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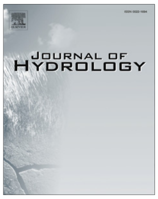

Expert knowledge based modeling for integrated water resources planning and management in the Zayandehrud River Basin

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SUMMARY

This study highlights the need for water resource planning and management using expert knowledge to model known extreme hydrologic variability in complex hydrologic systems with lack of data. The Zayandehrud River Basin in Iran is used as an example of complex water system; this study provides a comprehensive description of the basin, including its water demands (municipal, agricultural, industrial and environmental) and water supply resources (rivers, inter-basin water transfer and aquifers). The objective of this study is to evaluate near future conditions of the basin (from Oct./2015 to Sep./2019) considering the current water management policies and climate change conditions, referred as *Baseline* scenario. A planning model for the Zayandehrud basin was built to evaluate the Baseline scenario, the period of hydrologic analysis is 21 years, (from Oct./1991 to Sep./2011); it was calibrated for 17 years and validated for 4 years using a *Historic* scenario that considered historic water supply, infrastructure and hydrologic conditions. Because the *Zayandehrud model* is a planning model and not a hydrologic model (rainfall–runoff model), an Adaptive Network-based Fuzzy Inference System (ANFIS) is used to generate synthetic natural flows considering temperature and precipitation as inputs. This model is an expert knowledge and data based model which has the benefits of Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS). Outputs of the ANFIS model were compared to the Historic scenario results and are used in the Baseline scenario. Three metrics are used to evaluate the goodness of fit of the ANFIS model. Water supply results of the Baseline scenario are analyzed using five performance criteria: time-based and volumetric reliability, resilience, vulnerability and maximum deficit. One index, the Water Resources Sustainability Index is used to summarize the performance criteria results and to facilitate comparison among trade-offs. Results for the Baseline scenario show that water demands will be supplied at the cost of depletion of surface and groundwater resource, making this scenario undesirable, unsustainable and with the potential of irreversible negative impact in water sources. Hence, the current water management policy is not viable; there is a need for additional water management policies that reduce water demand through improving irrigation efficiency and reduction of groundwater extraction for sustainable water resources management in the Zayandehrud basin.

1. Introduction

Rapid population growth, high agricultural use and industrial development, coupled with climate changes during the past few decades have caused increasing pressure on land and water resources in almost all regions of the world. The challenge is how to improve the management of water resources for present and future generations. Water resources planning and management requires the deep understanding of the special value of water for human life, interaction of human beings and nature, and the social significance of water resources for national economic development (Rosenberg, 2008). Water resources planning and management tries to meet the water requirements of all the water users, although, sometimes this is not possible. Frequently, conflicts among water users arise because water is a scarce and shared resource. The difficulties increase when the systems become large with numerous water users, several types of use, with unequal spatial distribution and such scarcity that water cannot be re-distributed without affecting other water users. Nowadays, this seems to be the common pattern of water allocation in large basins (Sandoval-Solis and McKinney, 2014).

Historically, fragmented water resources management has resulted in degradation of rivers and water bodies in many of the

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watersheds in the world, especially in arid and semi-arid regions (e.g. Aral Sea). Today, integrated water resources management (IWRM), especially in areas facing limited water resources, has become an indispensable approach. IWRM was introduced in 1980s to optimize water uses between different water demand sectors and water sources (Ludwig et al., 2014). The goal of this approach is to balance water availability and demand, human and environmental water requirements, taking into account all the available water sources (surface water, groundwater, reclaimed and desalinated water) which provides sustainability of water resources (Molinos-Senante et al., 2014; Dukhovny, 2004).

Meire et al. (2008) argue that the IWRM concept was originated at the first United Nations (UN) conference on the human environment in Stockholm in 1972. According to Porto and Porto (2008), the Dublin Principles and the 1992 UN summit at Rio de Janeiro reinforced this concept through the agenda 21's principles (Coelho Maran, 2010). It is important to note that IWRM is a process, not a product, and that it serves as a tool for assessment and program evaluation. IWRM does not provide a specific blueprint for a given water management problem but rather is a broad set of principles, tools, and guidelines, which must be tailored to the specific context of the country or region or a river basin (Xie, 2006). Stakeholder participation is the key point in IWRM approach. That is the empowered community has the responsibility to address local issues in a coordinated and integrated way (Matondo, 2002).

Many scientists and experts believe that water resources modeling is one of the most important preconditions that facilitate the application of IWRM in large basins. Models help to organize information related to water availability and water requirements of stakeholders. Using a "bottom-up" approach stakeholders can evaluate local alternatives for IWRM, while whole basin regulations can be evaluated using a "top-down" approach, taking into account physical limitations of existing infrastructure (Cai, 1999; Cai et al., 2006; Dukhovny and Sokolov, 2005). It is important to note that during the implementation of IWRM, there is no need to seek universal and stereotyped approaches that are acceptable for all (IWRM Toolbox, 2003). Due to these justifications, many researches have documented many IWRM case studies using different decision support systems (DSS). For instant, Letcher et al. (2006a,b), developed a DSS for Mae Chaem catchment in Northern Thailand. This DSS contains models of crop growth, erosion and rainfall–runoff, as well as household decision and socioeconomic impact models; Weng et al. (2010) developed an integrated scenario based multi-criteria support system for planning water resources management in the Haihe River basin. They defined some policy parameters or policy scenarios such as: water saving intensity, excessive volumes of groundwater extraction, volume of untreated wastewater and the amount of water supplied from transfer project for IWRM implementation to develop a DSS model that used a fuzzy multi-criteria decision analysis as the evaluation model. During the construction of DSS, special attention should be given to the definition of scenarios (Katsiardi, 2005; Liu et al., 2007; Soussa and Vekerdy, 2005; Van beek and Meijer, 2006; ZhenGfu et al., 2009; Ni et al., 2012). Gaiser et al. (2008) developed the Model for Sustainable Development of Water (MOSDEW) in the Neckar basin in South-west Germany. There are nine sub-models covering large scale hydrology, groundwater flow, water demand, agricultural production, point and non-point pollution and chemical as well as biological water quality. One of sub-models was the agroeconomic sector model, referred as ACRE model, developed by Henseler et al. (2005, 2009). This model is very useful for IWRM but it is very complex due to its hybrid modeling nature; Davies and Simonovic (2011), employed a system-dynamic integrated assessment model that incorporates socio-economic and environmental change. Their model includes global climate system, carbon cycle, economy, population, land use and agriculture, and novel versions of the hydrological cycle, global water use and water quality. Also, some of researchers focused on effects of IWRM implementations at the catchment scale. For instant, Ako et al. (2010), investigated methods to improve water resources management in Cameroon and to implement IWRM at the catchment scale. Coelho et al. (2012) employed a multi-criteria DSS for IWRM implementation in the Tocantins-Aragauia River Basin in Brazil. Safaei et al. (2013) applied the concept of IWRM to Zayandehrud River Basin in Iran. These studies considered stakeholder participation, scenario analysis, dispute resolution and climate change conditions. Also Georgakakos et al. (2012), Dawadi and Ahmad (2012), and Vargas-Amelin and Pindado (2014) surveyed the impacts of climate changes in water management in Northern California, Colorado River and Spain, respectively.

Nowadays, water resources planning and management processes are moving away from top down approaches to bottom up approaches. There is a variety of generic software platforms used to evaluate water planning and management policies and to facilitate stakeholder involvement during the planning and decision-making process (Assata et al., 2008). The models such as MODSIM, River Basin Simulation Model (RIBASIM), MIKE Basin, Water balance Model (WBalMo), MULti-sectoral, Integrated and Operational Decision Support System (MULINO-DSS), Water Evaluation and Planning System (WEAP) can be used for planning purposes at catchment scale, evaluation of current and alternative water allocation policies, river flow routing, reservoir routing, water demand analysis, rainfall–runoff modeling, water balance, water quality and sedimentation transport, and in general, watershed management (Mugatsia, 2010). The comparisons of these tools are described in Mugatsia (2010) and Jakeman et al. (2008).

WEAP is one of the IWRM platforms that seamlessly integrate water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. New versions of WEAP consider demand priority and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches (Yates et al., 2005a,b). WEAP has been applied in Ghana to simulate the impact of small reservoirs in the Volta (Hagan, 2007), in Olifants catchment in South Africa to analyze current and future demands (Arranz and McCartney, 2007), in Perkrra catchment to analyze scenario implementation (Mugatsia, 2010), in Rio Grande/Rio Bravo transboundary basin to implement IWRM in large scale river basin (Sandoval-Solis and McKinney, 2014). These case studies show a good performance of this platform. It is clear that modeling of large basins implies sets of known and unknown parameters. Hydrologic and climatic time series, geologic data, water demands and historic water supply, and a variety of information of catchments and basins are used for modeling. However, in large basins for one period of time there is data with many gaps for a variety of known parameters. Also in many case studies there is not data at all for some important parameters.

This study presents how engineering judgment and expert knowledge could be used for integrated water resources planning and management in Zayandehrud River Basin. Modeling distributed water demands considering all sources such as surface and ground water resources and interaction between them regarding to the lack of data and information are difficulties which are surveyed in this study. Simulation of rainfall–runoff at the whole of basin to calculate natural flows due to climate change in the future is another challenges which is studied in this research. The Zayandehrud River Basin is one of the largest and most important basins in central Iran. Because of existence of different water sources, water demands, environmental needs, and water transfers from/to other basins, this basin is one of the best case studies for IWRM modeling. There are many studies and reports for water resources management in this basin (Madani and Mariño, 2009; Nikouei et al., 2012; Gohari et al., 2013b; Safaei et al., 2013) but there is not a comprehensive model to address IWRM in this basin. The reason is the lack of data for many important parameters for modeling. Based on a 21-year recorded data (1991–2011) and applying expert knowledge, a water planning model referred as *Zayandehrud Model* is developed for surface and ground water resources; after estimating the interaction between water sources and parameters. The *Zayandehrud model* was calibrated from 1991 to 2006 and validated from 2007 to 2011.

In this study, a scenario analysis technique is employed as an appropriate approach, because it is well known that stochastic optimization approaches cannot be used when there is insufficient statistical information on data estimation to support the model, when probabilistic rules are not available, and/or when it is necessary to take into account information not derived from historical data. In these cases, the scenario analysis technique could be an alternative approach to address the "What if . . .?" situations, called scenarios. Scenario analysis can model many real problems where decisions are based on an uncertain future, whose uncertainty is described by means of a set of possible future outcomes, called "Scenarios" (Pallottino et al., 2005). Scenarios have been used as an important tool for exploring future uncertainties in a coherent, consistent and plausible way, and such as, they have been widely used for strategic planning and policy making (Dong et al., 2013). In this study, a baseline scenario is developed (from 2015 to 2019) to assess the current water management policies into the near future and considering climate change conditions. In order to account for future climate change condition, an Adaptive Network-based Fuzzy Inference System (ANFIS) is developed to model rainfall–runoff processes in this basin. Outputs from this model are used as inflows into the *Zayandehrud model*.

2. Case study: the Zayandehrud River Basin

The Zayandehrud River Basin is the most important watershed and a crucial source of water for irrigation, as well as for industries, animal farming, municipal supply and wastewater dilution (Safavi and Alijanian, 2010). This basin is located in center of Iran with the area of 26,972 km^2 of which 16,649 km^2 is in mountainous area and the rest in the foothills and plains (Fig. 1). The basin is a part of Esfahan and Sirjan Catchment in the Iran's central plateau according to the Iran's hydrology classification.

The Zayandehrud River is a vitally important river for agricultural development as well as domestic water supply and economic activity of the Isfahan province in west-central Iran. It is a completely closed basin having no outlet to the sea. The river is about 350 km long and runs in a roughly west–east direction, originating in the Zagros Mountains, west of the city of Isfahan, and terminating in the Gavkhooni wetland to the east of the city (Murray-Rast et al., 2000). The Zayandehrud contains more water than any other river in central Iran. Nevertheless, the management of the water resource in the catchment area has become a source of conflict between different parties; a conflict which has become exacerbated in recent years. Municipal water utilities, industry such as cement companies, large steel rolling mills, pulp and paper, power plant companies and irrigation-dependent agriculture, all have high priority water demands (IWRM in Isfahan: Industry Report, 2014; Paydar Consulting Eng., 2010). On the other hand, as such under the Ramsar Convention, because of climate change and drought, the Gavkhooni wetland does not receive enough water; so this led to deterioration of this wetland status (Matthews, 1993). Madani and Mariño (2009) have been introduced the Zayandehrud Basin as a complex water system. They discussed the lack of complete understanding about all interacting sub-systems. However, it is important to note that there is valuable experience, expertise and information regarding this basin and the interactions of sub-basins, water sources and water demands that can be used for research and studies in this basin.

According to the recent studies in Esfahan Regional Water board Company (ESRW), the Zayandehrud Basin is divided into sixteen sub-basins (Table 1). There are four aquifers very important, in terms of their interaction with the river: Kuhpayeh-Sagzi (KS), Esfahan-Borkhar (ESB), Najafabad (NJ) and Lenjanat (LJ). These sub-basins are known as complex sub-systems of the Zayandehrud Basin because of the conjunctive use of the surface water and groundwater and interaction between river and groundwater resources as well as development of agriculture, industries and urban population density in these areas.

Therefore, research related to IWRM in this basin is very necessary and important given the vulnerability and complexity of the water system. The innate complexity of the basin is the reason for choosing it as the case study for this research, for instance: different water sources including surface water and groundwater, conjunctive use of water and interaction between surface and groundwater, inter-basin water transfers and several types of use such as domestic and sanitation, agriculture, industries and environmental water demands. This research also shows that in cases with lack of data for modeling, the valuable expert knowledge can be used to develop a reliable model to manage water resources system.

2.1. Water resources in the Zayandehrud Basin

2.1.1. Surface water resources

There are three main rivers in the Zayandehrud Basin: Zayandehrud River, Pelasjan River and Samandegan River (see Fig. 1). Based on 21-year historic data (from water year 1991 to 2011), the average annual runoff of these rivers is approximately 990 Million Cubic Meters (MCM) above Zayandehrud Dam, 87% from the Zayandehrud River, 12% from Pelasjan River and less than 1% from Samandegan River. Runoff from these rivers is strategically stored in the Zayandehrud Dam, constructed in 1971 (Fig. 1). Because of its characteristics as shown in Table 1, the Chelgerd_Ghal'e Shahrokh sub-basin is the most important sub-basin and primary source of surface water in this basin.

Downstream of Zayandehrud Dam, there should be lateral contributions to the Zayandehrud mainstem from seasonal river tributaries; however, because of the fragmentation of water resources management, these rivers often do not reach to the Zayandehrud River; thus, they have little regional importance (Molle et al., 2009). In contrast, recharge to the aquifers from effective rainfall and the Zayandehrud River in this area is very important (Zayandab Consulting Eng., 2008).

With the opening of the first inter-basin tunnel, named Kuhrang tunnel No.1, the basin resources were augmented in 1953. This tunnel could divert an annual volume of 340 MCM from Kuhrang River. In 1970, the storage capacity Zayandehrud Dam was completed (1470 MCM) to regulate the water regime upstream of this dam (IWRM in Isfahan, 2014). These projects have increased the water supply and storage in the Zayandehrud basin dramatically. Another tunnel from Kuhrang River was built in 1986 with capacity to divert approximately 250 MCM/year, on average. In addition, Cheshmeh-Langan tunnel delivered 164 MCM/year of water from Dez River Basin since 2009 (Gohari et al., 2013a). Based on 21-year historic data, the two Kuhrang tunnels and the Cheshmeh-Langan tunnel delivered annually about 238, 309 and 86 MCM from Karun and Dez River Basins, respectively. Locations of these tunnels are illustrated in Fig. 1. Table 2 shows the main surface water resources in the Zayandehrud Basin.

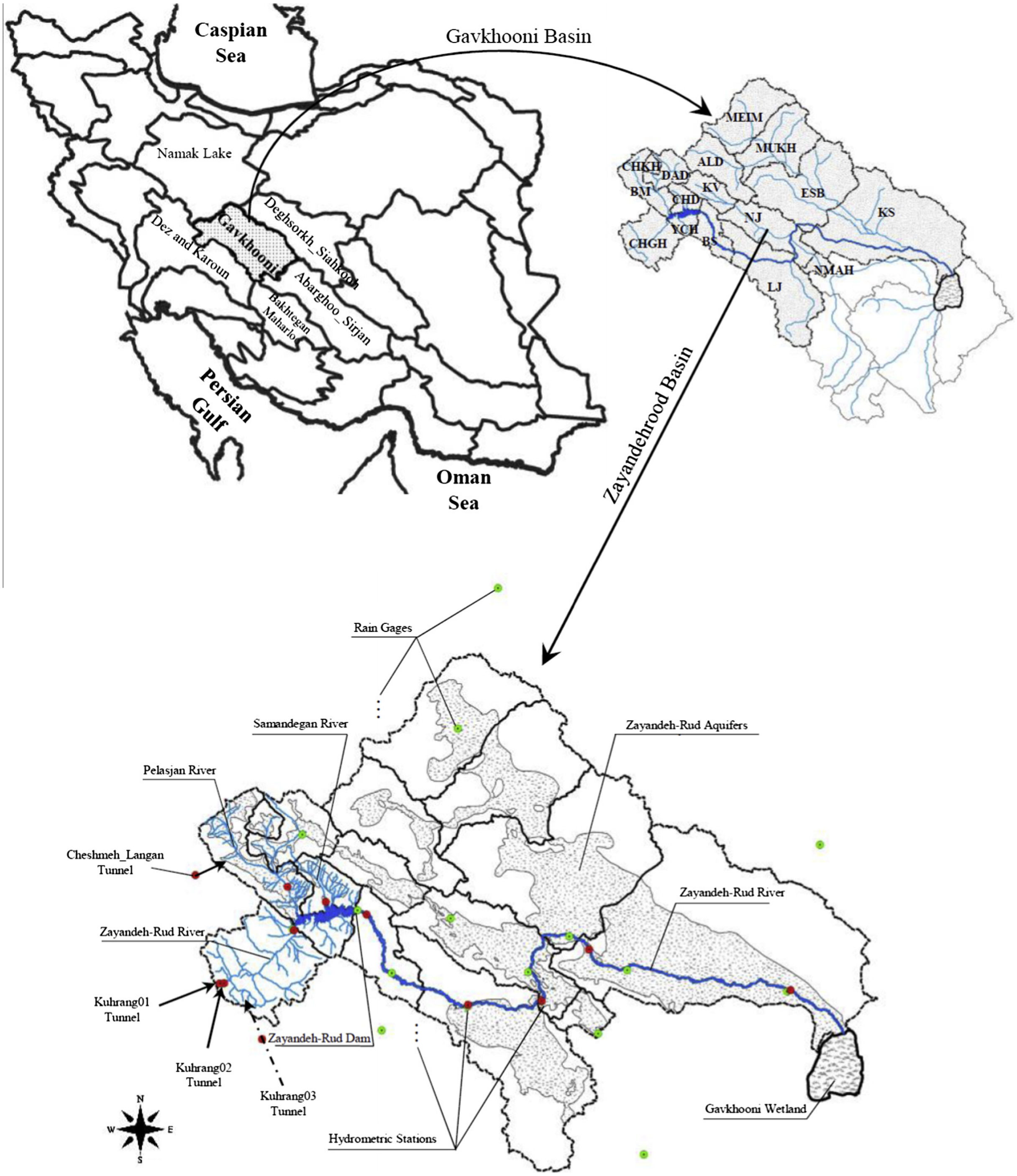


Fig. 1. Situation of the Gavkhooni Basin in Iran and the Zayandehrud Basin and its sub-basins.

2.1.2. Groundwater resources

The limits of the groundwater aquifers in the Zayandehrud Basin are shown in Fig. 1. Out of sixteen sub-basin introduced in Table 1, there are thirteen sub-basins with active aquifers of which, six (two in the upper basin and four in the lower basin) have interaction with the main rivers in their respective sub-basin. There is little information about the geology and hydrologic interaction of groundwater and revers in these areas. Experts widely accepted that a 10-m thick clay layer exists in Kuhpaye-Sagzi sub-basin. This layer separates the upper unconfined from lower confined aquifer (IWRM in Isfahan Reports, 2014). These regions have been analyzed by Gieske and Miranzadeh (2000) which presented a map for Transmissivity for the sub-basin Lenjanat, Safavi and Bahreini (2009) surveyed the Transmissivity and specific storage for the Najafabad sub-basin and presented a map for them, and Paydar Consulting Eng. in 2010, analyzed the data and information of the Gavkhooni basin and presented the average values of specific storage and recharge from surface water consumptions for all sub-basins using a mass-balance method. This data were obtained through 50 exploration wells and was manually checked for plausibility and completeness by Groundwater Management (GWM) plan of the IWRM in Isfahan (2014). Also, Water and Wastewater Research Institute (WWRI) (2012), provided the map of bed-rock of the Zayandehrud aquifers excluding upstream aquifers and LJ aquifer from downstream. Using these information and data as well as digital elevation model (DEM) with a cell size 90 m, the

Table 1
The Zayandehrud sub-basins and their characteristics.

Sub-basin name (abbreviation)	Area (km^2)	Annual average precipitation (mm)	Annual average precipitation (MCM)	Position relative to the dam
Damaneh_Daran (DAD)	710.70	362	257	Upstream (upper basin)
Chelkhaneh (CHKH)	161.85	362	59	
Boein_Miandasht (BM)	981.41	378	371	
Chadegan (CHD)	425.67	299	127	
Chelgerd_Ghal'e Shahrokh (CHGH)	1504.17	896	1347	
Yan Cheshmeh (YCH)	338.24	325	110	
Ben_Saman (BS)	834.32	292	244	Downstream (lower basin)
Karvan (KV)	727.33	252	184	
Lenjanat (LJ)	3362.68	164	553	
Najafabad (NJ)	1753.56	161	282	
North Mahyar (NMAH)	267.15	140	37	
Alavijeh_Dehagh (ALD)	1442.73	259	374	
Meimeh (MEIM)	2063.88	159	328	
Murchehkhort (MUKH)	2203.25	158	348	
Esfahan_Borkhar (ESB)	3772.99	134	506	
Kouhpayeh_Sagzi (KS)	6422.35	103	660	
Total	26972.28	4444	5787	

average groundwater levels and some of unknown characteristics of the aquifers are estimated in this study. The characteristics of the Zayandehrud aquifers are presented in Table 3.

2.2. Water demand and supply in the Zayandehrud Basin

In general, there are four types of water use in the Zayandehrud Basin: municipal, environmental, industrial and agricultural. Fig. 2 shows the schematic of the Zayandehrud Basin, including all major water demands and their supply sources considered in this study. This figure also shows aquifers that have interaction with the main river.

Table 2
General characteristics of the Zayandehrud surface water resources.

Attribute	Value
Precipitation	
Total (MCM)	5788
Upstream of dam (MCM)	2271
Downstream of dam (MCM)	3207
Zayandehrud River	
Length upstream of dam (km)	47
Length downstream of dam (km)	313
Annual stream flow (MCM) in CHGH sub-basin	858
Monthly min., max and average temperature of origin area (°C)[a]	−9, 24.7 and 10.13
Pelasjan River	
Length (km)[b]	72.5
Annual stream flow (MCM)	122
Monthly min., max and average temperature of origin area (°C)[a]	−10, 24.7 and 10.04
Samandegan River	
Length (km)[b]	26.9
Annual stream flow (MCM)	7
Monthly min., max and average temperature of origin area (°C)[a]	−10, 26.5 and 11.51
Zayandehrud Dam[c]	
Height of dam from foundation (m)	100
Crest level (m.a.s.l)	2063
Normal water level (m.a.s.l)	2059
Max. reservoir volume (MCM)	1470
Effective reservoir volume (MCM)	1260
Year of completion	1969
Max. discharge (m^3/s)	1910
Monthly min., max and average temperature of the area of dam (°C)[a]	−9.7, 28.7, 12.16
Annual evaporation from reservoir (MCM)[d]	73.87

[a] Based on 21-year data (from Oct.-1991 to Sep.-2011) (unpublished data).
[b] Yekom Consulting Eng. (2013).
[c] ESRW Company Brochure of the Zayandehrud Dam.
[d] Based on volume–elevation curve of the Zayandehrud Dam (unpublished data).

Municipal demand in the basin includes: (a) greater Isfahan city and it metropolitan area, (b) other municipal demands in the Zayandehrud basin and (c) exporting of water to other cities out of the basin such as Shahre-Kord, Yazd and Kashan cities. About two-thirds of municipal water supplies come from the Baba-Sheikh-Ali water treatment plant (WTP) which directly diverts water from the Zayandehrud River. The remaining water comes from the Mobarakeh and Isfahan Felman well fields, whose main recharge source is the Zayandehrud River (about 70%) and the water supply comes from LJ, NJ and ESB aquifers (Salemi and Murray-Rust, 2002; ESRW Company, unpublished data). There are return flows from urban areas which can be used by downstream irrigation systems. About 40% of return flows are treated by South Isfahan wastewater treatment plant and returns to the Zayandehrud River.

One of the most important demands in the Zayandehrud basin is the environmental demand for the Gavkhooni wetland, located at the end of the Zayandehrud River on the east side of basin. Currently, there is no defined surface water allocation to protect this wetlands or in-stream requirements. Sarhadi and Soltani (2013) have determined the minimum flow requirement of the Gavkhooni wetland for normal water years (141 MCM/year) and drought periods (60 MCM/year). In recent years, because of successive droughts and unauthorized extractions from upstream and downstream water users of the Zayandehrud Dam, the Gavkhooni wetland has been destroyed.

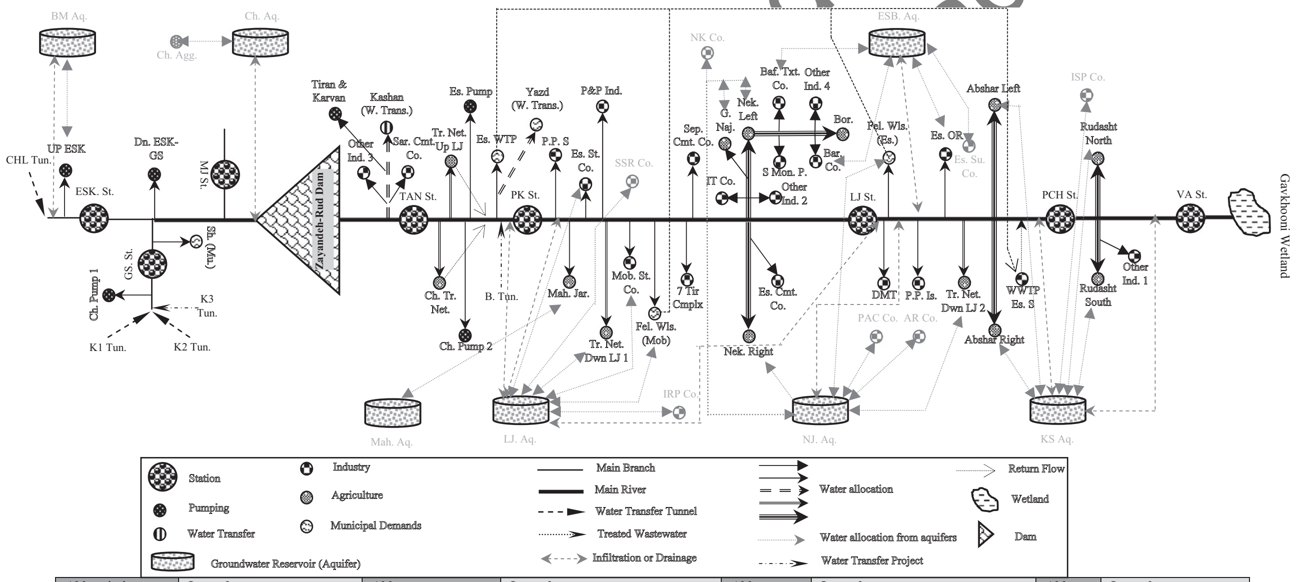
There are about 13,000 industrial units in the Zayandehrud basin of which about 30 large industrial units appropriating more than 75% of the industrial demands (IWRM in Isfahan, Industry Report, 2014). These are mainly in the sectors of steel, petrochemical, cement and power stations, they have high water demand and are mostly located between Pol-Kalleh and Lenj hydrometric stations. There are fifteen large water demands of industries supplied exclusively by the Zayandehrud River, ten industries from groundwater sources and the rest by both water sources. In general, about 87% of industrial demands is supplied by the Zayandehrud River and the rest by groundwater resources.

Agricultural demand accounts for 85% of the water demand and it is the main consumer of both surface and groundwater resources in the Zayandehrud Basin. Fig. 3 shows the overall layout of different

Table 3
General characteristics of the Zayandehrud aquifers (groundwater resources).

Sub-basin name (abbreviation)	Aquifer			Specific storage (%)[a]		Recharge from surface water consumption (%)[a]		Average piezometric level		
	Area (km^2)	Average thickness (m)	Max. water storage capability (MCM)	Unconfined (U.C.)	Confined (C)	Agriculture	Municipal and industrial	Beginning of period (Oct. 1991)	End of period (Sep. 2011)	
Damaneh_Daran (DAD)	219.47	64.00	702	5	–	33.2	65.1	31.14	48.72	Upstream aquifers
Chelkhaneh (CHKH)	48.82	60.00	146	5	–	28.9	69.0	21.78	31.28	
Boein_Miandasht (BM)	498.13	63.00	1569	5	–	27.0	52.2	21.32	26.19	
Chadegan (CHD)	146.02	60.00	438	5	–	26.4	59.8	28.49	39.11	
Karvan (KV)	247.75	43.50	536	5	–	38.0	63.0	13.94	20.31	
Lenjanat (LJ)	1228.11	52.00	2554	4	–	27.5	37.0	21.29	18.83	Downstream aquifers
Najafabad (NJ)	952.12	69.45	3297	5	–	44.75	68.0	19.92	38.65	
North Mahyar (NMAH)	127.09	179.98	1584	7	–	44.8	70.0	101.62	117.86	
Alavijeh_Dehagh (ALD)	317.76	60.61	573	3	–	19.0	49.0	14.93	25.94	
Meimeh (MEIM)	620.96	132.82	2464	3	–	24.0	53.0	40.32	55.30	
Murchehkhort (MUKH)	825.62	118.39	2920	3	–	26.5	64.0	38.13	60.40	Plain area
Esfahan_Borkhar (ESB)	1606.00	166.64	13,366	5	–	40.0	11.0	39.72	54.88	
Kouhpayeh_Sagzi (KS)	2906.84	228.04	≈26,400	4	3	45.0	56.0	15.00	18.68	
Total	9744.69	–	56,549	–	–	–	–	–	–	

[a] Paydar Consulting Eng. (2010).



Abbreviation	Legend	Abbrev.	Legend	Abbrev.	Legend	Abbrev.	Legend
Ki Tun.	Kuhrang Tunnel i	Es. St. Co.	Esfahan Esteel Company	Bar. Co.	Baresh (Textile) Company	PCH St.	Pol chum station
CHL Tun.	Cheshmeh Langan Tunnel	P&P Ind.	Pulp and Paper Industry	Nek. Right	Nekouabad, Right Channel	VA St.	Varzaneh station
Ch. Pump i	Chaharmahal Pumping i	Tr. Net. UP LJ	Trad. Nets. Upstream of Lenjanat	Es. Cmt. Co.	Esfahan Cement Company	Aq.	Aquifer
Sh. (Mu.)	Shahre-Kord (Municipal)	Mob. St. Co.	Mobarakeh Steel Company	DMT	Fiber Intermediate Products Co (DMT)	BM	Boein_Miandasht
Kashan (W. Trans.)	Kashan (Water Transfer)	GW Re.	Groundwater Recharge	P.P. Is.	Islamabad Power Plant	LJ	Lenjanat
Other Ind.	Other Industries	Fel. Wls. (Mob) , (Es.)	Felman Wells (Mobarakeh), (Esfahan)	WWTP Es. S	WWTP of South Esfahan	IRP	Iran Refractory Products
Sar. Cmt. Co.	Sarooj cement Company	7Tir Cmplx	7Tir Complex	Es. OR	Esfahan Oil Refinery	SSR	Saba Steel Resuscitation
Tr. Net.	Traditional Networks	Sep. Cmt. Co.	Sepahan Cement Company	G.W.	Groudwater	NK	Niloo Kashi
Ch.	Chaharmahal	Tr. Net. Dwn LJ	Trad. Nets. Downstream of Lenjanat	GS St.	Ghale Shahrokh Station	PAC	Polyacryl Company
Es. Pump	Esfahan Pumping	Nek. Left	Nekouabad, Left Channel	ESK. St.	Eskandari Station	AR	Azar Refractory
Es. WTP	Esfahan Water Treatment Plant	IT Co.	Iran Tel. Company	MJ St.	Menderjan station	ESB	Esfahan_Borkhar
Yazd (W. Trans.)	Yazd (Water Transfer)	G. NJ	Great Area of Najafabad	TAN St.	Tanzimi dam station	Es. Su.	Esfahan Suger
B. Tun.	Beheshtabad Tunnel	Bor.	Borkhar Channel	PK St.	Pol Kalleh station	KS	Kouhpayeh_Segzi
P. P. S	Power plant, South	S. Mont. P.	Shahid Montazeri Plant	DIZ St.	Dizicheh station	ISP	Iran Spiral (Pipes)
Mah. Jar.	Mahyar Jarghouyeh	Baf. Txt. Co.	Bafnaz Textile Company	LJ St.	Lenj station		

Fig. 2. Schematic of the Zayandehrud River Basin including hydrometric stations, surface water and groundwater resources and demand sites.

irrigation systems which are located in the downstream and after Pol-Kalleh station. Based on the normal water year of 2006, irrigation area in the Zayandehrud Basin is about 266,000 ha of which 229,000 ha is cultivated for crops and 36,000 ha for orchards (IWRM in Isfahan, Agriculture Report, 2014). Most of agricultural areas are irrigated by flood irrigation method. In 2006, all irrigated crops were supplied with flood irrigation whereas most of orchards were supplied by pressurized irrigation systems.

The main source of water supply for agriculture irrigation is the Zayandehrud River. There are some traditional networks to divert and allocate water to agriculture areas upstream of Pol-Kalleh station. Experts believe that about 60% of allocated water to these networks return to the river. After Pol-Kalleh station, eight modern canals namely Mahyar-Jarghouyeh, Nekouabad Right and Left, Borkhar, Absharl Right and Left and Rudasht North and South are constructed and operated to allocate the surface water to

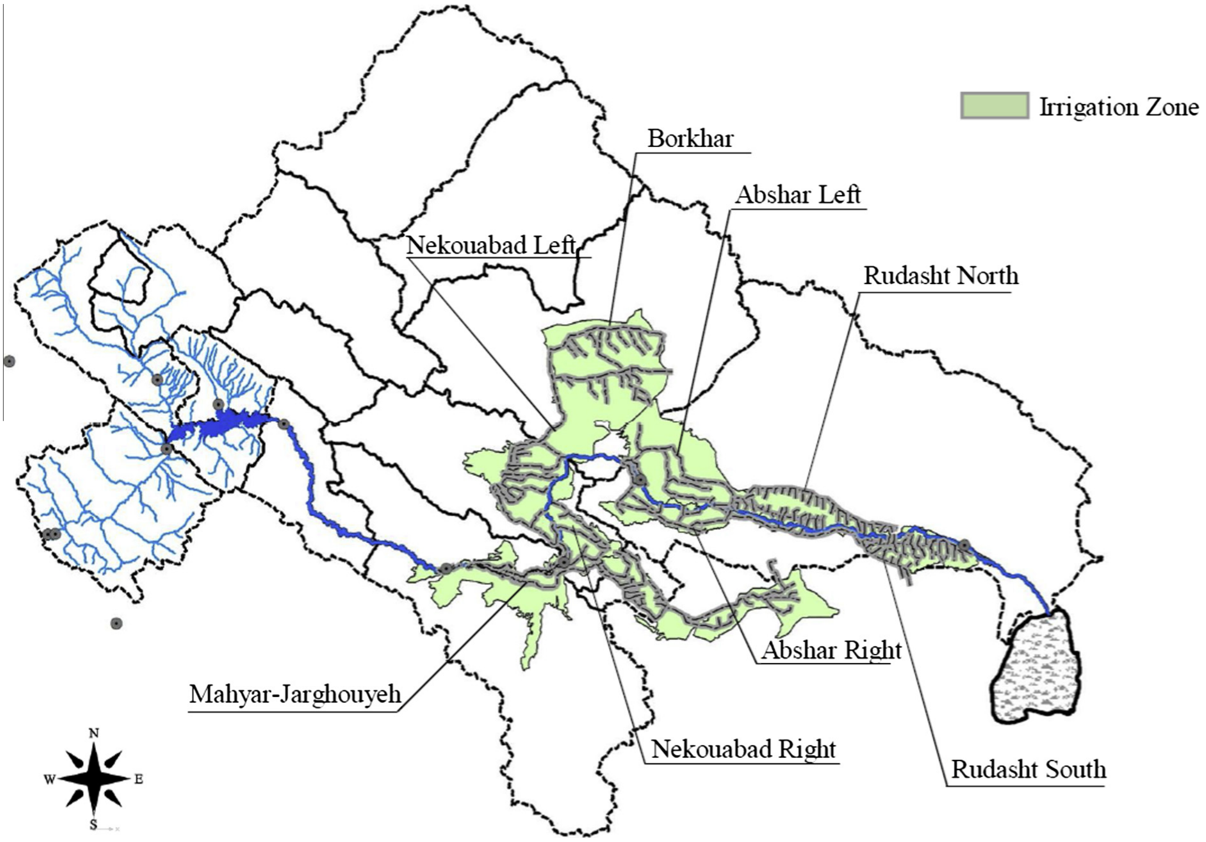


Fig. 3. Main irrigation zones and constructed modern canals.

agriculture areas (Fig. 3). Table 4 presents the characteristics of these modern canals in the Zayandehrud basin.

Table 5 presents the characteristics of all water demand sectors which are supplied by surface and ground water resources. Values indicate that during the period of analysis, more than two-thirds of water demands was extracted from groundwater resources.

Table 4
Main features of modern canals of main irrigation area in the Zayandehrud basin.

Name of canal		Date of construction	Design discharge (m^3/s)	Length of canal (km)
Mahyar_Jarghouyeh		2000	12	120
Nekouabad	Right	1979	15	35.5
	Left	1979	50	60
Borkhar		1997	18	29
Abshar	Right	1972	15	38
	Left	1972	15	33
Rudasht	North	2003	50	157
	South	2005	50	199

Table 5
Water demand by type of use in the Zayandehrud Basin (based on water year 2006 as a normal year except municipal demand).

Demand sector	Water demand (MCM)	Supplied by			
		Surface water resources		Groundwater resources	
		(MCM)	(%)	(MCM)	(%)
Municipal	429	402	94	27	6
Environmental	60	60	100	0	0
Industrial	112	98	87.5	14	12.5
Agriculture	4287	1016	23.7	3271	76.3
Total	4888	1576	32	3312	68

Unlike surface water resources in the basin which are controllable, groundwater resources are uncontrollable. In the Zayandehrud basin there are many unauthorized-uncontrolled wells and owners of approved wells have the right to deepen their wells; so there is not an appropriate control of groundwater extractions. When surface water becomes deficient, farmers or owners rely on wells to compensate their water supply and when their well dries, they deepen their wells to reach water. Thus, there is not an adequate control on groundwater extractions, generally. Today, the over allocation of water resource in the Zayandehrud basin have resulted in an increase in groundwater extraction for agriculture and industrial demands and has been led to a continuous decline of the groundwater table.

There is a need for a comprehensive model to simulate the effects of management decisions on water resources in the basin. In recent years, some researches and experts with this aim are worked on the Zayandehrud Basin (Safaei et al., 2013; IWRM in Isfahan, 2014; Tavakoli Nabavi et al., 2011; Gohari et al., 2013b) but all models in these studies have suffered from the lack of data. Also some of researches focused on a special subject, type of water use or a specific region of the basin, none of them have considered all types of use, water demands and regions of the Zayandehrud Basin. In some of studies, a set of models using different software was built to model the basin; the issue with this approach is the need of a group of experts to learn how to use the different pieces of software. The present study considers all types of use, water demands and water sources for the whole Zayandehrud Basin, the *Zayandehrud model* is developed to explore IWRM policies in the Zayandehrud Basin; it was built using expert knowledge in the case of imperfect or lack of data and can evaluate strategies for improving the integrated management in the basin.

3. Methodology

The *Zayandehrud model* is a water resources model developed to evaluate current and proposed water management policies. This model consists of a rainfall–runoff model (ANFIS Model) with a priority-based water allocation system to represent regional hydrology, infrastructure, and water management on a monthly step (Planning Model). The Water Evaluation and Planning System (WEAP) platform is used for the planning model, it calculates a monthly water balance of inflows, changes in reservoir and groundwater storages, water supply allocated to water demands and outflows based on a 21-year hydrologic period of analysis (Oct./1991–Sep./2011). This period of analysis contains the historical record of the water abundant period of 1992–1995, the drought period of 2001–2003 and part of the most recent drought of the years 2008–2011. Visual Basic scripts converted data between WEAP and Excel. In this study a model is developed for the Zayandehrud Basin using a multi-step methodology as illustrated in Fig. 4.

This methodology includes: (i) an ANFIS model to simulate rainfall–runoff in the basin, this data is used as inputs in the planning model; (ii) a reach-scale water planning model that considers water supply from the ANFIS model, projected water demands and allocation system, and surface water and groundwater interaction; and (iii) an automated evaluation system using 5 performance criteria and one summary index to evaluate present water management policies under different climate change conditions.

3.1. ANFIS model

ANFIS is a multi-layer adaptive network-based fuzzy inference system initially developed by Jang (1993), and later on widely applied in engineering (Jang and Sun, 1995). The general structure of the ANFIS is presented in Fig. 5. The corresponding equivalent ANFIS architecture which is used Takagi–Sugeno FIS is presented in Fig. 5b, where nodes of the same layer have similar functions.

A Sugeno system by two inputs and one output can be expressed by two rules as:

Rule 1: if x is A_1 and y is B_1, Then $f = p_1x + q_1y + r_1$
Rule 2: if x is A_2 and y is B_2, Then $f = p_2x + q_2y + r_2$

The functioning of the ANFIS is as follows (Jang et al., 1997):

Layer 1: Each node in this layer generates membership grades of an input variable. The node output OP_i^1s defined by:

$$OP_i^1 = \mu_{A_i}(x) \quad \text{for} \quad i = 1,2 \quad \text{or} \quad OP_i^1 = \mu_{B_{i-2}}(y) \quad \text{for} \quad i = 3,4 \tag{1}$$

where x (or y) is the input to the node; A_i (or B_{i-2}) is a fuzzy set associated with this node, characterized by the shape of the membership functions (MFs) in this node and can be any appropriate functions that are continuous and piecewise differentiable such as Gaussian, generalized bell-shaped, trapezoidal shaped, or triangular-shaped functions. Because of their smooth and nonzero at all points, Gaussian and bell MFs are more popular methods for specifying fuzzy sets although the bell-MF has one more parameter than the Gaussian MF (Sumathi and Paneerselvam, 2010). Assuming a generalized bell function as the MF, the output OP_i^1 can be computed as:

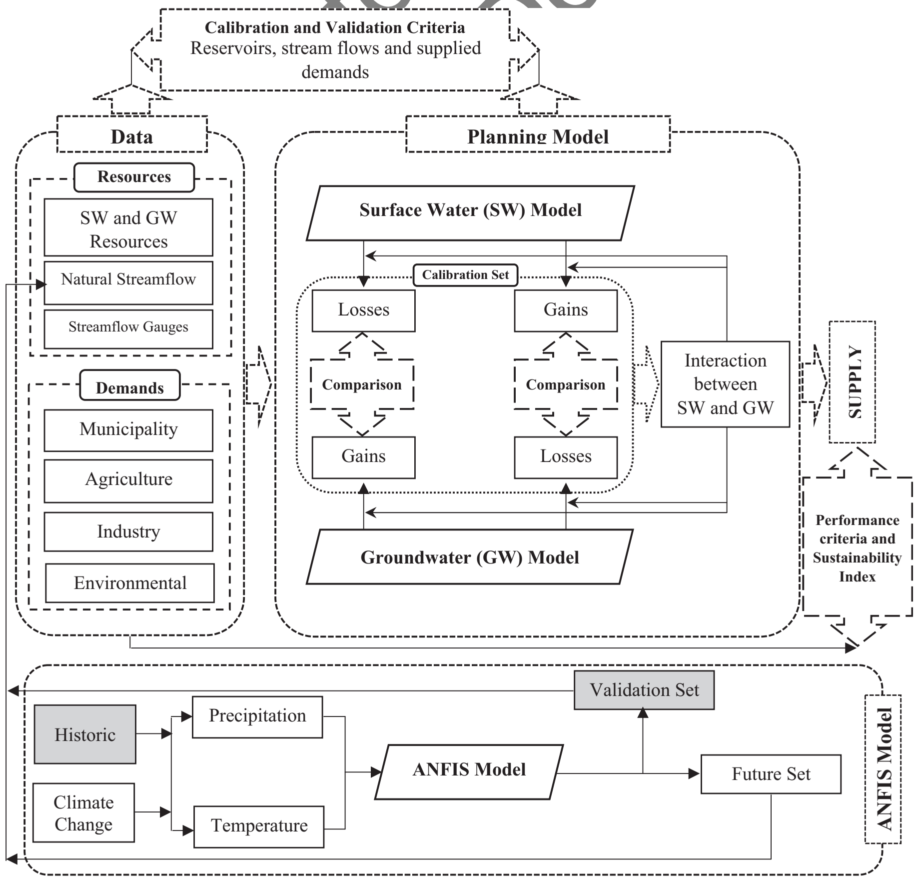


Fig. 4. Study method framework and conceptual model.

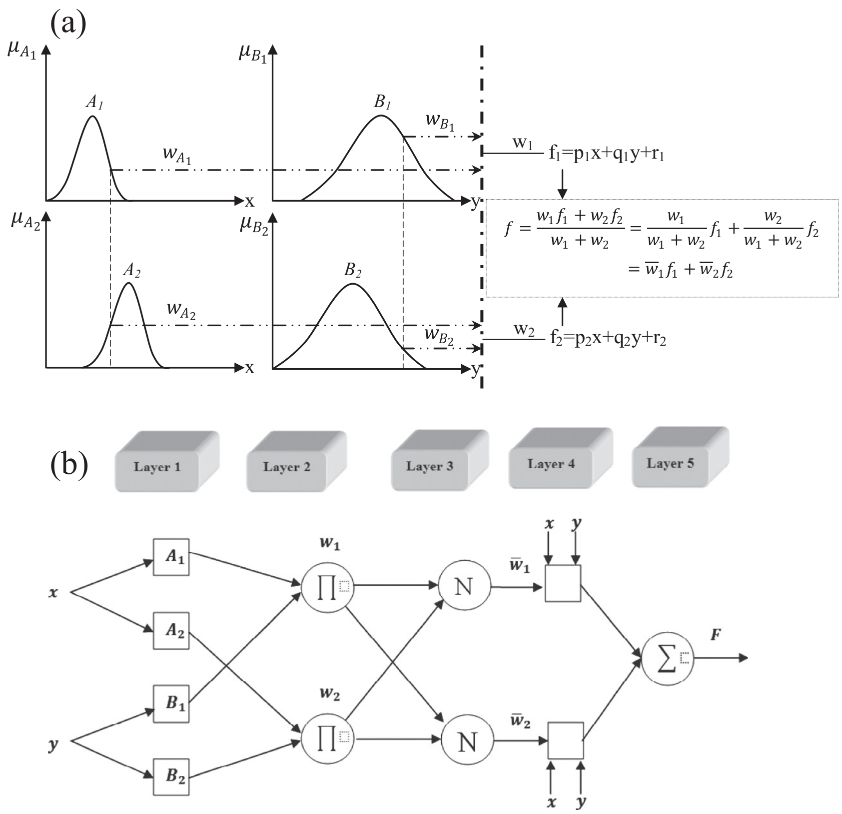


Fig. 5. (a) Fuzzy inference system. (b) Equivalent ANFIS architecture (Jang et al., 1997; Nayak et al., 2004).

$$OP_i^1 = \mu_{A_i}(x) = \frac{1}{1+\left(\frac{x-c_i}{a_i}\right)^{2b_i}} \tag{2}$$

where $\{a_i, b_i, c_i\}$ is the parameter set that changes the shape of the MF with a maximum equal to 1 and a minimum equal to 0.

Layer 2: Every node in this layer multiplies the incoming signals, denoted by π, and the output OP_i^2 that represents the firing strength of a rule computed as:

$$OP_i^2 = w_i = \mu_{A_i}(x) \times \mu_{B_i}(y), \quad i = 1,2 \tag{3}$$

where w_i is the activation weight.

Layer 3: The ith node of this layer, labeled as N, computes the normalized firing strengths as:

$$OP_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1,2 \tag{4}$$

Layer 4: Node i in this layer compute the contribution of the ith rule toward the model output, with the following node function:

$$OP_i^4 = \bar{w}_i f_i = \bar{w}_i(p_i x + q_i y + r_i) \tag{5}$$

where $\bar{w}$ is the output of layer 3 and $\{p_i, q_i, r_i\}$ is the parameter set.

Layer 5: The single node in this layer computes the overall output of the ANFIS as:

$$OP_i^5 = Overall\ output = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{6}$$

Training of these systems means that by using training data, nonlinear parameter of layer 1 and linear parameter of layer 4 are set, so that for each input desired output is achieved. Hybrid-learning algorithm is one of the most important methods of training ANFIS. In this method, for training parameters in the layer 1 and layer 4, back propagation (BP) and least square error (LSE) methods are used, respectively. Details of algorithm and mathematical background can be found in Jang and Sun (1995).

Since the information of soil texture and structure, watershed management projects and many diversion dams are insufficient in the Zayandehrud basin, there is not the possibility of developing a reliable hydrologic model. Intelligent systems such as ANN and ANFIS are very useful and practical technique in these cases (Chau, 2007; Chen and Chau, 2006; Muttil and Chau, 2006; Cheng et al., 2005). So, in this study, ANFIS model is developed to simulate rainfall–runoff with two inputs as temperature and precipitation and one output as runoff for each considered river or node. ANFIS has been widely used for deriving rainfall–runoff models because it has the advantages of both Artificial Neural Networks (ANN) and the Fuzzy Inference System (FIS) methods (Safavi et al., 2013; Nourani and Komasi, 2013; Akrami et al., 2013; Wang et al., 2009; Nayak et al., 2004; Özgar, 2009). In ANFIS, ANN is used for developing the fuzzy rules which are constructed regarding historic data or expert knowledge. The aim of developing ANFIS model in this study is to simulate natural flows in the basin especially for streamflows of the main rivers and relating this estimation to temperature and precipitation. So this model can be used in case of climate change conditions to simulate natural flows in the basin. Outputs of the ANFIS model, which are natural flows in the future, are used as inputs of the *Zayandehrud model* (Fig. 4).

3.2. Planning model

To develop the planning model, first the naturalized flows were estimated. Naturalized flows are calculated to represent historical streamflow in a river basin in the absence of human development and water use (Wurbs, 2006). It is used in the Zayandehrud Basin model as input for both headflows and Incremental Flows (IFs). In the Zayandehrud Basin model, headflows are specified for three main rivers and IFs are calculated for ten sites (station by station illustrated in Fig. 2) to represent gains and losses along stream reaches (Danner et al., 2006). In summary, IFs discretize: (a) local watershed contributions to runoff, (b) surface water–groundwater interactions, and (c) unaccounted-extractions from river or aquifer. Same as surface water resources, this process is used to calculate IFs for 13 aquifers of the Zayandehrud Basin. So the *Zayandehrud model* is governed by the continuity equation for an *i*th subreach in month *t* as follows (Lane, 2014):

$$\Delta Storage_t^i = Inflows_t^i - Outflows_t^i + IF_t^i \tag{7}$$

where $\Delta Storage_t^i$ is the change of reservoir storage, $inflows_t^i$ include streamflow inputs, water imports, and returns for surface water resource or recharges, and leakage ponds for groundwater resource, $Outflows_t^i$ include streamflow outputs, water exports, evaporation and diversions out of the reach for surface water resource or extracted or pumped water from aquifer, and drainage water to the rivers for groundwater resource, and IF_t^i refer to water gains if its value is positive and losses if it is negative.

The *Zayandehrud model* considers two main water sources, surface and groundwater. Because of this, it is important to specify the interaction between them. In order to consider the conjunctive use of these two sources of water and to estimate amount of water exchanged between them, gains and losses of river in the sites which have interaction with aquifers have been compared with losses and gains of those aquifers, respectively (Fig. 2). Historical streamflows, inter-basin water imports and exports, precipitation, water allocations from rivers and aquifers, diversions, Zayandehrud Dam specifications, operation, volume and evaporation, aquifer specifications provided by ESRW and recharge to the aquifers regarded average precipitation data of rain gauges (showed in Fig. 1) and percentage of overall precipitation reached to the aquifers (presented in Table 3) are used to estimate IFs. Also monthly evaporation of one climatology gauge located close to the Zayandehrud Dam and volume–area–elevation curve of the dam is used to estimate historic evaporation volume exported from the Zayandehrud reservoir.

After calculating streamflows and natural flows in the main rivers IFs were estimated for surface water model. Similarly, IFs for groundwater storage (aquifers) were estimated using the same procedures as for surface water sources. The interaction of river with aquifer can be estimated with comparing the losses from surface water with groundwater water gains of each sub-basin which river is flowed on it. Experts believe that because of their geological characteristics, interaction of four aquifers of LJ, NJ, ESB and KS is quite evident and obvious. So these process were applied to the river and these aquifers which are located from PK station to VA station (refer to Figs. 1 and 2) (IWRM in Isfahan, Groundwater Report, 2014) and other sub-basins have not any considerable interaction with river in downstream of dam. Thus, the integration of expert's knowledge, reports and calculation of IFs (IWRM in Isfahan-Groundwater Report, 2014; Zayandab Consulting Eng., 2008; Paydar Consulting Eng., 2010) lead to the estimation of exchanged water between surface and ground water resources.

Fig. 6 shows the comparison of aquifer water gain and river water loss and their trend lines to compare them.

As shown in Fig. 6, in KS, ESB and NJ sub-basins, the total water lost from the river is gained by these aquifers. Thus, water losses from rivers are considered as recharge to these aquifers and the remaining recharge to the aquifers are considered as calibration set. For instance, in LJ sub-basin about 75% volume of water losses from river are gained to the LJ aquifers; so about 75% volume of water losses from river is considered as recharge from river to the LJ aquifer and the remaining recharge is considered as calibration set. Physically, these calibration set can be attributed to natural recharge due to rain, or horizontal groundwater movement from neighbor aquifers. Experts believe that due to drawdown of groundwater level in recent years, there is no considerable water drainage from aquifers to the river (IWRM in Isfahan, Groundwater Report, 2014). Table 6 shows the average estimated recharge from river to these aquifers for the period under investigation. Here the exchange rates were normalized to exchange per kilometer, which make all sections comparable to each other. Also Fig. 7 shows the total annual water infiltration from river to the aquifers.

After estimation of water recharge from river to the aquifers and considering them to re-calculate the calibration sets (IFs), the Zayandehrud WEAP model was calibrated with the calibration set. To model water recharge from river to the aquifers, these are considered as demand sites with maximum historic recharges. IFs were adjusted during the calibration process (Lane, 2014; Lane et al., 2014; Sandoval-Solis, 2011; Danner et al., 2006). IFs are one of the main uncertainties in the model, mostly during drought periods.

To estimate evaporation of dam in the future, a discrete equation is derived from historic data as follows:

$$E_v = \begin{cases} 0 & \text{if } T < 0 \\ 15.367 \times T + 3.1558 & \text{if } Ts > 3 \\ 0 & \text{if } Ts \leqslant 3 \text{ and } T < 4 \\ 15.367 \times T + 3.1558 & \text{if } Ts \leqslant 3 \text{ and } T > 4 \end{cases} \tag{8}$$

where E_v is monthly evaporation (mm) from the Zayandehrud Dam, T is measured temperature (°C) at dam gauge and Ts is the number of month started from Jan. equal 1.

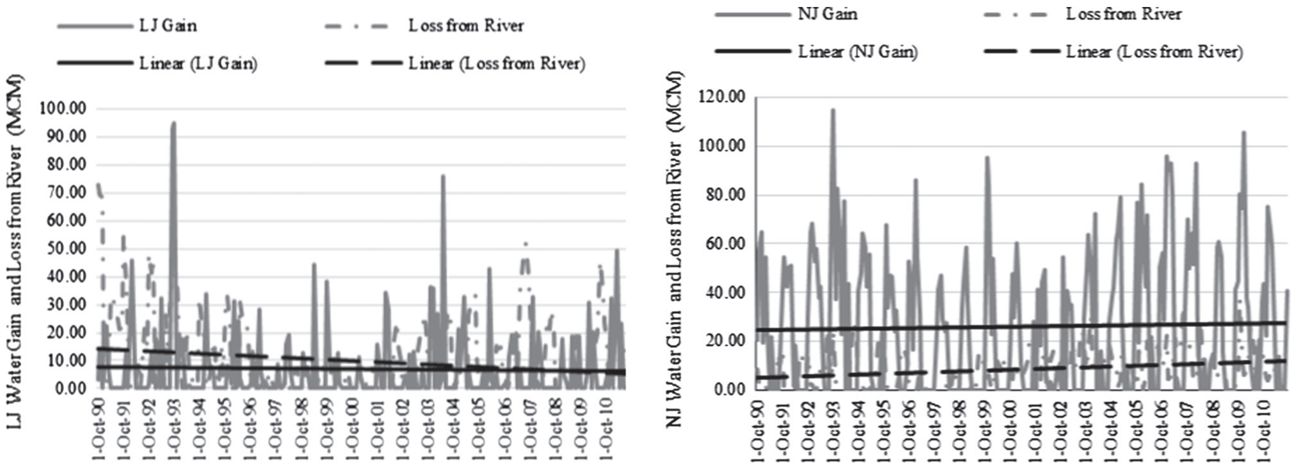
3.3. Model testing

The *Zayandehrud model* was calibrated for a 17 years period (Oct./1991 to Sep./2007) adjusting two important sets of parameters: calculating headflows and IFs (based on reach gains and losses as mentioned above) and adjusting water allocations and reservoir operation via numerous model inputs. Model accuracy is surveyed through a validation period (from Oct. 2007 to Sep. 2011). The performance of the model for the validation period is evaluated suing three sets of parameters: (i) measured streamflows at hydrometric gauge stations, (ii) storage volume at surface water (Zayandehrud Dam) and groundwater (aquifers) storages and (iii) water supply for historic water demands. Set of parameters (iii) is an input for the Zayandehrud WEAP model. Regarding to the research objectives and characteristics of goodness of fit criteria presented by Legates and McCabe (1999), three goodness of fit criteria are used to evaluate sets (i) and (ii). They are: coefficient of determination (Eq. (9)) (Steel and Torrie, 1960, and Glantz et al., 1990)]; coefficient of efficiency (E), (Eq. (10)) (Nash and Sutcliffe, 1970), and the index of agreement (d) (Eq. (11)) (Willmott et al., 1985). These coefficients compare the observed values (Ot) against the predicted or simulated values (Pt) from the model at time step t, over n number of total time steps.

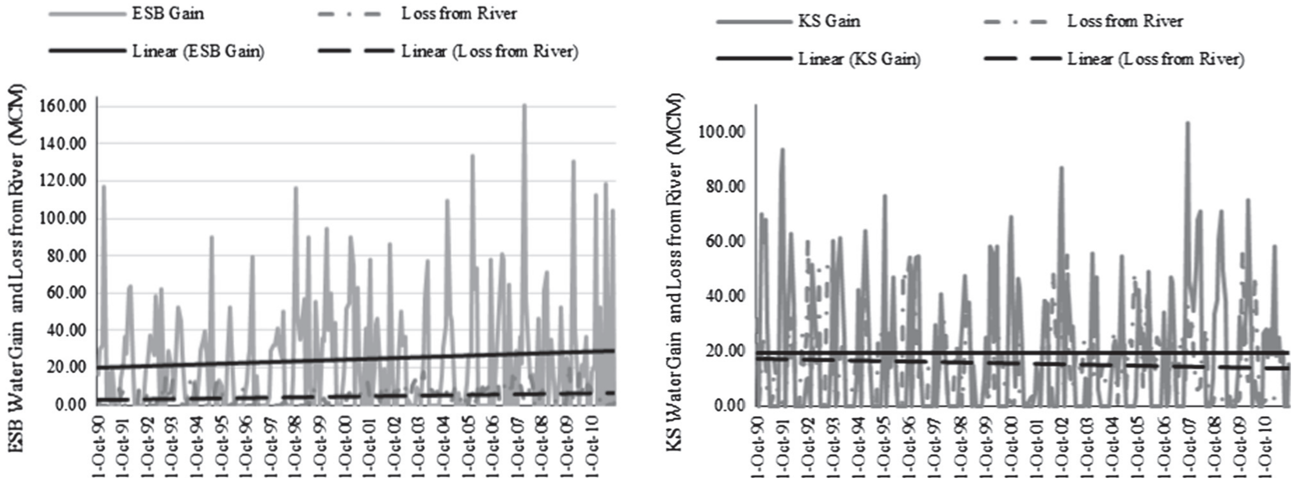
$$R^2 = \left(\frac{cov(O,P)}{\sigma_O \sigma_P}\right)^2 \tag{9}$$

$$E = 1 - \frac{\sum_{t=1}^{n}(O_t - P_t)^2}{\sum_{t=1}^{n}(|O_t - \overline{O}|)^2} \tag{10}$$

$$d = 1 - \frac{\sum_{t=1}^{n}(O_t - P_t)^2}{\sum_{t=1}^{n}(|P_t - \overline{O}| + |O_t - \overline{O}|)^2} \tag{11}$$



(a) LJ water Gain versus Loss from river (b) NJ water Gain versus Loss from river



(c) ESB water Gain versus Loss from river (d) KS water Gain versus Loss from river

Fig. 6. Comparison between aquifers water gain and losses from the Zayandehrud River.

Table 6
Average water recharge from the Zayandehrud River to the aquifers (from Oct. 1991 to Sep. 2011).

Aquifer	Length of river located in sub-basin (km)	Exchange rate (MCM/year/km)	Exchange rate (MCM/year)
LJ aquifer	65.36	1.37	89.42
NJ aquifer	37.35	2.67	99.59
ESB aquifer	20.72	2.64	54.78
KS aquifer	114.74	1.62	185.49
Sum	238.17	–	429.28

where

$$\overline{O} = \frac{1}{n}\sum_{t=1}^{n} O_t \qquad (12)$$

where $Cov(O, P)$ is covariance of observed values regarding predicted or simulated values. Covariance is a measure of how much two sets of values change together. σ_O and σ_P are the standard deviations of these two sets.

The coefficient of efficiency (E) ranges from minus infinity to 1, values closer to 1 indicate better goodness of fit. The index of agreement (d) varies from 0 to 1, values closer to 1 indicate better goodness of fit between the model and the observations (Legates and McCabe, 1999; Wu et al., 2009).

It is important to mention that due to the lack of climatologic data it is not possible to build a hydrologic (rainfall–runoff) model. In this case, ANFIS model is used to simulate rainfall–runoff in the future. The ANFIS model was developed by historic data to simulate natural flows in the basin regarding the data of temperature and precipitation. ANFIS model was trained by historic monthly data from Oct. 1991 to Sep. 2005 (70% of data) and validated for from Oct. 2005 to Sep. 2011 (30% of data). Independent validation set is employed to check over-training of ANFIS models in training process (Dawson and Wilby, 2001; Taormina et al., 2012). During various run of ANFIS model with different structures (change in the number and type of member functions and training epochs) for each river and natural flow along the river, the best models with best goodness of fit and less error were selected. For all rivers and natural flows, model with 7 bell functions and 500 training epochs was selected as the best ANFIS model to simulate rainfall–runoff in the Zayandehrud basin. Table 7 shows the performance of three ANFIS models in training and validation processes using two goodness of fit criteria, R^2 and d; these models are developed to estimate runoff of three main rivers of the Zayandehrud basin. Results show that these models passed the over-training test.

Then, the historic water demands for the evaluation period were loaded into the model. Also natural flows and streamflows exported from ANFIS model are imported to the *Zayandehrud model.*

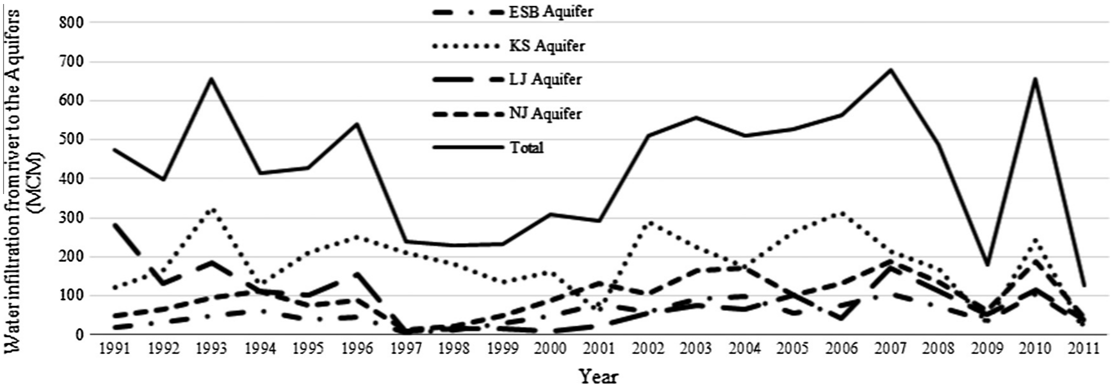


Fig. 7. Annual water recharge from the Zayandehrud River to the aquifers.

The *Zayandehrud model* accuracy was evaluated through a validation test from Oct. 2007 to Sep. 2011. Using historic data of demand sites and streamflows and natural flows which are outputs of ANFIS regarding historic data of temperature and precipitation, water reliability and surface and ground water resources status are compared with historic data.

During the calibration and validation processes, historic demands were declared as inputs values to the model and the goodness of fit for sets (i) streamflows in gauges and (ii) reservoir and aquifer storages were very close to 1 ($R^2 > 0.862$, $E > 0.821$ and $d > 0.947$). The goodness of fit of Zayandehrud WEAP model is very good accordingly to Moriasi et al. (2007); and it has been calibrated and validated (Figs. 8–10).

3.4. Baseline scenario development

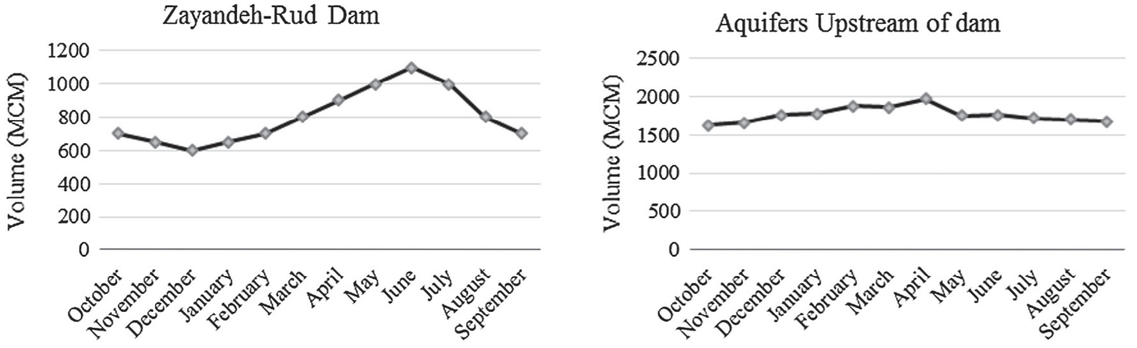
The purpose of the planning model is to evaluate the water supply performance of the Zayandehrud basin under current water management policies, referred as Baseline scenario, which is the water management before any new policy is implemented. This scenario is developed for the near future (Oct. 2015–Sep. 2019). In this period the climate changes will have an impact on temperature and precipitation. Data of temperature and precipitation under climate change conditions for those stations used in this study have been getting from the climate change studies in the Zayandehrud Basin researched by WWRI (2012). Therefore, natural flows, evaporation and groundwater recharges will change in the future. Natural flows are simulated by ANFIS model and groundwater recharge to the aquifers are estimated like before. These are the key assumptions considered for the baseline scenario:

(1) Scenario period is from Oct. 2015 to Sep. 2019.
(2) Climatic data are based on A_2 scenario (the high scenario) of climate change (IPCC, 2007) and climate change report of the Zayandehrud Basin (WWRI, 2012).
(3) Demands of industries and agriculture areas are considered as supplied demands in the water year 2006 which is known as a normal year (IWRM in Isfahan, Agriculture Report, 2014).
(4) Demand of the Gavkhooni wetland is considered as the minimum required water for survival birds which is about 60 MCM (Sarhadi and Soltani, 2013).
(5) Municipality demand is considered as demands in water year 2009 which have the maximum supplied municipal water demand during the modeling period.
(6) The first allocation priority is for municipal demand and other demands have the same preference with second priority (like present water management policy in the basin).
(7) Percentage of demand extracted from groundwater resources versus surface water resources are as in the past.
(8) Yearly inter-basin water transferred from/to other basin are as in the past with the same monthly variation.
(9) The third Kuhrang tunnel will delivered about 60 MCM water annually from Karun basin (Figs. 1 and 2).
(10) If reservoir volume of the Zayandehrud Dam be less than 250 MCM the release will be only equal the municipal demand.
(11) Reservoir volume and aquifers volume at the beginning of water year 2015 is assumed that will be equal their value at the end of water year 2011.

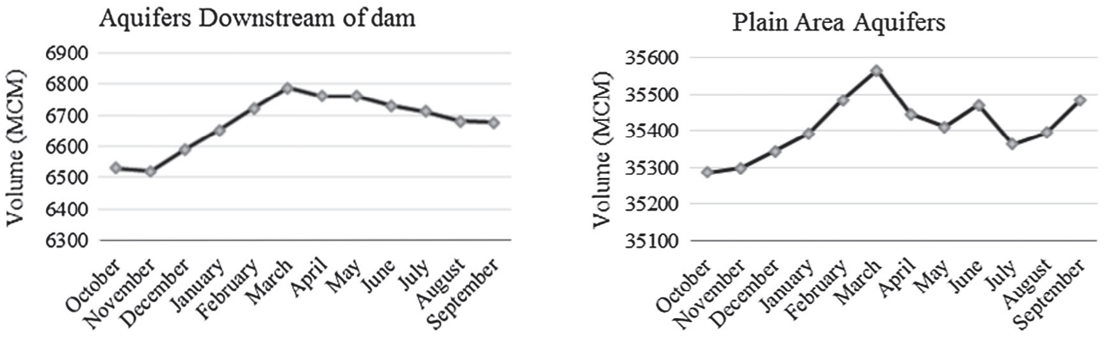
The previous assumptions are declared into the Zayandehrud model to evaluate the status of the basin in the near future. The status of water allocations to the demand sites and status of the aquifers and the Zayandehrud Dam can be analyzed after running model under current water management policies. Performance criteria are used to evaluate the Baseline scenario. Specifically, five water supply performance criteria and one summary index are calculated (Sandoval-Solis, 2011; Lane, 2014): time-based and volumetric reliability, resilience, vulnerability, maximum deficit and sustainability index. Reliability is the probability that the system will remain in a non-failure state; resilience is the ability of the system to return to non-failure state after a failure has occurred; vulnerability is the likely damage of a failure event (Kjeldsen and

Table 7
Results of the training and validating process of ANFIS models for three main rivers of the basin.

ANFIS model structure		Process	Coefficient of determination (R^2)	Index of agreement (d)
Number of MFs (MF type)	Epochs			
Zayandehrud River				
7 (Bell)	500	Training	0.88	0.96
		Validation	0.76	0.92
Pelasjan River				
7 (Bell)	500	Training	0.89	0.97
		Validation	0.76	0.90
Samandegan River				
7 (Bell)	500	Training	0.84	0.95
		Validation	0.67	0.79

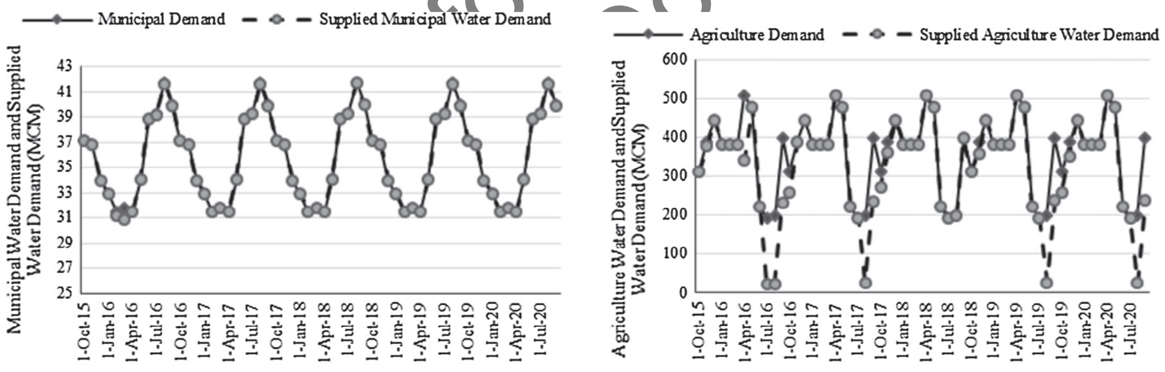


(a) Desired status of the Zayandehrud Dam (b) Desired status of the aquifers upstream of dam

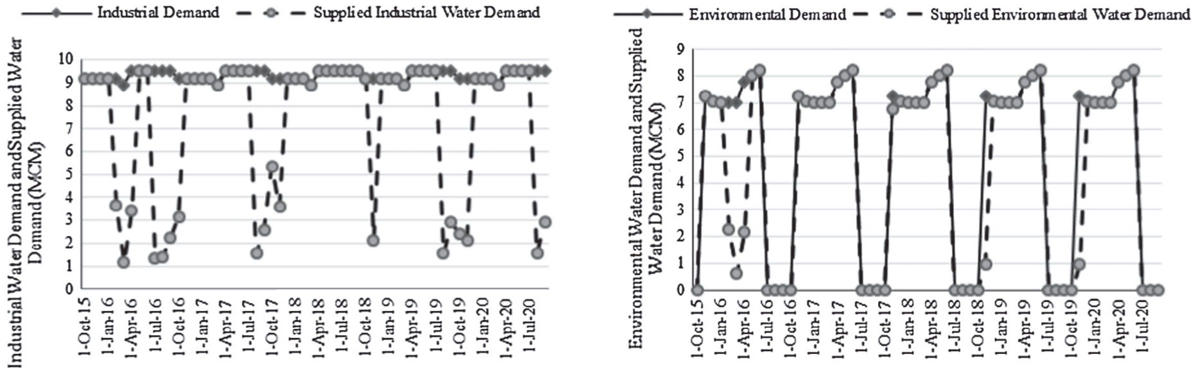


(c) Desired status of the aquifers downstream of dam (d) Desired status of the aquifers located in plain area

Fig. 8. Desired status of the Zayandehrud water resources based on experts belief.

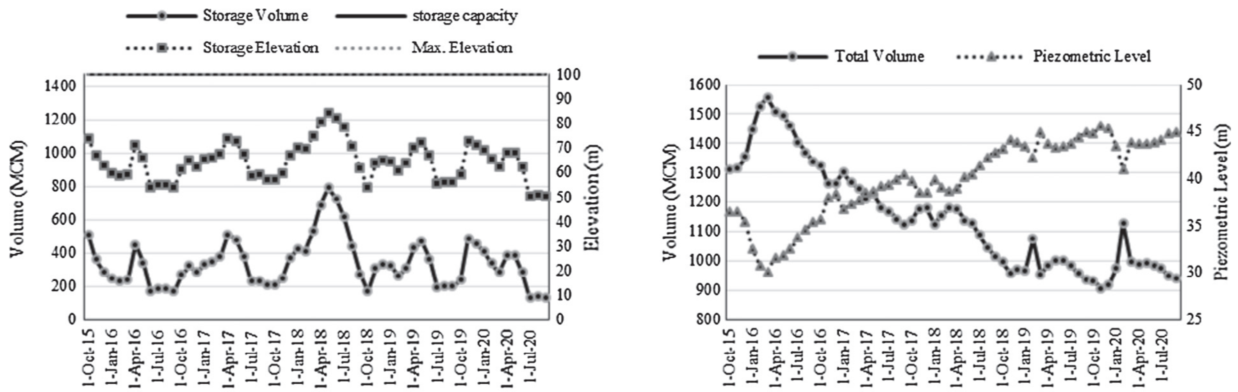


(a) Municipal water demand and supplied (b) Agricultural water demand and supplied

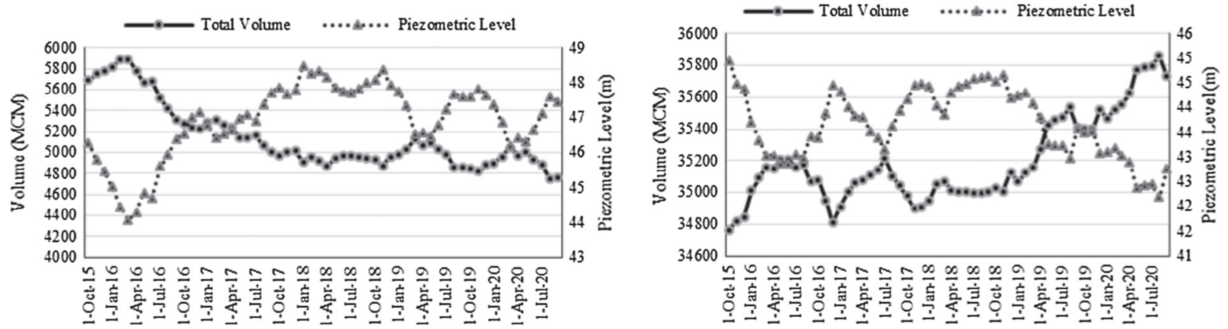


(c) Industrial water demand and supplied (d) Environmental water demand and supplied

Fig. 9. Total water demand and supply delivered under baseline scenario.



(a) Zayandehrud Dam reservoir (b) Aquifers located upstream of dam



(c) Aquifers located downstream of dam (d) Aquifers located the plain area

Fig. 10. The Zayandehrud water resources status under Baseline scenario.

Rosbjerg, 2004; Asefa et al., 2014); and maximum deficit is the worst-case annual deficit which is occurred (Moy et al., 1986; Sandoval-Solis, 2011). These criteria relate water demand ($Demand_t^i$) and water supply ($Supply_t^i$) for a determined jth water user (Eq. (13)) defined as an agricultural, municipal, environmental or industrial demand objective; or relate reservoir status ($Reserv_t^i$) and desired status ($Desire_t^i$) for a determined jth water resource defined as an aquifer or a dam. Equations for the performance criteria are same for water user and water resources (Vigerstol, 2002). Only with replace the $Demand_t^i$ with $Reserv_t^i$ and $Supply_t^i$ with $Desire_t^i$ the criteria can be calculated for another objective. If deficit (D_t^i) is defined as follows (Loucks, 1997):

$$D_t^j = \begin{cases} Demand_t^j - Supply_t^j & \text{if } Demand_t^j > Supply_t^j \\ 0 & \text{if } Demand_t^j = Supply_t^j \end{cases} \tag{13}$$

The following equations show the mathematical procedure to estimate the five performance criteria: time-based reliability [Rel_{time}^j, Eq. (14), (McMahon et al., 2006)], volumetric reliability [Rel_{vol}^j, Eq. (15), (Hashimoto et al., 1982)], resilience [Res^j, Eq. (16), (Hashimoto et al., 1982; Moy et al., 1986)], vulnerability [Vul^j, Eq. (17) (Sandoval-Solis, 2011)] and maximum deficit [$Max.\ Def^j$, Eq. (18), (Moy et al., 1986; Lane, 2014; Sandoval-Solis, 2011)]:

$$Re\ l_{time}^j = \frac{N_s}{N} \times 100\%; \quad 0 < Re\ l_{time}^j < 100\% \tag{14}$$

$$Re\ l_{vol}^j = \frac{\sum_{t=1}^{t=N} Supply_t^j}{\sum_{t=1}^{t=N} Demand_t^j} \times 100\%; \quad 0 < Re\ l_{vol}^j < 100\% \tag{15}$$

$$Re\ s^j = \frac{\#\ of\ times\ D_t^j = 0\ follows\ D_t^j > 0}{\#\ of\ times\ D_t^j > 0\ occured} \times 100\%; \quad 0 < Re\ s^j < 100\% \tag{16}$$

$$Vul^j = \frac{\dfrac{\sum_{D_t^j > 0} D_t^j}{\#\ of\ times\ D_t^j > 0\ occured}}{\sum_{t=1}^{t=N} Demand_t^j} \times 100\%; \quad 0 < Re\ l_{vol}^j < 100\% \tag{17}$$

$$Max.\ Def^j = \frac{\max(D_{Annual}^j)}{\sum_{t=1}^{t=12} Demand_t^j} \tag{18}$$

where N_s is the number of time steps that the water demand was fully supplied and N is the total number of steps.

Desired status to estimate performance criteria of surface and ground water resources is given by experts in the Zayandehrud Basin. They believed that normal and desired status of the Zayandehrud Dam and aquifers can be considered as monthly status of the water year 2007. Fig. 8 shows monthly desired status of the Zayandehrud Dam and all aquifers.

The Water Resources Sustainability Index (SI^j), the geometric mean of the above mentioned performance criteria (Loucks, 1997; Sandoval-Solis et al., 2011), it summarizes the performance of results to facilitate comparison among complex trade-offs which is defined as (Sandoval-Solis and McKinney, 2014; Lane, 2014):

$$SI^j = \left\{ Re\ l_{time}^j \times Re\ l_{vol}^j \times Re\ s^j \times (1 - Vul^j) \times (1 - Max.\ Def^j) \right\}^{1/5} \tag{19}$$

4. Results and discussion

To run the Zayandehrud WEAP model for the baseline scenario, natural flows and streamflows were simulated by ANFIS model regarding climate change data for precipitation and temperature from Oct. 2015 to Sep. 2019. All hypotheses noted at methodology section were applied to the model. Fig. 9 shows water demand and

Table 8
Performance of the water supply under Baseline scenario.

Criterion	Demand			
	Municipal	Agricultural	Industrial	Environmental
Reliability of time (%)	70.0	66.7	70	90
Reliability of volume (%)	99.9	91	78	90
Resilience (%)	27.8	35	27.8	66.7
Vulnerability (%)	0.0	0.4	1.2	1.7
Max. Deficit (%)	0.4	16	38.3	28.2
Sustainability (%)	72.0	70.8	62.1	82.5

supply delivered for municipal, agricultural, industrial, and environmental demands.

Table 8 shows the results of the performance criteria and the sustainability index results by type of use of water demands and supplied by surface and groundwater sources.

Baseline performance indicates that the reliability of agricultural and municipal water supplies in volume is higher than it in time. This indicates that the monthly volume of delivered water is nearly sufficient to supply these demands but not with the appropriate timing, especially for municipal demand. This shows that the governing water management policies and water extractions from surface and ground water resources should be revised for times of release from the Zayandehrud Dam or extractions from aquifers. Under Baseline scenario, industries will not receive enough water than they need. Also, according to Fig. 9, water management of the basin will be in trouble to supply water for agriculture and industry demand sites in the summer. Because of recent applied policies in the Zayandehrud Basin to bring back to life the Gavkhooni wetland considered in the Baseline scenario, the minimum water demand for surviving birds almost will be supplied. Generally, sustainability index will be desirable; but it is important how the status of the water resources in the basin will change under governing policies of the Baseline scenario.

Fig. 10 shows the status of the Zayandehrud Dam and aquifers under Baseline scenario.

To clarify the status of all aquifers, groundwater level fluctuations and performance criteria for their status regarding desirable status are shown in Tables 9 and 10, respectively.

Very low reliability and resilience while high vulnerability show that the Zayandehrud Dam in this period will have very critical conditions. Reservoir storage will fluctuate around critical threshold which is about 250 MCM (Fig. 10a). These times municipal water supply would be extremely difficult. Also, because of low quality of water in this level of dam, water treatment will face many problems. The Gavkhooni wetland which is supplied only with river will be dry (Fig. 9d) and industries will face to many problems due to their unmet demands in these times (Fig. 9c). Agricultural demand sites will extract water from the aquifers with maximum withdrawal capacity, so they will supply their demands most of the time (Fig. 9b). The Zayandehrud status in this period shows that users will extract the groundwater resources to maintain their life and productions (Fig. 10).

Performance criteria in Table 10 show that the sustainability of the Zayandehrud water resources is at high risk. Reliability of the Zayandehrud resources in time is zero, but reliability in volume is high especially for groundwater resources which is very high. This implies that the volume of extracted water from aquifers is nearly sufficient but not with the appropriate timing. Water supplying for Gavkhooni wetland and flowing water in the river to its end, cause to rise the piezometric level of Karstic aquifers in plain such as KS; but excessive withdrawal from other aquifers especially from NJ aquifer causing the piezometric water level is going down (Fig. 10c and Table 9). Because of uncontrollability of the groundwater extractions in the Zayandehrud Basin, water supplying from it will done and gradually the piezometric level of aquifers will decline (Fig. 10b and c). There is no resilience for both surface and ground water resources in the Zayandehrud Basin which is indicated that there will be no capacity to recover from failure and there is no feasibility of new allocations or plans under water management policies applied in Baseline scenario.

Table 10
Performance criteria of the Zayandehrud surface and groundwater resources under baseline scenario.

Criterion	Resource	
	Zayandehrud Dam	Total aquifers
Reliability of time (%)	0.0	0.0
Reliability of volume (%)	42.6	94.4
Resilience (%)	0.0	0.0
Vulnerability (%)	57.4	5.6
Max. Deficit (%)	64.5	6.54
Sustainability (%)	0.0	0.0

Table 11
Average water recharge from the Zayandehrud River to the aquifers in the baseline period.

Aquifer	LJ	NJ	ESB	KS	Sum
Exchange rate (MCM/year)	26.01	95.06	54.40	240.11	415.58

Interaction between river and aquifers will be as shown in Table 11. KS aquifer will received more water than long-term average in the past (Table 6) because the river will flow on it to supply Gavkhooni wetland demand.

5. Conclusions

This study proves that it is possible to build an IWRM planning model, the Zayandehrud WEAP model, in basins with limited data availability by: (a) providing a calibration set under a mass balance equation, (b) gathering of expert knowledge about aquifers, water demands and water sources hydrologic behavior and (c) developing an ANFIS model to simulate natural and stream flows regarding precipitation and temperature. This model was calibrated and validated for a period of 21-year with monthly steps. Model accuracy during the validation process was evaluated using three goodness of fit criteria. Results showed that the performance of the model is very good. Using the calibrated Zayandehrud WEAP model, future water supply performance of the basin was evaluated considering current water demands and water allocation systems depicted as

Table 9
Groundwater level fluctuations during the period of baseline scenario.

Aquifer	DAD	CHKH	BM	CHD	KV	LJ	NJ	NMAH	ALD	MEIM	MUKH	ESB	KS
PL1[a] (m)	48.7	31.2	25.0	39.1	20.3	18.8	38.6	117.9	26.0	55.3	60.4	54.9	18.4
PL2[b] (m)	64.0	35.4	30.7	49.7	21.1	24.7	56.8	100.5	33.1	48.5	63.1	56.8	8.3
Drop (−) or rise (+) (m)	−15.3	−4.2	−5.7	−10.6	−0.8	−5.9	−18.2	17.4	−7.1	6.8	−2.7	−1.9	10.1

[a] PL1: piezometric level at the beginning of Oct. 2015 which was assumed same as piezometric level at the end of Sep. 2011.

[b] PL2: piezometric level at the end of Sep. 2019.

Baseline scenario. The baseline scenario considers continuing current water management under climate change conditions in the basin before implementing any new policy. Results from the baseline scenario were evaluated using five performance criteria: reliability (time and volumetric), resilience, vulnerability, maximum deficit. One index was used to summarize the results, the water resources sustainability index. The aforementioned metrics were estimated for water demands and water sources. Results showed that all demands almost will be supplied under this scenario while surface and ground water resources would be in critical conditions. In other words, water management in the Zayandehrud Basin is based on supplying water demands at the expense of loss of water resources. Under baseline scenario, although the sustainability of water demands will be desirable but water resources will be thoroughly unsustainable. Analyzing the future status under baseline scenario implies that future studies to apply IWRM in the Zayandehrud Basin should be emphasized on scenarios which be developed based on: (i) demand management especially for domestic and agricultural demands, (ii) controlling water extractions from aquifers, (iii) reducing pressure on groundwater resources, (iv) setting appropriate times to water supply especially for groundwater resources and agricultural and municipal demands, (v) studying water transfer from other basins, (vi) changing the method of irrigation from flooding to pressurized systems, (vii) optimizing standard operational policy (SOP) and rule curve of the Zayandehrud Dam to improve its performance. Developing the hydrologic model, linking a distributed groundwater model to the Zayandehrud WEAP model and assessing socio-economic parameters are suggested for future studies in the basin. In future research, the authors will introduce three scenarios for IWRM for this basin using the Zayandehrud WEAP model explained in this document and evaluate the sustainability of each scenario and compared with baseline scenario that presented at this paper.

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