




# Ecohydrology and flood risk management under climate vulnerability in relation to the sustainable development goals (SDGs): a case study in Nagaa Mobarak Village, Egypt

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## Abstract

This article aims to provide a thorough assessment of water quality and quantity incorporating the estimation of future patterns as a result of climate change from economic, environmental and social perspectives. Its scope extends from studying the physical parameters and rainfall patterns to maintaining an environmental flow with a better water quality using ecohydrological techniques. The village of Nagaa Mobarak in Souhag, Egypt, is taken as a case study being in a critical location that is vulnerable to flash floods. This paper managed to quantify change in water quantity and quality due to the impacts of flash floods and climate change. Several traditional engineering alternatives are proposed for flood management such as constructing a dam, a storage pond and a routing channel to the nearest water body; as well as non-traditional ecohydrological alternatives such as constructing a dam with vegetated foreshore, natural levees and constructed wetlands. The results of applying these methods for our case study showed that a hybrid solution that employs both traditional and non-traditional solutions for flood management is optimal. A constructed wetland along a section of the constructed channel for diverting flow into the Nagaa Hammade Canal would decrease the runoff volume and peak time so that the capacity of the Canal is not exceeded in a flood event and purifies the incoming stormwater improving its quality and the health of the ecosystem within the canal. Moreover, our proposed approach was investigated and found to target 10 out of the 17 UN SDGs.

**Keywords** Climate change · Ecohydrology · Nature-based solutions · Flood risk management · Hydrological modeling · SDGs · Structural flood management

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## Abbreviations

AIC	Akaike Information Criterion
CFSR	Climate Forecast System Reanalysis
CN	Curve number
DEM	Digital elevation model
EPA	Environmental Protection Agency
EWE	Extreme weather events
FAO	Food and Agriculture Organization
GG	Generalized gamma
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
Hyfran-plus	Hydrological Frequency Analysis Plus
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
RAS	River Analysis System
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SWMM	Storm Water Management Model
TMPA	TRMM Multi-Satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
UN SDG	United Nations Sustainable Development Goals
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VT Builder	Virtual Tour Builder
WMS	Watershed Modeling System

## 1 Introduction

Flash floods are dangerous because they strike with no advance warning after rainfall events (El-Afandi and Morsy 2020; Fathy et al. 2019; Atwa 2020). They threaten the lives and livelihoods of people as well as their assets and properties (Parvin et al. 2016; Abdel-dayem et al. 2020; Kumar et al. 2018). Flash floods intensities and the risk of their occurrence are related to several factors, including rainfall intensity and distribution, soil type and water content, and vegetation type in the catchment area (U.S. Department of Commerce 2015), so mainly precipitation, geology and topography data.

Climate change plays a significant role in flash floods because the warmer atmosphere holds and releases more water, resulting in an increased frequency and intensity of storms (Hettiarachchi et al. 2018). Because of climate change, the incidence of flash flood in Egypt has become more frequent, causing loss of life, destruction of agricultural lands, and property damage (Mashaly and Ghoneim 2018; Youssef and Hegab 2019; Prama et al. 2020). Additionally, the country is currently facing water scarcity challenges because of rapid population growth and reduced river flow, which will inevitably result from the construction of the Grand Ethiopian Renaissance Dam (Abdelhafez et al. 2020; Yassen et al. 2020; Abdelrady et al. 2020; Morsy et al. 2020a, b; Morsy et al. 2021). To alleviate these effects, developing a national plan for sustainable flood management is essential to protecting areas

and lives from flood danger, maximizing stormwater benefits, and redirecting runoffs into the nearest surface water system for irrigation and groundwater recharge (Mostafa et al. 2016; Wakode et al. 2018; Spiliotis and Skoulikaris 2019; Freni and Liuzzo et al. 2019; Rajasekhar et al. 2020 ;Golian et al. 2020; Ostad-Ali-Askari et al. 2019).

Traditional engineering approaches are to thank for protecting human life from natural threats from wild animals to natural hazards such as floods. Of the traditional approaches for flash flood risk reduction, structural measures (e.g., ditches, embankments, diversion channels, dikes, dams, culverts, and ponds) are considered the most efficient for controlling flash floods (Kumar et al. 2017; Zhu and Chen 2017; Kim et al. 2005; Destro et al. 2018; Sikorska et al. 2018; Kundzewicz et al. 2019). Selecting the most suitable protection method depends on site-specific factors, such as catchment size, rainfall intensity, and the runoff-generating process (Sikorska et al. 2018). However, structural measures are only applicable over the short term because their efficiency decreases over the long term, usually because of land-use change and unplanned development within the flood-protected areas (Shah et al. 2018; Di Baldassarre et al. 2018).

Non-traditional structural flood protection measures have recently gained research interest. Those measures rely on natural systems and ecosystem services, as well as eco-hydrology concepts included within the nature-based solutions (Cohen-Shacham et al. 2016; Zalewski et al. 1997; Nafchi et al. 2021). Nature-based solutions (NBS) address a variety of environmental, social, and economic challenges in sustainable ways (European Commission 2015). The solutions are inspired by, supported by, or copied from nature, using and enhancing existing solutions to challenges and exploring novel applications. The NBSs are aligned with the United Nations Sustainable Development Goals (SDGs) (United Nations 2015) and serve as the three main pillars of sustainability that consider people well-being, ecosystem vitality, and economic feasibility (Matute et al. 2016; Scheres and Schüttrumpf 2019). Similarly, flood protection measures and especially nature-based flood protection measures support the achievement of the SDGs, where they target specific indicators especially in goals six on water management and eleven of resilient cities (United Nations 2015).

Numerous researchers have explored strategies for flood management. Regrettably, recent studies consistently ignore the effects of climate change on water quality while developing flood risk management strategies (Abd-El Monsef 2018; Abdulrazzak et al. 2019; Abdeldayem et al. 2020; Fatahi Nafchi et al. 2021; Hafshejani et al. 2019), which is particularly common in developing countries because of a lack of financial resources. This lack in quality is commonly caused by increased precipitation washing away more pollution to water bodies or by extreme droughts increasing the concentration of pollutants in water bodies (Abd-El Monsef 2018; Abdulrazzak et al. 2019; Abdeldayem et al. 2020).

The goal of this study is to evaluate a flash flood risk management strategy for arid regions that targets the expected water quantity while considering solutions for managing water quality. The novelty of this study is based on addressing the dual effect of climate change on water quantity and quality. Moreover, it highlights the contribution of nature-based flood management methods to the SDGs. The dual impacts of climate change on water quantity and quality in response to flooding illustrate the importance of considering the impacts of climate change on flood scenarios. Data retrieved from the World Meteorological Organization were used to predict changes in the rainfall regime due to climate change, as well as changes in temperature. Hydrological and hydraulic software models were used for flash flood and runoff simulation, flash flood management, and a comparison between the efficiency of three traditional methods (artificial pond, artificial flood channel, and dam) in flood water conservation and cost-effectiveness. Three non-traditional flood

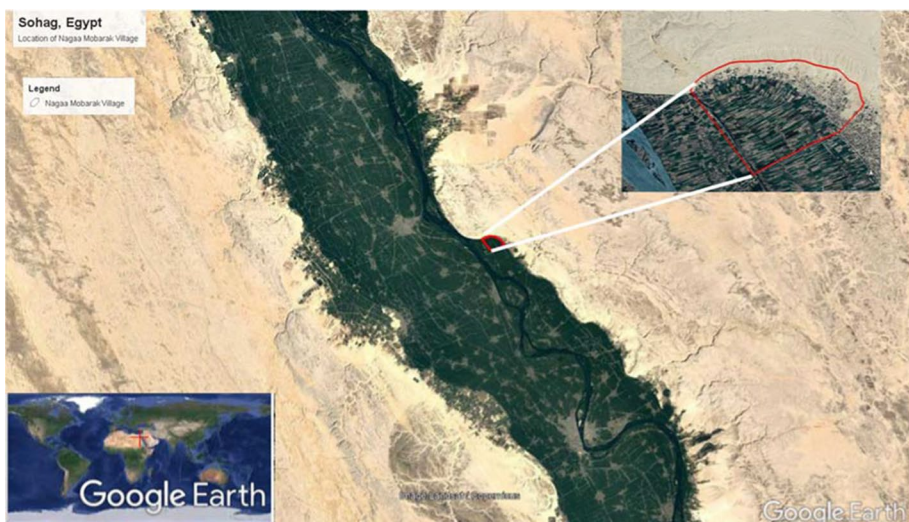
management methods (natural levees, vegetated foreshores, and wetlands) were also compared based on their capability to prevent water quality deterioration and cost-effectiveness. The selection of these methods was based on their common use in the market as well as suitability for the site. By integrating the two management methods as will further be explained, a holistic management approach was developed to target both water quantity and quality. Therefore, this study can be used as a guideline for flash flood management in regions that share similar conditions. Finally, our holistic ecohydrological approach contribution to the achievement of the SDGs is discussed in a separate section on the basis of it being both ecohydrological and used for flood management.

## 2 Materials and methods

### 2.1 Case study area

Sohag Governorate in Upper Egypt has suffered from the loss of lives and major property damage due to severe flooding events in 1994, 2014, and 2016 (El-Magd et al. 2020). The 1994 flash flood collapsed over 100 homes and destroyed 400 acres of reclaimed lands in Sohag (Ali 2014). Sohag Governorate is located in a mountainous region with most villages directly at the foot of the mountains, which poses a great danger of flash flood to the inhabitants (Yasser 2017). To deal with the problem, Sohag authorities decided to create a comprehensive plan for flood management aimed at protecting areas affected by frequent flash floods (Maqbool 2019; Khalid 2019; Al-Ghwait 2019), including Nagaa Mobarak Village.

Nagaa Mobarak Village is located in the eastern region of Sohag Governorate, Egypt (latitude 26°45'31" N to 26°44'45" N, longitude 31°37'02" E to 31°35'44" E, Fig. 1). The total village area is 4.2 km<sup>2</sup> out of which 28% represents inhabited area, 2% is unoccupied desert, and 70% is agricultural area. The soil texture data in the study area obtained



**Fig. 1** Location of Nagaa Mobarak Village (the Study Area)

from the SoilGrids system (ISRIC 2020) determined the area were comprised of sandy clay with gravel classified as group D according to the United States Department of Agriculture (USDA)- Natural Resources Conservation Service (NRCS) (USD 1968). The elevation ranges from 34 to 50 m above sea level (MASL), and the area is bounded from the east by a limestone plateau with elevations ranging from 59 to 87 MASL. The village is at a high risk of flash floods, especially from the eastern part. Based on the Egyptian governmental data, the village population is 13,000. According to the Köppen climate classification, Nagaa Mobarak Village has a hot desert climate and receives between 25 and 200 mm of rainfall annually (Laity 2008).

## 2.2 Methodology

The methodology followed in this paper is summarized in Fig. 2 and elaborated on further in the following sections.

### 2.2.1 Data Collection

The topography of the study area and the historical precipitation data play a role in determining the catchment characteristics. The current physical and chemical characteristics of the water are required to understand the baseline situation on water quality and estimate the future situation. Finally, climatic data (including temperature) are required to analyze the impact of climate change on water quality and quantity. Precipitation, topography, and climatic data as well as physical and chemical water characteristics were collected as follows:

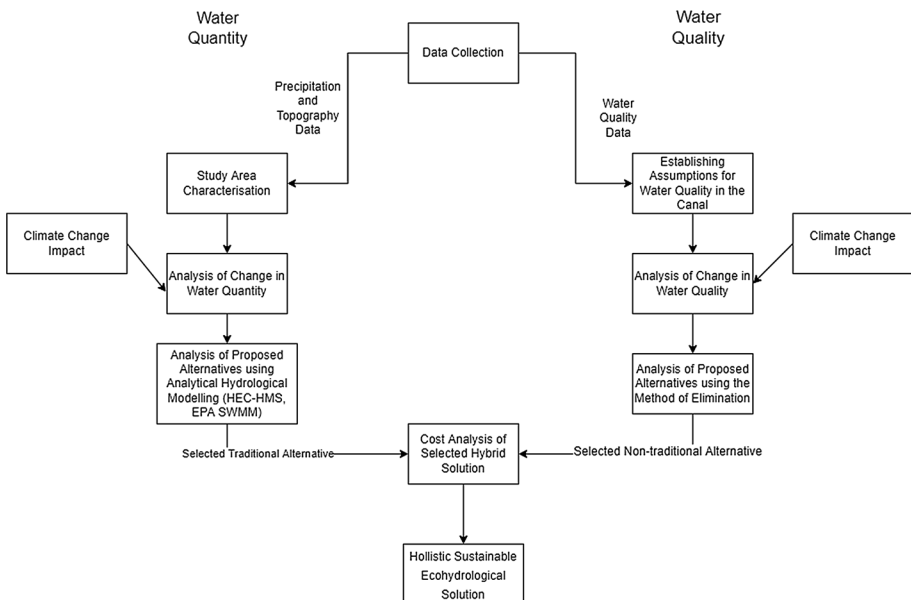


Fig. 2 Methodological framework

- (a) **Climate Data.** Three datasets were used to collect climate data from the Climate Explorer website of the World Meteorological Organization, namely AR5 CMIP5, CMIP5 ensemble, and CMIP5 one member (Climate Explorer 2020). Two different datasets were obtained from the latter, one for when the risk ratio (RR) was greater than 95% and one for when it was greater than 99%.
- (b) **Annual Precipitation Data.** Rainfall data (Fig. 2) were obtained from the Tropical Rainfall Measuring Mission (TRMM) satellite and Global Weather Data for Soil & Water Assessment Tool (SWAT) 2019 (Global Weather Data for SWAT 2020; NASA 2020). The highest value (83 mm) was considered to be the design basis for water quantity analysis as a conservative measure.
- (c) **Water Quality Data.** Very little is known about water quality data for the Nagaa Hamadi Canal (NHC, Table 1) with the only available information coming from sampling campaigns in 2001 (El-Sheekh 2009) and 2008 (NRI 2008). The time of sample collection is unclear but by comparing the data with data from other water bodies in Egypt, it can be assumed that the measurements were obtained in the winter (Fig. 3).

However, data that are two decades old are unreliable, especially considering the major developments in the country. Therefore, recent water quality data from another waterbody connected to the NHC were used for water quality analysis. Morsy et al. (2020a, b) examined water quality in several Egyptian lakes (e.g., Lakes Maryut, Idku, Burullus, and Manzala), highlighting variations in parameter values across the year. Lake Manzala, which had the lowest dissolved oxygen (DO) and highest biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values, was selected as the basis for the water quality assessment in this study. To ensure a fair comparison of the water quality data, a water quality index (WQI) was determined using the methodology reported by Sanchez et al. (2007). These authors proposed using Eq. (1) as the empirical representation of the WQI:

$$WQI = k \frac{\sum_i C_i P_i}{\sum_i P_i} \quad (1)$$

where  $k$  is a subjective constant with a maximum value 1.0 for apparently good quality water and 0.25 for apparently highly polluted water,  $C_i$  is the normalized value of the parameter, and  $P_i$  is the relative weight assigned to each parameter.

As suggested by Sanchez et al. (2007), the constant  $k$  was not considered to avoid subjective evaluation, and the suggested values for  $P_i$  and  $C_i$  are summarized in Table 2. The WQI values from 0 to 25 were ranked as very bad, values ranging from 26 to 50 were bad, values ranging from 51 to 70 were fair, values ranging from 71 to 90 were good, and values ranging from 91 to 100 were excellent. Because of the lack of water quality data, the WQI was estimated using only OD ( $P_i=4$ ) and temperature ( $P_i=1$ ). Table 3 summarizes the corresponding water quality parameters at Lake Manzala for different sampling months.

## 2.2.2 Data analysis

For water quantity, analytical tools in hydrological software were used to estimate the impacts of climate change on flooding in the study area. The selection of these analytical tools was done to minimize the model inputs as much as possible given the uncertainty associated with obtaining outdated real-life data, which is the main available data source. Additionally, this study aims at estimating a one-of-the-worst-case scenario flash flood event analyzing the magnitude of the impact only and proposing conservative

**Table 1** Water quality at the Nagaa Hammadi Canal (NHC)

Canal	DO (mg/L)	COD (mg/L)	BOD (mg/L)	TDS <sup>a</sup> (mg/L)	TSS <sup>b</sup> (mg/L)	FC <sup>c</sup> (MPN <sup>d</sup> /100 mL)	Reference
East NHC	6.3	25	5.8	213	9	1750	El-Sheekh (2009)
West NHC	7.2	18	4.3	200	6	2500	El-Sheekh (2009)
Average WQ* at NHC	6.8	21.5	5.1	206.5	7.5	2125	El-Sheekh (2009)
NHC	8.5 to 9.5	11 to 17	1.5 to 3.5	NA	NA	NA	NRI (2008)
Egyptian Standard	>5	<10	<6	<500	NA	<2500	(Law 48/1982)

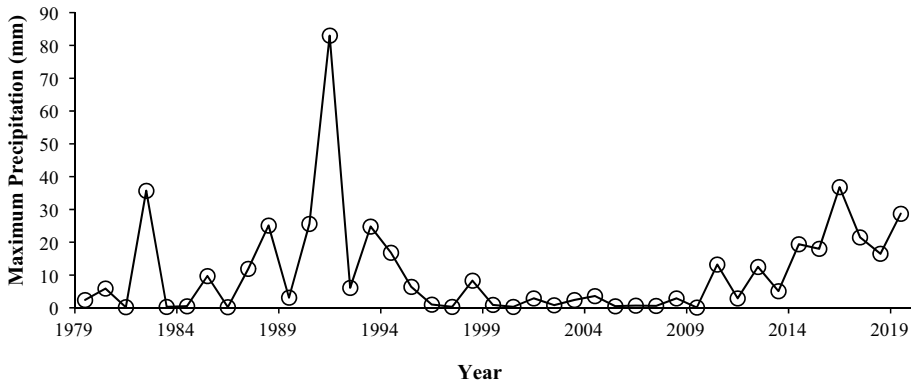
\*Calculated from (El-Sheekh 2009);

<sup>a</sup>TDS=Total dissolved solids;

<sup>b</sup>TSS=Total suspended solids;

<sup>c</sup>FC=Fecal coliforms;

<sup>d</sup>MPN=Most probable number



**Fig. 3** Annual maximum precipitation from 1998 to 2019 based on TRMM satellite data (NASA 2020)

**Table 2**  $P_i$  and  $C_i$  values for DO and temperature ( modified from Sanchez et al. (2007))

Parameter	$P_i$	$C_i$										
		100	90	80	70	60	50	40	30	20	10	0
DO	4	7.5	>7.0	>6.5	>6.0	>5.0	>4.0	>3.5	>3.0	>2.0	>1.0	<1.0
Temperature	1	12/16	22/15	24/14	26/12	28/10	30/5	32/0	36/-2	40/-4	45/-6	>45/<-6

**Table 3** Water quality for Lake Manzala (adopted from Morsy et al. (2020a, b))

Parameter	January	March	June	September	December
Temperature (°C)	15.3	22.1	32.3	33.2	17.2
DO (mg/L)	5.1	5.3	3.0	3.2	5.4
pH (unitless)	8.2	8.1	8	8.5	8.7
Turbidity (NTU)	6.9	13.2	16.3	12.1	2.95
TSS (mg/L)	22	18.6	74.1	71.9	62.85
BOD (mg/L)	15	30	48.6	35	13.5
COD (mg/L)	120	240	388.8	280	106.2
WQI	66	66	32	30	68

alternatives to manage the event. Risk assessment methods commonly used in the literature (Lyu et al. 2018, 2020; Lyu et al. 2019a, b, c) are not within the scope of this research as the probability of occurrence is out of boundaries.

The Watershed Modeling System (WMS 11.0) software developed by Aquaveo (Utah, United States) was used for watershed delineation. The Environmental Protection Agency Storm Water Management Model (EPA-SWMM) was used to design the proposed structural element (the routing channel). The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) developed by the U.S. Army Corps of Engineers was used to simulate flash floods to obtain useful data such as the peak discharge flow, time to peak discharge, and runoff volume.



The terrain surface was represented using a 30×30 m digital elevation model (DEM) called the Shuttle Radar Topography Mission (SRTM) (Survey 2020). Virtual Terrain Builder (VT Builder) was used to interpolate the missing data in the DEM (Project 2018). The complete DEM retrieved from VT Builder as well as the watershed characteristics (i.e., soil type, curve number (CN), slope) was used by the WMS software for watershed delineation into basins and subbasins, as well as computing accumulated flow and flow directions. The hypothetical Soil Conservation Service (SCS) type II distribution was found to be suitable for deriving the 24-h time distribution during extreme events in the study area (Awadallah et al. 2016, 2017; Romero and Emanuel 2017; El-Sayed 2018). The return period was estimated to be 100 years (Water Resources Publication 2008; Youssef 2016).

The HEC-HMS was used to simulate flash floods in every basin and subbasin in the study area (Hydrologic Engineering Center 2006), which provided details on the peak discharge flow, time to peak discharge, and runoff volume (Dweependra 2008). Finally, EPA SWMM was used for simulating a 100-year return period flash flood using 30-min time steps (U.S. EPA 2020).

Given the complexity of natural processes and the required amounts of high-quality accurate data to be able to model ecohydrological solutions with acceptable results, this study analyzes the methods proposed to safeguard water quality during flash floods using the scientific logical elimination approach based on data collected from the lecture.

### 2.3 Contribution to the SDGs

As mentioned, this research also studies the contribution of hybrid ecohydrological solutions to the achievement of the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations 2015). Through systematically reviewing the description of the UN SDGs, we have identified which standards exactly are supported by our solution. A discussion of the contribution to the SDGs follows presenting and discussing our results and exploring the proposed solution for our case study.

## 3 Results and discussion

### 3.1 Study area characterization

Figure 4 shows the results of the full catchment delineation study, which were obtained following the same approach reported by Abdeldayem et al. (2020), Ramakrishnan et al. (2009), and Durga Rao et al. (2003). During the design of the proposed flood management solution, the collection site was assumed to be initially empty. Rainwater infiltration and evaporation were also considered during channel design. Based on the weather conditions in the study area, the evapotranspiration rate was assumed to be 5 mm/day (Baldi et al. 2020). Subsurface storage depends mainly on the soil type, which is classified as cultivated sandy clay with an infiltration rate of 6.5 mm/h in the study area (Mangala et al. 2016).

As mentioned, the DO contents of Egyptian water bodies under current weather conditions and water temperatures were obtained from the study by Morsy et al. (2020a, b). The DO concentration was used because of its simple relation to water temperature. Water quality at Lake Manzala was considered representative of the NHC because it exhibited the lowest DO concentration. However, because temperatures at Lake Manzala are for water (Morsy et al. 2020a, b) and temperatures predicted by the model are for air, the relationship



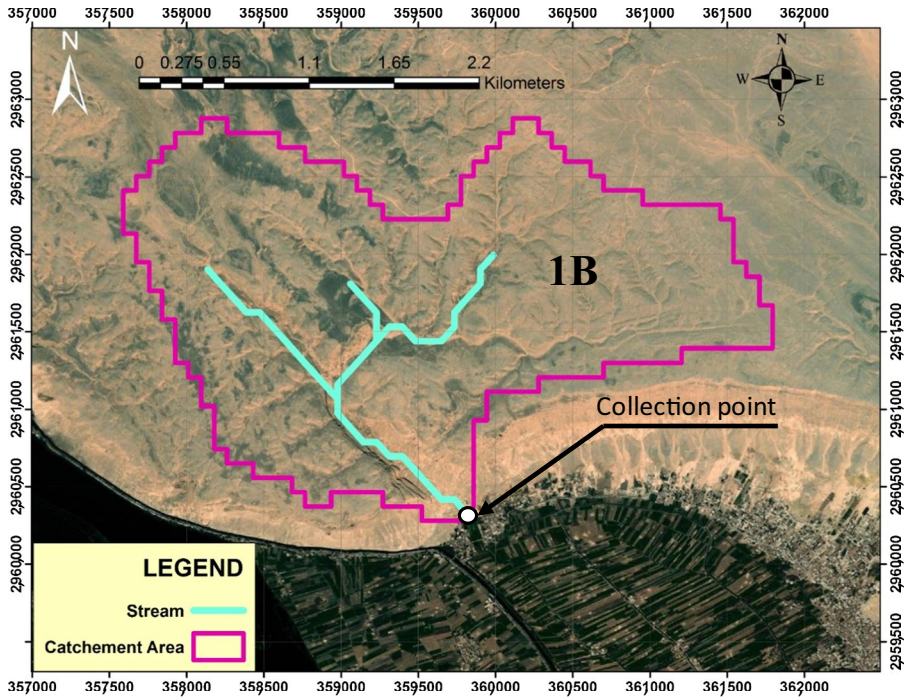
**Fig. 4** The United Nations Sustainable Development Goals

between water and air temperatures must be determined. Morrill et al. (2005) identified a relationship between water and air temperatures for diverse streams. Their results show that a 0.6 °C increase in water temperature occurs for each 1 °C increase in air temperature given the higher water heat capacity. It is estimated that every 1.7 °C increase in air temperature corresponds to 1 °C increase in water temperature, which is associated with a 0.25 mg/L decrease in DO content. Therefore, a 1.8 °C increase in water temperature corresponds to a 3 °C increase in air temperature (Morrill et al. 2005) and a 0.45 mg/L decrease in DO concentration. These estimates were used to predict any decreases in the DO concentration that reach critical levels and endanger the stream ecology. By identifying these events, mitigation measures can be implemented to protect water quality from the impacts of climate change, which are needed considering the expected decrease in fresh water quantities in Egypt associated with climate change (Omar et al. 2021).

### 3.2 Climate change analysis

Climate change is associated with increased temperatures and changes in precipitation regimes (Orlob et al. 1996). These two factors lead to variations in water quantity and quality from usual conditions (Morsy et al. 2017; Moss et al. 2011). For example, an increase in precipitation leads to an increase in water nutrients, which encourages harmful algal blooms and depletes DO concentrations in water. Similarly, increased temperatures increase sediment and soil mineralization that spike nutrient loads, which increases the risk of harmful algal blooms that in turn consume DO (Ostad-Ali-Askari et al. 2020). Quantifying nutrient content in water is complex because it involves considering multiple factors, from air quality to land use in the catchment area (Jeppesen et al. 2009). The DO concentration was selected as a proxy for water quality because this parameter is largely directly affected by temperature (Mackay and Fleming 1969).

Figures 5, 6, and 7 show the expected precipitation variation using different risk ratios (RRs) obtained from Coupled Model Intercomparison Project – Phase 5 (CMIP5) and the expected change in air temperature due to climate change from the AR5 CMIP dataset. As shown in Fig. 5, an increase in precipitation is expected in the study areas for all scenarios



**Fig. 5** The watershed and collection point for the study area

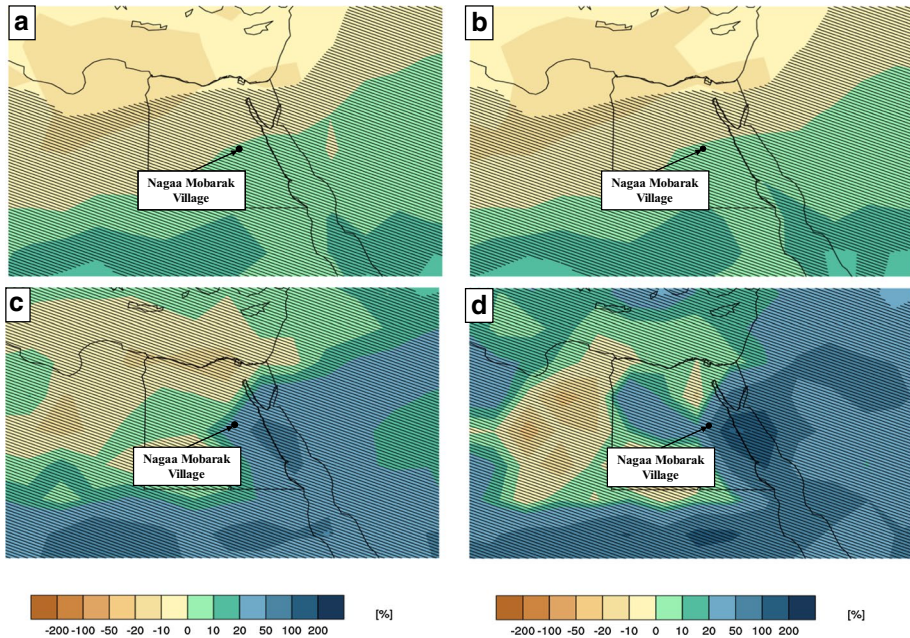
ranging from 10 to 100% based on the different datasets. In Fig. 6, the CMIP5 one member datasets with different RRs show a precipitation increase of up to 120 mm/year, which represents a 50% increase from the 83 mm/year estimated in a 1991 report (the highest in 40 years). Finally, according to the National Oceanic and Atmospheric Administration (NOAA), the world has witnessed a 0.8 °C increase over the past 100 years (Bradford 2017). Figure 7 shows that temperature in the study area is expected to increase 3 °C.

### 3.3 Water quantity analysis

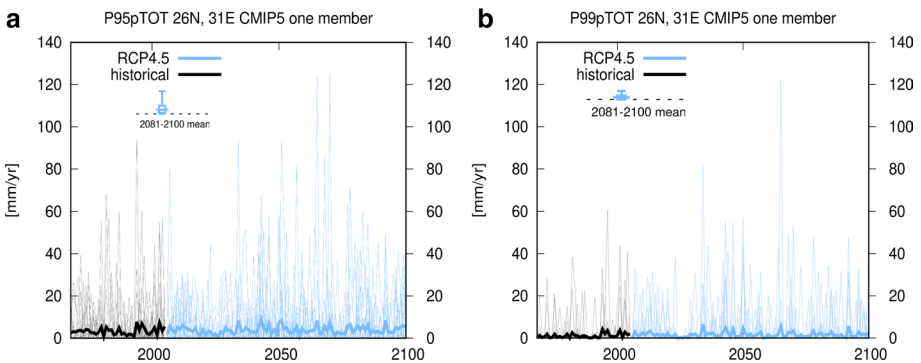
The WMS software generated a delineated watershed with a 6.40 km<sup>2</sup> area. Table 4 summarizes the morphological data of the basin. The short lag time is mainly due to the small area of the watershed and the high stream slope (0.0576 m/m).

The total runoff volume estimated for Nagaa Mobarak Village is 275,000 m<sup>3</sup> for the 100-year return period considering the increase in precipitation due to climate change. Although this is not a significant amount of water, it poses a great risk because the short lag time (Abdulkareem et al. 2019) and low elevation of the village, which is located 25 m below the watershed at almost 51.5 MASL at the scale locations (Fig. 8).

A variety of solutions for flood management were identified that are commonly implemented, including storage ponds, routing channels, and dam construction (van Wesenbeeck et al. 2014). All these potential solutions are discussed in Sect. 4. It is worth noting that all are considered end-of-pipe solutions that focus on handling the generated floodwater and



**Fig. 6** Expected change in future precipitation due to climate change, mean Representative Concentration Pathway (rcp45) relative precipitation 2081 – 2100 minus 1986 – 2005: **a** AR5 CMIP5, **b** CMIP5 ensemble, **c** CMIP5 one member when risk ratio (RR)>95p, and **d** CMIP5 one member when RR>99p (Climate Explorer 2020)



**Fig. 7** Expected change in precipitation due to climate change CMIP5 one member when: **a** RR > 95p and **b** RR > 99p (Climate Explorer 2020)

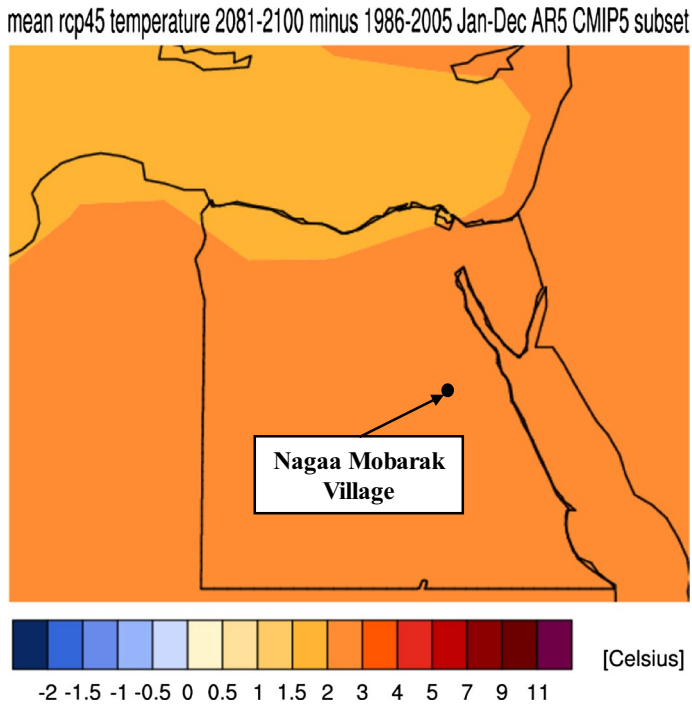
not on decreasing its amount or using it for other purposes, which is considered a major drawback (Marijnissen et al. 2020; Stefanakis 2019; van Wesenbeeck et al. 2014).

### 3.4 Water quality analysis

Table 5 shows water temperature and DO concentration changes due to climate change. Figure 9 shows the DO and temperature variation throughout the year considering climate

**Table 4** The morphology characteristics of the basin (IB) in the study area

Parameter	Area (km <sup>2</sup> )	Basin slope (m/m)	Max flow slope (m/m)	Max stream length (m)	Max stream slope (m/m)
Value	6.4	0.0005	0.05	3822	0.06
Parameter	Basin length (m)	Basin perimeter (m)	Basin shape factor (m <sup>2</sup> /m <sup>2</sup> )	Basin Average elevation (m)	Lag time (h)
Value	3039	15,149.5	1.4	232.9	0.6



**Fig. 8** Expected change in the future air temperature due to climate change (AR5 CMIP5) (Climate Explorer 2020)

**Table 5** Expected temperature and DO content due to climate change

Parameter	January	March	June	September	December
Temp (°C)	17.13	23.87	34.1	34.97	19.04
DO (mg/L)	4.62	4.81	2.5	2.75	4.96
WQI	58	58	24	24	60

change impacts. As shown in Table 5, temperature increased 1.8 °C and DO concentration decreased 0.45 mg/L from the values shown in Table 2. Considering the DO concentration values shown in Table 2, this decrease in DO may not significantly impact water quality or harm aquatic organisms during winter months. However, DO concentration during the summer reaches a minimum of 2.5 mg/L, which is lower than the recommended minimum DO for a level B protection of the health of aquatic organisms in fresh water bodies (4 mg/L) (Davis 1975). Level B protection implies that some organisms may exhibit symptoms of oxygen distress if the DO value remains at a set level for more than few hours (Davis 1975). Additionally, when the WQI values are used to compare water quality, the results are significant. As shown in Table 3, water quality in the NHC was found to be fair for the sampling campaigns in January (WQI=66) and March (WQI=66), whereas it was found to be bad in June and September (WQI=32 and 30, respectively) followed by a recovery in December when the water quality was fair again (WQI=68). The effect of climate change is significant in results from Table 5 because although water quality remains

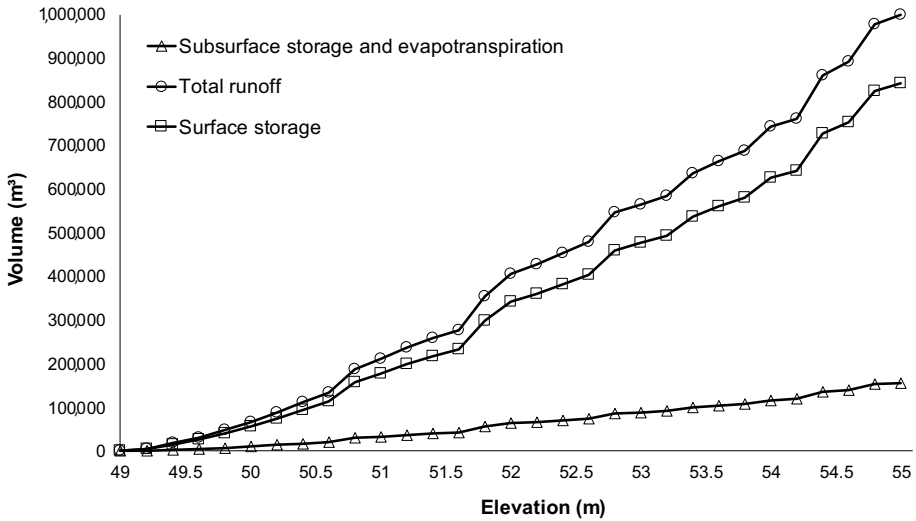


Fig. 9 Cumulative storage volume curve for the Naga Mobarak Village

fair for the January to March period (WQI=58 in both cases), it reaches the very bad category during June and September (WQI=2.5 and 2.75 for June and September, respectively) and does not recover until later in December (WQI=60). Clearly, the increase in water temperature significantly affects water quality and poses a threat to aquatic organisms, basin productivity, and the local economy (Fig. 10).

A sustainable approach is needed to design flood management alternatives that considers the three pillars of sustainability: people, profit, and the planet. The first two pillars

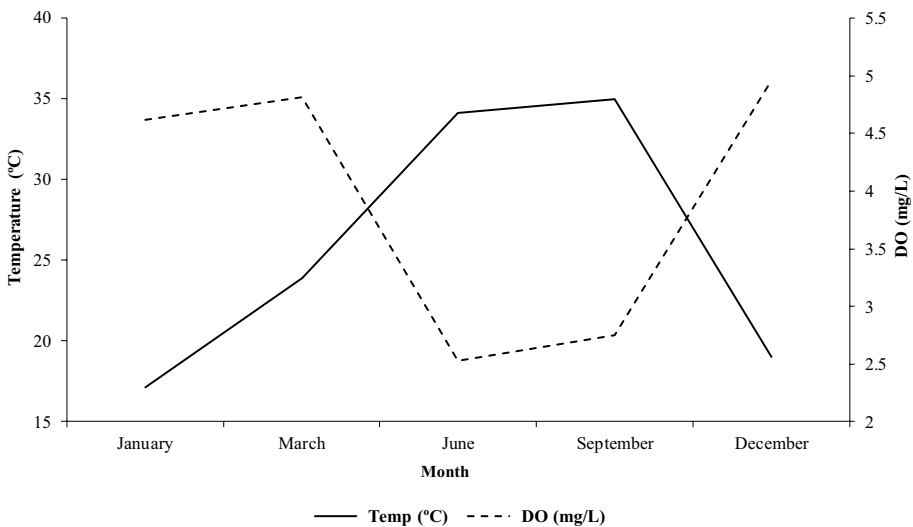


Fig. 10 DO and temperature variation given the impacts of climate change



**Fig. 11** The location of the proposed flood channel

were achieved by analyzing management alternatives to protect against the increased precipitation and associated damage to lives and properties. Only the third pillar still needs to be addressed. By using water quality to identify and analyze alternatives, the selection is bound to be more sustainable and resilient. This shall be further enhanced by integrating concepts of ecohydrology that focus on the interactions between biological systems and water bodies to ensure the prosperity of both (Fig. 11).

## 4 Holistic, sustainable ecohydrological solutions

### 4.1 Traditional management alternatives

The first proposed alternative is an artificial pond to collect the runoff at the collection point. The flood water collected in the artificial pond can be used for groundwater recharge (Morsy et al. 2018). However, a geological study found that Nagaa Mobarak Village is located on karstified carbon aquifer zone characterized by high salinity (Mosaad 2019). Consequently, using harvested rainfall for groundwater recharge is not feasible. Moreover, the pond would require a large area of land that might result in physical or economic displacement for local inhabitants in the area. Therefore, this alternative was not considered further (Ostad-Ali-Askari and Shayannejad, 2021).

The second proposed alternative was a dam that would act as a water barrier and store flood water. However, damming is a high-cost alternative for infrequent flash flood events. Damming is also considered a gray infrastructure solution, which is considered to be unsustainable and even increase climate change impacts (de Vriend et al. 2015; Peng et al. 2017). Therefore, this alternative was rejected based on economic and environmental points of view and was not considered further.

The third alternative was to construct a routing channel to transfer flood water directly to the NHC, which would protect the village from flash flood risks and conserve water by reusing flood water for irrigation (Mostafa and Peters 2015). This alternative was found to be cost-effective compared with the relatively high costs of dam and pond construction.



**Table 6** Properties of the proposed flood channel (FAO Training 2016; Abdelhaleem et al. 2016)

Parameter	Unit	Proposed flood channel	Existing infrastructure (NHC)
Depth	m	1.0	4.0
Bottom width	m	2.0	8.0
Side slope	–	1:1	3:2
Longitudinal slope	cm/km	1.5	2.03
Flow rate	m <sup>3</sup> /sec	6.0	5.0

Moreover, it introduces the possibility of reusing almost 275,000 m<sup>3</sup> of flood water for irrigation. The most common crop in this region is sugarcane, which needs almost 18,000 m<sup>3</sup> of water per hectare (Petheram and McMahon 2019). Conserving 275,000 m<sup>3</sup> of flood water would help cultivate approximately 15 hectares of sugarcane. Sugar beet is also commonly cultivated in this region and requires almost 5950 m<sup>3</sup> of water per hectare (Farang et al. 2017). In this case, approximately 46 hectares of sugar beets can be cultivated. Therefore, constructing a routing channel is considered the optimal traditional solution to manage the increase in water quantity from flash floods in light of climate change.

Table 6 shows the necessary characteristics of the proposed flood channel for the NHC generated using the EPA SWMM software to ensure the extra flow can be accommodated. The results show that the existing canal cross section will accommodate the flood water and the water depth in the canal will not exceed 2 m, which is less than its design capacity (2.5 m).

## 4.2 Non-traditional management alternatives

Although traditional engineering solutions (gray infrastructure) have been commonly used in flood management, scientific evidence has been found that links increasing urbanization to a decrease in the provision and regulation of ecosystem services, including flood management (Peng et al. 2017). Therefore, the use of traditional solutions is considered unsustainable in light of the role played by ecosystem services in the environment (Bolund and Hunhammar 1999). The concept of NBS could be beneficial in planning for flood management measures that have the potential to improve water quality and protect lives and assets.

Wetlands, including constructed wetlands, are essential components for climate change adaptation and mitigation, as well as core elements for nature-based stormwater flood management (Erwin 2009; Malaviya and Singh 2012; Scholz and Lee 2005). Their advantages include achieving peak flow attenuation and water purification (Heal et al. 2006; Malaviya and Singh 2012; Wheeler and Evans 2009) using natural elements with a net positive environmental impact. The concept of constructed wetlands has been widely described as a nature-based flood defense, and its efficacy has been proved at the landscape scale in several countries (de Vriend et al. 2015; Dou et al. 2017; McVittie et al. 2018). Generally, urban and agricultural stormwater runoff is characterized by a variety of pollutants from suspended solids to heavy metals depending on the land use (Kadlec 2009; Stefanakis 2019). Constructed wetlands have shown their potential to remove pollutants with varying efficiency (Fralely-McNeal et al. 2007). Therefore, including a constructed wetland along a section of the channel built to divert flow into the NHC would decrease runoff volume and peak time so that the capacity of the canal is not exceeded during a flood event

and incoming stormwater is purified, which would improve stormwater quality and ensure NHC ecosystem health (Pirnazar et al. 2018). This was considered the optimal alternative from an ecohydrological perspective. Harrington (2019) estimated that the typical required hydraulic retention time (HRT) in a constructed wetland for stormwater management is five days and Blick et al. (2004) suggested an average depth of 3 m is required for treatment. For the purposes of this study case, in which the main wetland function is as a storage buffer and water purification is an auxiliary benefit, the proposed HRT is one day for half runoff flow ( $137,500 \text{ m}^3$ ) and the required area equals  $45,000 \text{ m}^2$ .

### 4.3 Economic analysis of the ecohydrological solutions

The main cost components for constructing the channel are the drilling and lining. The cost of different construction items was estimated based on quotations received from independent contractors working near to the study area (Sohag Governorate) in late 2020. The quotations included materials, transportation, and labor costs (Table 7). The operational and maintenance cost was assumed to be 5% of the capital costs for the routing channel (Houle et al. 2013; Petheram and McMahon 2019).

A cement lining with a thickness of 5 cm was selected based on the channel discharge and water depth and because of its long life, high durability, resistance to erosion, structure stability, and high permissible velocity. Table 8 illustrates the total cost estimate for channel construction operations. The total cost was \$92,050 including construction and operations and maintenance (O&M) costs.

As for the constructed wetland, the main cost components are listed in Table 9 along with the cost per acre ( $\sim 4047 \text{ m}^2$ ). It is worth noting that cost estimates were published from Texas, the United States of America (Sea Grant Texas 2012). The total construction of 11 acres would cost a minimum of \$275,000. However, costs could fluctuate from the

**Table 7** Cost estimate per meter per process

Item	Cost (\$)
Drilling	0.45
Pitching	19.23
Cement	58.00
Reinforced concrete	46.50

**Table 8** Total construction costs of the channel for the 100-year return period

Length (m)	Area ( $\text{m}^2$ )	Perimeter (m)	Lateral Area ( $\text{m}^2$ )
<i>Construction Cost</i>			
313	3	4.83	4.83
Drilling cost	\$423		
Cement lining cost	\$87,200		
Total construction cost	\$87,650		
O&M costs	\$4400		
Total cost	<b>\$92,050</b>		

**Table 9** Cost estimate per acre per component (Sea Grant Texas 2012)

Item	Cost per Acre
Earthworks and grading	\$5000 to 15,000
Aquatic plants	\$10,000 to 20,000
Spillway structure	\$10,000 to 15,000
Total	\$25,000 to 50,000

stated values and are expected to decrease significantly when relying on local supplies for the construction of the wetland.

#### 4.4 Limitations and application range of the proposed solution

Although the proposed solution provides a plethora of benefits compared to traditional engineering flood management solutions, it still has its disadvantages. Wetlands, for example, require a large land footprint; they require more time for water treatment compared to traditional technologies and are associated with more uncertainties and vulnerabilities being dependent of natural resources to function (Andrikopoulou et al. 2021; Haddis et al. 2020; Oral et al. 2020; Rigotti et al. 2020). All of these requirements limit the large-scale implementation of nature-based and hybrid solutions despite their proved environmental superiority (Haddis et al. 2020; Oral et al. 2020). However, Egypt, and especially upper Egypt, is not in need of physical space. The area is mostly arid with groundwater only found at hundreds of meters below ground level. The wetland can be constructed at a vacant area at a distance from the village to be able to retain the water until its quality improves and provides enough buffer time to prevent the flooding of the canal. Finally, given the innovation of the solution, constant monitoring is imperative, especially in the early life of the project, in order to ensure the technology is working probably and further learn about the processes.

### 5 Contribution to the SDGs

According to Vörösmarty et al. (2018), investing in water security and flood management directly support to adoption of and public commitment to the SDGs. After assessing the impacts of our research using the UN's sustainable development goals, targets and indicators, our results found that through implementing the holistic sustainable approach to flood management, 10 out of the 17 goals will be impacted positively. Out of the 169 SDG targets and 232 unique indicators, the proposed approach to flood management contributes to 26 targets and 29 indicators, as presented in Table 10 below. The solution proposed in this study contributes, as would be expected, to two goals more than others, namely the sixth and eleventh goals. The solution supports to five indicators of the sixth goal on sustainable management of water; and six indicators of the eleventh goal on making cities safe, resilient and sustainable. The results of our SDG analysis are similar to what Andrikopoulou et al. (2021) found when applying their framework to identify the SDG contribution of fluvial nature-based solutions.

**Table 10** A summary of the contribution of our research to the UN SDGs

SDG goal	Relevant SDG target description	Relevant SDG indicator description	Relation to the solution
Goal 1 (End poverty in all its forms everywhere)	1.5 Disaster Mitigation	1.5.2 economic losses due to natural (flooding) disasters 1.5.3 Number of countries aligning with Sendai Framework for Disaster Risk Reduction	Minimizing economic losses by saving already existing assets from flooding risks The project will enhance Egypt's Aligning with Sendai Framework for Disaster Risk Reduction
Goal 3 (Ensure healthy lives and promote well-being for all at all ages)	3.9 Reduction of pollutants and contaminants	3.9.1 Air pollution 3.9.2 Unsafe water	The solution would help in decreasing the rate of mortality due to air pollution, water contamination and flooding
Goal 6 (Ensure availability and sustainable management of water and sanitation for all)	6.3 Decreasing water pollution	6.3.2 Improving water quality	The solution leads in water purification by decreasing a set of water pollutants like nitrates, phosphorus, and suspended sediments
	6.5 Integrated water resources management at all levels	6.5.1 Integrated water resources management 6.5.2 Transboundary water cooperation	Integration between different water management systems
	6.6 Protection of water-related ecosystems	6.6.1 Variation of Extent of water-related ecosystems	The solution provides protection to water-related ecosystems like wetlands, rivers and aquifers
	6.b Support the participation of local communities in improving water management	6.b.1 Community engagement	The planning and implementation of this project would require participatory processes and Community engagement
Goal 8 (Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all)	8.3 Promoting development-oriented policies	8.3.1 Employment	New jobs created (constructing the channel and maintaining natural elements as vegetation)
	8.5 Achieve full and productive employment	8.5.2 Unemployment rate	Preserving the employment rate by protecting the existing assets
Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation)	9.4 Reducing CO <sub>2</sub> emissions	9.4.1 CO <sub>2</sub> emissions	The vegetation will lead in capturing and reducing CO <sub>2</sub>

**Table 10** (continued)

SDG goal	Relevant SDG target description	Relevant SDG indicator description	Relation to the solution
Goal 11 (Make cities and human settlements inclusive, safe, resilient, and sustainable)	11.3 sustainable human settlement planning and management in all countries	11.3.2 Public engagement strategies	Public party would be considered as a main stakeholder in this project
	11.5 Reducing number of deaths due to natural disasters	11.5.1 Number of deaths	The solution will decrease the number of people affected by floods that could threaten their lives
		11.5.2 Direct economic losses due to damage to services and infrastructure	Preserving the values of the assets from being damaged by the floods
	11.7 Access to safe green and public spaces	11.7.1 Open space for public use	Accessibility to public areas will be maintained or increased with the availability to perform regular activities
	11.a Positive economic, social and environmental links	11.a.1 Development plans accounting for future projections	This solution works mainly for development of better future
	11.b Holistic disaster risk management at all levels	11.b.1 Aligning with Sendai Framework	The project aligns with Sendai Framework
		11.b.2 Alignment of local and national strategies	Integrating between local and national strategies
Goal 12 (Ensure sustainable consumption and production patterns)	12.2 Achieving the sustainable management and efficient use of natural resources	12.2.2 Domestic material consumption per capita	Less money spent on this solution comparing to traditional management
	12.7 Procurement of sustainable practices	12.7.1 Sustainable action plans	Engagement of different stakeholders like the public and governmental parties

Table 10 (continued)

SDG goal	Relevant SDG target description	Relevant SDG indicator description	Relation to the solution	
Goal 13 (Take urgent action to combat climate change and its impacts)	13.1 Strengthen resilience and adaptive capacity	13.1.1 Number of directly affected persons attributed to disasters per 100,000 population 13.1.2 Aligning with Sendai Framework for Disaster Risk Reduction	Expected decrease in the number of persons affected by floods  The proposed solution goes with aligning with Sendai Framework	
	13.2 Integrating climate change measures into national policies	13.2.1 adaptations to climate change	The solution will ease the process of adaptability to climate changes policies	
	13.3 Climate change education	13.3.1 Knowledge and development spread	Increase awareness of climate change technologies and policies	
	Goal 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss)	15.1 Biodiversity and protected areas	15.1.2 Providing protected areas for biodiversity	The solution creates protected areas and eliminates flooding risk factors that could threaten the biodiversity in the area
		15.3 Preventing land degradation	15.3.1 Halting the degradation and erosion of land and soil	Elimination of erosion and sediments traps
		15.6 Sharing benefits	15.6.1 Policy frameworks to ensure fair and equitable sharing of benefits	Sharing of benefits between different stakeholders
Goal 17 (Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development)	15.a Biodiversity and ecosystems	15.a.1 Conservation of biodiversity and ecosystems	Decreasing the risk of floods helps in preserving biodiversity and ecosystems	
	17.14 Aligning with national policies	17.14.1 Mechanisms for sustainable development	The solution goes in coherence with national policies and development plans	
	17.15 Respect country's policies	17.15.1 Utilizing country-owned resources		
	17.17 Encourage and promote effective public, public–private and civil society partnerships	17.17.1 Partnerships	Forming partnerships	

## 6 Conclusions

This paper offers a sustainable strategy for flash flood risk management in arid regions. The novelty of this study is based on addressing the dual effect of climate change on water quantity and quality. Moreover, it highlights the contribution of nature-based flood management methods to the SDGs. The village of Nagaa Mobarak in Souhag, Egypt, was taken as a case study given its historical precipitation record and vulnerability to flash floods. Due to climate change, the average precipitation in the study area is expected to increase by about 50%, while the temperature in the area is expected to increase by 3°C. Changes in these two factors lead to variations in water quantity and quality from regular conditions, and these variations need to be quantified and assessed in order to develop a holistic sustainable strategy for flood risk management. The study utilized modeling software to estimate the change in water quantity as a result of climate change and an ecohydrological approach covering to improve the expected water quality deterioration for watershed assessing both traditional and non-traditional management solutions. A comparative analysis was carried out for the proposed management alternatives in terms of efficiency and sustainability, followed by a cost estimate for the selected solution. The results of the study show that the optimal flood management measure is a hybrid one that employs both traditional and non-traditional solutions for flood management. A constructed wetland along a section of the constructed channel for diverting flow into the Nagaa Hammade Canal would serve to decrease the runoff volume and peak time so that the capacity of the Canal is not exceeded in a flood event as well as purify the incoming stormwater improving its quality and ensuring the health of the ecosystem within the canal. It is considered the most optimal of the three alternatives from an ecohydrological perspective. The proposed alternative supported the accomplishment of 29 indicators, 26 targets and 10 SDGs. The most indicators fell under goals 6 and 11 on sustainable water management and resilient cities, respectively.

This study highlights the importance of integrated approaches in managing water resources and their potential to supporting the implementation of the SDGs. The main problem with most developing countries is that they overlook the effect of climate change during flood management planning. It is imperative to understand the relationship between the climate change, water quantity and quality to ensure the resilience and sustainability of our cities. Therefore, future research is required to further explore the relationship between the three especially between climate change and water quality.

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## Declarations

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