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OVERVIEW

The need for green and atmospheric water governance

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Abstract

A review of the literature on water governance reveals that most studies focus on blue water governance; while there is some literature on green and atmospheric water, explicit literature on how to govern green and atmospheric water is lacking. Hence, this paper addresses the question: What are the arguments for governing green and atmospheric water? In order to address this question, we have undertaken a scoping analysis of the literature on green and atmospheric water. We conclude that water governance must proactively address green and atmospheric water since: (a) blue water represents only a part of the available fresh water; (b) blue river basins represent only a subset of the wider systemic nature of water; (c) land use change has significant impacts on various water flows, which all may need to be governed; (d) climate variability and change influences blue, green, and atmospheric water availability; (e) an understanding of the socio-ecological uses of the different colors of water is critical for a more optimal and legitimate governance of water; (f) new water technologies make it increasingly possible to modify the use of green and atmospheric water; and (g) global trade infrastructures pressurize local green water resources. Neglecting the need for explicit governance of green and atmospheric water could create new forms of “water grabbing” that would impact water availability beyond the basin scale.

This article is categorized under:

Human Water > Water Governance

Science of Water > Hydrological Processes

Water and Life > Stresses and Pressures on Ecosystems

KEYWORDS

atmospheric water, green water, water governance

1 | INTRODUCTION

Water resources are becoming increasingly scarce in many places worldwide. Although water scarcity and dropping groundwater tables jeopardize drinking water supplies (Veldkamp et al., 2017), there is more to it than appears at first glance. Blue water—surface water, such as in streams, rivers, lakes, ponds and ditches, and groundwater captured in aquifers underneath the earth's surface—is becoming increasingly scarce due to human demand from agriculture, households, and industries; over 70% of blue water extracted by society is used for agricultural production (Foley et al., 2011). Many river basins globally are *closing* (i.e., fresh water supply is not meeting the demand) due to unsustainable modes of water extraction (IPCC, 2014) and

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are polluted from inadequately treated industrial, agricultural, and/or domestic waste. In general, the governance challenges around blue water quantity and quality are well mapped out and hence contribute to our common understanding of global water issues, often remaining within the domain of drinking water, sanitation, and irrigation issues. Yet, there are far more *invisible* water resources that are facing similar challenges but receive less attention. First, *green water*—the water available to plants in the unsaturated soil—is increasingly appropriated for agricultural production at the cost of green water-dependent natural ecosystems (Schyns, Hoekstra, Booij, Hogeboom, & Mekonnen, 2019). Green water is essential for global food production and ecosystem service generation, such as nutrient recycling, soil functioning, and carbon sequestration (Feger & Hawtree, 2013; Rockström & Karlberg, 2010). Yet, green water is at best governed indirectly in agricultural policy or nature and biodiversity policy, and remains absent from the water governance agenda. Second, *atmospheric water* refers to water in the atmosphere that becomes available as it condenses and subsequently precipitates as rainfall onto the earth's surface. Sometimes referred to as rainbow water (Van Noordwijk, Namirembe, Catacutan, Williamson, & Gebrekirstos, 2014), atmospheric water refers to all water present in the atmosphere (in vapor and liquid form), and forms the source of all available fresh water on earth, yet it remains an ungoverned resource. Recent insight into the impact of land-use changes on available atmospheric moisture and local to regional precipitation patterns (Keys, Wang-Erlandsson, Gordon, Galaz, & Ebbesson, 2017; Sheil, 2018; Staal et al., 2018; Wang-Erlandsson et al., 2018), as well as the development of water technologies that potentially affect spatial and temporal precipitation patterns (i.e., cloud seeding programs and atmospheric water generators), begs the question whether atmospheric water is a resource that should be governed.

Although the growing literature on water *governance* is broadening the scope of issues that need to be governed it has yet to explicitly acknowledge green and atmospheric water (see Figure 1). While there are some examples in the literature that provide governance strategies for green water (e.g., Green Water Credit schemes described in Hunink, Droogers, Kauffman, Mwaniki, & Bouma, 2012), and atmospheric water (e.g., moisture recycling governance in Keys et al., 2017), there is no coherent governance framework that includes both resources. There is an incorrect assumption that water law and policy refer to all sources of water. We address this misconception in this paper. Green and atmospheric water remain an ignored source of water, while leaving only blue water to be directly governed by water law and policy (Falkenmark, 1999; Rockström et al., 2004; Wisser et al., 2010). To a lesser extent, gray water (blue water that is extracted for domestic or industrial use and subsequently becomes polluted) and black water (sewage water) are also governed (Liu et al., 2010). Gray and black water governance literature evolves mainly around emission standards and the evaluation of water treatment technologies, and urban and rural policies concerning quality criteria, reuse standards and costs (Ghunmi, Zeeman, Fayyad, & van Lier, 2011). Although gray and black water are less relevant to this research, it is clear that the socio-hydrological cycle represents many *colors of water* (i.e., blue, green, “rainbow,” gray and black) that differ in physical form, accessibility and human use, and exhibit various local and global challenges that are to a greater or lesser extent governed. This review paper therefore addresses the question: *What are the arguments for governing green and atmospheric water?* In order to address this question, we have conducted a scoping review based on more than 50 academic articles using the structural method outlined by Arksey and O'Malley (2005). We identify seven key arguments (see Section 3) to increase focus on governing green and atmospheric water, based on a rough representation of the processes described in the literature. We acknowledge that spatial and seasonal variation in climate, vegetation, and hydrology often result in a more nuanced reality than the general picture presented here. That being said, we have tried to account for this limitation by adding illustrative examples from various regions. Furthermore, we outline existing governance tools and principles that

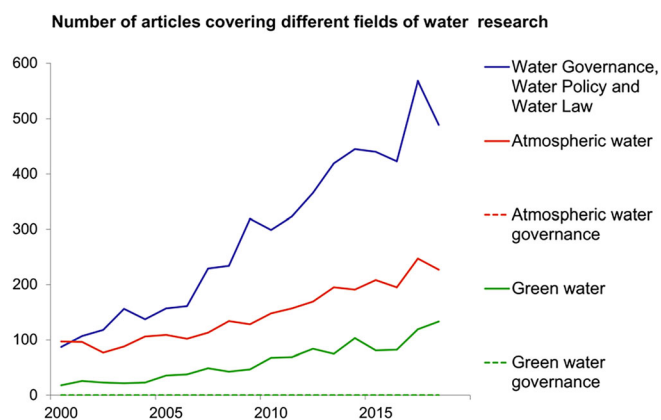


FIGURE 1 Papers covering green water, atmospheric water and water governance, water policy, and water law. There has been increasing academic research that explicitly addresses water governance (1,671 references), water policy (2,803 references), and water law (1,003 references), in the period from 2000 to 2018. The literature covering green and atmospheric water is also increasing, although green water and atmospheric water governance remain absent in the literature (both return 0 search results). Search criteria were based on the explicit use of terms (e.g., “green water governance” or “governance of green water”) in the title, abstract and keywords. *Source:* Scopus (Scopus www.scopus.com, May 21, 2019)

cover green and atmospheric water (Section 4). We conclude that, considering the systemic nature of water in the hydrological cycle and increasing societal pressure on green and atmospheric water resources, reconsideration of the current scope of water governance is needed.

2 | THE EVOLUTION AND SCOPE OF EXISTING WATER GOVERNANCE

This section reviews how water governance has evolved historically and the current state of such governance. We then examine why there has been a preeminent focus on blue water thus far in the existing governance literature.

2.1 | The evolution of water governance

Water law and governance can be traced back some 5,000 years (Dellapenna & Gupta, 2009) with community water governance systems evolving simultaneously in different parts of the world. Later, ancient societies developed either along rivers forming the early river basin civilizations or in drier areas where they focused on accessing groundwater. These early civilizations made rules regarding surface and ground water—who could access and/or own such water; how such water could be used; and who was to construct and maintain related water bodies and infrastructures (e.g., in Mesopotamia; Kornfeld, 2009). With the development of religion, many of the rules regarding water were embedded within religious doctrine. Hinduism, Judaism, and Islam were among the first religions to specifically make rules on water. Although the first formal scientific understanding of water circulation only stems from the 16th–17th century (Creed & Van Noordwijk, 2018), these early religions were already conscious of the nature of water: Hinduism argued against water ownership and only allowed usufructuary rights to water or the legal right to use water (Cullet & Gupta, 2009); Islam saw water as a gift of God to be treated with care and did not allow for the sale of water (Naff, 2009); Judaism debated the legal ownership of water but allowed private and state ownership of, for example, ground water in wells; and people within and between communities had rights of access to water (Laster, Aronovsky, & Livney, 2009). However, historically none of them actually addressed the invisible sources of water.

2.2 | The current state of water governance

Over time, the historic rules and practices have become institutionalized from local to global levels, but it is increasingly clear that current day principles, rules and instruments of water governance focus essentially on the liquid water we can see—blue surface and ground water, gray, and black water. Even snow and ice, although visible to the eye, are less regulated. Principles of water law and policy ranging from sovereignty, equity, avoidance of harm, participation, conflict resolution, prior informed consent, and human rights are all focused on surface and ground water. Environmental principles such as the polluter pays principle, notification of accidents, environmental impact assessments, and others are also specifically centered around blue water and increasingly on gray and black water flows. The Glacier Protection Law in Chile is one of few focusing on the solid frozen component of water (Hurlbert & Gupta, 2017). Water-related instruments such as ambient water standards, pollution standards, and permits and licenses almost exclusively focus on blue water.

At the international level, the over 900 transboundary water agreements focus solely on blue water. The Ramsar Convention on Wetlands of 1972, the UN Convention on the Non-Navigational Uses of International Watercourses 1997 and the 1992 UNECE Water Convention, also primarily address blue water. The draft Groundwater Rules being discussed within the UN focus, as the name states, on the (blue) groundwater component. The European Union Water Framework Directive focuses on the basin approach, which also encompasses a blue water approach. The recently adopted Agenda 2030 and the Sustainable Development Goals are somewhat more ambiguous, yet explicit policies, principles and instruments for green and atmospheric water governance remain absent.

2.3 | The predominant focus on blue water

It is logical that until recently the focus of water governance has been on blue, gray, and black water. First, in most parts of the world, blue water has scarcely been managed successfully and so the need to address other forms of water is less relevant and the ability is limited. Blue water remains a serious challenge in countries like the United States, Central European countries, Australia, most of Asia, Africa, and Latin America (UN Environment, 2019). A key indicator of this is the challenge of providing potable water and sanitation services worldwide (WHO/UNICEF, 2017). As a consequence, most societies move

incrementally in the governance process not least because they have limited resources. Second, in areas where water problems appear to be reasonably well under control, such as the European Union, there is less of a need to tap into additional water resources since these areas are relatively rich in blue water. The conventional blue water approach, that neglects green water consumption from biomass, has evolved from a water management paradigm developed in the temperate zone in the Global North where evaporative demand is low (Falkenmark, 2001). Historically, this made the need to work on green and atmospheric water governance less pressing. Third, water is a cross-cutting issue; it is very difficult to draw the boundaries of what is a water issue and what is not. For example, freshwater is closely linked to land and water ownership in English common law and Spanish legal systems; Freshwater is also linked to land-based ecosystems, as well as to all sectors of production, distribution, and consumption; its use is intertwined with activities that contribute to national GDP. Keeping water governance manageable thus led to an exclusive focus on blue water. Fourth, until recent decades, the scale of human influence on green and atmospheric water flows has been limited (Sheil, 2018). In turn, this explains why the motivation to govern green and atmospheric water has historically also been quite limited. As a consequence, even the recently adopted Sustainable Development Agenda 2030 only implicitly mentions green and atmospheric water in its water related goal (see Table 1).

3 | ARGUMENTS FOR EXTENDING GOVERNANCE TO GREEN AND ATMOSPHERIC WATER

Until the 1990s, calculations of water flows were missing an important component, which led to the identification of green (Falkenmark & Rockström, 1993) and atmospheric water (Savenije, 1995) in catchment modeling. Quantifying green water has since revealed that green water comprises a substantial part of available global fresh water. Although hydrologists and climate scientists have researched atmospheric water extensively, it is only recent that hydrological land-atmosphere relationships have been covered in academic literature concerned with *water basin management* (Keys et al., 2017; Wang-Erlandsson et al., 2018). The field of *ecohydrology* has recently come into existence and focuses specifically on the links between green water, vegetation, and climate (Rodríguez-Iturbe, 2000). An examination of the green water literature in Scopus, Web of Science, and GreenFILE reveals that 499 references directly discuss green water. For these references, a bibliometric network has been made with VOSviewer 1.6.10 (VOSviewer, 2019) to explore the prevailing themes discussed in this body of literature (see Figure 2). Many cover the “water footprint” concept which illustrates the large focus on agriculture in the green water discourse. For this scoping review, we selected 57 articles concerned with conceptual development and mechanistic understanding of green water and the quantification of global green water flows. Context-specific case studies were excluded. The selection was further complemented with literature on land-atmosphere hydrological relationships to cover atmospheric water literature. The latter selection procedure was not as structured as the one for green water, as atmospheric water is more broadly covered in this body of literature (an initial search on Scopus revealed >4,000 articles). Therefore, hand searching and backward citation tracking was used to identify relevant literature. A critical assessment of this literature reveals seven arguments as to why water governance should move from a blue water basin scale approach to an integrated approach taking into account the multiplicity of colors of water.

3.1 | Blue water represents only a part of the available fresh water

Our first argument is that green and atmospheric water are a substantial part of the water cycle, and therefore must also be governed. Hydrological modeling efforts in the last decade have significantly improved our understanding of global hydrological flows and storage capacities of blue, green, and atmospheric water (Gerten et al., 2005; Rost et al., 2008; Van der Ent & Savenije, 2011; Wang-Erlandsson, Van der Ent, Gordon, & Savenije, 2014). Blue water can be estimated based on quite reliable and easily measurable statistics (i.e., river water discharge, dam storage capacities), whereas green water is more difficult to estimate. Initial estimations were based on compilations of crude climate (i.e., precipitation and potential evapotranspiration) and vegetation data. More recent references use global dynamic vegetation and water balance models (i.e., LPJ, see Gerten et al., 2005; Rost et al., 2008), advanced crop models (Liu & Yang, 2010) and Soil and Water Assessment Tools (SWAT) (Zang & Mao, 2019), that account for many variables that influence local green water availability. Green water *flow* estimations, are similarly derived from modeling efforts based on crop water footprints (Schyns et al., 2019), coupled vegetation and climate models (Wang, Feng, Wang, Wang, & Cai, 2018) and water balance models (i.e., STEAM, see Wang-Erlandsson et al., 2014). Green water flow, which is the upward vertical flux of evaporation and transpiration from the terrestrial surface, together with evaporation from ocean water, feeds into the atmospheric water component that forms the source of all precipitation. Atmospheric moisture and precipitation can be measured with high precision from satellite observations

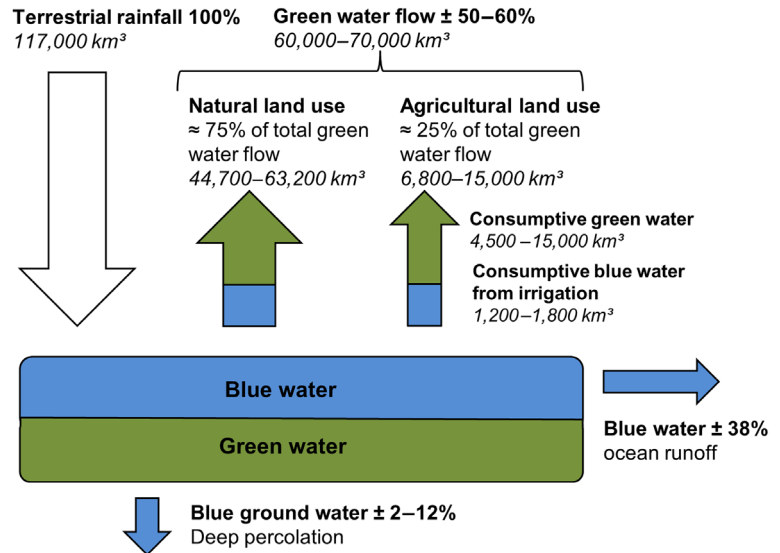


TABLE 1 SDG 6 on water and its focus on green and atmospheric water

SDG6: “Ensure availability and sustainable management of water and sanitation for all and its treatment of green and atmospheric water”		
Targets	Indicators	Main focus and treatment of green and atmospheric water
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Proportion of population using safely managed drinking water services	Drinking water and sanitation (blue water)
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1 Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water	Drinking water and sanitation (blue, gray, and black water)
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1 Proportion of wastewater safely treated 6.3.2 Proportion of bodies of water with good ambient water quality	Drinking water and sanitation (blue, gray and black water)
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1 Change in water-use efficiency over time 6.4.2 Level of water stress: Freshwater withdrawal as a proportion of available freshwater resources	Water resource management (blue and possibly also gray and black water)
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	6.5.1 Degree of integrated water resources management implementation (0–100) 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation	Water Resource Management (blue, and possibly also green and atmospheric water)
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	6.6.1 Change in the extent of water-related ecosystems over time	Water Resource Management (blue and green water)
6.A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	6.A.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan	Water cooperation and capacity building (blue, gray, black, and possibly also green and atmospheric water)
6.B Support and strengthen the participation of local communities in improving water and sanitation management	6.B.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management	Water cooperation and capacity building (blue water)

Notes: The columns in bold indicate the targets that implicitly refer to green and/or atmospheric water governance.

FIGURE 3 Flowchart for average global annual green and blue water flows and storage on the terrestrial surface. *Source:* Flow estimations are based on Rockström and Gordon (2001), Rockström, Lannerstad, and Falkenmark (2007), Rost et al. (2008), Hoekstra and Mekonnen (2012), Wang-Erlandsson et al. (2014), and Sheil (2018)



water partitioning (Stewart & Peterson, 2015), although the absolute annual mean runoff in the tropics remains highest (Gerten et al., 2005).

In terms of *water use*, the agricultural sector is the largest blue and green water consumer of all human activity. Global blue water extraction to produce food, fiber, fuel, fodder, and timber amounts to 1,200–1,800 km³/year (Hoekstra & Mekonnen, 2012; Rockström et al., 2007). When accounting for green water use, the total consumption of freshwater by agriculture increases dramatically. Globally, croplands alone consume between 5,400 and 7,250 km³/year of green water (Rockström & Gordon, 2001; Rost et al., 2008). Croplands and grazing lands are together responsible for at least 25% of terrestrial green water flow (Rost et al., 2008). Globally, about 80% of the agricultural lands are rainfed and dependent on green water (Liu, Zehner, & Yang, 2009; Rockström et al., 2009) producing 60% of the food (Rockström et al., 2014). Thus, most food is produced with “invisible” green water, yet many statistics presenting the pressure of the food system on water only reflect the blue water extracted for irrigation (UN Environment, 2019). Natural terrestrial ecosystems are the largest green water consumers, adding up to a total of 44,723–63,200 km³/year (Rockström & Gordon, 2001; Rost et al., 2008). Global green water flows are necessary for ecosystem functioning, as they support vegetation growth, regulate climate, and ensure carbon sequestration (Falkenmark, Wang-Erlandsson, & Rockström, 2019), nutrient cycling and soil enrichment (Feger & Hawtree, 2013; Rockström & Karlberg, 2010). Generation of these ecosystem services are of vital importance for local to global socio-economic development. Due to human appropriation of land, there are trade-offs between green water for natural systems and for agriculture (Schyns et al., 2019). Both natural ecosystems and agricultural systems remain dependent on green water hence water governance should account for green water use by different land uses and develop mechanisms and rules for accessing and using this water resource.

3.2 | Blue water is a subset of the wider hydrological cycle

The second argument is that the available blue water on the earth's surface is only a subset of water within the hydrological cycle and water keeps cycling through the system (see Figure 4). The continuous movement of water in different forms (solid, liquid, and vapor) is represented by the average residence time of a water molecule in a particular subset of the hydrological cycle. Water vapor, for instance, has an average residence time of ±9 days (van der Ent & Tuinenburg, 2017), meaning that a water molecule remains on average 9 days in the atmosphere before it precipitates and becomes blue or green water over land, or is stored in the ocean or ice caps. When rainfall reaches the terrestrial surface, it is partitioned into blue or green water. This partitioning process is at least determined by vegetation cover, infiltration capacity, and the temporal distribution of rainfall (Falkenmark, 2013; Rockström, 1999; Weiskel et al., 2014). A second partitioning process occurs when green water is captured by the soil, and can either return to the atmosphere as green water flow or percolate downwards to replenish groundwater. The global average residence time of green water is around 5 months, but the local variation within and between the different components making up green water flow is large (Table 2). Rainfall that is intercepted by vegetation is returned in a matter of hours to the atmosphere, whereas rainfall that is eventually used by plants via transpiration can take more than a year. When following a water particle throughout a basin, a continuous partitioning process between blue and green water can

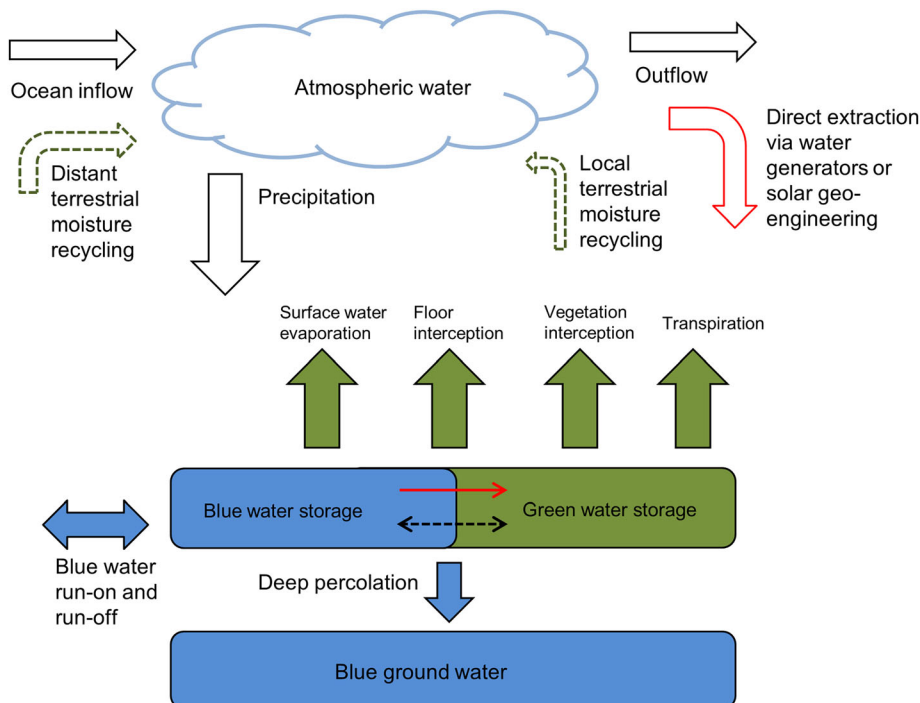


FIGURE 4 Conceptual diagram showing the systemic nature of water, intrinsically linked to land use, including blue, green, and atmospheric water storages and flows. The dotted line connecting green and blue water storage represents the continuous partitioning process that can take place in the river basin; the red line indicates extraction of surface water for irrigated agriculture and direct extraction of atmospheric water via water generators and solar geo-engineering (see Section 3.6)

Water resource	Av. residence time
Atmospheric water	9 days
Green water	5 months
• Vegetation interception	1.1–1.6 hr
• Floor interception	5.2–11.6 hr
• Soil moisture evaporation	42–46 days
• Transpiration	95–434 days
Blue water	16 days–2.7 years
• Lakes	17 years
• Rivers	16 days
Blue ground water	150–1,500 years
Terrestrial ice and glaciers	800 years
Ocean water	2,500–28,000 years

TABLE 2 Average residence time of various water resources, which is determined by the total amount of the water resource per annual flow rate (storage/flux)

Notes: The residence times specified for the components of green water refer to the time it takes for the water to be returned to the atmosphere. Note that estimations for blue water, blue ground water, and ocean water have a high variation. For blue water, these variations may be explained Shiklomanov (2000) presents the residence time for lakes (17 years) and rivers (16 days), which are lumped together as blue water having a proportional average residence of 2.7 years, as presented by Savenije (2000). The large variation in ground water and ocean water might be explained by high spatial variation (“deep” groundwater and ocean water in some regions have longer residence times than others). Yet, no clear explanation has been found for the large variation in estimated average residence times.

Source: Based on data presented by Savenije (2000), Shiklomanov (2000), Wang-Erlandsson et al. (2014), and van der Ent and Tuinenburg (2017).

occur before the particle is returned to the atmosphere or ocean, which is referred to as “the water cycle continuity” (Falkenmark, 2001). Human activities can influence this cycle and the partitioning process by irrigation practices (converting blue water to green water), and land management (Falkenmark, 2008; Jewitt, 2006), which can have direct impacts on aquifer replenishment, ecosystem service generation, or downstream blue water availability.

The water basin has generally been used as the *management boundary* in conventional blue water management, and the *resource base* to be governed is the available surface water in lakes and rivers. In transboundary river systems, the available

resource that the region has at its disposal is the incoming flow of blue water from river systems. Historically, this has resulted in many disputes between regions regarding both water quantity and quality issues. Upstream users are in a favorable position relative to downstream users, as they can—knowingly or not—decide how much, when and how downstream water becomes available (due to surface water extraction, dam construction, land use change, and pollution). Accordingly, Falkenmark and Folke (2002) argue that in order to ensure equitable water allocations in a water basin—the resource base to be governed should not only cover incoming blue water flow, but consider the total precipitation within a river basin, by “making catchment management rainfall management.” Considering precipitation as the resource base to be governed is supported by Van Noordwijk and Ellison (2019), who argue that precipitation governance is necessary in both the conventional watershed as well as in the *precipitationshed* and *evaporationshed*. These concepts represent spatial units for analysis of teleconnected regions, which are regions that are linked via atmospheric water flows (Keys et al., 2017). For example, the majority of the water running through the Nile basin derives from precipitation over the Ethiopian highlands, which is fed by atmospheric moisture coming from the Mediterranean Sea, the Indian Ocean and Atlantic Ocean (Gebrehiwot et al., 2019). Accordingly, water availability in the Nile basin is determined by an area much larger than the basin itself. An analysis on precipitationsheds of 29 mega-cities show that the majority of urban areas are dependent on terrestrial evaporation for one third of their water supply (Keys & Falkenmark, 2018). Yet, most institutional arrangements are based on the river basin as the natural boundary and are only concerned with blue surface water and, to some extent, ground water (Warner, Wester, & Bolding, 2008). Managing only blue water in a basin is limited as it does not account for this water cycle continuity that exists beyond the water basin scale. As precipitationsheds often cross national borders, transboundary agreements are needed that include the governance of green and atmospheric water (Gebrehiwot et al., 2019).

3.3 | Land-use changes

The third argument is that global land use changes affect both blue, green, and atmospheric water flows on local and regional scales. In the last decades, agricultural expansion following deforestation has reduced global transpiration by 7% (Gerten et al., 2005). Analysis of global land cover changes have revealed a total decrease in terrestrial green water flow of 3,500 km³/year (5–6%) compared to a situation where anthropogenic influence would be absent (Sterling, Ducharne, & Polcher, 2013). The impact varies largely between different land use conversions: conversion to nonirrigated cropland reduces evapotranspiration for wetlands, forests, and grasslands by 106, 36, and 30% respectively (Sterling et al., 2013).

The impact of land use conversion on the hydrological cycle is debated. The removal of forests generally results in higher surface runoff (Peña-Arancibia, Bruijnzeel, Mulligan, & van Dijk, 2019; Sterling et al., 2013; Tague, Moritz, & Hanan, 2019) since forests are substantial water consumers (Falkenmark, 2003). Although varying between climatic zones, an average forest patch consumes an additional 200–300 mm/year through transpiration only (Van Noordwijk et al., 2014), compared to a situation in which trees are absent. In the Heihe River basin in China, the total average green water flows range from 306, 260, 173 mm/year in arid forests, cropland and grassland ecosystems (Zang & Mao, 2019), whereas in tropical forests such as the Amazon, the average green water flow is about 1,096–1,370 mm/year (Fisher et al., 2009). Forests also intercept a relatively larger percentage of precipitation in the canopy that is directly returned to the atmosphere and hence not available to downstream users (Wang-Erlandsson et al., 2014). On the other hand, forests are associated with a “sponge” effect, referring to the higher infiltration capacity of the soils underneath forest systems. Peña-Arancibia et al. (2019) show that in seasonal tropical catchments, reduction of infiltration capacity after deforestation reduces the base flow in the dry-season. In Mediterranean dry forests characterized by high inter-annual variability in precipitation, deforestation increases peak streamflow, which can—in the case of extreme weather events—lead to severe environmental damage from flash-floods (Tague et al., 2019). Vice versa, the process of reforestation on former degraded lands might not return the system to the initial hydrological state associated with intact forest. Evidence from the Mediterranean furthermore shows that reforestation of former degraded lands after more than 50 years still results in higher peak discharges and faster hydrological response times (which is the time between rainfall and observed discharge) compared to intact forest (Nadal-Romero, Cammeraat, Serrano-Muela, Lana-Renault, & Regüés, 2016). Accordingly, nonlinear hydrological responses in land use change can be expected.

Different land use types retain various spatial and temporal distribution of green water flows. Forests maintain water locally and return it to the atmosphere in a slower and more spatially distributed manner than in the absence of forests (Wang-Erlandsson et al., 2014) (Figure 5). In the Amazonian tropical forests, the capability of trees to reach deeper groundwater with their rooting system maintains a critical transpiration flow in the dry season (Castelli, Castelli, & Bresci, 2019; Staal et al., 2018). This vertical flow of water can precipitate again or even attract moisture via a pressure gradient, a mechanism referred

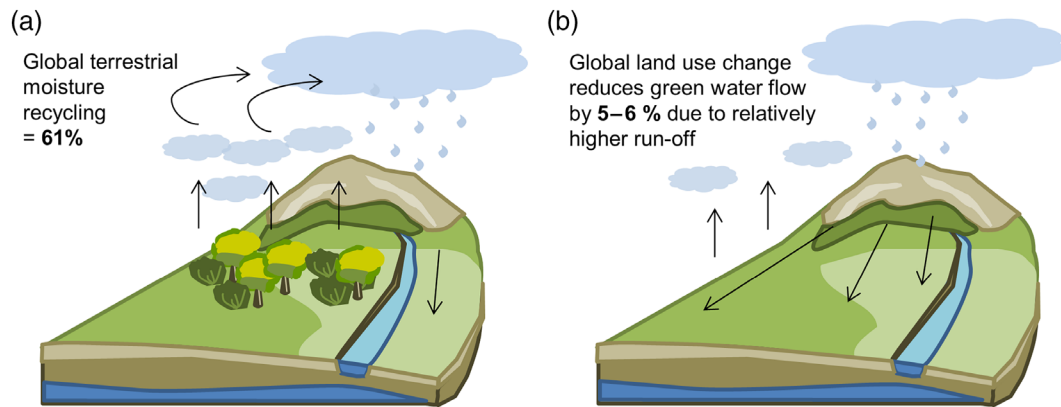


FIGURE 5 (a) The process of terrestrial moisture recycling throughout intact forest systems. Forests trap run-off and sometimes reach groundwater with their root system. The water that is evaporated is released to the atmosphere in a more spatially and temporally homogenous manner. The atmospheric water subsequently reprecipitates and can be used to support further vegetation growth. On average, 61% of the precipitation on land derives from terrestrial green water flow. (b) The process of (reduced) terrestrial moisture recycling throughout deforested lands. Water run-off is not captured by vegetation, increasing the relative surface run-off toward the ocean. The global annual average of 5–6% reduction of green water flow probably underestimates the local effects of land use change green water flow, as the presented average also includes local increases in green water flow, for example due to downstream increases in irrigated agriculture facilitated by the higher runoff rates. *Source:* Estimations are based on Sheil (2018) and Sterling et al. (2013)

to as the “biotic pump.” Some studies suggest that plants can attract rainfall via volatile organic particles emitted by plants when they experience water stress (for an extensive synthesis, see Sheil, 2018). Tropical forests, due to their large canopy, have a relatively high interception ratio that is associated with short recycling length scales (see Table 2) meaning that it quickly returns to the atmosphere (Wang-Erlandsson et al., 2014), and back to the surface as precipitation (Van der Ent & Savenije, 2011; Van der Ent, Wang-Erlandsson, Keys, & Savenije, 2014). On average, a water molecule entering the atmosphere falls 2.6 times as rainfall on land before it returns to the ocean (Van Noordwijk & Ellison, 2019), but this recycling ratio varies greatly between seasons and the continents (Van der Ent, Savenije, Schaefli, & Steel-Dunne, 2010). In general, continental moisture recycling in winter is much lower than in summer due to lower evaporation, yet some regions are highly dependent on moisture recycling throughout the year. China for instance, depends on recycled moisture from the Eurasian continent for about 40–60% even in winter. In the Congo basin, a large part of rainfall derives from evaporated water in Eastern Africa, whereas the Congo basin itself is important to sustain rainfall in the Sahel (Van der Ent et al., 2010). Evaporated water from terrestrial origin can precipitate locally or travel up to 500–2,000 km (in the tropics), 3,000–5,000 km (in temperate regions) or more than 7,000 km (in deserts) before it precipitates again elsewhere (Staal et al., 2018; Van der Ent & Savenije, 2011). The specific composition of green water flow also influences the scale of the moisture recycling process. Evaporated water remains in the atmosphere for a shorter period compared to transpiration, and generally contributes to local recycling, whereas transpiration precipitates further from its evaporative source (Van der Ent et al., 2014). This implies that land cover conversions that change the partitioning of green water flow, can have far-reaching impacts (Keys et al., 2017; Wang-Erlandsson et al., 2018).

Land use decisions are thus water decisions, raising questions regarding forest and agricultural governance to secure local and regional water availability (Ellison, Futter, & Bishop, 2012). The process of terrestrial moisture recycling is currently not governed, even though it is an important ecosystem service (Falkenmark et al., 2019). The common land-water dichotomy which is represented by a separated institutional framework (i.e., law and policy) for land governance (e.g., agriculture and nature) and water governance hinders the governance of forests and ecosystems from a water perspective. In order to avoid sectoral management of land and water, some scholars recommend that science and policy should focus on “eco-hydrological management” which accounts for both *land* and *water uses* (Falkenmark, 2001).

3.4 | Climate change and variability

Fourth, climate change is expected to influence transpiration, evaporation, and precipitation patterns worldwide. The rising atmospheric carbon dioxide concentration has both positive and negative effects on vegetation productivity and the associated green water flow. Higher CO₂ concentrations result in increased water use efficiency by plants, meaning

that the productivity rate per unit of water increases (De Boer, Lammertsma, Wagner-Cremer, Wassen, & Dekker, 2011). Whether this will result in a net decrease in transpiration depends on whether increased water use efficiency will counteract the effects of increased primary production, higher leaf temperature, and differences in soil moisture due to the rising temperatures from atmospheric carbon (Gerten et al., 2005). A simulated hypothetical CO₂-doubling scenario from a dynamic global vegetation model (Gerten et al., 2005) shows high global variation in the impact on runoff, transpiration, evaporation, and interception. Transpiration decreases mostly in the wet tropics, whereas in very arid environments the primary productivity is already severely water limited. In savannah and grasslands, transpiration rates increase due to forest encroachment (Gerten et al., 2005). Overall, the global average shows a significant increase in runoff (5.5%). On the other hand, climate change might also increase overall field evapotranspiration due to rising temperatures (Dominguez-Faus, Folberth, Liu, Jaffe, & Alvarez, 2013). Furthermore, rising temperatures can restrict plant photosynthesis by increasing the vapor pressure deficit (VPD) due to the higher water-holding capacity of the warmer atmosphere. This metric refers to “the difference between the water vapour pressure at saturation and the actual water vapour pressure for a given temperature” (Yuan et al., 2019, p. 1). Increased VPD is significantly correlated with reductions in forest productivity, and forest mortality (Yuan et al., 2019). Accordingly, the question is whether the effect of increasing water use efficiency will counter-balance reduced photosynthesis rate due to increasing VPD, and what this implies for hydrological flows.

Meteorological dry spells and droughts, extreme weather events and prolonged dry seasons are also expected to increase and constrain agricultural production by high potential evaporation (Falkenmark, 2007; IPCC, 2019). Many *agricultural* dry spells and droughts on the other hand, are partly surmountable through better land management that improves soil quality, infiltration capacity, and reduces evaporation to hold green water during dry periods, which is especially critical for drylands characterized by erratic rainfall patterns. Increasing soil infiltration capacity also reduces surface run-off that can cause undesirable environmental off-site effects, such as flooding or sedimentation. Furthermore, increased soil moisture (i.e., green water) in the post-rain period, reduces land surface heating significantly by converting energy into latent heat, instead of sensible heat (Castelli et al., 2019). Global patterns of deforestation have changed the global energy balance through an increased albedo effect from deforested, barren areas. Although this would imply a cooling effect, there is a significant *increase* in surface temperature, as the albedo effect does not counter-balance the increasing temperature from sensible heat through reduced transpiration capacity (Duveiller, Hooker, & Cescatti, 2018).

Scholars suggest that ensuring soil quality and preserving vegetation to support water infiltration and reduce land surface heating should be a major target (Feger & Hawtree, 2013) to adapt to rainfall variability and climate change, especially in degraded *drylands*. Restoration of degraded ecosystems creates more favorable microclimates and might even enhance moisture recycling on broader spatial and temporal scales (Keys & Falkenmark, 2018; Rockström et al., 2014; Van Noordwijk et al., 2014). Ecological restoration initiatives worldwide are gaining ground (Chazdon & Brancalion, 2019), but their effect on hydrology should be considered as run-off reductions can be expected (Bai, Mo, Liu, & Hu, 2019; Farley, Jobbagy, & Jackson, 2005). Although enhancing land management is increasingly recognized as necessary for both mitigating and adapting to climate change (IPCC, 2019), the links between hydrology and land use in relation to climate change, are still poorly understood. Instruments in global climate change policy that relate to land use have been command-and-control (e.g., protection of important carbon sinks, see IPCC, 2019), market-based incentives (e.g., REDD+, see Hein, Guarin, Frommé, & Pauw, 2018) and policy guidelines for sustainable or adaptive management (e.g., Sustainable Land Management, see UN Environment, 2019). Hence, green water has implicitly been governed in global climate policy focusing on the domain of land use. For atmospheric water governance, policy instruments using regulatory, market, or community-based management may be needed to address expected climate-induced changes in atmospheric water. Making ecosystems resilient and adaptive to climate change should be a key priority in climate change policy in order to safeguard blue, green, and atmospheric water availability in the long term.

3.5 | Different colors of water are used and polluted differently

The fifth argument relates to the fact that water resources occur in many different colors (blue, green, gray, black, and “rainbow”), and understanding how different consumers use and pollute different colors of water is crucial to prevent unexpected trade-offs. From an anthropocentric perspective, water can be categorized based on the *direct (societal)* and *indirect (natural)* uses of water (Figure 6) (Rockström et al., 2004).

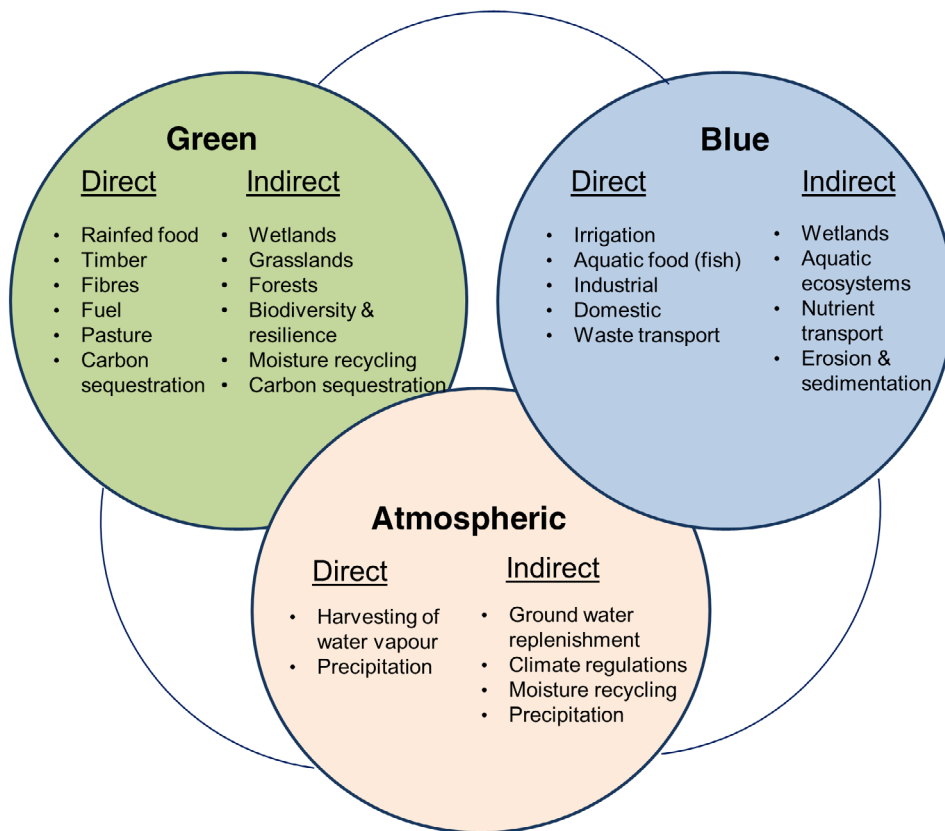


FIGURE 6 Diagram showing nonexhaustive functional properties (direct and indirect) of green, blue, and atmospheric water resources.

Source: Adapted and complemented from Rockström et al. (2004), Hayat and Gupta (2016), and Falkenmark et al. (2019). Note that carbon sequestration is both listed as a direct and indirect functional property of green water, as carbon sequestration policies to mitigate climate change offer a financial benefit to countries (direct) and natural ecosystems capture carbon (indirect). Similarly, precipitation is both a direct and indirect atmospheric water use

3.5.1 | Direct use of green and blue water

Both green and blue water resources that support socio-economic development are becoming increasingly scarce under growing human populations and changing consumption patterns. It is estimated that the global freshwater deficit in 2050 will amount 2,400 km³/year (Rockström et al., 2014), mainly due to the expected increase in global agricultural production (Falkenmark & Rockström, 2006; Hoff et al., 2010; Sulser et al., 2010). Furthermore, increasing production of biofuel puts additional pressure on water resources globally (De Fraiture, Giordano, & Yongsong, 2008). Producing 1 L of biofuel takes roughly 2,800 L of green water and 820 L of blue irrigation water. Furthermore, global carbon sequestration policies that provide financial incentives for afforestation also consume large amounts of water. Many regions—especially tropical drylands that are characterized by large yield gaps—experience large water losses from nonproductive green water flows (i.e., soil evaporation). Soil and water management techniques to improve water productivity in these regions have the potential to save 500 km³/year globally (Rockström, 2003). Reducing food waste, currently at 33% globally (UN Environment, 2019), could also reduce the pressure on blue and green water. In China, food losses in 2010 were associated with a total water footprint of 60 billion m³, which is equivalent to 20% of the total water footprint of the national crop production (Liu, Lundqvist, Weinberg, & Gustafsson, 2013). Although these measures would take some pressure off the future increase in global water demand, they may not meet the expected deficit in 2050 completely. Accordingly, rules and regulations for green water use are required to secure future water resources and agricultural needs on a global level.

3.5.2 | Indirect use of green and blue water

Ecosystem functioning is vital to provide biodiversity and ecosystem services (e.g., carbon sequestration, nutrient recycling, pollination, and pest control) to natural and human systems, yet green water flows that sustain those services on the terrestrial surface receive little attention (Rockström & Gordon, 2001). The trade-offs between blue and green water for societal needs (direct use) and natural ecosystems (indirect use), are becoming more explicit due to continuing expansion of agricultural land (Foley et al., 2011). Ignoring the limits of sustainable societal use of green water poses a risk to ecosystem service generation that depends on green water flows from natural areas (Schyns et al., 2019). Blue water requirements for natural aquatic ecosystems (i.e., such as wetlands) are often described based on the concept of *environmental flow* which is the minimum blue water flow that is needed to protect *aquatic ecosystem* functioning and biodiversity. It is often estimated at 20–50% of the base run-off flow on average (Smakhtin, Revenga, & Doll,

2003). Yet, green water requirements of natural areas to maintain ecosystem functioning and the implications of disturbance to these flows are less well understood (Rockström et al., 2004). Further appropriation of green water for consumptive uses at the cost of nature can be detrimental to biodiversity and the provisioning of ecosystem services (Vaux, 2012) which begs for the recognition of the environment as an essential green water user in order to protect the generation of those services.

3.5.3 | Different uses of atmospheric water

For atmospheric water, the direct and indirect uses are less researched and straight-forward compared to blue and green water. Apart from it being the source of precipitation, direct uses of atmospheric water in the form of vapor extraction (see Section 3.6) are still relatively unexplored. Indirectly, atmospheric water plays an important role in moisture recycling (Falkenmark et al., 2019) and climate regulation (Hayat & Gupta, 2016). Pollution of atmospheric water has been a major problem in the 1970s and 1980s, when *acid deposition* caused major environmental problems in Europe and North-America. Acid rain resulted from emissions of nitrogen oxide and sulfur dioxide from industry, agriculture, and burning of fossil fuels. International recognition of the issue led to legislation on emission and air pollution (Menz & Seip, 2004). Understanding the different ways in which the various colors of water are used and polluted is crucial to develop governance mechanisms and principles that can make informed trade-offs between different water resource uses, and prevent unexpected consequences of changing water flows to other users.

3.6 | New technologies enable accelerated use of green and atmospheric water

The sixth argument is that the development of technologies restructure power relationships around available water resources. For example, existing energy production technologies are hugely dependent on (blue) water. Going beyond, new water technologies pose new challenges. First, advanced technologies are being developed that harvest water directly from the air with *atmospheric water generators* (Kim et al., 2018). Although these technologies offer promising opportunities to tap into unconventional water sources, they also retain the risk of creating new *hydrosocial territories*, defined as the “spatial configurations of people, institutions, water flows, hydraulic technology and the biophysical environment that revolve around the control of water” (Boelens, Hoogesteger, Swyngedouw, Vos, & Wester, 2016, p. 1), and raise questions regarding the conditions of access to and control of this water resource. The lack of policies regarding atmospheric water harvesting is problematic (Qadir, Jiménez, Farnum, Dodson, & Smakhtin, 2018) as it is increasingly understood that regions are hydrologically connected via atmospheric water flows (i.e., in evaporation- and precipitationsheds). Second, cloud seeding programs that eject particles into the air to enhance condensation, can stimulate local precipitation where it would otherwise not occur (French et al., 2018). Large scale solar geo-engineering projects (e.g., injecting particles in the air to reflect solar radiation) are gaining more attention worldwide as a means to combat global warming, but also carry the risk of distorting the hydrological cycle (Bala, Duffy, & Taylor, 2008). Third, the use of water-use efficiency technologies in one place (such as in irrigation), may distort precipitation patterns elsewhere. de Vrese, Hagemann, and Claussen, (2016) conclude that irrigated agriculture in Southern Asia contributes to ~40% of the rainfall in Eastern Africa. The increased upward moisture flux from the applied irrigation water is transported over more than a thousand kilometers to be released again as rainfall on the African continent.

The above technologies all have the potential to alter local and distant precipitation patterns. Accordingly, understanding their climatic impact is important to prevent a new form of *atmospheric water grabbing*, referring to the process of harvesting atmospheric water in one place which subsequently might change rainfall patterns elsewhere. Furthermore, the institutional framework in which such technologies are developed and implemented should be addressed and governed.

3.7 | Global trade infrastructures stimulate local consumptive green water use

The last argument is that global trade infrastructure for agricultural and industrial products puts additional pressure on regional green water resources, which especially concerns arid regions. The development of the global food system since the 1980s has been characterized by the increasing power and influence of transnational corporations (Allan, 2015) that operate around the world in vertically integrated long global food supply chains that increase trade in *virtual water*. Virtual water is the consumptive water use needed to produce agricultural goods and other consumer products for trade. The global virtual water balance reveals that many water scarce countries are net exporters of virtual water (Hoekstra & Mekonnen, 2012). This implies that the net water footprint of their national production for export is larger than the water footprint from imported products (Hoekstra & Mekonnen, 2012). In theory, virtual water trade could help overcome regional water scarcity when it is applied the other way around: by importing high water demanding products from water rich countries which are too costly (in terms of water use) to produce domestically. Yet, evidence from China shows that virtual water trade put additional water stress on

exporting regions as the water transfers appear to flow from less to more economically developed regions. By focusing on the supply-side (i.e., exporting virtual water from water rich regions), the false impression of unlimited water availability might be created (X Zhao et al., 2015). Furthermore, much of the current transfers are explained by land productivity rather than water productivity or availability (Zhao, Hubacek, Feng, Sun, & Liu, 2019). There is currently a lack of policy and reporting rules that can account for the regional hydrological impact of agricultural production (Liu, Antonelli, et al., 2019). Keys and Falkenmark (2018) also refer to this as the “blindspot” in the Sustainable Development Goals, as SDG 6 (*ensure availability and sustainable management of water and sanitation for all*) addresses water, but there is no mention of the water needed for food production to reach SDG 2 (*zero Hunger*), despite water scarcity being the largest constraint on food production. Accordingly, appropriation of green water in global agricultural and industrial trade needs to be recognized and accounted for to prevent *green water grabbing* and jeopardize food security in water scarce areas (Rulli & D'Odorico, 2013).

4 | THE TOOLS FOR GREEN AND ATMOSPHERIC WATER GOVERNANCE

The literature suggests the following tools to govern green and atmospheric water. Examples of green water governance principles appears to be more advanced and prominent than for atmospheric water. An extensive review of green water indicators already shows that around 80 indicators exist to describe green water availability and scarcity (see Schyns, Hoekstra, & Booij, 2015). Considering atmospheric water governance, there are few references that describe tools to govern atmospheric water. Keys et al. (2017) provide a first attempt to describe moisture recycling governance strategies, by classifying the various networks that exists between teleconnected countries. They also outline four existing governance strategies that could support moisture recycling governance: funding mechanisms, trade and certification schemes, planning methods, and ecosystem assessment tools. Below, we outline three examples from the literature that describe three different approaches to green and atmospheric water governance.

4.1 | PES schemes

A payment for ecosystem services (PES) scheme can provide incentives and funding mechanisms to improve green water use-efficiency within a basin, and make trade-offs between water uses based on economic principles. PES schemes enable poor upstream land and water users (e.g., farmers) to invest in green water use efficiency measures to increase downstream water availability which is financed by downstream users. It provides a “fair and transparent” mechanism for adoption of better land management on a local, water basin scale (Lal, 2013). In Kenya, a Green Water Credit scheme was developed in the Upper Tana Basin in 2008; in this pilot, downstream public and private water users (hydropower companies, water suppliers, and irrigating farmers) were targeted to pay for upstream management interventions by over 100,000 smallholder farmers (Hunink et al., 2012). In the Kenyan case, the PES scheme provided the financial opportunities for farmers to enhance their land management practices and improve plot-level water use efficiency (Kauffman et al., 2014). PES schemes could also be applied to govern atmospheric water and moisture recycling processes, in which *downwind countries* pay *upwind countries* for the preservation of forests to secure rainfall.

4.2 | Global agricultural trading schemes based on water footprints

The global trade in virtual water has rapidly increased in the last few decades (Xu et al., 2019). Agricultural products grown for export are now responsible for ~30% of the total fresh water withdrawal (Chen & Chen, 2013). The observed imbalance in global virtual water trade (see Section 3.7) might be addressed by a global *food-water trading scheme* that divides the world into agricultural exporters and importers based on their relative water availability (Falkenmark, 2013), provided that the huge social and institutional drawbacks of such trading schemes (see Section 3.7) are taken into account. Furthermore, *water labeling* of products—which shows their consumptive water use—can increase consumer awareness and stimulate informed decision-making whether or not to purchase high water demanding products on the consumer side (Antonelli & Greco, 2015). Although both trading schemes and water labeling might reduce the global pressure human society puts on available water resources, they do not include mechanisms to make informed trade-offs between green water use for agricultural or natural uses, due to their narrow focus on agricultural production.

4.3 | Water certification and licenses for land use systems

Some water legislation policies have moved toward the integration of green water. A much cited example is the Working for Water programme in South-Africa, administrated by the Ministry of Water Affairs and Forestry (current Department of

Environmental Affairs). The Working for Water Programme aims to eradicate high-water demanding invasive species and safeguard water resources accordingly. An invasive, fast-growing and high water demanding *Acacia* species that is native to Australia, has emphasized the substantial hydrological impact vegetation can have on the ecosystem. Accordingly, in South African Water Policy, *forest plantations* need to acquire licenses and pay water charges, as they are explicitly defined as stream-flow reduction activities (Van Noordwijk et al., 2014).

5 | CONCLUSION: WHAT DOES A SYSTEMIC UNDERSTANDING OF GREEN AND ATMOSPHERIC WATER MEAN FOR WATER GOVERNANCE?

The above sections have shown that there are no articles that focus explicitly on green and atmospheric water governance. It is logical that there are few policies and articles on this issue given the evolution of water governance, but that there is a growing need for a more systemic understanding of the water cycle. They have also revealed seven arguments why water governance should include green and atmospheric water resources. These arguments represent an initial framework for researching the implications of water governance relating to green and atmospheric water (see Figure 7). First, blue water is only a part of the available fresh water, as green water comprises a substantial part of terrestrial fresh water and is vital for agricultural production. Therefore, water governance should account for green water and develop rules and mechanisms for accessing and using this water resource. Second, conventional blue water governance only accounts for a subset of the hydrological cycle. As water particles continuously move between various interrelated states on varying spatial and temporal scales, governing efforts should account for the *water cycle continuity* (Falkenmark, 2001). Third, it becomes increasingly apparent how land-use influences green, blue, and atmospheric water availability and flows on various scales. Therefore, the process of terrestrial moisture recycling must be governed, which requires land and water governance in a common institutional framework (i.e., eco-hydrological management). Fourth, climate change will change transpiration, evaporation, and precipitation patterns which will influence both green and atmospheric water availability worldwide. This requires building climate resilient ecosystems and adaptive water policies. Fifth, different water resources are used and polluted differently by nature and society.

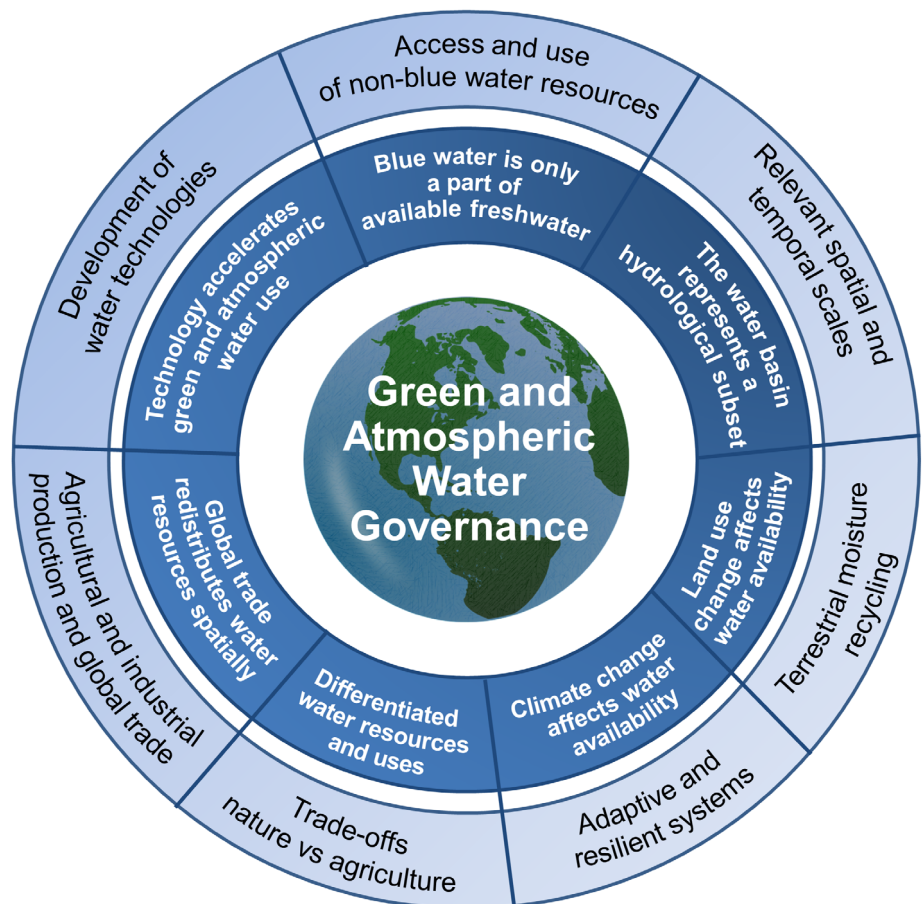


FIGURE 7 Arguments in favor of explicitly governing green and atmospheric water (inner ring) and the associated implications for water governance (outer ring)

Understanding the various uses is vital to make informed trade-offs and water allocation decisions, and prevent unexpected consequences of such water allocations. Sixth, the development of new water technologies might affect the hydrological cycle and result in atmospheric water grabbing. Further research is needed to better understand the climatological impact of these technologies. The development of such technologies should therefore also be governed. Finally, global trade infrastructure poses the risk of green water grabbing in the form of virtual water trade. Green water in agriculture and industrial production should therefore be recognized and accounted for. Existing attempts at governing green water are limited to PES schemes and water certificates for high water demanding land uses; attempts remain basically absent for atmospheric water.

The systemic nature of the water cycle that is inextricably linked to many components in nature (i.e., soils, vegetation, and climate) and society (i.e., politics, economy, and law) requires us to revisit how water governance is undertaken. To generate further knowledge on green and atmospheric water governance and develop effective solutions and institutions, the cross-sectional and systemic nature of the hydrological cycle requires an interdisciplinary approach to connect various disciplines in a “web of knowledge generation” (Liu, Bawa, et al., 2019). Water governance should move beyond the basin scale to include all colors of water, especially in the context of growing water scarcity in the Anthropocene. Proactive and preemptive governance is urgently needed before perceived and actual water shortage is used to “enclose” the waters—both visible and invisible in a neo-liberal context.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Sofie te Wierik: Conceptualization-equal; formal analysis-lead; methodology-lead; visualization-lead; writing-original draft-lead. **Joyeeta Gupta:** Conceptualization-lead; supervision-lead; writing-original draft-supporting; writing-review and editing-lead. **Erik Cammeraat:** Conceptualization-equal; supervision-equal; writing-review and editing-equal. **Yael Artzy-Randrup:** Conceptualization-equal; supervision-equal; visualization-supporting; writing-review and editing-equal.

ENDNOTE

¹ The nonproductive green water flow is sometimes also referred to as “white water” (Savenije, 2000; Van Noordwijk et al., 2014) although in this paper we use green water flow to refer to all upward vertical components of the hydrological cycle from the terrestrial surface (based on the initial definition by Falkenmark (1997)).

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