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

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Abstract

Studies dealing with water flow and preferential flow are of typically importance because there are still many unresolved water security and scarcity problems. It may indeed be a valuable idea to provide a special review of the progress in the water flow and preferential flow for the applied water science community and to identify what is still missing or unresolved to improve predictions of surface water and groundwater quality within multiscale. This paper aims to review the state of the art on water flow and preferential flow published per year from 1995 to 2015, respectively, and to present a discussion of perspectives and some significant advances in the main themes of water flow and preferential flow that have emerged in recent years, with insights, some promising areas for future work, and suggestions also being provided regarding potential research trends, requirements and solutions. Recorded reports show that it is of general interest in water flow in the period 1995-2015 and also there are clear significant trends from physical hydrology and socio-hydrology perspectives. The future trend of water flow which is predicted in some way indicates a general increase. The term of preferential flow, its significance and progress in the period 1995-2015, shows that despite the increasing number of papers published on preferential flow, there has not been as much attention paid to this topic as we have expected, given its vital role in soil hydrology, water sustainability, slope stability and agricultural management. Finally, existing love-hate relationship between water flow and preferential flow pathways is reviewed.

Keywords

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

1. Introduction

Most concerning environmental, economic and social issues threaten livelihoods of people worldwide, agricultural production, industrial chain, energy projects, other forms of anthropogenic water consumption and ecological use since water natural resources are getting scarce and polluted with increasing population and temperature, higher food demand and changing precipitation patterns. These issues also exert significant influences on sustaining the survival of ecosystems (Van Oel and Hoekstra, 2012; Schewe et al., 2014; Elliott et al., 2014; Cazcarro et al., 2014; Lee and Bae, 2015; Dalin et al., 2015; Johansson et al., 2016; Michalak, 2016; McColl et al., 2017). Water is one of the most complex components on the planet operating at the interface of the hydrosphere, atmosphere, pedosphere and biosphere. Long-term water use sustainability, in some way, tends to be the most significant consideration at global scales. Agriculture is the largest consumptive sector of water use in global water systems (Schewe et al., 2014; Haddeland et al., 2014). In addition to agricultural sectors, water is also used for domestic and industrial sectors. Large scale transfer of water from water rich regions to water poor regions has been conducted to meet water demands (Troy et al., 2015). However, increased aridity, reduced soil water content, changes in climate variability and frequency of extreme weather events pose highly direct threat to water resources sustainability, water security and agricultural food security even severe land degradation and desertification (Maestre et al., 2015; Phalkey et al., 2015). An unprecedented global water crisis in human history has been predicted (Elshafei et al., 2014) which is dramatically related to land degradation processes that are millennia old (Cerdà and Lavee, 1999; Jafari and Bakhshandehmehr, 2016).

It is typically evident that the function, cycle, intrinsic property and in particular the flow of water are critical to sustain health and stability of natural and man-made ecosystems. We have considerable knowledge of water, its formation and distribution, but our understanding upon water flow and preferential flow is incomplete and rather faraway. In the previous, as well as in the recent, more studies relating to water flow including oil-water flow (Gao et al., 2015; Boostani et al., 2017), air-water flow (Felder and Chanson, 2016; Felder and Pfister, 2017), canopy water flow in plant (Fricke, 2015), water flow in rock fracture or glacier (Fountain et al., 2005; Neuman, 2005), debris-water flow (Malet et al., 2005), flooding-water flow (Gaines, 2016), river-water flow (Derx et al., 2013), subsurface storm-water flow (van Schaik et al., 2008; Nieber and Sidle, 2010), water flow in soils (preferential flow and soil matrix flow) and water flow within watersheds (surface water flow and groundwater flow) have got a broader interest in some way (Keesstra, 2007; Zema et al., 2016).

The studies of water flow above are implied from physical hydrological perspectives and are relating to water security and sustainability. However, with regard to socio-hydrological perspectives, the human-society-water nexus could change water resources management and could be better understood when virtual water flow is introduced. Global virtual water flow is estimated based on trade in agricultural and industrial sectors. The sum of global virtual water flow related to trade in agricultural and industrial products in the period from 1996 to 2005 was 2320 $Gm^3 y^{-1}$ on average. The largest share (76%) of the virtual water flow between countries is related to global trade in crops and derived crop products. Virtual water flow trade in animal products and industrial products contributed 12% each to the global virtual water flow. The volume of global virtual water flow related to domestically produced products was 1762 $Gm^3 y^{-1}$ (Hoekstra and Mekonnen, 2012). The total volume of global virtual water flow includes virtual water flow that is related to re-export of imported products. In light of the concept of virtual water flow, water footprint including consumptive and degradative water footprint was highlighted to emphasize on the link between human and water to produce the products (Hoekstra, 2013) and was used to characterize the volume of freshwater resources consumption and pollution in relation to production or consumption (Hoekstra, 2003). The blue, green and grey water flow, are three components of the water footprint (Hoekstra and Mekonnen, 2011). Blue and green water flow are two aspects of the consumptive water footprint, while grey water flow which represents the volume of water assimilating pollutants is not significantly neglected as people consider the degradative water footprint. The water in runoff, lakes, reservoirs, wetlands and man-made structures can be directly used by human consumption, in general, and could be regarded them as blue water (surface water and groundwater). Blue water is equal to the difference between evapotranspiration and precipitation when evapotranspiration is higher than the effective precipitation, while blue water is zero when evapotranspiration is lower than precipitation. Water evaporation during and after irrigation process is not the component of blue water. Because this part is back the natural system afterwards. Furthermore, the water stored in unsaturated soil layers is defined as green water (precipitation), either reclaimed by the atmosphere through soil evaporation or consumed by the plant roots and lost through transpiration during photosynthesis (Vanham, 2016). Green water is the major part of water use for agricultural sector. In general, green water is equal to the effective precipitation when evapotranspiration is higher than the precipitation during crop growth, while green water is equal to evapotranspiration when evapotranspiration is lower than effective precipitation. While the grey water refers to the volume of freshwater which can assimilate the concentration of given pollutants into natural back ground concentration to satisfy the ambient water quality standards. It is not a real water volume used along production processes, but the volume used to restore water quality (Lovarelli et al., 2016). Therefore, the three component of virtual water flow is highly interactive and important for the water balance and stability. For example, the increase of green water flow to the atmosphere due to the high agricultural management or forested practices leads to the decrease of regional surface water flow. This in turn affects the availability of long-term blue water flow and the change of groundwater table.

In addition to the significance of water flow above, preferential flow is a common and widespread phenomenon of water flow in soils with macropores (Beven and Germann, 2013; Zhang et al., 2016a). Just now we referred that agriculture was the largest consumptive sector of water use. However, large numbers of pesticides were put into agricultural catchments with the development of urbanization, industrial and agricultural developments (Kim et al., 2017). Those pesticides could be carried by water flow through the soil profiles to the groundwater table quickly. So a wider range of studies in some way should often provide more data to interpret why agricultural pesticides and other contaminants that should sorb strongly onto soil particles were being detected in groundwater tables and drains. Even if these contaminants sorb onto fine colloidal materials, it was still confused to explain how water flow pathways could carry those fine materials to depths without being filtered out by the surrounding soil matrix. The occurrence of preferential flow might be the significant driver for the phenomenon. As an unpredicted water flow in vadose zone, preferential flow is continuing to get more attentions despite lots of unresolved questions due to the complexity of vadose zone. Because it is clear that the vadose zone in which water, gas and solute transfer between the soil surface and water table is involved in many aspects of soil hydrology, such as soil water storage, soil erosion, water infiltration, evaporation, groundwater recharge and so forth (Nielsen et al., 1986).

In this review, it is immediately clear that water flow are preferential flow are such broad subjects so that this short review is necessarily selective rather than comprehensive. We focus on the study and resulting scientific literature of water flow in soils and within watersheds from physical hydrological and socio-hydrological perspectives and preferential flow. It aims at evaluating to what improvements in recent water flow and preferential flow have made, whether the love-hate relationship between water flow and preferential flow pathways have been evaluated. It is the objective of this paper to review the progress of water flow and preferential flow with the aim of delineating global water resources security which may be elucidated by organic matters, pesticides, contaminants and heavy metal to the groundwater table without resistance.

2. Methods

A comprehensive literature search was conducted to conclude the significance and progress of “water flow” and “preferential flow”, respectively. Based on the extensiveness of the existing literatures and the availability of most studies, we focused on and started with the set of published papers with the topic of “water flow” and “preferential flow” from 1995 to 2015 using the database of Web of Science (WoS). No restrictions on research types were applied.

In light of the literature survey, the term "water flow" and "preferential flow" in their titles, abstracts or keywords were used as search concepts. We then refined the scope of water flow studies in physical hydrology and socio-hydrology, respectively. For water flow in physical hydrology we considered surface water flow, groundwater flow and water vapor flow into the atmosphere, while for virtual water flow, green water flow, blue water flow and grey water flow were implied for water flow in socio-hydrology. An analysis of published papers with the topic of water flow on the temporal and geographical dimension was performed. A map was made for the total number of published papers of water flow (Fig. 1). In preferential flow studies, we statistically analyzed all papers by drivers, degrees, properties, scales, models, methods, mechanisms and types of preferential flow. Methods applied for considering the two topics include descriptive analyses. A descriptive approach is to compare the existing trends of the two and make clear sense of their interactions in a single analysis framework. Additionally, the number of publications per year and the number of references per country by author affiliations and area in which the research was conducted were summarized. Finally, a database with the topic of water flow and preferential flow pathways—a love-hate relationship was produced from the published literature. Relationship between water flow and preferential flow pathways was investigated through a diagram (Fig. 7).

3. Results and discussion

3.1 State of the art on water flow

3.1.1 Water flow on a world extent

The special section themed with water flow has got broader interests in the period 1995-2015. In recent years, there has been a growing body of research relating to water flow. It is easy to rapidly discern the similarities (studies on drivers of water flow) and differences (studies in physical hydrology and socio-hydrology) in these literatures. For example, the similarities of water flow studies were concentrated on their drivers, such as human activities (Jiang et al., 2015), changes in climate variability (Haddeland et al., 2014; Gan et al., 2015; Jiang et al., 2015; Lee and Bae, 2015; Najafi and Moradkhani, 2015; von Blanckenburg et al., 2015; Wang et al., 2015; Zhou et al., 2015a); land use changes (Algeet-Abarquero et al., 2015; Nourani et al., 2015; Yuan et al., 2015; Zhou et al., 2015b; Rodriguez-Lloveras et al., 2016a, b; Zhao et al., 2017); afforestation or vegetation reconstruction (Zhang et al., 2015a; Hayashi et al., 2015; Buendia et al., 2016); precipitation (Lutz et al., 2014: Emmanuel et al., 2015; Sadeghi et al., 2016); soil water content (Lal et al., 2015); biological soil crusts or microbiotic crusts thickness (Chamizo et al., 2015; Kidron, 2015); hillslope (Liu et al., 2000; Michaelides et al., 2002; Fujimoto et al., 2008); atmospheric carbon dioxide (CO_2) (Field et al., 1995; Gedney et al., 2006); solar dimming (Stanhill and Cohen, 2001); management regimes (van Oudenhoven et al., 2015); soil burn (Vieira et al., 2015) and so forth.

Based on the recorded reports of studies, a global network termed with water flow is summarized. A total of 180751 publications which met the selection criteria were obtained online from WoS. The distribution of document types and disciplines was also analyzed. Articles (175104) were the dominant document type, comprising 97% of the total publications. Meanwhile, the studies were mainly concentrated on the inter-disciplines, such as water resources (29969), environmental sciences (26849), geosciences (19725) and engineering chemical (14839). Papers were published in 100 languages. English was the dominant language for papers published on water flow and represented 98% of all published papers. From 1995 to 2015, the number of published papers increased from 4077 in 1995 to 15395 in 2015. The annual number of published papers increased remarkably. With respect to water flow in journal publication patterns, Journal of Hydrology ranked first in the number of published papers (3170, 2%), and followed by Water Resources Research (2628), Hydrological Processes (1913), Water Science and Technology (1642). The survey data in Fig. 1 demonstrated: from 1995 to 2015, the largest number of published papers with the topic of water flow was typically distributed in USA, followed by China, Canada, England and Japan. However, the number of this project was significantly lower than the number of papers published by USA and so forth, and was represented with blue darks in

Fig. 1. In addition, from 1995 to 2015, the annual growth rate of published papers of water flow was typically higher than growth rate in planning. The above results concluded that studies on water flow significantly increased year by year.

It is immediately clear where current hot spots might be achieving mathematical models that integrate surface water flow and groundwater flow, assessing regional or national or global water footprint (green water flow, blue water flow and grey water flow) in the studies of water flow. As a result of the literature research and selection, studies on water footprint take on a growing trend. The online database WoS search for literatures using the term “blue water flow” resulted in a total of 2058 publications in the period 1995-2015, and 3016, 700 publications for the term “green water flow” and “grey water flow”, respectively. For studies of blue water flow, articles (1882) were the dominant document type, comprising 91% of the total publications. In general, water resources (357), environmental sciences (353) and chemistry analytical (323) are the main research fields. The number of published papers increased from 40 in 1995 to 190 in 2015. With respect to green water flow, articles (2548) were the dominant document type, comprising 85% of the total publications. The studies were mainly concentrated on the environmental sciences (518), water resources (470) and chemistry analytical (256). From 1995 to 2015, the number of published papers increased from 45 in 1995 to 324 in 2015. In addition, for grey water flow, articles (601) were the dominant document type, comprising 86% of the total publications. The number of published papers increased from 18 in 1995 to 55 in 2015. In light of the recorded reports, a variety of topics are relating to water science and environmental science. Blue water flow, in some way, is the most water use component and is typically important for household or drinking water uses, industrial water uses and agricultural water uses (Fig. 2). Advanced studies concluded that countries with higher amount of green water flow tend to have intense agricultural sectors and more water bodies (Veettil and Mishra, 2016).

3.1.2 Water flow in physical hydrology

Traditional hydrological science focuses on the study of physical water flow and water stock based on hydrological models. In particular, hydrological models rely on physical principles of mass and momentum balance to characterize water flow and stock. With regard to physical hydrology, precipitation refers to a key input of freshwater resources to the surface, while evapotranspiration refers to a key pathway for freshwater to return to the atmosphere. Surface water flow and groundwater flow are two key components of water flow in physical hydrology. In general, surface water flow is generated due to precipitation excess and not due to soil saturation (Hueso-González et al., 2015). Surface water flow on the land surface or watershed is a key unit of analysis in physical hydrology due to the significance of landscape topography in characterizing surface water flow. Surface water which provides wide ecosystem services is only a part of water resources in the world, but it is more accessible to people (Pekel et al., 2016). Permanent surface water in North America accounts for almost 52% of the total surface water resources for less than 5% of the Planet's population, however, permanent surface water only accounts for 9% in Asia where 60% of the Planet's population occurs (Pekel et al., 2016). Seasonal surface water flow changes with high heterogeneity, fluctuates in wet/dry conditions and even shifts geographically (Pekel et al., 2016). So predicting and modelling surface water flow are challenging because of strong variability of surface water flow occurrence. Chen and Wang (2015) concluded that modelling seasonal surface water flow is not accurate because of the heterogeneity of soil properties including soil infiltration, soil storage capacity, land use cover and topography. Tesemma et al. (2015) stated that making accurate predictions for surface water flow was challenging due to the changing conditions like climate changes and human activities and also showed that some models were found to function poorly, especially the factors of climate. Groundwater flow which belongs to subsurface aquifers is a key component of water flow that supports riparian ecosystems during drought conditions (Rassam et al., 2013). It is typically evident that groundwater flow from shallow aquifers to catchment surface water is the major part of the total water flow volume in most rivers (Wittenberg, 2003). Groundwater is also benefit for ecosystem services, energy and food security, human health and water security and scarcity. Groundwater flow is a critical component of the hydrological cycle (Gleeson et al., 2016). Groundwater recharge which is more heterogeneous than water table gradients is difficult to measure directly at local or regional scales (Gleeson et al., 2016). Taylor et al. (2013) showed that understanding groundwater flow could be benefit for global energy, water and food security under climate change, in particular the increase of frequent and intense droughts and floods events. de Graaf et al. (2015) presented a high-resolution global-scale groundwater model to construct groundwater flow variations. Sakakibara et al. (2017) stated that both local and regional groundwater flow space-time variations are crucial for water resources management, in particular for low precipitation regions. In previous studies, water flow models have focused on surface water flow or groundwater flow individually. In recent advances, water flow models that integrate surface water and groundwater, such as MODHMS (Panday and Huyakorn, 2004), PARFLOW (Kollet and Maxwell, 2006), GSFLOW (Markstrom et al., 2008), HydroGeoSphere (Therrien et al., 2010; Brunner and Simmons, 2012), MIKE-SHE (Graham and Butts, 2005) and SWATMOD (Sophocleous et al., 1999), have been developed in recent years. Kollet and Maxwell (2006), Engelhardt et al. (2014), De Schepper et al. (2015), by a coupled integrated surface and subsurface flow modelling approach, accounted for the water flow processes in complex systems at field scales.

Surface water, such as reservoirs, rivers, lakes and wetlands, may interact with groundwater directly. The interaction between surface water flow and groundwater flow is a critical component of hydrological processes within multiscale. Surface water flow and groundwater flow interaction tends to proceed in two ways: surface water infiltrates into the groundwater table, and groundwater flows into the surface water (Kalbus et al., 2006). However, the interaction between surface water flow and groundwater flow is often more complex because this interaction affects both water security and scarcity (Pahar and Dhar, 2014). The contamination or development of one is bound to have effects on another (Sophocleous, 2002). Sakakibara et al. (2017) concluded that both surface water flow and precipitation affected groundwater flow in the rainy season, whereas in the low precipitation periods, both reservoir and stream water flow affected that most. Understanding the interaction is important for determining contaminants transport pathways as well as for water resources management. Alley et al. (2002) reviewed the interaction between surface water flow and groundwater flow was mostly focused on streams from environmental flow (i.e., chemical composition in water bodies) perspectives, whereas few studies on lakes, wetlands and oceans. Scibek et al. (2007) explored the effects of climate change on the interaction between surface water flow and groundwater flow using a high-resolution transient groundwater model. Li et al. (2014) stated that metals from geogenic and atmospheric factors, agricultural and industrial activities could disperse to surface water bodies through surface water flow or penetrate to groundwater table through preferential flow pathways with the influences of surface-groundwater interaction. The interaction between surface water flow and groundwater flow also affected the mass and energy exchange between the two water systems. The magnitude and direction of exchange between surface water (e.g., rivers) and groundwater is mainly determined by the hydraulic gradient between rivers and aquifers (Rassam, 2011). The exchange between rivers and groundwater not only influence water flow velocities in rivers but also exert effects on water security and riparian zone characteristics (Sophocleous, 2010). In riparian zones, the interaction between surface water flow and groundwater flow is the major part for the exchange of mass and energy. However, previous studies of surface water flow were often managed without sufficient consideration to the impact on groundwater flow and without available integration with groundwater flow (Nielsen et al., 1986). In recent studies, the interaction, exchange and integrated conceptual models for surface water flow and groundwater flow are generally interesting year by year.

Despite the significant importance of surface water flow and groundwater flow in water updating, the water vapor flow into the atmosphere is also a neglecting component. Water vapor flow is sometimes called green water flow. Rockström et al. (1999) estimated the water vapor flow of major terrestrial biomes and the total water vapor flow from continents. Gordon et al. (2005) stated that both deforestation and agricultural irrigation were the main driving forces for the alteration of global water vapor flow, and they also raised questions related to the influences of land use and climate change on altering water vapor flow at global scales. Bittelli et al. (2008), by a fully coupled numerical model, concluded that water vapor flow affected soil mass and energy budget highly and that water vapor flow induced the small fluctuations of soil water content near the surface. However, this component could bring about unpredictable problems with the change of natural conditions and human activities. According to the atmosphere interface, water holding capacity increases with temperature. The average temperature is rising from global scales. Global warming is possible to increase the intensity of precipitation events. The increase of precipitation intensity affects the frequency of flooding (Dankers et al., 2014). The water holding capacity of the atmosphere has been increasing due to the frequent global warming events caused by the combined effects of climate variability and human intervention. Such will result in the frequency of precipitation extremes, the increase of dry periods and the intensification of floods and droughts (Prudhomme et al., 2014; Schewe et al., 2014).

3.1.3 Water flow in socio-hydrology

Advances in the understanding of water flow in physical hydrology on the land surface or in the subsurface aquifers offer interests and promises in recent years. However, water flow assessment in physical hydrology often does not consider human-induced effects on hydrological processes. In particular, estimates of water flow at local or global scales may not be accurate until human actions are considered. In recent years, human impacts on the hydrological processes are only considered in regional hydrological distortion metrics (Weiskel et al., 2014). However, human impacts in those studies tend to be regarded as external driving force or as a parameter simply incorporated into hydrological models instead of being an internal driver along water flow assessment (Troy et al., 2015; Levy et al., 2016).

Socio-hydrology, the science of people and water aiming at understanding the dynamics and co-evolution of coupled human water systems (Troy et al., 2015), is an inter-disciplinary field studying the dynamic interactions and feedbacks between water and people. Areas of research in socio-hydrology include the historical study of the interplay between hydrological and social processes, comparative analysis of the evolution and self-organization of human and water systems in different cultures and process-based modelling of coupled human water systems. Di Baldassarre et al. (2013) developed a simple, dynamic model to conceptualize the interactions and feedbacks between social and hydrological processes to avoid flooding-water flow based on socio-hydrology framework. Elshafei et al. (2014) worked towards a conceptual framework for socio-hydrology model to better understand human feedbacks on hydrological processes (i.e., water flow) and to make water resources sustainability at global scales. Gober and Wheater (2014) concluded that it was impossible to predict long-term water system dynamics without considering socio-hydrology. Viglione et al. (2014), by socio-hydrology modelling approach, perceived the risk of flooding-water flow due to its high damage to community development, however, they also stated that the dynamic conceptual model overestimated flood risk which led to low economic opportunities and prosperities. Di Baldassarre et al. (2015) proposed a modeling framework to give feedbacks between social and hydrological processes involving the perception of flooding-water flow risk in urban areas. Blair and Buytaert (2016) stated the art review on more in-depth socio-hydrology modelling. Those studies are in attempt to apply socio-hydrology modelling framework to perceive human-water systems interactions and feedbacks. Socio-hydrology is related to integrated water resources management. In particular, integrated water resources management aims at controlling the water system to get desired outcomes for the environment and society. The scenario based approach is often used to explore the interaction between humans and water during integrated water resources management. However, this approach may be unrealistic, especially for long term predictions, as it does not account for the dynamics of the interactions between water and people. The focus of integrated water resources management is on controlling or managing the water systems to reach desired outcomes for society and the environment, while the focus of socio-hydrology is on observing, understanding and predicting future trajectories of coevolution of coupled human water systems. It is promisingly noted that we better understand the interaction between human activities and water systems within the watershed unit to sustainably control water resources management. However, models incorporating socioeconomic systems or human-hydrology interactions remain open questions. Socio-hydrology has three goals: 1) characterize multiscale, spatial and temporal changes and features of socio-hydrological processes; 2) interpret socio-hydrological processes to human-induced effects and predict the future scenarios of their interplay; and 3) understand the significance of water systems on people (Sivapalan et al., 2014). According to socio-hydrology framework, three pathways that human-induced effects on water flow are considerable: 1) internal modifications; 2) infrastructure-based external transfer; and 3) virtual water flow transfer. Human activities, such as land cover change and urbanization, typically affect surface water flow and other hydrological processes within the watershed unit. Those human activities refer to internal modifications. Moreover, human activities change the physical boundary of watershed to prompt it more linked in some way to the socioeconomic driving forces. During hydraulic engineering process, human infrastructure could alter water flow to ensure water security and scarcity. Infrastructure includes both hard-path engineering projects (e.g., dams and weirs) and soft-path measures (e.g., water allocation rules, demand management practices and other policies). These human-induced measures within the watershed unit refer to infrastructure transfers. The human-induced virtual water exchange within the watershed unit is regarded as virtual water flow transfer (Konar et al., 2016). In socio-hydrology, a wider range of drivers control the interaction between socioeconomic and hydrological processes at large catchment scales. Drivers tend to be difference in policy, technology, fuel cost, trade barrier and historical factor. Water flow in natural systems downhill, while it can uphill as social drivers affect. An example of water flow that socio-hydrology may address is referred to as virtual water flow. In particular, the topic of virtual water flow falls within the science of socio-hydrology (Sivapalan et al., 2012; Konar et al., 2013). Virtual water flow is defined as the transferring volume of virtual water from one area to another when goods and services occur (Hoekstra and Mekonnen, 2011). When the concept of virtual water was introduced (Allan, 1997), many researchers predicted that global commodities would self-organize to alleviate water scarcity. People set out to look for solutions to water resources crisis because of the significance of virtual water flow in balancing regional and global water security and scarcity (Sivapalan et al., 2014; Sun et al., 2016). For example, Konar et al. (2013) investigated the impacts of changing climate on global virtual water flow and concluded more water resources saving under climate change were encouraged by international virtual water flow trade at global scales. More papers have growing focused on the virtual water flow of grain products and goods either in global or regional or national perspectives (Table 1).

In principle, virtual water flow should be from regions rich in water resources and high water use efficiency to those that poor in water resources and low water use efficiency. However, many local and regional virtual water flow trades lead to irrational water resources management. With respect to virtual water flow in China as an example, studies are of generally high interests. According to the report of Water Resources, China, water resources in southern China account for more than 80% of total water resources. Grain products in southern China is less than that in northern China even though the climate of southern China is more favorable to grain growth, which leads southern China transferring from grain exporter to grain importer. Thus virtual water flow is transferred from water poor regions to water rich regions (Wang et al., 2014; Sun et al., 2016) (Fig. 3). Though water resources are being transferred from southern China to northern China in real form by the South-to-North Water Diversion Project, water resources in virtual form are being transferred from northern China to southern China (Sun et al., 2016). Meanwhile, northern China exports more water intensive grain products and thus water scarcity is more serious in northern China (Sun et al., 2016). In fact, northern China annually exports about 52 billion m^3 of virtual water to southern China, which is more than the maximum proposed real water transfer volume along the three routes of the South-North Water Transfer Project (Ma et al., 2006). It is immediately clear that researchers state that this transfer project could not meet China's water needs (Barnett et al., 2015). China is a net importer of virtual water flow in agricultural products. In particular, soy accounts for more than 93% of global virtual water flow (Dalin et al., 2014). However, China is a net exporter of virtual water flow when considering all sectors including agriculture, industry and services (Mekonnen and Hoekstra, 2012). Therefore, food trade from northern to southern China amounts to a total virtual water flow more than the proposed diversion of real water through the South-North Water Transfer Project (Ma et al., 2006; Sivapalan et al., 2014). The proposed diversion might form when complex systems dynamics controlled by policies, multinationals, supermarkets, retailers and powerful countries (Savenije, 2000). In northern, northeastern and northwestern China, green water accounts for the main part and the green water proportion is 85%, 67%, and 73%, respectively, but in eastern, western and southwestern China, green water accounts for 49%, 49%, and 52%, respectively (Fig. 3). In the main part of southern China, blue water resources are rich but southern China is a net importer from northern China. As can be seen from Fig. 3A, large number of water use volume is from eastern, northern and southern China, and agricultural products are the most water use, followed by industrial and domestic water use. From Fig. 3B, surface water flow and groundwater flow are mainly located into the eastern, southern and southwestern China. In particular, southern China accounts for the main part of total water resources, which also shows that it is not appropriate to transfer agricultural food from north to south of China. In light of the report of Water Resources, Beijing, China, the development area in which the available water per person is only 3% of the world's average has been suffering serious water scarcity. Researchers have concluded that the 2022 Winter Olympics in Beijing will exacerbate water scarcity of Beijing due to the huge water use from blue water flow, energy and hydropower to cool water, and the low precipitation in February, and showed that Olympics will make Beijing water scarcity worse (Yang et al., 2015).

3.1.4 Water flow future challenges

Following future challenges:

- How to assess the effects of water flow in soils on water flow within the watersheds.
- How to in an attempt to construct a framework of “Big data” to imply long-term changes of water flow.

- Understanding which way the water flow is and why this is so is the major part of water flow in socio-hydrology.

- How human-water systems are coupled, develop and evolve? And how to incorporate social and hydrological processes into socio-hydrology models? These issues are in question (Troy et al., 2015).

- One important applied research thesis for the future is for studies on how virtual water flow will change and co-evolve if taxes are placed on the virtual water trade (Sivapalan et al., 2014).

- Studies on global virtual water flow have been undertaken between countries. In general, the volume of virtual water flow is transferred from countries with abundant water resources to countries with higher water scarcity. These studies aims to provide policy strategies (e.g., a country or region through exporting water intensive agricultural food from water rich countries or regions to secure their domestic water resources) and water management practices making for the government to alleviate the domestic water resources stress and guarantee agricultural food security in importing countries. However, little attention has been paid to the study of virtual water flow in exporting countries (da Silva et al., 2016).

- How to construct a mathematical model that incorporates ecology, hydrology and economy modules to better assess blue, green and grey water flow within multiscale.

- Hydrological connectivity is crucially significant for watersheds where water flow is dominated by rapid surface water flow. So, how to quantify water flow between different water bodies across different landscapes, or among in soils, atmosphere and plants, or between the hillslope and the watersheds, or surface water flow and groundwater flow, and the aquifers accurately, based on the hydrological connectivity, is still in question. In light of the hydrological connectivity between surface water flow and groundwater flow, the interaction between surface water flow and groundwater flow tends to recharge to or discharge from the aquifers. In future, human activities should fully incorporate the concept of hydrological connectivity into water flow modelling to better assess water resources sustainability. In future, understanding the role of hydrological connectivity and integrating the concept of hydrological connectivity into hydrological models could benefit for the policy makers to know how water flow connects between or among different water bodies, in particular the occurrence of preferential flow. Hydrological connectivity is the concept that water flow provides a pathway for the exchange of mass and energy between different environments and may occur only during wet conditions or during seasonal snowmelt conditions. Assessing the strong variability of space-time dynamics of hydrological connectivity is better to understand its high influences on water security and ecosystem services progressively, in particular for understanding of hydro-logic, hydro-geologic and hydro-ecological processes.

3.2 State of the art on preferential flow

3.2.1 Preferential flow on a world extent

The special section themed with preferential flow has also got broader interests in the period 1995-2015. These researches comprise inter-disciplinary efforts which have advanced our understanding of preferential flow. The special section preferential flow emphasized the need to link with the studies of groundwater pollution, land degradation, soil physical and hydrological processes (Zhang et al., 2017). The number of studies increased in the most recent years, proving the growing interest on the indicator. The online database WoS search for literatures using the term "preferential flow" resulted in a total of almost 7608 publications in the period 1995-2015. The distribution of document types and disciplines of preferential flow studies was analyzed. Articles (6717) were the dominant document type, comprising 88% of the total publications. The studies were mainly concentrated on water resources (1711) and environmental sciences (1317). With respect to journal publication patterns, Journal of Hydrology ranked first in the number of published papers (274, 4%) and followed by Water Resources Research (241), Vadose Zone Journal (179) and Hydrological Processes (141). The survey data in Fig. 4 demonstrated: from 1995 to 2015, the number of published papers increased from 168 in 1995 to 496 in 2015. The annual number of published papers increased remarkably. The largest number of published papers of preferential flow was typically distributed in USA, followed by Germany, France and China. In addition, from 1995 to 2015, the annual growth rate of published papers of preferential flow was also typically higher than growth rate in planning. The above results concluded that studies on preferential flow were significantly interesting year by year. Fig. 4 provides a summary of the recent and previous studies.

The co-authorship networks of countries in the world are social networks constructed by connecting actors in case they have co-authored together. Collaborative papers published with the topic of preferential flow and academic communication and collaboration in the study of preferential flow during the last 20 years from 1995 to 2015 are increasingly broader. The contribution of different countries to papers published was indicated in this review. Based on the results, 17 countries of the world had published papers of preferential flow with the number > 100. Among these countries, USA has published 681 papers concentrating on preferential flow from 1995 to 2015, flowed by Germany (368), France (284) and England (273). The name and share of countries are shown in Fig. 5. It is immediately clear that the collaboration between other countries and USA is more active.

3.2.2 Preferential flow: Significance and progress

In the 19th and beginning of the 20th century, macropores as continuous openings influencing water flow was observed which could provide big footprints of preferential flow for soil hydrologists in the near future (Schumacher, 1864; Lawes et al., 1882; Engler, 1919). Preferential flow refers to all phenomena where 70-85% water flow in the unsaturated zone through localized pathways relatively quickly bypassing the surrounding soil matrix, which makes it difficult to predict water flow in the field conditions (Kapetas et al., 2014). Preferential flow phenomena do favors of understanding of ecological and hydrological functions of soil, such as the transformation of substances and energy entering the soil, sorption of substances and water by soil, formation of chemical composition of groundwater and the regulation of water balance of landscapes (Zhang et al., 2017). Helling and Gish (1991) distinguished root channels, cracks, fissures as preferential flow pathways because of their promotion in water flow. Li and Ghodrati (1994), by breakthrough curve methods, concluded the influences of root channels on preferential transport of Nitrates. Hagedorn and Bundt (2000) stated that preferential flow pathways in forest soils could persist for decades. Jørgensen et al. (2002) reported that water flow was more obvious in soil profiles with root channels than that without root channels. Franklin et al. (2007) showed that the mechanisms of preferential flow were ambiguous though a wide range of studies had been done for preferential flow. Bogner et al. (2010) found that root biomass was larger in preferential flow pathways than that in the surrounding soil matrix. Etana et al. (2013) implied that persisted compaction of subsoil might enhance the degree of preferential flow. Xin et al. (2016) found that water flow increased remarkably for soils with distributed macropores compared with soils without macropores. Zhang et al. (2017) concluded that preferential flow was more obvious in stony soils and that preferential flow patterns were distributed in soil profiles with high heterogeneity.

Stronger preferential flow phenomena occur in the fine texture soils and in the vicinity of trees than is found elsewhere (Benegas et al., 2014), while weaker preferential flow phenomena occur in larger organic carbon content soils (Ghafoor et al., 2013). Preferential flow phenomena in some soils are enhanced in wetting soil conditions due to reduced lateral water flow from the preferential flow pathways to the surrounding soil matrix (Hardie et al., 2013). The occurrence of preferential flow occurs at different soil types, such as forest soils (Van Der Heijden et al., 2013; Guo et al., 2014; Laine-Kaulio et al., 2014; Zhang et al., 2015b, c; Zhang et al., 2017); constructed wetland soils (Hua et al., 2014); and agricultural soils (Koestel et al., 2013; Zhang et al., 2014, 2015d; Jiang et al., 2017). With respect to agricultural soils in particular, the rising effects of preferential flow on soil water conservation prompt people to conduct better management practices. Because preferential flow exerts highly influences on seed emergence, crop growth and even crop yield. Williams et al. (2016) stated the variability of preferential flow dynamics in agriculture both in tillage and no-tillage management measures and concluded that the interaction between preferential flow pathways and the surrounding soil matrix were found to perform highly along water flow processes. Jiang et al. (2017), by dye tracing experiments, implied the influences of different management practices on preferential flow occurrence and concluded that both alfalfa and conservation tillage in agricultural field which could increase continuity order and connectivity degree of macropores systems were preferential management practices. Furthermore, the occurrence of preferential flow originates from the spatial variations in water flow velocity due to major heterogeneities in soil profiles. Zhang et al. (2017) stated that preferential flow dye patterns in the soil profiles were highly different in stony soils and they implied that the spatial heterogeneity of stony soils, especially the occurrence of rock fragments distribution, prompted the results. The occurrence of preferential flow pathways tend to be rich in the place where near-ponding conditions takes place on the soil surface or where water flow encounters less permeable layers within the soil profiles or where vegetation canopy architecture adjusts the redistribution of precipitation above soil surface (Bogner et al., 2013). Preferential flow pathways are complex networks of large pores and void spaces within soils which are typically formed by living or decaying root-induced channels, soil biota, soil fauna, soil cracks, drying-wetting cycles and freezing-thawing process. For example, root-induced channels within topsoil constitute main preferential flow pathways, while unstable water transfer from preferential flow pathways to the surrounding soil matrix occurs because root biomass decreases in subsoil. Preferential flow along root-induced channels could carry large amount of bacteria. Root-induced channels as preferential flow pathways due to roots shrink provide more space for water flow. Moreover, root-induced channels harbor high amounts of bacteria than the surrounding soil matrix and are hot spots of bacteria activity (Dibbern et al., 2014). Larger and deeper root systems constitute a complex network within the soil profile for alfalfa cultivation-a perennial and long lived plant-than wheat cultivation-an annual and short lived plant. Decayed alfalfa root systems could create more preferential flow pathways (Yousefi et al., 2014). For soil cracks and biopores, higher water infiltration rate occurs in cracked soils and this rate decreases when cracks are closed during wetting. Preferential flow in cracked soils was a matter of very short time due to crack closure resulted from rapid and heterogeneous swelling processes (Liu et al., 2003). However, other researchers stated that cracks did not close after rewetting, leading to high water infiltration during wetting. Soil cracks remain preferential flow pathways even after they are closed on soil surface (Zhang et al., 2014). The drivers, occurrence mechanisms, types, degrees and properties of preferential flow (Fig. 6) could be better assessed and predicted in soil hydrology if a potentially glance of interdisciplinary, in particular soil physics, soil chemistry, soil biology and plant physiology, is considered (Zhang et al., 2016a).

Preferential flow could displace older water stored in the surrounding soil matrix deeper into the soil even into the streams. The interactions between preferential flow pathways and the surrounding soil matrix affect the ability of solute transport based on different soil water content conditions (Laine-Kaulio et al., 2014). At the primary stage, the dominant water transfer is from the preferential flow pathways into the surrounding soil matrix when the water content is lower in the surrounding soil matrix than that in the preferential flow pathways. Meanwhile, interactions between preferential flow pathways and the surrounding soil matrix increase with the sand content (Bogner et al., 2012). Preferential flow and soil matrix flow are the typical two regimes of water flow within the soil profiles (Hirashima et al., 2014). Soil matrix flow is a relatively slow and even movement of water and solutes through the bulk soil (Stamm et al., 1998; Allaire et al., 2009). Soil physicochemical and biological properties may be different between preferential flow pathways and the surrounding soil matrix (Bogner et al., 2012). Preferential flow pathways not only determine the spatial pattern of solutes but also exert vital significance on soil properties and are regarded as a contaminant sink on the basis of contaminant species (Garrido, et al., 2014; Zhang et al., 2016b). The high organic matter content in the preferential flow pathways was attributed to three main sources: greater proportion of living or decayed roots in preferential flow pathways than in the surrounding soil matrix; preferential input of dissolved organic matter from the surface; enhanced release of microbial biomass C from rewetting of relatively dry soil (Morales et al., 2010). Mass transfer between preferential flow pathways and the surrounding soil matrix is typically common and also different from soil texture, soil organic matter content, land coverage type and so forth (Jarvis et al., 2007; Alaoui et al., 2011; Backnäs et al., 2012; Zhang et al., 2017). Martin and Dean (2001) who treated the surrounding soil matrix as reservoir effect identified that water with high permeability and hydraulic conductivity exchanged between preferential flow pathways and the surrounding soil matrix. Peterson and Wicks (2005) concluded that only 1% of the volume of water and <<1% of the amount of solute moved from preferential flow pathways to the surrounding soil matrix. However, they did not regard the surrounding soil matrix as a reservoir in fact. Mohanty et al. (2016) concluded that extent of hysteresis increased with increases in exchange of water and solute between preferential flow pathways and the surrounding soil matrix. The surrounding soil matrix exchanged the old infiltrating water with new infiltrating water during successive infiltration (Mohanty et al., 2016). Preferential flow not only exerts significant effects on both surface water and groundwater security but also affects the physical hydrological processes to precipitation (Beven and Germann, 2013; Khan et al., 2016). Quantification and characterization of preferential flow is vital for groundwater recharge, waste disposal risk assessment, contaminants spatial pattern and heavy metal redistribution in soils (Saravanathiiban et al., 2014). In particular, the topic of preferential flow is of generally high significance and scientifically interest, but it is too complex to be solved from a theoretical and experimental point. However, despite the increasing number of papers published on the topic, there has not been as much attention paid to preferential flows as we might have expected, given its significance in all areas of soil and catchment hydrology, water quality, slope stability and agricultural management.

3.2.3 Preferential flow future challenges

Given the growing interests of preferential flow in past few years worldwide, a real opportunity and challenge of preferential flow studies from a global perspective in future occurs for hydrologists. Given the unpredictable significance of preferential flow in all areas of large scale catchment hydrological processes, groundwater resources security, agricultural non-point source pollution, and soil heavy metal pollution, large number of unanswered questions and disputes still confuse researchers (Beven and Germann, 2013).

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

- Any new theory of preferential flow, in particular mathematical models, needs to be rigorously tested with wider range of experimental data. A fully convincing integrated physical theory still has not yet been achieved (Beven, 2010).
- Yet to date, however, most preferential flow studies have focused on its drivers, with limitation of studies implying the space-time changes, mathematical models, new measurement techniques and theoretical approaches predicting the process of preferential flow accurately. It is noteworthy that preferential flow effects are generally ignored in lumped hydrological models even physically based models (Weiler, 2017). Integration of all the purported drivers, in particular preferential flow, into mathematical models framework is required to achieve the fully integrated analysis. An active field for future research needs to extend, develop and assess the effects of preferential flow on models sensitivity within multiscale.
- There is an urgent need to greatly enhance our ability to imply a wide range of unpredictable preferential flow process under different environments.
- When and how does water flow through preferential flow pathways within the soils? How does water in preferential flow pathways interact with water in the surrounding soil matrix? How does solute exchange between preferential flow pathways and the surrounding soil matrix? How important are preferential flow pathways in terms of water flow at the hillslope or catchment scales? How does solute process adsorption and degradation on preferential flow pathways walls? These need to be investigated further (Beven and Germann, 2013).
- Does preferential flow matter at catchment scales? Preferential flow occurs only during specific conditions linked to soil water content, soil properties, high precipitation and so forth. However, these conditions could not be met to assess hydrographs in the long run due to the small proportion of preferential flow time. Thus hydrologists suppose

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

Even if some questions still remain unresolved, our understanding of preferential flow in the vadose zone is continuing to be facilitated.

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

Before we deal with the topic, it is worthwhile to clearly understand the progress of water flow and preferential flow, respectively. In recent advances, studies have implied that water flow in the vadose zone often occurs through a small fraction of the soil along preferential flow pathways. Groundwater quality could be influenced by the arrival of both dissolved and suspended contaminants which are carried by gravity-driven water flow through preferential flow pathways to the water table. There is increasing doubt that whether a love-hate relationship between water flow and preferential flow pathways. Recently, Weiler (2017) presented a review and study on the relationship between macropores and preferential flow. This study concluded that preferential flow is of high relevance for surface water flow in the soil or watershed. In previous studies, Beven and Germann (1982, 2013) also discussed the relationship between macropores and water flow extensively. Even more importantly, it is indeed evident that recent and precious studies have conducted limiting assessment to state the importance of macropores on water flow or preferential flow. Hydrologists had a love-hate relationship with water flow and preferential flow pathways like a love-hate relationship between water flow and preferential flow pathways (Fig. 7). A complex relationship between water flow and preferential flow pathways emerges early at birth and continues throughout life. Even though water flow and preferential flow pathways have been extensively concluded, their interaction remains obscure. Hence, it becomes immediately clear to have insights on the love-hate relationship between water flow and preferential flow pathways. The interaction between water flow and preferential flow pathways becomes crucial in situations when water security and scarcity could be controlled by its interaction.

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

The most convincing evidence of the occurrence of water flow through preferential flow pathways at profile and plot scales has come from dye tracing experiments (Flury et al., 1994; Zehe and Flühler, 2001; Hagedorn and Bundt, 2002; Öhrström et al., 2002; Kamolpornwijit et al., 2003; Morris and Mooney, 2004; Köhne et al., 2006; Mooney and Morris, 2008; Klaus and Zehe, 2010; Backnäs et al., 2012; Bargúes Tobella et al., 2014; Mossadeghi-Björklund et al., 2016; Zhang et al., 2017). Water flow through preferential flow pathways at profile and plot scales could be achieved from the continuous change of dye tracers (i.e., Brilliant Blue, Bromide, Chloride and so forth). Hagedorn and Bundt (2002), Backnäs et al. (2012) for example concluded difference of the chemical properties between preferential flow pathways and the surrounding soil matrix by dye tracing patterns. Morris and Mooney (2004) stated that water flow through preferential flow pathways recorded as instantaneous responses both in the 50- and 130-mm probes using TDR and showed that preferential flow pathways might be responsible for a significant portion of the total water flow in light of the breakthrough curve results (Mooney and Morris, 2008). Köhne et al. (2006) stated that water flow through preferential flow pathways at column scales could not be predicted accurately based on water flow and solute concentration data used in dual porosity model. Dye staining patterns may not reveal all preferential flow pathways within soil profiles in fact (Beven and Germann, 2013). However, at field scales, the convincing evidence of water flow through preferential flow pathways tends to be indirect and may be inferred from the response of tracer concentration at some point. In light of the studies of water flow through preferential flow pathways at field scales, it is typically interesting to understand why solutes (i.e., nutrients, contaminants and so forth) could be reported at depths much greater than would be expected in groundwater table. In general, contaminants could be carried by water flow through preferential flow pathways to the groundwater table quickly. It is also clearly evident that researchers conduct a wide range of studies to quantify the effects of preferential flow on contaminants transport by mathematical modelling and promising methodology. These studies could ahead clarify the origin of groundwater pollution and could also benefit for water resources sustainability. Therefore, from the groundwater security perspectives, we conclude that a hate relationship between water flow and preferential flow pathways because water flow could carry more contaminants and pesticides to the groundwater table through a small portion of preferential flow pathways.

However, with respect to the nutrients availability in the rhizosphere, it is well known that plant roots not only grow into the preferential flow pathways within the soil profiles but also form lots of preferential channels themselves and that there is a love relationship between water flow and preferential flow pathways. Preferential flow pathways have higher amounts of nutrients and organic matters than the surrounding soil matrix, which prompts plant growth. In general, preferential flow pathways are regarded as storage of micro-organism, nutrients and organic matters. During plant growth, root systems must absorb more soil water and nutrients to maintain their sustainability. Water flow carrying nutrients to the rhizosphere quickly through preferential flow pathways is benefit for plant growth, because preferential flow pathways could be treated as storage of organic matters. The framework could benefit for the plant growth, as well as agricultural crop production, because preferential flow pathways could be persistent for decades.

3.3.2 Water flow through preferential flow pathways at hillslope scales

Hillslopes act as filters for water flow to the surface water bodies or even to the groundwater table in many landscapes. Water flow through preferential flow pathways at hillslope scales is highly related to morphological properties like regolith, glacial till and bed rock (Beven and Germann, 2013). There are now a wide range of studies concluding that preferential flow might be crucial in controlling hillslope hydrological processes. Interests in the role of preferential flow in hillslope hydrology have increased dramatically (Leaney et al., 1993; Guebert and Gardner, 2001; van Schaik et al., 2008; Anderson et al., 2009; Klaus et al., 2013; Guo et al., 2014). Noguchi et al. (1999) for example concluded that water flow through preferential flow pathways formed by living or decayed roots, bedrock fractures might be important in determining hydrological processes at hillslope scales. Anderson et al. (2009) stated that preferential flow pathways carried most of water flow during storms at hillslope scales due to the very small groundwater table responses.

A hate relationship between water flow and preferential flow pathways is also necessarily concluded from the perspective of debris-water flow acceleration and subsurface storm-water flow especially under wet conditions and high precipitation. With regard to debris-water flow on the land surface, preferential flow pathways provide the nearest channels for this process. It is typically clear that the property of sheet or splash erosion could make the surface smoothly by eroding clods to flat the roughness and in final to fill the depression with the sediments, which leads the increase of surface water flow on the land surface and the decrease of storing water for the depression during high precipitation. In particular, once the spilling process is initiated in the depression, preferential flow pathways occur among these depressions along the steep slope. Preferential flow pathways on the land surface could prompt, route and concentrate the surface water flow, sediment, gravel and stone transport with high water flow velocity due to high precipitation (Peñuela et al., 2016). The synthesis of turbulent surface water flow, sediment and gravel is the origin of debris-water flow which exerts a hate relationship with preferential flow pathways on the land surface.

For subsurface storm-water flow at hillslope scales, this water flow as a term of repaid water flow through preferential flow pathways with much higher water flow velocity than the surrounding soil matrix dominates hillslope hydrology and also has a hate relationship with preferential flow pathways when we address hillslope stability and landslides. Where preferential flow pathways are crucial parts of subsurface water systems, these pathways could feed water to make water pressures develop. As the landslide develops, the water storage continues to feed water even drainage occurs. Subsurface storm-water flow may develop to accelerate as landslide happens (Hencher, 2010). Preferential flow pathways are dramatically treated as conduits of subsurface storm-water flow in hillslopes. Rapid subsurface storm-water flow depends on the fluxes of both vertical and lateral preferential flow pathways (van Schaik et al., 2008; Nieber and Sidle, 2010). Subsurface storm-water flow at hillslope scales is a combination of preferential flow and soil matrix flow. Leaney et al. (1993) concluded that > 90% subsurface storm-water flow was mainly carried by preferential flow pathways bypassing the surrounding soil matrix; Anderson et al. (2009) stated that subsurface storm-water flow velocity was governed by the connectivity of hillslope preferential flow pathways. Stumpp and Maloszweski (2010) found the contribution of preferential flow pathways to subsurface storm-water flow was between 1.1 and 4.3% for the lumped parameter approach and 1.1 and 20.5% for the HYDRUS 1-D approach, respectively; Vogel et al. (2010) found that only 24% subsurface storm-water flow was transported through preferential flow pathways. Repaid subsurface storm-water flow through preferential flow pathways processes could affect the stability of hillslopes for addressing issues of hillslope sustainability, storm water management and other hydrological and biogeochemical responses.

3.3.3 Water flow through preferential flow pathways at catchment scales

If water flow through preferential flow pathways is crucial at hillslope scales then it is also crucial at catchment scales (Beven and Germann, 2013). However, evaluation of water flow through preferential flow pathways at catchment scales remains in question because of the high temporal and spatial heterogeneity of water flow dynamics (Allaire et al., 2009; Beven, 2010; Darracq et al., 2010; Godsey et al., 2010; Beven and Germann, 2013; Wiekenkamp et al., 2016). The geometry, connectivity and tortuosity of preferential flow pathways networks remain an issue in practice at catchment scales than that at soil columns scales (Ghafoor et al., 2013). Direct tracing of water flow through preferential flow pathways remains an issue even at zero-order catchment scales. A promising technique to assess space-time dynamics of preferential flow at catchment scales is the use of sensor response times (Hardie et al., 2013; Liu and Lin, 2015; Wiekenkamp et al., 2016). Christiansen et al. (2004) found that preferential flow pathways had significant influences on contaminants leaching into the groundwater table at catchment scales though preferential flow pathways had no dominating influences on groundwater recharge or discharge at catchment scales. Wiekenkamp et al. (2016) concluded that the spatial and temporal occurrence of water flow through preferential flow pathways using sensor response times was triggered by the amount and intensity of precipitation at catchment scales. Moreover, public authorities need integrated large-scale models and decision-support tools that can decide the effects of water flow through preferential flow pathways on contaminants leaching at catchment scales.

All hydrological processes are irregular in temporal and spatial scales and water flow through preferential flow pathways may be measured everywhere (Uhlenbrook, 2006). A hydrological processes phenomenon, for example, flooding-water flow originating from a catchment, varies with high heterogeneity. Flooding-water flow displaced from those surface water bodies (i.e., rivers, lakes, reservoirs and so forth) in a catchment. The connectivity of surface water bodies and preferential flow pathways in the catchment may prompt the understanding of rapid water flow contributions to the flooding events. A hate relationship between water flow and preferential flow pathways is also necessarily concluded from the perspective of flooding-water flow at catchment scales. For flooding-water flow during extreme storm events, it is widely known that hillslope acts as a buffer of temporary storage to reduce the capacity of flooding-water flow and the damage caused by flooding. However, frequency of flooding is typically high due to the increased influences of human activities and climate variabilities. Along the disastrous flooding-water flow, water flow is driven by gravity, tends to be downhill without resistance, and even disturbs urban traffic, submerges village, and endangers human life. Flooding-water flow will be accelerated as the process passes through the flatting areas or through the areas with micro- or macro-gradient. These areas could be referred to preferential flow pathways in some way. In particular, flooding-water flow to the nearest areas without resistance by preferential flow pathways could take more serious disasters.

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

It is not indeed immediately clear for the assessment of virtual water flow from socio-hydrological perspectives. Considering previous studies, it is clearly stated that these papers only assess the volume of virtual water flow of products in the regions or in the world. However, it is our opinion that which is preferential type of crop product to import, preferential choice of country to export products, preferential choice of tax to import or export products along virtual water flow trade, to alleviate water security and scarcity, these questions should be assessed immediately. Then the question arises: how does water stress could be alleviated from the perspective of virtual water flow and preferential flow pathways along regional or national or global virtual water flow trade. It is due to the presence of preferential policy (i.e., trade, tax, human needs and so forth) conducted to make water resources sustainability. In light of the socio-hydrological perspectives, these preferential policies along virtual water flow trade could form a global framework in some way to alleviate global water crisis. For example, the policy makers could decide which crop should be imported or exported preferentially with virtual water flow pattern from other regions or countries to keep real water balance. However, it is not optimistic because of water allocation rule, demand management practices, current policy, history, political security, food security, local economy and environments. Although global virtual water flow trade has a complex network structure and is increasingly complex dynamic system, in fact, preferential bilateral agreement between countries and multilateral trade agreements could enhance global virtual water flow trade in some way. Policy and decision makers should consider both short and long term virtual water flow trade plan based on those preferential trade agreements from network perspectives. Therefore, preferential virtual water flow trade agreements between regions or countries should open quickly to alleviate global water crisis.

In this section, “preferential flow pathways” is not the term of real preferential flow pathways which could prompt repaid water flow without resistance from physical and hydrological perspectives. However, “preferential flow pathways” is related to the preferential policy adjustment during virtual water flow trade between regions or countries. In general, this “preferential flow pathways” is mainly controlled by policy makers and could make global water balance in some way if the adjustment is fully considered. In general, we could not avoid some facts that virtual water flow is transferred from regions poor in water resources to regions rich in water resources. If the preferential policy is took on with global endeavors, more water resources will be saved during virtual water flow transfer. The policy makers could decide which kind of crop products should be preferentially imported from other countries to alleviate water crisis. For example, China is a net importer of virtual water flow in agricultural products, especially soy. Chinese government set out to import soy products instead of other agricultural products because of their necessity for human life, livestock feed and their much higher virtual water content during production than paddy, wheat, maize and so forth, in particular because of their low yield during production. Chinese farmers also realize that no more incomes from soy production. Therefore, the policy makers of China import more soy with the form of virtual water flow from other countries preferentially to alleviate serious water stress in some way. Apart from the preferential virtual water flow trade, policy and tax in alleviating water crisis, real water transfer from rich regions should also be considered preferentially. Regions rich in water resources not only satisfy their needs but also provide water sustainability for regions poor in water resources. In particular for policy makers, they clearly understand which is more necessary to make water resources available. For example, water resources from Hebei Province or nearby Beijing regions should supply the development areas, in particular Beijing, preferentially. It is clearly noted that almost 70% water resources of Beijing is from Miyun Reservoir, Beijing. Recently, Chinese government set out to make an agenda for the development of Jing-Jin-Ji region, China to prompt people in these areas more improvement. The policy that water resources should be supplied for Beijing preferentially might alleviate water crisis of Beijing in some way. In addition to the real water resources supplied for Beijing preferentially, the most developed area of Beijing must also import more virtual water from other regions or countries. A love relationship between virtual water flow and "preferential flow pathways" is necessarily indicated in light of the virtual water flow transfer from socio-hydrological perspectives.

4. Conclusions

The large number of studies reviewed in this paper show that there is a promising development of water flow and preferential flow from 1995 to 2015 though lots of questions have not been unresolved yet to date. People set out to alleviate water resources considering the human-society-water-food-energy nexus from socio-hydrological perspectives instead of concentrating on studies in physical hydrology only. So it is evident from the literatures that there is a need to consider the complex relationship between water flow and preferential flow pathways. This review of the topic then leads to the development of an integrated study on water flow. In addition, based on this review, further work could include as the inter-disciplines are proposed.

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Figure Captions

Figure 1. A global network of published papers themed with water flow in the period 1995-2015. Dark red dots indicate papers published by USA, and red dots by China, Canada and Japan. Dark blue dots indicate few papers published by those countries.

Figure 2. The three components of water footprint including blue water flow, green water flow, and grey water flow incorporating into a clear framework (Falkenmark and Rockström, 2006; Lathuillière et al., 2016).

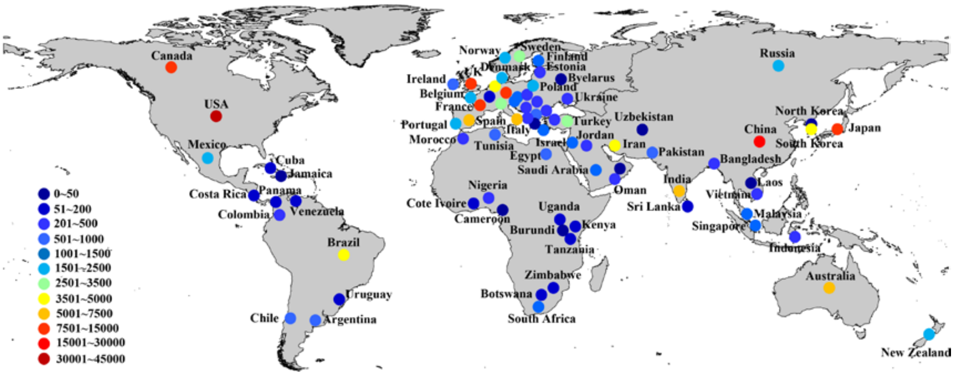
Figure 3. The average volume ($\times 10^8 m^3$) of water use and water resources in the period 1995-2015 in China including the North, East, Northeast, South, Southwest and Northwest. A represented the average volume of water use of industry, domestic water use and agricultural products in the six parts of China, and B represented the average volume of water resources of surface water, groundwater and total water resources in the six parts of China, respectively.

Figure 4. The development of preferential flow from the number of publications per year and per country in the period 1995-2015, and the focus of preferential flow where studies were conducted in different inter-disciplines. In Fig. 4 a, a wider range of studies are relating to water science, environmental science, and soil science; In Fig. 4 b, the number of published papers > 100 each country was indicated; In Fig. 4 c, the number of literatures on preferential flow per year was showed.

Figure 5. The global framework of cooperation among countries in the world studying on preferential flow at a global scale was showed, and the number of publications per country by author affiliations and area in which the research was conducted.

Figure 6. Preferential flow integrated analysis in this composite Figure. Family branches are shown in an unrooted phylogenetic tree from the drivers, occurrence mechanisms, types, degrees, properties, models, methods, scales of preferential flow, to the progress of preferential flow. The composite figure summarizes the development of preferential flow across-the-board.

Figure 7. A love-hate relationship between water flow and preferential flow pathways.



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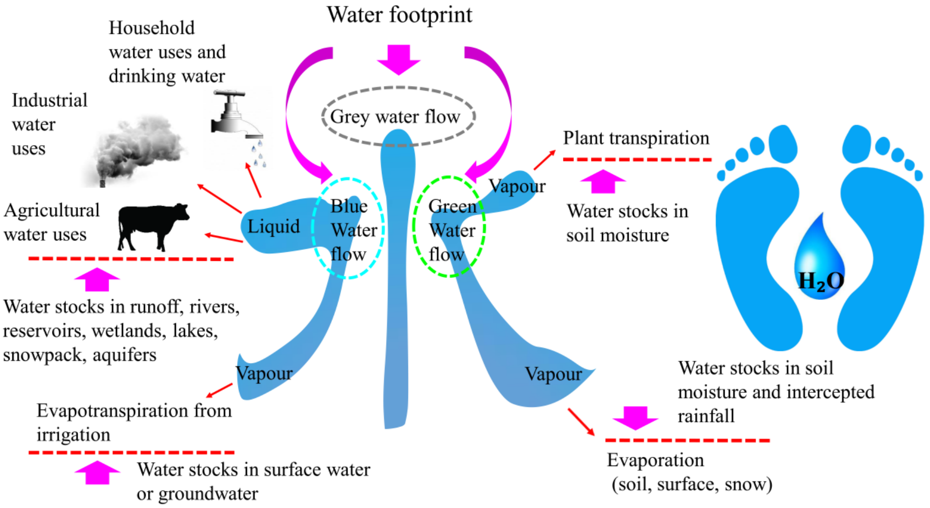

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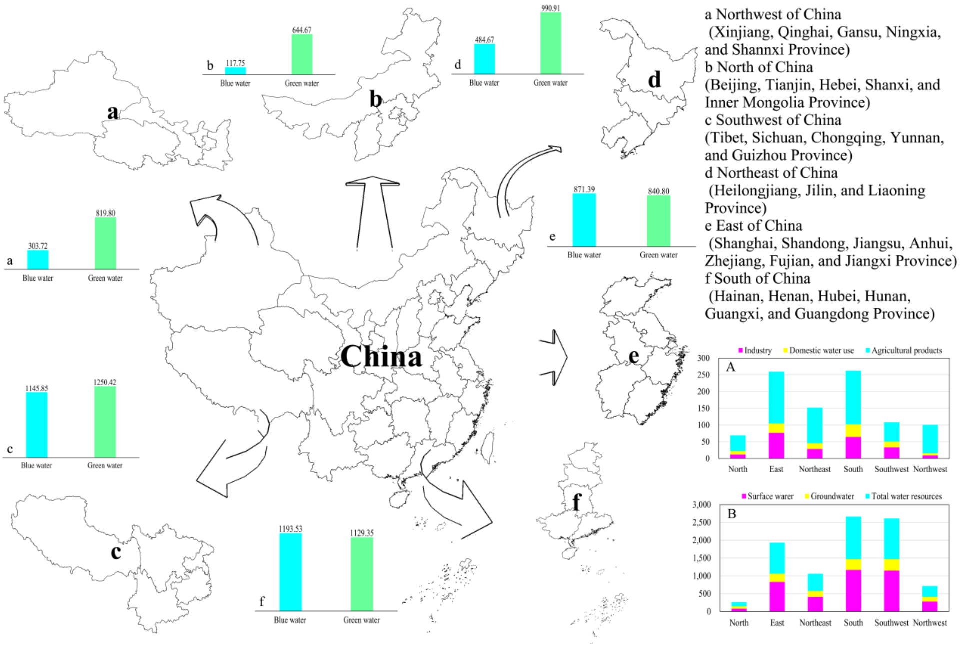

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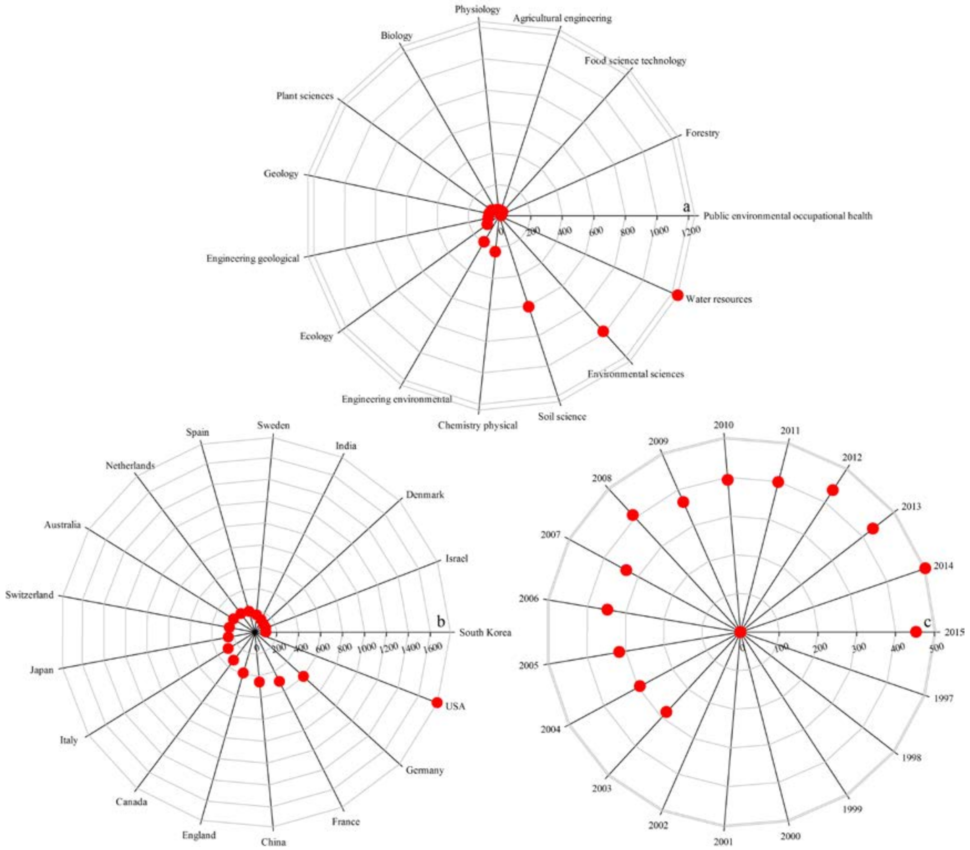

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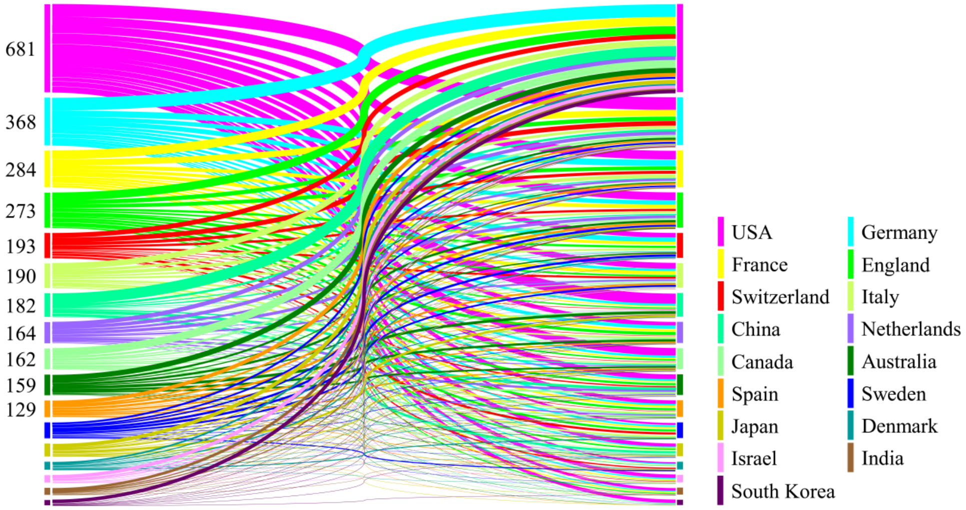

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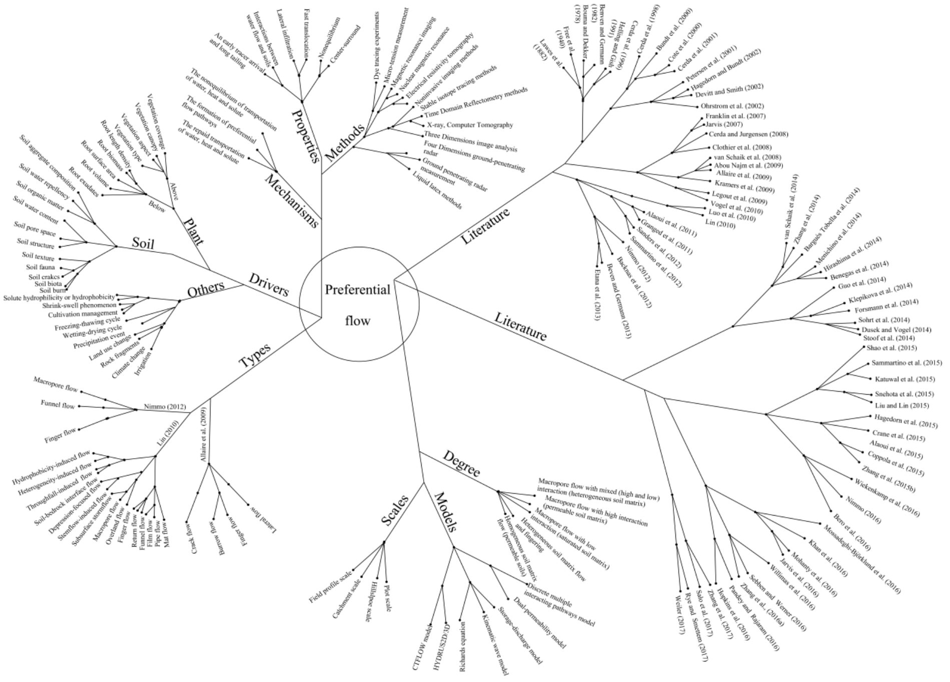

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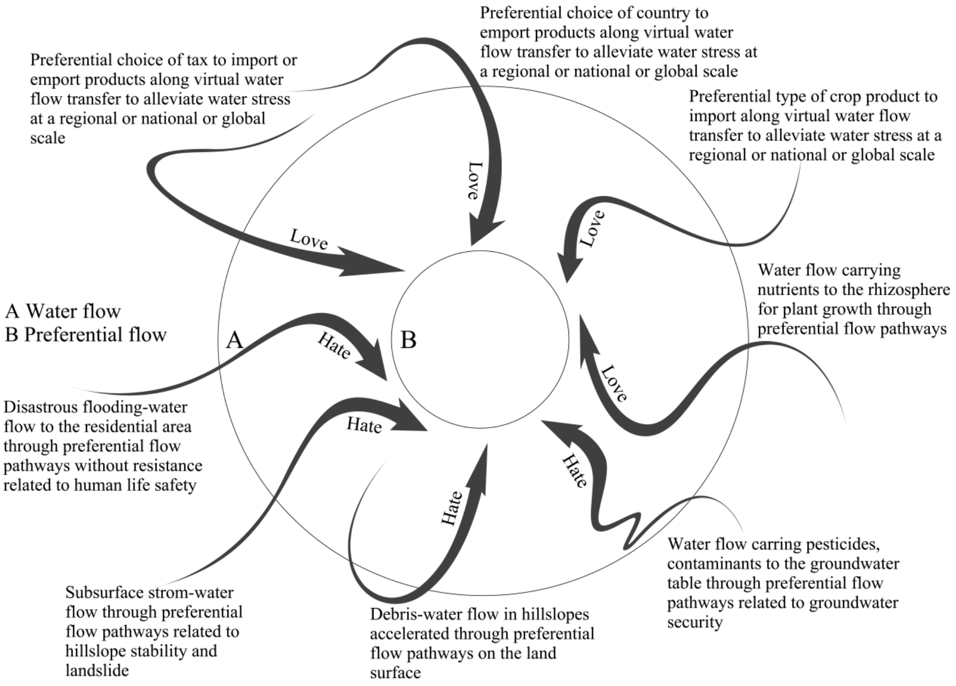

Figure 7. A love-hate relationship between water flow and preferential flow pathways.

Table Captions

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