1   **"Water flow" and "preferential flow": A State-of-the-Art throughout the literature**

2   **review**

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12   **Abstract**

13   Studies dealing with water flow and preferential flow are of typically importance because there are still many

14   unresolved water security and scarcity problems. It may indeed be a valuable idea to provide a special review of the

15   progress in the water flow and preferential flow for the applied water science community and to identify what is still

16   missing or unresolved to improve predictions of surface water and groundwater quality within multiscale. This paper

17   aims to review the state of the art on water flow and preferential flow published per year from 1995 to 2015,

18   respectively, and to present a discussion of perspectives and some significant advances in the main themes of water

19   flow and preferential flow that have emerged in recent years, with insights, some promising areas for future work, and

20   suggestions also being provided regarding potential research trends, requirements and solutions. Recorded reports

21   show that it is of general interest in water flow in the period 1995-2015 and also there are clear significant trends from

22   physical hydrology and socio-hydrology perspectives. The future trend of water flow which is predicted in some way

23 indicates a general increase. The term of preferential flow, its significance and progress in the period 1995-2015,

24 shows that despite the increasing number of papers published on preferential flow, there has not been as much attention

25 paid to this topic as we have expected, given its vital role in soil hydrology, water sustainability, slope stability and

26 agricultural management. Finally, existing love-hate relationship between water flow and preferential flow pathways is

27 reviewed.

29 **Keywords**

30 Water flow; Virtual water flow; Blue water flow; Green water flow; Water footprint; Preferential flow

1. Introduction

33 Most concerning environmental, economic and social issues threaten livelihoods of people worldwide, agricultural

34 production, industrial chain, energy projects, other forms of anthropogenic water consumption and ecological use since

35 water natural resources are getting scarce and polluted with increasing population and temperature, higher food

36 demand and changing precipitation patterns. These issues also exert significant influences on sustaining the survival of

37 ecosystems (Van Oel and Hoekstra, 2012; Schewe et al., 2014; Elliott et al., 2014; Cazcarro et al., 2014; Lee and Bae,

38 2015; Dalin et al., 2015; Johansson et al., 2016; Michalak, 2016; McColl et al., 2017). Water is one of the most

39 complex components on the planet operating at the interface of the hydrosphere, atmosphere, pedosphere and

40 biosphere. Long-term water use sustainability, in some way, tends to be the most significant consideration at global

41 scales. Agriculture is the largest consumptive sector of water use in global water systems (Schewe et al., 2014;

42 Haddeland et al., 2014). In addition to agricultural sectors, water is also used for domestic and industrial sectors. Large

43 scale transfer of water from water rich regions to water poor regions has been conducted to meet water demands (Troy

44 et al., 2015). However, increased aridity, reduced soil water content, changes in climate variability and frequency of

45 extreme weather events pose highly direct threat to water resources sustainability, water security and agricultural food

46 security even severe land degradation and desertification (Maestre et al., 2015; Phalkey et al., 2015). An unprecedented

47 global water crisis in human history has been predicted (Elshafei et al., 2014) which is dramatically related to land

48 degradation processes that are millennia old (Cerdà and Lavee, 1999; Jafari and Bakhshandehmehr, 2016).

49 It is typically evident that the function, cycle, intrinsic property and in particular the flow of water are critical to

50 sustain health and stability of natural and man-made ecosystems. We have considerable knowledge of water, its

51 formation and distribution, but our understanding upon water flow and preferential flow is incomplete and rather

52 faraway. In the previous, as well as in the recent, more studies relating to water flow including oil-water flow (Gao et

53 al., 2015; Boostani et al., 2017), air-water flow (Felder and Chanson, 2016; Felder and Pfister, 2017), canopy water

54   flow in plant (Fricke, 2015), water flow in rock fracture or glacier (Fountain et al., 2005; Neuman, 2005), debris-water

55   flow (Malet et al., 2005), flooding-water flow (Gaines, 2016), river-water flow (Derx et al., 2013), subsurface

56   storm-water flow (van Schaik et al., 2008; Nieber and Sidle, 2010), water flow in soils (preferential flow and soil

57   matrix flow) and water flow within watersheds (surface water flow and groundwater flow) have got a broader interest

58   in some way (Keesstra, 2007; Zema et al., 2016).

59   The studies of water flow above are implied from physical hydrological perspectives and are relating to water

60   security and sustainability. However, with regard to socio-hydrological perspectives, the human-society-water nexus

61   could change water resources management and could be better understood when virtual water flow is introduced.

62   Global virtual water flow is estimated based on trade in agricultural and industrial sectors. The sum of global virtual

63   water flow related to trade in agricultural and industrial products in the period from 1996 to 2005 was 2320 $Gm^3 y^{-1}$ on

64   average. The largest share (76%) of the virtual water flow between countries is related to global trade in crops and

65   derived crop products. Virtual water flow trade in animal products and industrial products contributed 12% each to the

66   global virtual water flow. The volume of global virtual water flow related to domestically produced products was 1762

67    $Gm^3 y^{-1}$ (Hoekstra and Mekonnen, 2012). The total volume of global virtual water flow includes virtual water flow that

68   is related to re-export of imported products. In light of the concept of virtual water flow, water footprint including

69   consumptive and degradative water footprint was highlighted to emphasize on the link between human and water to

70   produce the products (Hoekstra, 2013) and was used to characterize the volume of freshwater resources consumption

71   and pollution in relation to production or consumption (Hoekstra, 2003). The blue, green and grey water flow, are three

72   components of the water footprint (Hoekstra and Mekonnen, 2011). Blue and green water flow are two aspects of the

73   consumptive water footprint, while grey water flow which represents the volume of water assimilating pollutants is not

74   significantly neglected as people consider the degradative water footprint. The water in runoff, lakes, reservoirs,

75   wetlands and man-made structures can be directly used by human consumption, in general, and could be regarded

76   them as blue water (surface water and groundwater). Blue water is equal to the difference between evapotranspiration

77   and precipitation when evapotranspiration is higher than the effective precipitation, while blue water is zero when

78   evapotranspiration is lower than precipitation. Water evaporation during and after irrigation process is not the

79   component of blue water. Because this part is back the natural system afterwards. Furthermore, the water stored in

80   unsaturated soil layers is defined as green water (precipitation), either reclaimed by the atmosphere through soil

81   evaporation or consumed by the plant roots and lost through transpiration during photosynthesis (Vanham, 2016).

82   Green water is the major part of water use for agricultural sector. In general, green water is equal to the effective

83   precipitation when evapotranspiration is higher than the precipitation during crop growth, while green water is equal to

84   evapotranspiration when evapotranspiration is lower than effective precipitation. While the grey water refers to the

85   volume of freshwater which can assimilate the concentration of given pollutants into natural back ground

86   concentration to satisfy the ambient water quality standards. It is not a real water volume used along production

87   processes, but the volume used to restore water quality (Lovarelli et al., 2016). Therefore, the three component of

88   virtual water flow is highly interactive and important for the water balance and stability. For example, the increase of

89   green water flow to the atmosphere due to the high agricultural management or forested practices leads to the decrease

90   of regional surface water flow. This in turn affects the availability of long-term blue water flow and the change of

91   groundwater table.

92   In addition to the significance of water flow above, preferential flow is a common and widespread phenomenon of

93   water flow in soils with macropores (Beven and Germann, 2013; Zhang et al., 2016a). Just now we referred that

94   agriculture was the largest consumptive sector of water use. However, large numbers of pesticides were put into

95   agricultural catchments with the development of urbanization, industrial and agricultural developments (Kim et al.,

96   2017). Those pesticides could be carried by water flow through the soil profiles to the groundwater table quickly. So a

97   wider range of studies in some way should often provide more data to interpret why agricultural pesticides and other

98   contaminants that should sorb strongly onto soil particles were being detected in groundwater tables and drains. Even

99   if these contaminants sorb onto fine colloidal materials, it was still confused to explain how water flow pathways could

100   carry those fine materials to depths without being filtered out by the surrounding soil matrix. The occurrence of

101   preferential flow might be the significant driver for the phenomenon. As an unpredicted water flow in vadose zone,

102   preferential flow is continuing to get more attentions despite lots of unresolved questions due to the complexity of

103   vadose zone. Because it is clear that the vadose zone in which water, gas and solute transfer between the soil surface

104   and water table is involved in many aspects of soil hydrology, such as soil water storage, soil erosion, water infiltration,

105   evaporation, groundwater recharge and so forth (Nielsen et al., 1986).

106   In this review, it is immediately clear that water flow are preferential flow are such broad subjects so that this short

107   review is necessarily selective rather than comprehensive. We focus on the study and resulting scientific literature of

108   water flow in soils and within watersheds from physical hydrological and socio-hydrological perspectives and

109   preferential flow. It aims at evaluating to what improvements in recent water flow and preferential flow have made,

110   whether the love-hate relationship between water flow and preferential flow pathways have been evaluated. It is the

111   objective of this paper to review the progress of water flow and preferential flow with the aim of delineating global

112   water resources security which may be elucidated by organic matters, pesticides, contaminants and heavy metal to the

113   groundwater table without resistance.

114

115   **2. Methods**

116   A comprehensive literature search was conducted to conclude the significance and progress of "water flow" and

117   "preferential flow", respectively. Based on the extensiveness of the existing literatures and the availability of most

118   studies, we focused on and started with the set of published papers with the topic of "water flow" and "preferential

119   flow" from 1995 to 2015 using the database of Web of Science (WoS). No restrictions on research types were applied.

120   In light of the literature survey, the term "water flow" and "preferential flow" in their titles, abstracts or keywords were

121   used as search concepts. We then refined the scope of water flow studies in physical hydrology and socio-hydrology,

122   respectively. For water flow in physical hydrology we considered surface water flow, groundwater flow and water

123   vapor flow into the atmosphere, while for virtual water flow, green water flow, blue water flow and grey water flow

124   were implied for water flow in socio-hydrology. An analysis of published papers with the topic of water flow on the

125   temporal and geographical dimension was performed. A map was made for the total number of published papers of

126   water flow (Fig. 1). In preferential flow studies, we statistically analyzed all papers by drivers, degrees, properties,

127   scales, models, methods, mechanisms and types of preferential flow. Methods applied for considering the two topics

128   include descriptive analyses. A descriptive approach is to compare the existing trends of the two and make clear sense

129   of their interactions in a single analysis framework. Additionally, the number of publications per year and the number

130   of references per country by author affiliations and area in which the research was conducted were summarized.

131   Finally, a database with the topic of water flow and preferential flow pathways—a love-hate relationship was produced

132   from the published literature. Relationship between water flow and preferential flow pathways was investigated

133   through a diagram (Fig. 7).

134

135   **3. Results and discussion**

136   **3.1 State of the art on water flow**

137   **3.1.1 Water flow on a world extent**

138   The special section themed with water flow has got broader interests in the period 1995-2015. In recent years, there

139   has been a growing body of research relating to water flow. It is easy to rapidly discern the similarities (studies on

140   drivers of water flow) and differences (studies in physical hydrology and socio-hydrology) in these literatures. For

141   example, the similarities of water flow studies were concentrated on their drivers, such as human activities (Jiang et al.,

142   2015), changes in climate variability (Haddeland et al., 2014; Gan et al., 2015; Jiang et al., 2015; Lee and Bae, 2015;

143   Najafi and Moradkhani, 2015; von Blanckenburg et al., 2015; Wang et al., 2015; Zhou et al., 2015a); land use changes

144   (Algeet-Abarquero et al., 2015; Nourani et al., 2015; Yuan et al., 2015; Zhou et al., 2015b; Rodriguez-Lloveras et al.,

145   2016a, b; Zhao et al., 2017); afforestation or vegetation reconstruction (Zhang et al., 2015a; Hayashi et al., 2015;

146   Buendia et al., 2016); precipitation (Lutz et al., 2014: Emmanuel et al., 2015; Sadeghi et al., 2016); soil water content

147   (Lal et al., 2015); biological soil crusts or microbiotic crusts thickness (Chamizo et al., 2015; Kidron, 2015); hillslope

148   (Liu et al., 2000; Michaelides et al., 2002; Fujimoto et al., 2008); atmospheric carbon dioxide (CO_2) (Field et al., 1995;

149   Gedney et al., 2006); solar dimming (Stanhill and Cohen, 2001); management regimes (van Oudenhoven et al., 2015);

150   soil burn (Vieira et al., 2015) and so forth.

151   Based on the recorded reports of studies, a global network termed with water flow is summarized. A total of

152   180751 publications which met the selection criteria were obtained online from WoS. The distribution of document

153   types and disciplines was also analyzed. Articles (175104) were the dominant document type, comprising 97% of the

154   total publications. Meanwhile, the studies were mainly concentrated on the inter-disciplines, such as water resources

155   (29969), environmental sciences (26849), geosciences (19725) and engineering chemical (14839). Papers were

156   published in 100 languages. English was the dominant language for papers published on water flow and represented 98%

157   of all published papers. From 1995 to 2015, the number of published papers increased from 4077 in 1995 to 15395 in

158   2015. The annual number of published papers increased remarkably. With respect to water flow in journal publication

159   patterns, Journal of Hydrology ranked first in the number of published papers (3170, 2%), and followed by Water

160   Resources Research (2628), Hydrological Processes (1913), Water Science and Technology (1642). The survey data in

161   Fig. 1 demonstrated: from 1995 to 2015, the largest number of published papers with the topic of water flow was

162   typically distributed in USA, followed by China, Canada, England and Japan. However, the number of this project was

163   significantly lower than the number of papers published by USA and so forth, and was represented with blue darks in

164   Fig. 1. In addition, from 1995 to 2015, the annual growth rate of published papers of water flow was typically higher

165   than growth rate in planning. The above results concluded that studies on water flow significantly increased year by

166   year.

167   It is immediately clear where current hot spots might be achieving mathematical models that integrate surface

168   water flow and groundwater flow, assessing regional or national or global water footprint (green water flow, blue water

169   flow and grey water flow) in the studies of water flow. As a result of the literature research and selection, studies on

170   water footprint take on a growing trend. The online database WoS search for literatures using the term "blue water flow"

171   resulted in a total of 2058 publications in the period 1995-2015, and 3016, 700 publications for the term "green water

172   flow" and "grey water flow", respectively. For studies of blue water flow, articles (1882) were the dominant document

173   type, comprising 91% of the total publications. In general, water resources (357), environmental sciences (353) and

174   chemistry analytical (323) are the main research fields. The number of published papers increased from 40 in 1995 to

175   190 in 2015. With respect to green water flow, articles (2548) were the dominant document type, comprising 85% of

176   the total publications. The studies were mainly concentrated on the environmental sciences (518), water resources (470)

177   and chemistry analytical (256). From 1995 to 2015, the number of published papers increased from 45 in 1995 to 324

178   in 2015. In addition, for grey water flow, articles (601) were the dominant document type, comprising 86% of the total

179   publications. The number of published papers increased from 18 in 1995 to 55 in 2015. In light of the recorded reports,

180   a variety of topics are relating to water science and environmental science. Blue water flow, in some way, is the most

181   water use component and is typically important for household or drinking water uses, industrial water uses and

182   agricultural water uses (Fig. 2). Advanced studies concluded that countries with higher amount of green water flow

183   tend to have intense agricultural sectors and more water bodies (Veettil and Mishra, 2016).

184

185   **3.1.2 Water flow in physical hydrology**

186   Traditional hydrological science focuses on the study of physical water flow and water stock based on hydrological

187   models. In particular, hydrological models rely on physical principles of mass and momentum balance to characterize

188   water flow and stock. With regard to physical hydrology, precipitation refers to a key input of freshwater resources to

189   the surface, while evapotranspiration refers to a key pathway for freshwater to return to the atmosphere. Surface water

190   flow and groundwater flow are two key components of water flow in physical hydrology. In general, surface water

191   flow is generated due to precipitation excess and not due to soil saturation (Hueso-González et al., 2015). Surface

192   water flow on the land surface or watershed is a key unit of analysis in physical hydrology due to the significance of

193   landscape topography in characterizing surface water flow. Surface water which provides wide ecosystem services is

194   only a part of water resources in the world, but it is more accessible to people (Pekel et al., 2016). Permanent surface

195   water in North America accounts for almost 52% of the total surface water resources for less than 5% of the Planet's

196   population, however, permanent surface water only accounts for 9% in Asia where 60% of the Planet's population

197   occurs (Pekel et al., 2016). Seasonal surface water flow changes with high heterogeneity, fluctuates in wet/dry

198   conditions and even shifts geographically (Pekel et al., 2016). So predicting and modelling surface water flow are

199   challenging because of strong variability of surface water flow occurrence. Chen and Wang (2015) concluded that

200   modelling seasonal surface water flow is not accurate because of the heterogeneity of soil properties including soil

201   infiltration, soil storage capacity, land use cover and topography. Tesemma et al. (2015) stated that making accurate

202   predictions for surface water flow was challenging due to the changing conditions like climate changes and human

203   activities and also showed that some models were found to function poorly, especially the factors of climate.

204   Groundwater flow which belongs to subsurface aquifers is a key component of water flow that supports riparian

205   ecosystems during drought conditions (Rassam et al., 2013). It is typically evident that groundwater flow from shallow

206   aquifers to catchment surface water is the major part of the total water flow volume in most rivers (Wittenberg, 2003).

207   Groundwater is also benefit for ecosystem services, energy and food security, human health and water security and

208   scarcity. Groundwater flow is a critical component of the hydrological cycle (Gleeson et al., 2016). Groundwater

209   recharge which is more heterogeneous than water table gradients is difficult to measure directly at local or regional

210   scales (Gleeson et al., 2016). Taylor et al. (2013) showed that understanding groundwater flow could be benefit for

211   global energy, water and food security under climate change, in particular the increase of frequent and intense droughts

212   and floods events. de Graaf et al. (2015) presented a high-resolution global-scale groundwater model to construct

213   groundwater flow variations. Sakakibara et al. (2017) stated that both local and regional groundwater flow space-time

214   variations are crucial for water resources management, in particular for low precipitation regions. In previous studies,

215   water flow models have focused on surface water flow or groundwater flow individually. In recent advances, water

216   flow models that integrate surface water and groundwater, such as MODHMS (Panday and Huyakorn, 2004),

217   PARFLOW (Kollet and Maxwell, 2006), GSFLOW (Markstrom et al., 2008), HydroGeoSphere (Therrien et al., 2010;

218   Brunner and Simmons, 2012), MIKE-SHE (Graham and Butts, 2005) and SWATMOD (Sophocleous et al., 1999),

219   have been developed in recent years. Kollet and Maxwell (2006), Engelhardt et al. (2014), De Schepper et al. (2015),

220   by a coupled integrated surface and subsurface flow modelling approach, accounted for the water flow processes in

221   complex systems at field scales.

222   Surface water, such as reservoirs, rivers, lakes and wetlands, may interact with groundwater directly. The

223   interaction between surface water flow and groundwater flow is a critical component of hydrological processes within

224   multiscale. Surface water flow and groundwater flow interaction tends to proceed in two ways: surface water infiltrates

225   into the groundwater table, and groundwater flows into the surface water (Kalbus et al., 2006). However, the

226   interaction between surface water flow and groundwater flow is often more complex because this interaction affects

227   both water security and scarcity (Pahar and Dhar, 2014). The contamination or development of one is bound to have

228   effects on another (Sophocleous, 2002). Sakakibara et al. (2017) concluded that both surface water flow and

229   precipitation affected groundwater flow in the rainy season, whereas in the low precipitation periods, both reservoir

230 and stream water flow affected that most. Understanding the interaction is important for determining contaminants

231 transport pathways as well as for water resources management. Alley et al. (2002) reviewed the interaction between

232 surface water flow and groundwater flow was mostly focused on streams from environmental flow (i.e., chemical

233 composition in water bodies) perspectives, whereas few studies on lakes, wetlands and oceans. Scibek et al. (2007)

234 explored the effects of climate change on the interaction between surface water flow and groundwater flow using a

235 high-resolution transient groundwater model. Li et al. (2014) stated that metals from geogenic and atmospheric factors,

236 agricultural and industrial activities could disperse to surface water bodies through surface water flow or penetrate to

237 groundwater table through preferential flow pathways with the influences of surface-groundwater interaction. The

238 interaction between surface water flow and groundwater flow also affected the mass and energy exchange between the

239 two water systems. The magnitude and direction of exchange between surface water (e.g., rivers) and groundwater is

240 mainly determined by the hydraulic gradient between rivers and aquifers (Rassam, 2011). The exchange between rivers

241 and groundwater not only influence water flow velocities in rivers but also exert effects on water security and riparian

242 zone characteristics (Sophocleous, 2010). In riparian zones, the interaction between surface water flow and

243 groundwater flow is the major part for the exchange of mass and energy. However, previous studies of surface water

244 flow were often managed without sufficient consideration to the impact on groundwater flow and without available

245 integration with groundwater flow (Nielsen et al., 1986). In recent studies, the interaction, exchange and integrated

246 conceptual models for surface water flow and groundwater flow are generally interesting year by year.

247 Despite the significant importance of surface water flow and groundwater flow in water updating, the water vapor

248 flow into the atmosphere is also a neglecting component. Water vapor flow is sometimes called green water flow.

249 Rockström et al. (1999) estimated the water vapor flow of major terrestrial biomes and the total water vapor flow from

250 continents. Gordon et al. (2005) stated that both deforestation and agricultural irrigation were the main driving forces

251 for the alteration of global water vapor flow, and they also raised questions related to the influences of land use and

252   climate change on altering water vapor flow at global scales. Bittelli et al. (2008), by a fully coupled numerical model,

253   concluded that water vapor flow affected soil mass and energy budget highly and that water vapor flow induced the

254   small fluctuations of soil water content near the surface. However, this component could bring about unpredictable

255   problems with the change of natural conditions and human activities. According to the atmosphere interface, water

256   holding capacity increases with temperature. The average temperature is rising from global scales. Global warming is

257   possible to increase the intensity of precipitation events. The increase of precipitation intensity affects the frequency of

258   flooding (Dankers et al., 2014). The water holding capacity of the atmosphere has been increasing due to the frequent

259   global warming events caused by the combined effects of climate variability and human intervention. Such will result

260   in the frequency of precipitation extremes, the increase of dry periods and the intensification of floods and droughts

261   (Prudhomme et al., 2014; Schewe et al., 2014).

262

263   **3.1.3 Water flow in socio-hydrology**

264   Advances in the understanding of water flow in physical hydrology on the land surface or in the subsurface

265   aquifers offer interests and promises in recent years. However, water flow assessment in physical hydrology often does

266   not consider human-induced effects on hydrological processes. In particular, estimates of water flow at local or global

267   scales may not be accurate until human actions are considered. In recent years, human impacts on the hydrological

268   processes are only considered in regional hydrological distortion metrics (Weiskel et al., 2014). However, human

269   impacts in those studies tend to be regarded as external driving force or as a parameter simply incorporated into

270   hydrological models instead of being an internal driver along water flow assessment (Troy et al., 2015; Levy et al.,

271   2016).

272   Socio-hydrology, the science of people and water aiming at understanding the dynamics and co-evolution of

273   coupled human water systems (Troy et al., 2015), is an inter-disciplinary field studying the dynamic interactions and

274   feedbacks between water and people. Areas of research in socio-hydrology include the historical study of the interplay

275   between hydrological and social processes, comparative analysis of the evolution and self-organization of human and

276   water systems in different cultures and process-based modelling of coupled human water systems. Di Baldassarre et al.

277   (2013) developed a simple, dynamic model to conceptualize the interactions and feedbacks between social and

278   hydrological processes to avoid flooding-water flow based on socio-hydrology framework. Elshafei et al. (2014)

279   worked towards a conceptual framework for socio-hydrology model to better understand human feedbacks on

280   hydrological processes (i.e., water flow) and to make water resources sustainability at global scales. Gober and

281   Wheater (2014) concluded that it was impossible to predict long-term water system dynamics without considering

282   socio-hydrology. Viglione et al. (2014), by socio-hydrology modelling approach, perceived the risk of flooding-water

283   flow due to its high damage to community development, however, they also stated that the dynamic conceptual model

284   overestimated flood risk which led to low economic opportunities and prosperities. Di Baldassarre et al. (2015)

285   proposed a modeling framework to give feedbacks between social and hydrological processes involving the perception

286   of flooding-water flow risk in urban areas. Blair and Buytaert (2016) stated the art review on more in-depth

287   socio-hydrology modelling. Those studies are in attempt to apply socio-hydrology modelling framework to perceive

288   human-water systems interactions and feedbacks. Socio-hydrology is related to integrated water resources

289   management. In particular, integrated water resources management aims at controlling the water system to get desired

290   outcomes for the environment and society. The scenario based approach is often used to explore the interaction

291   between humans and water during integrated water resources management. However, this approach may be unrealistic,

292   especially for long term predictions, as it does not account for the dynamics of the interactions between water and

293   people. The focus of integrated water resources management is on controlling or managing the water systems to reach

294   desired outcomes for society and the environment, while the focus of socio-hydrology is on observing, understanding

295   and predicting future trajectories of coevolution of coupled human water systems. It is promisingly noted that we better

296 understand the interaction between human activities and water systems within the watershed unit to sustainably control

297 water resources management. However, models incorporating socioeconomic systems or human-hydrology

298 interactions remain open questions. Socio-hydrology has three goals: 1) characterize multiscale, spatial and temporal

299 changes and features of socio-hydrological processes; 2) interpret socio-hydrological processes to human-induced

300 effects and predict the future scenarios of their interplay; and 3) understand the significance of water systems on

301 people (Sivapalan et al., 2014). According to socio-hydrology framework, three pathways that human-induced effects

302 on water flow are considerable: 1) internal modifications; 2) infrastructure-based external transfer; and 3) virtual water

303 flow transfer. Human activities, such as land cover change and urbanization, typically affect surface water flow and

304 other hydrological processes within the watershed unit. Those human activities refer to internal modifications.

305 Moreover, human activities change the physical boundary of watershed to prompt it more linked in some way to the

306 socioeconomic driving forces. During hydraulic engineering process, human infrastructure could alter water flow to

307 ensure water security and scarcity. Infrastructure includes both hard-path engineering projects (e.g., dams and weirs)

308 and soft-path measures (e.g., water allocation rules, demand management practices and other policies). These

309 human-induced measures within the watershed unit refer to infrastructure transfers. The human-induced virtual water

310 exchange within the watershed unit is regarded as virtual water flow transfer (Konar et al., 2016). In socio-hydrology, a

311 wider range of drivers control the interaction between socioeconomic and hydrological processes at large catchment

312 scales. Drivers tend to be difference in policy, technology, fuel cost, trade barrier and historical factor. Water flow in

313 natural systems downhill, while it can uphill as social drivers affect. An example of water flow that socio-hydrology

314 may address is referred to as virtual water flow. In particular, the topic of virtual water flow falls within the science of

315 socio-hydrology (Sivapalan et al., 2012; Konar et al., 2013). Virtual water flow is defined as the transferring volume of

316 virtual water from one area to another when goods and services occur (Hoekstra and Mekonnen, 2011). When the

317 concept of virtual water was introduced (Allan, 1997), many researchers predicted that global commodities would

318   self-organize to alleviate water scarcity. People set out to look for solutions to water resources crisis because of the

319   significance of virtual water flow in balancing regional and global water security and scarcity (Sivapalan et al., 2014;

320   Sun et al., 2016). For example, Konar et al. (2013) investigated the impacts of changing climate on global virtual water

321   flow and concluded more water resources saving under climate change were encouraged by international virtual water

322   flow trade at global scales. More papers have growing focused on the virtual water flow of grain products and goods

323   either in global or regional or national perspectives (Table 1).

324   In principle, virtual water flow should be from regions rich in water resources and high water use efficiency to

325   those that poor in water resources and low water use efficiency. However, many local and regional virtual water flow

326   trades lead to irrational water resources management. With respect to virtual water flow in China as an example,

327   studies are of generally high interests. According to the report of Water Resources, China, water resources in southern

328   China account for more than 80% of total water resources. Grain products in southern China is less than that in

329   northern China even though the climate of southern China is more favorable to grain growth, which leads southern

330   China transferring from grain exporter to grain importer. Thus virtual water flow is transferred from water poor regions

331   to water rich regions (Wang et al., 2014; Sun et al., 2016) (Fig. 3). Though water resources are being transferred from

332   southern China to northern China in real form by the South-to-North Water Diversion Project, water resources in

333   virtual form are being transferred from northern China to southern China (Sun et al., 2016). Meanwhile, northern

334   China exports more water intensive grain products and thus water scarcity is more serious in northern China (Sun et al.,

335   2016). In fact, northern China annually exports about 52 billion m^3 of virtual water to southern China, which is more

336   than the maximum proposed real water transfer volume along the three routes of the South-North Water Transfer

337   Project (Ma et al., 2006). It is immediately clear that researchers state that this transfer project could not meet China's

338   water needs (Barnett et al., 2015). China is a net importer of virtual water flow in agricultural products. In particular,

339   soy accounts for more than 93% of global virtual water flow (Dalin et al., 2014). However, China is a net exporter of

340   virtual water flow when considering all sectors including agriculture, industry and services (Mekonnen and Hoekstra,

341   2012). Therefore, food trade from northern to southern China amounts to a total virtual water flow more than the

342   proposed diversion of real water through the South-North Water Transfer Project (Ma et al., 2006; Sivapalan et al.,

343   2014). The proposed diversion might form when complex systems dynamics controlled by policies, multinationals,

344   supermarkets, retailers and powerful countries (Savenije, 2000). In northern, northeastern and northwestern China,

345   green water accounts for the main part and the green water proportion is 85%, 67%, and 73%, respectively, but in

346   eastern, western and southwestern China, green water accounts for 49%, 49%, and 52%, respectively (Fig. 3). In the

347   main part of southern China, blue water resources are rich but southern China is a net importer from northern China.

348   As can be seen from Fig. 3A, large number of water use volume is from eastern, northern and southern China, and

349   agricultural products are the most water use, followed by industrial and domestic water use. From Fig. 3B, surface

350   water flow and groundwater flow are mainly located into the eastern, southern and southwestern China. In particular,

351   southern China accounts for the main part of total water resources, which also shows that it is not appropriate to

352   transfer agricultural food from north to south of China. In light of the report of Water Resources, Beijing, China, the

353   development area in which the available water per person is only 3% of the world's average has been suffering serious

354   water scarcity. Researchers have concluded that the 2022 Winter Olympics in Beijing will exacerbate water scarcity of

355   Beijing due to the huge water use from blue water flow, energy and hydropower to cool water, and the low

356   precipitation in February, and showed that Olympics will make Beijing water scarcity worse (Yang et al., 2015).

357

358   **3.1.4 Water flow future challenges**

359   Following future challenges:

360   • How to assess the effects of water flow in soils on water flow within the watersheds.

361   • How to in an attempt to construct a framework of "Big data" to imply long-term changes of water flow.

362   • Understanding which way the water flow is and why this is so is the major part of water flow in

363   socio-hydrology.

364   • How human-water systems are coupled, develop and evolve? And how to incorporate social and hydrological

365   processes into socio-hydrology models? These issues are in question (Troy et al., 2015).

366   • One important applied research thesis for the future is for studies on how virtual water flow will change and

367   co-evolve if taxes are placed on the virtual water trade (Sivapalan et al., 2014).

368   • Studies on global virtual water flow have been undertaken between countries. In general, the volume of virtual

369   water flow is transferred from countries with abundant water resources to countries with higher water scarcity. These

370   studies aims to provide policy strategies (e.g., a country or region through exporting water intensive agricultural food

371   from water rich countries or regions to secure their domestic water resources) and water management practices making

372   for the government to alleviate the domestic water resources stress and guarantee agricultural food security in

373   importing countries. However, little attention has been paid to the study of virtual water flow in exporting countries (da

374   Silva et al., 2016).

375   • How to construct a mathematical model that incorporates ecology, hydrology and economy modules to better

376   assess blue, green and grey water flow within multiscale.

377   • Hydrological connectivity is crucially significant for watersheds where water flow is dominated by rapid surface

378   water flow. So, how to quantify water flow between different water bodies across different landscapes, or among in

379   soils, atmosphere and plants, or between the hillslope and the watersheds, or surface water flow and groundwater flow,

380   and the aquifers accurately, based on the hydrological connectivity, is still in question. In light of the hydrological

381   connectivity between surface water flow and groundwater flow, the interaction between surface water flow and

382   groundwater flow tends to recharge to or discharge from the aquifers. In future, human activities should fully

383   incorporate the concept of hydrological connectivity into water flow modelling to better assess water resources

384   sustainability. In future, understanding the role of hydrological connectivity and integrating the concept of hydrological

385   connectivity into hydrological models could benefit for the policy makers to know how water flow connects between

386   or among different water bodies, in particular the occurrence of preferential flow. Hydrological connectivity is the

387   concept that water flow provides a pathway for the exchange of mass and energy between different environments and

388   may occur only during wet conditions or during seasonal snowmelt conditions. Assessing the strong variability of

389   space-time dynamics of hydrological connectivity is better to understand its high influences on water security and

390   ecosystem services progressively, in particular for understanding of hydro-logic, hydro-geologic and hydro-ecological

391   processes.

392

393   **3.2 State of the art on preferential flow**

394   **3.2.1 Preferential flow on a world extent**

395   The special section themed with preferential flow has also got broader interests in the period 1995-2015. These

396   researches comprise inter-disciplinary efforts which have advanced our understanding of preferential flow. The special

397   section preferential flow emphasized the need to link with the studies of groundwater pollution, land degradation, soil

398   physical and hydrological processes (Zhang et al., 2017). The number of studies increased in the most recent years,

399   proving the growing interest on the indicator. The online database WoS search for literatures using the term

400   "preferential flow" resulted in a total of almost 7608 publications in the period 1995-2015. The distribution of

401   document types and disciplines of preferential flow studies was analyzed. Articles (6717) were the dominant document

402   type, comprising 88% of the total publications. The studies were mainly concentrated on water resources (1711) and

403   environmental sciences (1317). With respect to journal publication patterns, Journal of Hydrology ranked first in the

404   number of published papers (274, 4%) and followed by Water Resources Research (241), Vadose Zone Journal (179)

405   and Hydrological Processes (141). The survey data in Fig. 4 demonstrated: from 1995 to 2015, the number of

406 published papers increased from 168 in 1995 to 496 in 2015. The annual number of published papers increased

407 remarkably. The largest number of published papers of preferential flow was typically distributed in USA, followed by

408 Germany, France and China. In addition, from 1995 to 2015, the annual growth rate of published papers of preferential

409 flow was also typically higher than growth rate in planning. The above results concluded that studies on preferential

410 flow were significantly interesting year by year. Fig. 4 provides a summary of the recent and previous studies.

411   The co-authorship networks of countries in the world are social networks constructed by connecting actors in case

412 they have co-authored together. Collaborative papers published with the topic of preferential flow and academic

413 communication and collaboration in the study of preferential flow during the last 20 years from 1995 to 2015 are

414 increasingly broader. The contribution of different countries to papers published was indicated in this review. Based on

415 the results, 17 countries of the world had published papers of preferential flow with the number > 100. Among these

416 countries, USA has published 681 papers concentrating on preferential flow from 1995 to 2015, flowed by Germany

417 (368), France (284) and England (273). The name and share of countries are shown in Fig. 5. It is immediately clear

418 that the collaboration between other countries and USA is more active.

419

420 **3.2.2 Preferential flow: Significance and progress**

421   In the 19th and beginning of the 20th century, macropores as continuous openings influencing water flow was

422 observed which could provide big footprints of preferential flow for soil hydrologists in the near future (Schumacher,

423 1864; Lawes et al., 1882; Engler, 1919). Preferential flow refers to all phenomena where 70-85% water flow in the

424 unsaturated zone through localized pathways relatively quickly bypassing the surrounding soil matrix, which makes it

425 difficult to predict water flow in the field conditions (Kapetas et al., 2014). Preferential flow phenomena do favors of

426 understanding of ecological and hydrological functions of soil, such as the transformation of substances and energy

427 entering the soil, sorption of substances and water by soil, formation of chemical composition of groundwater and the

428   regulation of water balance of landscapes (Zhang et al., 2017). Helling and Gish (1991) distinguished root channels,

429   cracks, fissures as preferential flow pathways because of their promotion in water flow. Li and Ghodrati (1994), by

430   breakthrough curve methods, concluded the influences of root channels on preferential transport of Nitrates. Hagedorn

431   and Bundt (2000) stated that preferential flow pathways in forest soils could persist for decades. Jørgensen et al. (2002)

432   reported that water flow was more obvious in soil profiles with root channels than that without root channels. Franklin

433   et al. (2007) showed that the mechanisms of preferential flow were ambiguous though a wide range of studies had been

434   done for preferential flow. Bogner et al. (2010) found that root biomass was larger in preferential flow pathways than

435   that in the surrounding soil matrix. Etana et al. (2013) implied that persisted compaction of subsoil might enhance the

436   degree of preferential flow. Xin et al. (2016) found that water flow increased remarkably for soils with distributed

437   macropores compared with soils without macropores. Zhang et al. (2017) concluded that preferential flow was more

438   obvious in stony soils and that preferential flow patterns were distributed in soil profiles with high heterogeneity.

439   Stronger preferential flow phenomena occur in the fine texture soils and in the vicinity of trees than is found

440   elsewhere (Benegas et al., 2014), while weaker preferential flow phenomena occur in larger organic carbon content

441   soils (Ghafoor et al., 2013). Preferential flow phenomena in some soils are enhanced in wetting soil conditions due to

442   reduced lateral water flow from the preferential flow pathways to the surrounding soil matrix (Hardie et al., 2013). The

443   occurrence of preferential flow occurs at different soil types, such as forest soils (Van Der Heijden et al., 2013; Guo et

444   al., 2014; Laine-Kaulio et al., 2014; Zhang et al., 2015b, c; Zhang et al., 2017); constructed wetland soils (Hua et al.,

445   2014); and agricultural soils (Koestel et al., 2013; Zhang et al., 2014, 2015d; Jiang et al., 2017). With respect to

446   agricultural soils in particular, the rising effects of preferential flow on soil water conservation prompt people to

447   conduct better management practices. Because preferential flow exerts highly influences on seed emergence, crop

448   growth and even crop yield. Williams et al. (2016) stated the variability of preferential flow dynamics in agriculture

449   both in tillage and no-tillage management measures and concluded that the interaction between preferential flow

450 pathways and the surrounding soil matrix were found to perform highly along water flow processes. Jiang et al. (2017),

451 by dye tracing experiments, implied the influences of different management practices on preferential flow occurrence

452 and concluded that both alfalfa and conservation tillage in agricultural field which could increase continuity order and

453 connectivity degree of macropores systems were preferential management practices. Furthermore, the occurrence of

454 preferential flow originates from the spatial variations in water flow velocity due to major heterogeneities in soil

455 profiles. Zhang et al. (2017) stated that preferential flow dye patterns in the soil profiles were highly different in stony

456 soils and they implied that the spatial heterogeneity of stony soils, especially the occurrence of rock fragments

457 distribution, prompted the results. The occurrence of preferential flow pathways tend to be rich in the place where

458 near-ponding conditions takes place on the soil surface or where water flow encounters less permeable layers within

459 the soil profiles or where vegetation canopy architecture adjusts the redistribution of precipitation above soil surface

460 (Bogner et al., 2013). Preferential flow pathways are complex networks of large pores and void spaces within soils

461 which are typically formed by living or decaying root-induced channels, soil biota, soil fauna, soil cracks,

462 drying-wetting cycles and freezing-thawing process. For example, root-induced channels within topsoil constitute main

463 preferential flow pathways, while unstable water transfer from preferential flow pathways to the surrounding soil

464 matrix occurs because root biomass decreases in subsoil. Preferential flow along root-induced channels could carry

465 large amount of bacteria. Root-induced channels as preferential flow pathways due to roots shrink provide more space

466 for water flow. Moreover, root-induced channels harbor high amounts of bacteria than the surrounding soil matrix and

467 are hot spots of bacteria activity (Dibbern et al., 2014). Larger and deeper root systems constitute a complex network

468 within the soil profile for alfalfa cultivation-a perennial and long lived plant-than wheat cultivation-an annual and short

469 lived plant. Decayed alfalfa root systems could create more preferential flow pathways (Yousefi et al., 2014). For soil

470 cracks and biopores, higher water infiltration rate occurs in cracked soils and this rate decreases when cracks are closed

471 during wetting. Preferential flow in cracked soils was a matter of very short time due to crack closure resulted from

472 rapid and heterogeneous swelling processes (Liu et al., 2003). However, other researchers stated that cracks did not

473 close after rewetting, leading to high water infiltration during wetting. Soil cracks remain preferential flow pathways

474 even after they are closed on soil surface (Zhang et al., 2014). The drivers, occurrence mechanisms, types, degrees and

475 properties of preferential flow (Fig. 6) could be better assessed and predicted in soil hydrology if a potentially glance

476 of interdisciplinary, in particular soil physics, soil chemistry, soil biology and plant physiology, is considered (Zhang et

477 al., 2016a).

478   Preferential flow could displace older water stored in the surrounding soil matrix deeper into the soil even into the

479 streams. The interactions between preferential flow pathways and the surrounding soil matrix affect the ability of

480 solute transport based on different soil water content conditions (Laine-Kaulio et al., 2014). At the primary stage, the

481 dominant water transfer is from the preferential flow pathways into the surrounding soil matrix when the water content

482 is lower in the surrounding soil matrix than that in the preferential flow pathways. Meanwhile, interactions between

483 preferential flow pathways and the surrounding soil matrix increase with the sand content (Bogner et al., 2012).

484 Preferential flow and soil matrix flow are the typical two regimes of water flow within the soil profiles (Hirashima et

485 al., 2014). Soil matrix flow is a relatively slow and even movement of water and solutes through the bulk soil (Stamm

486 et al., 1998; Allaire et al., 2009). Soil physicochemical and biological properties may be different between preferential

487 flow pathways and the surrounding soil matrix (Bogner et al., 2012). Preferential flow pathways not only determine the

488 spatial pattern of solutes but also exert vital significance on soil properties and are regarded as a contaminant sink on

489 the basis of contaminant species (Garrido, et al., 2014; Zhang et al., 2016b). The high organic matter content in the

490 preferential flow pathways was attributed to three main sources: greater proportion of living or decayed roots in

491 preferential flow pathways than in the surrounding soil matrix; preferential input of dissolved organic matter from the

492 surface; enhanced release of microbial biomass C from rewetting of relatively dry soil (Morales et al., 2010). Mass

493 transfer between preferential flow pathways and the surrounding soil matrix is typically common and also different

494 from soil texture, soil organic matter content, land coverage type and so forth (Jarvis et al., 2007; Alaoui et al., 2011;

495 Backnäs et al., 2012; Zhang et al., 2017). Martin and Dean (2001) who treated the surrounding soil matrix as reservoir

496 effect identified that water with high permeability and hydraulic conductivity exchanged between preferential flow

497 pathways and the surrounding soil matrix. Peterson and Wicks (2005) concluded that only 1% of the volume of water

498 and <<1% of the amount of solute moved from preferential flow pathways to the surrounding soil matrix. However,

499 they did not regard the surrounding soil matrix as a reservoir in fact. Mohanty et al. (2016) concluded that extent of

500 hysteresis increased with increases in exchange of water and solute between preferential flow pathways and the

501 surrounding soil matrix. The surrounding soil matrix exchanged the old infiltrating water with new infiltrating water

502 during successive infiltration (Mohanty et al., 2016). Preferential flow not only exerts significant effects on both

503 surface water and groundwater security but also affects the physical hydrological processes to precipitation (Beven and

504 Germann, 2013; Khan et al., 2016). Quantification and characterization of preferential flow is vital for groundwater

505 recharge, waste disposal risk assessment, contaminants spatial pattern and heavy metal redistribution in soils

506 (Saravanathiiban et al., 2014). In particular, the topic of preferential flow is of generally high significance and

507 scientifically interest, but it is too complex to be solved from a theoretical and experimental point. However, despite

508 the increasing number of papers published on the topic, there has not been as much attention paid to preferential flows

509 as we might have expected, given its significance in all areas of soil and catchment hydrology, water quality, slope

510 stability and agricultural management.

511

512 **3.2.3 Preferential flow future challenges**

513 Given the growing interests of preferential flow in past few years worldwide, a real opportunity and challenge of

514 preferential flow studies from a global perspective in future occurs for hydrologists. Given the unpredictable

515 significance of preferential flow in all areas of large scale catchment hydrological processes, groundwater resources

516   security, agricultural non-point source pollution, and soil heavy metal pollution, large number of unanswered questions

517   and disputes still confuse researchers (Beven and Germann, 2013).

518   The proposed suggestions are on the following topics, but not limited to:

519   • Any new theory of preferential flow, in particular mathematical models, needs to be rigorously tested with wider

520   range of experimental data. A fully convincing integrated physical theory still has not yet been achieved (Beven, 2010).

521   • Yet to date, however, most preferential flow studies have focused on its drivers, with limitation of studies

522   implying the space-time changes, mathematical models, new measurement techniques and theoretical approaches

523   predicting the process of preferential flow accurately. It is noteworthy that preferential flow effects are generally

524   ignored in lumped hydrological models even physically based models (Weiler, 2017). Integration of all the purported

525   drivers, in particular preferential flow, into mathematical models framework is required to achieve the fully integrated

526   analysis. An active field for future research needs to extend, develop and assess the effects of preferential flow on

527   models sensitivity within multiscale.

528   • There is an urgent need to greatly enhance our ability to imply a wide range of unpredictable preferential flow

529   process under different environments.

530   • When and how does water flow through preferential flow pathways within the soils? How does water in

531   preferential flow pathways interact with water in the surrounding soil matrix? How does solute exchange between

532   preferential flow pathways and the surrounding soil matrix? How important are preferential flow pathways in terms of

533   water flow at the hillslope or catchment scales? How does solute process adsorption and degradation on preferential

534   flow pathways walls? These need to be investigated further (Beven and Germann, 2013).

535   • Does preferential flow matter at catchment scales? Preferential flow occurs only during specific conditions linked

536   to soil water content, soil properties, high precipitation and so forth. However, these conditions could not be met to

537   assess hydrographs in the long run due to the small proportion of preferential flow time. Thus hydrologists suppose

538   that preferential flow does not matter at catchment scales. It is not the case in some way.

539   Even if some questions still remain unresolved, our understanding of preferential flow in the vadose zone is

540   continuing to be facilitated.

541

542   **3.3 Water flow and preferential flow pathways: A love-hate relationship**

543   Before we deal with the topic, it is worthwhile to clearly understand the progress of water flow and preferential

544   flow, respectively. In recent advances, studies have implied that water flow in the vadose zone often occurs through a

545   small fraction of the soil along preferential flow pathways. Groundwater quality could be influenced by the arrival of

546   both dissolved and suspended contaminants which are carried by gravity-driven water flow through preferential flow

547   pathways to the water table. There is increasing doubt that whether a love-hate relationship between water flow and

548   preferential flow pathways. Recently, Weiler (2017) presented a review and study on the relationship between

549   macropores and preferential flow. This study concluded that preferential flow is of high relevance for surface water

550   flow in the soil or watershed. In previous studies, Beven and Germann (1982, 2013) also discussed the relationship

551   between macropores and water flow extensively. Even more importantly, it is indeed evident that recent and precious

552   studies have conducted limiting assessment to state the importance of macropores on water flow or preferential flow.

553   Hydrologists had a love-hate relationship with water flow and preferential flow pathways like a love-hate relationship

554   between water flow and preferential flow pathways (Fig. 7). A complex relationship between water flow and

555   preferential flow pathways emerges early at birth and continues throughout life. Even though water flow and

556   preferential flow pathways have been extensively concluded, their interaction remains obscure. Hence, it becomes

557   immediately clear to have insights on the love-hate relationship between water flow and preferential flow pathways.

558   The interaction between water flow and preferential flow pathways becomes crucial in situations when water security

559   and scarcity could be controlled by its interaction.

560

3.3.1 Water flow through preferential flow pathways at profile, plot, and field scales

562   The most convincing evidence of the occurrence of water flow through preferential flow pathways at profile and

563   plot scales has come from dye tracing experiments (Flury et al., 1994; Zehe and Flühler, 2001; Hagedorn and Bundt,

564   2002; Öhrström et al., 2002; Kamolpornwijit et al., 2003; Morris and Mooney, 2004; Köhne et al., 2006; Mooney and

565   Morris, 2008; Klaus and Zehe, 2010; Backnäs et al., 2012; Bargúes Tobella et al., 2014; Mossadeghi-Björklund et al.,

566   2016; Zhang et al., 2017). Water flow through preferential flow pathways at profile and plot scales could be achieved

567   from the continuous change of dye tracers (i.e., Brilliant Blue, Bromide, Chloride and so forth). Hagedorn and Bundt

568   (2002), Backnäs et al. (2012) for example concluded difference of the chemical properties between preferential flow

569   pathways and the surrounding soil matrix by dye tracing patterns. Morris and Mooney (2004) stated that water flow

570   through preferential flow pathways recorded as instantaneous responses both in the 50- and 130-mm probes using TDR

571   and showed that preferential flow pathways might be responsible for a significant portion of the total water flow in

572   light of the breakthrough curve results (Mooney and Morris, 2008). Köhne et al. (2006) stated that water flow through

573   preferential flow pathways at column scales could not be predicted accurately based on water flow and solute

574   concentration data used in dual porosity model. Dye staining patterns may not reveal all preferential flow pathways

575   within soil profiles in fact (Beven and Germann, 2013). However, at field scales, the convincing evidence of water

576   flow through preferential flow pathways tends to be indirect and may be inferred from the response of tracer

577   concentration at some point. In light of the studies of water flow through preferential flow pathways at field scales, it is

578   typically interesting to understand why solutes (i.e., nutrients, contaminants and so forth) could be reported at depths

579   much greater than would be expected in groundwater table. In general, contaminants could be carried by water flow

580   through preferential flow pathways to the groundwater table quickly. It is also clearly evident that researchers conduct

581   a wide range of studies to quantify the effects of preferential flow on contaminants transport by mathematical

582   modelling and promising methodology. These studies could ahead clarify the origin of groundwater pollution and

583   could also benefit for water resources sustainability. Therefore, from the groundwater security perspectives, we

584   conclude that a hate relationship between water flow and preferential flow pathways because water flow could carry

585   more contaminants and pesticides to the groundwater table through a small portion of preferential flow pathways.

586   However, with respect to the nutrients availability in the rhizosphere, it is well known that plant roots not only

587   grow into the preferential flow pathways within the soil profiles but also form lots of preferential channels themselves

588   and that there is a love relationship between water flow and preferential flow pathways. Preferential flow pathways

589   have higher amounts of nutrients and organic matters than the surrounding soil matrix, which prompts plant growth. In

590   general, preferential flow pathways are regarded as storage of micro-organism, nutrients and organic matters. During

591   plant growth, root systems must absorb more soil water and nutrients to maintain their sustainability. Water flow

592   carrying nutrients to the rhizosphere quickly through preferential flow pathways is benefit for plant growth, because

593   preferential flow pathways could be treated as storage of organic matters. The framework could benefit for the plant

594   growth, as well as agricultural crop production, because preferential flow pathways could be persistent for decades.

595

596   **3.3.2 Water flow through preferential flow pathways at hillslope scales**

597   Hillslopes act as filters for water flow to the surface water bodies or even to the groundwater table in many

598   landscapes. Water flow through preferential flow pathways at hillslope scales is highly related to morphological

599   properties like regolith, glacial till and bed rock (Beven and Germann, 2013). There are now a wide range of studies

600   concluding that preferential flow might be crucial in controlling hillslope hydrological processes. Interests in the role

601   of preferential flow in hillslope hydrology have increased dramatically (Leaney et al., 1993; Guebert and Gardner,

602   2001; van Schaik et al., 2008; Anderson et al., 2009; Klaus et al., 2013; Guo et al., 2014). Noguchi et al. (1999) for

603   example concluded that water flow through preferential flow pathways formed by living or decayed roots, bedrock

604   fractures might be important in determining hydrological processes at hillslope scales. Anderson et al. (2009) stated

605   that preferential flow pathways carried most of water flow during storms at hillslope scales due to the very small

606   groundwater table responses.

607   A hate relationship between water flow and preferential flow pathways is also necessarily concluded from the

608   perspective of debris-water flow acceleration and subsurface storm-water flow especially under wet conditions and

609   high precipitation. With regard to debris-water flow on the land surface, preferential flow pathways provide the nearest

610   channels for this process. It is typically clear that the property of sheet or splash erosion could make the surface

611   smoothly by eroding clods to flat the roughness and in final to fill the depression with the sediments, which leads the

612   increase of surface water flow on the land surface and the decrease of storing water for the depression during high

613   precipitation. In particular, once the spilling process is initiated in the depression, preferential flow pathways occur

614   among these depressions along the steep slope. Preferential flow pathways on the land surface could prompt, route and

615   concentrate the surface water flow, sediment, gravel and stone transport with high water flow velocity due to high

616   precipitation (Peñuela et al., 2016). The synthesis of turbulent surface water flow, sediment and gravel is the origin of

617   debris-water flow which exerts a hate relationship with preferential flow pathways on the land surface.

618   For subsurface storm-water flow at hillslope scales, this water flow as a term of repaid water flow through

619   preferential flow pathways with much higher water flow velocity than the surrounding soil matrix dominates hillslope

620   hydrology and also has a hate relationship with preferential flow pathways when we address hillslope stability and

621   landslides. Where preferential flow pathways are crucial parts of subsurface water systems, these pathways could feed

622   water to make water pressures develop. As the landslide develops, the water storage continues to feed water even

623   drainage occurs. Subsurface storm-water flow may develop to accelerate as landslide happens (Hencher, 2010).

624   Preferential flow pathways are dramatically treated as conduits of subsurface storm-water flow in hillslopes. Rapid

625   subsurface storm-water flow depends on the fluxes of both vertical and lateral preferential flow pathways (van Schaik

626   et al., 2008; Nieber and Sidle, 2010). Subsurface storm-water flow at hillslope scales is a combination of preferential

627   flow and soil matrix flow. Leaney et al. (1993) concluded that > 90% subsurface storm-water flow was mainly carried

628   by preferential flow pathways bypassing the surrounding soil matrix; Anderson et al. (2009) stated that subsurface

629   storm-water flow velocity was governed by the connectivity of hillslope preferential flow pathways. Stumpp and

630   Maloszweski (2010) found the contribution of preferential flow pathways to subsurface storm-water flow was between

631   1.1 and 4.3% for the lumped parameter approach and 1.1 and 20.5% for the HYDRUS 1-D approach, respectively;

632   Vogel et al. (2010) found that only 24% subsurface storm-water flow was transported through preferential flow

633   pathways. Repaid subsurface storm-water flow through preferential flow pathways processes could affect the stability

634   of hillslopes for addressing issues of hillslope sustainability, storm water management and other hydrological and

635   biogeochemical responses.

636

637   **3.3.3 Water flow through preferential flow pathways at catchment scales**

638   If water flow through preferential flow pathways is crucial at hillslope scales then it is also crucial at catchment

639   scales (Beven and Germann, 2013). However, evaluation of water flow through preferential flow pathways at

640   catchment scales remains in question because of the high temporal and spatial heterogeneity of water flow dynamics

641   (Allaire et al., 2009; Beven, 2010; Darracq et al., 2010; Godsey et al., 2010; Beven and Germann, 2013; Wiekenkamp

642   et al., 2016). The geometry, connectivity and tortuosity of preferential flow pathways networks remain an issue in

643   practice at catchment scales than that at soil columns scales (Ghafoor et al., 2013). Direct tracing of water flow through

644   preferential flow pathways remains an issue even at zero-order catchment scales. A promising technique to assess

645   space-time dynamics of preferential flow at catchment scales is the use of sensor response times (Hardie et al., 2013;

646   Liu and Lin, 2015; Wiekenkamp et al., 2016). Christiansen et al. (2004) found that preferential flow pathways had

647   significant influences on contaminants leaching into the groundwater table at catchment scales though preferential flow

648   pathways had no dominating influences on groundwater recharge or discharge at catchment scales. Wiekenkamp et al.

649   (2016) concluded that the spatial and temporal occurrence of water flow through preferential flow pathways using

650   sensor response times was triggered by the amount and intensity of precipitation at catchment scales. Moreover, public

651   authorities need integrated large-scale models and decision-support tools that can decide the effects of water flow

652   through preferential flow pathways on contaminants leaching at catchment scales.

653   All hydrological processes are irregular in temporal and spatial scales and water flow through preferential flow

654   pathways may be measured everywhere (Uhlenbrook, 2006). A hydrological processes phenomenon, for example,

655   flooding-water flow originating from a catchment, varies with high heterogeneity. Flooding-water flow displaced from

656   those surface water bodies (i.e., rivers, lakes, reservoirs and so forth) in a catchment. The connectivity of surface water

657   bodies and preferential flow pathways in the catchment may prompt the understanding of rapid water flow

658   contributions to the flooding events. A hate relationship between water flow and preferential flow pathways is also

659   necessarily concluded from the perspective of flooding-water flow at catchment scales. For flooding-water flow during

660   extreme storm events, it is widely known that hillslope acts as a buffer of temporary storage to reduce the capacity of

661   flooding-water flow and the damage caused by flooding. However, frequency of flooding is typically high due to the

662   increased influences of human activities and climate variabilities. Along the disastrous flooding-water flow, water flow

663   is driven by gravity, tends to be downhill without resistance, and even disturbs urban traffic, submerges village, and

664   endangers human life. Flooding-water flow will be accelerated as the process passes through the flatting areas or

665   through the areas with micro- or macro-gradient. These areas could be referred to preferential flow pathways in some

666   way. In particular, flooding-water flow to the nearest areas without resistance by preferential flow pathways could take

667   more serious disasters.

668

669   **3.3.4 Virtual water flow through preferential flow pathways in socio-hydrology**

670   It is not indeed immediately clear for the assessment of virtual water flow from socio-hydrological perspectives.

671   Considering previous studies, it is clearly stated that these papers only assess the volume of virtual water flow of

672   products in the regions or in the world. However, it is our opinion that which is preferential type of crop product to

673   import, preferential choice of country to export products, preferential choice of tax to import or export products along

674   virtual water flow trade, to alleviate water security and scarcity, these questions should be assessed immediately. Then

675   the question arises: how does water stress could be alleviated from the perspective of virtual water flow and

676   preferential flow pathways along regional or national or global virtual water flow trade. It is due to the presence of

677   preferential policy (i.e., trade, tax, human needs and so forth) conducted to make water resources sustainability. In light

678   of the socio-hydrological perspectives, these preferential policies along virtual water flow trade could form a global

679   framework in some way to alleviate global water crisis. For example, the policy makers could decide which crop

680   should be imported or exported preferentially with virtual water flow pattern from other regions or countries to keep

681   real water balance. However, it is not optimistic because of water allocation rule, demand management practices,

682   current policy, history, political security, food security, local economy and environments. Although global virtual water

683   flow trade has a complex network structure and is increasingly complex dynamic system, in fact, preferential bilateral

684   agreement between countries and multilateral trade agreements could enhance global virtual water flow trade in some

685   way. Policy and decision makers should consider both short and long term virtual water flow trade plan based on those

686   preferential trade agreements from network perspectives. Therefore, preferential virtual water flow trade agreements

687   between regions or countries should open quickly to alleviate global water crisis.

688   In this section, "preferential flow pathways" is not the term of real preferential flow pathways which could prompt

689   repaid water flow without resistance from physical and hydrological perspectives. However, "preferential flow

690   pathways" is related to the preferential policy adjustment during virtual water flow trade between regions or countries.

691   In general, this "preferential flow pathways" is mainly controlled by policy makers and could make global water

692   balance in some way if the adjustment is fully considered. In general, we could not avoid some facts that virtual water

693   flow is transferred from regions poor in water resources to regions rich in water resources. If the preferential policy is

694   took on with global endeavors, more water resources will be saved during virtual water flow transfer. The policy

695   makers could decide which kind of crop products should be preferentially imported from other countries to alleviate

696   water crisis. For example, China is a net importer of virtual water flow in agricultural products, especially soy. Chinese

697   government set out to import soy products instead of other agricultural products because of their necessity for human

698   life, livestock feed and their much higher virtual water content during production than paddy, wheat, maize and so

699   forth, in particular because of their low yield during production. Chinese farmers also realize that no more incomes

700   from soy production. Therefore, the policy makers of China import more soy with the form of virtual water flow from

701   other countries preferentially to alleviate serious water stress in some way. Apart from the preferential virtual water

702   flow trade, policy and tax in alleviating water crisis, real water transfer from rich regions should also be considered

703   preferentially. Regions rich in water resources not only satisfy their needs but also provide water sustainability for

704   regions poor in water resources. In particular for policy makers, they clearly understand which is more necessary to

705   make water resources available. For example, water resources from Hebei Province or nearby Beijing regions should

706   supply the development areas, in particular Beijing, preferentially. It is clearly noted that almost 70% water resources

707   of Beijing is from Miyun Reservoir, Beijing. Recently, Chinese government set out to make an agenda for the

708   development of Jing-Jin-Ji region, China to prompt people in these areas more improvement. The policy that water

709   resources should be supplied for Beijing preferentially might alleviate water crisis of Beijing in some way. In addition

710   to the real water resources supplied for Beijing preferentially, the most developed area of Beijing must also import

711   more virtual water from other regions or countries. A love relationship between virtual water flow and "preferential

712   flow pathways" is necessarily indicated in light of the virtual water flow transfer from socio-hydrological perspectives.

713

714   **4. Conclusions**

715   The large number of studies reviewed in this paper show that there is a promising development of water flow and

716   preferential flow from 1995 to 2015 though lots of questions have not been unresolved yet to date. People set out to

717   alleviate water resources considering the human-society-water-food-energy nexus from socio-hydrological

718   perspectives instead of concentrating on studies in physical hydrology only. So it is evident from the literatures that

719   there is a need to consider the complex relationship between water flow and preferential flow pathways. This review of

720   the topic then leads to the development of an integrated study on water flow. In addition, based on this review, further

721   work could include as the inter-disciplines are proposed.

722

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727

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1222

1223 **Figure Captions**

1224 Figure 1. A global network of published papers themed with water flow in the period 1995-2015. Dark red dots indicate papers published

1225 by USA, and red dots by China, Canada and Japan. Dark blue dots indicate few papers published by those countries.

1226 Figure 2. The three components of water footprint including blue water flow, green water flow, and grey water flow incorporating into a

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1228 Figure 3. The average volume ($\times 10^8 \, m^3$) of water use and water resources in the period 1995-2015 in China including the North, East,

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1238 Figure 6. Preferential flow integrated analysis in this composite Figure. Family branches are shown in an unrooted phylogenetic tree from

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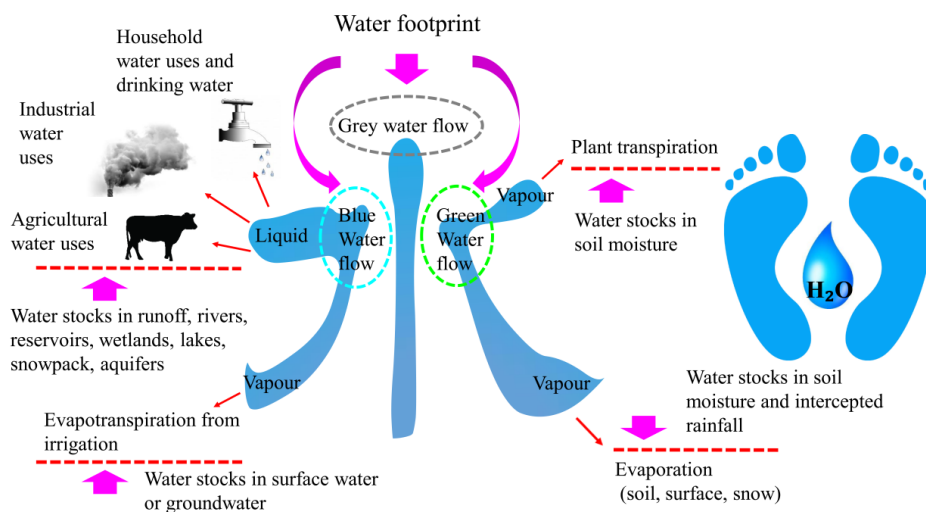
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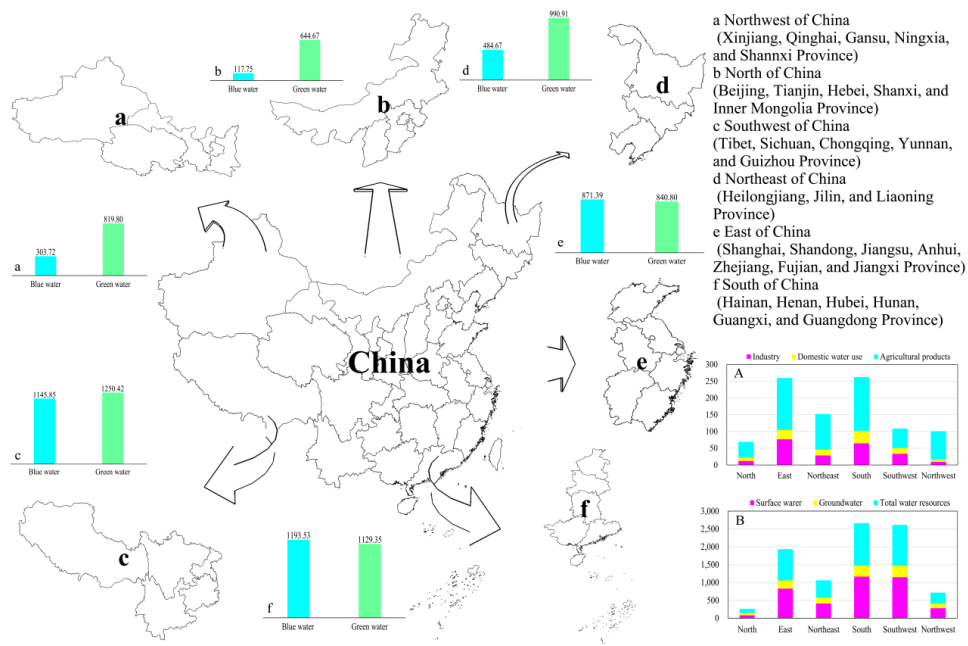
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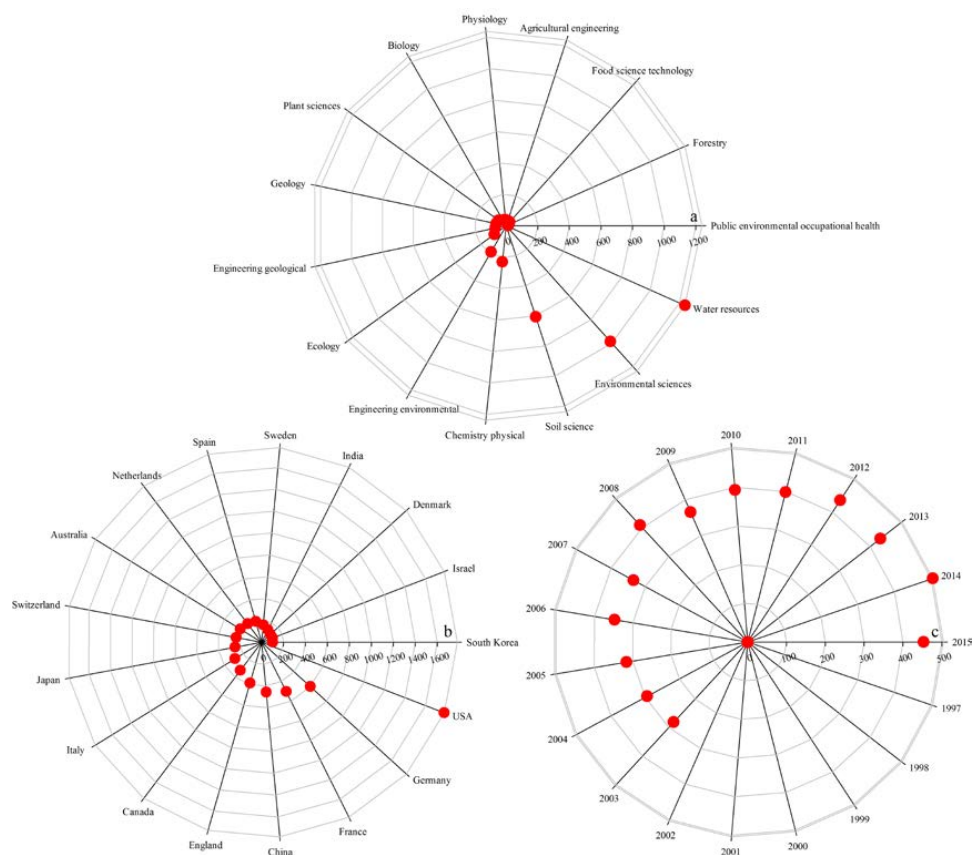
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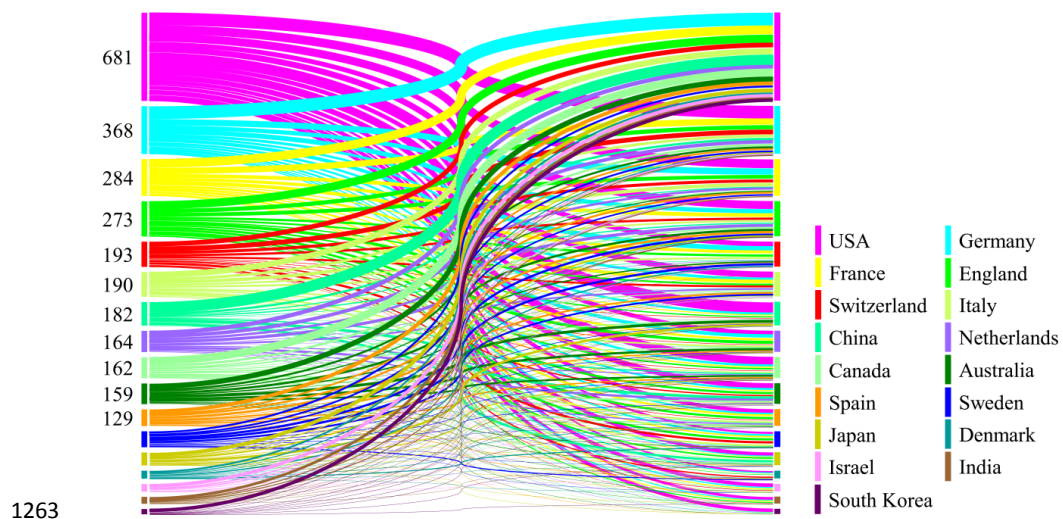
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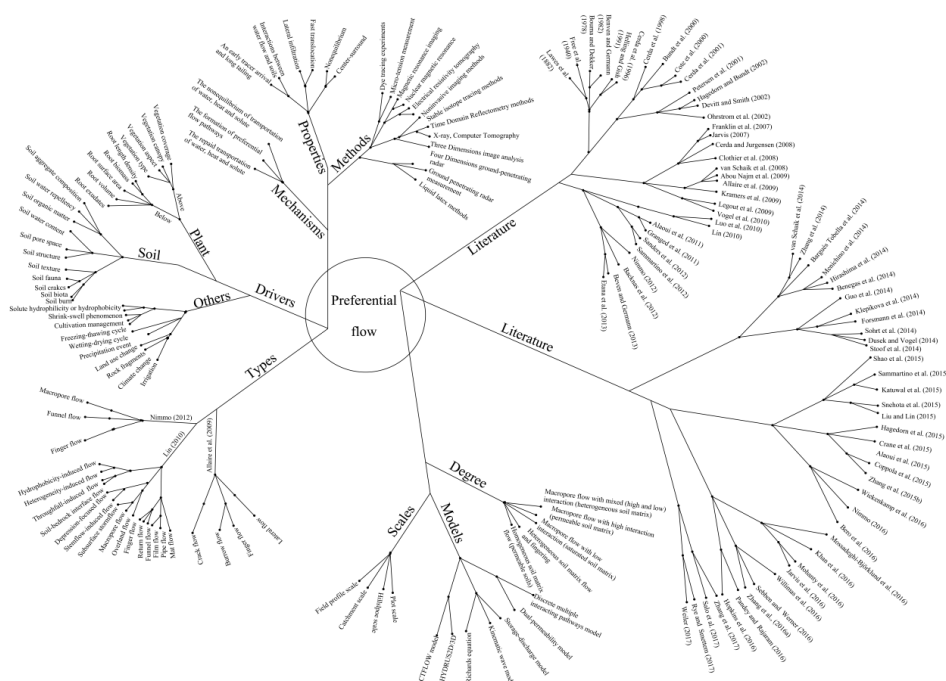
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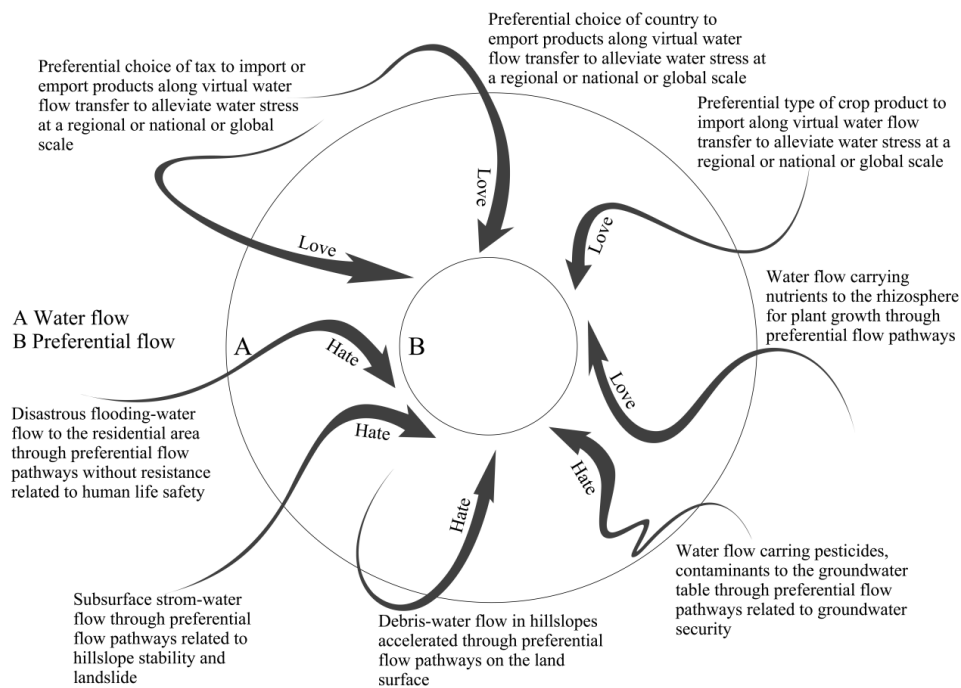
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1275   **Table Captions**

1276   Table 1. Studies on the progress of virtual water flow in global or regional or national perspectives.

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Literature	Objective	Key findings
Hoekstra and Hung (2005)	Virtual water flow between nations	Virtual water flow between nations at about 1000 km^3 a^{-1} at the turn of 20th century, and agricultural products accounting for almost 70%
Ma et al. (2006)	Virtual water flow between north and south in China	More virtual water flow from north to south in China than the maximum real water transfer volume along the Water Transfer Project from south to north
Chapagain et al. (2006)	Global virtual water flow	Importing products alleviating water at a global scale if virtual water flow from sites rich in to sites poor in water resources
Kumar and Jain (2007)	Virtual water flow in India	India is a net importer of virtual water
Dabrowski et al. (2009)	Virtual water flow of maize in the Southern African Development Community region	Virtual water flow of agricultural products at different spatial scales benefits water allocation, water use efficiency and alleviation of water scarcity
Zeitoun et al. (2010)	Virtual water flow of crop and livestock products in Nile Basin states, 1998-2004	Virtual water flow benefits devising policy of national water security
Zhang et al. (2011)	Virtual water flow of individual sectors in China	China is a net virtual water exporter, and water scarce regions have higher percentages of virtual water exports
Feng et al. (2012)	Virtual water flow in the Yellow River Basin, China	The Yellow River Basin, China is a net virtual water exporter, and the most water scarce region in the basin should increase the import of irrigated crops and processed food products
Antonelli et al. (2012)	Alternative estimation of virtual water flow	More accurate estimates of virtual water flow in global trade combining input-output techniques from qualitative points of view
Mubako et al. (2013)	Virtual water flow in US states of California and Illinois	California and Illinois are net virtual water exporter in 2008, and virtual water flow pattern and volume cannot be explained in terms of water endowments alone
Tamea et al. (2013)	Virtual water flow in Italy from local and global perspectives, 1986-2010	Italy import and export of virtual water have grown markedly. In Italy, the dependence on import has increased over the last decades and has overcome the internal production since the year 2000
Konar et al. (2013)	Global virtual water flow under climate change	The total volume of virtual water flow is likely to decrease under climate change
Sun et al. (2013)	Virtual water flow of crops between regions in China	Grain diversion from northern regions to southern regions is disproportionate to the distribution of water resources in China
Dong et al. (2014)	Inter-provincial virtual water flow in China	Developed areas, such as Shanghai, Beijing, import virtual water to alleviate their water scarcity, and agricultural sector is the main part of virtual water flow among provinces in China
Dalin et al. (2014)	Virtual water flow of food from	Water savings from foreign imports actually are even greater

	interprovincial and global perspectives in China	than the global water savings in China, and 93% of these foreign virtual water imports are associated with soy-based commodities
Dang et al. (2015)	Agricultural virtual water flow in US	The volume of virtual water flow in US is equivalent to 51% of global virtual water flow, and the network of virtual water flow in US is more social, homogeneous, and equitable than the global virtual water trade network
Goswami and Nishad (2015)	Temporal scales virtual water flow in India and China	Virtual water flow can affect overall water sustainability and the net virtual water export alone can lead to loss of water sustainability of a nation in time scales but cannot be considered too long for a nation
Schwarz et al. (2015)	Virtual water flow of global agricultural food trade in the period of 1986-2011	In Africa and Southern America, virtual water flow has roughly quadrupled since 1986. In all regions, staples and industrial products account for the largest share in virtual water trade
Fracasso et al. (2016)	Virtual water flow of agricultural goods in the Mediterranean basin	Larger water endowments do not necessarily lead to a larger export of virtual water and higher water irrigation prices reduce (increase) virtual water exports (imports).
Zhang et al. (2016c)	Global virtual water flow of agricultural products in China	The trend that China exported virtual water per year was on the decline while the imported was on a rising trend
Flach et al. (2016)	Virtual water flow from Brazilian municipalities to countries of consumption	Policy relevance of current assessments of virtual water flow at the national level may be hampered
Sun et al. (2016)	Virtual water flow of grain between regions in China	Virtual water flow changes the original water distribution and has a significant effect on water resources in both virtual water import and export regions

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