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Review Paper

Water reuse in river basins with multiple users: A literature review

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SUMMARY

Unraveling the interaction between water users in a river basin is essential for sound water resources management, particularly in a context of increasing water scarcity and the need to save water. While most attention from managers and decision makers goes to allocation and withdrawals of surface water resources, reuse of non-consumed water gets only marginal attention despite the potentially significant volumes. As a consequence, claims of water saving are often grossly exaggerated. It is the purpose of this paper to explore the processes associated with water reuse in a river basin among users of varying nature and review existing methods for directly or indirectly describing non-consumed water, recoverable flow and/or water reuse. First a conceptual representation of processes surrounding water withdrawals and associated definitions is discussed, followed by a section on connectivity between individual withdrawals and the complex dynamics arising from dependencies and tradeoffs within a river basin. The current state-of-the-art in categorizing basin hydrological flows is summarized and its applicability to a water system where reuse occurs is explored. The core of the paper focuses on a selection and demonstration of existing indicators developed for assessing water reuse and its impacts. It is concluded that although several methods for analyses of water reuse and recoverable flows have been developed, a number of essential aspects of water reuse are left out of existing indicators. Moreover, a proven methodology for obtaining crucial quantitative information on recoverable flows is currently lacking. Future studies should aim at spatiotemporal tracking of the recoverable portion of water withdrawals and showing the dependency of multiple water users on such flows to water policy makers.

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Contents

Abbreviations: CF, Consumed Fraction; NCF, Non-Consumed Fraction; DRR, degree of return flow reuse; ET, evapotranspiration; FAO, Food and Agricultural Organization of the United Nations; IWMI, International Water Management Institute; NRF, Non-Recoverable Fraction; RD, reuse dependency; RE, Reuse Efficiency; RF, Recoverable Fraction; RFR, Return Flow Ratio; SDG's, Sustainable Development Goals; SEEA-Water, system of environmental-economic accounting for water; WRI, Water Reuse Index; WSE, Water Saving Efficiency; WWPS, Water Withdrawal Permit System (China).

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1. Introduction

Water scarcity is regarded as one of the world's biggest challenges (FAO, 2012; UN-Water, 2012). Growing water scarcity increases the need for effective management of water resources, with sustainable and affordable access to water expected to be a priority in the post-2015 Sustainable Development Goals (SDG's) under development by the United Nations (Griggs et al., 2013; UN-Water, 2013). Factors such as population growth and changing diets influence demand, while climate change is expected to affect regional availability of renewable water resources (Falkenmark, 2013; Oki and Kanae, 2006). Semi-arid and arid areas are particularly vulnerable to water scarcity due to limited replenishment of available surface freshwater from precipitation, often triggering ground water overexploitation (Döll et al., 2012; Wada et al., 2014; Konikow, 2011). Various estimates of people currently affected by water scarcity can be found in the literature (Hoekstra et al., 2011; Wada et al., 2011). For example, Molden et al. (2007) estimated that 1.2 billion people currently live in river basins experiencing physical water scarcity and another 1.6 billion live in areas of economical water scarcity, where affordable water supply works are not available.

The river basin, containing a variety of water users requiring access to a share of the available inflow, is the natural unit that is used for developing strategies to cope with water scarcity. Decisions need to be taken based on the integrated hydrological, economic and environmental systems. However, in practice, development of infrastructure in river basins to capture sufficient water for satisfying local demand often results in reduced downstream water quantity or quality up to the point where commitments can no longer be met. Such commitments include agreed water quota to downstream users and sustaining certain environmental flow levels. The phenomenon of basin closure (Molle et al., 2010; Seckler, 1996) is currently the reality in a substantial number of the world's river basins, with famous examples being the Yellow River (Yang and Jia, 2008), Krishna (Venot et al., 2008a), and Jordan basins (Venot et al., 2008b). Increases in diversion and consumption of water for agricultural or urban purposes induce tradeoffs of hydrological flows, often occurring at substantial social and environmental cost (de Fraiture et al., 2010).

The growing complexity of the network of water users in many basins has led to extensive discussion regarding appropriate methodologies and terminology to describe and evaluate water use. The desire exists for standardized indicators to communicate complex hydrological information generated by the scientific community to water policy makers, facilitating comparisons between individual water users and river basins, as well as monitoring progress toward policy goals (e.g. UN, 2008) However, ambiguous definitions and disagreement on proper applications of indicators have resulted in a range of examples of erroneous and often misleading or false interpretations of the water balance (Frederiksen and Allen, 2011; Perry, 2007). The discussion is strongly connected to the issue of scale, and is in particular associated with accounting for water that is withdrawn by a certain user, but not consumed. The extent to which non-consumed water at the local level is a water loss, or a source of water for downstream water users, is the crucial question; one that can only be answered when a basin-level overview of hydrological interaction between the different water users is available. Non-consumed water may become available for withdrawal by downstream users through natural and artificial pathways. Where, when and whether water reuse occurs is often unknown, while such information is essential for evaluating the existing network of water users and predicting basin-wide implications of locally altered flows. This question is also important when investigating the total water saving potential at basin level, an aspect that is currently often overestimated due to the disregard of downstream water reuse (Molle and Turral, 2004).

Systems for regulating and evaluating water management are traditionally based on water withdrawals only. Consequently, water saving studies generally focus on analyzing the magnitude of water withdrawals, which may overestimate the full impact on downstream water users as reuse is ignored by definition. Examples of water right systems based on withdrawals are the Chinese Water Withdrawal Permit System (WWPS) (WB, 2012), and the Australian national water accounting system (BOM, 2012). AQUASTAT, the global information system on water and agriculture of the Food and Agriculture Organization of the United Nations (FAO) is arguably the most comprehensive data source on water use that is available, but is also focused on withdrawals rather than the distinction between consumed and non-consumed water. Flow valuation concepts provide interesting opportunities for basing water allocation on the value generated by a water particle along its full flow path (Seyam et al., 2002), but should not neglect the downstream values generated by non-consumed flows.

Chapagain and Tickner (2012) described how consideration of consumed flows rather than withdrawals provides valuable insights in the pressure on water resources; illustrating the need to go beyond water withdrawals when regulating water permits, particularly in water-scarce areas. Over-exploited basins have the undesirable situation that evapotranspiration (comprising both landscape ET and incremental ET as a result of irrigation) exceeds precipitation, and that the shortage of water is supplemented from the surface water and ground water storage systems. Reduction of this excessive consumptive use will automatically restore stream flow (e.g. Bastiaanssen et al., 2008). Thevs et al. (2015) investigated the discrepancies between water consumption and water withdrawal quota for the overexploited Aksu-Tarim Basin, China. Shifting from withdrawal allocations to water consumption management is a measure that is advocated by the World Bank (2012), Wu et al. (2014) and Zhong et al. (2009) in the context of the Hai Basin. This general notion is supported by Hoekstra (2013) who advocated restrictions of water consumption through "blue water footprint caps", proposing a value of 20% of natural runoff as a rule of thumb.

Managing non-consumed flows provides another way of adapting water management to water-scarce conditions. Examples of intervention strategies targeted at non-consumed water are waste water treatment, water retention, and reuse of drainage water for irrigation. From an economic point of view, not consuming withdrawn water can have positive externalities that need to be addressed in water pricing systems (Macdonald, 2005; Taylor et al., 2014). Certain countries include return flow obligations as part of their water right systems and thus explicitly recognize the need to quantify non-consumed water flow and reuse. The basin-wide effectiveness of managing non-consumed water depends strongly on where, relative to the hydrological system of the basin, it is implemented. Delineating water management zones can be helpful to outline appropriate management strategies for different locations in a river basin. The concept of hydronomic zones (Molden, 2009; Molden et al., 2001b) is a method of catchment zonation primarily based on the potential for reuse of non-consumed water from an area, including the impact of water quality loss due to pollution or salinity. It is helpful as an initial tool to provide contextual information, but more detailed information on recoverable flows is needed for proper management application.

A framework for assessing water use based on consumed and non-consumed water demands a set of tools for basin-wide categorization and quantification of these flows. Remotely sensed ET mapping by means of surface energy balances has developed rapidly, and spatially discrete ET maps can be used to describe consumed flows (e.g. Anderson et al. (2012)). However, substantially less attention is paid to identifying the non-consumed portion of water withdrawal, distinguishing between recoverable and non-recoverable water, and the downstream reuse processes that may be relying upon recoverable return flow.

It is the purpose of this paper to explore the processes associated with water reuse in a river basin among users of varying nature and review existing methods for directly or indirectly describing non-consumed water, recoverable flow and/or water reuse. Selected indicators are demonstrated through application for the example case of the Arkansas Basin in Colorado, USA. Based on relevant literature, existing research gaps are identified with regard to the development of a basin wide framework to assess the fate of non-consumed flow in a cascade of multiple water users.

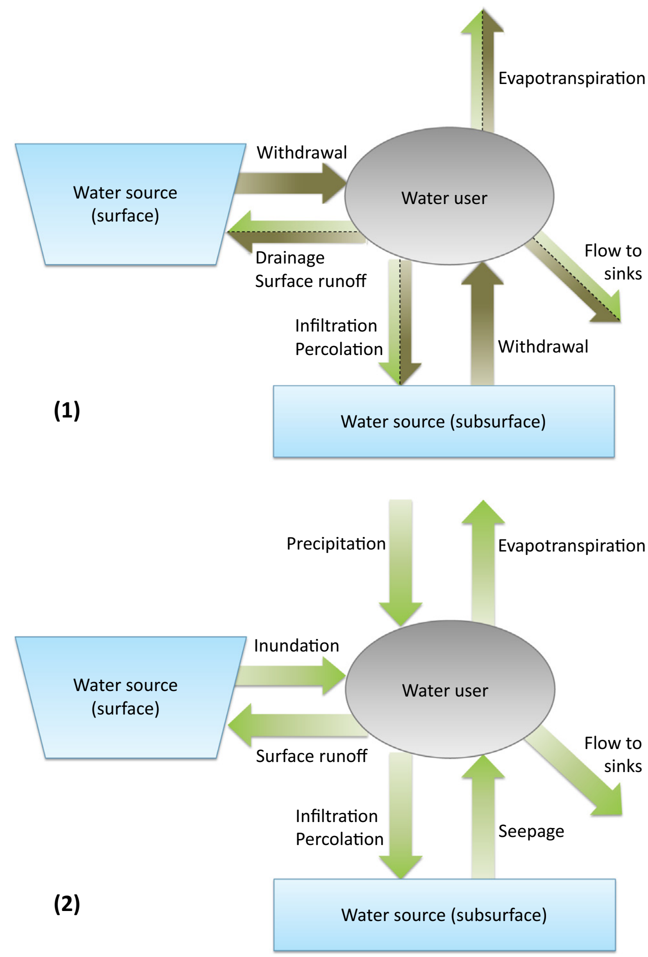

Fig. 1. Typical hydrological flows associated with water users dependent on (1) water withdrawal and (2) natural inflow. Green arrows indicate flows governed by natural processes; brown arrows indicate anthropogenic flows (managed by humans).

2. Definition of water (re)use – flows and processes

2.1. Definitions of a single water user

The gross inflow available to a water user consists of the sum of artificially withdrawn and naturally supplied water (Perry, 2011). Two principal types of water users can be distinguished, based on the extent to which they are dependent on natural and artificial water supply. The flow processes associated with these classes of users, and therefore the options for management interventions, are fundamentally different. Fig. 1 gives a schematic overview of the typical hydrological flows at water users relying on (1) water withdrawals, and (2) natural inflow. Some of the flows depicted in Fig. 1 are managed, others are manageable, and some are non-manageable (Karimi et al., 2013a).

Type 1 water users depend on ground water withdrawals and/or surface water withdrawals for example with the purpose of domestic use or irrigation in the dry season. Desalinization, as well as inter-basin transfers, can also be viewed as forms of anthropogenic water supply. Type 2 water use comprises natural systems such as wetlands, lagoons, aquatic ecosystems, ground water dependent ecosystems, as well as agriculture that is entirely rainfed. Naturally supplied water is mostly precipitation, but can also include ground water seepage, interflow and inundations. A combination of both types, thus a mixture of natural and anthropogenic inflow, is occurring for example for irrigation under conditions of erratic rainfall, or a combination of rainfall and controlled inundations for certain wetlands. The concepts presented in this paper from this point onwards are focused on users under (or approaching) Type 1 conditions, which have a direct and potentially significant anthropogenic influence on the hydrological cycle. Mitigation activities to manage supply and demand have the biggest potential for this type of users.

The following equations are used to describe the basic categorization of flow processes to distinguish between consumed and non-consumed water (Frederiksen and Allen, 2011; Perry, 2007):

$$Qw = Qc + Qnc \tag{1}$$

$$Qnc = Qr + Qnr \tag{2}$$

where Qw is water withdrawn from surface water or ground water, Qc is consumed water, Qnc is non-consumed water, Qr is recoverable water, and Qnr is non-recoverable water.

Consumed water is defined as the water that is removed from surface water or ground water systems and that is no longer available for downstream users. It consists mainly of evapotranspiration, but in specific situations also includes water incorporated in agricultural or industrial products and drinking water for humans and livestock. Recoverable water is withdrawn but feeds back into the hydrological system, and is available for capture and reuse downstream. Non-recoverable water flows toward deep aquifers that are unprofitable to exploit, oceans, or other saline bodies, and is therefore unavailable for downstream reuse. An especially complex issue is the potential deterioration of water quality by point source and nonpoint source pollution. Whether pollution levels indeed cause water to become non-recoverable is dependent on water quality requirements of the specific downstream users. Non-recoverable water from a water user may in turn cause other water bodies to become non-recoverable. Other factors that may cause water to become non-recoverable are salinized soils or heating in industrial processes. All water that is not consumed in the process of withdrawal, is denoted by the term non-consumed water. This is synonymous to return flow. A full glossary of terms used in this paper is provided in the Appendix A.

Ratios between consumed and non-consumed water are typically determined by the nature of the user. Agricultural water withdrawals are known to have large proportions of non-consumed flows with irrigation efficiencies (consumed water divided by withdrawals) typically between 30% and 70% (Bos and Nugteren, 1990; Brouwer et al., 1989; Perry, 2007). The irrigation efficiency of sprinkler and drip systems can be as high as 70–95%. Irrigation technique, drainage infrastructure, crop type, soil and topography all affect the irrigation efficiency. Water withdrawals for livestock are typically largely consumed, as cattle drinking water. On the global scale, consumptive use in livestock is an agricultural water use of secondary importance (Wada, 2013), although it should be noted that the livestock sector is a principal water user in countries like Botswana (FAO, 2006). Industrial water consumption varies greatly depending on the type of industry, the nature of the water supply, technological processes, and climatic conditions, but is usually an insignificant fraction of water intake. A primary application is cooling water for thermal and nuclear power stations. Other significant industrial water users are the chemical, metallurgy, and paper industries (Shiklomanov, 2000). Domestic water withdrawals are made by municipal services and private homes. Consumptive losses occur from evaporation of the water used by municipalities for plants, streets, recreation zones, and personal gardens, with drinking water for private homes being insignificant (Shiklomanov, 2000). Other, largely non-consumptive, sectors are hydropower generation, mining, and fisheries.

2.2. Hydrological connectivity between multiple water users and its impacts

The non-consumed flow from an upstream water user enters a network of hydrological flow paths and may ultimately be recovered for reuse at a downstream location. In this paper, water reuse is defined as the downstream re-application of non-consumed water from an upstream water use for a specified purpose, such as agricultural and landscape irrigation, industrial processes, domestic use, aquaculture and ground water recharge. Reuse is thus interpreted literally as "used again". *Water recycling* is defined here as reusing water on-site, for the same purpose. This distinction between reuse and recycling follows definitions agreed to in recent frameworks such as SEEA-Water (UN, 2012) and Water Footprint (Hoekstra et al., 2011). Water reuse thus does not necessarily involve a treatment process, as is the case in some definitions where reuse is synonymous to *water reclamation.* Water treatment is a necessary process to enable water reuse in cases where the quality of non-consumed water has deteriorated to such a degree that it is no longer suitable to be applied for a specific downstream purpose.

The concept of hydrological connectivity relates to the ease with which water can move across the landscape in different ways (Lexartza-Artza and Wainwright, 2009), and is determined by factors such as topography, geology, soil type, presence of water ways and hydraulic infrastructure. In developed areas, non-consumed water is generally transported by either sewerage systems or agricultural surface drainage systems, ultimately to end up in a river where a next user may tap into. Subsurface drainage removes excess water through conduits, deep open drains and wells, feeding streams through piped outlets. Water infiltrated through the soil profile into the ground water recharges the aquifer, and this water may again contribute to the river base flow, or be put to (often ecological) use in downstream ground water seepage zones. Non-consumed water that was initially recoverable may become non-recoverable along its flow path, for example due to injection with pollutants or leakage of water through faults systems to deep geological formations. Similarly, non-recoverable water may become recoverable due to dilution by rainstorms.

Hydrological connectivity is a broad term for which many different definitions have been developed over the years (Bracken et al., 2013). In the context of reuse, it is important to not only account for the spatial aspects of connectivity but to also acknowledge the temporal component. It is relevant to know whether a user relies on water directly from a river, recoverable water from upstream users delayed through canals and drains, or recapturing ground water from an aquifer. There is a substantial difference in timing of water delivery to the downstream user, which can be several orders of magnitude. Depending on regional climatic and hydrological conditions, shifts in the existing timing of water supply may be detrimental to the purpose of the downstream user (King, 2008; Lankford, 2006).

The recoverable flow from a water user may be reused once or multiple times by downstream water users. A schematic impression of a cascading system of water users within a river basin is presented in Fig. 2. The figure depicts three water users connected by either natural waterways such as a network of streams and/or aquifers, or artificial flow paths such as canals, subsurface drains and sewerage. In order to satisfy its water demand, the downstream water user is dependent on the non-consumed flow from the upstream user. Decreasing non-consumed flow from A and B by reducing withdrawals and/or increasing consumption, as commonly happens when irrigation technology or management is improved (Contor and Taylor, 2013), may be detrimental to water availability for the respective downstream users. Assuming C as the final user before water leaves the basin and flows out into the sea, saving water here will actually free up water. However, it could be inappropriate to consider all outflow from C as non-recoverable, as a certain level of reserved flow may exist that provides ecological benefits or prevents saltwater intrusion. It should be noted that Fig. 2 is simplified to illustrate the concept of water reuse and hydrological connections. In reality, B and C will likely have other sources of inflow in addition to non-consumed flow from A, and there could be a portion of non-recoverable outflow from each user.

The above description shows that one should be very careful when identifying water savings and water losses. Knowledge of water reuse is a necessity for proper decision-making. At the scale of the river basin, water can only be truly saved by reducing consumptive use or non-recoverable flows (Allen et al., 2005; Seckler et al., 2003). Various authors even warn for an increase in basin-wide water consumption due to local water conservation measures disregarding the hydrological setting of water users (Ahmad et al., 2013; Ward and Pulido-Velazquez, 2008). Recoverable water flows should only be reduced when somehow a more valuable purpose is designated to the upstream user. This approach to water reuse is now widely acknowledged, and has triggered a questioning of the efficiency concepts that are often utilized in irrigation accounting (Jensen, 2007; Perry, 2007; Seckler et al., 2003). Optimizing the ratio between consumed and diverted water (e.g. an increase from 40% to 50% for A in Fig. 2) may be desirable at the local level, but it is crucial to realize the implications for downstream water users. This demonstrates the need to quantitatively express basin-wide

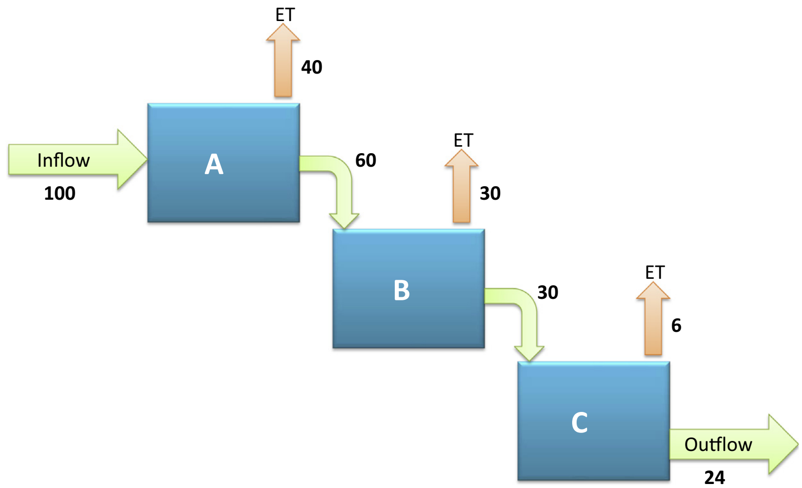

Fig. 2. Hypothetical cascade of different types of water users (A, B, C) in a river basin that all have their own consumed fraction (i.e. consumption divided by withdrawal).

reuse processes. It should be noted that benefits other than water saving could be achieved by increased efficiencies, such as improved upstream production, reduced water-related energy costs (although e.g. switching from surface irrigation to pressured systems may in fact increase energy costs), increase in-stream flow and ecological health, and improved downstream water quality (Clemmens et al., 2008; Gleick et al., 2011). Elaborate discussion of such co-benefits is outside the scope of this paper.

Molden and Bos (2005) explored how systems of cascading water users typically develop when water demand exceeds supply, triggering a response of construction of hydraulic infrastructure to facilitate reliable water delivery to and drainage from the water users under stress. Water scarcity is conventionally regarded as a main driver for water reuse, but the variability of water supply is also an important factor (Hermanowicz, 2006). The reuse of agricultural drainage water is one of several non-conventional sources of water to alleviate water scarcity in arid countries (Qadir et al., 2007). It is a popular way of optimizing the usage of the available water supply, and at the same time disposing of drainage water. A famous example is Egypt's Nile Delta, where reuse of drainage water reduces the irrigation water requirements by 20% (Barnes, 2012). Serial Biological Concentration, effectively applied in California and Australia (Ayars et al., 2007), provides a framework for integrated water and salt management by sequential reuse of drainage water on successively more salt-tolerant crops. Engineering projects such as reservoir storage and conjunctive surface and ground water use can potentially increase the portion of non-consumed water that can be reused. The same effect can be achieved by treatment of industrial water, if technologically and economically feasible.

An increased complexity and intensity of the network of water use and reuse means that changes in quantity, quality and timing of flows will have greater implications in closed river basins than in basins where water is abundant. Natural and anthropogenic reuse thus ought to be quantitatively understood.

3. Analytical description of the recoverable flow from water withdrawals

The use of hydrological fractions is widely acknowledged as a comprehensive and objective way of quantifying all inflows and outflows associated with water withdrawals (Allen et al., 2005; Karimi et al., 2013a; Perry, 1999, 2007; Willardson et al., 1994). The concept consists solely of quantitative terms that are consistent with the fundamental principles of hydrology. Water use indicators can be defined based on the basic fractions (e.g. Pereira et al. (2012). This section presents an analytical framework relevant for a quantitative analysis of recoverable flow at the level of a water withdrawal, based on hydrological fractions.

Building on Eqs. (1) and (2), the following hydrological fractions can be defined:

$$CF = Qc/Qw \tag{3}$$

$$NCF = Qnc/Qw \tag{4}$$

$$RF = Qr/Qw \tag{5}$$

$$NRF = Qnr/Qw \tag{6}$$

where CF is the Consumed Fraction, NCF is the Non-Consumed Fraction, RF is the Recoverable Fraction and NRF is the Non-Recoverable Fraction.

Based on the recoverable fractions of upstream users, it is possible to determine the recoverable flow that arrives at a certain location in a cascade of interconnected water users. We derive the following equation for a hypothetical system in which all of Qnc is reused, with three different RF values occurring in the system:

$$Qr = ((Qw_{init} * RF_x)^{nx} * (Qw_{init} * RF_y)^{ny} * (Qw_{init} * RF_z)^{nz})/Qw_{init}^{\Sigma n-1} \tag{7}$$

where Qw_{init} is the withdrawal by the first user in the cascade, RF_x, RF_y and RF_z are different values of the recoverable fraction, n_x, n_y and n_z are the number of users in the system with RF_x, RF_y and RF_z respectively, and Σn is the amount of times water is used by subsequent individual water users prior to arriving at the location for which the calculation is performed. For the simple case of Fig. 2, Eq. (7) can be solved to compute recoverable flow at user C as $Qr = ((100 * 0.6)^1 * (100 * 0.5)^1)/100^{(2-1)} = 30$. The concept of Eq. (7) can be adjusted for the amount of different RF values in a cascade. In the case all water users have the same RF, or in the water *recycling* case, the equation amounts to:

$$Qr = (Qw_{init} * RF)^n / Qw_{init}^{(n-1)} \tag{8}$$

Or:

$$Qr = Qw_{init} * RF^n \tag{9}$$

Based on a Qw_{init} of 100 units, Fig. 3 explores how Eqs. 7–9 dictate that Qr decreases as the number of withdrawals increases along a flow path. For demonstration purposes, the system is simplified to consist of users with a single *RF*. Four scenarios were selected (0.9, 0.75, 0.5 and 0.3). These values can be seen as representative of different types of water users. An *RF* of 0.9 is typically representative of an industrial water user where most withdrawals return back into the hydrological system (Wada et al., 2011). An *RF* of 0.75 is a plausible value for domestic withdrawals, as not all households are connected to a sewage system and people and animals consume water by respiration. An *RF* of 0.5 typically holds for the irrigation sector, and an *RF* of 0.25 could be found in greenhouses where return flow is small (and sometimes even 0 when all water is recycled internally). Fig. 3 demonstrates that after 5–6 reuse cycles, hardly any recoverable water will be left in a chain of water users with an RF of 0.5 or lower.

To put the portion of recoverable water into perspective of total non-consumed water, it is meaningful to express *Qr* as a fraction of *Qnc* as follows:

$$RE = Qr/Qnc \tag{10}$$

$$RE = RF/NCF \tag{11}$$

with *RE* being termed Return Flow Efficiency by King (2008) and Recycling Efficiency by Wallace and Gregory (2002). For the sake of consistency with other terminology used in this paper, we propose to utilize the term Reuse Efficiency for *RE*. An *RE* of 1 means that *RF* = *NCF* and all non-consumed water is recoverable downstream. Irrespective of whether the water user is primarily consumptive or non-consumptive, a high value for *RE* is a desirable situation.

Fig. 4 displays the *CF* of a cascade of water users for different values of *RF* and *RE*. The *CF* value of the individual water users was chosen to be 0.4, with 40% described as a “reasonable” value for scheme irrigation efficiency (Brouwer et al., 1989). A range of *RE* values is given, with the corresponding *RF* under the given *CF* of 0.4. The figure, modeled after an earlier analysis performed by Wallace and Gregory (2002), shows that the system-scale *CF* value does increase with water reuse, but that the recoverable fraction is key in determining the extent to which *CF* increases with scale. Depending on *RF*, a maximum value for *CF* is approached after roughly a number of 2–6 uses. Even when *RF* is high, water has to be reused a substantial number of times before a value of 70–80% can be achieved.

Further sub-division of non-consumed water into more specific fractions provides additional value for identifying water management options. King (2008) performed several analyses that highlighted the role of ground water recharge through deep percolation for downstream reuse. Due to the significant differences in processes that govern transport of recoverable water to and through the ground water as opposed to surface water, added value lies in the distinction of a Qr_{sw} and Qr_{gw} term. Or, in fractions:

$$RF_{sw} = Qr_{sw}/Qr \tag{12}$$

and:

$$RF_{gw} = Qr_{gw}/Qr \tag{13}$$

where Qr_{sw} and Qr_{gw} are the portions of recoverable water that contribute to surface water and ground water recharge respectively, RF_{sw} is the fraction of recoverable water feeding into surface water and RF_{gw} is the fraction of recoverable water contributing to ground water recharge. High values for RF_{gw} may indicate a more complex reuse system and greater uncertainty of the time scale associated with recharge, transport and downstream recovery.

Even when focusing solely on deliberate withdrawals, return flow can be discharged through both anthropogenic and natural pathways. Knowledge on whether recoverable flow is driven by natural or artificial processes gives insight in the opportunities for spatio-temporal management of this flow. This differentiation can be described as follows:

$$Qr = Qr_n + Qr_a \tag{14}$$

$$RFa = Qr_a/Qr \tag{15}$$

$$RFn = Qr_n/Qr \tag{16}$$

where Qr_n represents the flow discharged through natural processes such as unmanaged surface runoff, infiltration and percolation, and Qr_a is the flow governed by man-made infrastructure such as canals, drains and sewerage. *RFa* and *RFn* are the anthropogenic and natural

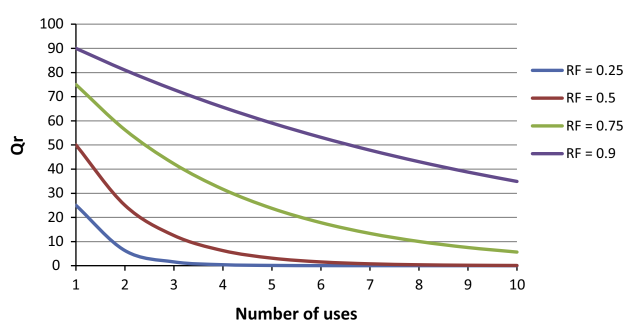

Fig. 3. Decrease of recoverable flow (*Qr*) with rate of reuse, for different Recoverable Fraction (RF) values.

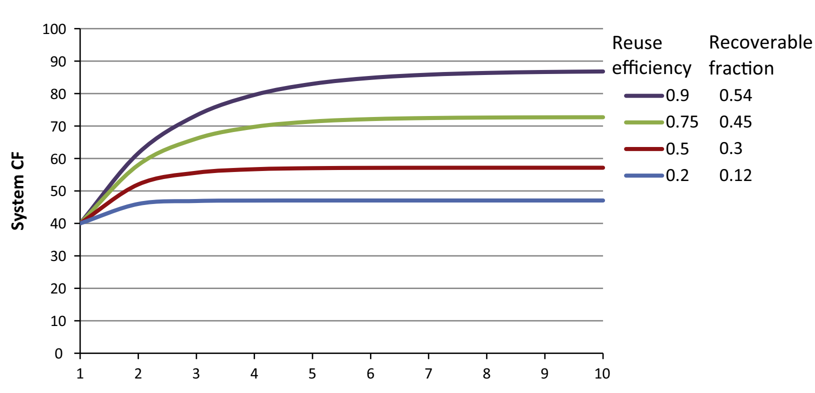

Fig. 4. Increase of system Consumed Fraction (CF) with rate of reuse, for different reuse efficiency values and the corresponding recoverable fractions. The CF of individual users is assumed at 0.4.

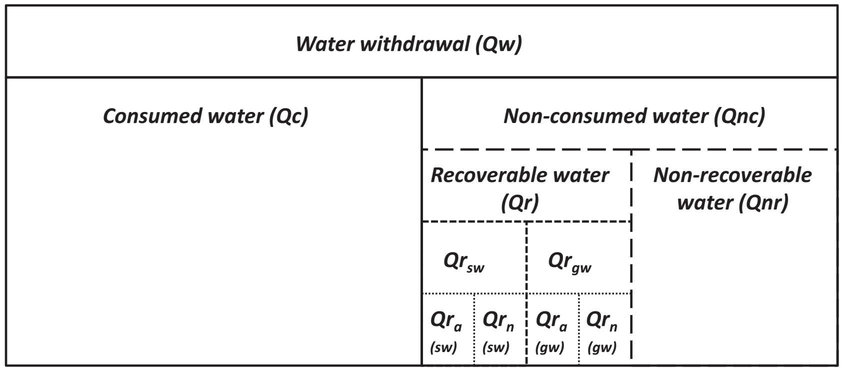

Fig. 5. Categorization of the relevant flows for assessing water reuse. Qr_{sw} and Qr_{gw} are the volumes of recoverable water recharging surface water and ground water respectively, Qr_a and Qr_n are the respective volumes of recoverable water discharged by anthropogenic and natural processes.

fractions respectively. A high *RFa* value indicates more direct opportunities for management interventions.

An overview of all relevant flows described in this chapter is provided by Fig. 5.

Some side notes in applying the above equations are appropriate. In reality, the situation will be more complex than displayed in Figs. 3 and 4. *Qw* of water user *n* in the cascade may not only be made up of *Qr* from $n - 1$, but additional rain water, surface water or ground water may be captured to satisfy water demand at *n*. Whether non-consumed water is reused by a downstream user depends on many factors, such as the profitability of recovery (e.g. pumping from a deep aquifer), the time frame in which the water arrives downstream the geographic location of streams and aquifers, and the quality levels and composition of water. These factors are highly dependent on local conditions and impede standardized definitions of recoverable and non-recoverable water. One should therefore be cautious in determining the recoverable and non-recoverable fractions in the early stages of an analysis. This approach is in line with Lankford (2012), who stated that the general assumption of the world's recoverable fraction being actually reused downstream is in fact a major oversimplification.

The presented framework of fractions for analyzing non-consumed and recoverable flows deliberately avoids subjective terms such as the distinction between *beneficial* and *non-beneficial* water consumption, and *productivity* of consumed water. As shown by Boelens and Vos (2012) and Frederiksen et al. (2012), views on what is regarded as beneficial or productive water consumption will differ among the different stakeholders in a river basin, implying that this should be left out of a basic framework for physical accounting. Similarly, the effect of pollutants on water reuse such as incorporated in the concept of effective efficiency (Haie and Keller, 2008) are left out of the basic definitions as put forward in this paper. In this way, no dependence on the type of the pollutant, or the nature of downstream water reuse, is introduced in the basic concept (Haie, 2008; Perry, 2008).

4. Selection and demonstration of relevant methods and indicators

This chapter explores a number of selected literature studies that present and apply methods and indicators to assess water reuse and/or its impacts. Although their approaches differ, these studies all express the interaction between different water users by means of a certain methodology, and thus go further than only accounting for conditions at the level of a single user. The applicability of the indicators is demonstrated for the water reuse system in the Arkansas Basin, Colorado. A synthesis of the review is given in Table 1.

4.1. Water reuse indicators from literature

4.1.1. Basin-level water accounting with multiple users

The International Water Management Institute (IWMI) developed a framework of irrigation accounting (Molden et al., 2001a) based on the concept of hydrological fractions. During recent years, this framework has been expanded to fit the requirements of a basin-wide analysis of a variety of water users of different natures (Karimi et al. (2013a), www.wateraccounting.org). Examples of published water accounting studies are abundant, e.g. Shilpakar et al. (2011), Bastiaanssen and Chandrapala (2003), Karimov et al. (2012), Harrington et al. (2009), and Karimi et al. (2013b). As in water accounting hydrological fractions are quantified on the (sub)basin scale; an entire water use and reuse network is reflected in the values of these indicators.

For example, Karimi et al. (2013b) used water accounting for the Indus Basin to determine that 20% of water withdrawals is recoverable for reuse, computing an *RF* for the entire basin of 0.2. Furthermore, they estimated that on average water is reused 4 times in the basin based on the discrepancy between computed basin-level *CF* in agriculture and literature values for field-scale irrigation efficiency. The basin *CF* itself, alternatively named Depleted Fraction or Basin Efficiency (Seckler et al., 2003), indirectly holds information on the occurrence of water reuse (as illustrated in Fig. 4). El-Agha et al. (2011) studied how drainage water reuse in the Nile Delta irrigation schemes is reflected in system-level *CF* values. For several branch canal command areas, monthly system *CF* values are substantially affected by the reuse of drainage water. Correctly interpreting high system *CF* values is however a complex exercise, as these are also typically found for unsustainable systems.

4.1.2. Water reuse as a function of scale

Hafeez et al. (2007) conducted a study primarily aimed at quantifying water reuse at different spatial scales, in a rice-based irrigation system in the Philippines. Their goal was to test the hypothesis of scale-dependent efficiencies due to water reuse, using the water accounting approach on different spatial scales within an irrigated rice system. The authors integrated an extensive set of field measurements of surface water flows, pumping records, and ground water depths, and remotely sensed ET to perform a multi-scale water accounting study. Linear regression was applied, and the rate of reuse was expressed in m^3 per additional unit of surface area under consideration. Based on measurements of reuse of pumped ground water and surface water through check dams, reuse of surface water and reuse of ground water were evaluated separately. The reuse of surface water was found to increase linearly with 4.6×10^6 m^3 per 1000 ha, with the farmers using pumps

Table 1
Review of selected concepts for assessing water reuse.

Concept	Key references	Formula	Definition	Input data required	Main advantages	Main limitations
Basin-level water accounting: Recoverable Fraction (RF)	Karimi et al. (2013a, 2013b)	$RF = Qr/Qw$	The portion of water withdrawals that is not consumed and can be recovered for reuse downstream	Water withdrawals, recoverable water	Gives insight into basin-level scope for water reuse and enables basin inter-comparisons	Results relate to a black box situation: no information is presented on what happens within
Basin-level water accounting: consumed fraction/depleted fraction (CF)	El-Agha et al. (2011)	$CF = Qc/Qin$	The portion of system inflow that is consumed	Consumed water, rainfall, water supply from outside the system	Gives insight into basin-level consumption, sustainability and enables basin inter-comparisons	Ambiguous meaning of high values: an efficient system, or an unsustainable system?
Linear regression of water reuse to scale: withdrawals per ha	Hafeez et al. (2007)	$y_{sw} = Qw_{sw\_ha} * x + B_{sw}$ $y_{gw} = Qw_{gw\_ha} * x + B_{gw}$	The amount of water that is reused per additional unit of surface area	Surface water withdrawals, deep percolation, groundwater pumping, surface area per user	Disaggregation of spatial units allows for assessing the effect of water reuse on system-level efficiency	Questionable applicability for heterogeneous systems, requires a lot of input data
Water Reuse Index	UN (2012), Vörösmarty (2000) and Vörösmarty et al. (2005)	$WRIx, y = \sum Qw_{upstream}/Q_{x,y}$	A measure of the number of times water is withdrawn consecutively during its passage downstream	Surface and shallow aquifer runoff, upstream water withdrawals	Requires little input data	Does not include a distinction between consumed and non-consumed water
Return Flow Ratio	Gassert et al. (2013)	$RFR_{x,y} = \sum Qnc_{upstream}/Q_{sw_{x,y}}$	The portion of available water previously used and discharged upstream as wastewater	Surface runoff, upstream non-consumed water	Distinguishes consumed and non-consumed water from withdrawals, requires little input data	Does not include a distinction between recoverable and non-recoverable water
Degree of return flow reuse	Chinh (2012))	$DRR = (x_{sw} * Qw_{sw_downstream} + x_{gw} * Qw_{gw_downstream})/Qnc$	The fraction of drainage water that is reused in the catchment	Non-consumed water, flow in external water sources (sw or gw), downstream withdrawals	A direct description of downstream dependency on a user's non-consumed water	Requires a lot of input data
Reuse dependency	Chinh (2012)	$RD = DRR * Qnc/(Qin)$	The fraction of the water supply of reuse areas which is actually covered by drainage reuse	Degree of return flow reuse, upstream non-consumed water, gross inflow	A direct description of water reuse by a certain user	Requires a lot of input data
Water saving efficiency	Törnqvist and Jarsjö (2011)	$WSE = (Qin_{new} - Qin_{old})/(Qw_{old} - Qw_{new})$	The ratio between the increase in river discharge and reduction in on-farm irrigation water application	Withdrawals, downstream water supply, future withdrawals, predicted downstream water supply	Assesses the effectiveness of water saving measures	Requires hydrological modeling of future conditions, introducing uncertainties
Downstreamness	van Oel et al. (2009, 2011)	$Dwd = \frac{\sum_{x=1}^{n} WDxDx}{\sum_{x=1}^{n} Dx}$	Ratio between upstream area and the total area of the river basin	Upstream surface area, total basin surface area	Can be applied to a variety of basin properties, little input data needed for basic principle	The basic concept does not include quantitative flows

for either complete or supplemental irrigation causing an increase in (re)use of water through pumping by 1.3×10^6 m^3 per 1000 ha.

Expressing this approach in a simple formula yields:

$$y_{sw} = Qw_{sw\_ha} * x + B_{sw} \quad (17)$$

$$y_{gw} = Qw_{gw\_ha} * x + B_{gw} \quad (18)$$

where y_{sw} and y_{gw} are the volumes of reused surface water and ground water respectively, Qw_{sw_ha} comprises use of water through check dams per ha, Qw_{gw_ha} represents ground water withdrawals per ha, and B a residual term close to 0. As percolation is found to be higher than ground water withdrawals, all ground water withdrawals are envisaged as reuse.

The concept of plotting reuse against area could potentially be upscaled to the river basin level. A steeper slope would then be expected for closing river basins. The slope of the resulting curve could thus serve as an indicator of water reuse, although the extent to which meaningful relations can be found for heterogeneous basins remains open for further research.

4.1.3. Water Reuse Index

The Water Reuse Index was developed by the Water Systems Analysis Group, University of New Hampshire (Vörösmarty, 2000) and was adopted by the United Nations in their World Water Development Reports (2003, 2006, 2009 and 2012) and the SEEAW water accounting framework (UN, 2012). The Water Reuse Index at a location (x,y) is computed by dividing the aggregate of upstream water (domestic, industrial and agricultural) withdrawals $Qw_{upstream}$ by the mean annual surface and subsurface runoff $(Q_{x,y})$ at that location:

$$WRI_{x,y} = \sum Qw_{upstream}/Q_{x,y} \tag{19}$$

As such, the index reflects the consecutive times that water is withdrawn during its passage downstream. The Water Reuse Index can be computed for any point in a basin and typically increases toward the basin mouth, representing a progressive increase in reuse of runoff. A high value at the basin level is an indication of high water competition among users. However, whether the upstream users are primarily consumptive or non-consumptive is not taken into account.

Vörösmarty et al. (2005) showed how plots of WRI against downstream distance indicate locations where a river encounters significant withdrawals, represented by high WRI values, and impacts of little water use and presence of runoff and tributary inputs in the form of low WRI values. Near the outflow point of the Nile River, a WRI of approximately 1 was found under mean annual flow conditions, indicating that the accumulated upstream water withdrawals are almost equal to mean annual discharge. They also evaluated the sensitivity of WRI to climate variability. For a river such as the Orange River, located entirely in a semi-arid region, a dramatic reaction to drought conditions was found, with the WRI rising an order of magnitude.

4.1.4. Return Flow Ratio

In the Aqueduct Global Risk Atlas (Gassert et al., 2013) of the World Resources Institute, the term Return Flow Ratio is calculated for a catchment, user, or location, as the amount of upstream non-consumed water divided by the available surface water. The *RFR* global base maps were computed using average values of available blue water (available surface water minus upstream consumptive use) over the period 1950–2008, and are publically available through http://www.wri.org/resources/maps/aqueduct-water-risk-atlas. Although it is mainly discussed in the context of potential water quality risks, *RFR* is essentially a quantitative term, indicating dependency on water that was previously applied upstream but not consumed. In generalized terms, *RFR* is defined as:

$$RFR_{x,y} = \sum Qnc_{upstream}/Q_{sw\_x,y} \tag{20}$$

where $Qnc_{upstream}$ is upstream non-consumed water and $Q_{sw\_x,y}$ is surface runoff at the location, user or catchment under consideration. Note that the difference between Eqs. (16) and (20) is the accumulated consumptive use in case ground water can be ignored.

The *RFR* map for the state of California shows a general southward increasing gradient of *RFR*, along a combination of natural waterways (e.g. the Sacramento River) and reservoirs, canals and aqueducts associated with large artificial projects such as the California State Water Project and Central Valley Project. Very high values of >80% occur at major urban centers such as Los Angeles, San Jose and San Francisco, indicating a high dependency of these areas on water that was previously used upstream.

It should be noted that the term Return Flow Ratio is also used to evaluating irrigation and drainage systems; in this context it is defined as the amount of water appearing in a drain divided by water supply to the scheme (Masashi et al., 2013). This definition is similar to the non-consumed fraction and does not provide additional insight in reuse.

4.1.5. Degree of return flow reuse

Chinh (2012) defined a set of indicators for a reuse system, particularly in the context of irrigation and drainage. However, their concepts apply in principle to different scales and different water users. The *degree of return flow reuse* is a parameter that indicates the fraction of recoverable water that is actually reused in the catchment. For specific irrigated conditions with clearly defined source and reuse schemes, and both an internal and external drain that collect drainage water that is potentially reused, it is defined as follows:

$$DRR = (x_D\,Q_{P,D} + x_D\,x_E\,Q_{P,E})/D_{cs} \tag{21}$$

where x_D is the mixing ratio between surface drainage from a source scheme and total inflow into a drain, x_E is the mixing ratio of catchment drainage water with external water sources, $Q_{p,d}$ and $Q_{p,e}$ are the volumes of pumping by internal and external reuse stations respectively, and D_{cs} is surface drainage from the source scheme.

The conceptual model can apply to a generalized water reuse system, irrespective of type of upstream water use (the "source scheme"), downstream water use ("reuse scheme"), or pathway between them ("drain"). In case of multiple reuses, a sequence of mixing ratios can be included. The concept acknowledges the presence of different destinations of the recoverable flow, allowing for a distinction between surface water and ground water as follows:

$$DRR = (x_{sw} * Qw_{sw\_downstream} + x_{gw} * Qw_{gw\_downstream})/Qnc \tag{22}$$

where x_{sw} is the mixing ratio of non-consumed water from a user with surface water, $Qw_{sw\_downstream}$ is surface water withdrawal downstream, x_{gw} is the mixing ratio of non-consumed water with ground water, $Qw_{gw\_downstream}$ is ground water withdrawal downstream, and Qnc is the non-consumed water from the user under consideration.

4.1.6. Reuse dependency

The fraction of gross inflow to a water user that is dependent on reuse of upstream non-consumed water is expressed as the reuse dependency *RD*, originally termed "dependency of reuse schemes" by Chinh (2012). Consistent with the terminology used in this paper, *RD* is expressed as:

$$RD = DRR_{upstream} * Qnc_{upstream}/(Qw + P) \tag{23}$$

or alternatively:

$$RD = x_{upstream} * Qw/(Qw + P) \tag{24}$$

where $x_{upstream}$ is the mixing ratio of upstream users of non-consumed water with the water source, and P is supply of precipitation to the user. The reuse dependency relates the portion of withdrawal that is provided by non-consumed recoverable water to the gross inflow. Reuse dependency may increase in case of either a higher mixing ratio, an increase in withdrawals, or a decrease of rainfall Similar to *DRR*, this indicator gives a direct assessment of water reuse, but requires a large amount of input data.

4.1.7. Water saving efficiency

Törnqvist and Jarsjö (2011) applied a calibrated distributed hydrological model to quantify the effect of reuse of return flows on potential for basin-wide water savings in the Amu Darya and Syr Darya basins, Central Asia. They found that the basin-scale water savings are approximately 60% lower than corresponding on-farm reductions in irrigation water application, since water is reused and, hence, return flows decrease when less water is applied.

To express this effectiveness of water saving measures in an indicator, the Water Saving Efficiency (WSE) is introduced. WSE is defined as the ratio between the increase in river discharge, and the reduction in on-farm irrigation water application that caused this increase in inflow. Or, in more general terms:

$$WSE = (Qsw_{downstream\_new} - Qsw_{downstream\_old})/(Qw_{old} - Qw_{new}) \quad (25)$$

where $Qsw_{downstream\_new}$ is surface runoff at a certain downstream point after implementation of the water saving measure, $Qsw_{downstream\_old}$ is downstream runoff before implementation, Qw_{old} is water withdrawal before implementation, and Qw_{new} is water withdrawal after implementation.

Thus, a WSE of 1 would indicate that no water reuse occurs before the drainage water returns to its source. In an illustrative example of applying WSE, Törnqvist and Jarsjö (2011) find the largest differences between the downstream part of the Amu Darya basin (~0.8) and the upstream part of the Syr Darya basin (~0.15). In terms of water savings, it would therefore be much more efficient to implement improvements in the irrigation system in the Amu Darya delta.

The WSE concept offers a parameter that can be mapped continuous in space, and provides a direct indication of the effectiveness of water saving measures. Thereby, it informs on the extent to which users downstream of a certain water use depend on recapturing its non-consumed flow.

4.1.8. Downstreamness

The concept of downstreamness, introduced by van Oel et al. (2009), defines a function in a river basin based on the area of its upstream catchment. In this way, downstreamness is valuable in raising awareness of the spatial context of water supply to a location, and in evaluating a certain location based on its upstream commitments. The approach allows for studying the process of closure in the sub-basin upstream from any point in a river basin, thus providing a framework for analysis of spatial hydrological flows at the level of individual water users or other geographical units.

The downstreamness (*Dx*) of a location is defined as the ratio between the area of upstream catchment and total basin surface area. Thus, with increasing *Dx*, larger natural runoff is expected. Measured or modeled surface runoff at a certain location can be compared to the expected linear relation between *Dx* and runoff, with a substantial deviation from this line being an indication of basin closure in the catchment of the measuring location. Closure may be caused by storage in reservoirs or by upstream water withdrawals for consumptive use.

The downstreamness of a function in the basin (e.g., water availability or water use) is defined as the downstreamness-weighted integral of that function divided by its regular integral. For example, the comparison between *Dx* of storage capacity and *Dx* of actual stored volume was proposed by van Oel et al. (2011) as an indicator of closure of the (sub-)basin that supplies the location under consideration. An analysis of downstreamness is useful to evaluate water reuse and the vulnerability of a type of water use. Taken from van Oel et al. (2011), for a basin with *n* geographical units:

$$Dwd = \frac{\sum_{x=1}^{n} WDx\, Dx}{\sum_{x=1}^{n} Dx} \quad (26)$$

where *Dx* = downstreamness of water demand at location *x*; and *WDx* = water demand of location *x*. *Dwd* is a measure of how far downstream water demand in the basin is located on average, and can therefore be viewed as a proxy for water reuse. When a high value for *Dwd* is found for a type of water use, this could indicate a larger dependence on recoverable water from upstream users.

4.2. Example application: the Arkansas Basin

To demonstrate the type of information provided by the selected water reuse indicators, we have computed their values for the Arkansas Basin in Colorado, USA. Data from the Draft Basin Implementation Plan (DBIP, WestWater, 2014) was used as the basis for this analysis. The DBIP lists the different users that are present in the Arkansas River Basin, with their main water sources, specific withdrawals for different years, and typical return flows for the agricultural and industrial users. For demonstration purposes, our analysis focuses on users that are at least partly consumptive and are connected through withdrawing from and discharging to the main stem of the Arkansas River. Some other, minor users exist in the area that rely on ground water pumping, however regulations prescribe that their return flows recharge the same aquifer rather than discharge to the surface water system (WestWater, 2014). Transbasin water supply projects are disregarded in our analysis. It is beyond the scope of this paper to examine the hydrological conditions in the Arkansas Basin in great detail, as the aim of this exercise is merely to illustrate the applicability of water reuse indicators.

Table 2 presents the relevant properties of the selected water users, as well as river flows (available water) and indicator values. All figures in Table 2 are valid for 2010, an average year in terms of rainfall (WestWater, 2014). Withdrawals and return flows of agricultural and industrial users were taken from the DBIP. For municipal water users, return flow values are not included in the DBIP, and an *NCF* of 40% was assumed based on typical municipal return flows in the Colorado River basin (Cohen, 2011). It is assumed that on a yearly time scale, all return flows from the listed users reenter the Arkansas River at the point of withdrawal, and that they are entirely recoverable for downstream users (*RE* = 1). Available water presented in Table 2 was measured by the upstream gauge nearest to the respective user. Gauged tributaries, intermediate withdrawals and return flows were used to provide river flow estimates for users lacking a flow gauge directly upstream. Downstreamness was computed based on sub-basin delineation derived from SRTM elevation data (USGS, 2004). *RD* was calculated relative to withdrawals only (excluding precipitation), and thus indicates the dependency of withdrawals on return flows in an average year. Of the indicators discussed in this paper, *WSE* could not be computed as outputs from simulation models are not available. Similarly, water reuse could not be examined as a function of scale, as the surface area of water users is unknown. All other indicators discussed in Section 4.1 of this paper are listed in Table 2.

Jointly, the reuse indicators provide an insight into the water use cascade along the Arkansas River. The overall recoverable fraction of the system is 0.44. With a *Dwd* of municipal water use of 12.6% and a *Dwd* of agricultural water use of 42.7%, it is clear that agricultural users are generally located downstream from municipal users. *Dx* describes the geographical position of each user relative to the basin area. *WRI* and *RFR* generally increase with *Dx*, as would be expected for most water reuse systems. As most major water users in the area have a similar *NCF*, a large increase in *WRI* often corresponds with a similarly large increase in *RFR*. For the final nine users in the cascade, the sum of upstream water withdrawals exceeds water availability (*WRI* > 1). For the final five users, the sum of upstream return flow exceeds water availability

Table 2
Overview of water users in the Arkansas River system and values of water reuse indicators at the user level. All volumes are in MCM and are valid for 2010. Water users are listed in a sequence corresponding with the cascade of users along the Arkansas River main stem.

Water user	Type	Available water (MCM)	*Qw* (MCM)	*Qnc* (MCM)	*Qc* (MCM)	NCF (–)	WRI (–)	RFR (–)	DRR (–)	RD (–)	Dx (–)
City of Salida	Municipal	335.5	3.7	1.5	2.2	0.40	0.01	0.00	1.00	0.00	0.04
Canon City	Municipal	608.1	7.2	2.9	4.3	0.40	0.01	0.00	1.00	0.00	0.11
City of Florence + CF&I steel	Municipal/ Industrial	603.8	60.7	47.3	13.4	0.78	0.02	0.01	1.00	0.01	0.13
Bessemer Ditch	Agricultural	637.7	84.5	36.3	48.2	0.43	0.11	0.08	1.00	0.08	0.16
City of Pueblo	Municipal	589.5	34.2	13.7	20.5	0.40	0.26	0.15	1.00	0.14	0.16
Comanche Power Plant	Industrial	688.7	13.1	2.1	11.0	0.16	0.28	0.15	1.00	0.13	0.17
Colorado Canal	Agricultural	732.7	84.7	36.4	48.3	0.43	0.28	0.14	1.00	0.12	0.25
Rocky Ford Highline	Agricultural	707.8	108.7	46.7	61.9	0.43	0.41	0.20	1.00	0.17	0.32
Oxford Farmer's Ditch	Agricultural	645.9	40.0	17.2	22.8	0.43	0.61	0.29	1.00	0.22	0.33
Otero Canal	Agricultural	623.1	8.1	3.5	4.6	0.43	0.70	0.33	1.00	0.25	0.34
Catlin Canal	Agricultural	629.7	118.3	50.9	67.4	0.43	0.71	0.33	1.00	0.25	0.38
Holbrook Canal	Agricultural	562.3	60.1	25.8	34.2	0.43	1.00	0.46	1.00	0.31	0.39
Rocky Ford Ditch	Agricultural	528.0	27.1	11.7	15.5	0.43	1.18	0.54	1.00	0.35	0.39
Fort Lyon Storage Canal	Agricultural	512.6	65.9	28.3	37.5	0.43	1.27	0.58	1.00	0.36	0.39
Fort Lyon Canal	Agricultural	475.0	270.1	116.2	154.0	0.43	1.51	0.68	1.00	0.40	0.42
Las Animas Consolidated	Agricultural	321.0	36.3	15.6	20.7	0.43	3.07	1.37	1.00	0.62	0.43
Fort Bent	Agricultural	252.9	23.4	10.1	13.4	0.43	4.04	1.80	1.00	0.75	0.66
Amity Canal	Agricultural	242.8	136.7	58.8	77.9	0.43	4.31	1.92	0.99	0.76	0.67
Lamar Canal	Agricultural	69.1	64.6	27.8	36.8	0.43	17.12	7.60	0.99	1.00	0.67
Buffalo Canal	Agricultural	32.2	31.7	13.6	18.1	0.43	38.70	17.15	0.00	1.00	0.83
System-scale indicators											
Recoverable fraction											0.44
Dwd municipal (%)											12.6
Dwd agricultural (%)											42.7

(*RFR* > 1). *RD* values show that the final five users in the cascade rely on return flow for more than 50% of their water withdrawals, thus providing a more direct indication of actual reuse than *WRI* and *RFR*. All three indicators logically rise quickly directly downstream of the discharge of a large volume of return flow, in particular when this coincides with a decrease of river flow (e.g. at Las Animas Consolidated). *DRR* values show that the return flow of all users is being reused in its entirety within the system. The high variance in withdrawal volumes means that the major part of this reuse does not necessarily take place at the subsequent user. The *DRR* of 0 for the Buffalo Canal should be interpreted with caution, as the Colorado–Kansas border was taken as the downstream boundary of the DBIP. River flow has been substantially reduced at this point, but water users are likely still relying on withdrawals from the Arkansas River across the state border.

Table 3
Classification of reuse indicators.

	Description	Indicator
A	Indicators producing a single value for a delineated geographical area with multiple water users	Basin-level RF (–) Basin-level CF (–) Withdrawals per hectare (m^3/ha)
B	Indicators defining a water user based on upstream flow processes	Water Reuse Index (–) Return Flow Ratio (–) Reuse dependency (–) Downstreamness (–)
C	Indicators defining a water user based on downstream reuse of its non-consumed water	Degree of return flow reuse (–) Water saving efficiency (–)

5. Discussion

This paper demonstrates that a systematic, fractions-based approach is instrumental in categorizing basin flows and identifying recoverable water and water "losses". For expressing the occurrence of water reuse in a way that is meaningful for water management decision-making, a methodology is required that takes into account multiple dimensions to water reuse in a river basin context. Relevant dimensions could include the volume of non-consumed water, fraction of recoverable water, spatial hydrological connectivity, travel time, water quality degradation toward the mouth of the river, and hydrological location of a water user.

The demonstrated water reuse indicators can be roughly divided into three classes. An overview is provided in Table 3. The first class (A) of indicators regards the entity of interest (a system of multiple users, often a (sub-)basin) essentially as a black box. A single value is produced for a delineated geographical area. Examples are the basin-level assessments of the recoverable fraction and consumed fraction in water accounting, and the withdrawals per hectare as determined by linear regression of water reuse on surface area. These concepts provide an indication of the impact of water reuse occurring within the area and time frame under consideration. They are particularly helpful in estimating, for example, the system-level sustainability of water management and the regional potential for water saving. However, no information is presented on local flows and interactions between water users within the study area.

Class B of reuse indicators relates a water user at a particular location in a basin to upstream flow processes, and directly or indirectly describe its dependency on reusing non-consumed water. Downstreamness, *WRI*, *RFR* and *RD* are examples of this approach. *Dx* of a single water user does not include quantitative flows and its interpretation relies largely on assumptions. This concept is more valuable when applied to more generalized water use properties of a basin, such as storage capacity or a specific type of water demand. The *RFR* is more directly related to reuse than *WRI*, as it accounts for upstream non-consumed water rather than total water withdrawals. Especially when highly consumptive users are present upstream, these two indicators will yield substantially different results. *RD* is the most direct assessment of water reuse, as here actual withdrawals are included rather than total available water. Class B indicators are especially useful when aiming to identify upstream water competition and possibly basin closure, and to assess the vulnerability of a water user to changes in upstream conditions. As their input data requirements are highly different, which indicator to use will largely depend on the information that is available.

Class C of reuse indicators define a water user based on the downstream reuse of its non-consumed water. Examples are *DRR* and *WSE*. These indicators give an indication of the likely effects of changes in flows. A user with a high *DRR* value (and thus a low *WSE*) plays an important role in the water reuse cascade, and should therefore not be a target of water saving measures. The value of these indicators lies in their direct link to water management interventions. They can be used to determine, or supplement, a distinction of different water management zones in a river basin. Drawbacks could be the large amount of input data needed to quantify *DRR* and the extra uncertainties introduced in *WSE* due to the need for simulation modeling.

The reviewed indicators offer a range of options for investigating water reuse on a variety of spatial scales, including the individual water user. Input information on a high spatial resolution to feed such analyses is increasingly available. However, our assessment of water reuse systems indicates that not only the spatial dimension, but also the temporal dimension of flow is relevant. It is a striking observation that none of the reviewed indicators integrate time-specific flows into their definitions. Defining recoverable flow as a function of time is a necessity for a better understanding of water reuse systems. Also, no distinction between surface water and ground water flow is made in the original definitions. This lack of information disregards the significant difference in both space and time between connectivity through the surface water system and the ground water system. Other relevant information, such as the recoverable portion of total return flow, and the distinction between anthropogenic and natural flows, is equally excluded from the indicators.

An important note is that, even if all relevant dimensions would be accounted for in the reuse indicators, the Arkansas River case study shows that the required input data is not available from a comprehensive management plan for a basin in one of the most data-abundant areas of the world. Indicators *DRR* and *RD* potentially hold the most direct information on water reuse, but the availability of input data is limiting. A number of important assumptions need to be made when assessing the Arkansas River reuse system, and as such our simple demonstration is exemplary for most basin-wide water use and water allocation studies. Typical assumptions include an equal *NCF* for all users of a similar nature, and the assumption that recoverable volumes equal non-consumed volumes ($RE = 1$). Such simplifications, forced by a lack of data, prohibit a thorough assessment of water reuse, and thus of water losses and potential for water savings. This problem requires the development of a method that integrates an analysis of connectivity between water users and computation of the relevant hydrological fractions. The spatio-temporal nature of the problem likely demands an integrated approach of simulation models, remote sensing and Geographic Information Systems.

6. Concluding remarks

As pressure on global water resources increases and more river basins approach a state of closure, there is an undeniable need for effective management of the finite amount of water available in a basin during the hydrological year. Local water saving measures do not work without an understanding of downstream impacts. There is a major pitfall in rushing to conclusions by applying subjective performance indicators at an early stage in water management analyses. When modifying hydrological fractions amounts to a redistribution of a fixed volume of water rather than true water savings, the question is whether the upstream advantages compensate the previous benefits of non-consumed flows now reduced. Quoting Contor and Taylor (2013): "Any proposal to improve irrigation technology or management must be accompanied by careful water budget analysis of the present-condition fate of the non-consumed fraction of applied irrigation water, and of the human and ecosystems made of the current waste stream."

Although the importance of data on water reuse for achieving goals on basin-scale water resources planning is now generally acknowledged, little work has been done with a primary focus on mapping the relevant dimensions of water reuse. It is argued that an improved analysis of water reuse will be helpful to understand existing interactions and localizing potential water supply issues, constructing sound basin water accounts, identifying appropriate water management strategies for different locations, and predicting effects of future interventions. Ultimately, this can support development of successful water allocation policies and water rights systems, both in terms of withdrawal permits and return flow obligations. Consistent use of terminology and definitions is essential to avoid misunderstanding of the water balance and subsequent adverse effects of interventions.

The need exists for a hydrologically consistent approach to express water reuse, strongly rooted in the concepts of consumptive use, non-consumptive use and hydrological connectivity. The key parameter to track is the recoverable portion of the non-consumed water at the water user level. Many services and benefits are potentially obtained from this water that is initially 'lost'. The indicators reviewed in this paper can be helpful in this regard, but need to be supplemented with an assessment of both the spatial and temporal dimension of the recoverable flow. There is a lack of geographical methods to quantify these recovery processes on a monthly and annual time frame. This is relevant for ungauged, poorly gauged and gauged basins because return flow cannot be measured in a straight-forward manner. Future studies should aim at tracking the recoverable portion of water withdrawals and showing the dependency of multiple water users on such flows to water policy makers.

Appendix A. Glossary

Term	Definition
Anthropogenic flows	Flows that are regulated by man-made hydraulic infrastructure such as drains, sewerage and aqueducts
Consumed water	Water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock
Gross inflow	The total amount of water that flows into the domain, this includes precipitation plus any inflow from surface or ground water sources and desalinized water
Natural flows	Flows that are defined by natural processes
Non-consumed water	Water that is not consumed in the process of water withdrawal
Non-recoverable water	Non-consumed water that cannot be reused at a downstream location for various reasons

(*continued on next page*)

Glossary (*continued*)

Term	Definition
Recoverable water	Non-consumed water that can be captured and reused at a downstream location
Reserved flow	Surface water that has been reserved to meet committed flows, navigational flow, and environmental flow
Utilizable water	Water available for additional resources development, that has not been previously withdrawn
Water recycling	Reuse of water on-site for the same purpose
Water reuse	Downstream re-application of non-consumed water for further use with or without prior treatment
Water withdrawal	The volume of freshwater abstraction from surface or ground water. Part of the freshwater withdrawal will evaporate, another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea

Sources consulted: Perry (2007), Hoekstra et al. (2011) and UN (2012), www.wateraccounting.org.

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