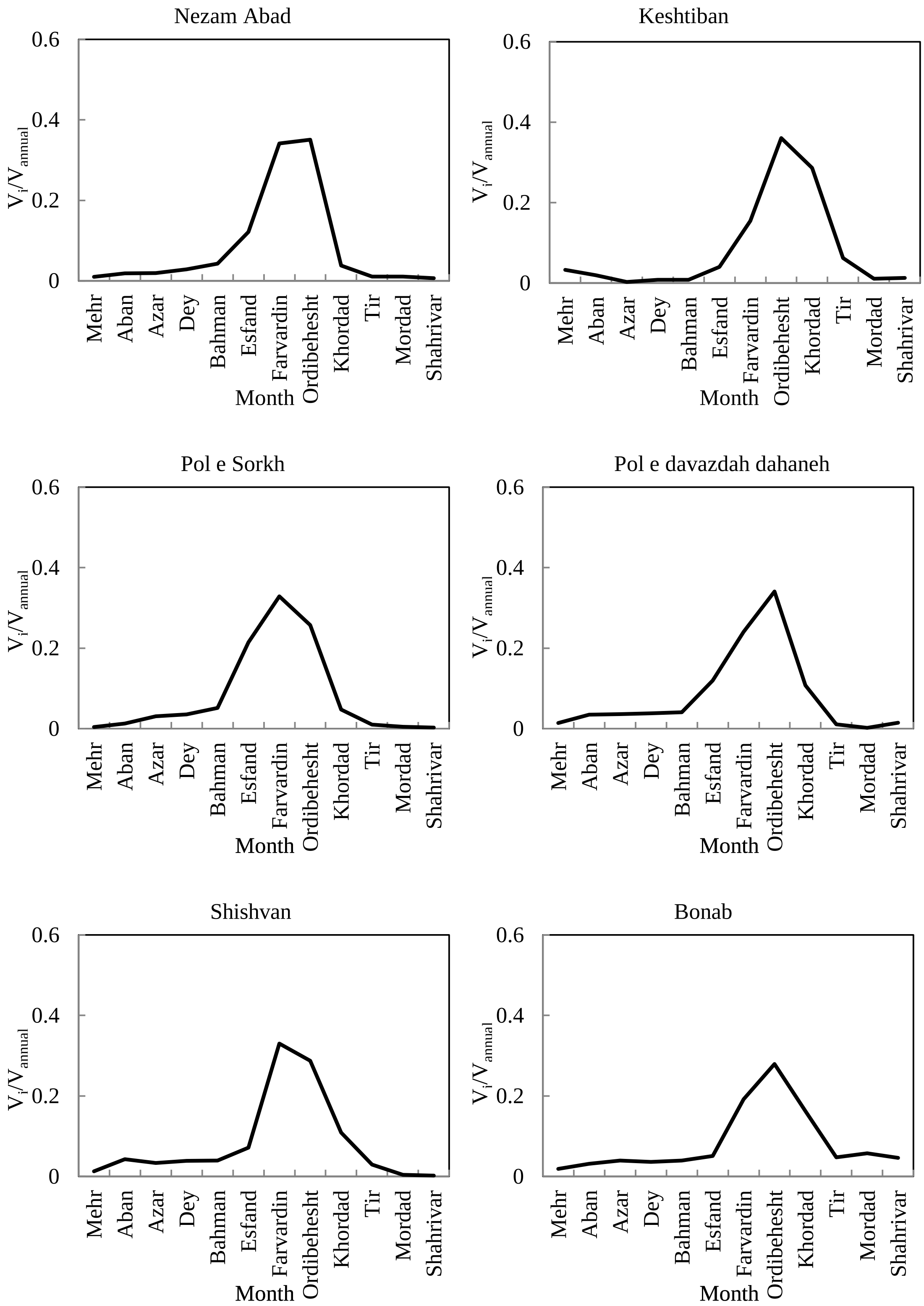
V. Closest Annual Hydrograph to natural flow after regulation at reference point (Q_{CAH})

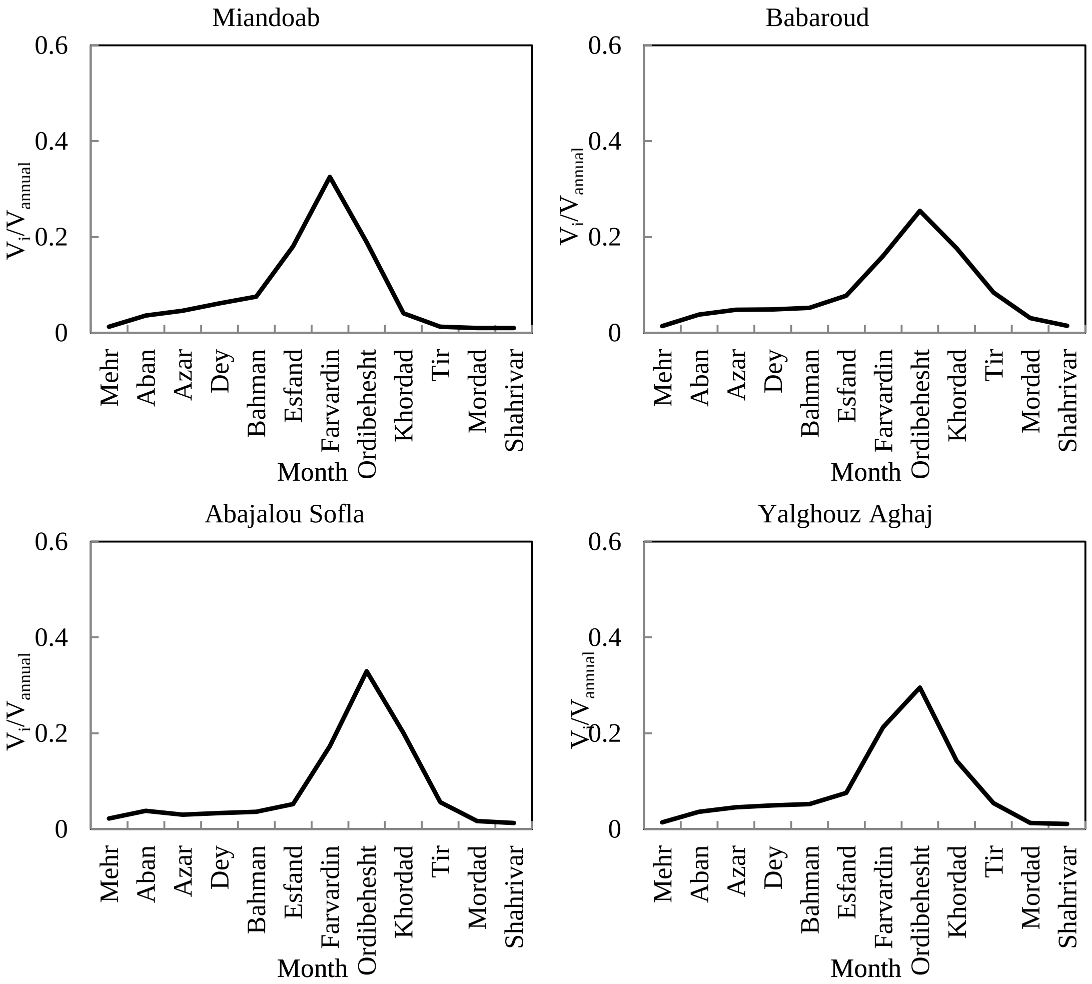
According to Table 4.11, $Q_{Residual}$ in most rivers (except the GadarChai and Siminehroud Rivers) has a negative value. It means that according to Equation 3.14 Q_{RW} has to be larger than Q_{CAH}. In Figure 4.7, Q_{EF} calculated by researchers for the last hydrometric stations (Reference points) of major rivers in the Urmia Lake basin by different methods (Table 4.14) have been compared with calculated Q_{CAH} (Table 4.15). According to the figure, for most stations Scenarios 1 and 2 do not meet the environmental flow requirements of the rivers, while Scenario 3 does. Because of the huge water consumption downstream of the dams it is then necessary to release 80% of the MAF to meet the EF at the last stations.

VI. Regulation rules of dams (Q_{RW})

By using Equation 3.13, the regulation rules of eleven major dams (Q_{RW}) under Scenario 3 have been calculated. According to Table 4.16, in some cases, due to the location of the dam and the area of the residual sub–catchment, for some months $Q_{Residual}$ can exceed Q_{CAH}. Thus it is recommended that the dam intra–annual regime is optimized based on the following condition:

$$\text{Minimise} \sum_{i=1}^{12}\left(Q_{CAH}i - \left(Q_{RW}i + Q_{Residual}i\right)\right) \text{ When } \left(Q_{CAH}i - \left(Q_{RW}i + Q_{Residual}i\right)\right) > 0 \qquad 4.1$$




Miandoab

Babaroud

Abajalou Sofla

Yalghouz Aghaj

Figure 4.6. Reference hydrograph

Table 4.10. The value of scaled natural annual hydrograph for the last hydrometric stations on the Urmia Lake tributaries.

River Name	Reference Station	Time Period	Shahrivar (Sep)	Mordad (Aug)	Tir (Jul)	Khordad (Jun)	Ordibehesht (May)	Farvardin (Apr)	Esfand (Mar)	Bahman (Feb)	Dey (Jan)	Azar (Dec)	Aban (Nov)	Mehr (Oct)
Zarrinehroud	Nezamabad	1964-1971	0.0067	0.0104	0.0110	0.0379	0.3506	0.3415	0.1215	0.0430	0.0287	0.0197	0.0187	0.0103
ShahrChai	Keshtiban	1964-1976	0.0132	0.0109	0.0623	0.2863	0.3607	0.1546	0.0404	0.0080	0.0080	0.0029	0.0196	0.0332
ZolaChai	Yalghouz Aghaj	1974-1996	0.0109	0.0128	0.0544	0.1423	0.2957	0.2122	0.0752	0.0518	0.0494	0.0454	0.0359	0.0140
NazlouChai	Abajalou Sofla	1964-1996	0.0130	0.0165	0.0561	0.2007	0.3295	0.1732	0.0518	0.0359	0.0333	0.0303	0.0379	0.0218
GhaleChai	shishvan	1983-1996	0.0017	0.0038	0.0297	0.1089	0.2871	0.3304	0.0714	0.0392	0.0389	0.0337	0.0425	0.0127
SoufiChai	Bonab	1965-1995	0.0459	0.0578	0.0473	0.1622	0.2795	0.1918	0.0506	0.0393	0.0358	0.0392	0.0316	0.0190
GadarChai	Pol-e Bahramlou	1957-1971	0.0039	0.0095	0.0493	0.1921	0.3036	0.1967	0.0894	0.0457	0.0425	0.0358	0.0266	0.0049
MardoughChai	Gheshlagh e Amir	1974-1996	0.0031	0.0024	0.0114	0.1079	0.2844	0.2431	0.0796	0.0597	0.0585	0.0621	0.0571	0.0307
AzarshahrChai	Azarshahr	1962-1993	0.0497	0.0261	0.0223	0.1104	0.2682	0.1795	0.0689	0.0376	0.0420	0.0448	0.0583	0.0921
Siminehroud	Miandoab	1966-1996	0.0097	0.0101	0.0124	0.0405	0.1894	0.3254	0.1803	0.0755	0.0616	0.0463	0.0364	0.0125
BarandouzChai	Babaroud	1949-1971	0.0149	0.0310	0.0841	0.1761	0.2546	0.1606	0.0774	0.0523	0.0488	0.0479	0.0382	0.0138
MahabadChai	PoleSorkh	1956-1969	0.0029	0.0049	0.0103	0.0474	0.2571	0.3286	0.2146	0.0515	0.0352	0.0309	0.0129	0.0038
SenikhChai	PoleSenikh	1965-1996	0.0249	0.0410	0.0232	0.0603	0.1675	0.1744	0.1066	0.1120	0.1150	0.0731	0.0683	0.0338
RozehChai	Goijali Aslan	1982-1996	0.0195	0.0257	0.0489	0.0978	0.1900	0.2071	0.1066	0.0681	0.0621	0.0663	0.0731	0.0347
ChwanChai	Khorrma Zard	1976-1993	0.0230	0.0276	0.0357	0.0442	0.2115	0.3378	0.1002	0.0763	0.0484	0.0389	0.0308	0.0256
AjiChai	Pole Davazdahdahane	1965-1975	0.0148	0.0021	0.0106	0.1076	0.3406	0.2405	0.1199	0.0406	0.0384	0.0363	0.0347	0.0139
LeilanChai	Shirin Kandi	1973-1996	0.0088	0.0061	0.0115	0.0431	0.1743	0.2829	0.1338	0.0930	0.0794	0.0709	0.0594	0.0368

Table 4.11. Values of MAF (Mm^3/month)

River Name	Reference Station	Location relative to the Dam	Time Period	MAF (Mm^3/month)												
				Mehr (Oct)	Aban (Nov)	Azar (Dec)	Dey (Jan)	Bahman (Feb)	Esfand (Mar)	Farvardin (Apr)	Ordibehesht (May)	Khordad (Jun)	Tir (Jul)	Mordad (Aug)	Shahrivar (Sep)	Total
Zarrinehroud	Sarigamish	Downstream of Dam	1382-1391 (2003-2012)	23.41	46.48	37.25	36.29	34.96	100.57	214.57	277.31	128.49	104.75	101.06	79.02	1184.16
ShahrChai	Band	Downstream of Dam	1376-1393 (1997-2014)	5.449	3.664	2.439	1.996	1.972	4.273	12.378	20.798	21.510	13.349	11.888	8.255	107.97
ZolaChai	Ajvaj	Downstream of Dam	1376-1387 (1997-2008)	4.21	5.01	4.17	3.53	3.52	5.57	10.43	14.08	9.26	6.27	5.93	4.12	76.09
DerikChai	Nazar Abad	Downstream of Dam	1376-1386 (1997-2007)	1.11	1.49	1.53	1.35	1.40	1.53	1.97	2.00	1.57	1.27	1.03	0.95	17.21
NazlouChai	Tapik	Upstream of Dam	1376-1394 (1997-2015)	3.33	7.74	8.12	8.87	9.68	20.02	50.68	83.20	38.94	12.11	4.69	3.17	250.55
GhaleChai	Yengije	Upstream of Dam	1376-1388 (1997-2009)	0.33	1.78	2.22	2.40	2.61	7.87	16.41	15.96	3.95	0.44	0.08	0.06	54.12
SoufiChai	Maragheh	Downstream of Dam	1344-1370 (1965-1991)	0.70	1.42	2.06	3.19	3.67	6.60	24.59	36.43	22.76	3.86	1.03	0.69	107.01
MardoughChai	Gheshlagh e Amir	Upstream of Dam	1376-1391 (1997-2012)	0.91	3.58	3.53	3.00	3.36	5.96	13.97	15.85	2.81	0.36	0.10	0.19	53.61
Siminehroud	+ Kavlan Gizilgonbad	Upstream of Dam	1376-1391 (1997-2012)	0.45	8.31	8.94	15.60	24.76	61.23	61.61	36.65	5.13	1.33	0.14	1.40	225.55
BarandouzChai	Dizaj	Downstream of Dam	1376-1391 (1997-2012)	2.94	9.94	8.39	8.81	9.22	15.26	33.21	55.85	26.82	7.67	1.34	2.36	181.82
RozeChai	Kalhour	Upstream of Dam	1376-1391 (1997-2012)	0.76	1.68	1.59	1.65	2.01	2.92	4.55	6.07	4.17	0.76	0.07	0.09	26.33
ChowanChai	Korrmazard	Upstream of Dam	1376-1391 (1997-2012)	0.13	0.19	0.19	0.23	0.34	0.79	1.87	1.58	1.95	0.16	0.13	0.09	7.64
AjiChai	Venyar	Upstream of Dam	1376-1390 (2001-2011)	1.4682	3.2584	4.1527	5.6798	7.466933	12.3401	28.4496	38.2649	13.36409	2.5316	1.08529	1.241415	119.3032

Table 4.12. Values of Q_{Residual} (Mm^3/month)

River Name	Release Point	Reference Station	Time Period	Q_{Residual} (Mm^3/month)												
				Mehr (Oct)	Aban (Nov)	Azar (Dec)	Dey (Jan)	Bahman (Feb)	Esfand (Mar)	Farvardin (Apr)	Ordibehesht (May)	Khordad (Jun)	Tir (Jul)	Mordad (Aug)	Shahrivar (Sep)	Total
Zarrinehroud	Shahidkazemi Dam (Sarigamish)	Nezamabad	1382-1391 (2003-2012)	-16.18	-34.75	-21.35	-15.88	-13.74	-0.46	-8.52	47.80	-101.48	-96.42	-90.33	-79.62	-430.93
ShahrChai	Shahr Chai Dam (Band)	Keshtiban	1376-1394 (1997-2015)	-4.10	-0.31	-1.15	-1.13	-0.53	-1.39	-6.45	-11.12	-14.80	-11.71	-11.16	-7.64	-71.49
ZolaChai	Zola Dam and Derik Dam	Yalghouz Aghaj	1376-1387 (1997-2008)	-5.46	-5.97	-5.01	-3.12	-2.80	-3.97	-5.69	-11.74	-9.55	-5.70	-2.92	-3.44	-65.37
NazlouChai	Nazlou Dam (Tapik)	Abajalou Sofla	1376-1388 (1997-2009)	-3.68	-5.19	-6.15	-6.85	-5.12	-3.08	-14.10	-16.05	-17.77	-11.62	-4.76	-3.34	-97.71
GhaleChai	Ajabshir Dam (Yengije)	shishvan	1376-1385 (1997-2006)	-0.31	-0.31	-2.29	-2.40	-2.13	-3.28	-7.30	-2.14	-3.17	-0.42	-0.10	-0.07	-23.92
SoufiChai	Alavian Dam (Maragheh)	Bonab	1344-1370 (1965-1991)	0.94	0.83	0.47	-1.26	-0.33	-2.28	-10.48	-17.50	-10.47	1.58	4.15	3.33	-31.02
GadarChai	Hassanlou Dam (Naghadeh)	PoleBahramlou	1360-1376 (1981-1997)	0.10	1.62	3.71	5.16	5.77	13.23	26.19	10.51	-2.83	1.81	1.73	1.02	68.02
GadarChai	Hassanlou Dam (Naghadeh)	PoleBahramlou	1376-1379 (1997-2000)	-1.15	-0.03	-1.45	0.26	-1.65	1.12	-16.35	-19.84	4.93	-2.12	-1.36	-0.78	-38.42
Siminehroud	Siminehroud Dam (Gizil Gonbad	Miandoab	1377-1391 (1998-2012)	2.52	5.40	-0.08	5.64	13.70	37.43	37.58	12.40	4.22	4.80	5.26	3.03	131.90
Siminehroud	Siminehroud Dam (Dashband	Miandoab	1376-1391 (1997-2012)	2.50	4.00	-1.60	-2.38	-1.80	7.54	1.94	4.03	1.89	4.94	5.24	3.60	29.90
BarandouzChai	Barandouz (Dizaj) Dam	Babaroud	1376-1391 (1997-2012)	-2.18	-1.73	-0.86	-2.09	-2.07	0.52	0.76	-0.07	-4.28	-5.13	-1.34	-2.28	-20.75
RozehChai	Kalhor Dam (Kalhor)	Goijali Aslan	1376-1394 (1997-2015)	-0.52	-0.75	-0.75	-0.57	-0.70	-0.04	-0.09	-1.31	-1.15	0.03	0.04	-0.06	-5.87
AjiChai	Venyar Dam (Venyar)	Akhoula	1376-1390 (1997-2011)	1.34	2.89	0.88	-1.00	-2.67	-0.20	-4.47	-4.90	-2.26	4.51	1.33	2.29	-2.26
AjiChai	Venyar Dam (Venyar)	Sarin Dizaj	1380-1390 (2001-2011)	0.982	0.247	-1.958	1	-1.106	5.648	-9.793	10.448	-9.286	-0.015	-0.390	-0.310	-4.532

Table 4.13. Available annual discharges at reference points, Q_{AAD} (Mm^3/year)

River Name	Release Point	Reference Station	Time Period	Q_{AAD} (Mm^3/year)		
				Scenario 1	Scenario 2	Scenario 3
Zarrinehroud	Shahidkazemi Dam	Nezamabad	1382-1391	-60.916	185.76	555.774
ShahrChai	ShahrChai Dam (Band)	Keshtiban	1376-1394	-39.342	-17.91	14.238
ZolaChai	Zola Dam and Derik Dam	Yalghouz Aghaj	1376-1387 (1997-2008)	-37.38	103.415	126.242
NazlouChai	Nazlou Dam (Tapik Station)	Abajalou Sofla	1376-1388	-22.545	27.565	102.73
GhaleChai	Ajabshir Dam (Yengije Station)	shishvan	1376-1385	-7.684	3.14	19.376
SoufiChai	Alavian Dam (Maragheh Station)	Bonab	1344-1370	1.083	22.485	54.588
Siminehroud	Siminehroud Dam (Dashband Station)	Miandoab	1376-1391	97.565	142.675	210.34
BarandouzChai	Barandouz Dam (Dizaj Station)	Babaroud	1376-1391	33.796	70.16	124.706
RozehChai	Kalhor Dam (Kalhor Station)	Goijali Aslan	1376-1394	2.029	7.295	15.194
AjiChai	Venyar Dam (Venyar Station)	Akhoula	1376-1390	47.654	80.93	130.844
AjiChai	Venyar Dam (Venyar Station)	Sarin Dizaj	1380-1390	31.259	55.1196	90.912

Table 4.14. Evaluation of environmental flows in the major rivers, the Urmia Lake basin (% MAR)

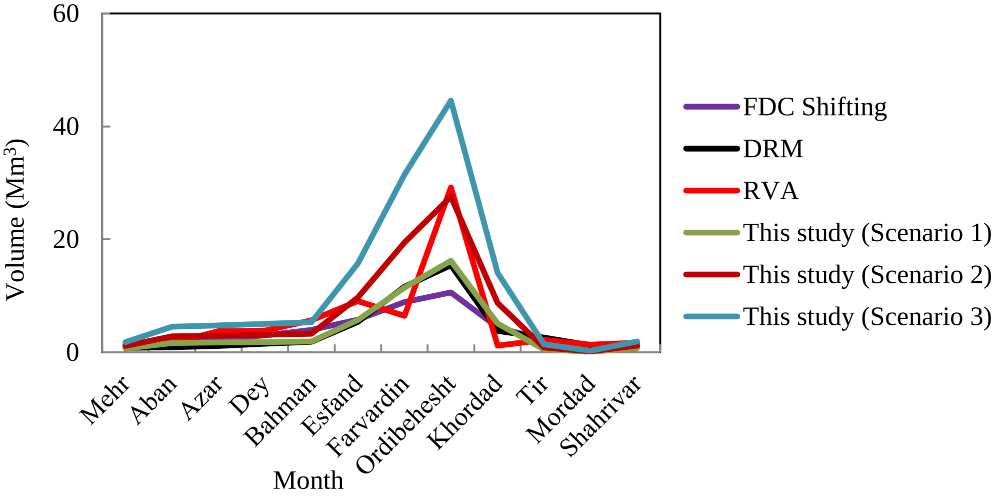
River Name	Reference Station	Smakhtin	FDC Shifting	Tenant		DRM (Class C)	RVA	Tessman	Low Flows Indices		Water Quality	Proposed EF	Dam Report	Reference
				Wet Monthes	Dry Monthes				$7Q_{10}$	$7Q_2$	Q Equation			
Zarrinehroud	Nezamabad	26	17	30	10	21	-	47	3	4	7	23	-	Ashouri (2015)
Zarrinehroud	Sarigamish	24	35	30	10	24	56	46	4	5	5	19	7-16	
ShahrChai	Keshtiban	31	28	30	10	24	51	50	7	1	-	24	-	Shaeri (2010)
ZolaChai	Yalghouz Aghaj	20	45	30	10	-	31	48	-	-	-	45	19	Ajh (2015)
DerikChai	Nazar Abad	36	-	30	10	35	-	45	74	38	-	35	-	Ajh (2015)
NazlouChai	Abajalou Sofla	29	29	30	10	23	-	53	5	1	-	23	-	Shaeri (2010)
NazlouChai	Abajalou Sofla		28.2	-	-	22.7	-	-	-	-	-	-	-	Ahmadpour (2014)
GadarChai	PoleBahramlou	19.98	32.2	30	10	21.7	72	41.42	-	-	29.8	32.2	-	Habibi (2015)
Siminehroud	Miandoab	22	23	30	10	23	50	48	2	9	7	23	5.5-11	Rezaie (2015)
BarandouzChai	Babaroud	30	37	30	10	26	66	52	3	0.68	58	26	4	Mostafavi (2013)
BarandouzChai	Babaroud	31	39	30	10	24	-	49	9	1	-	24	-	Shaeri (2010)
MahabadChai	Gord e Yaghoub	20	26	30	10	22	71	52	39	13	9	26	-	Razzaghi (2017)
RozehChai	Goijali Aslan (PoleOzbak)	20	41	30	10	10	65.13	49	-	-	73.39	10	-	Gholamzadeh (2014)
AjiChai	Akhoula	26	22	30	10	22	32	57	14	4	9	22	-	Alizadeh (2017)

Table 4.15. Calculated valuesof Q_{CAH} (Mm^3/month) for reference stations in Scenario 3.

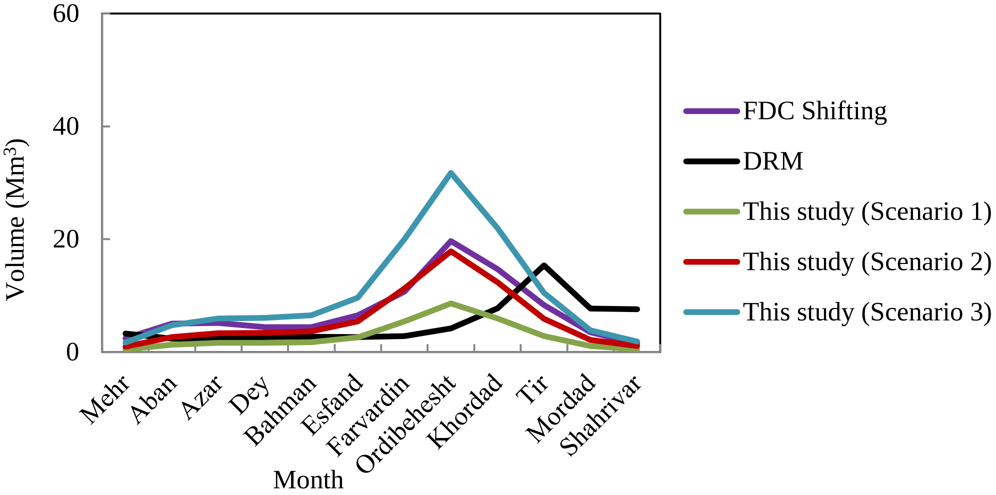
Month	Station Name									
	Zarrinehroud	ShahrChai	ZolaChai	NazlouChai	GhaleChai	SoufiChai	Siminehroud	Barandouz-Chai	RozehChai	AjiChai
	Nezamabad	Keshtiban	Yalghouz Aghaj	Abajalou Sofla	Shishvan	Bonab	Miandoab	Babaroud	Goijali Aslan	Sarin Dizaj
Mehr (Oct)	5.724472	0.4727	2.5504	2.2395	0.2461	1.0372	2.6293	1.7209	0.5272	1.2637
Aban (Nov)	10.39297	0.2791	4.7329	3.8935	0.8235	1.7250	7.6564	4.7638	1.1107	3.1546
Azar (Dec)	10.94875	0.0413	4.2156	3.1127	0.6530	2.1398	9.7387	5.9734	1.0074	3.3001
Dey (Jan)	15.95071	0.1139	4.6202	3.4209	0.7537	1.9543	12.9569	6.0857	0.9435	3.4910
Bahman (Feb)	23.89828	0.1139	4.9432	3.6880	0.7595	2.1453	15.8807	6.5221	1.0347	3.6910
Esfand (Mar)	67.52654	0.5752	7.1444	5.3214	1.3834	2.7622	37.9243	9.6522	1.6197	10.9003
Farvardin (Apr)	189.7968	2.2012	22.8735	17.7928	6.4018	10.4700	68.4446	20.0278	3.1467	21.8643
Ordibehesht (May)	194.8544	5.1356	40.7228	33.8495	5.5628	15.2573	39.8384	31.7501	2.8869	30.9646
Khordad (Jun)	21.06383	4.0763	23.8267	20.6179	2.1100	8.8542	8.5188	21.9607	1.4860	9.7821
Tir (Jul)	6.113514	0.8870	7.0382	5.7632	0.5755	2.5820	2.6082	10.4878	0.7430	0.9637
Mordad (Aug)	5.78005	0.1552	1.9873	1.6950	0.0736	3.1552	2.1244	3.8659	0.3905	0.19092
Shahrivar (Sep)	3.723686	0.1879	1.5868	1.3355	0.0329	2.5056	2.0403	1.8581	0.2963	1.3455

Table 4.16. Calculated values of Q_{RW} (Mm^3/month) for dams in Scenario 3.

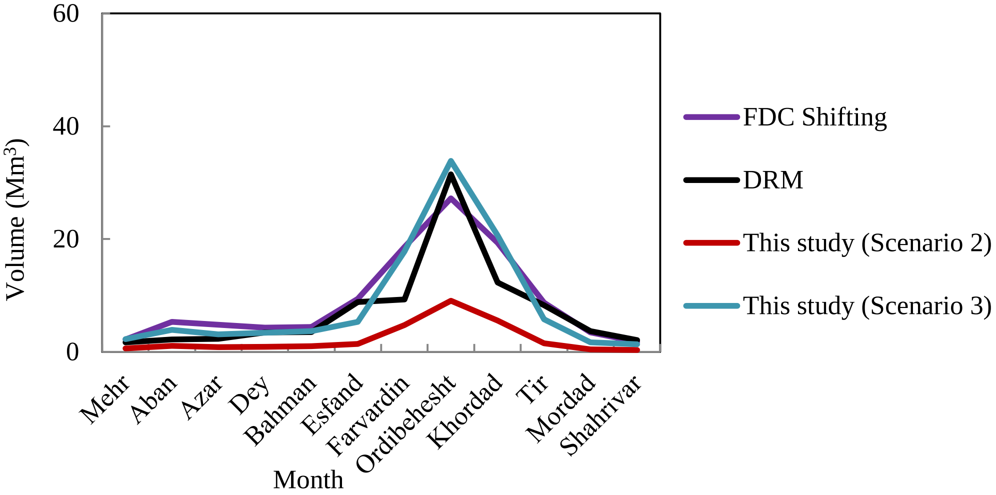
Month	Dam Name										
	ShahidKazemi	ShahrChai	Zola	Derik	Nazlou	Ajabshir	Alavian	Siminehroud	Barandouz	Kalhour	Venyar
Mehr (Oct)	21.9045	4.5727	6.3697	1.6407	2.5495	-0.6939	-1.4628	4.8093	2.2409	0.0072	0.2817
Aban (Nov)	45.143	0.5891	8.5107	2.1922	4.2035	-0.0065	-2.2750	9.3864	5.5138	-0.5293	2.9076
Azar (Dec)	32.2987	1.1913	7.3360	1.8896	5.4027	0.1830	3.7398	10.5987	6.7234	1.8974	5.2581
Dey (Jan)	31.8307	1.2439	6.1548	1.5853	5.8209	2.0137	4.3343	15.0469	6.6557	0.9135	2.4910
Bahman (Feb)	37.6383	0.6439	6.1573	1.5860	5.8180	1.0895	3.9453	17.9507	7.2221	5.7347	4.7970
Esfand (Mar)	67.9865	1.9652	8.8379	2.2764	8.6014	3.6634	-4.7778	37.4043	9.6922	1.9397	5.2523
Farvardin (Apr)	198.3168	8.6512	22.7132	5.8504	25.0928	16.8818	8.5300	67.6846	20.1178	22.5367	31.6573
Ordibehesht (May)	147.0544	16.2557	41.7174	10.7454	35.9895	23.0628	11.2273	39.9084	33.0601	37.3169	20.5166
Khordad (Jun)	122.5438	18.8763	26.5405	6.8362	23.7879	12.5800	6.9642	12.7988	23.1107	19.1160	19.0681
Tir (Jul)	102.5335	12.5970	10.1292	2.6090	6.1832	-1.0045	-2.3580	7.7382	10.4578	2.1630	0.9787
Mordad (Aug)	96.11	11.3152	3.9022	1.0051	1.7950	-4.0764	-2.0848	3.4644	3.8259	2.2205	0.5809
Shahrivar (Sep)	83.3437	7.8279	3.9973	1.0296	1.4055	-3.2971	-1.0944	4.3203	1.9181	0.8863	1.6555



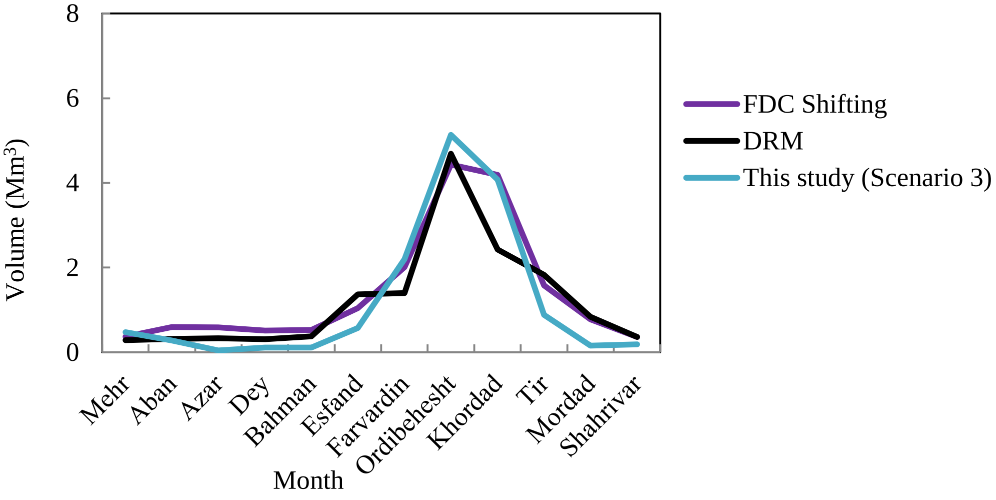
(a) The Akhoula Station on the AjiChai River



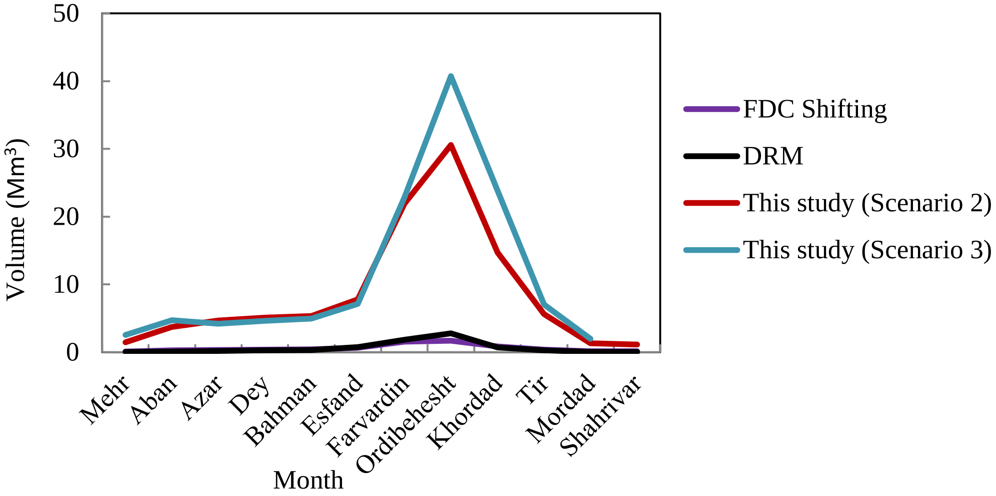
(b) The Babaroud Station on the BarandouzChai River



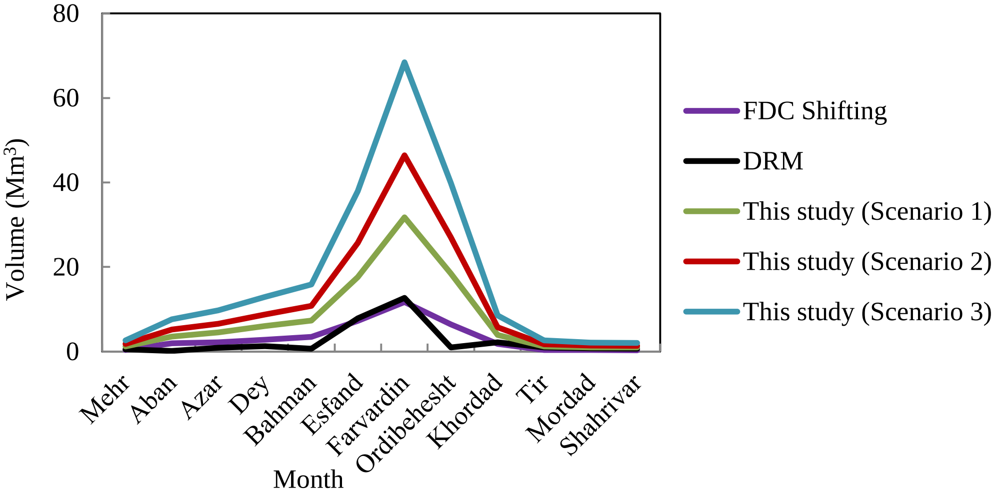
(c) The Abajalou Sofla Station on the NazlouChai River



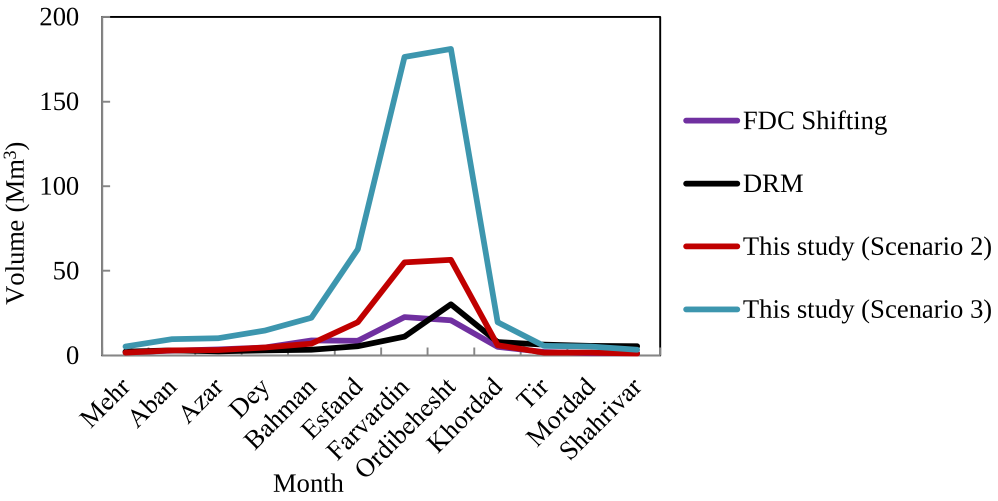
(d) The Keshtiban Station on the ShahrChai River



(e) The YalghouzAghaj Station on the ZolaChai River



(f) The Miandoab Station on the Siminehroud River



(i) The Nezamabad Station on the Zarrinehroud River

Figure 4.7 Comparison between Q_{CAH} with calculated EF of last stations by researchers

4.5. Calibration of MIKE 3 Flow Model FM

The MIKE 3 Flow model FM solver was calibrated according to some relevant physical parameters, namely bed roughness height, wind friction coefficient, vertical eddy viscosity and initial salinity of the lake. Flow velocity and salinity distribution were adopted as target variables through comparison with available field measurements. The mentioned parameters were object of a sensitivity analysis, where ME, MAE, RMSE, STD, R^2 and d (according to Table 3.13) goodness-of-fit metrics were employed to estimate the model accuracy.

Eleven model runs (Table 4.17) were performed for the sensitivity analysis of the hydraulic solution to the physical parameters listed above, as well as to the order-of-accuracy of the adopted solver. All simulations are compared with a Reference Run, as defined in Table 4.17. Results at the Reference Point in the North basin identified in Figure 3 were considered for comparisons among simulations.

Table 4.17. Parameters of the model run in the sensitivity analysis

Model Runs	Order of accuracy of the solver	Roughness height (m)	Wind Friction Coefficient calculation method	Vertical eddy viscosity calculation method	Initial Salinity (PSU)	Simulation period
Reference Run	First order	0.07	Equation 3.22	0.001 (m^2/s)	220	Sep1991 to Dec 1991
SIM 1	Second order	0.07	Equation 3.22	0.001 (m^2/s)	220	Sep1991 to Dec 1991
SIM 2	First order	0.07	0.00283	0.001 (m^2/s)	220	Sep1991 to Dec 1991
SIM 3	First order	0.12	Equation 3.22	0.001 (m^2/s)	220	Sep1991 to Dec 1991
SIM 4	First order	0.25	Equation 3.22	0.001 (m^2/s)	220	Sep1991 to Dec 1991
SIM 5	First order	0.07	Equation 3.22	0.01 (m^2/s)	220	Sep1991 to Dec 1991
SIM 6	First order	0.07	Equation 3.22	Log Law	220	Sep1991 to Dec 1991
SIM 7	First order	0.07	Equation 3.22	k-ε turbulence model	220	Sep1991 to Dec 1991
SIM 8	First order	0.07	Equation 3.22	0.001 (m^2/s)	220	May200 to-Oct 2004
SIM 9	First order	0.07	Equation 3.22	0.00001 (m^2/s)	220	May2004 to Oct 2004
SIM 10	First order	0.07	Equation 3.22	0.001 (m^2/s)	230	Sep1986 to Sep1987
SIM 11	First order	0.07	Equation 3.22	0.001 (m^2/s)	250	Sep1986 to Sep1987

Comparison of the results of SIM1 with the Reference Run (Table 4.18) shows that the RMSE index for current velocities is even marginally larger for the 2nd order solution technique than for the 1st order one. The lower-order solver was therefore selected; the influence of the solution technique appears to be negligible, while reducing the computational time is considerably reduced.

According to the Figure 4.8, the streamlines produced by SIM 2 are different from those in the Reference Run, resulting in different flow pattern. In SIM 2, the velocity values are significantly less than those in the Reference Run

The simulated current velocities at the reference point for SIM 2 compared to those of the Reference Run (Figure 4.8) show that the wind friction coefficient is highly relevant, actually being the most effective input variable in the model, as also inferred from Table 4.18, in which a higher RMSE than that of the Reference Run is obtained for SIM 2. According to Figure 4.8, the streamlines produced by SIM 2 are different from those in the Reference Run, resulting in different flow pattern. In SIM 2, the velocity values are significantly smaller than those in the Reference Run.

Figure 4.9 shows the time series of the flow velocities for two different values of the bottom roughness height at the surface and bottom layers, i.e. for SIM 3 and SIM 4. As can be deduced from Figure 4.9 and the results in Table 4.18 for SIM 3 and SIM 4, bed roughness has a slight effect on flow velocity in the deep layer (the higher the bottom roughness, the lower the flow velocity), while it has a negligible effect on the velocities in the surface layer. . However, as evident from Figure 4.8, bottom roughness is less influential than the wind friction coefficient.

Table 4.18. Goodness-of-fit metrics for flow velocity at the Reference Point for different model runs

Model run	ME (m/s)	MAE (m/s)	RMSE (m/s)	STD (m/s)	R^2	d
SIM 1	-0.0007	0.0023	0.0031	0.0031	0.9758	0.9744
SIM 2	-0.0023	0.0097	0.0159	0.0157	0.5110	0.4937
SIM 3 (surface layer)	0.0004	0.0022	0.0037	0.0037	0.9941	0.9939
SIM 3 (bottom layer)	0.0012	0.0020	0.0026	0.0023	0.9806	0.9650
SIM 4 (surface layer)	0.0012	0.0029	0.0046	0.0044	0.9915	0.9904
SIM 4 (bottom layer)	0.0024	0.0035	0.0048	0.0041	0.9495	0.8465

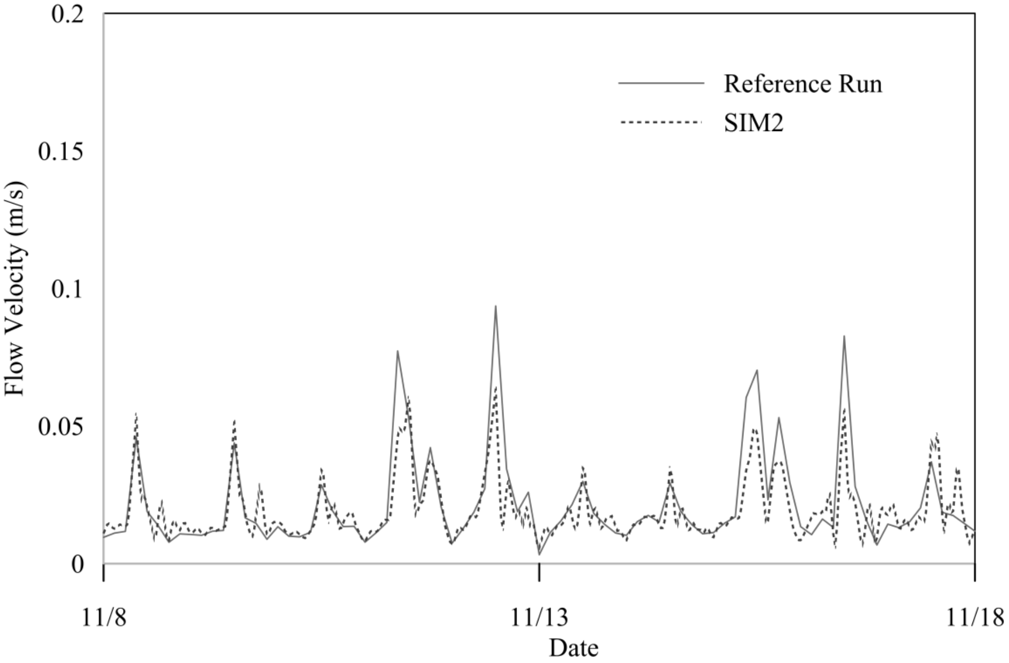
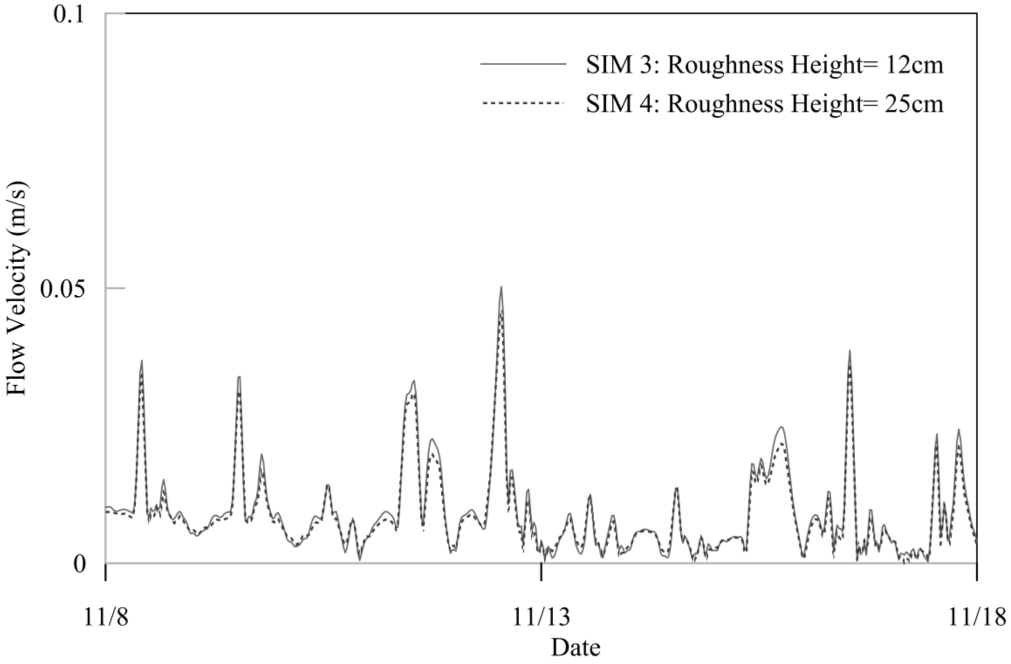
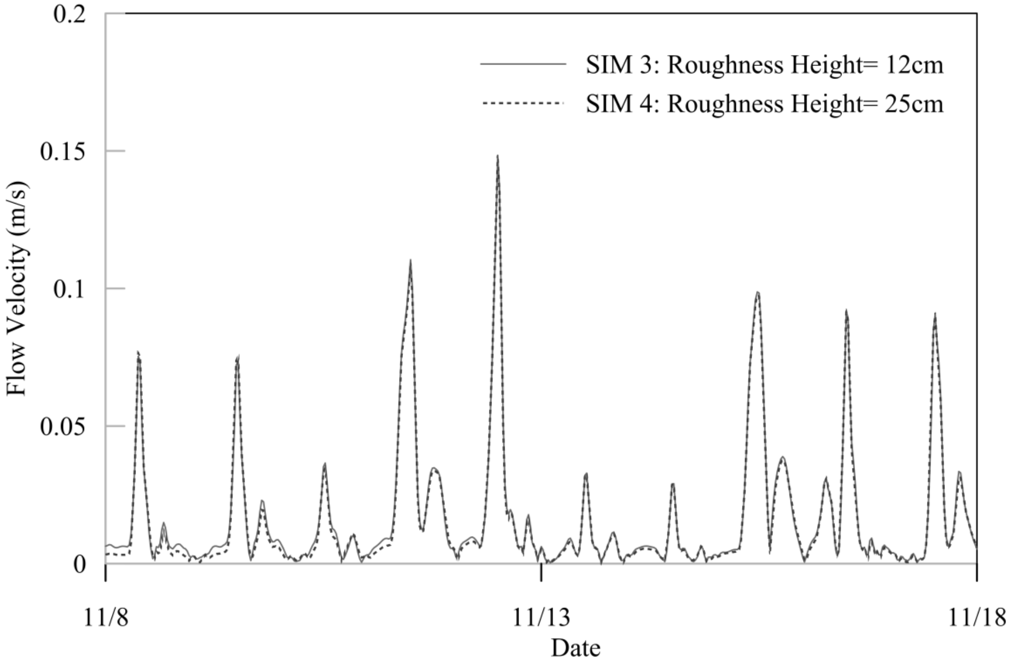


Figure 4.8. Comparison of flow velocity time series for Reference Run and SIM 2 at the Reference Point in Figure 3.39.



(a)



(b)

Figure 4.9. Comparison of flow velocity time series for SIM 3 and SIM 4 at bottom (a) and surface (b) layers at the Reference Point in Figure 3.39.

Figure 4.10 displays the velocity profiles along the vertical at points A_3 and C_3 in Figure 3.38 for different calculation methods of the vertical eddy viscosity, i.e. for SIM 5, SIM 6 and SIM 7 in Table 4.14. Results show that, in general, adopting a logarithmic wall-law to evaluate the vertical eddy viscosity leads to results closer to the measured values. Figure 4.11 shows the horizontal salinity distribution at a central layer of the computational mesh for different fixed values of the vertical eddy viscosity, i.e. for SIM 8 and SIM 9 in Table 4.14. The results show that low value of the vertical eddy viscosity lead to an average increase of flow velocity. This causes also the salinity distribution to become more homogeneous, So vertical eddy viscosity is then a key parameter for the correct simulation of flow velocity and on salinity distribution.

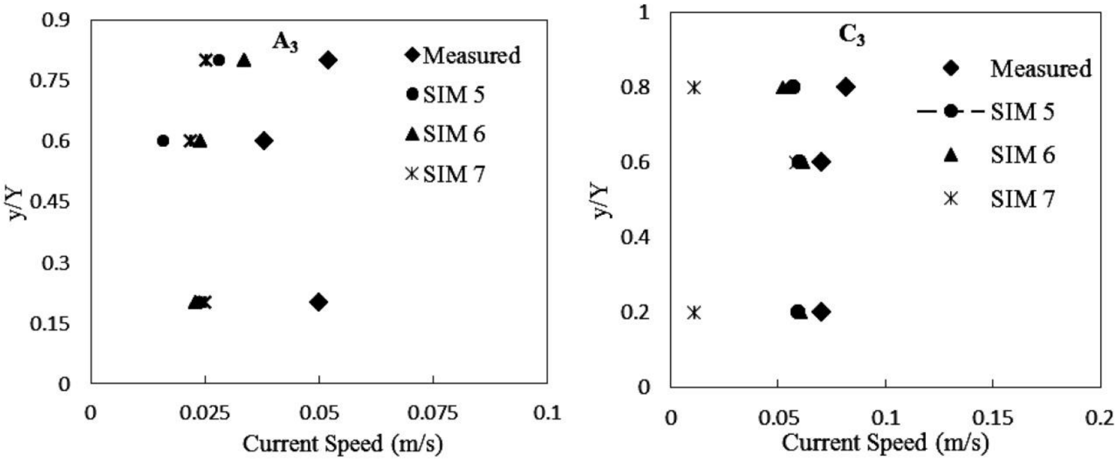
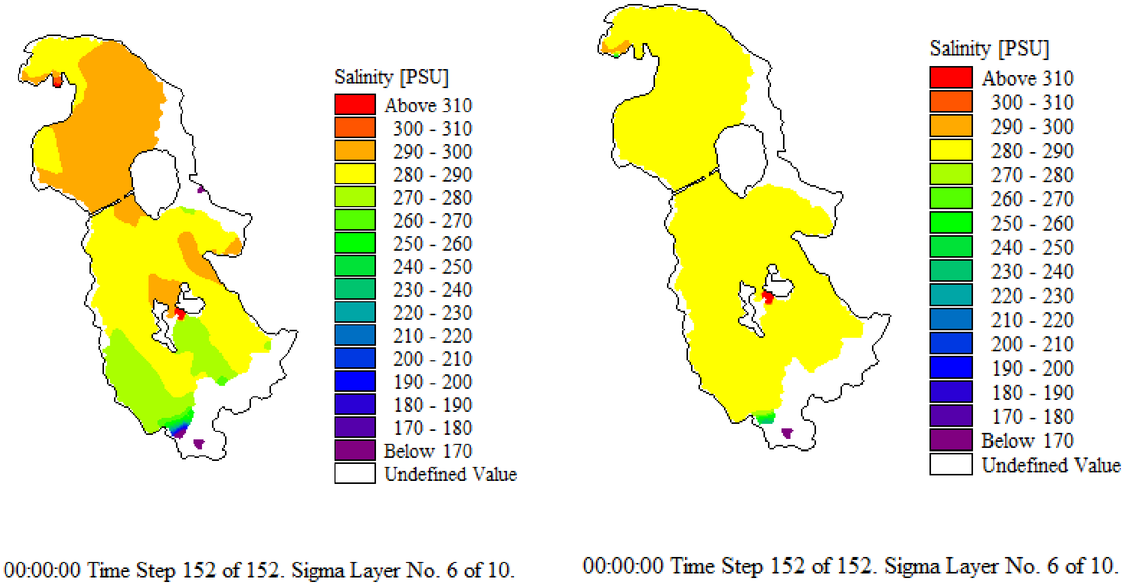


Figure 4.10. Velocity profiles along the vertical at points A_3 and C_3 in Figure 3.38 for SIM 5, SIM 6 and SIM 7 for November 1991



(a) (b)

Figure 4.11. Horizontal salinity distributions at layer 6 out of 10 from the bottom for SIM 8 (a) and SIM 9 (b) on 2th September 2004

Different constant initial salinity values were tested to determine the influence of the initial condition on density and subsequently on flow velocity, i.e. SIM 10 and SIM 11 in Table 4.17. Figure 4.12 shows the time series of salinity at the reference point for the two runs. It can be seen that the initial salinity difference between the simulations remains more or less constant during the rest simulation, showing that the simulation results are largely dependent on the initial salinity, which must be carefully assigned.

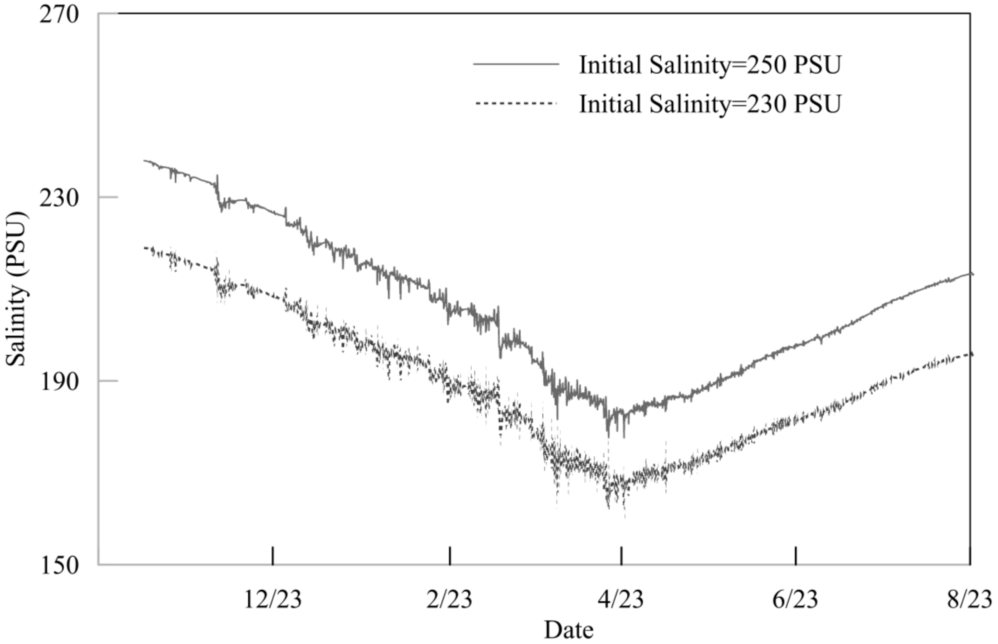


Figure 4.12. Time series of salinity at reference point in Figure 4.19 (a) for SIM 10 and SIM 11 from September 1986 till September 1987

Summarizing, the performed sensitivity analyses revealed that in MIKE 3 Flow Model FM the most important parameters to be calibrated to obtain realistic flow velocities and salinities for the Urmia Lake are the vertical eddy viscosity and the wind friction coefficient. A correct initial condition for salinity is also fundamental.

4.6. Calibration and validation

4.6.1. Calibration of flow velocity

Calibration of flow velocity was performed by comparison with the measurements taken by Ab Nirou (1995) in three different relative depths for each station (h/H= 0.2, 0.6 and 0.8) in November 1991 at the points shown in Figure 3.38. Based on the scatter plots in Figure 4.13 the model performed reasonably well in simulating flow velocities, with an overall ME = 0.04 m/s. Occasional large errors should also be attributed to improper wind modelling, both as regards the low time resolution of measurements and the missing modelling of wind speed distribution along the water surface (Fenocchi and Sibilla, 2016; Nekouee et al., 2016). Interpolation of wind data among multiple stations near the lake could improve the results. Unfortunately, such data are not available for 1991, the year in which flow velocity calibration is performed. Simulations revealed very low values of the vertical eddy viscosity improved slightly the flow velocity estimates, but significantly worsened predictions of salinity distribution.

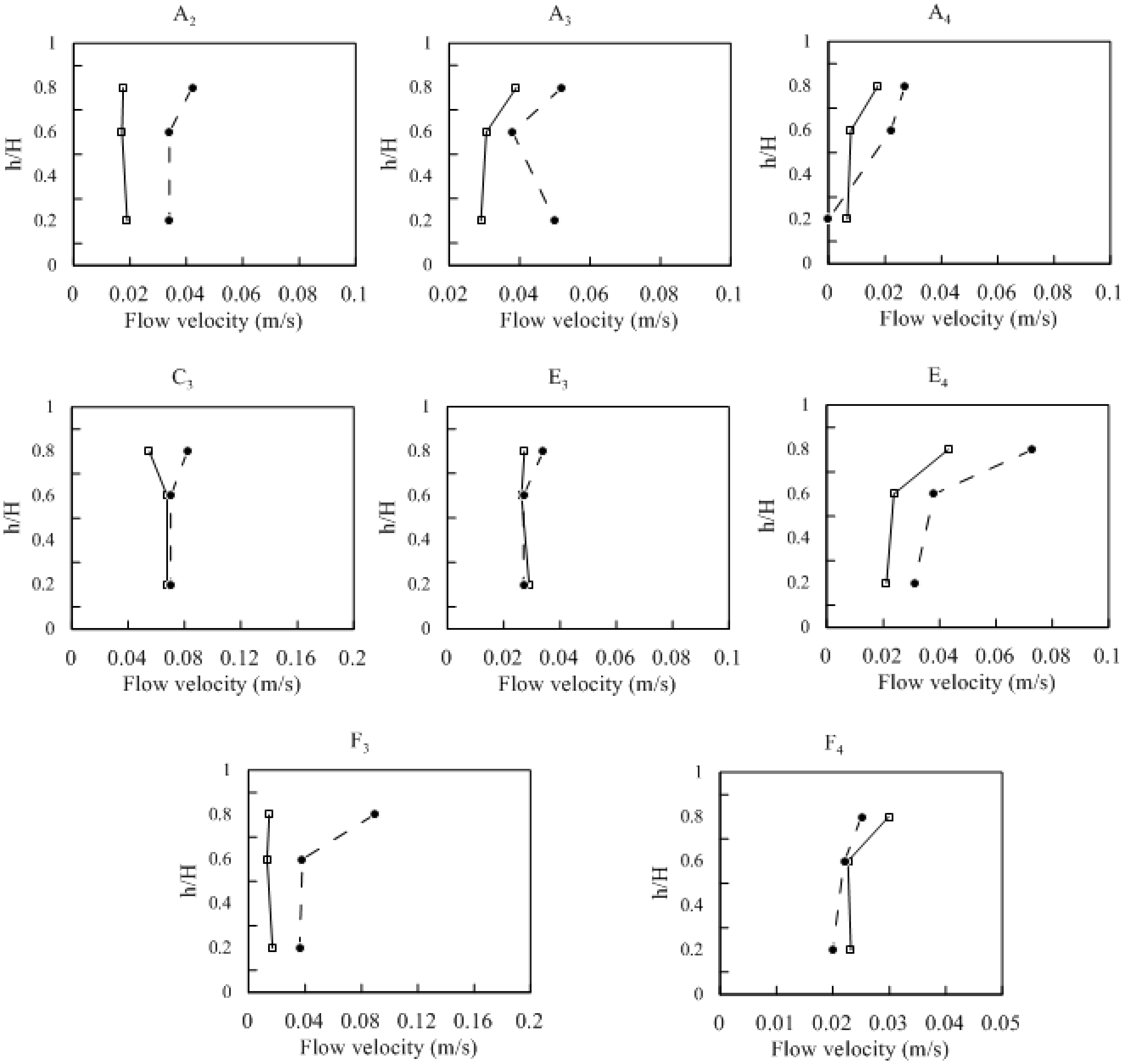
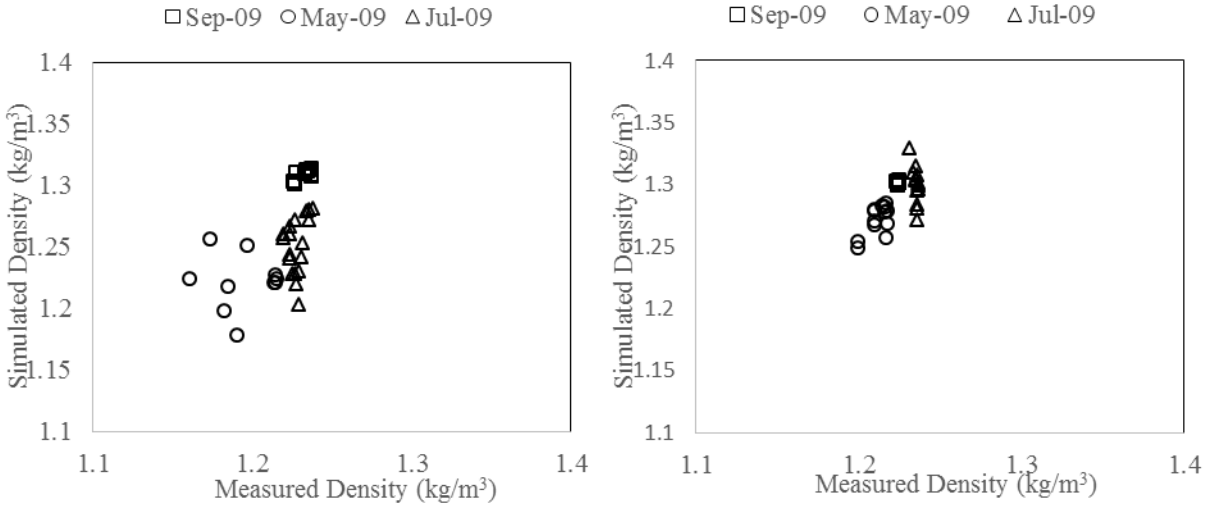


Figure 4.13. Modeled calibrated (solid line) and measured by Ab Nirou (1995) (dashed line) flow velocities at selected points in Figure 3.38 in November 1991

4.6.2. Calibration of density

Salinity mismatch between simulated and measured values occurs in the northern part of the lake. In particular, use of the UNESCO equation for the Urmia Lake leads to density overestimation for the salinity values typical of the studied basin. The suggested maximum salinity for its application is 45 PSU, so that its application to the density estimate in hypersaline lakes such as the Urmia Lake leads unavoidably to errors.

Simulated density in the Urmia Lake for 2009-2010 was compared with the measurements of Sima and Tajrishi (2014). The results of the comparison are displayed in Figure 4.14.

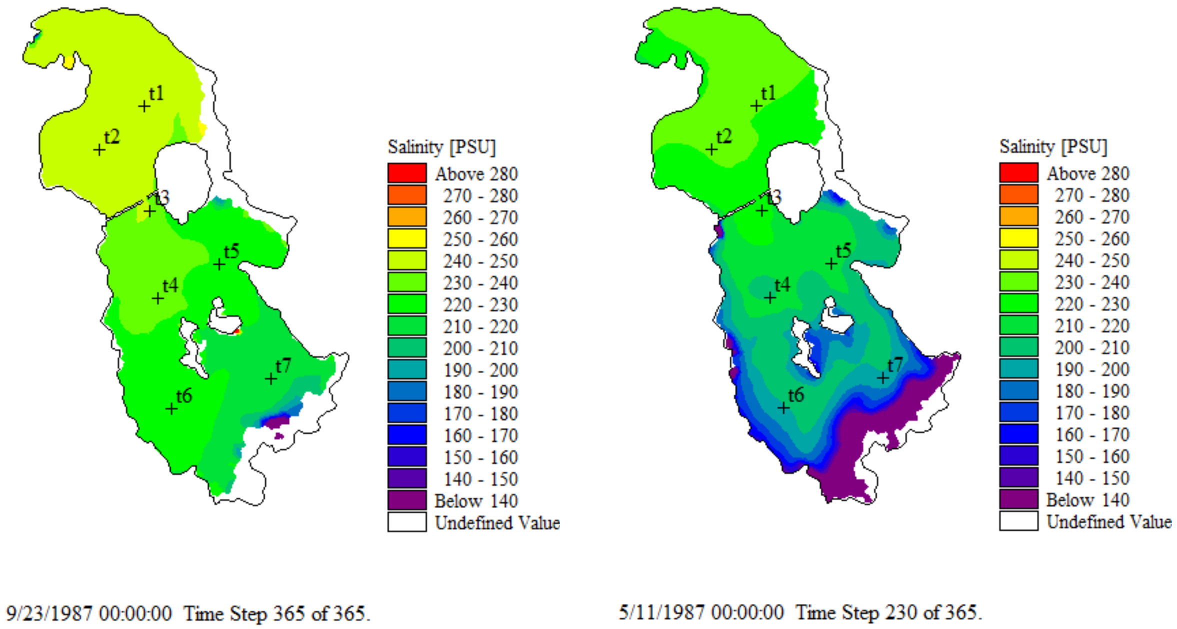


(a) (b)

Figure 4.14. Comparison between measured (Sima and Tajrishi, 2014) and simulated water densities for points in Figure 3.38 in the South (a) and in the North (b) basins.

4.6.3. Validation of density and salinity

Salinity and water density data for the Urmia Lake are available for April and September 1987, making validation possible. Modelled horizontal salinity distributions on 5th April and on 23rd September are shown in Figure 4.15. According to the model results, salinity is nearly uniform over the lake in September, whereas in April a significant difference arises between the southern and northern basins of the lake, due to the entrance of freshwater from southern tributaries. As presented in Table 4.19, these results are in good agreement with those of Daneshvar and Ashassi (1994).



(a) (b)

Figure 4.15. Simulated horizontal salinity distributions on 5th April 1987 and on 23rd September 1987 and salinity sampling points of Daneshvar and Ashassi (1994) at the surface layer

Table 4.19. Comparison between the averages measured (Table 3.11) and simulated salinity and density on 5th April and 23rd September 1987

	Salinity on 5th April (PSU)	Salinity on 23rd September (PSU)	Density on 5th April (Kg/m^3)	Density on 23rd September (Kg/m^3)
Calculated	244.016	231.034	1.2	1.186
Measured	251±2.5	235±3	1.159	1.146

4.7. Hydrodynamic behavior of the Urmia Lake

The results of the model for 1986-1987 and 2004-2005 reveal that exchanging flow between basins occurred due to water level differences between the basins. Water level differences are created by both wind setup and river discharges. Simulated net daily and monthly discharges exchanged between North and South basins across the causeway in 1986-1987 and 2004-2005 are shown in Figure 4.16 and 4.17, respectively. According to Figure 4.16, the exchanged discharge isn't constant and changes direction frequently.

Time integration of the computed discharges yields the amount of the water volumes exchanged monthly between the two parts of the lake. According to Figure 4.17, where these volumes are shown for the period September 2004 August 2005, the exchanged volumes peak in March, owing to inflows from the southern rivers and to the subsequent difference in the water level. Furthermore, the difference in exchanged flow volume from south to north and north to south is in this month more relevant.

The simulated overall net exchanged water volumes from 23th September 1986 to 28th August 1987 and from 23th September 2004 to 28th August 2005 are 1.05 and 0.676 km^3 respectively, the direction of both of them being from South to North due to the contributions of the main tributaries located in the southern basin. In recent years, the water volume flowing from the South to North basin considerably reduced with lake draining, due to the drop of inflowing discharges from the main southern tributaries.

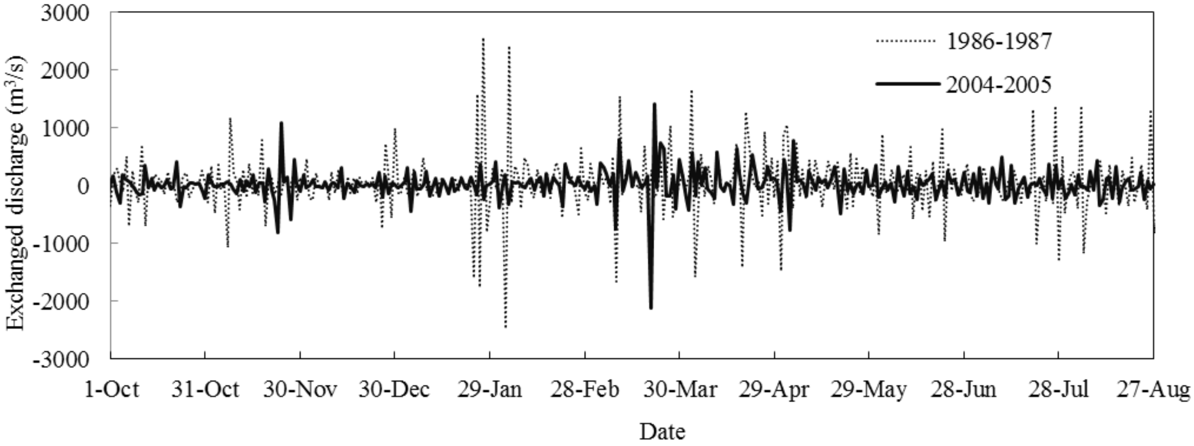


Figure 4.16. Comparison of the exchanged daily discharge between the North and South basins across the causeway between 1986-1987 and 2004-2005 (northbound discharges are positive).

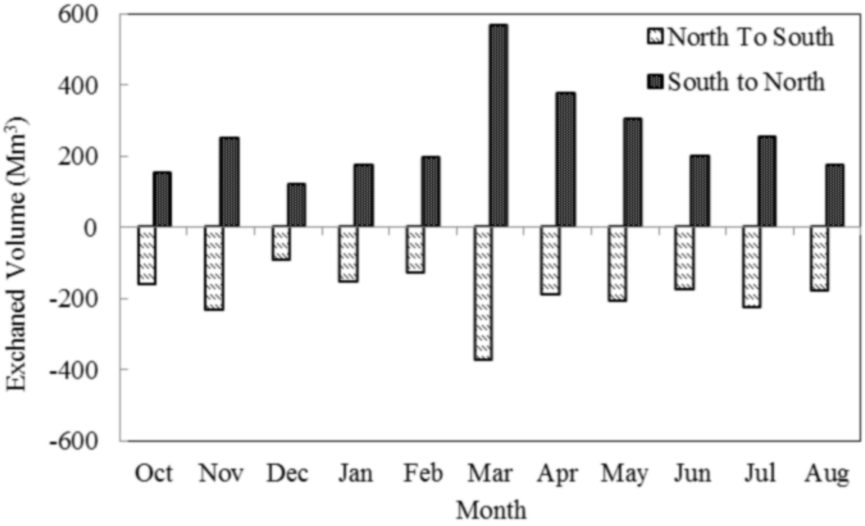


Figure 4.17. Exchanged monthly volumes between the North and South basins across the causeway from October 2004 to August 2005 (northbound volumes are positive).

As shown in Figure 4.18, the difference in daily and monthly water level between the northern and southern of the lake reaches its maximum due to wind force and inflows from the southern rivers during spring.

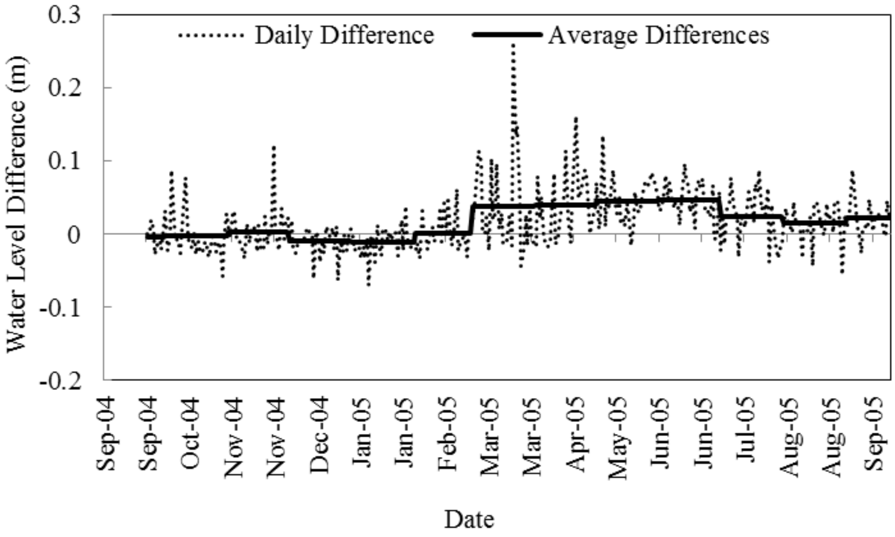


Figure 4.18. Difference in daily and monthly water level between the northern and southern basins

According to the simulation results for 1991-1992, 1986-1987, 2004-2005 and 2009-2010 (Figure 4.19) the northern basin has an almost homogeneous salinity, whereas a strongly heterogeneous distribution occurs in the southern basin due to the flow of freshwater from tributaries. Salinity differences between North and South basins increased with the lake draining. The reduced exchanged discharge between North and South basins due to the decrease of inflowing discharges from the main southern tributaries contributes to this.

Figure 4.20 shows that the difference in salinity reaches in the highest level in May because of rivers freshwater inflows following the snow melting season, and then declining till September.

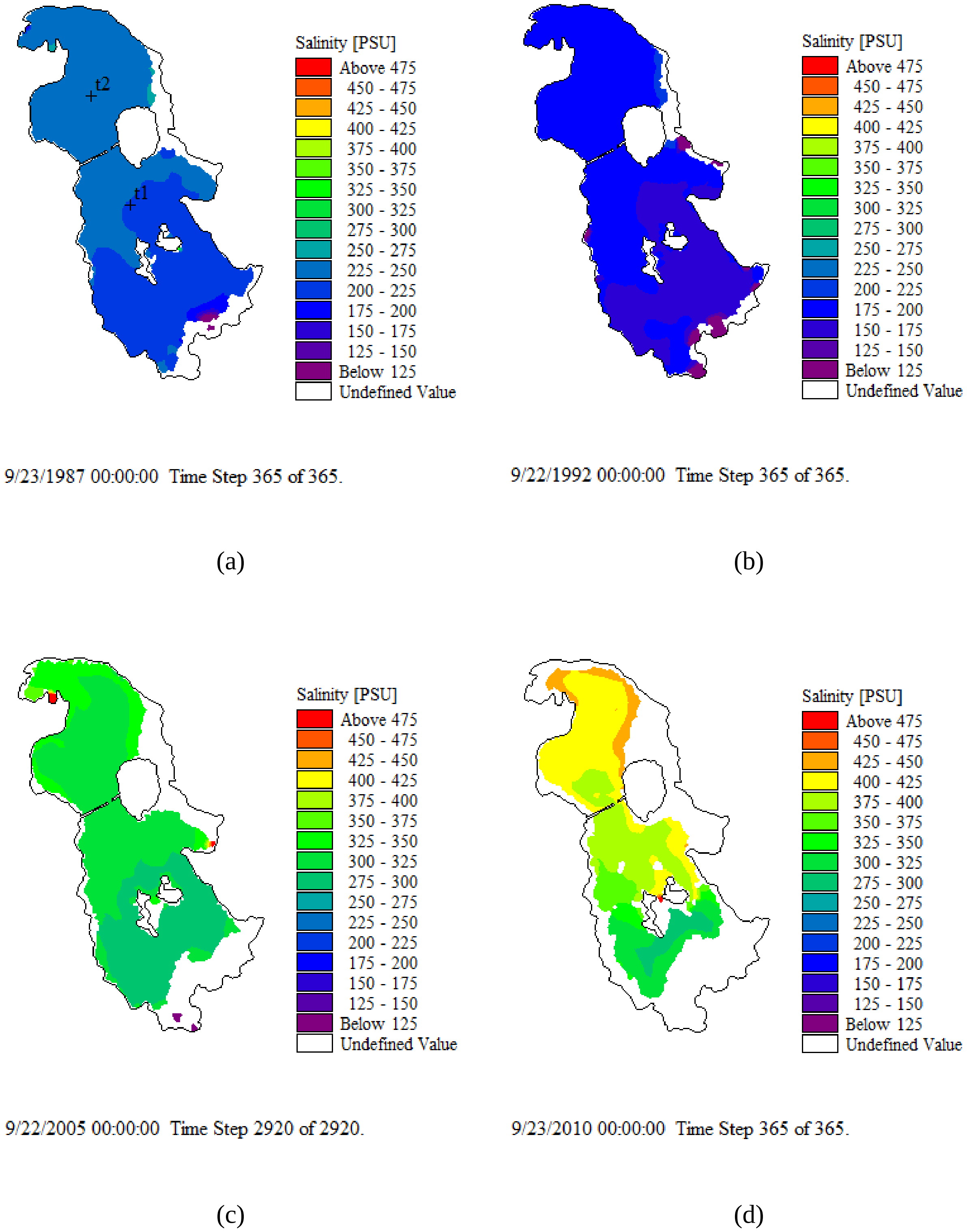


Figure 4.19. Comparison of salinity distributions in the wet lake condition for year 1987 (a) and 1992 (b), during lake reduction for year 2005 (c) and in dry lake conditions for year 2010 (d).

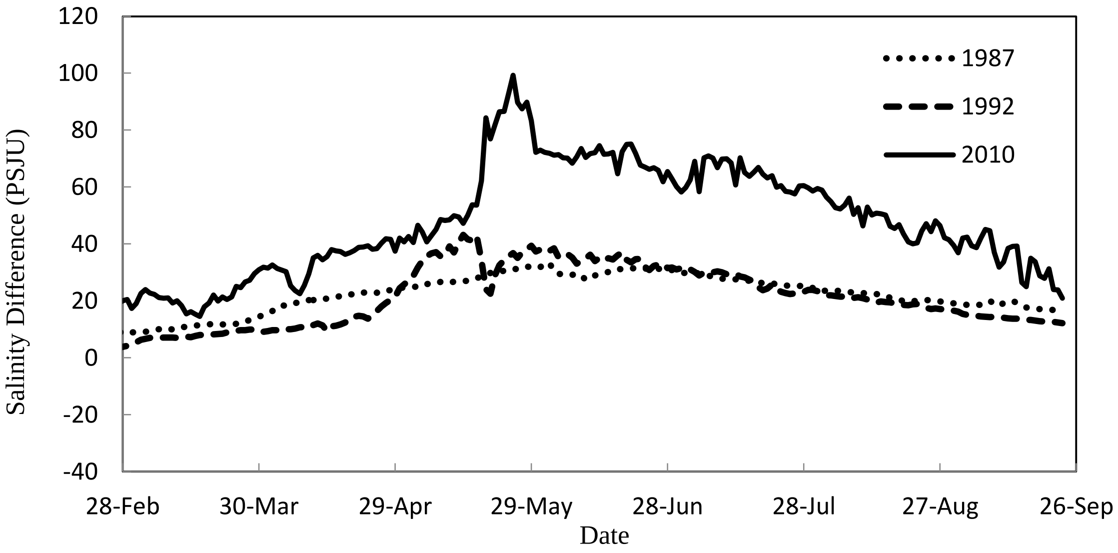


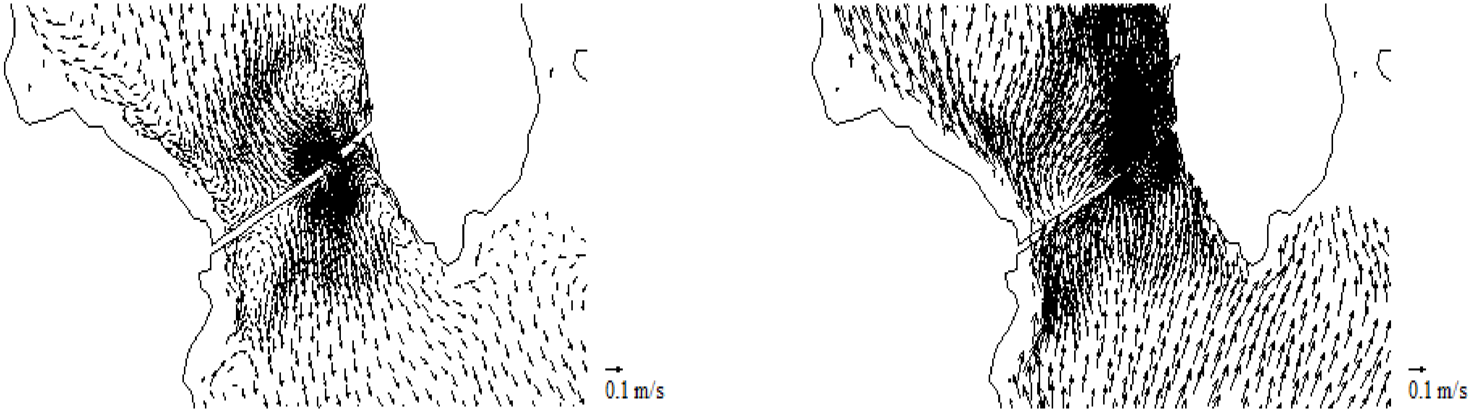
Figure 4.20. Graph of salinity difference between the northern and southern basins

4.7.1. Two -way flows

In this study, since the surface and bottom exchange is very important in the water circulation process and the importance is generally more significant when the depth of the lake is shallow, which would also change the water quality in the lake, 3D case is setup. As shown in Figure 4.21, the flow pattern at the surface and bottom layers on 24th March 2005 is shaped by a southern wind with a high velocity of 7.9 m/s. In the surface layer of the lake, the flow pattern is aligned with the direction of the wind, whereas in the bottom of the lake, the flow is in the opposite direction. Figure 4.22 shows a difference in water level between the northern and southern basins of about 0.2 m, caused by the wind blowing and dragging water towards the North. Return flow at the bottom occurs due to the pressure gradient induced by the surface setup, ensuring volume conservation of lake water. Since the lake is shallow, complete-mixing of water across over the vertical direction is carried out by wind force.

(a) Bottom Layer in the northern

(b) Surface Layer in the northern



(c) Bottom Layer in Central Part

(d) Surface Layer in Central

Figure 4.21. Flow pattern in surface and bottom layer in Central and Northern part of the lake on 03/24/2005 created by a wind speed U_{10}=7.9 m/s

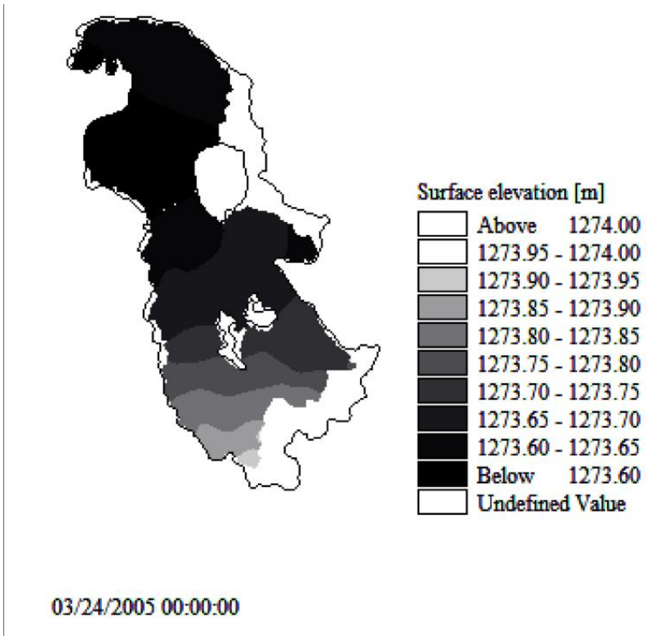


Figure 4.22. Surface elevation over the lake on 24th March 2005

4.8. Simulation of the Urmia Lake response to non-impoundment of the ShahidKazemi Dam

As mentioned in Chapter 3, the ShahidKazemi Dam is the most important dam in the Urmia Lake basin that is located on main reach of the Zarrinehroud River, the river has highest inflow to the lake (about 41% of total inflows), so the ShahidKazemi Dam has been selected for investigation the effects of dams on the hydrodynamics and salinity distribution of the lake. Comparison between inflow and outflow from the dam for periods of 23th September 2009 till 23th September 2009 revealed that 2452.626 Mm^3 volume of water was inflowed to the dam, but 1142.131 Mm^3 was exited from the dam. The volume of $Q_{Residual}$ between the Sarighamish and Nezamabad stations was -430.828 Mm^3. The effect of the impoundment on the lake surface water level has been shown in Figure 4.23. According to the figure the impoundment of ShahidKazemi has created 32 cm differences on the lake water level. Also comparison between salinity distribution on the Figure 4.24 indicates that non-impoundment of the ShahidKazemi dam can be effective on salinity distribution and it decreased average salinity of the lake about 40 PSU. Because of the mouth of the Zarrinehroud is located in the southern basin declining of salinity in the southern basin is more evident.

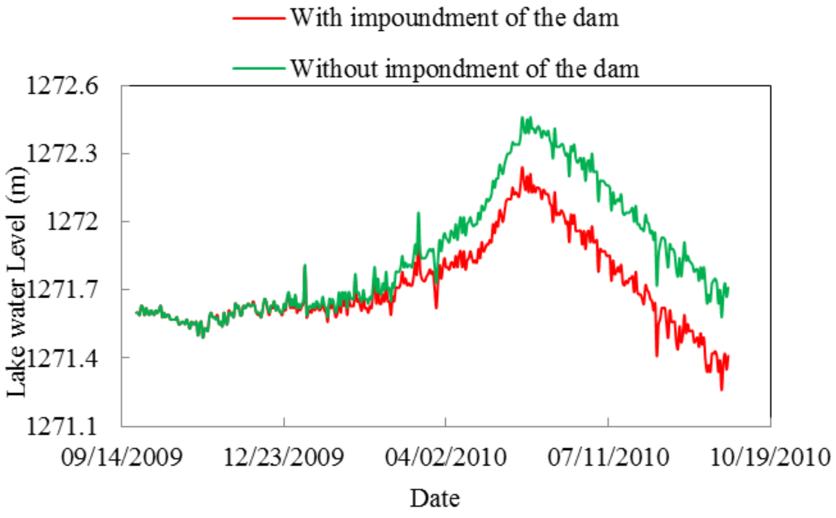


Figure 4.23. Effect of the ShahidKazemi Dam on the water level of the Urmia Lake at the reference point

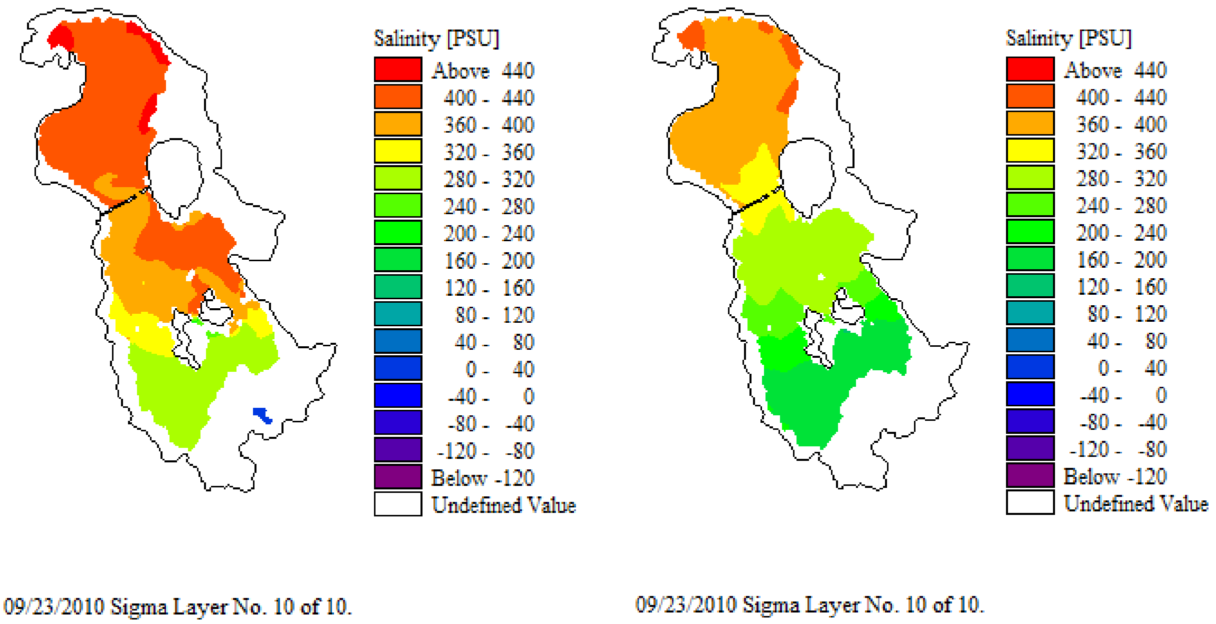


Figure 4.24. Effect of the impoundment of the ShahidKazemi Damon salinity distribution over the Urmia Lake in the surface layer

CHAPTER 5: CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDIES

5.1. Conclusion

The Urmia Lake has been encountered with serious environmental crisis, because of mismanagement in water recourse uses. To overcome this problem, in this study eight active dams (ShahidKazemi, Shahr-Chai, Ajabshir, Alavian, Venyar, Siminehroud, Zola and Derik) and three under constructed (Nazlou, Baranouz and Kalhor Dam) dams have been evaluated and regulation curve of those has been presented by calculation of $Q_{Residual}$ in downstream of dams. Comparison between calculated value for regulation by dams and by calculated EF by other studies revealed that for investigation of the effects of dams on water level and salinity distribution of the lake and study of hydrodynamic behavior of the lake, the 3-D numerical model MIKE 3 Flow Model FM was used. First, numerical model Sensitivity analyses of flow velocities and salinity distribution have been done, then it be calibrated for flow velocity by using field data taken in October 1991 and density data taken in September, May and July 2010. Sensitivity analyses of the model were tested using 11 sets of experiments have been performed. Effects of wind friction coefficient, roughness height, vertical eddy viscosity, initial condition of water salinity and numerical techniques were investigated on the flow velocity and salinity distribution over the lake. The results revealed that wind data and vertical eddy viscosity are effective input variables on flow velocities and subsequently on salinity distribution. The roughness height has less effect on the flow velocity and the effect of bed roughness on the velocities in the surface layer is negligible. There is some underestimation in simulated flow velocities. The use of small vertical-eddy viscosity function improves the estimated velocity field, but weakens the reproduction of salinity distribution. Introduction of the UNESCO-density function leads to an overestimation in density values. The verification results of the model in the period of 1986-1987 indicated that the accuracy of the model in prediction of salinity is good enough for practical. Assessment of hydrodynamic characteristics of the Urmia Lake, before and after drying period of the Urmia Lake, indicates that the salinity differences between north and south basins significantly increased after the drying process due to the decrease in the exchanged flows between the two basins. The difference in salinity reaches in the highest level in May because of rivers freshwater inflows following the snow melting season. The simulation results showed that the velocity and direction of the wind are the most effective input variables in the flow circulation patterns, especially in the water surface layer of the lake. Results also revealed that there is a two-way opposed flows over the water depth due to the wind blowing over the lake and water inflows mainly from southern rivers. The model is to be run for any time periods either in normal or in drought conditions of the Urmia Lake, and is capable enough to satisfactorily simulate the hydrodynamics characteristics and salinity distribution over the Urmia Lake.

Finally the effect of impoundment of the ShahidKazemi Dam, the largest dam in the Urmia Lake basin, has been evaluated by the model. Results revealed that the ShahidKazemi Dam has remarkable effect on the lake's water level and salinity distribution so reoperation of it can be effective of restoration of the lake.

This study was completed to indicate that the model can be run for any time period in wet and dry conditions of the Urmia Lake and can be simulate accurate results of hydrodynamic of the lake.

5.2. Suggestions for future studies

In this study there is some simplification in the water balance equation of the lake as following:

- Ground water has been eliminated.
- Evaporation coefficient has been assumed constant, although it's a function of humidity and temperature.

- Estimated volume of water consumption after the last hydrometric stations reported by Ministry of Energy (2004) in Table 3.4 is for 2002, because of the some changes in land use occurred in recent years, the new field survey is necessary in future research.

Also, there are some recommendations in hydrodynamic modelling of the lake:

- In this study wind speed and wind direction have been assumed constant in domain because of the lack of measured wind data for simulation periods. In future studies, the case with wind varying both in time and domain by preparing a data file containing the wind speed components and air pressure in some synoptic stations before setting up the hydrodynamic simulation is necessary. The Bonab Station in 1290 m elevation in Southern part of the lake is the appropriate station for mentioned purpose. The elevation from the surface of the lake and distance from the lake is an important parameter in determining of Stations site.
- For the simulation of the lake water level, using some different water level monitoring stations such as one station in the Causeway, northern basin and southern basin of the lake beside the Golmankhaneh Station is necessary.
- Results reveled that wind speed is the most important input variable in hydrodynamics of the shallow the Urmia Lake so for future studies being recommended that flow velocity be measured by ADV[1] or other three dimensional velocity monitoring tools accompanied by wind.
- According to results using of the UNESCO equation for calculation of density in the Urmia Lake leads to overestimation of density for salinity values corresponding to the measured value, so monitoring of Salinity and density of the lake simultaneously for extraction of equation of state in the Urmia Lake such as other saline lakes in the world (Dead Sea and Aral Sea) is necessary. In evaluation of dams effects on rivers and the lake regime:
- In behind of the some dams such as Zola, Barandouz and Mahabad dams, there is no hydrometric station on some of the input river courses so there are some errors in the amount of the input hydrograph of the dam.
- The MalekKandi Station on the MadoughChai River (Figure 3.13) has been deactivated in 1971, due to the relatively large distance of the Gheshlagh e Amir Station to the Urmia Lake (about 46 km) it's recommended that the MalekKandi Station be activated.
- The PoleSorkh Station on the Mahabad River was activated from 1956 to 1968 in downstream of the constructing site of the Mahabad Dam, in this study because of the non-overlapping of the monitoring periods in mentioned station and the GordeYaghoub Station (nearest active hydrometric station to the lake), it wasn't possible to calculate the $Q_{residual}$ in the residual part of the MahabadChai River. It is recommended that the Pol eSorkh Station be activated for future researches.
- There are no hydrometrics stations in upstream and downstream of the Hassanlou Dam on the GadarChai River so it is impossible to calculate the $Q_{residual}$ in the residual part of the GadarChai River.
- To minimize the uncertainty of input rivers discharge to the lake and determine of water losses and yields in residual part 2, it is necessary to construct nearest possible hydrometric stations at the mouth of the input rivers.

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[1] Acoustic Doppler Velocimetry

- The Khormazard Station on the ChwanChai River has long distance (about 16 km) to the lake. Another hydrometric station needs in the nearest possible distance for monitoring the ChwanChai River's discharge to the lake.
- The GharePapagh Station on the Zarrinehroud River after the Nezamabad Station (Figure 3.14) is the nearest hydrometric station to the lake on the Zarrinehroud River, but it has been deactivated since 1966. For more accurate estimation of the Zarrinehroud River's discharge to the lake recommended that the GharePapagh Station be reactivated.
- Economic assessment of the proposed operation policies of dams is necessary because of relevant change in the water allocation policy over local agriculture sector. Also the stability of dams before releasing huge amount of water has to be assessed.

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