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Developing an Approach for Equitable and Reasonable Utilization of International Rivers: The Nile River

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Abstract: The absence of a basin-wide apportionment agreement on using the Nile River equitably has been a long-standing source of disagreement among Nile riparian states. This study introduces a new approach that the riparian states can consider that quantifies the Nile River's apportionment. The approach includes (1) developing a basin-wide database of indicators representative of the United Nations Watercourse Convention (UNWC) relevant factors and circumstances, (2) developing an ensemble of indicator weighting scenarios using various weighting methods, and (3) developing six water-sharing methods to obtain a range of apportionments for Egypt, Sudan, Ethiopia and the group of the White Nile Equatorial States for each weighting scenarios. The results illustrate a relatively narrow range of country-level water apportionments, even though some individual factor weights vary from 3% to 26%. Considering the entire Nile River, the water apportionment for Ethiopia ranges from 32% to 38%, Sudan and South Sudan from 25% to 33%, Egypt from 26% to 35%, and the Equatorial States from 5% to 7%. We trust that the six proposed equitable water-sharing methods may aid in fostering basin-wide negotiations toward a mutual agreement and address the dispute over water sharing.

Keywords: equitable water apportionment; UN water convention; Nile; international rivers; fuzzy analytical hierarchical process; equitable water sharing model

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1. Introduction

In recent decades, conflicts over the utilization of transboundary rivers have risen drastically [1], intensified by ever-increasing demands on dwindling supplies. Rapid population growth, food production, urbanization, pollution, losses and climate change are believed to be the predominant drivers globally [2,3]. Concurrently, the failure to ensure the equitable and reasonable utilization of international watercourses is a pressing challenge, often resulting in major disagreements between riparian countries [1,4–6]. A startling number of past and present disputes in many river basins have been recorded [7], leading to anticipated conflicts in as many as 108 countries, primarily in South and Southeast Asia, Africa, Eastern Europe and South America [8]. The tension becomes exponentially severe in locations where all-inclusive and legally binding watercourse agreements do not exist.

The Nile River basin represents a trouble spot where basin countries are currently mired in negotiations with no clear pathway forward. Based on bilateral treaties fashioned during the colonial era, Egypt and Sudan claim a full share of the Nile despite the entire river flow originating in upstream riparian countries. While more than 680 international freshwater treaties exist globally [9], the Nile River treaty is unique because it apportions all of the water to two non-flow contributing downstream states. Egypt is allocated 55.5 km^3y^{-1} (billion cubic meters per year), Sudan at 18.5 km^3y^{-1} and none to the eight upstream riparian states [10]. The remaining 10 km^3y^{-1} is reserved for evaporative losses. The upstream riparian states have consistently objected to the treaties signed without their consent by the colonial countries. Resolving these issues has led to the development of various institutions—most notably the Nile Basin Initiative to resolve equitable use disagreements and foster cooperation among the basin countries. However, breakthroughs on equitable water shares that involve all countries have remained elusive.

The dispute intensified in 2011 when Ethiopia began constructing the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River. Downstream countries considered the GERD a counter-hegemonic measure, and the disagreement escalated to a higher level [11]. Since then, Ethiopia, Sudan and Egypt have participated in negotiations on the filling and long-term operations of the GERD, but an agreement has not been reached. Although the major debate focuses on the GERD's impact on downstream water use, the challenge regarding downstream countries holding fast to water quotas established in the 1959 bilateral agreement remains central [12]. Meanwhile, Ethiopia has already started filling the reservoir, so Egypt calls for the international community to block Ethiopia's actions. In response, the United States withheld development aid to Ethiopia until an agreement with downstream countries was reached [13]. Undeterred, Ethiopia has continued the filling, and the reservoir is nearly at full capacity.

In the absence of a basin-wide water-sharing agreement, other upstream countries are also considering unilateral actions, including additional dam development, further heightening the situation [14]. A mutually acceptable pathway forward is desperately needed before the situation escalates to a severe regional conflict.

Past research has considered the application of water allocation models to evaluate water sharing, ranging from hydrologic assessments to incentive-based methods [15,16]. For example, Dinar and Nigatu [15] presented three water allocation alternatives, including water trades among the Nile countries, to illustrate benefit sharing. These allocations are based on (i) Egypt's long-term use, (ii) population and (iii) flow contribution by state. While laudable, this approach faces challenges. First, even though benefit sharing is a promising approach, Egypt will reject the proposed solution if it does not reflect its existing share. Second, their assumption that "Ethiopia respects the 1959 agreement" is misguided. Third, benefit distribution and water trade can be only feasible when a mutually agreeable water-sharing policy exists among states.

In a situation with zero upstream entitlements and colonial treaties in force, it is unclear which criteria each country will accept in considering benefit sharing and compensation. Therefore, given the dichotomy of maintaining the status quo versus equitable utilization, neither the reconstruction of water allocation approaches by Onencan and Van de Walle [17] nor the establishment of an equitable sharing plan has proven successful in the past three decades. It suggests the need for evaluating equitable water shares based on international law before addressing the impacts and benefit-sharing.

While research on the suitability of equitable and reasonable utilization exists [18], quantifying water quotas of Nile riparian countries has not been explicitly determined based on this principle. Therefore, the objective of this study is to use the principle of equitable and reasonable utilization to obtain water apportionments in the Nile River basin. This paper is a follow-up on Gari et al. [19], in which indicators that best describe reasonable and equitable principles under Article 6 of the United Nations Watercourse Convention (UNWC) were identified and evaluated for the Nile River. The information in Gari et al. [19] is employed to calculate a range of water allocations.

Amid the escalating crisis, this study gains significance by introducing a novel approach to address the persistent disputes over equitable water utilization in the Nile River basin. By quantifying Nile River apportionment through a comprehensive methodology, including basin-wide indicators, diverse weighting scenarios and proposed water-sharing methods, this research stands as a beacon for riparian states grappling with disagreements. The study's methodology offers a potential breakthrough, presenting a framework that aims to guide stakeholders toward a mutual agreement, ensuring the sustainable and equitable utilization of the Nile River's vital water resources. As tensions continue rising, this research provides meaningful insights and solutions to foster cooperation in the Nile River basin and beyond.

2. Provisions of the UNWC towards Equitable and Reasonable Water Utilization

The UNWC contains 37 Articles in seven parts (ILC-International Law Commission, 1994) [20]. Article 5 introduces the principle of equitable and reasonable utilization in which states are apportioned water shares based on facts and evidence. Factors to guide this apportionment are listed under Article 6, which states that the weight given to each factor is determined by its importance compared to other factors" (Article 6.3). The water allotments are subject to meeting all the vital human needs (Article 10) in the basin. Thus, the minimum apportionment of riparian states is expected to be at least the amount of water to prevent dehydration, reduce the risk of water-related diseases and provide for consumption, cooking and personal and domestic hygiene [21].

Allocation of water for other needs requires negotiation and cooperation among states to adhere to "no significant harm" (Article 7) and protection of the watershed and ecosystem (Article 20). This manuscript does not address the significant harm aspect because a strict definition for this does not exist in international law. However, the UN convention implicitly considers these aspects through factors Article 6(1) d and f. Yet, compliance with Articles 7 and 20 is not solely dependent on equitable apportionment. Rather, it is determined by a state's conduct in avoiding harm to others. An example is Uruguay and Argentina's pulp mills project dispute [22]. Even though the two countries share the Uruguay River, and a treaty protects their respective shares, Argentina made claims to the International Court of Justice about pollution from the pulp mills in Uruguay.

3. Study Area—The Nile River

The Nile River basin extends from a latitude of 4° S to 32° N and from a longitude of 23° E to 40° E. It encompasses 3.2 million km^2 across eleven riparian countries (Figure 1). The world's longest river originates from the Ethiopian Highlands and equatorial African lakes and flows north to the Mediterranean Sea, traversing nearly 6800 km. The climate varies from extreme aridity in Egypt and Sudan in the north to the tropical rainforests in Central and East Africa and some portions of Ethiopia. It is a home for more than 54% of the population in these countries residing within the basin [23].

The Nile that begins in Khartoum has four major tributaries: the Blue Nile, the Tekeze-Atbara, the Baro-Akobo and the White Nile. The six Equatorial States (Tanzania, Rwanda, Burundi, Democratic Republic of Congo, Uganda and Kenya) are in the White Nile basin, contributing 15% of the annual flow at Khartoum. The Ethiopian Highlands provide the remaining 85%, of which the Blue Nile supplies 60% of the flow, the Tekeze-Atbara 13%, and the Baro-Akobo Rivers 12% [24]. The downstream countries, Sudan and Egypt, do not add appreciable flow.

Egypt and Sudan depend heavily on the Nile. Egypt has the second-largest economy in Africa, with the Nile water being the main factor. Ninety-nine percent of the population in Egypt has electricity. As of 2022, hydroelectric energy from the Nile contributes approximately 45% to the country's total renewable energy capacity [25]. Eighty-five percent of the Nile water use also goes to food production through irrigation [26]. Consequently, in addition to ensuring food self-sufficiency, Egypt's annual agricultural exports exceeded 4.8 million tons [27]. Concurrently, the remaining upstream states only consume 3–4% of the Nile water, with most of their population severely vulnerable to famine and drought and lacking electricity and sanitation [23].

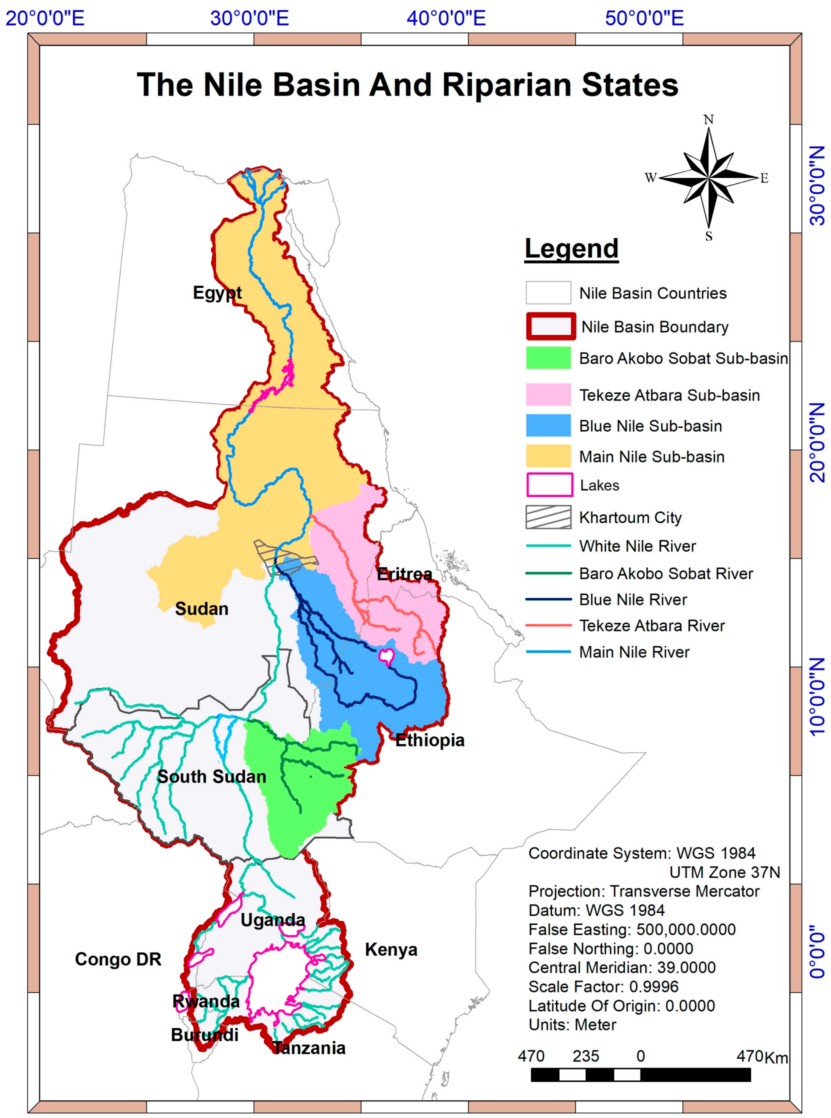


Figure 1. The Nile basin and its riparian countries with flow contribution from White Nile, Baro-Akobo, Blue Nile and Tekeze-Atbara. Note that for this analysis, all watershed outlets are located at the entrance of the Mediterranean Sea.

4. Methodology

4.1. Equitable Water-Sharing Model

An equitable water-sharing model was developed for the apportionment of water to riparian states in the Nile basin, according to the United Nations Watercourses Convention (UNWC). Our main emphasis is on the water sharing between Egypt, Sudan (North and South Sudan) and the remaining riparian countries in the White Nile Basin. To simplify the calculations, we group the riparian countries in the White Nile basin as one state. They are called the "Equatorial States". The resulting water-sharing model is similar to the legal assessment model concept applied to the Sirwan–Diyala transboundary river shared by Iran and Iraq [28] and the Jordan River basin [29].

The equitable sharing of water depends on many indicators. Based on the analysis of indicators by experts [19], seven factors, 25 subfactors and 65 indicators were introduced (Figure 2). As described in Appendix A, the seven factors in level I (depicted in Figure 2) represent the natural, socio-economic, population, effects of water use, existing use, conservation of uses and availability of alternative circumstances of the riparian countries. Twenty-five closely related subfactors at level II further defined the seven factors (Figure 2). These subfactors were specified earlier in Gari et al. [19]. More details about the subfactors are provided in Supplementary Materials Table S1. Under each subfactor, indicators (level III) were defined. We used 65 (56 highly and nine median important) indicators identified by Gari et al. [19]. According to their manuscript, these indicators could capture the Nile basin's unique features and accommodate the riparian states' conflicting interests. They are quantifiable for each riparian country in the various basin-wide databases, as described in more detail in Section 4.1.3. These indicator values were normalized before they could be used in the equitable sharing model. More detailed information on the subfactors and indicators is given in Appendix A from Tables A1–A9.

Not all indicators contribute equally to the water share of the countries in the four sub-basins. Article 6 of the UNWC indicates that assigning weights to each indicator, subfactor and factor is necessary. Indicators of greater importance receive greater weights to account for unequal importance. After assigning weights, they are normalized so that the Level I weight for each sub-basin adds up to one. Similarly, for each factor, the sum of the weights of its subfactors at level II adds up to one. Finally, indicator weights are normalized in the same way. After normalization, the water share can be computed by the multiplication of indicator values by its weight and then performing aggregation for sub-basins and riparian countries. The mathematical description is given below.

4.1.1. Computational Approach

The Equitable Water Sharing Model is run separately for the four sub-basins: Blue Nile, Baro-Akobo, Tekeze-Atbara and White Nile. Although physically, the sub-basins end at the location where the river enters the Nile, in the UNWC approach, each sub-basin ends in Alexandria, where the Nile enters the Mediterranean. Thus, for example, Egypt is included in the Blue Nile basin. As introduced before, note that all riparian equatorial White Nile countries are combined as the "White Nile Equatorial State". Sixty-five indicators are used to determine the water share for each country in each sub-basin.

The normalized water shares for each country C in sub-basin SB, $P^{SB}[SB, C]$, is obtained as the sum of the product of the normalized indicator value, $V^I[i, C, SB]$ and the normalized weight, $W[i]$ of the indicator, i describing the Nile basin.

$$P^{SB}[SB, C] = \sum_{i=1}^{65} \Big(W[i] \; V^I[i, C, SB] \Big) \tag{1}$$

The following nomenclature is used in this manuscript. The variables in the square brackets are the independent variables of the dependent variable. Lowercase letters for the independent parameters are used as indices; uppercase letters indicate that the dependent variable was evaluated for a specific independent parameter. The upper case represents the normalized value for the dependent variables, and the lower case represents the actual value. Thus, for example, $V^I[i, C, SB]$ is the normalized value of the ith indicator for country C in sub-basin SB.

Once the water share $P^{SB}[SB, C]$ was obtained for each country in the four sub-basins, the total volume of water share for a country $P^C[C]$ was calculated as the sum of the product of the country's share within a sub-basin and the total flow from the sub-basin, Q^{SB}.

$$P^C[C] = \frac{\sum_{sb}^{n} \left(P^{SB}[sb] Q^{SB} \right)}{Q^B} \tag{2}$$

where n is the number of sub-basins in the country, Q^B is the sum of all river flows from the four sub-basins and Q^{SB} is flow from each sub-basin. For example, based on the definition of the sub-basins above, Egypt and Sudan have four sub-basins (i.e., n = 4).

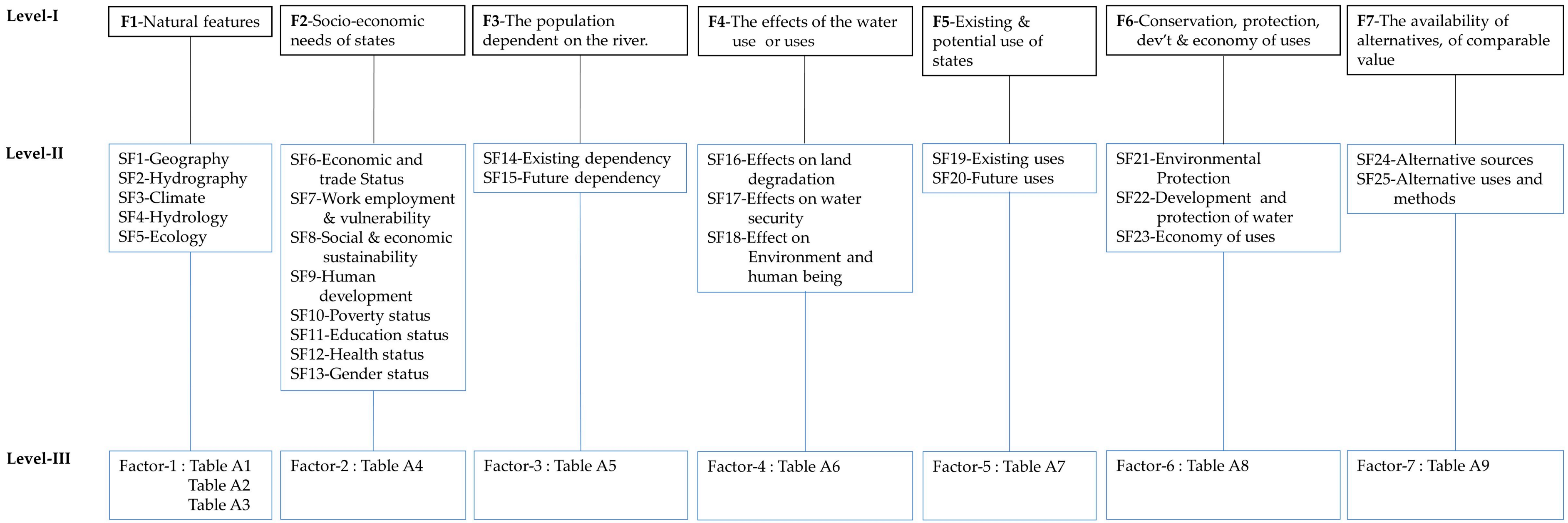


Figure 2. The hierarchical structure illustrates the seven factors (F1 to F7), 25 subfactors (SF1 to SF25) and the 65 indicators in the United Nations Watercourse Convention (UNWC). The indicators are listed in Tables A1–A9 in Appendix A.

The normalization of the actual indicator values $v^I[I, C, SB]$ is achieved by dividing the actual indicator value of a particular indicator I in country C and sub-basin SB by the sum of the actual indicator values in all countries in a sub-basin. Two cases are considered. The first case is when increasing values of the not normalized specific indicators, $v^I[I, C, SB]$, result in a greater share of the water, the normalized value is calculated as follows:

$$V^I[I, C, SB] = \frac{v^I[I, C, SB]}{\sum_{c=1}^{n} v^I[I, c, SB]} \quad (3)$$

where $v^I[I, C, SB]$ is the specific value for an indicator I in a specific country C in a sub-basin SB, and $\sum_{c=1}^{n} v^I[I, c,\ SB]$ is the sum of the actual values of the indicator I in countries in a particular basin SB. The second case is for other indicators (such as total greenhouse gas emission in each country), which for increasing value have an adverse impact and decrease the share of the water. In this instance, we take the reciprocal to obtain the normalized value:

$$V^I[I, C, SB] = \frac{\sum_{c=1}^{n} v^I[I, c, SB]}{v^I[I, c, SB]} \quad (4)$$

In almost all cases, the indicator values for a country are independent of the sub-basin. One of the exceptions is the river length.

4.1.2. The Three Weighting Functions

The weighting was accomplished using three techniques: fuzzy analytical hierarchical process (FAHP), equal weighting, and sequential ranking.

FAHP. The FAHP method provides the best weights given the wide range of professional experience and knowledge in determining the conventional ranking methods [30]. The FAHP approach [31] calculates the weight, $W^Y_{FAPH}[Y]$, as:

$$W^Y_{fahp}[Y] = \frac{w^Y[Y]}{\sum_{i=1}^{n} w^Y[y]} \quad (5)$$

where the subscript indicates the weighting type used, and the superscript Y is a placeholder that is changed depending on what level the FAHP is applied. For level I, Y is a factor (F); for level II, Y is a subfactor (SF); and for level III, Y is an indicator (I). W^Y[Y] is the normalized weight of factors, subfactors or indicators. And, $w^Y[Y]$ is the actual de-fuzzified crisp numeric value.

Equal weighting. The equal weighting method assigns a given weight uniformly and can be simply expressed as:

$$W^Y_{ew}[Y] = \frac{1}{n} \quad (6)$$

where n is the number of factors for level I. Thus, the weights for each of the seven factors (level I) were 1/7 or 0.143%. For level II, n is the number of subfactors under each factor; for level III, n is the number of indicators under a subfactor.

Sequential ranking. For sequential ranking, the factors, subfactors or indicators are sequentially ranked from 1 to n according to their increasing importance. The normalized weights were computed as follows:

$$W^Y_{sr}[Y] = \frac{r^Y[Y]}{\sum_{y=1}^{n} r^Y[y]} \quad (7)$$

where $W^Y[Y]$ is the weight of factor Y, $r^Y[Y]$ is its rank assigned and $\sum_{y=1}^{n} r^Y[y]$ is the sum of the ranks. For example, for the seven factors at level I, $\sum R = 1 + 2 + 3 + 4 + 5 + 6 + 7 = 28$.

4.1.3. Implementation

Basin-Wide Indicators Database

The basin-wide database of the UNWC's 65 quantifiable indicators of the Nile River basin and riparian states identified earlier by Gari et al. [19] was developed, collecting the values of indicators for each riparian country from different global data sources. The primary sources were the Nile Basin Initiative documents, World Bank data portal, UNDP data portal, African Development Bank documents, Food and Agriculture Organization, International Water Management Institute and Google Earth engine data. The collected data for the riparian countries and their sources are described are provided in Tables A1–A9 in the Appendix A. Because of the difficulty of compiling indicator data for South Sudan, we lumped the data for both North and South Sudan.

Table A1 describes indicator values of Nile Basin countries' proportional sub-basin areas of the riparian countries in the Nile Basin and each country's administrative boundaries. Table A2 lists the values for flow contributions, river length and aridity index for the riparian country. Environmental flow requirements and some indices related to drought, resilience and environmental performance indicators are described in Table A3. Socio-economic indicators are described in Tables A4 and A5. They show more indicators of population dependency on the Nile water. Indicators about the current and future water use for conservation and protection needs and the availability of alternative uses and methods are described in Tables A6–A9. Note that country apportionment was quantified at the sub-basin level.

Survey Development and Distribution

The expert judgment on the relative importance of UNWC factors and subfactors was determined by Gari et al. [18] with a pairwise comparison questionnaire designed and distributed to 200 professionals globally via email. The questionnaire was designed to allow experts to compare factors and subfactors from their professional perspectives only. The questionnaires were distributed to experts in the Nile basin countries (Ethiopia [10], Sudan and South Sudan [10], Egypt [10], the six Equatorial States [10]) and internationally (China, India, Jordan, Iran, the United States, Canada, Brazil, Mexico, Belgium, Germany, the Netherlands and Italy) [29]. Professionals were drawn from the fields of water science, environmental science, law, socioeconomics and political science. The comparison of indicators used a Likert scale ranging from 1 (equally important) to 9 (extremely more critical).

4.2. Application of Weighting Methods

In Equation (1), the indicator weights, $W[I]$, which are independent of the sub-basin and the country, can be calculated as the product of normalized weights of the factors, $W^F[F]$ at level I, subfactors, $W^{SF}[SF]$ at level II and indicators $W^I[I]$ at level III (Figures 2 and 3).

$$W[I] = W^F[F]\, W^{SF}[SF]\, W^I[I] \tag{8}$$

where the specific factor and subfactors for each of the 65 indicators can be found using Figure 2 and the appendices

The weight $W[I]$ can be obtained using any weighting function in Equations (5)–(7). In practice, using all three weighting functions at the three levels (resulting in 27 combinations of weights) is too complex. Therefore, for the Nile basin, selected weight functions are used at each level, as shown in Figure 3.

All three weighting factors (i.e., $W^F_{fahp}[F]$, $W^F_{ew}[F]$ and $W^F_{sr}[F]$) were employed at level I (Figure 3). These produce 44 potential weighting scenarios for each factor: 42 from all combinations of sequential ranking, one from FAHP and one from equal weighting. All these 44 scenarios had different weight values of $W^F[F]$. To reduce computational complexity, only the FAHP and equal weighting (i.e., $W^{SF}_{fahp}[SF]$, $W^{SF}_{ew}[SF]$ were employed at level II. The combination of levels I and II resulted in 88 scenarios. Finally, the equal weight method (i.e., $W^I_{ew}[I]$) was used with the indicator values at level III.

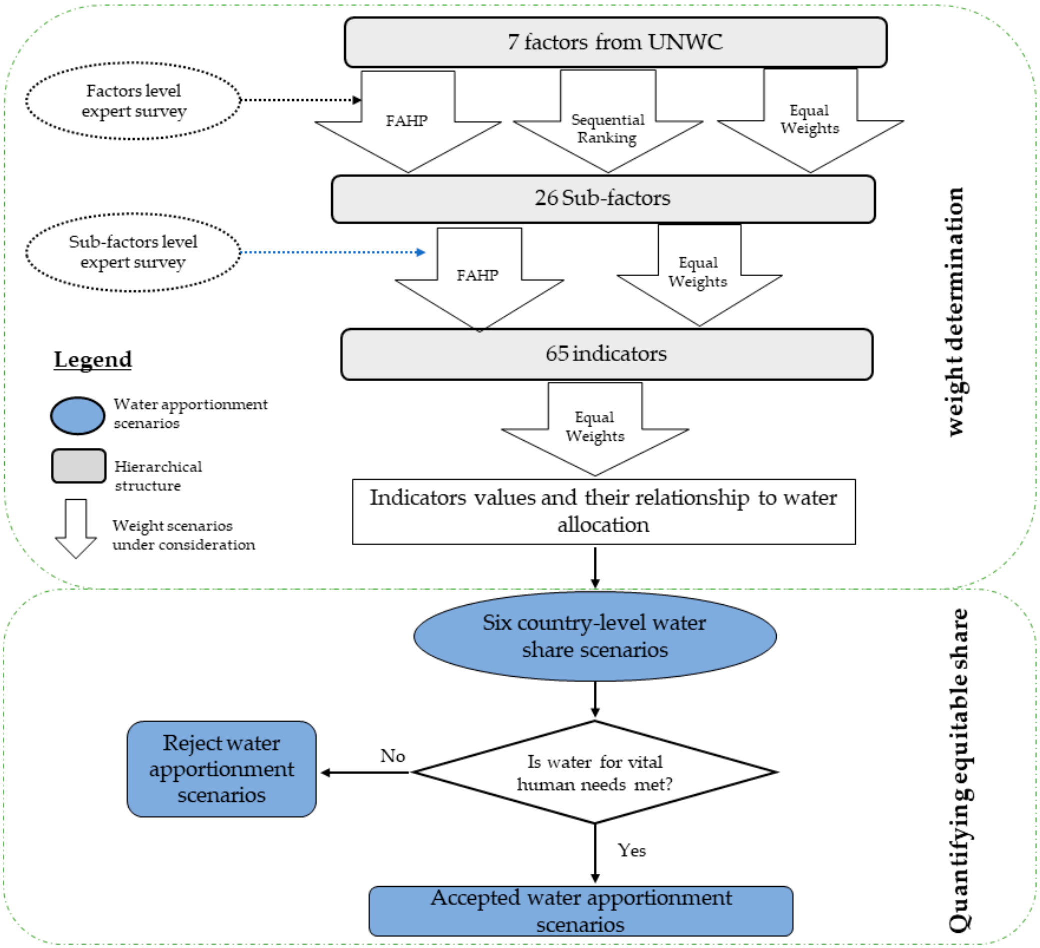


Figure 3. Weighting methods at factor, subfactor and indicator levels (**top**) and UNWC Article 10 (water for vital human need) validation (**bottom**).

To implement the intent of Article 10 of the UNWC, weighting scenarios that do not meet full water allocation for vital human needs were rejected. The full weighting method process is illustrated in Figure 3, including the process for Article 10 validation.

5. Results

This section presents survey outcomes, weights of factors, subfactors, indicators and sub-basin level apportionment ranges for Egypt, Sudan, Ethiopia and the White Nile Equatorial States.

5.1. Survey

From a total of 200 targeted experts, one incomplete and 160 complete responses to the pairwise comparison of factors that make up the equitable water share used in the FAHP method were received from experts in water resources (#39), environmental science (#39), socio-economics (#36), law (#30) and political science (#17) (Table A10). The responses were widely distributed across all ranking categories, indicating a broad and scattered set of responses (Table 1, Figure 4). Most environmental and water experts responded similarly and ranked F1 and F2 as the highest priority (i.e., highest FAHP weight) and F7 as the lowest priority (i.e., lowest FAHP weight); other experts prioritized F4 and F2 and similarly ranked F6 and F7 as low (Table 1). Various experts considered F3, F4 and F5 intermediate priority factors.

Table 1. Ranking of factors (F) by experts based on their priority, with 1 being the highest priority and 7 being the least priority. The factors F1–F7 are defined in Figure 4 and Appendix A.

	Ranking						
Experts	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Water resources	F1	F5	F4	F2	F3	F6	F7
Environmental science	F1	F5	F4	F2	F6	F3	F7
Socio-economics	F4	F2	F1	F3	F5	F6	F7
Law	F4	F2	F1	F3	F5	F7	F6
Political science	F4	F1	F2	F3	F5	F6	F7

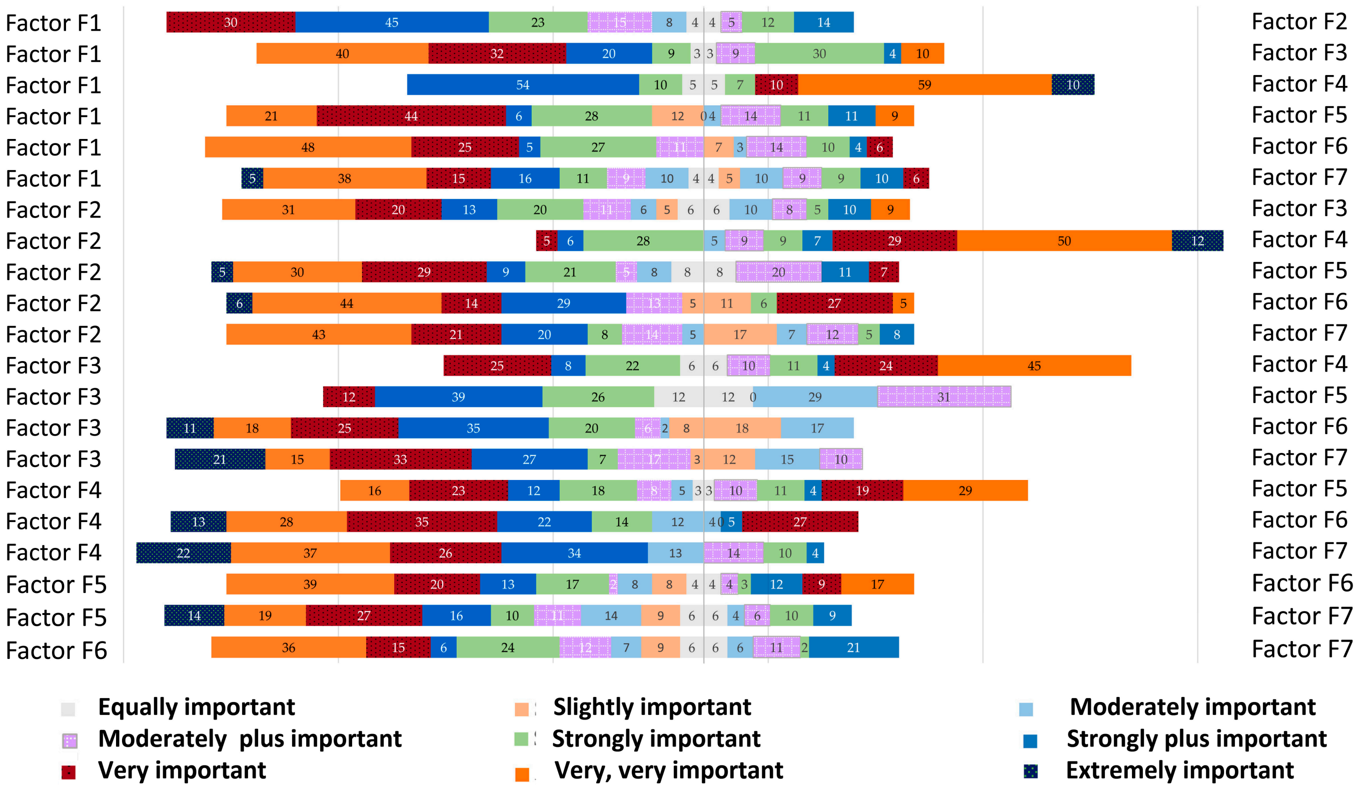


Figure 4. A summary of factor pairwise comparisons from 160 experts who responded to the survey (n = 161). The number in each bar is the number of experts with that opinion. Factor #1 (F1) is natural features; factor #2 (F2) is socio-economic needs of water states; factor #3 (F3) is the population dependent on the watercourse; factor #4 (F4) is the effect of water uses on other states; factor #5 (F5) is existing and potential uses of the watercourse; factor #6 (F6) is conservation, protection, development and economy of water uses and the costs; factor #7 (F7) is the availability of alternatives water uses and comparable values. A more detailed description of the factors is given in Appendix A (Section S1 and Table A11).

In determining the water allotment to a county with the FAHP method, the weight of F4 (i.e., the effect of water withdrawal on another country) was highest at 25.6% (Table 2). Natural features (F1, weight 24.9%), socio-economic needs (F2, weight 15.6%) and existing and potential water uses (F5, weight 10.6%) were the next in importance in determining the size of the water allocation with the FAHP method (Table 2). Population-dependent watercourses (F3) and the conservation, protection, development and economy of water uses (F6) factors were considered of minor importance for allocating water. The availability of alternatives (F7) was less important. The equal weight and the sequential ranking methods did not discriminate between factors (Table 2).

Table 2. UNWC factor and subfactor weights (%) for the FAHP (Equation (5)), equal weighting (Equation (6)) methods and sequential ranking (Equation (7)). The subfactor normalized weights are computed by the FAHP (Equation (5)) and equal weight method (Equation (6)). The bold numbers are the normalized weight of the factors in % and the regular numbers are the normalized weight of the subfactors in %. For sequential ranking, the normalized weights are the minimum and maximum values t in %. Refer to Figure 2, Appendix A and Table A11 for the descriptions of factors and subfactors.

Level I Factors	Level II Subfactors	FAHP $W^F_{fahp}, W^{SF}_{fahp}$	Equal Weighting $W^F_{ew}, W^{SF}_{ew},$	Seq. Ranking W^F_{sr}
F1		**24.9**	**14.3**	**3.57–25**
	SF1	8.7	20	
	SF2	5.6	20	
	SF3	30.8	20	
	SF4	30.8	20	
	SF5	24	20	
F2		**15.6**	**14.3**	**3.57–25**
	SF6	15.2	12.5	
	SF7	8.1	12.5	
	SF8	24.9	12.5	
	SF9	7.2	12.5	
	SF10	16.6	12.5	
	SF11	8.3	12.5	
	SF12	15.7	12.5	
	SF13	4.1	12.5	
F3		**11.2**	**14.3**	**3.57–25**
	SF14	50	50	
	SF15	50	50	
F4		**25.6**	**14.4**	**3.57–25**
	SF16	35	33.3	
	SF17	47.8	33.3	
	SF18	17.2	33.3	
F5		**10.6**	**14.3**	**3.57–25**
	SF19	50	50	
	SF20	50	50	
F6		**8.2**	**14.3**	**3.57–25**
	SF21	33.7	33.3	
	SF22	49.8	33.3	
	SF23	16.5	33.3	
F7		**3.9**	**14.3**	**3.57–25**
	SF24	50	50	
	SF25	50	50	

5.2. Factors, Subfactors and Indicator Weights

5.2.1. Factors and Subfactor Weights

The FAHP weighting approach yielded the highest weight for F5 (effect of water use on another state) and F1 (natural features) (Table 2). F7 (availability of alternative and comparable values) was assigned the lowest weight (Table 2). For sequential ranking (Equation (7)), 42 unique rank combinations were obtained, and these ranks were converted into weight values as tabulated in Table S2 of the Supplementary Materials. The weighting values vary from 3.6% as the minimum to 25% as the maximum value (Table 2). The sequential ranking method rendered various weights compared to the FAHP and equal weighting approaches (Figure A1). It did not favor one factor over the other, similar to the equal weighting method. While the FAHP and equal weighting approaches have unique weighting values, the sequential ranking method results in a set of weighting values (42 in our case).

5.2.2. Indicator Weights

The calculated normalized indicator weights with Equation (8), $W[I]$, for 88 weighting scenarios (as specified in Section 4.2 and Figure 3), are listed in Tables S3 and S4 and Figure 5. The normalized factor weights in bold (for FAHP, equal weighting and sequential ranking) from Table 2 and the product of the factor and the subfactor weight (in italics) are also shown in the tables. Table S3 uses the equal weight method for the subfactor weights, and Table S4 uses the FAHP weighting method.

As expected, the normalized weight of the indicators that make up Factor F4 (i.e., fertile soil loss, volumetric reliability index, and water quality index) has the greatest weight (up to 12%) when the FAPH weight is used for the factors and subfactors. Factor F1 also has a large weight in water allocation, but since there are 11 indicators under this factor, the individual normalized indicators have normalized weights between 1 and 4%.

5.3. Sub-Basin and Country-Level Apportionment Ranges

The water apportionment (using Equations (1), (3) and (4)) for Egypt, Sudan, Ethiopia and the White Nile Equatorial States in the four sub-basins in the Nile basin are listed in Table 3 using the six weighting schemes defined in Section 4.2 and Figure 3. The way these water appointments are calculated is illustrated for the Blue Nile (Table S5), Tekeze-Atbara (Table S6), Baro-Akobo (Table S7) and the White Nile (Table S8) sub-basins using the FAHP weights for the factors and equal weights for the subfactors and indicators. In Tables S5–S8, the indicator values, v^I, and their sources are listed in Tables A1–A8. The water share for each country in a sub-basin, P^{SB}, is calculated by first normalizing the indicator values, V^I, using Equations (3) and (4). The product of V^I and indicator weight, W^I (listed in Tables S3 and S4), is the water apportionment for a country in the sub-basin for each indicator. Figure 6 illustrates the water shares for the Blue Nile sub-basin for Egypt and Ethiopia (Table S5). It demonstrates again that F4 and F1, when the expert advice is taken into account in the FAHP method, are the most influential in determining the water share a country receives. Interestingly, the soil degradation indicator represented by the "fertile soil loss" under F4 makes up 8% of the water share in Ethiopia, while none in Sudan and Egypt. Similarly, annual surface water contribution under Factor F1 contributes 2.5% in Ethiopia, while none in Sudan and Egypt. The water share indicators representing the geographical factors, such as river length basin area in each country, are larger for Egypt than the other two countries.

By summing all water apportionment for the individual indicators (Equation (1)), the water share for each country per sub-basin, P^{SB}, for all the 88 weighting scenarios was calculated for the Blue Nile basin (Table S9), the Baro-Sobat basin (Table S10), the Tekeze-Atbara basin (Table S11) and the White Nile (Table S12). A summary is given in Table 3. The water allocations among the 88 scenarios were surprisingly small. When averaged over the scenarios, Ethiopia's share of the Blue Nile, Tekeze-Atbara and Baro-Sobat was slightly over 40% (Table 3). Egypt's share was approximately 30%, and both Sudans' was approximately 28% for the three basins (Table 3). Ethiopia does not share in the White Nile water. The Equatorial States's only water share was from the White Nile, with an allotment of approximately 38%. Egypt's share of the White Nile was slightly less than 30%, and both Sudans were allotted somewhat more than 30%.

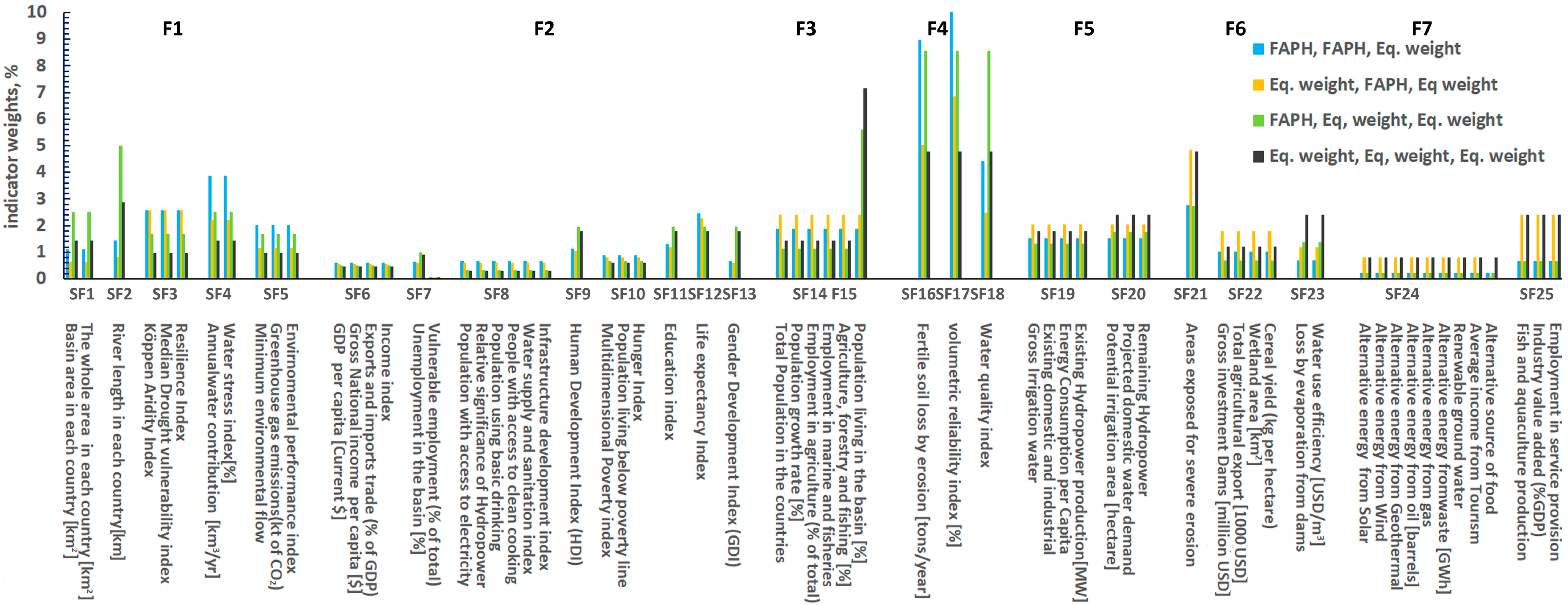


Figure 5. Weights of the individual indicators in percent for four weighting scenarios consisting of combinations of the fuzzy analytical hierarchical process (FAPH) and equal weights (Eq. weight). In the legend, the first entry is the weighting method for the factor, the second is for the subfactor, and the last is the weighting of the indicators. All weights, including sequential weighting, are listed in Supplementary Materials Tables S3 and S4. Note that the outlet of the Blue Nile basin is in Alexandria in Egypt, and includes Sudan and Egypt. The full names of the factors are given in Appendix A, Section S1; the names of the subfactors are listed in Table A11; the names and the units of each indicator are provided in Table A11 as well.

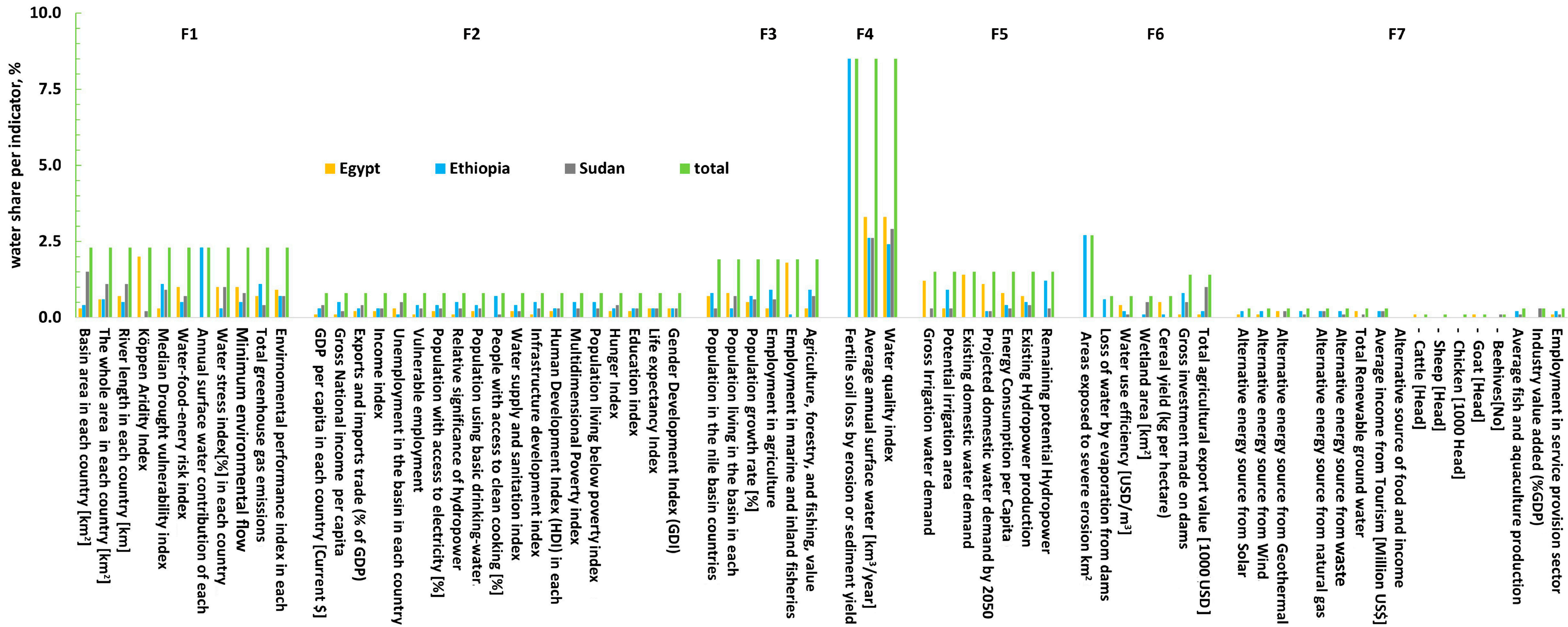


Figure 6. Example of the percentage of the water share of the total share of the 65 indicators in the Blue Nile basin for Egypt, Ethiopia and Sudan and the total with weights determined with the FAHP method at the factor level I and equal weights method at the subfactor level II and indicator level III. The water shares for the other basins and weight ratios are presented in Tables S5–S9 in the Supplementary Materials. Note that the outlet of the Blue Nile basin is in Alexandria in Egypt and includes Sudan and Egypt. The full names of the factors are given in Appendix A, Section S1; the names of the subfactors are listed in Table A11; the names and the units of each indicator are provided in Table A11 as well.

Table 3. Summary of sub-basin level apportionments in percent of total flow per sub-basin for Ethiopia, Sudan, Egypt and the White Nile Equatorial States for the six weighting scenarios as shown in Figure 3. As sequential ranking has 42 combinations of weights, the minimum and maximum apportionment percentages are given.

Weighting Type Factor-Subfactor-Indicator	# of Scenarios	Apportionment Blue Nile			Apportionment Tekeze-Atbara		
		Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt
FAHP-FAHP-Eq.W.	1	43.5	26.3	30.2	41.8	27.5	30.7
FAHP-Eq. W-Eq.W.	1	41.5	29.1	29.4	39.6	29.9	30.5
Seq. rank.-Eq.W.-Eq.W.	42	38.7–43.7	26.4–32.3	26.4–33.3	35.3–42.2	28.7–33.1	26.5–34.0
Seq. rank.-FAHP-Eq.W.	42	39.8–45.1	23.9–29.7	26.3–34.7	36.6–43.8	26.0–30.5	26.5–35.3
Eq.W.-FAHP-Eq.W.	1	42.9	27.1	30	41.1	28.4	30.5
Eq.W.-Eq.W-Eq.W.	1	41.3	29.5	29.2	39.5	30.8	29.7
Weighting type Factor-Subfactor-Indicator	**# of Scenarios**	**Apportionment Baro-Sobat**			**Apportionment White Nile**		
		Ethiopia	**Both Sudans**	**Egypt**	**Equa. States**	**Both Sudans**	**Egypt**
FAHP-FAHP-Eq.W.	1	42.5	26.4	31.2	37.2	32.2	30.6
FAHP-Eq. W-Eq.W.	1	40.2	28.4	31.4	36.2	34.7	29.0
Seq. rank.-Eq.W.- Eq.W.	42	37.4–43.3	26.3–31.9	27.8–34.4	35.4–41.6	30.5–34.4	25.3–32.2
Seq. rank.-FAHP-Eq.W.	42	38.4–44.3	24.6–30.2	27.3–35.5	35.2–42.2	28.3–32.6	25.5–34.5
Eq.W.-FAHP-Eq.W.	1	41.8	27.0	31.2	39.8	30.4	29.8
Eq.W.-Eq.W-Eq.W.	1	40.5	28.7	30.8	39.1	32.3	28.4

6. Discussion

6.1. Evaluating Weighting Methods and Indicator Value in a Data-Scarce Environment

A novel method based on the United Nations Watercourse Convention (UNWC) was developed to quantify the Nile River's apportionment among riparian states utilizing 65 indicators. The indicator values were determined using global databases and some locally available data. The factor, subfactor and indicator weights were found using three weighting methods. The weights in the FAHP method were found by analyzing a survey by professionals within and outside the basin. The other two weighting methods were purely mechanical and did not involve expert judgment. The question arises as to whether the indicator values and weights are so uncertain that the results are meaningless in the data-scarce environment and complex Nile basin.

The precision of the weighting methods can be checked with the water shares calculated in Table 3 since the same indicator values are used in the calculations, and only the weights are varied. Table 3 shows that the apportionment for the countries in the four basins between the expert-dominated weighting (i.e., using FAPH weights at the factor level I and subfactor level II and equal weights at the indicator level III) and the purely mechanical weighting (i.e., equal weights at all three levels), in we find that the maximum difference in water share is 3.3% for Sudan in the Tekeze-Atbara basin. The mechanical weighting method calculates a water share of 30.8 (last line), while the expert method comes up with a share of 27.5% (first data line). A similar difference between the two methods can be found for Sudan in the Blue Nile Basin. Thus, the weighting method introduces a maximum difference of 11% in the apportionment.

However, any error in the indicator value directly affects the water share. Therefore, one can imagine that when this method, based on the United Nations Watercourse Convention (UNWC), is used as a tool under actual conditions, the indicator values for each country can be negotiated.

Sequential ranking produces ensembles of weighting scenarios that give different water shares among the riparian countries. As an illustration, the factor weights for Scenarios 48, 43 and 79 (as specified in Tables S9–S12) using the sequential ranking are shown in Figure 7. High weights for F1 (representing the natural and physical features of the basin) in Scenarios 79 and 43 increase the water share of Egypt and Sudan because large portions of the basins are in these two countries. High weights for F4, F5 and F6, as in Scenario 48, give greater water share for the upstream countries where the water originates, with severe soil degradation. Tables S9–S12, where the water shares in the basin are calculated, confirm these observations.

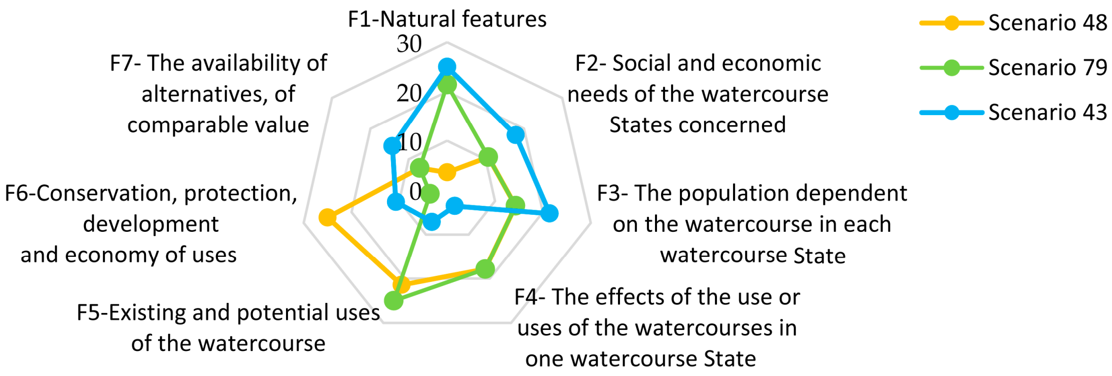


Figure 7. Illustration of factor weights for three scenarios that use sequential weights. The scenarios are listed in Tables S9–S12, and the factors are detailed in Appendix A, Section S1.

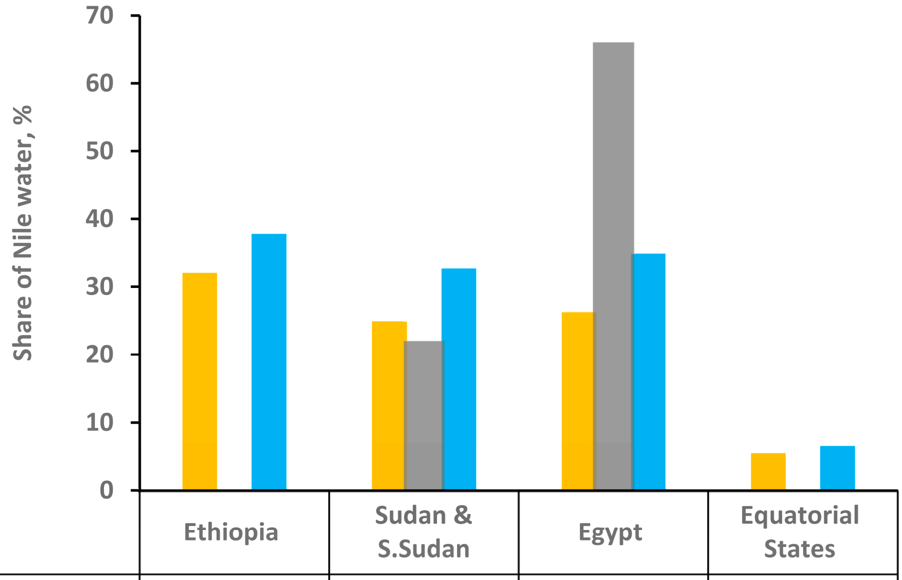
6.2. Sharing the Nile Water

Using Equation (2), the aggregated water apportionment to Ethiopia, Sudan, South Sudan, Egypt and the Equatorial States in Figure 8 is calculated from the data in Table 3. According to these calculations, the share of Ethiopia ranges from 32 to 38%, Sudan from 25 to 33%, Egypt from 26 to 35%, and the White Nile Equatorial States from 5 to 7%. These water shares deviated from those set up during the colonial times when Egypt was allotted 66% of the Nile flow, Sudan 22% and none to the other riparian states [10]. The calculated water share using the UN Watercourse Convention for Sudan is close to that assigned earlier. However, the water share for Egypt is halved compared with historical bilateral treaties due to the inclusion of all riparian basin states. While the current status quo on water sharing reflects the bilateral treaties during colonial times, the calculated water shares in Figure 8 are in agreement with the upstream countries' right to water (Article 10 of the UNWC) and the principle of equitable and reasonable utilization agreed in the declaration of principles [32,33]. Note that we do not advocate that the water shares be implemented. Still, it could be used as a justification for the payment of ecological services by Egypt to the upstream riparian countries.

These apportionments also satisfy the water requirement for vital human needs and environmental flow as stipulated in Article 10 of the UNWC (Figure 9) based on mean annual flows at the national borders of each sub-basin (NBI Report, 2017 [34]).

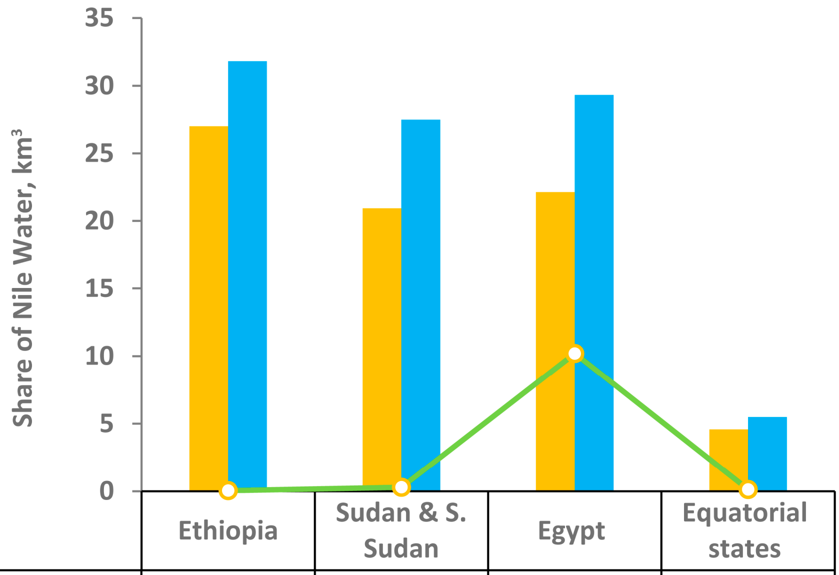
6.3. Limitations and Way Forward

Although the water-sharing model and outcomes illustrate a quantifiable method to include Articles 5, 6 and 10 of the UNWC, some limitations remain. First, due to challenges in conducting surveys, the FAHP analysis was conducted with a limited number of responses. Second, to reduce computational complexity, not every weighting scenario was considered. Third, indicator values were compiled without evaluating their consistency across databases. Finally, a follow-on study may be warranted to assess additional scenarios according to provisions of Articles 7 (significant harm) and 20 (protection and preservation of ecosystems).



	Ethiopia	Sudan & S.Sudan	Egypt	Equatorial States
UNWC min share, %	32.0	24.9	26.3	5.5
UNWC max share, %	37.8	32.7	34.9	6.5
1959 Bil. Agreem, %	0.0	22.0	66.1	0.0

Figure 8. Maximum and minimum share of the Nile water of 88 weighting scenarios for Ethiopia, South Sudan and Sudan, Egypt and the White Nile riparian countries (Equatorial States). The share according to the 1959 Bilateral Agreements is also shown. The shares for the countries and the sub-basin level are shown in Tables S9–S12 in the Supplementary Materials comparison of weighted scenarios versus colonial share (Abdalla, [8]) for the entire Nile River.



	Ethiopia	Sudan & S. Sudan	Egypt	Equatorial states
Min equitable share, km^3	27.0	20.9	22.1	4.6
Max equitable share, km^3	31.8	27.5	29.3	5.5
Municipal & industrial demand, km^3	0.05	0.29	10.2	0.13

Figure 9. Comparison of domestic water demand and equitable water share in km^3 (mean annual flows of Blue Nile = 49 km^3, Tekeze-Atbara = 10.6 km^3, Baro-Akobo = 12 km^3 and White Nile = 13.5 km^3 [34]).

7. Conclusions

The absence of an inclusive water-sharing agreement between Nile riparian countries hampers individual and cooperative efforts addressing multiple transboundary challenges, including intensifying food insecurity [35,36], energy insecurity [37,38]) and environmental degradation [39–43]. If the current situation persists, the basic need to provide sufficient food across the basin may be at risk as the population is expected to exceed one billion by 2050 [44].

This study develops an approach to quantify water apportionment based on the equitable and reasonable utilization principle stated in the UNWC by engaging multidisciplinary experts. Integrating quantifiable factors drawn from Articles 5, 6 and 10 of the UNWC, three-factor weighting approaches are evaluated, with country-level apportionments varying by approximately 10% between weighting methods. Applying the ensemble of weighting approaches to a water-sharing model produces estimated country-level aggregated equitable water shares to Ethiopia (32–38%), Sudan and South Sudan (25–33%), Egypt (26–35%) and the Equatorial States (5–7%). None of the scenarios were found to violate Article 10 of the UNWC—the requirement to meet the vital human needs of countries. The differences in water shares are attributable to a few key indicators, providing prospects for cooperative strategies resulting in upstream and downstream benefits. The quantified water-sharing scenarios could be used to frame and facilitate ongoing negotiations and work toward resolving disputes in the basin. Country-level apportionments can also be paired with cooperation modalities, drawing on examples from the Danube, Senegal, Orange and Mekong basins, including joint development projects, direct or virtual water trade, arrangement of compensation for damages, water-saving strategies, data sharing, etc. [45,46].

A relatively modest number of experts were surveyed in this study; factor weights may change as additional experts are surveyed and may alter the apportionment ranges. However, such potential shifts were predominantly captured through the sequential ranking approach.

The models and approaches proposed here apply to other river basins, with consideration of unique characteristics. Beyond quantifying apportionments to facilitate equitable water sharing, the outcomes of this model and approach can inform basin-wide water management operations from regulatory perspectives, development of agreements and cooperation policies, and limitations of legal instruments. Extending the approach proposed here to account for "significant harm" (Article 7) and "protection and preservation of ecosystems" (Article 20) is warranted.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15244312/s1, Table S1: The UNWC factors and list of indicators adopted from Gari et al. [19]; Table S2: Factor weight using sequential ranking method; Table S3: Weight scenarios in which factors were weighted by the FAHP and equal and sequential ranking method, and subfactor and indicator weights were distributed equally; Table S4: Weight scenarios in which factors were weighted by the FAHP and equal and sequential ranking method, and the subfactors were weighted using FAHP; Table S5: A sample calculation of riparian states' water apportionment from the Blue Nile sub-basin in which factors are weighted by the FAHP and subfactors weight was distributed equally; Table S6: A sample calculation of riparian states' water apportionment from the Tekeze-Atbara sub-basin in which factors are weighted by the FAHP and subfactors weight was distributed equally; Table S7: A sample calculation of riparian states water apportionment from the Baro-Akobo-Sobat sub-basin in which factors are weighted by the FAHP and subfactors weight was distributed equally; Table S8: A sample calculation of riparian states' water apportionment from the White Nile sub-basin in which factors are weighted by the FAHP and subfactor weight was distributed equally; Table S9: A summary of Blue Nile sub-basin water entitlement scenarios and Outputs; Table S10: A summary of Baro-Akobo-Sobat sub-basin water entitlement scenarios and Outputs; Table S11: A summary of Tekeze-Atbara sub-basin water entitlement scenarios and outputs; Table S12: A summary of White Nile sub-basin water entitlement weight scenarios and outputs.

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Data Availability Statement: Data is contained within the article.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Section S1: Description of the Factors

Factors earlier defined by Gari et al. [19] are described first. It is followed by tables showing indicator values in the Nile basin countries: Ethiopia, Egypt, Sudan and the Equatorial States. The Equatorial States data consider all information together for countries of Kenya, Tanzania, Uganda and Congo. In these tables, information for Sudan was recorded as either as Sudan or both Sudans. This is because of the difficulty of compiling indicator data for South Sudan from different sources. Therefore, we compiled them as Sudan, for example, to use indicators for the Blue Nile and Tekeze-Atbara basins and both Sudan for the White Nile and Baro-Akobo sub-basins.

Factor F1—Natural features

This factor includes geographic, hydrographic, hydrological, climatic, ecological and other related features of the basin. In addition to its focus on natural features, it contains human-induced influences on the natural system and resources. F1 is represented through 11 indicators: basin area, river length, aridity index, annual water contribution, drought vulnerability index, resilience index, sustainable development goal water stress index and environmental flow. Furthermore, indicators representing greenhouse gas emissions and environmental pollution are included to characterize anthropogenic activities related to industrialization, urbanization, deforestation and other factors. The indicator values are listed in Tables A1–A3.

Factor F2—Social and economic needs of states

This factor emphasizes economic, social, health, education status and human welfare development. A set of 19 indicators is adopted to represent the varying socio-economic contexts within the basin. Its values are listed in Table A4.

Factor F3—The population dependent on the watercourse

The concept of dependency on international rivers refers to the extent to which people in the riparian states rely on a shared water source for food, drinking water, energy, livelihood, etc. Factor 3 includes indicators representing dependency ratio, total population size, population growth rate and employment in agriculture and fisheries. The indicator values are shown in Table A5.

Factor F4—The effects of the use of the watercourses by one state on other states

This factor represents the potential impacts of one country on another from quality and quantity perspectives. These effects can be realized downstream (e.g., reduced flow of water [18,47] and upstream (e.g., limiting development [48]). Three indicators are adopted to reflect this dynamic: soil erosion, volumetric reliability and water quality index. The indicator values are in Table A6.

Factor F5—Existing and potential uses of the watercourse

This factor refers to basin countries' need to abstract water from the river for domestic, irrigation, hydropower and other uses now and into the future, and is represented by indicators focused on existing and potential water demands for irrigation, municipal and industrial, hydropower and energy consumption per capita. The indicator values can be found in Table A7.

Factor F6—Conservation, protection, development and economy of use of the water resources of the watercourse and the costs of measures taken to that effect

This factor considers the role and effort that individual basin countries play in the protection of the watershed, ecology, efficient water utilization, reduction of water loss and the costs and benefits of water resource projects. These aspects are represented by seven indicators: area exposed for severe soil erosion, water loss by evaporation, water use efficiency, wetland areas, agricultural yield, investments made on dams and agricultural export value. See Table A8 for the indicator values.

Factor F7—The availability of alternatives of comparable value to a particular planned or existing use

This factor emphasizes the exploration of alternatives to existing or proposed drinking water, food, energy and economic generating projects (Table A9). To represent Factor 7, 12 indicators were selected, including alternative energy sources from wind, solar, geothermal, oil and gas and waste recycling to water, food and income from renewable and non-renewable groundwater resources, tourism income, livestock resources, fish and aquatic production, employment in the service sector and contribution of industry to GDP (Table A9).

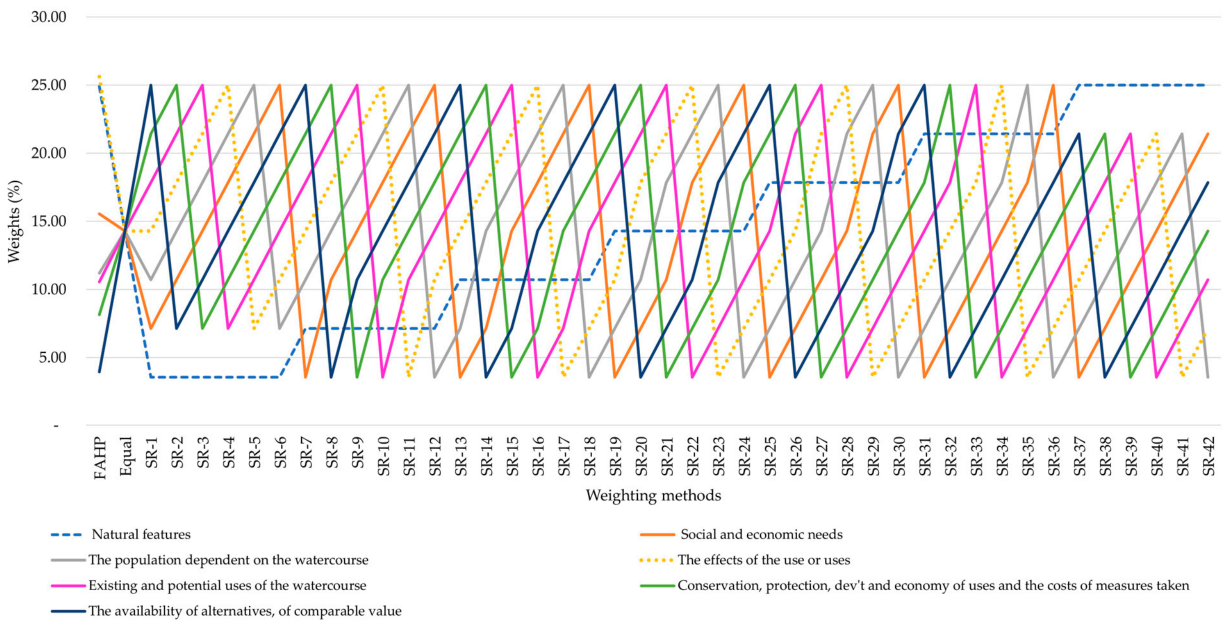

Figure A1. Factor weight pathways through three different weighting techniques (where SR is represents sequential ranking method scenarios).

Table A1. Total areas and areas in the Nile basin of the riparian countries.

Nile Basin Country	Countries Total Area (1000 km^2)	Area in the Nile Basin (1000 km^2)	Area in the Nile Basin (% of Total Basin Area)	Area in the Country (% of Total Country Area)
Egypt	997	302	9.5	30.3
Eritrea	122	26	0.8	21.1
Ethiopia	1144	365	11	31.9
South Sudan	644	621	19.5	97.7
Sudan	1864	1396	43.9	75.0
Burundi	28	14	0.4	49.4
DR Congo	2345	22	0.7	0.9
Kenya	593	51	1.6	8.7
Rwanda	26	21	0.6	84.0
Tanzania	945	119	3.7	12.7
Uganda	241	240	7.6	99.5
Total	**8950**	**3177**	**100**	

Note: (Source: NBI Water Resources Atlas [23]).

Table A2. Flow contribution, river length and aridity index of Nile basin countries.

Watercourse Countries	Nile Basin System											
	Blue Nile Sub-System			White Nile Sub-System			Baro-Akobo Sub-System			Tekeze-Atbara Sub-System		
	River Len. (km)	Aridity Index	Inflow (km^3)	River Len. (km)	Aridity Index	Inflow (k m^3)	River Len. (km)	Aridity Index	Inflow (k m^3)	River Len. (km)	Aridity Index	Inflow (k m^3)
	a	b	c	a	b	c	a	b	c	a	b	c
Egypt	1747	0.5	-	1747	0.5	-	1747	0.5	-	1747	0.5	-
Ethiopia	1321	20.0	53	-	-	-	838	21.0	12.43	1146	12.9	13.7
Both Sudans	2827	4.26	-	3657	10.4	-	1428	10.4	-	2307	4.3	-
Equatorial states	-	-	-	969	20.5	31.3	-	-	-	-	-	-

Notes: Source: a—measured from the shape file, b—calculated by the Koppen aridity formula (precipitation/temperature + 33) presented in the Supplementary Materials, c—"baseline on water demand and supply" NBI Report [34].

Table A3. Environmental flow and indices of Nile basin countries.

Natural Feature Indicators	Egypt	Ethiopia	Sudan	South Sudan	Equatorial States
Drought vulnerability index [1]	0.20	0.72	0.61	0.61	0.65
Resilience index [2]	1.51	2.94	2.06	2.06	2.76
SDG water stress (%) [3]	117	32	119	61	10
Environmental flow (mcm/year) [4]	2093	652	1678	1678	292
Total greenhouse gas emissions (kt of CO_2 equivalent) [5]	295,500	185,292	491,982	491,982	197,599
Environmental performance index [6]	43.30	34.40	34.8.49	34.49	33.10

Notes: (Source: [1,2] Calculation presented in the Supplementary Materials, [3] [49], [4] IWMI global environmental flow calculator (i.e., the environmental flow rate at the border of states was distributed to all four tributaries based on their water contribution), [5] The World Bank data portal: https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE accessed on 11 October 2021 and [6] Wendling et al. [50] environmental performance index: https://epi.yale.edu/downloads accessed on 20 December 2021 and Srebotnjak et al. [51].

Table A4. Socio-economic profile of Nile basin countries.

Socio-Economic Indicators	Egypt	Ethiopia *	Sudan	South Sudan	Equatorial States
GDP per capita [current USD] [1]	3020	857	781	634	887
Gross national income per capita [USD] [2]	11,350	2140	4430	2885	2183
Exports and imports trade (% of GDP) [3]	48.3	31.2	22.6	38.4	46.3
Income index [4]	0.71	0.44	0.56	0.48	0.42
Unemployment [%] [5]	10.8	2.1	16.5	14.4	2.2
Vulnerable employment (% of total) [6]	21	86	50	67	75
Population with access to electricity [%] [7]	100	45	60	44	36

Table A4. *Cont.*

Socio-Economic Indicators	Egypt	Ethiopia *	Sudan	South Sudan	Equatorial States
Relative significance of hydropower [%] [8]	12	95	49	49	67
Population using basic drinking water [%] [9]	99	41	60	51	54
People with access to clean cooking [%] [10]	98	4	41	21	4
Water supply and sanitation index [11]	98	40	67	56	58
Infrastructure development index [12]	88	10	17	11	18
Human development index (HDI) [%] [13]	0.70	0.47	0.51	0.46	0.51
Multidimensional poverty index [14]	0.02	0.49	0.28	0.43	0.30
Popul. below income poverty line [%] [15]	1.3	27.3	14.9	28.8	55.2
Hunger Index [16]	14.6	28.9	32.8	32.8	28.4
Education index [17]	0.61	0.34	0.34	0.32	0.48
Life expectancy index [18]	71.66	65.86	64.6	60.99	63.19
Gender development index (GDI) [%] [19]	0.88	0.84	0.84	0.84	0.92

Notes: Source: [1,2,3,5,6,7,9,10,18] World Bank data portal: https://data.worldbank.org/indicator/, accessed on 11 October 2021 [4,13,14,15,17,19] UNDP data portal: http://hdr.undp.org/en/data, accessed on 30 September 2021 [11,12] African Development Bank: http://infrastructureafrica.opendataforafrica.org/pbuerhd/africa-infrastructure-development-index-aidi-2020, accessed on 12 September 2021 [16] Klaus et al. [52] "Global hunger index: the challenge of hunger and climate change", [8] [53]. * for the Tekeze-Atbara sub-system the score of Ethiopia and Eritrea was lumped.

Table A5. Indicators that demonstrate dependency of riparian countries.

Indicators for Watercourse States Population Dependency	Egypt	Ethiopia	Sudan	Both Sudan	Equatorial States
Population in the Nile basin countries [in millions] [1]	100	112	43	54	266
Population living in the basin [%] [2]	94	38	87	93	50
Population growth rate [%] [3]	2.0	2.6	2.4	1.5	3.0
Employment in agriculture (% of total employment) [4]	24	66	40	48	68
Employment in marine and fisheries in thousands employed [5]	796	23.4	17.4	20.9	114
Agriculture, forestry, and fishing, value added (% of GDP) [6]	11	34	28	20	26

Notes: (Source: [1,3,4,6] World Bank data portal: https://data.worldbank.org/indicator/, accessed on 11 October 2021, [2] NBI [23], [5] De Graaf and Garibaldi [54] The value of African Fishery from FAO, Barange [55], fisheries and aquaculture statistics from FAO and http://www.fao.org/fishery/facp/SDN/en accessed on 14 September 2021).

Table A6. Indicators implying the effect of water use.

The Effects of the Use or Uses of the Watercourses on Another Watercourse State	Egypt	Ethiopia	Sudan	Both Sudan	Equatorial States
Fertile soil loss by erosion [million ton/year] [1]	0.00	140.0 *	0.00	0.87	0.47
Average annual volumetric reliability index [%] [2]	0.80	1.00	1.00	1.00	1.00
Water quality index [3]	78	55	67	67	63

Notes: (Source: [1] ENTRO Sediment tool and [56]: * the soil loss varies by sub-basin in million tons/year: Blue Nile = 140, Baro-Akobo = 14.6, White Nile = 1.5 and Tekeze-Atbara = 145.37), [2] calculation is presented in the Supplementary Materials, [3] [51]).

Table A7. Indicators that represent the current and future water use of watercourse.

Indicators for Existing and Potential Uses of the Watercourse	Egypt	Ethiopia	Sudan	Both Sudans	Equatorial States
Current net irrigation water demand in each basin country [km^3/year.] [1]	57.1	2.0	13.3	13.3	0.79
Projected irrigation water demand by 2050 in each basin country [km^3/year.] [2]	80.5	22.2	25.5	30.4	3.1
Potential irrigation area in each basin country [million ha] [3,*]	4.4	2.7	2.5	4.0	9.9
Existing domestic and industrial water use in each basin country [km^3/year] [4]	10.2	0.0	0.3	0.3	0.1
Projected domestic water demand by 2050 in each basin country [km^3/year] [5]	13.1	2.4	2.9	3.1	11.4
Energy consumption per capita (kg of oil equivalent per capita) [6]	913	493	342	342	410
Existing hydropower production in the basin in each country [MW] [7]	2862	1070	1592	1592	713
Potential hydropower generation in the basin in each country [MW] [8]	2902	17,355	4873	7443	5364

Notes: (Source: [1,2,4,5,7] NBI Technical Note III [34], [3] Frenken, K. and Gillet, V [57], [6] African Development Bank data portal: http://infrastructureafrica.opendataforafrica.org/kjxrpbg/afdb-socio-economic-database-1960%E2%80%932016 accessed on 12 September 2021, [7,8] NBI Comprehensive Basin Wide Study of Power Development Options and Trade Opportunities [34] and chapter 6 of the State of the River Nile Basin (2012) report). *: Out of potential irrigable land, currently Egypt irrigated = 3,600,000 hectares (ha), Ethiopia = 134,000 ha, Sudan = 1,765,000 ha, South Sudan = 500 ha, Equatorial States = 99,600 ha).

Table A8. Indicators that represent the conservation and protection needs of the Nile water system.

Indicators of Conservation, Protection, Development and Economy of Uses and the Costs of Measures Taken	Egypt	Ethiopia	Sudan	Both Sudan	Equatorial States
Areas exposed to severe soil erosion in each country at a rate of over 80 ton/ha/year [1000 km^2] [1]	0	39.3	0	0	16.9
Water loss by evaporation from dams in each basin country [km^3/year] [2]	12.6	0.2	4.6	4.6	0.0
Water use efficiency [USD/m^3] [3]	3.8	1.9	1.6	1.6	11.6
Wetland area [km^2] [4]	4	28	108	690	126
Agricultural (cereal) yield (ton/ha) [5]	72	22	6	6	16
Gross investment made on dams [billion USD] [6]	1.00	7.84	4.38	4.38	0.88
Total agricultural export value [million USD] [7]	4056	2374	552	552	878

Notes: (Source: [1] Borrelli, et al. [58], [2] [34] "Baseline and projected future water demand and use", [3] FAO report (2018), [4] [22], [5,7] African Development Bank data portal: http://infrastructureafrica.opendataforafrica.org/kjxrpbg/afdb-socio-economic-database-1960-2016 accessed on 12 September 2021, [6] Project cost of all dams along with data source is presented in Supplementary Material).

Table A9. Indicators that demonstrate the availability of alternative use and methods in the Nile basin.

Indicators for Availability of Alternative Uses and Comparable Values	Egypt	Ethiopia	Sudan	Both Sudans	Equatorial States
Alternative energy from solar (both PV and CSP) [TWh/year] [1]	58,823	50,113	165,239	165,239	27,573
Alternative energy from wind [TWh/year] [2]	36,601	14,838	61,661	61,661	7320
Alternative energy from geothermal [MW] [3]	-	10,000	-	-	-
Alternative energy from oil [proved oil reserves in billion barrels] [4]	3.33	-	1.50	5.00	-
Alternative energy from natural gas [proved reserves trillion m^3] [5]	1.8	-	-	49,326	12,261

Table A9. *Cont.*

Indicators for Availability of Alternative Uses and Comparable Values	**Egypt**	**Ethiopia**	**Sudan**	**Both Sudans**	**Equatorial States**
Alternative energy from waste recycling via incineration method [GWh] [6]	287,088	49,946	107,020	107,020	37,087
Total renewable groundwater resource [km^3/year] [7]	1.5	20.0	3.0	7.0	83.0
Total non-renewable groundwater resource [km^3] [8]	6000	-	40	40	-
Average tourism income [million USD] [9]	6900	1010	1029	527	902
Alternative source of food and income from livestock resource					
-Cattle [1000 head] [10]	5064	60,927	30,734	21,285	10,481
-Sheep [1000 head] [11]	5698	31,837	40,574	29,198	5044
-Chicken [1,000,000 head] [12]	156	59	48	31.65	25
-Goat [1000 head] [13]	4351	30,719	31,444	22,504	11,158
-Beehives [1000 no] [14]	877	6140	76	76	983
Average fish and aquaculture production [1000 metric ton/year] [15]	732	12	38	37	139
Industry value added (% GDP), including construction industry [16]	35	27	2	11	22
Employment in service provision sector [% of total employment] [17]	49	22	42	38	22

Notes: (Source: [1,2] [59], [3] Kebede [60], [4,5] U.S. Energy Information Administration (2017) and British Petroleum [61], [6] Mwangomo [62] and Scarlat et al. [63], [7] [49], [8] Table 3: Data on the non-renewable resources [64], [9,15–17] World Bank data portal: https://data.worldbank.org/indicator/ accessed on 11 October 2021, [10–14] FAO (2019): http://www.fao.org/faostat/en/?#data accessed on 14 September 2021).

Table A10. Target (a) and actual (b) survey response.

Country	**Continent**	**Target Survey**	**Experts Profession**										**Total Collected Responses**
			Water Science		**Environmental Science**		**Socioeconomics**		**Law**		**Political Science**		
			a	**b**	**a**	**b**	**a**	**b**	**a**	**b**	**a**	**b**	
Egypt	Africa	10	2	2	2	2	2	2	2	2	2	0	8
Ethiopia	Africa	10	2	2	2	2	2	2	2	2	2	2	10
Eq. states	Africa	10	2	2	2	2	2	2	2	2	2	1	9
Sudans	Africa	10	2	2	2	2	2	2	2	2	2	1	9
Belgium	Europe	10	2	2	2	2	2	2	2	1	2	1	8
England	Europe	10	2	2	2	2	2	2	2	1	2	1	8
Italy	Europe	10	2	2	2	2	2	2	2	2	2	1	9
Netherlands	Europe	10	2	2	2	2	2	2	2	2	2	1	9
China	Asia	10	2	2	2	2	2	2	2	2	2	1	9
Jordan	Asia	10	2	2	2	2	2	2	2	1	2	1	8
India	Asia	10	2	2	2	2	2	2	2	1	2	1	8
Iran	Asia	10	2	2	2	2	2	2	2	2	2	1	9
USA	N. America	20	4	4	4	4	4	4	4	3	4	2	17
Canada	N. America	20	4	4	4	3	4	3	4	3	4	1	14
Brazil	S. America	20	4	4	4	4	4	3	4	2	4	1	14
Argentina	S. America	20	4	3	4	4	4	2	4	2	4	1	12
Total		**200**	**40**	**39**	**40**	**39**	**40**	**36**	**40**	**30**	**40**	**17**	**161**

Table A11. The UNWC Factors and list of indicators adopted from Gari et al. (2020) [19].

Code	**Relevant Factors**	**Sub-factors**	**Indicators**	**Relationship**
F1	Natural features			
SF1		Geography	Basin area in each country [km^2]	Direct
			The whole area in each country [km^2]	Direct
SF2		Hydrography	River length in each country [km]	Direct
SF3		Climate conditions	Köppen Aridity Index in each country	Reverse
			Median Drought vulnerability index	Direct
			Water-food-energy risk index or [Resilience Index]	Reverse

Table A11. *Cont.*

Code	Relevant Factors	Sub-factors	Indicators	Relationship
SF4		Hydrology	Annual surface water contribution of each country [km^3/year]	Direct
			Water stress index [%] in each country	Direct
SF5		Ecology and Environment	95%-time flow exceeded minimum environmental flow with moderate management class [Million m^3/year]	Direct
			Total greenhouse gas emissions (kt of CO_2 equivalent) in each country	Reverse
			Environmental performance index in each country	Direct
F2	Social and economic needs of the watercourse States			
SF6		Economic and trade Status	GDP per capita in each country [Current $]	Reverse
			Gross National income per capita in each country [$]	Reverse
			Exports and imports trade (% of GDP)	Reverse
			Income index	Reverse
SF7		Work employment and vulnerability	Unemployment in the basin in each country [%]	Direct
			Vulnerable employment (% of total employment)	Direct
SF8		Social and economic sustainability	Population with access to electricity [%]	Reverse
			Relative significance of hydropower in each Nile basin countries [%]	Direct
			Population using basic drinking-water supply [%]	Reverse
			People with access to clean cooking [%]	Reverse
			Water supply and sanitation index	Reverse
			Infrastructure development index	Reverse
SF9		Human development	Human Development Index (HDI) in each country [%]	Reverse
SF10		Poverty status	Multidimensional Poverty index	Direct
			Population living below income poverty line [%]	Direct
			Hunger Index	Direct
SF11		Education status	Education index	Reverse
SF12		Health status	Life expectancy Index	Reverse
SF13		Gender status	Gender Development Index (GDI) in each country [%]	Reverse
F3	The population dependent on the watercourse in each watercourse state			
SF14		Existing dependency	Population in the nile basin countries [in millions] in 2019	Direct
			Population living in the basin in each country [%]	Direct
			Employment in agriculture (% of total employment)	Direct
			Employment in marine and inland fisheries [No]	Direct
			Agriculture, forestry, and fishing, value added (% of GDP)	Direct

Table A11. *Cont.*

Code	Relevant Factors	Sub-factors	Indicators	Relationship
SF15		Future dependency	Population growth rate [%]	Direct
F4	The effects of the use or uses of the watercourses in one watercourse State on other watercourse states			
SF16		Effects on land degradation	Fertile soil loss by erosion or sediment yield per year [M tons/year]	Direct
SF17		Effects on water security	Average annual surface water volumetric reliability index [%]	Reverse
SF18		Effect on Environment and human being on downstream neighbors	Water quality index	Direct
F5	Existing and potential uses of the watercourse			
SF19		Existing uses	Gross Irrigation water demand in each basin countries [km^3/yr]	Direct
			Existing domestic and industrial water demand in each basin countries [km^3/year]	Direct
			Energy Consumption per Capita (Kg of oil equivalent per capita)	Direct
			Existing Hydropower production in the basin in each country [MW]	Direct
SF20		Future Uses	Potential irrigation remaining area in each basin country [ha]	Direct
			Projected domestic water demand by 2050 in each basin countries [km^3/year]	Direct
			Remaining potential Hydropower production in the basin in each country [MW]	Direct
F6	Conservation, protection, development and economy of uses and the costs of measures taken			
SF21		Environmental Protection and Conservation	Areas exposed for severe soil erosion in each country with a rate of (>80 kg/ha/yr) [km^2]	Direct
SF22		Development and protection of water resources	Wetland area [km^2]	Direct
			Cereal yield (kg per hectare)	Direct
			Gross investment made on hydraulic structures or Dams [million USD]	Direct
			Total agricultural export value (1000)	Reverse
SF23		Economy of uses	Loss of water by evaporation from dams in each basin countries [BCM/year]	Reverse
			Water use efficiency [USD/m^3]	Direct
F7	The availability of alternatives, of comparable value			

Table A11. *Cont.*

Code	Relevant Factors	Sub-factors	Indicators	Relationship
SF24		Alternative sources	Alternative energy source from Solar (both PV and CSP) [TWh/year]	Reverse
			Alternative energy source from Wind [TWh/year]	Reverse
			Alternative energy source from Geothermal [MW]	Reverse
			Alternative energy source from oil [proved oil reserves in thousand million barrels]	Reverse
			Alternative energy source from natural gas [proved reserves trillion cubic meters]	Reverse
			Alternative energy source from generated waste via incineration method [GWh]	Reverse
			Total Renewable ground water resource[km^3/yr]	Reverse
SF25		Alternative uses and methods	Average income from Tourism [Million US$]	Reverse
			Alternative source of food and income from Livestock resource	
			Average fish and aquaculture production [metric ton/yr]	Reverse
			Industry value added (%GDP)- including construction industry	Reverse
			Employment in service provision sector [% of total employment]	Reverse

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