



Win–win Strategies for Transboundary Water Management During the GERD Operating Stage

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Abstract

The list of challenges associated with the operation of the Grand Ethiopian Resistance Dam (GERD) now includes global concern over climate change. Due to their inability to reach a legally enforceable agreement on how to address watershed degradation and water quality, riparian nations are already experiencing peace and security issues. A win–win strategy seeks to develop collaborative solutions to transboundary water management problems while maximizing the benefits for both parties. This paper aims to develop, evaluate, and analyze win–win transboundary water management strategies during the operating stage of GERD. Using value engineering (VE), functional analysis system technique (FAST), and life cycle cost (LCC), the optimal win–win strategy is determined. The study uncovered four distinct value options for various win–win strategies. According to the study results, the third win–win strategy is the most effective way to help both upstream and downstream nations retain peace, as it seeks to encourage riparian countries to collaborate by: i) developing cooperative regulatory policy; ii) switching to renewable energy supported by GERD; and iii) reducing water loss. This study advances our understanding of the topic by providing policymakers with a tool to: i) evaluate win–win strategies for managing transboundary water; and ii) incorporate the added value and functionality into policies regarding transboundary water management.

Keywords Win–win · Strategy · GERD · Water management · Value engineering · Life cycle cost

1 Introduction

Climate change is a significant factor in water rights disputes. Climate change will exacerbate water conflicts by altering the amount and timing of precipitation. Droughts caused by climate change pose a serious threat to the Nile basin, with

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cloudiness increasing by more than 15% when precipitation is low, especially in dry areas (Valjarević et al. 2022).

The problem is frequently exacerbated by nations' desire to meet their energy needs using accessible resources, which causes extensive environmental degradation. Across the Nile Basin, the proportion of the population with access to electricity is quite low by international standards, except for Egypt, where nearly every citizen has access.

With the Grand Ethiopian Renaissance Dam (GERD) in operation, Ethiopia intends to use its hydrological resources to lift its citizens out of poverty. Because of the current development's insatiable desire for massive electrification, as well as the possibility of a prolonged drought and the need to reduce poverty, Ethiopia has been under intense pressure to use natural resources such as the Blue Nile.

The GERD is situated in the Benishangul-Gumaz region along the Blue Nile, about 500 km to the north-west of Addis Abeba, the country's capital. As shown in Fig. 1, the GERD coordinates are $35^{\circ} 5' 36.96''$ east and $11^{\circ} 13' 5.7''$ north. GERD, which will be 1,800 m long, 155 m high, and hold 74 BCM of water, will be the biggest dam in Africa. 640 and 590 m above sea level will be the typical and minimum operational water levels, respectively. GERD has two power stations installed at the dam's base (Negm et al. 2018).

The majority of the world's regions are vulnerable to serious hydro-political conflicts, which could occur in several hotspot basins. In an increasing number of

Fig. 1 Geographical location of GERD



international river basins in the Middle East, North Africa, Central Asia, the Indian sub-continent, or Southeast Asia, the risk of severe political violence is likely to develop or worsen. To maintain peace and security among upstream and downstream nations, win–win strategies must be developed to reduce losses for downstream nations while maximizing benefits for upstream nations.

Numerous studies have examined the effects of GERD on downstream countries, particularly Egypt, which is the most affected nation. Among the most significant negative effects of GERD regulatory policy on Egypt are the loss of green energy produced by the Aswan High Dam (AHD), the annual water deficit, the depletion of soil due to salinity, and the decline in rural development rates (Nigatu and Dinar 2016; Hamada 2017; El-Nashar and Elyamany 2018a). In contrast, the primary effect of GERD on Sudan is a reduction in the amount of silt required to fertilize the region near the Blue Nile (Tayie 2018).

The annual goal of GERD's steady-state operation is 1500 MW of constant power generation. The energy generated by GERD will enhance regional and economic integration. GERD will also reduce CO₂ emissions that would be produced by equivalent power generation from fossil fuels (Abteu and Dessu 2019; Elagib and Basheer 2021). Hydropower dams can indirectly reduce greenhouse gas emissions by allowing the replacement of current and/or planned conventional energy generation with cleaner intermittent wind and solar energy sources (Sterl et al. 2020).

Downstream countries can benefit from GERD in several ways. The annual hydropower output from the Merowe dam in Sudan will increase by 27% when GERD is fully operational (Elsahabi and Negm 2018); reducing floods that affect the Sudan, especially at the "Rusairis" Dam; storing the Blue Nile silt, which is estimated to amount to 420 billion cubic meters per year; extending the life of the Sudanese dams and the Aswan High Dam (Benishangul-Gumuz 2017; Tesfa 2013; Kahsay et al. 2015).

Even though downstream nations have every reason to be concerned, upstream nations have the right to develop and prosper. If both sides view GERD as an opportunity rather than a challenge, all riparian nations can benefit, and the conflict can be mitigated. Consequently, it is essential to adopt a win–win approach through the innovative application of water diplomacy and transboundary water management instruments. Broad collaboration is essential to adopt a win–win strategy and guarantee mutual benefit for all riparian nations. The mutual recognition of upstream and downstream water requirements, which promotes transboundary cooperation and regional integration, creates opportunities for sharing resources and devising solutions that benefit all parties involved. When both sides know what they want out of a negotiation, it can lead to a situation where everyone wins.

It is feasible to include the "best available science" in water planning and monitor the results of its application. This is a practical illustration of how to manage water resources adaptively and sustainably. The adaptive management method, which integrates monitoring and assessment efforts to confirm win–win situations, takes environmental and economic effects into account when developing policies focused on a single species (Espinoza et al. 2022).

Even though numerous studies have proposed operating plans and strategies for GERD, additional research is still required to refine the win–win strategies. This knowledge zone lacks a comparison of different GERD operation strategies to arrive at the most feasible one. The goal of this paper is to 1) compare different GERD win–win strategies, 2) identify how these win–win strategies affect everyone, and 3) arrive at a win–win strategy to deal with GERD.

2 Research Methodology

The Value Engineering (VE) Methodology is utilized to achieve the study goals. VE is a multidisciplinary problem-solving technique designed to maximize the value of the functions required to achieve the goal of a product, process, or service (Chen et al. 2013). VE employs function analysis and logical reasoning to identify value-enhancing connections. The use of VE methodology in water management studies is not yet widespread. El-Nashar (2017) and El-Nashar and Elyamany (2018b) are two examples of studies that used value engineering to come up with and evaluate alternatives to the drain covering and water shortage at canals' tails. VE was also utilized to select the optimal irrigation strategy for mitigating the effects of climate change (El-Nashar and Elyamany 2022).

In this study, the VE is utilized to generate multi-value alternatives to win–win strategies, assess the value of these alternatives based on key evaluation criteria, compare the results, and select the optimal win–win strategy. Life cycle costing (LCC) is utilized to estimate the value of alternative win–win strategies. Using LCC, the cost and return for each win–win strategy are calculated, and the optimal strategy is then chosen.

There are five phases to follow when employing VE to investigate win–win strategies. These phases include information, functional analysis, creativity, evaluation, and development (El-Nashar and Elyamany 2018b).

2.1 Information Phase

This phase analysis and clarifies the study's objectives and the current state of the system. One or more of the following factors contribute to the evaluation of the win–win strategy: i) encourage upstream and downstream countries to collaborate to mitigate the negative effects of GERD; ii) manage transboundary water to maximize the benefits for all countries; and iii) improve water management to enhance water productivity and efficiency.

2.2 Function Analysis Phase

During this phase, the terms "active verb" and "measurable noun" are used to define each function. To determine which ones are necessary to accomplish the goals, these functions are analyzed and studied. Achieving peace and security is the main function. Optimizing water sharing and managing transboundary water are secondary functions. A function analysis system technique (FAST) diagram is used to define the functions of win–win strategies. By reducing the disadvantages and maximizing the advantages, this diagram helps in swiftly defining the goals and identifying the resources needed to achieve peace and security as shown in Fig. 2.

2.3 Creativity Phase

During this phase, creative ideas to achieve the main function of the system are generated. Accordingly, creative ways to manage transboundary water consumption have been proposed. Table 1 shows the generated win–win strategies.

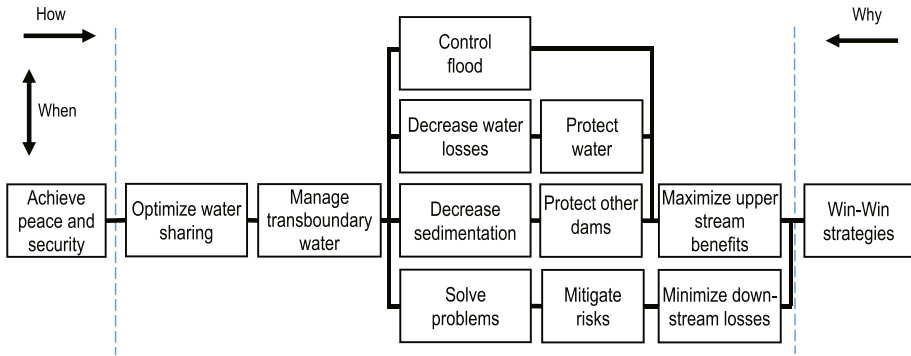


Fig. 2 Fast Diagram to Adopt Win-Win Strategies

2.4 Evaluation Phase

A questionnaire survey was carried out to evaluate the generated win-win strategies and reject the unrealistic and/or unproductive ones based on the opinions of experts. The following three criteria were the main determinants of an expert's eligibility to take part in the questionnaire survey: 1) understanding of the value engineering approach, 2) proficiency in water management, and 3) deep awareness of GERD. The questionnaire survey was emailed to 96 experts who satisfied the eligibility criteria. 42 experts responded to the questionnaire survey, yielding a response percentage of 43.75%.

According to the demographic profile of the respondents, 40.5%, 47.6%, and 11.9% of the respondents had less than five years' experience, between five-and ten-years' experience, and more than ten years' experience, respectively. The respondents' affiliations were 21.4%, 47.6%, and 31% are project managers, hydrological specialists, and water engineers, respectively. The expert was asked to rate the generated win-win strategies based on three performance criteria: economic return, avoiding disagreements, and ease of application. A 5-point Likert scale was used to rate the performance criteria, where 1 means low performance and 5 means high performance (Kaplan et al. 2021).

Ten win-win strategies were generated and presented to the experts for evaluation. Table 2, columns 2 through 13, displays the statistics of the experts' responses for each criterion of each strategy. While column 14 of Table 2 displays the total score for each strategy, column 15 indicates whether each of the generated strategies is accepted or rejected. The acceptance/rejection threshold is the neutral point of the total score, 2.5. Accordingly, seven strategies were qualified to move on to the next VE phase, the development phase.

2.5 Development Phase

The objective of this step is to develop Value Alternatives to the problem under study. These Value Alternatives are covered in the next sections.

Table 1 Proposed Strategies after GERD Operating

Strategy Code	Strategy Name	Strategy Description
S _i	Decreasing water losses	Decreasing evaporation losses by storing water in GERD in Ethiopia and covering the Nasser Lake with circular foam sheets
S _{ii}	Modifying the crop pattern	Replacing crops with other crops to fit the water decreasing and salinity increase
S _{iii}	Constructing other water projects	Building more water projects, such as the Moshar Swamps Project in southern Sudan, the Bahr El-Ghzal Project, and the Jonglei Canal in southern Sudan, will prevent water from being divided between Egypt and Sudan
S _{iv}	Ethiopian energy production maximization policy	Production of the maximum target of energy without any live storage
S _v	Cooperative regulatory policy, which mandates keeping a 20 BCM reserve	Employing the practice of maintaining a reserve of 20 BCM of GERD live storage for the downstream nations' usage as necessary
S _{vi}	Cooperative regulatory policy, which mandates keeping a 10 BCM reserve	Employing the practice of maintaining a reserve of 10 BCM of GERD live storage for the downstream nations' usage as necessary
S _{vii}	Using the suitable irrigation strategy	Using the suitable irrigation strategy by selecting suitable irrigation method for crop pattern and soil characteristic
S _{viii}	Replacement of fossil fuels by renewable energy, backed by GERD	By establishing massive solar and wind farms, and after that, agreeing to run Ethiopia's GERD in conjunction with solar and wind power
S _{ix}	Cultivation of major crops in Ethiopia	Cultivation of major crops which need high consumptive use such as rice, sugarcane, and wheat in Ethiopia
S _x	Water resources alternatives	a. Reusing treated wastewater and drainage water b. Desalination of seawater as a drinking and agricultural substitute c. Dig water wells in the arid landscape

Table 2 Win-Win Strategy Questionnaire Result

Strategy Code	Economic Return			Alleviate Disagreements			Ease of Application			Score	Decision			
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean					
			Stdev			Stdev			Stdev					
Si	5	3	4.12	0.80	5	3	4.12	0.71	2	1	1.45	0.50	3.19	Accept
Sii	5	4	4.43	0.50	5	3	4.24	0.85	5	3	4.05	0.85	4.24	Accept
Siii	2	1	1.55	0.50	2	1	1.45	0.50	2	1	1.36	0.48	1.45	Reject
Siv	5	3	4.19	0.77	5	3	4.02	0.81	5	3	3.98	0.84	4.06	Accept
Sv	3	1	2.02	0.84	5	3	4.12	0.86	5	4	4.60	0.50	3.72	Accept
Svi	2	1	1.31	0.47	3	1	1.88	0.77	3	2	2.48	0.51	1.82	Reject
Svii	5	3	4.10	0.79	5	3	3.88	0.86	5	4	4.38	0.49	4.12	Accept
Sviii	2	1	1.43	0.50	5	3	3.95	0.76	5	4	4.48	0.51	3.29	Accept
Six	5	4	4.57	0.50	5	3	4.05	0.82	3	1	2.05	0.82	3.56	Accept
Sx	2	1	1.40	0.50	4	3	3.45	0.50	3	1	1.93	0.84	2.26	Reject

2.5.1 Value Alternatives

Four win–win strategies were developed using the seven qualified strategies with the purpose of achieving peace and security for all parties. These win–win strategies were created by merging a few of the qualified strategies together. Alternatives to the suggested value are discussed in the following sections.

(i) **Win–win Strategy 1 (WS-1)**

This strategy aims to achieve the maximum benefits to upstream and downstream countries and minimize the negative impacts during the operation phase of GERD. The first value alternative combines three of the qualified strategies to form a win–win strategy i) Ethiopian energy production maximization policy (S_{iv}); ii) using suitable irrigation strategy (S_{vii}); and iii) replacement of fossil fuels by renewable energy produced by GERD (S_{viii}).

The policy of maximum energy production is to generate 14,285.42 GWh of energy by GERD throughout the course of a 100-year period. This would be achieved when the starting level of GERD is 620 m and the water level of Aswan High Dam (AHD) is 165 m. In which case, the total water deficit downstream of AHD is 45.14 BCM. Assuming the spread of the water deficit across 3 years with a maximum value of 16.42 BCM, AHD's turbines will shut down 32 times when it is unable to produce power (Sharaky et al. 2017).

“More crop per drop” could be achieved by using suitable irrigation strategies to recover as much deficit water as possible. Improvement of the surface irrigation system by converting tiny field canals to pipes would save about 7.4 BCM of water, which is lost due to seepage and evaporation. The use of contemporary irrigation techniques would save about 8.8 BCM of water (El-Nashar and Elyamany 2018a).

To offset the AHD's lack of hydropower capacity, Ethiopia should deploy massive solar and wind farms to work in conjunction with GERD to produce the needed electricity during dry seasons. GERD would produce less electricity during dry seasons and more during the wet seasons, which would follow naturally from this synergistic operation. In essence, Ethiopia would gain all the anticipated advantages from GERD while Egypt could mitigate the danger of a power shortfall caused by AHD. To safeguard Sudan from floods and droughts, the Roseires Dam would operate in seasonal synergy with solar and wind power. For Ethiopia, Sudan, and Egypt, integrated hydro-solar-wind planning offers a path ahead with shared goals and interests (Sterl et al. 2021).

(ii) **Win–win Strategy 2 (WS-2)**

This strategy aims to promote more cooperative methods that manage transboundary water and maximize the benefits from them. This value alternative determines how the riparian nations might cooperate to achieve a win–win strategy. The second value alternative combines i) cooperative regulatory policy, which mandates keeping a 20 BCM reserve (S_v); ii) modification of the crop pattern (S_{ii}); and iii) cultivation of major crops in Ethiopia (S_{ix}).

If the upstream and downstream nations choose to follow the strategy of saving a reserve of 20 BCM of GERD live storage for usage as needed, 14,151.13 GWh of energy could be generated from GERD throughout the course of a 100-year period. In this case, the power generation from GERD is less than its maximum annual power by just 1%. The highest annual value of the water deficit downstream of AHD

in this case becomes 14.91 BCM, during which AHD's turbines will shut down 32 times when it is unable to produce power throughout the course of a 100-year period (Sharaky et al. 2017).

"More crop per drop" must be taken into consideration due to the anticipated water shortage and salinity increase post GERD. More crop per drop can be accomplished by replacing high-water-use crops with lower-water-use crops, planting drought-tolerant cultivars, lowering the cultivated area of rice, and switching to beet farming in place of sugarcane. With various irrigation systems, energy crops like jojoba and palm are the best alternatives in saline soil (Amer et al. 2021).

Adopting a policy of water conservation and expanding salinity-tolerant, low-water-use crops will result in a shortage of staple crops. To mitigate this shortage, the riparian nations may agree to produce the most water-intensive crops, including wheat, rice, and sugarcane upstream of GERD in Ethiopia.

(iii) **Win-win Strategy 3 (WS-3)**

This strategy aims to achieve the desired collaboration between the riparian nations. It combines i) cooperative regulatory policy, which mandates keeping a 20 BCM reserve (S_v); ii) replacement of fossil fuels by renewable energy, backed by GERD (S_{viii}); and iii) decreasing water losses (S_i).

As described in Section WS-2 concerning the cooperative regulatory policy, the electricity generation from GERD will approach its maximum value. Modifying GERD operation to promote grid integration with solar and wind power would provide regional win-win scenarios for all participating nations with respect to energy and water resources. (Sterl et al. 2021),

By storing water in GERD and covering Lake Nasser in Egypt with circular foam sheets, it is possible to reduce evaporation-related water losses. Since most of the water reaches Lake Nasser between late August and early September, the excess water is kept for ten months, until the agricultural season's peak in July of the following year. Remote sensing and GIS readings show that 12 percent of the monthly evaporation rates were lost due to evaporation throughout this 10-month period (Hassan et al. 2018). If this amount of excess water is stored in Lake GERD, a location with a more temperate climate, evaporation rates will be reduced owing to the lake's altitude of 570–650 m above sea level. Before the peak of the growing season, water might be released from Lake GERD to downstream countries that need it (Kahsay et al. 2015).

On the other side, to avoid the evaporation of more than 1 million cubic meters of water from Lake Nasser, circular foam sheets with a 90% coverage rate might be deployed over a surface area of 0.5 km². However, it is possible to adjust the circular foam system so that it has no effect on the flow of sunlight to aquatic life (Omran and Negm 2018).

(iv) **Win-win Strategy 4 (WS-4)**

The development of the fourth win-win strategy might help to ease the conflict between Ethiopia, Sudan, and Egypt. The fourth value alternative combines i) Ethiopian energy production maximization policy (S_{iv}); ii) decreasing water losses (S_i); cultivation of major crops in Ethiopia (S_{ix}). This alternative allows Ethiopia to fully utilize the infrastructure of GERD, River ecology safeguarded, mitigate the risks on the downstream countries as described previously in WS-1, WS-2, and WS-3.

GERD significantly affects how drought and flood management are handled. During dry seasons, GERD will provide regulated and sustainable minimum flow levels. By guaranteeing a reliable all-season supply of water to downstream irrigation systems, it allows for a boost in agricultural production upstream and minimizes

harvest losses brought on by water shortages. The management of sediment in Sudan and Egypt will be significantly impacted by GERD. When GERD is operating at its full capacity, sedimentation in the Blue Nile will decrease by up to 86%. Additionally, dredging expenses will be lowered for Sudan alone, and savings on turbine maintenance and replacement costs will also be realized (Tesfa 2013).

2.5.2 Evaluation Criteria of Alternatives

The assessment criteria in Table 3 have been culled from the literature to distinguish between the proposed value alternatives from a technical perspective. During this step, the same 42 experts who responded to the evaluation questionnaire during the VE evaluation phase were contacted again for their input on the relative importance of the assessment criteria of the value alternative. The panel was asked to rate each assessment criterion on a Likert scale ranging from 0 to 5, where 0 indicates no relevance of a criterion and 5 indicates the significance of the criterion over the other. Table 3 depicts the assessment criteria questionnaire’s format as a comparison matrix. After receiving three reminder emails, all 42 experts responded to the questionnaire. Table 3 is a sample of one expert’s response to the questionnaire. The relative weights of the assessment criteria, as computed by averaging the responses of the experts, are displayed in column 2 of Table 4.

2.5.3 Value Alternative Scoring

The scoring of the 4-value alternative was inquired from the same 42 experts who was helping throughout this study. The panel was instructed to rate each value alternative against each assessment criterion on a scale from 0 to 10, where 0 indicates that alternative’s relevance to this criterion is null and 10 indicates the alternative’s relevance to this criterion is the highest. After receiving three reminder emails, 33 experts responded to the questionnaire.

The scores given to the alternatives by expert #1 appears in columns 3, 4, 5, and 6 of Table 4. The weighted score in columns 7 of Table 4 is computed by multiplying the average alternatives’ scores of all experts for each of criterion in column 3, by the weights of the criterion in column 2. The Technical Score (TS) for the value alternative is computed by adding

Table 3 Sample weighting of assessment criteria

Evaluation Criteria	A	B	C	D	E	F	G	H	I	J	K
Water saving	A	A-4	C-2	0	A-4	A-3	A-4	A-3	A-3	A-3	A-4
Regulation of Blue Nile flow	B		C-4	D-4	E-2	F-2	B-2	H-2	I-3	J-4	B-2
Shearing of transboundary water	C			D-3	C-3	C-2	C-4	H-2	I-3	J-3	C-3
Providing food	D				D-4	D-4	D-4	D-3	D-2	D-2	D-4
Elimination of the pollution	E					E-2	E-2	H-3	I-3	J-3	K-2
Cooperation among riparian nations	F						F-2	H-3	I-3	J-3	K-3
Effect on sedimentation	G							H-3	I-3	J-3	G-3
Impact on the environment	H								H-3	H-3	K-2
Energy producing	I									I-2	I-3
Cost of application	J										J-3
River ecology safeguarded	K										

Table 4 Evaluation Criteria Weights and Value Alternatives Score

Evaluation Criteria	Weight	Alternative Scores by expert #1				Weighted Scores of all experts			
		WS-1	WS-2	WS-3	WS-4	WS-1	WS-2	WS-3	WS-4
A	0.177	9	8	9	7	1.239	1.770	1.768	1.769
B	0.025	8	8	8	8	0.250	0.150	0.200	0.175
C	0.114	7	8	8	7	0.912	0.798	0.912	0.798
D	0.190	7	8	7	8	1.330	1.900	1.710	0.950
E	0.038	8	8	8	8	0.304	0.342	0.190	0.304
F	0.025	9	8	9	7	0.125	0.225	0.200	0.250
G	0.019	8	8	8	8	0.114	0.114	0.095	0.190
H	0.120	8	8	9	9	0.600	0.720	1.200	0.720
I	0.127	9	8	9	7	1.016	0.889	1.016	0.635
J	0.120	9	8	9	7	1.080	0.960	0.720	1.080
K	0.044	8	8	8	8	0.440	0.352	0.352	0.440
Total Score	1.000					7.410	8.220	8.365	7.312

the weighted scores for all the assessment criteria as shown in the bottom row of Table 4, which indicates that WS-3 has the highest technical score. Following this step, it is necessary to calculate the Life Cycle Cost (LCC) of each value alternative to determine the Value Index (VI) which would lead to define the best alternative.

2.5.4 Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCC) is utilized to assess the four proposed win-win strategies. LCC is a method for estimating the total cost and anticipated revenue of a system. LCC considers both recurring and one-time expenses, including acquisition, installation, operation, and maintenance. In conjunction with LCC, net present value (NPV) is used to evaluate the overall value of an alternative. The net present value (NPV) is the difference between the present value of cash inflows and outflows. Equation (1) is used to calculate NPV (Peterson 2005).

$$NPV = C_i + R_e - S_r + A_a + M + E \quad (1)$$

where: C_i : investment costs; R_e : replacement costs; S_r : resale value towards the end of its lifespan; A_a : annually recurring operating, maintenance, and repair costs; M : non-annually recurring operating, maintenance, and repair cost; E : energy costs.

The results of Eq. (1) for the four win-win strategies are presented in Tables 5, 6 and 7. Under the assumption that GERD has a 100-year life expectancy, the expenses and income of the four win-win strategies are calculated for this timeframe. The total NPV for each win-win strategy is calculated by using Eq. (2).

$$NPV(ws) = Total\ NPV\ of\ revenue - Total\ NPV\ of\ costs \quad (2)$$

LCC for WS-1 Table 5 displays the PV of the cost, benefits, and NPV of each strategy employed for WS-1. It shows the PV and NPV of costs and benefits for maximum hydro-power energy generated by both GERD and renewable energy. 30% of the anticipated

Table 5 Cost, Revenue and NPV for WS-1 Strategies used for SW-1

	Value	Unit
Ethiopian energy production maximization policy (S_{iv})	80	\$/MWh
Cost of hydropower energy (Sterl et al. 2021)	14,285,420	MWh
Maximum hydropower energy from GERD (Sharaky et al. 2017)	1.14	Billion \$
Total PV of cost of hydropower energy	1	Billion \$
Annual benefits from hydropower energy (Sterl et al. 2021)	9.92	Billion \$
PV of benefits from hydropower energy	8.78	Billion \$
NPV of hydropower energy	0.067	\$/m ²
PV of main crops cost	0.4945	\$/m ²
PV of main crops revenue	0.3	\$/m ²
PV of initial cost of surface irrigation method with pipeline	0.022	\$/m ²
PV of (O&M) costs for surface method with pipeline	18	Billion m ²
Recertificated agricultural land in Egypt due to GERD (El-Nashar and Elyamany 2018a)	5.4	Billion m ²
Area (30% 18 billion m ²) of which is cultivated by main crops and irrigated by surface irrigation method with pipeline		
Total PV of the area 5.4 billion m ² cost	2.1006	Billion \$
Total PV of the area 5.4 billion m ² revenue	2.6703	Billion \$
NPV of the area 5.4 billion m ²	0.5697	Billion \$
PV of low consumptive use crops cost	0.09	\$/m ²
PV of low consumptive use crops revenue	0.645	\$/m ²
Initial cost of modern irrigation method	0.4	\$/m ²
(O&M) cost for modern method	0.0305	\$/m ²
Area (70% 18 billion m ²) which is cultivated by low consumptive use crops and irrigated by modern irrigation method	12.6	Billion m ²
Total PV of the area 12.6 billion m ² cost	6.5583	Billion \$
Total PV of the area 12.6 billion m ² revenue	8.127	Billion \$
Total NPV of the area 12.6 billion m ²	1.5687	Billion \$

Table 5 (continued)

Strategies used for SW-1	Value	Unit
Replacement of fossil fuels by renewable energy, backed by GERD (S _{viii})	75.75	\$/MWh
Average cost of renewable energy (Sterl et al. 2021)	2,567,000	MWh
Needed renewable energy (El-Nashar and Elyamany 2018a)	0.194	Billion \$
Total PV of cost of renewable energy	1.7	Billion \$
PV of benefits from renewable energy	1.51	Billion \$
NPV of renewable energy	10	Billion \$
Total NPV of costs for SW-1	22.4	Billion \$
Total NPV of revenue for SW-1	12.42	Billion \$
NPV for SW-1		

Table 6 Cost, Revenue and NPV for WS-2 Strategies used for SW-2

	Value	Unit
Cooperative regulatory policy, which mandates keeping a 20 BCM reserve (S_v)	80	\$/MWh
Cost of hydropower energy (Sterl et al. 2021)	14,151,130	MWh
Hydropower energy from GERD (Sharaky et al. 2017)	1.132	Billion \$
Total PV of cost of hydropower energy	0.99	Billion \$
Annual benefits from hydropower energy	9.8208	Billion \$
PV of benefits from hydropower energy	8.6328	Billion \$
NPV of hydropower energy	0.09	\$/m ²
PV of low consumptive use crops cost	0.645	\$/m ²
PV of low consumptive use crops revenue	0.4	\$/m ²
Initial cost of modern irrigation method (O&M) cost for modern method	0.0305	\$/m ²
Recertificated agricultural land in Egypt due to GERD (El-Nashar and Elyamany 2018a)	18	Billion m ²
Saline land in Egypt due to GERD	14.7	Billion m ²
Area which is cultivated by low consumptive use crops and irrigated by modern irrigation method	3.3	Billion m ²
Total PV of the area 3.3 billion m ² cost	1.71765	Billion \$
Total PV of the area 3.3 billion m ² revenue	2.1285	Billion \$
Total NPV of the area 3.3 billion m ²	0.41085	Billion \$
PV of energy crops cost	0.13	\$/m ²
PV of energy crops revenue	0.6785	\$/m ²
Area which is cultivated by energy crops and irrigated by modern irrigation method	14.7	Billion m ²
Total PV of the area 14.7 billion m ² cost	8.24	Billion \$
Total PV of the area 14.7 billion m ² revenue	9.97	Billion \$
Total NPV of the area 14.7 billion m ²	1.73	Billion \$

Table 6 (continued)

Strategies used for SW-2	Value	Unit
Cultivation of major crops in Ethiopia (S_{ix})	0.067	\$/m ²
PV of main crops cost	0.4945	\$/m ²
PV of main crops revenue	0.298	\$/m ²
PV of initial cost of surface irrigation method	0.02	\$/m ²
PV of (O&M) costs for surface method	15.4	Billion m ²
Area which is cultivated by main crops and irrigated by surface irrigation method	5.929	Billion \$
Total PV of the area 15.4 billion m ² cost	7.62	Billion \$
Total PV of the area 15.4 billion m ² revenue	1.69	Billion \$
NPV of the area 15.4 billion m ²	17.02	Billion \$
Total NPV of costs for SW-2	29.54	Billion \$
Total NPV of revenue for SW-2	12.52	Billion \$
NPV for SW-2		

Table 7 Cost, Revenue and NPV for SW-3

Strategies used for SW-3		Value	Unit
Cooperative regulatory policy, which mandates keeping a 20 BCM reserve (S_v)	Total PV of cost of hydropower energy	1.132	Billion \$
	PV of benefits from hydropower energy	9.8208	Billion \$
	NPV of hydropower energy	8.6328	Billion \$
Replacement of fossil fuels by renewable energy, backed by GERD (S_{viii})	Total PV of cost of renewable energy	0.194	Billion \$
	PV of benefits from renewable energy	1.7	Billion \$
	NPV of renewable energy	1.51	Billion \$
Decreasing of water losses (S_i)	Initial cost of circular foam sheets	0.7	Billion \$
	Area which is cultivated by water saved	0.24	Billion m^2
	PV of low consumptive use crops cost	0.09	\$/ m^2
	PV of low consumptive use crops revenue	0.645	\$/ m^2
	Initial cost of modern irrigation method	0.4	\$/ m^2
	(O&M) cost for modern method	0.0305	\$/ m^2
	Total PV of the area 0.24 billion m^2 cost	0.12492	Billion \$
	Total PV of the area 0.24 billion m^2 revenue	0.1548	Billion \$
	Total NPV of the area 0.24 billion m^2	0.03	Billion \$
Total NPV of costs for SW-3	2.151	Billion \$	
Total NPV of revenue for SW-3	11.676	Billion \$	
NPV for SW-3	9.52	Billion \$	

recertified agricultural area in Egypt would be planted with major crops and irrigated by surface irrigation with pipes, while 70% would be cultivated with low consumptive use crops and irrigated by modern technique. The initial, operating, and maintenance costs of irrigation methods and crop revenue per unit area are computed, followed by the overall NPV.

LCC for WS-2 Table 6 depict the PV of the cost, benefits, and NPV of each strategy employed for WS-2. The PV and NPV of hydropower energy generated from GERD (1% losses in hydropower generation) are presented. According to El-Nashar and Elyamany (2018a), the projected GERD saline area in Egypt is 14.7 billion m^2 , while the expected area of desertification is 18 billion m^2 . The saline land would be used to cultivate energy crops, while the remaining area (3.3 billion m^2) would be used to cultivate crops with low consumptive use. Utilize the current watering system. It is anticipated that 15.4 billion m^2 of prime agricultural land will be lost. In Ethiopia, this region would be cultivated using surface irrigation. The initial, operating, and maintenance expenses of irrigation methods and crop revenue per unit area are computed, followed by the overall NPV.

LCC for WS-3 Table 7 displays the PV of the cost, benefits, and NPV of each strategy employed for WS-3. Cooperative regulatory policy, which involve maintaining a 20 BCM reserve (S_v), is adopted from WS-2 estimated in Table 6. Replacing fossil fuels with renewable energy supported by GERD (S_{viii}) is adopted from WS-1 estimated in Table 5. The conserved 20.68 billion m^3 of water will be used to cultivate additional land (Kahsay et al. 2015). Low consumptive use crops would be grown on an additional 0.24 billion m^2 of land using a modern irrigation system. The initial cost of the circular foam sheets, the

initial, operating, and maintenance costs of irrigation methods, the crop revenue per unit area, and the total NPV are shown in Table 7.

LCC for WS-4 Table 8 shows the PV of the cost, benefits, and NPV of each strategy employed for WS-3. Calculations of the Ethiopian energy production maximization policy (S_{iv}) are adopted from WS-1 in Table 5. Calculations of reducing water losses (S_i) are adopted from WS-3 in Table 7. Calculations of the cultivation of Ethiopia's primary crops (S_{ix}) are adopted from WS-2 in Table 6.

2.5.5 Alternatives Evaluation

To determine the optimum win-win strategy, the four win-win strategies are evaluated in this section. The value index (VI), whose highest value indicates the optimal strategy, is used to carry out this evaluation. The VI for each win-win strategy is calculated using Eq. (3), as shown in Table 9.

$$\text{Value Index} = \frac{\text{Technical Score}}{\text{Net Present Value}} \quad (3)$$

As Table 9 shows, WS-3 is the finest win-win strategy, as VI and TS concur. Therefore, WS-3 is a strategy that promotes more flexible cooperation, achieves benefits for both upstream and downstream countries, and maximizes the available resources.

3 Results and Discussion

The primary benefit of implementing win-win strategies is the capacity to optimize water use, hence achieving benefits for both upstream and downstream countries and lowering operating risks associated with GERD. The four proposed win-win strategies are evaluated based on extremely essential evaluation criteria, such as their ability to conserve water, supply food, generate energy, and control the flow of Blue Nile. The evaluation assessed how the win-win strategy promotes transboundary water sharing, its cooperation with Nile Basin countries, and its environmental implications.

The results demonstrated that each win-win method achieves these qualities with slight variations in value. WS-3 has the highest technical score. By calculating total NPV for each win-win strategy using LCC, WS-2 delivers the maximum total NPV. Calculating the VI for each win-win strategy reveals that WS-3 has the highest value. Consequently, WS-3 is the optimal win-win strategy. The benefits of WS-3 implementation for Ethiopia, Egypt, and Sudan are realized through i) a cooperative regulatory policy mandating a 20 BCM reserve (S_v), ii) the replacement of fossil fuels with renewable energy supported by GERD (S_{viii}), and iii) the reduction of water losses (S_i).

The strategy of retaining a reserve of 20 BCM of GERD live storage accomplishes the objective for Ethiopia because the power generation from GERD is just 1% less than the maximum power generation. If necessary, the live storage will be utilized for downstream countries during drought seasons. The integration of hydroelectric, solar, and wind energy into the grid creates regional win-win situations. More area might be cultivated with water stored in GERD or by covering Nasser Lake with circular foam sheets. GERD will contribute to the reduction of greenhouse gas and carbon emissions by providing environmentally friendly electricity, flood management, drought mitigation, and water vapor regulation.

Table 8 Cost, Revenue and NPV for SW-4

Strategies used for SW-4	Value	Unit
Ethiopian energy production maximization policy (S_{1N})	1.14	Billion \$
Total PV of cost of hydropower energy	9.92	Billion \$
PV of benefits from hydropower energy	8.78	Billion \$
NPV of hydropower energy	0.7	Billion \$
Decreasing of water losses (S_1)	0.12492	Billion \$
Initial cost of circular foam sheets	0.1548	Billion \$
Total PV of the area 0.24 billion m^2 cost	0.03	Billion \$
Total PV of the area 0.24 billion m^2 Revenue	5.929	Billion \$
Total NPV of the area 0.24 billion m^2	7.6153	Billion \$
Cultivation of major crops in Ethiopia (S_{1N})	1.6863	Billion \$
Total PV of the area 15.4 billion m^2 cost	7.9	Billion \$
Total PV of the area 15.4 billion m^2 Revenue	17.6	Billion \$
NPV of the area 15.4 billion m^2	9.79	Billion \$
Total NPV of costs for SW-4		
Total NPV of revenue for SW-4		
NPV for SW-4		

Table 9 Value Index for Win-win Strategies

	WS-1	WS-2	WS-3	WS-4
Total NPV (Billion US\$)	12.42	12.52	9.52	9.79
Technical Score (TS)	7.410	8.22	8.365	7.312
Value Index (VI)	0.6	0.66	0.88	0.75

Each year, the Upper Blue Nile basin produces around 131 million tons of sediment. It is estimated that reduced sediment loads resulting from GERD will increase the lifespan of Sudan's and Egypt's reservoirs and reduce the amount of silt that accumulates in their irrigation canals; Sudan may save \$50 million per year on dredging expenses alone (Tesfa 2013).

4 Conclusions

There was substantial evidence that climate change was already negatively impacting regional security, biodiversity, water supply, healthcare, and food security. The precipitation has become erratic and unsteady. Both the frequency and intensity of extreme droughts and floods have increased.

Tensions are rising between Egypt, Sudan, and Ethiopia due to GERD. Egypt is concerned about the anticipated water deficit and decrease in power generation from AHD, whilst Sudan is afraid that GERD's operation could compromise the security of its dams and make it more difficult for the government to manage its own development plans. Cooperation is required at the local, national, regional, and international levels to address water distribution possibilities, transboundary water management, and usage of freshwater resources. All parties must be involved in a win-win approach and discuss the possibilities that contribute to mutual gains. Win-win outcomes are the most trustworthy; if both parties are satisfied with the agreement, they are less likely to complain later.

Even though numerous studies have proposed operating plans and strategies for GERD, additional research is still required to refine the win-win strategies. This paper compared various win-win strategies, evaluated their effects on all parties, and developed a win-win approach to the effective collaborative management of GERD.

Value Engineering (VE) methodology is used in this study to create and analyze win-win strategies. VE provides a novel way of comparing win-win strategies to select the optimum win-win strategy. Finding the "best value," or the ideal balance between merit and expense, is the aim of VE. The win-win strategies that lead to peace and security for both upstream and downstream nations are defined using a FAST diagram. Ten innovative suggestions for GERD operational techniques have been introduced by experts. These strategies were whittled down to seven, which were then combined to generate four win-win strategies.

The first win-win strategy includes: i) Ethiopian energy production maximization policy; ii) using a suitable irrigation strategy, and iii) replacement of fossil fuels by renewable energy, backed by GERD. The second strategy includes: i) cooperative regulatory policy, which mandates keeping a 20 BCM reserve; ii) modifying the crop pattern; and iii) cultivation of major crops in Ethiopia. The third strategy includes: i) cooperative regulatory policy, which mandates keeping a 20 BCM reserve; ii) replacement of fossil fuels by renewable energy, backed by GERD; and iii) decreasing water losses. The fourth strategy

includes: i) Ethiopian energy production maximization policy; ii) decreasing water losses; and iii) cultivation of major crops in Ethiopia.

The performance attributes considered in the evaluation of win–win methods are economic return, reducing disagreements, and ease of application. Several criteria were used to assess these four win–win strategies, such as how they affect energy production, water conservation, river ecology, and the environment. Each win–win strategy has been assigned a score against each of the assessment criteria. The total of all the weighted scores for the value alternative's assessment criteria is the TS. LCC techniques are used to calculate the total cost, total benefits, and NPV for each alternative. According to the study results, the third win–win strategy has the highest VI, therefore, is the most effective way to help both upstream and downstream nations retain peace, reduce conflicts, attain economic success, and protect the environment and water resources. This strategy is significant for the region's renewable energy supported by GERD and would provide Ethiopia with all the advantages associated with a large dam. It will enable water conservation by reducing evaporation losses and environmental conservation by replacing fossil fuels with renewable energy.

The primary contribution of this paper is the introduction of multiple win–win strategies for both upstream and downstream nations, as well as the proposal of a framework for selecting the optimal win–win strategy following GERD operation to minimise downstream nation losses while maximizing upstream nation benefits.

Abbreviations AHD : Aswan High Dam; BCM : Billion cubic meters; GERD: Grand Ethiopian Resistance Dam; GWh: Giga watt per hour; LCC: Life Cycle Cost; NPV: Net present value; O&M: Operating and maintenance; PV: Present value; TS: Technical Score; VE: Value Engineering; VI: Value Index; WS-1 : Win–win Strategy 1; WS-2 : Win–win Strategy 2; WS-3 : Win–win Strategy 3; WS-4 : Win–win Strategy 4

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Declarations

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