The Nile Basin waters and the West African rainforest: Rethinking the boundaries

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This focus article presents the state of the West African rainforest (WARF), its role in atmospheric moisture transport to the Nile Basin, and the potential impact of its deforestation on the Nile Basin’s water regime, as well as options for improving transboundary water governance. The Nile is the longest river in the world, but delivers less water per unit area than other major rivers. Pressures from the Basin’s rapidly growing population and agricultural demand risk exacerbating transboundary water conflicts. About 85% of the surface water reaching Aswan in Egypt originates from the Ethiopian Highlands which comprise less than 10% of the Nile Basin’s total area (3.3 million km²). Some of the atmospheric moisture reaching the Highlands crosses over the WARF; other moisture source areas include the Mediterranean Sea, the Indian Ocean, and the Atlantic Ocean. The WARF adds atmospheric moisture and modifies the regional climate system. Deforestation in the WARF has the potential to alter rainfall patterns over the Ethiopian Highlands and thus flows in the Nile River, with reductions a likely outcome. Transregional governance that looks beyond basin boundaries to the sources and routes of moisture transport (the precipitationshed) has yet to be integrated into land–atmosphere and water management negotiations. To better achieve sustainable land management and water resource development in the Nile Basin, scientific and governance frameworks need to be established that include the WARF region states in the ongoing negotiations between the Nile riparian states.

This article is categorized under:
Engineering Water > Planning Water
Human Water > Water Governance
Science of Water > Methods

KEYWORDS
deforestation, ethiopian highlands, moisture transport, transboundary, transregional

1 | INTRODUCTION

The Nile is the longest river in the world (6,700 km), and supplies water to more than 200 million people. The population is expected to grow to more than 550 million people by 2030 (NBI, 2012; Figure 1). The Basin covers 3.3 million km², extending from 4.5°S to 31°N and 24°E to 39°E. The Nile Basin comprises 11 riparian states: Burundi, the Democratic Republic of Congo (DRC), Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The Nile Basin delivers less...
water per unit area than other major rivers of the world (Mohamed, van den Hurk, Savenije, & Bastiaansen, 2005; Sutcliffe & Parks, 1999) and possesses a hydroclimate that is tremendously difficult to predict (Di Baldassarre et al., 2011). The high level of resource scarcity relative to demand contributes to international tensions regarding management of the Basin’s water.

Transboundary cooperation is based on traditional concepts for defining river basin area. Such a governance structure, however, may not be adequate to address current and future challenges to providing water security for the Nile Basin’s population. One shortcoming in the transboundary concept derives from excluding the source regions responsible for the production and transport of the moisture that becomes rainfall in the headwaters of the Basin—the precipitationshed. The precipitationshed is the geographical boundary of major source areas (both oceanic and terrestrial) for the atmospheric moisture that becomes precipitation (rainfall) in a given area (Keys et al., 2012). Management choices in the precipitationshed that influence rainfall reaching the Basin are simply not included in the traditional transboundary water management framework. This shortcoming is particularly acute for the Nile because the precipitation falling on just 10% of the River Basin area in the Ethiopian Highlands provides 85% of the freshwater reaching Aswan in Egypt (NBI, 2012).

Choices that influence land–atmosphere interactions in the precipitationshed (such as deforestation), however, have yet to find their way into the transboundary water management framework of the Nile Basin. This is not surprising, of course, given that awareness of the precipitationshed as a factor in regional governance is only just beginning to be recognized (Keys, Wang-Erlandsson, Gordon, Galaz, & Ebbesson, 2017). Some publications have explicitly insisted on the importance of considering moisture fluxes between land and atmosphere in regions where water scarcity is a concern, like the Nile Basin (e.g., van der Ent, Savenije, Schaeli, & Steele-Dunne, 2010). Knowledge about the role and long-range transport of atmospheric moisture in the region and the sources of this moisture has been accumulating in recent years; though many questions remain about their precise quantification (Keys, Barnes, van der Ent, & Gordon, 2014; van der Ent et al., 2010; Viste & Sorteberg, 2013a, 2013b).

The central point of this paper is that precipitation in key regions of the Nile Basin (the Ethiopian Highlands) is influenced by extra-basin processes which drive the production and transport of atmospheric moisture and thus the flow of the Nile. Of the extra-basin processes affecting rainfall dynamics in the Ethiopian Highlands, the state of the West African rainforest (WARF) is particularly important and can further be controlled by decisions about land (and water) management. Significant change in the integrity of the WARF due to ongoing deforestation could result in far-reaching consequences for Nile River flows due to changes in one or more of several mechanisms. We pay particular attention to the implications of change in the WARF with respect to the scarce and variable water resources of the Basin. We then move on to suggest a transregional framework for managing the scarce, highly variable water resources of the Nile Basin; as well as the moisture source and travel path that is threatened (i.e., the WARF as part of the precipitationshed).

2 | WATERS OF THE NILE BASIN: VARIABLE AND SCARCE

Annual rainfall in the Nile Basin is less than 100 mm in the arid and semiarid areas, while the humid areas receive more than 1,200 mm/year. The Equatorial Lakes region and the Ethiopian Highlands are the two major areas receiving high rainfall in
the Basin, 1,100 and 1,400 mm/year, respectively (NBI, 2012). The Equatorial Lakes region is the source of the White Nile. Nevertheless, much of the water from this region evaporates before reaching Egypt and Sudan. However, the Ethiopian High-lands deliver more than 85% of the Nile waters, as measured at Aswan, thus providing most of Ethiopia, South Sudan, Sudan and Egypt's freshwater supply (Sutcliffe & Parks, 1999).

The Nile discharge in Egypt is distinctly seasonal, stemming from the rainy season in the Ethiopian Highlands. The Ethiopian Highlands, representing just 10% of the Nile Basin area, produce $89 \times 10^9$ m$^3$ of annual discharge (70% of all flows in Ethiopia). These flows are concentrated in the three Nile tributaries: the Blue Nile, Sobat (joining the White Nile in South Sudan), and Atbara (NBI, 2012). The average specific discharge from the Blue Nile Basin is 82 mm/year, compared to the discharge from the whole Nile Basin, which is 26 mm/year (NBI, 2012; Sutcliffe & Parks, 1999). Approximately 75% of the annual discharge is concentrated in 4 months from July to October (Figure 1).

The spatial variability of actual evapotranspiration is strongly related to rainfall variability and vegetation cover. The Sudd swamp in South Sudan is the source of the highest amount of evapotranspiration, ca 2000 mm/year (Sutcliffe & Parks, 1999). Due to cooler temperatures, the Ethiopian Highlands have relatively less evapotranspiration compared to other areas in the Nile Basin. The mean annual evapotranspiration from the Blue Nile (originating from the Ethiopian Highlands) is 500 mm, while that of the White Nile is 700 mm (Senay, Asante, & Artan, 2009).

Mainly due to high evapotranspiration, the Nile River Basin is one of the most water-stressed regions of the world. The Nile's specific discharge in Egypt is 2% of the Amazon River's and 12% of the Congo River's. The basin's rapidly growing population will escalate water stress in the future, most likely exacerbated by climate change impacts (Di Baldassarre et al., 2011).

Rainfed agriculture accounts for 80% of total agricultural production in the Nile Basin, and is the predominant form of agriculture in the riparian countries upstream of Egypt and Sudan (Johnston, 2012). The availability of water will become an increasingly critical agricultural constraint as the population continues to grow (Figure 2) and climate change further complicates matters. Agricultural production is the key to fulfilling food security and nutrition needs for most of those living in the Basin where per capita incomes are some of the lowest in the world (Johnston, 2012). More water is needed to better satisfy food security and nutrition concerns. But per capita water availability is diminishing in the Basin (Figure 2), while the area under rainfed agriculture continues to increase.

3 MOISTURE SOURCES AND TRANSPORT TO THE ETHIOPIAN HIGHLANDS

The Intertropical Convergence Zone (ITCZ) is the low-pressure area circling the Earth near the equator which is responsible for bringing rainfall to the Ethiopian Highlands. The meeting of the trade winds from the Northern and Southern hemispheres
is responsible for bringing seasonal rainfall to the Ethiopian Highlands. The monsoonal patterns, coupled with the rugged topography, cause variability (drought, average, and wet years) in the summer rainfall in the Highlands (Viste & Sorteberg, 2013b). The variable summer rainfall supplies much of the growing season water demands for agriculture, making it a key factor for both agricultural production, as well as the Nile flows (Awulachew et al., 2007).

The ITCZ is fed by moisture transported from the East, West, and North (Viste & Sorteberg, 2013a; Figure 3). For the winds coming from the North across the Red Sea and the Arabian Peninsula, the Mediterranean is the main source of moisture. From the East, the Indian Ocean supplies the atmosphere with moisture, and from the west, the Atlantic is the main source. The atmospheric moisture transport routes originating from the Indian Ocean (partly) and from the Atlantic cross the WARF on their way to the Ethiopian Highlands (Viste & Sorteberg, 2013a).

The terrestrial tropical region which includes the WARF is situated along a major atmospheric moisture transport route to the highlands and is thus an important source of the moisture which ends up falling on the Ethiopian Highlands (Viste & Sorteberg, 2013a). As such, it fits the definition of the “precipitationshed” proposed by Keys et al. (2012), which consists of

**FIGURE 3** The Nile River Basin (outlined in blue), and the four major routes for atmospheric moisture transport to the Ethiopian highlands (“a” in red); indicated by blue-black arrows (Adapted from Viste and Sorteberg (2013a)). West African rainforest (“C” in red and the whole greenish area); the reddish-purple in “C” indicates the progressive deforestation (Forest cover and deforestation from Global Forest Watch, 2015). “B” in red indicates the Equatorial Lakes region, the source of the White Nile.
major areas contributing moisture, their transport paths and sink (precipitation) regions (Figure 3). In addition to the WARF, the precipitationshed of the Ethiopian Highlands consists of countries in the Mediterranean, Northern Africa, Eastern Africa, and the Arabian Peninsula (Figure 3). However, the WARF component of the precipitationshed is the most vulnerable to changes in land use (Malhi, Adu-Bredu, Asare, Lewis, & Mayaux, 2013). Major deforestation looms as a distinct possibility for the WARF. Such changes would alter terrestrial moisture and energy fluxes, which could then alter moisture source strength and transport routes to the Ethiopian Highlands. The importance of air masses moving over the WARF to the Ethiopian Highlands can be inferred indirectly from the fact that one of the most important characteristics of regional climate variation is change in the air-mass moving in from the Atlantic Ocean and then traveling across the WARF (Pokam, Djiotang, & Mkankam, 2012).

A number of studies have asked how large a fraction of the rainfall on the Ethiopian Highlands can accurately be attributed to the WARF (Ellison et al., 2017; Locatelli et al., 2015). Although much of that water has an oceanic origin, the WARF’s contribution to the atmospheric moisture is known to increase towards the latter part of the summer rains (Pokam et al., 2012). The duration and magnitude of these summer rains are critical for rainfed subsistence agriculture.

The WARF is not only a major terrestrial area along the routes bringing moisture to the Ethiopian Highlands, but also the area with the greatest potential for atmospheric moisture recycling. Indeed, the contribution of moisture by forests through evapotranspiration to advective winds is emphasized by an increasingly large number of studies (Ellison et al., 2017; Staal et al., 2018). Moisture that travels over forests produces almost twice the amount of rainfall as moisture traveling over non-forest areas, according to an analysis of satellite data in tropical regions (Spracklen, Arnold, & Taylor, 2012).

4 │ THE STATE AND ROLE OF THE WARF

The WARF region comprises about 13% of the total area of Africa. It stretches across the Democratic Republic of Congo (DRC), Gabon, Congo, Cameroon, the mainland of Equatorial Guinea and the Central African Republic (CAR). Sixty-one percent of the dense rainforest is located in the DRC (Figure 3). The WARF accounts for more than 30% of the global rainforest cover, second only to the Amazon rainforest. In addition to being the principal haven for 50% of global biodiversity and storing more than $250 \times 10^{12}$ kg of carbon, tropical rainforests are likewise sources of moisture for surrounding environments (Malhi et al., 2013). Between 1990 and 2010, net annual forest loss in the WARF was estimated at 0.7% year$^{-1}$ ($6.6 \times 10^{3}$ km$^2$/year) (Mayaux et al., 2013). Agricultural expansion, urbanization, mining, and logging are the main drivers of deforestation in the region (Akkermans, Thiery, & van Lipzig, 2014). However, overall forest loss in the Congo Basin, which is the heart of the WARF, is still as low as 0.17% year$^{-1}$. The rate of loss could be much greater in the future though, particularly given increases in human population, together with ongoing agricultural and urban expansion.

When rainforests are lost, the land is often transformed into woody patches, grasslands and agricultural landscapes. Recognizing the global importance of the WARF and the current rate of loss, efforts are being made to protect the forests; for instance, by the Congo Forest Fund, the Congo Basin Forest Partnership (CBFP), and the Central African Forest Commission (COMIFAC). These international, collaborative efforts, however, have thus far not produced the desired results, primarily due to lack of accessibility, lack of funding, limited scientific and management capacities, population growth, smuggling, illegal logging, and so on (Malhi et al., 2013; Mayaux et al., 2013).

Several studies describe the multiple roles of the WARF in the land–atmosphere moisture fluxes of the regional climate system. One of these roles is the addition of moisture to the trade winds (Pokam et al., 2012; Spracklen et al., 2012). A second role is the modification of the route of the Southeast trade winds to the East because of changes in roughness/friction (Bell, Tompkins, Bouka-Biona, & Sanda, 2015). A third role is the modification of moisture flux and rainfall patterns in the Sahel region (Mayaux et al., 2013).

Viste and Sorteberg (2013a) analyze the moisture contribution of different routes and find that the air masses crossing the WARF during summer rains carry 38% of the moisture reaching the Highlands. However, the air mass coming via the WARF accounts for 47% of the moisture release in the highlands, where percentage release indicates the net release out of the entire air mass coming to the Highlands that potentially becomes rainfall. More release of moisture by air masses crossing the WARF could be attributed to the longer continental travel of that specific air mass as compared to air masses from other routes (Figure 3). Deforestation is directly linked to a reduction in the upward moisture release, thereby directly affecting moisture release in the Ethiopian Highlands. While the possibility of reduced rainfall in the Ethiopian Highlands is potentially significant in its own right, not just the amount but also the pattern of rainfall affects water security. Rainfall-related variables, including timing, intensity, seasonality, and interannual fluctuation are affected by the climatic variables that land cover change influences. For instance, the addition of moisture by the WARF to the trade winds is more pronounced during the months between wet and dry seasons, thereby moderating the extreme seasonality of the rainfall (Pokam et al., 2012).
In addition to the direct impact of moisture reduction, other impacts associated with WARF deforestation could alter the regional patterns of atmospheric moisture transport. For instance, one modeling study demonstrates that deforestation in the Congo Rainforest will increase albedo and reduce evapotranspiration (Akkermans et al., 2014). Other studies also found that there is a linear relationship between albedo, surface roughness and evapotranspiration; where an increase in albedo is inversely related to surface roughness and evapotranspiration (Bell et al., 2015). The WARF’s impact on the Nile flows can thus be seen from different angles. This is a region at risk for major changes in land cover (deforestation), where changes in the WARF land cover will not be limited to affecting provision of moisture to the atmosphere but can also alter the whole process of atmospheric energy fluxes. This latter effect can influence regional air flows, with further repercussions for precipitation in the highlands, thus illustrating the multifaceted nature of teleconnections.

Compared to the WARF, more work has been done on assessing the consequences of deforestation for regional rainfall in the Amazon Basin (Drumond et al., 2014; Nobre, Sellers, & Shukla, 1991; Staal et al., 2018). The moisture release from the Amazon rainforest eventually becomes the main rainfall source for the southeastern part of South America. This moisture transport also fluctuates based on climatic influences (Drumond et al., 2014). Previous studies suggest that forests replaced by grassland reduce rainfall in the Amazonian region by as much as 25% (Nobre et al., 1991). Deforestation not only leads to significant losses of evapotranspiration, it also leads to significant increases in sensible heat and rising surface temperatures, soil moisture loss, degradation, and thus reduced soil infiltration.

The WARF, like the Amazon Rainforest, faces profound threats. If deforestation on the scale experienced in the Amazon were to occur in the WARF, it could lead to important changes in the amount and timing of atmospheric moisture transport to the Ethiopian Highlands. Compared to the situation in the Amazon, since the Nile Basin hydroclimate is highly variable and water scarce, even small changes in the WARF may have large impacts.

In general, the role of the WARF in moisture transport, and its subsequent downwind contribution to the Ethiopian Highlands, may boil down to three specific feedbacks (Akkermans et al., 2014; Bell et al., 2015; Pokam et al., 2012; Spracklen et al., 2012). To summarize, these are: the addition/loss of moisture to the winds traversing the WARF, the modification of albedo and surface roughness, and the resulting impact on atmospheric moisture transport patterns across the Sahel.

5 | COOPERATION WITHIN THE NILE BASIN

For centuries, the Nile Basin has been a hotbed of conflict as well as cooperation over water resources. The central issue in the history of cooperation and conflicts has been the right to water use and the equitable and reasonable distribution of available water without causing significant harm. The first modern agreement signed bilaterally in 1929 between Sudan and Egypt gave Egypt the right to veto future water development projects in the British colonies of that time (Kenya, Sudan, Tanganyika, and Uganda). The second, signed in 1959, again bilaterally between Egypt and Sudan, replaced the 1929 treaty and gave Sudan and Egypt exclusive rights over the Nile waters. In the second agreement, 75% (55.5 km³) of the Nile waters were allocated to Egypt and 25% (18.5 km³) to Sudan, with 10 km³ allocated for evaporation.

In the beginning of the 1990s, a framework development plan was initiated by the riparian countries. In 1999, this initiative was named the Nile Basin Initiative (NBI). After some 11 years of negotiation, six of the upstream riparian countries (Ethiopia, Rwanda Tanzania, Uganda, Kenya, and Burundi) independently and unilaterally signed a Cooperative Framework Agreement (CFA) in May of 2010 that provides a basin-wide framework within which the upstream riparian countries can gain access to the Nile waters.

In 2011, Ethiopia unilaterally announced plans for the construction of the Grand Ethiopian Renaissance Dam (GERD). The GERD is being constructed on the Blue Nile and will be the largest hydroelectric dam in Africa with installed capacity of 6,450 MW. While Egypt expresses concern over its future water flows, in particular during reservoir filling, other upstream riparian states are likewise contemplating construction of additional hydroelectric power stations. The GERD and other new water resource structures have led to new bi- and trilateral negotiations. For example, a trilateral declaration of principles on the Eastern Nile management, including the GERD, was signed between Egypt, Sudan and Ethiopia in March 2015. The search for a strategy that would fully reconcile the upstream riparian countries with Egypt and Sudan over the use of the Nile waters, however, continues to elude the parties to the NBI and the threat of conflict persists.

In general, at least 16 bi- and multilateral water agreements concerning the utilization of the Nile waters have been signed since the beginning of the 20th century (UNEP, 2013), with lengthy controversies preceding many of those agreements. Long-term mean river flow volumes are an explicit target of these agreements and conflicts, as well as of current negotiations on the development of Nile Basin water resources. However, the regional/global moisture transport and recycling that determine Basin rainfall, including rainfall on the Ethiopian Highlands are neglected in all these agreements and negotiations. Presumably because of this, these discussions have also not considered the potential for further deforestation of the WARF.
Discussions in the NBI, CFA and other bi- and multilateral negotiation frameworks have focused on ensuring and securing Nile flow quantities for the future. Given the demonstrated potential for brinkmanship and conflict within the conventionally defined Nile Basin, we think it a serious oversight that key issues concerning the future of atmospheric moisture flows in the precipitationshed of the Ethiopian Highlands and their impact on the Nile river flows as a whole are not considered in current decision-making frameworks. We emphasize in particular that many of the factors potentially impacting future Nile River flows lie beyond the control of the Nile Basin riparian countries. Principle among these is land resource management in the WARF and its potential to influence the amount and timing of precipitation in the Ethiopian Highlands, and thereby the flow of the Nile, as well as the livelihoods of over 40 million subsistence farmers in the highlands.

6 | BEYOND TRANSBOUNDARY COOPERATION TO TRANSREGIONAL

This article has sought to provide an overview of the importance of the WARF for Nile Basin flows, and with it, the need to secure collaboration on aspects of the water balance that lie outside traditional basin boundaries in order to ensure the rainfall and river flow for future livelihoods. There are in fact many other areas besides the WARF that lie outside the boundaries of the Nile Basin, but within the precipitationshed. Due to the importance of the WARF for precipitation in the Ethiopian Highlands, and thus the Nile flows in Sudan and Egypt, the specific emphasis in this paper has been on incorporating the WARF region into current and future negotiations between the Nile Basin riparian states. The threat of deforestation in the WARF and the implications for moisture travel to the Ethiopian Highlands places even greater pressure on the Nile riparian countries to support and provide a framework for transregional cooperation within the precipitationshed and the region(s) that influence the major land–atmospheric moisture fluxes. The development of transregional governance structures that explicitly recognize the importance of the precipitationshed for the discussions of Nile River flows would represent a key step in this direction.

Some studies have explored the complexities and potential paths for including the precipitationshed in governance (Ellison et al., 2017; Keys et al., 2017). Transregional cooperation frameworks for the Nile Basin could consider the amounts of atmospheric moisture contributed by the WARF, as well as mitigation of the regional eco-climatological impacts from deforestation on transpiration, albedo, winds and air temperature. The 11 Nile riparian countries would thus be well-advised to form a transregional collaboration framework together with the non-Basin sharing WARF countries (Cameroon, the Central African Republic, Congo, Equatorial Guinea, and Gabon), in order to collaborate on conservation of the WARF (i.e., a WARF–Nile Basin cooperation framework).

This study has focused on how land cover changes may impact the rainfall and availability of surface water in the Nile. However, another impact which also needs consideration is climate change. Climate change has been found to exacerbate the existing and already pronounced spatial and temporal variability of surface water in the Nile Basin (Siam & Eltahir, 2017). Another issue, this paper does not specifically address is the continuation of the hydrologic cycle beyond the Nile Basin. The hydrologic cycle does not end at the Nile Basin. The Nile Basin is itself a source of water for other regions. The endless cycling of water thus raises the fundamental question of water ownership over and over again. In order to concentrate on what the specific example of WARF deforestation means for the value of considering the precipitationshed in transboundary water management, we have had to leave many dimensions of this and other relevant issues for future studies.

Both scientific and governance frameworks are needed for the implementation of such transregional cooperation. Global and regional environmental cooperation initiatives can be used as entry points for scientific forums. These forums could take responsibility for producing recommendations that political processes then decide upon. In the Nile Basin, such future scientific work should further investigate deforestation, climate change and their influence on the three WARF impacts highlighted above—moisture addition, change in climate parameters like albedo and surface roughness, as well as the possibility for perturbing atmospheric circulation patterns. Furthermore, future management measures should be harmonized with progressive developments in the water resources of the Nile Basin. Allocation of specific contributions from the Nile Basin countries to support the integrity of the WARF will be one of the issues future research needs to resolve.

Political efforts could further explore existing forums like the Reduced Emissions from Deforestation and Forest Degradation (REDD+) framework, country level Nationally-Determined Contributions (NDC's) under the UNFCCC Paris Agreement, climate change mitigation and adaptation strategies, as well as different forest conservation programs. Taking part in and inducing transregional cooperation on regional land–atmosphere management could provide additional reciprocal support for these emerging frameworks. Transregional payment for ecosystem services is a special type of governance model that may be appropriate for the above mentioned international forums to work with.

To the best of our knowledge, all existing international transboundary arrangements are based entirely on the participation of countries within the surface water flow region and never consider the involvement of countries in the precipitationshed and areas providing moisture transport services. We suggest it is time to consider regional land (and water) management beyond conventional basin boundaries as the new basis for transboundary cooperation. WARF–NBI negotiations on the future of Nile Basin flows would be an excellent candidate for pioneering efforts in this direction.
CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

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How to cite this article: Gebrehiwot SG, Ellison D, Bewket W, Seleshi Y, Inogwabini B-J, Bishop K. The Nile Basin waters and the West African rainforest: Rethinking the boundaries. WIREs Water. 2019;6:e1317. https://doi.org/10.1002/wat2.1317