1   **Analysis of effective environmental flow release strategies for Lake Urmia restoration**

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13

14   **Abstract**

15   Saline lakes have diminished considerably due to large-scale irrigation projects throughout the

16   world. Environmental flow (EF) release from upstream reservoirs could help conserve and

17   restore these lakes. However, experiences from regions lacking environmental legislation or

18   with insufficient water resources management show that, despite EF allocation, farmers tend

19   to use all available water for agriculture. In this study, we employed a new method for

20   designing environmental flow release strategies to restore desiccated terminal lakes in arid and

21   semi-arid regions with intensive cultivation within the catchment. As a novelty, the method

22   takes into account farmers' water use behavior, return flow from irrigation, interaction with

23   groundwater, evaporation together without considering any detail of each and natural flow

24   regime in upstream systems to design an optimum monthly EF release strategy for reservoirs.

25   We applied the method to the water resource system of Lake Urmia, once the largest saline

lake in the Middle East and now one of the most endangered saline lakes in the world. The analysis showed that the EF released is exploited by lowland farmers before reaching Lake Urmia and that inflow to the lake from some rivers has decreased by up to 80%. We propose a new EF release strategy that requires a considerable change in practice whereby water is released in the shortest possible time (according to reservoir outlet capacity) during the period of lowest irrigation demand in winter. Restoring the lake to minimum ecological level would require 2.4-3.4 km^3 EF allocation by different methods of release based on the recent condition (2002-2011) of the lake.

Key words: Lakes, water scarcity, agriculture, irrigation, compliance.

1. Introduction

Due to increased irrigation in arid and semi-arid regions, most closed lakes with intensive agriculture in their catchment are decreasing in size. The Aral Sea in central Asia and Lake Chad in Africa are two well-known examples of such lakes with severe water level decline (Torabi Haghighi and Kløve, 2017). In Iran, the lakes and wetlands drying out include e.g., Lake Urmia , Lake Hamoun , Gavkhuni marsh , and Hoor-Al-Azim wetland (Madani., 2014). Lake desiccation is typically accompanied by other environmental problems such as groundwater decline, river flow reduction, reduced water quality, habitat loss, land subsidence, and dust and sand storms.

Lake Urmia has received most research attention, as it is the largest hypersaline lake in the Middle East and has been shrinking dramatically since 1995, with this desiccation mainly being attributed to anthropogenic causes (Abbaspour et al., 2012; Hassanzadeh et al., 2012; UNEP &

51 GEAS, 2012; Fathian et al., 2014; Madani, 2014; Tourian et al., 2015; Fazel et al., 2017a;).

52 The total cultivated area in the lake catchment has increased from 150 km^2 in 1980 to 400 km^2

53 in 2007 and is considered the main reason for lake drying (Nouri et al., 2017). The water level

54 decline and the related environmental crisis have been widely reported (Abbaspour &

55 Nazaridoust, 2007; Karbassi et al., 2010; Zarghami, 2011; Hassanzadeh et al., 2012; UNEP &

56 GEAS, 2012; Kakahaji et al., 2013; Fathian et al., 2014; Tourian et al., 2015). Thus, lake

57 restoration is now a major task for governmental and non-government organizations, in Iran

58 and elsewhere (Hassanzadeh *et al.*, 2012; Fathian *et al.*, 2014).

59

60 Environmental flow (EF) is a tool for assigning water release from dams to restore lake inflows,

61 in order to increase lake levels. EF regimes can be designed to mimic natural flow regimes

62 (Poff *et al.*, 1997; Lytle and Poff, 2004; Torabi Haghighi and Kløve 2015) or to meet specific

63 flow targets (Poff *et al.*, 1997; Lytle and Poff, 2004). In arid regions, EF allocation must also

64 consider water consumption patterns in order to be successful, as shown by Torabi Haghighi

65 and Kløve (2017). The main objective of the present work was to design an EF release scheme

66 for Lake Urmia that can achieve the minimum ecologically acceptable water level of about

67 1274.1 masl (meter above sea level), as proposed by Abbaspour and Nazaridoust (2007). The

68 methodology presented builds on recent work on EF regimes (Torabi Haghighi & Kløve, 2017),

69 on the sensitivity of lakes to flow regime change (Torabi Haghighi & Kløve 2015) and lake

70 hydrogeography (Torabi Haghighi et al., 2016).

71

72 **2. Material and method**

73

74 **2.1 Study area**

75 Lake Urmia is a large (maximum 6000 km^2 area) hypersaline lake in north-west Iran, extending

76 from 37°06'15'' to 38°15'15''N and from 45° 00'13'' to 45°55'20''E. The lake is a Natural

77 Park and UNESCO biosphere reserve (since 1976), and was listed as a Ramsar site in 1971

78 (Nouri et al., 2017). The lake and its 51,876 km^2 catchment (Fig. 1) are important for 6.5

79 million people whose main sources of income are agriculture and industry. Cropland and

80 orchards comprise about 10% of the catchment area, but consume more than 90% of all

81 renewable water resources in the Lake Urmia basin (Fazel et al., 2017b). Surface water

82 provides about 60% of agricultural water demand (OWWMP, 2011a), via reservoirs, diversion

83 dams, canals, and pumps from rivers and streams. The construction of large dams along the

84 main stream and major tributaries has significantly changed the natural flow regime of the

85 basin's rivers. Mean annual precipitation in the basin is about 357 mm, mainly falling in winter

86 and spring (Fazel et al., 2017a). Annual potential evaporation in the area varies from 1050 mm

87 in the north-east to 1550 mm in the south-west (OWWMP, 2011b). General overview of

88 irrigation, allocation mechanisms and responsible institutions in Urmia lake has been presented

89 in Annex 1.

90 The main rivers in Lake Urmia basin are the Zarinehroud, Siminehroud, Mahabadchay,

91 Gadarchay, Ajichay, Zulachay, Brandooz, Qalechay, Laylan, Nazluchay, and Rovzehchay.

92 More than 75% of lake inflow is supplied by six rivers (Fig. 1). In this study, we used data

93 from for each sub-basin of the major rivers (the closest gauge to Lake Urmia and one gauge

94 from the upstream, Fig. 1a). Based on the recorded flow at the last station on each river flowing

95 into the lake, mean annual available flow in the Lake Urmia basin for the four decades since

96 1971 has been 4.4, 5.0, 3.4 and 2.3 km^3 (Fig. 1b-e). During this time, the total cultivated area

97 has expanded significantly (approximately tripling in less than three decades), resulting in

98 irrigation water consumption increasing annually from 1.8 to 5.5 km^3 (Nouri et al., 2017).

99

2.2 Methodology

2.2.1 Environmental flow scenarios

The approach developed here to assess EF builds on a few hydrological statements and facts. We assumed that lake inflow is the response of its upstream basins to rainfall. Moreover, in pristine basins, the flow rate typically increases along major rivers due to increasing contributing area (Eq. 1) and the flowrate at headwater (upstream) gauges is a fraction of that at downstream gauges. Thus the flow rate at downstream gauges is a function of that at upstream gauges (where the downstream gauge is the last gauging point on the river before discharging into the lake). This (for month i) can be expressed as:

$$Qi_{downstream} = f\left(Qi_{upstream} \right) \qquad (1)$$

==Over time, due to increasing water consumption by the agricultural sector, the flow regime changes,== since, farmers use as much water as possible during the irrigation season to expand their business and upgrading the facilities for irrigation. Thus, the water consumption in the lower part of basin is then a function of available water in the river (Eq. 2). Consequently, the flow rate at downstream gauges (here inflow to Lake Urmia) is the difference between upstream gauge and water consumption amounts (Eq. 3), which can be expressed by the functions (for month i):

$$Qi_{consumption} = f\left(Qi_{upstream} \right) \qquad (2)$$

$$Qi_{consumption} = Qi_{upstream} - Qi_{downstream} \qquad (3)$$

In seasonally irrigated regions, the monthly relationship between upstream and downstream flow can be divided into two seasons: natural season, where the upstream and downstream monthly discharge has better fits the relationship in Eq. 1, and modified season, where the

125   upstream and downstream monthly discharge better fits the relationship in Eq. 2. Thus, the

126   monthly contribution (percentage) of upstream flow to downstream flow (here called P_1- P_{12})

127   can be calculated by using one of Eq. 1 or 2 (which has higher monthly regression coefficient),

128   depending on the status of the water system (pristine or extensively irrigated). The main

129   advantage of these functions (Eqs. 1-3) is that, the approach consider the system as a black box.

130   The water release (EF) to the lake can be affected by several factors such as return flow from

131   irrigation, interaction with groundwater, evaporation and so on. Our functions (Eqs. 1-3) and

132   our approch, however, present all potential flows and process without the need on detail

133   information of individual flow processes and parameters.

134   For lake restoration (the target for allocating EF in Lake Urmia basin), the optimum condition

135   for EF release is to maximize the amount of flow at downstream gauges, i.e., inflow to the lake.

136   Assuming a monthly EF release (Eq. 4) for different periods (1-12 months), each month will

137   have a release coefficient (C_i) that defines the monthly contribution to annual release (Eq. 4).

138   We considered the annual EF ($EF_{An.}$) to be released based on two monthly distribution

139   approaches: I) uniform release and II) weighted release. In method I, we considered uniform

140   monthly release, whereby $EF_{An.}$ is divided by number of months and an equal magnitude of EF

141   is released during each month of the release period (Eqs. 4 and 5). In method II, we considered

142   weighted monthly release, where the monthly release coefficient (C_i) is based on the

143   contribution of upstream gauges to downstream gauges (P_1-P_{12}) for each month (Eqs. 4 and

144   5). In this method, the months in which upstream flow make a greater contribution to

145   downstream flow (larger P_x or lower irrigation effect in this case) are a higher priority for

146   release (coefficient C_i is greater):

147   $$EF_{MR_i} = C_i \times EF_{An.} \tag{4}$$

148   $$C_i = \begin{cases} Method\ I: \dfrac{1}{n} \\[2ex] Method\ II: \dfrac{P_i}{\sum_{j=1}^{n} P_j} \end{cases} \tag{5}$$

149   where EF_{MRi} is monthly environmental flow release at the upstream point (in i^{th} month), C_i is

150   monthly release coefficient for month i, $EF_{An.}$ is the annual EF allocated, n is the number of

151   months during the release period (can vary between 1-12 months), and P_i is the contribution of

152   upstream flow to downstream flow.

153   The target for EF release is to increase water levels and restore the lake and the main goal of

154   the EF regime is maximizing inflow to the lake. By considering this fact and based on Eqs. 4

155   and 5, different options for monthly EF release were generated. Each release period included

156   the months with the greatest contribution to lake inflow. For example, if the ranking of monthly

157   contribution in descending order were May, April, March, February, January, December, June,

158   November, October, July, August and September, the four-month release period would be

159   February-May (i.e., May, April, March, and February).

160   Using the two methods (I, II) developed for water release and considering the period for release,

161   we developed two groups of monthly EF release: short-period release and annual release. In

162   short-period release, we assumed $EF_{An.}$ release in a period of 1-6 months and with nine different

163   options for this monthly release: (monthly release (same for both methods), and four uniform

164   (Method I) and four weighted (Method II) release options for 3-, 4-, and 5-month release). For

165   annual release, in addition to one uniform and one weighted release, we developed another

166   annual release scenario based on the Tennant method (Tennant 1976), which is the

167   recommended method in Iran (Tharme, 2003). Based on the Tennant method, EF in the Lake

168   Urmia basin must be released during two periods (April-September (60%) and October-March

169   (40%)). Thus in total, we had 12 different release options (nine short-period and three annual

170   releases). For each option, we had a monthly distribution of release as:

171   MEFU= $\{c_1, c_2 \dots c_i \dots c_{11}$ and $c_{12}\}$ (6)

172     $\sum_{i=1}^{i=12} c_i = 1.0$ (7)

173   where MEFU is the distribution of of monthly release of EF at the upstream and c_i is the

174   percentage of monthly release upstream for month i.

175   Net monthly EF release is dependent on the amount of annual EF ($EF_{An.}$) allocated by the

176   decision maker:

177   NMEFU= {NMEFU $_1$, NMEFU$_2$… NMEFU$_i$… NMEFU$_{11}$ and NMEFU$_{12}$}

178   NMEFU $_i$= $c_i \times EF_{An}$ (8)

179     $\sum_{i=1}^{i=12}$ NMEFU i $= EF_{An}$ (9)

180   where NMEFU $_i$ is net available EF upstream in month i.

181   Due to hydrological responses and also water consumption of sub-basins between upstream

182   gauge and downstream gauge (closest gauge to the lake), part of this NMEFU will be lost

183   depending on the month. By considering the number of months, the inflow to the lake is a

184   portion of NMEFU:

185   NMEFL= {NMEFL $_1$, NMEFL$_2$,…, NMEFL$_i$.,….., NMEFL$_{11}$ and NMEFL$_{12}$}   (10)

186   NMEFL$_i$=$P_i \times$ NMEFU $_i$ (11)

187   where P_i is the contribution of upstream flow to downstream flow (obtained from either Eq. 1

188   or Eq. 2) and NMEFL$_i$ is the net monthly EF successfully discharged into the lake during month

189   i.

190   Total inflow to the lake (I_i) is then the sum of current monthly inflow to the lake and net

191   monthly EF:

192   I_i=MI_i + NMEFL$_i$ (12)

193   where MI_i is monthly flow to the lake (here the monthly time series of lake inflow during 2001-

194   2010 was considered, because it represents a period of major modification in the river basin

195   following dam construction; see Fig. 1f)) and NMEFL$_i$ is the net monthly EF successfully

196   discharged to the lake during month i, which is dependent on annual EF (EF$_{An.}$ in Eq. 9), the

197   EF release strategy upstream (Eq. 6), and the contribution of upstream flow to downstream

198   flow.

199   To find the best monthly EF release strategy, we calculated the equilibrium water level (EWL)

200   for different values of $EF_{An.}$ from 0.2 to 3.4 km^3 at 0.1 km^3 volume intervals (31 different

201   annual EF magnitudes), through water balance simulation (in total 372 (31×12) scenarios).

202   EWL was taken as mean water level of the lake in each scenario when the lake reached

203   equilibrium conditions (Torabi Haghighi and Kløve, 2015). To find EWL, the water balance

204   simulation run was repeated (with same time series of rainfall, evaporation, and inflow for

205   2001-2010, plus relevant monthly EF) until the difference between mean water level of the

206   lake during two continuous runs was less than 0.05%. The mean water level for the last run

207   was taken as EWL. Finally, we estimated the amount of water required to reach the minimum

208   ecological level of Lake Urmia (1274.1 masl; Abbaspour and Nazaridoust, 2007) for different

209   EF release scenarios.

210

211   **2.2.2 Water balance simulation of the lake**

212   To evaluate the performance of EF release scenarios, we used a monthly time step water

213   balance simulation (Torabi Haghighi and Kløve 2015):

214    $V_{i+1} = V_i + (\Sigma Q_I - \Sigma Q_O)_i$ (13)

215    $\Sigma Q_I = R_I + P_I + G_I$ (14)

216    $\Sigma Q_O = R_O + E_O + G_O$ (15)

217   where R_I is lake inflow, P_I is precipitation on the lake, G_I is lake groundwater inflow, R_O is

218   surface water lake outflow, E_O is lake evaporation, G_O is groundwater outflow, and V_i and V_{i+1}

219   are lake volume on the first day of the current and next month.

220   In Lake Urmia groundwater exchange is very low, due to a dense sediment with low

221   permeability deposited on the bed of the lake (OWWMP, 2011), so we set Go and GI equal to

222   zero. As Lake Urmia is a closed system, the outflow of the system is only evaporation (E_O) and

223   Ro was thus also set at zero. This reduced the monthly balance equation to:

224    $V_{i+1} = V_i + (I + 10^{-6} \times (P - c \times E) \times A)_i$ (16)

225   where V_i and V_{i+1} (km^3) is lake volume on the first day of the current and next month, V_i (km^3)

226   (i^{th} month of simulation), P and E (mm/month) are rainfall and evaporation in the current

227   month, A (km^2) is lake area in the current month, I (km^3) is lake inflow, and c is a pan

228   coefficient to convert from pan evaporation to evaporation from a free water body surface. The

229   recommended coefficient for a class A land evaporation pan is 0.7 (Kohler et al., 1955, Webb,

230   1966). The water balance simulation was performed based on the lake hypsometric curve

231   developed by Sima and Tajrishi (2013) (see Fig. 2d) and flow and climate data for the last

232   decade (2001-2010) that stabilized Lake Urmia in its current situation (Fig. 2), because in that

233   period inflow to the lake was lowest (Fig. 1e). We knew that the flow change during this period

234   resulted from river modification by dams and water development, as most dams were

235   constructed before this period (Fig. 1f). Rainfall and evaporation from the lake area (Fig. 2a

236   and b) and monthly inflow to the lake (sum of all available flow data for the closest gauges on

237   each river flowing to the lake; Fig. 2c) for this period were used to simulate the lake water

238   balance.

239   Using the Nash-Sutcliffe model efficiency coefficient (Eq. 17), efficiency of simulation model

240   was evaluated (Menberu et al. 2014).

241    $E = 1 - \dfrac{\sum_1^n (WL_{obs} - WL_{sim})^2}{\sum_1^n (WL_{obs} - WL_{ave})^2}$ (17)

242

243   where WL_{obs} is observed water level in the lake, WL_{sim} is simulated water level in the lake,

244   WL_{ave} is mean observed water level in the lake, and n is number of months in the simulation.

245   The simulation code was validated using observed water level data for the period 2001-2009.

246   To validate the simulation, the observed lake water level on September 22, 2000 was defined

247 as lake initial condition for simulation. Then by using time series of rainfall, inflow, and

248 evaporation (Fig. 2 a-c), the monthly lake water levels for the period 2000-2009 were simulated

249 (Fig. 2e). The modeled water levels showed a good fit with the observed data as the Nash-

250 Sutcliffe model efficiency (Eq. 17) was 0.92.

251

252 **3. Results and discussion**

253

254 **3.1 Changes in hydrological responses in sub-basins after dam construction**

255

256 For all major rivers in Lake Urmia basin, over time the relationships of flow rate at upstream

257 and downstream gauge were changed. Over time, the number of months with a natural response

258 (stronger relationship in Eq. 1) decreased and the number with a modified response increased

259 (stronger relationship in Eq. 2). This is well demonstrated by the largest river, Zarinehroud

260 (Fig. 3). It is clear from the diagram that, before 1981, in all 12 months the contribution to lake

261 inflow was a function of upstream flow at the Sariqamish gauge. Thus the blue lines, which

262 represent the results of regression for Eq. 1, had a stronger regression coefficient than the red

263 lines (part I in Fig. 3a-l). During the second, third and fourth periods, the number of months

264 with a stronger regression in Eq. 1 (blue lines) decreased to 10, 8, and 6, respectively (parts II,

265 III, and IV in Fig. 3).

266 In the Zarinehroud river basin (During recent period (2002-2011)), where there is large-scale

267 irrigation in July-December, the flow reduction between upstream and lake inflow (which

268 represents water consumption) was a function of the upstream gauge flow (part IV, Fig. 3j, k,

269 l, a, b and c; red lines show higher correlation coefficient (R^2)). This clearly confirms that water

270 consumption is currently a function of available water in the river and that most available water

271   in the river during these months (those with red lines in Fig. 3) will be used for irrigation even

272   if the water is released as EF.

273   Based on similar evaluation of relationship between flow at upstream and downstream gauges

274   (Eqs. 1 and 2), we found that, over time, the hydrological response during the irrigation season

275   changed considerably from the natural response to a new pattern of flow for all major rivers

276   in the Lake Urmia basin (Fig. 4). The greatest river regime alteration was observed in the river

277   Ajichay, for the period 1984-1992, in 11 months of the year Eq. 1 showed a better regression

278   (blue circles in Fig. 4b1), while during 2002-2010, after significant river modification, there

279   were pristine flow conditions in only four months (blue circle in Fig. 4b2).

280

281   **3.2 Possible scenarios for releasing EF**

282

283   Based on the overall results of monthly regression (Eqs. 1 and 2) in the Lake Urmia basin, the

284   monthly contribution of upstream gauges to lake inflow was estimated for 10 major rivers

285   (Zarinehroud, Siminehroud, Mahabadchay, Gadarchay, Ajichay, Zulachay, Barandooz,

286   Qalechay, Nazluchay and Rovzehchay) for the current situation in Urmia basin (2001-2010).

287   The monthly ranking (descending order) in terms of contribution of upstream gauges discharge

288   to lake inflow was May, April, March, February, January, December, November, June,

289   October, July, August and September, for which discharge was 94.5%, 87.5%, 83.8, 69.6%,

290   58.8%, 53.9 %, 34.1%, 34.0%, 14.1, 11.2%, 9.0%, and 8.2%, respectively. Thus, the

291   contribution of headwaters to lake inflow is lowest during the irrigation season (June-October),

292   while the majority of the upstream flow (54-95%) is discharged to Lake Urmia during winter

293   and spring, due to high soil moisture, high rainfall, low temperatures, and farmers not using

294   river flow for irrigation. These results indicate that if the annual allocated EF_{An} release occurred

295   during May, more than 94% of flow would be discharged to the lake, while water release in

296   September would result in less than 9% of flow reaching the lake. By considering descending

297   order of percentage monthly contribution (and considering Eqs. 4 and 5), 12 different options

298   (A-L) for monthly EF release were generated (Fig. 5). Each release period included the months

299   with the greatest contribution to lake inflow. The EF release options A-L were calculated as

300   monthly percentage, considering different magnitudes of EF_{An} (31 different magnitudes from

301   0.20 to 3.2 km^3 at 0.1 km^3 intervals), which resulted in 372 different scenarios (using Eqs. 7

302   and 8) for EF release.

303

304   **3.3 Lake water level simulation and performance of EF scenarios**

305

306   In total, 372 scenarios for water balance simulation for Lake Urmia were developed by using

307   all 372 EF release scenarios, which were added to lake inflow during 2000-2010 (see Fig. 2c)

308   and combined with other components of water balance: rainfall (see Fig. 2a) and evaporation

309   (see Fig. 2b). Equilibrium water level (1269.6 masl) for the period 2001-2010 was considered

310   as the initial condition for simulation of EF scenarios (Fig. 6a).

311   The EWL was dependent on the magnitude of EF_{An} and EF release (Figs. 7). For instance, for

312   3.0 km^3 of EF, EWL was 1272.51, 1274.23, 1275.22 and 1277.22 masl for EF release options

313   A, C, G, and L, respectively (Fig. 6d). For 2.0 km^3 of EF, the corresponding EWL values were

314   1271.58, 1272.47, 1272.94 and 1273.78 masl, respectively, and for 1.0 km^3 of EF they were

315   1270.58, 1271.05, 1271.27 and 1271.58 masl, respectively (Fig. 6a).

316   Overall, the results showed that EF releases based on the Tennant method (release option A in

317   Fig. 5) and uniform annual release (EF release option B) are the most inefficient methods.

318   Decreasing the period of EF release led to increasing inflow to the lake and higher EWL (Fig.

319   7). Releasing the whole EF during May (release option L) was most effective for lake level

320   restoration. The possibility of achieving this form of EF release will depend on dam and

321 reservoir outlet capacity. Overall, according to our results, the best time for EF release is during

322 winter and spring (November-May). The reason is that, during this period, soil moisture content

323 is high (rainfall season) and temperature and evapotranspiration are low (winter), so

324 agricultural water consumption is low and the majority of the EF released will reach the lake.

325 Among the annual release options (A, B and C in Fig. 5a), the EF release based on the weighted

326 scheme (option C) showed a considerable increase in lake water level compared with options

327 A and B (compare lines B and C in Fig. 7). As can be seen, the most increase in water level

328 occur after switching the EF release options from B to C. The advantage of the designed EF

329 release is clearly shown by the increase in lake water level (e.g., 1.6 m increase in water level

330 for 3.4 km^3 as annual EF; see Fig. 7). The designed EF release showed better efficiency when

331 the magnitude of annual EF increased (see the length of parallel lines in Fig. 7, each

332 representing one magnitude of annual EF). By decreasing the release period, the difference

333 between EWL in method I (uniform release) and II (weighted release) was decreased, as can

334 be seen by comparing the difference between options B and C (twelve-month release) and

335 options D and E (six-month release) or options J and K (three-month release) (Fig. 7).

336

337 The choice of EF regime scenario had a considerable effect on lake level. The same target point

338 (lake re-creation by reaching a certain water level) could be obtained with different EF releases

339 and magnitudes (Fig. 7). The common part of the vertical parallel line in Fig. 7 reveals how the

340 magnitude of EF can be minimized for a certain target point (lake re-creation). For instance,

341 reaching a level of 1272.8 masl (as EWL) can be achieved by releasing 1.6 km^3 (using EF

342 release option L) or 3.2 km^3 (using release option A) (following the red line in Fig. 7). Saving

343 1.8 km^3 water through a careful EF release policy would be equal to irrigation for 150 000 ha

344 agriculture land and jobs for about 10 000 people in Lake Urmia basin. The design of EF

345 regimes is a fundamental issue for lake rehabilitation, by optimizing available water resources.

346 As mentioned, the minimum ecological level for Lake Urmia is 1274.1 masl (Abbaspour &

347 Nazaridoust. 2007). To reach to this target water level (from the recent state of the lake during

348 2001-2010 (EWL=1269.6 masl)), reservoirs need to release at least 2.4 km^3 in the best release

349 policy for EF (release option L, see black dashed line in Fig. 7). Any change in EF release (e.g.,

350 from option L to option A) would need more water to stabilize the lake at the minimum

351 ecological level. For example, the magnitude of annual allocated EF to stabilize the lake at

352 1274.1, are 2.7 and 3.0 km^3 water for release options E and C, respectively (Fig. 7).

353

354 **3.5 Environmental flow release for lake restoration or river ecosystems?**

355 According to past studies, the main concern in Iran is Lake Urmia restoration, without much

356 focus on river ecosystems (Abbaspour & Nazaridoust, 2007; Karbassi et al., 2010; Zarghami,

357 2011; Hassanzadeh et al., 2012; Kakahaji et al., 2013; Fathian et al., 2014). Therefore, the

358 present work concentrated on lake recreation by designing a EF release regime based on river

359 modification and changes in hydrological regime of sub-basins. As our results showed, the best

360 EF regime was to release the allocated EF in the greatest possible amount during the shortest

361 possible period, for example May. Undoubtedly, the major criticism of this kind of release

362 would be that it neglects riverine ecosystems. As shown in the past decade, in most of the

363 months water consumption is a function of available water in the river as seen increasing red

364 squares on the right-hand side of Fig. 4 compared with the left for major rivers in Lake Urmia

365 basin. Thus, discharging EF water to the lake during the irrigation season (red-square months

366 in Fig. 4) would not assist in lake restoration. Furthermore, more intensely irrigated areas are

367 located near the lake (Fazel, et al. 2017b), which are mostly irrigating by river flow. Therefore,

368 it can be deduced that, during the irrigation season, in most rivers there is still some flow for

369 meeting riverine ecological demands.

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4. Conclusions

Restoration of Lake Urmia is an urgent issue. Regulation of rivers (as major water supplier for the lake) have led to increased water consumption and shrinking of the lake. The results show that farmers use as much water as possible during the irrigation season (i.e., the surface water consumption is a function of available water) and often do not comply with regulations. Consequently, the relationship between lake inflow and upstream flow changes over time. Due to the large size of the Urmia basin, a large number of beneficiaries and lack of legislation, the control of water consummation in the basin is difficult or impossible. When allocated EF is released during the irrigation season, it will be used mainly for more irrigation and farming. This tendency is a threat to most closed lake systems that are located downstream of major irrigation areas on fertile plains such as Lake Urmia. Beside the need to implement policies and incentives to reduce the irrigation demand, the optimum monthly EF allocation is important and can lead to a more efficient restoration for the lake. For Urmia lake the best period for EF release is between Nov-May when the crop water demand is low. With the allocated EF, the lake at minimum ecological level can be established at 2.4-3.3 km^3. The method shows by using the black box system between upstream and downstream flow regime, we could consider overall change on upstream flow through the passing watershed which is affected by different interaction like account farmers' water use behavior, return flow from irrigation, interaction with groundwater, evaporation together without considering any detail of each .

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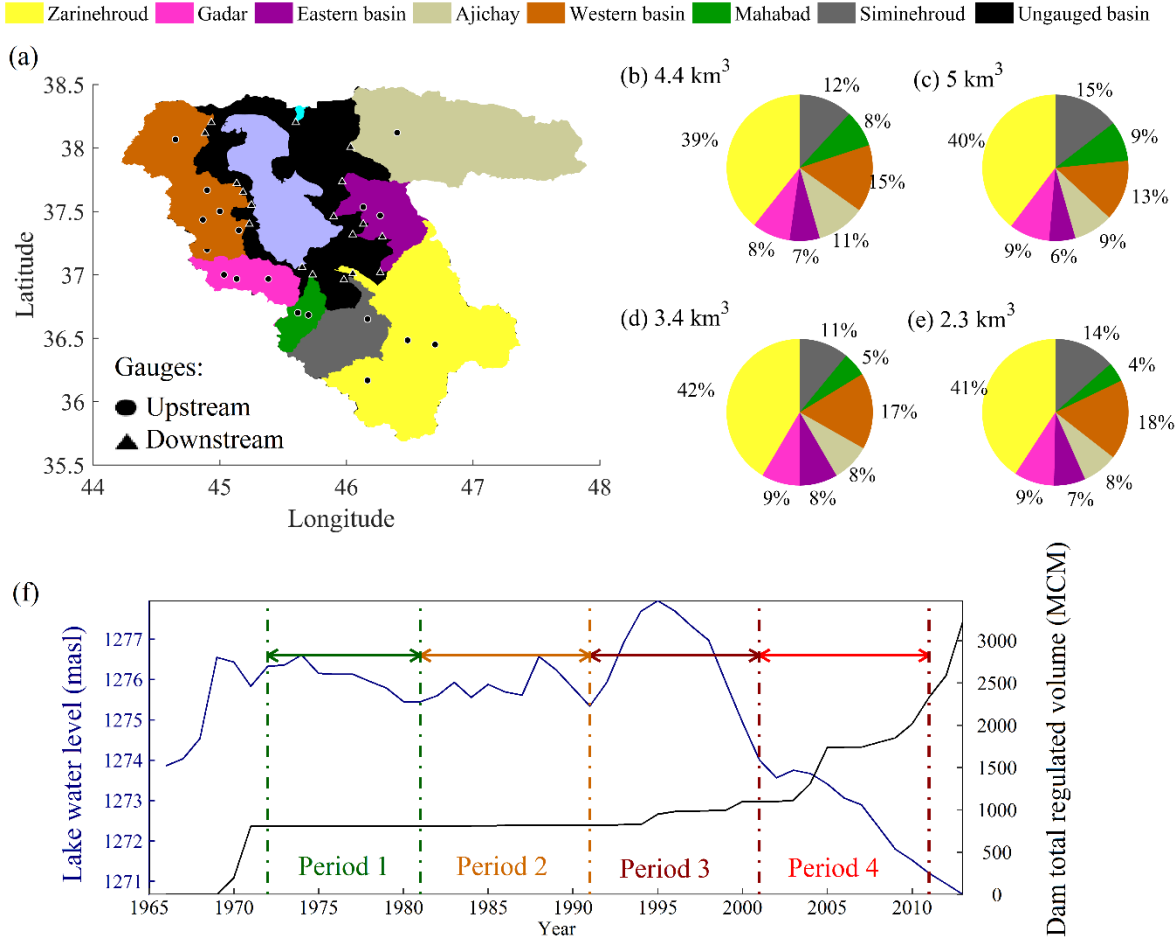457   **Figures**

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461   Fig. 1. a) Lake Urmia and its sub-basins and contribution of different sub-basins to lake inflow

462   in the period: b) 1972-1981, c) 1982-1991, d) 1992-2001, and e) 2002-2011. f) dam regulation

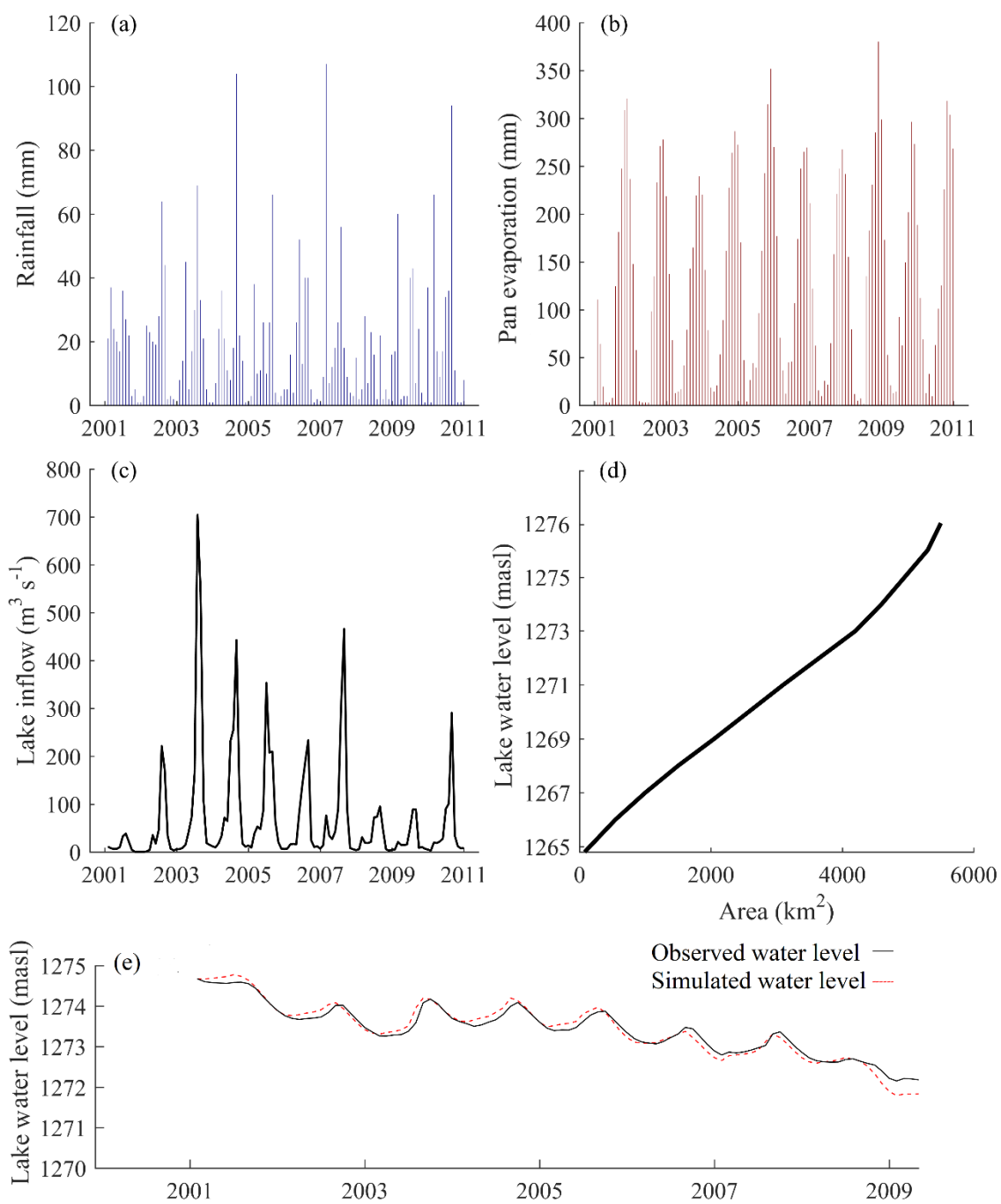463   volume and lake level changes for 1965-2011 (MCM: million cubic meter).

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473   Fig. 2. Input data for Lake Urmia water balance simulation. a) rainfall (mm), b) pan evaporation

474   (mm), and c) inflow, September 2001- September 2010. d) area-water level curve of lake and

475   e) simulated and observed water level (2001-2009).

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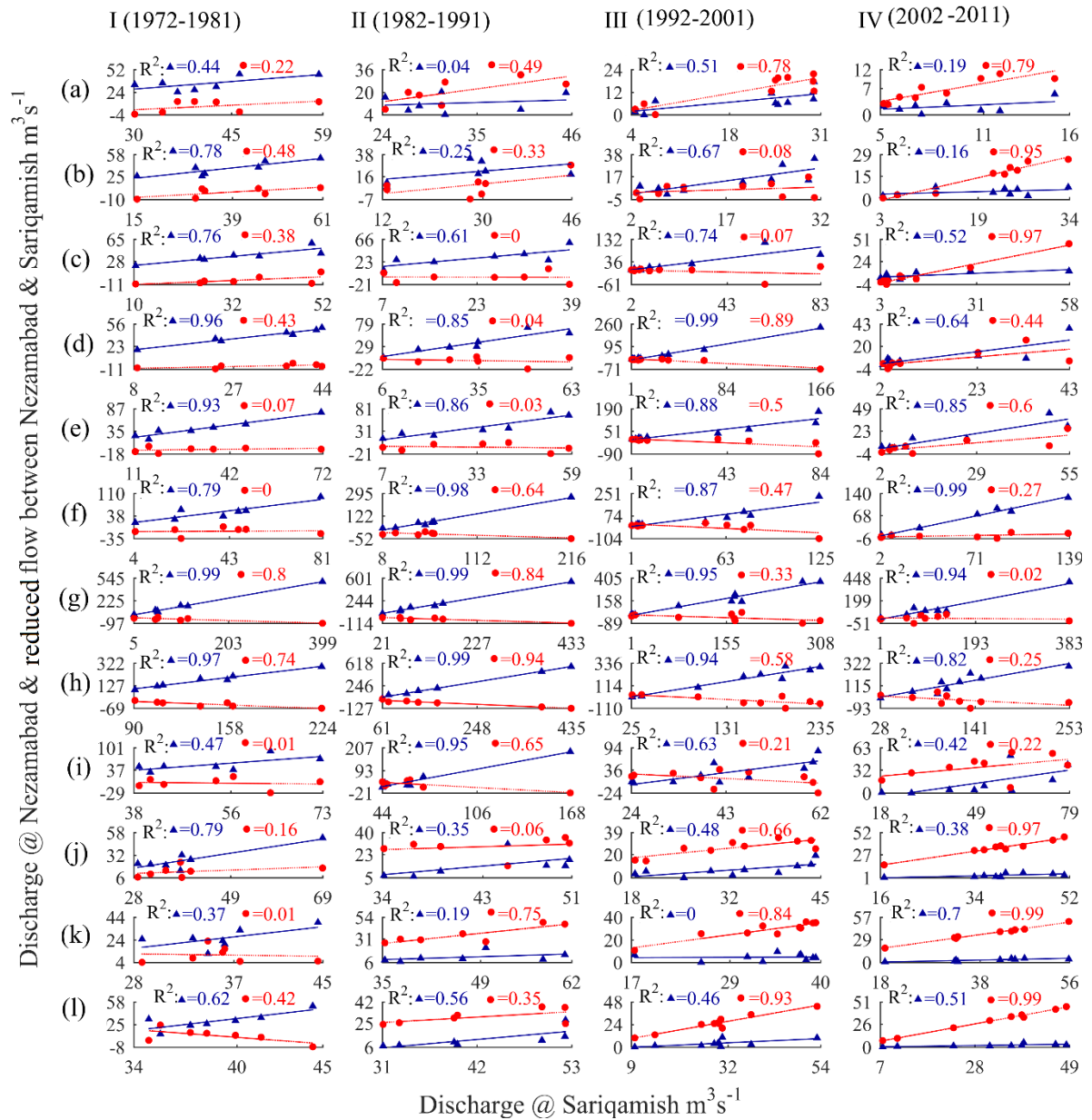
478   Fig. 3. Upstream (Sariqamish gauge) and downstream (Nezamabad gauge) monthly (a-j:

479   October-September) flow relationship in the river Zarinehroud in different periods (I-IV). Blue

480   lines and triangles: regression line and points for Eq. 1, red line and circles: regression line and

481   points for Eq. 2.

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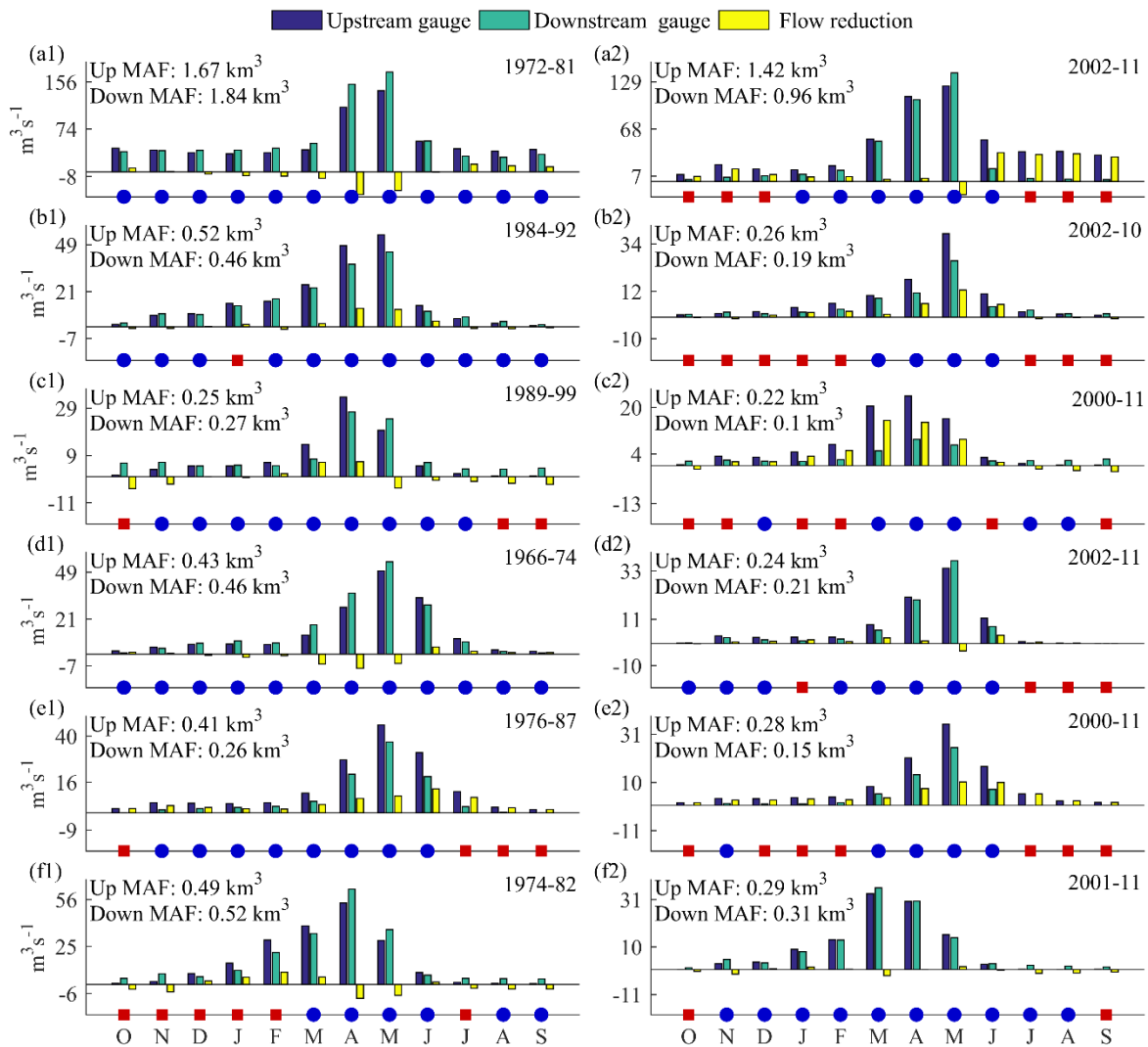
Fig. 4. River flow at the closest gauge to Lake Urmia (Down) and at upstream gauges (Up) in major rivers in the basin: a) Zarinehroud, b) Ajichay, c) Mahabadchay, d) Gadarchay, e) Nazluchay, and f) Siminehroud, where the suffixes 1 and 2 refer to earliest and latest period, respectively, when both gauges have flow data. Blue circles and red squares indicate whether Eq. 1 or 2, respectively, has the stronger regression coefficient, O-S: October-September, MAF: mean annual flow.

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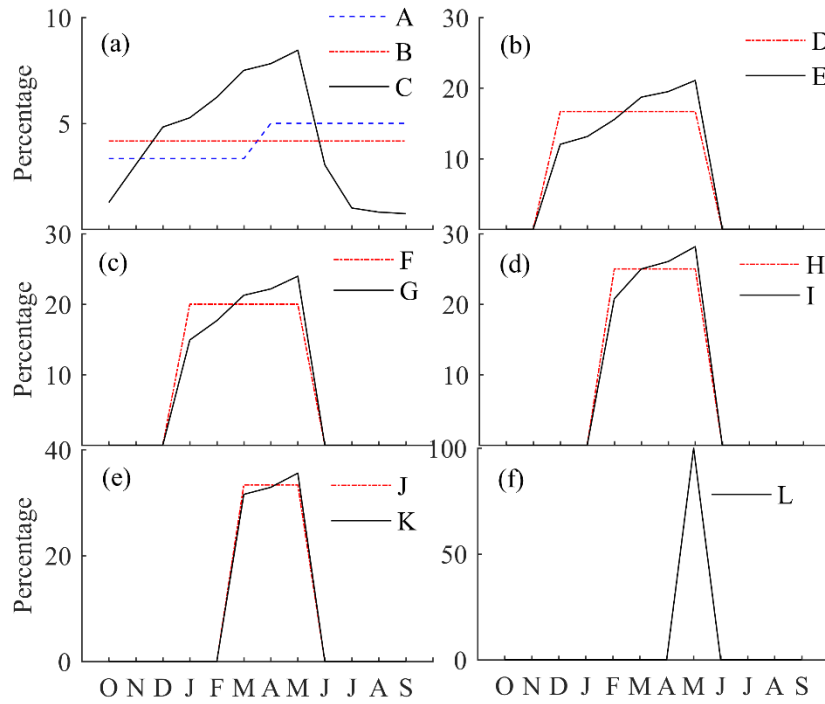
Fig. 5. Monthly distribution options for environmental flow (EF) release: a) twelve-month

release (A: Tennant, B: uniform, C: weighted), b) six-month release (D: uniform, E: weighted),

c) five-month release (F: uniform, G: weighted); d) four-month release (H: uniform, I:

weighted), e) three-month release (J: uniform, K: weighted), f) one-month release (L: uniform
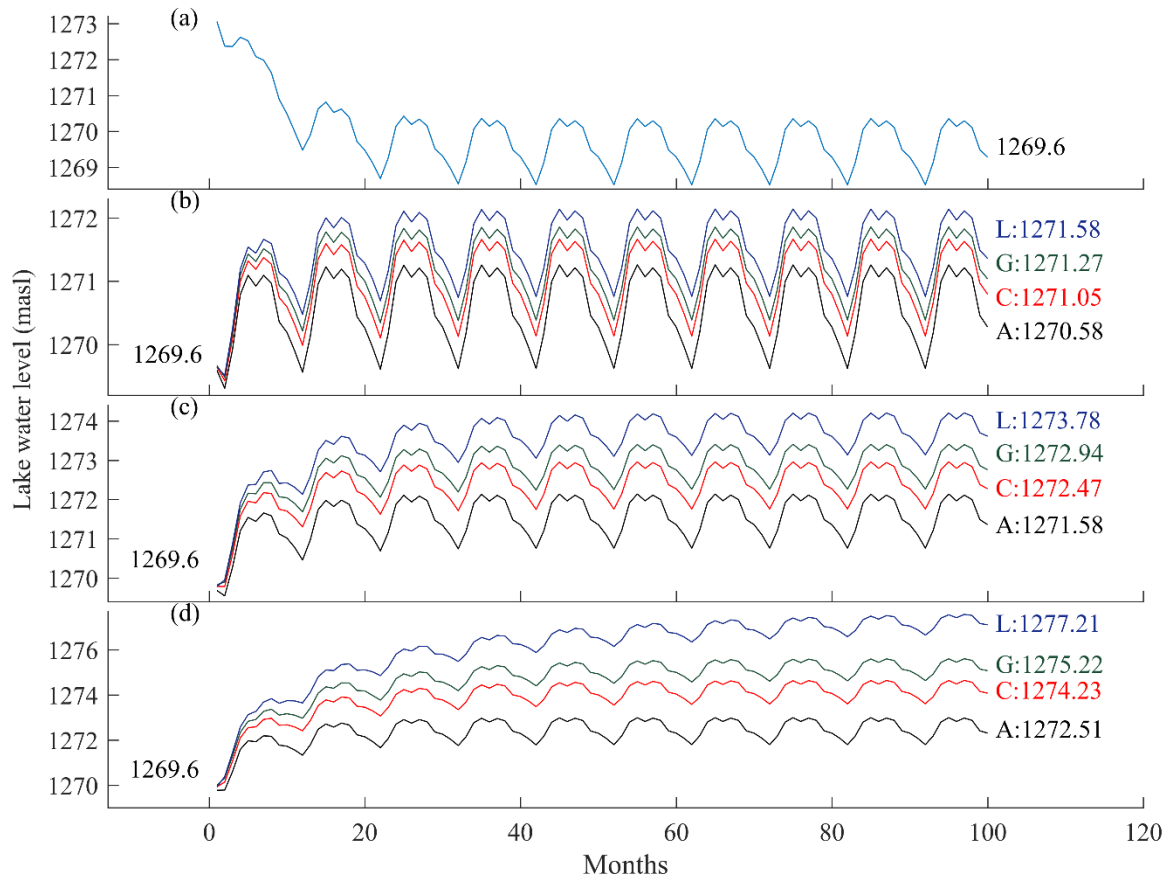
or weighted).

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Fig. 6. Water level fluctuation in Lake Urmia. a) Long-term water level simulation to calculate environmental water level (EWL) for the current situation (based on lake condition 2001-2010). b, c, d) Performance of selected environmental flow (EF) release options (A and C: Tennant and weighted twelve-month release, respectively; G: five-month weighted release; L: one-month release) for three magnitudes of annual EF: 1.0, 2.0 and 3.0 km^3.

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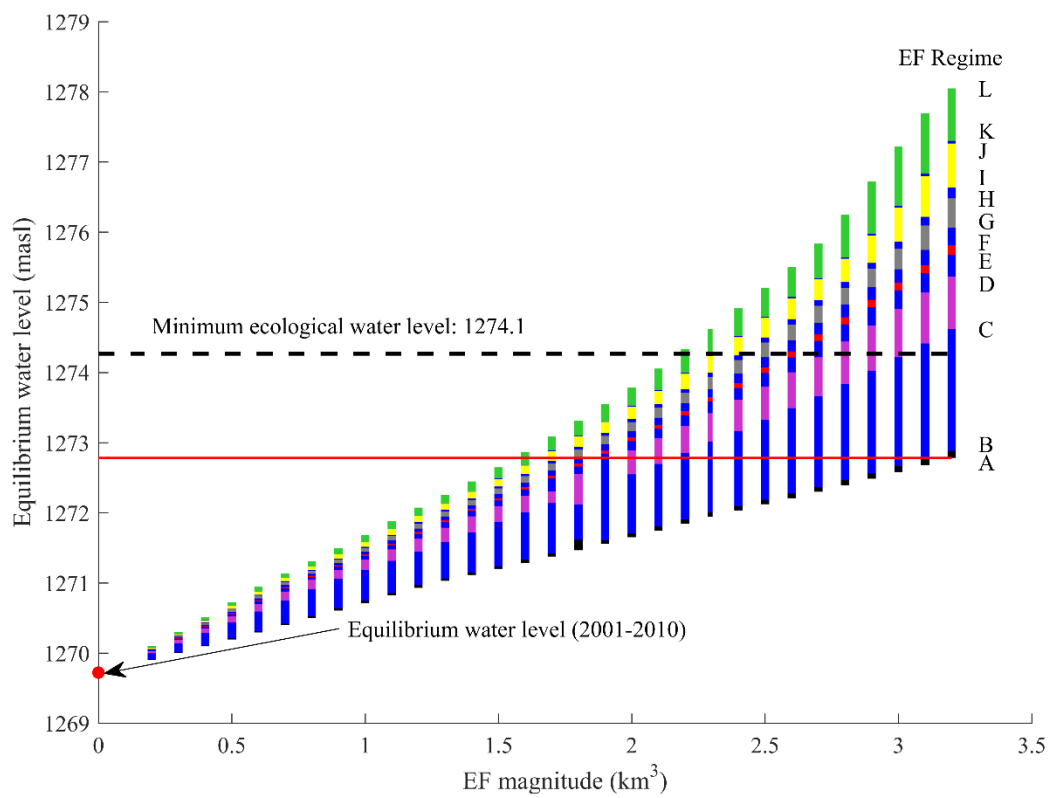
Fig. 7. Equilibrium water level (EWL) for different environmental flow (EF) scenarios. A change in the color in each parallel line shows the water level increase when switching from one EF release option (A-L) to other.