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Climate Change Adaptations for Food Security in Vulnerable Areas of the Egyptian Nile—For Tackling the Overlooked Nexus Hazards of Hydrological Extremes and Waste Pollutions

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Abstract: The Nile Delta has been suffering from complex environmental hazards caused by climate change and human-induced evolvements, which have led to adverse impacts on national food security. An unfavourable nexus between solid waste management issues and extreme hydrological events is examined mainly through extensive field investigation and literature research, which is an emerging issue affecting food safety and security whilst still being overlooked so far. The findings not only reveal the significance of the emerging issue but also support our proposed recommendations in the policy/legislation and technology sphere. This interdisciplinary research employs a holistic lens that covers diverse perspectives, including systemic problems, wastewater treatment, and environmental neuroscience, to explore the relationship between food, climate change, water management, and waste pollution, and to achieve novel discoveries for the practical adaptations of Egypt's challenges.

Keywords: the Nile Delta; solid waste management; flood management; climate change; irrigation drainage; environmental neuroscience; wastewater treatment

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1. Introduction

The Nile Delta is an important region in Egypt since the ancient time, whilst it is vulnerable in a significant part of the region in terms of economy and environment, facing complex environmental issues involving extreme weather events, soil deterioration, water shortage, pollution and sea-level rise, as well as socio-economic challenges, which are particularly acute in the West Nile Delta. In recent decades, the region suffered more weather extremes due to climate change; the severe rainfall events resulted in flooding disasters leading to heavy casualties and economic loss. In October and November of 2015, the area was exposed to severe rainfall with more than one hundred millimetres accumulated in a couple of days which destroyed more than 70,000 ha of agricultural lands and significant loss of livestock [1,2]. The extreme hydrological events not only attracted attention towards climate change effect on food security in Egypt but also highlighted some emerging adverse effects due to human-induced evolvements towards the environment, such as solid waste pollution.

The delta begins slightly around the downstream of River Nile from Cairo, which is approximately 160 km (99 mi) in length, from south to north. The focus of the study area, the West Nile Delta, has a total area of 179,000 km^2, representing around 17.7% of the total area of Egypt. The area has national significance in agricultural, livestock breeding, and aquacultural production in Egypt and relies on mainly three water sources, namely the Nile water, groundwater and rainfall (only in the northern/coastal area where rainfall substantially contributes to agricultural production). Farmers are the main stakeholders in the area, whilst many of them live in the lower places which are flood-prone areas with relatively lower socio-economic status, meaning higher community and societal vulnerability. However, the vulnerability has been further passed to food production.

Notwithstanding modern dam-building substantially mitigates fluvial flooding and increases the utilisation of river water, Egypt is, in fact, facing complex environmental problems related to and even caused by the elimination of annual flooding of the Nile River. As we can see from the aforementioned environmental issues that the complexity of them primarily comes from the combination of some natural adverse conditions of Egypt, which are climate change, extreme arid climate, and reliance on a single river. Plus, some anthropogenic evolvements, including huge and intensive population, poor economy, political upheaval, and ineffective government, some human-induced issues have hence occurred, which have been interacting with the natural ones to exacerbate the vulnerability of food security. The unique Nile water system is one of the responses to the natural constraints, which features three subsystems, namely the Nile River, supply canals, and drainage canals. Each subsystem plays a different role in the utilisation of water resource, as well as the hydrological cycle, whilst the complexity of operation involving multiple purposes has made the whole system inadequate to adapt to the complex environmental issues. On the other hand, a long-lasting challenge of country—solid waste management—is one of the most significant human-induced issues interacting with natural environmental hazards to harm food security. Although the aforementioned issues all have been discussed and studied abundantly, they were generally conducted separately. To our best knowledge, there is insufficient research in exploring the issue of unfavourable nexus between extreme hydrological events and waste management. Although this issue has just emerged due to climate change, it seems overlooking the issue is by no means a good idea as it is expected to keep increasing in the future. This paper will explore this issue through the investigation of three complex water subsystems, as the whole water system is at the frontline and most associated with waste problems in the hydrological cycle. We expect that the methodology will provide a more holistic lens to see how the nexus issue affects food security and provide new insights through such a novel approach.

This paper is organised as follows. Section 2 describes the complex environmental and food security challenges related to climate change and extreme hydrological events, followed by research questions, methodology, and study design. Section 3 presents the broad findings from the field investigation regarding the waste pollutions affecting water system and discusses specific findings in greater depth and identifies promising areas for further research. We also reflect our findings on practical recommendations proposed. Finally, conclusions are drawn and presented in Section 4.

2. Materials and Methods

2.1. Environmental Issues and Climate Change

2.1.1. Changing Flooding Pattern

The modern demand of Egyptian life has forced to change the way people use water resources and respond to natural hydrometeorological events (e.g., flooding). However, it consequently yields some environmental problems that have become dilemmas of Egyptians, especially worsened by the effects of climate change.

The Nile River has two major tributaries, namely the White Nile and the Blue Nile. Notwithstanding the White Nile is considered to be the primary stream of the Nile itself, the Blue Nile contributes 80 percent of the water of the Nile River. The two tributaries meet at the north of the Sudanese capital, Khartoum, as can be seen in Figure 1. It shows the discharges of the river at Aswan in three different periods of time, including before, during, and after the construction of the Aswan dam. Some periods are also available for discharge data at Khartoum (blue line) and El Ekhsase (yellow line). The discharges at

Khartoum show the changed pattern of discharge from the Blue Nile into the Nile River, whilst the discharges at El Ekhsase show the pattern of the Nile before water entering the delta. The annual floods in the past were generally caused by the discharges of the Blue Nile. As we can see from Figure 1, the building of the Aswan dam (in 1970) and dams upstream in the Blue Nile River dramatically reduce the annual peak of river discharge in the Nile. As a result, the annual fluvial flooding of the Nile has become history in Egypt. Moreover, although water accessibility has hence improved during dry seasons due to increased river flow, also the variability of discharge decreases in the Nile and the Blue Nile, which are the bright side of building the dams, the total volume of water in the Nile River has had significant reduction since then.

Then the ease of annual Nile flooding has incurred more settlements in the floodplain of the Nile; however, without cautiousness towards fluvial flooding that Egyptian used to have, plus the dry climate makes Egyptians neglect the importance of stormwater drainage system, even rainfall events with merely 50 mm/day intensity are prone to cause flooding disasters, which reflect the fact that the emerging pluvial flooding in the recent decades was prone to cause disasters and casualties whilst climate change has yielded more extreme weather events in recent decades. Egypt is facing more disastrous pluvial flooding events in recent decades, including 25 October 2015 in Alexandria, 4 November 2015 in Alexandria, 27 October 2016 in Hurghada, Ras Gharib, and Sohag, 24 April 2018 in the east suburb of Cairo, which have caused not only crop and livestock loss but also casualties [3–5].

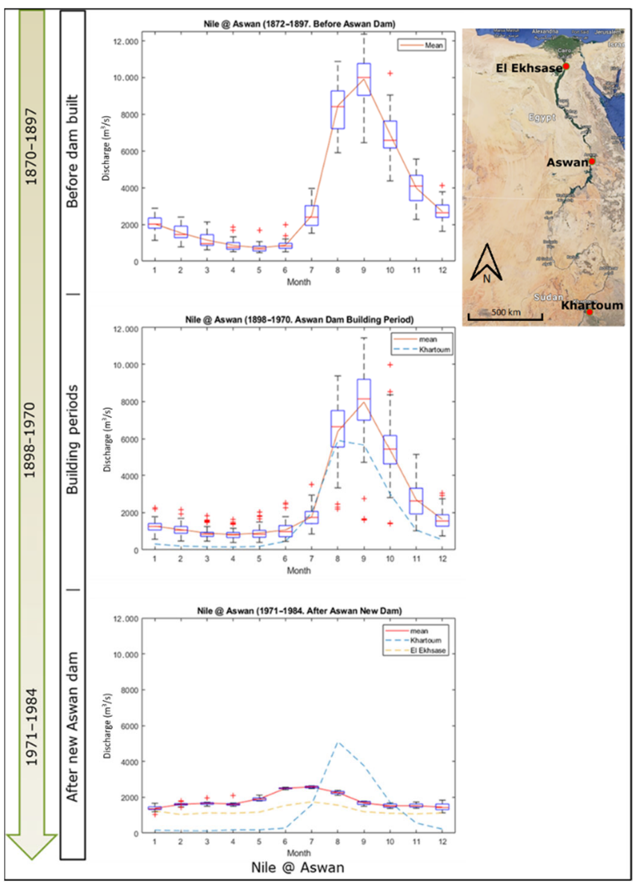

Figure 1. The change of the discharge pattern of the Nile River. Legend: The red "mean" lines in three discharge figures show the mean discharge rate of the Nile River at the downstream side of the Aswan dam; the blue lines are the mean discharge rate at Khartoum; the yellow line is the mean discharge rate at El Ekhsase.

People with relatively lower socioeconomic status often have a limited choice and would end up living in high flood risk areas such as riverbanks and coastlines, particularly during population explosion as happened in Egypt, which is one significant feature in the West Nile Delta [6]. In this area, a significant proportion of the lower socio-economic status residents are farmers. As pluvial flood events just emerged in recent decades due to climate change, Egyptians are still unaware of the risk and unprepared to react to pluvial floods, particularly for the new communities living in the lower areas which used to be suffering annual fluvial flood before late human settlements. As the discouragement of late human settlements in flood-prone areas would not be feasible due to the financial infeasibility of these residences and the lack of adequate early warning systems particularly for pluvial flood, the shifting pattern from fluvial flooding to pluvial flooding has significantly increased the vulnerability on labour and production of food security in Egypt. It also reveals that the introduction of early warning systems particularly for pluvial flood prediction is hence urgently needed. However, to achieve the establishment of early warning systems for pluvial flood, it reflects an even higher demand in ground precipitation observation than for fluvial flooding, in both spatial and temporal dimension (i.e., high spatial and temporal resolution rainfall data with sufficient coverage including the Mediterranean Sea where many storms originate), whilst ground precipitation observation is still scarce in Egypt. In fact, Egypt is still absent of ground weather radar and with a rather low density of rain gauge observations. The current ground rainfall observation system hampers the development of flood risk management tools.

The annual flooding of the Nile used to bring lots of silt, which substantially enhance the productivity and thickness of the soil [7]. However, the disappeared fluvial flood, as well as the intensive agriculture and irrigation activities after the building of the Aswan dam have caused the continuous compaction of the soil [8]. With the rise of sea level by climate change and extreme storm and rainfall, the delta is facing a serious risk of land erosion and increasing storm and pluvial flooding [9].

Meanwhile, the booming population and intensive irrigation activities after the building of the Aswan dam have increasingly caused the potential risk of water shortage. Plus, the building of the Grand Ethiopian Renaissance Dam on the upstream of the Nile River in Ethiopia causing potential negative impacts on the water supply to Egypt during the filling and operation stages [6], as well as more evaporation from reservoirs and irrigation canals caused by infrastructure expansion and rising temperature, the shortage is expected to get worse in the future [10]. It has reflected not only on water quantity, but also on water quality, whilst both effects are adverse towards food security.

To expand the cultivated area for increasing food security and economy, the Egyptian government has conducted several new reclamation projects in recent decades, whilst the increasing reclaimed land has led to excessive exploitation of groundwater, which causes great concern on seawater intrusion [11,12]. Meanwhile, another part of the west delta suffers from severe soil salinization caused by the inappropriate reuse of irrigation drainage water. Intensive irrigation activities and continuous expansion of irrigation canals have caused wet soil conditions in many areas of the west delta where there are particularly lower lands and relatively higher groundwater level. The wet soil condition, with high evaporation, has caused severe salinisation that used to be washed out by the annual Nile flooding, which has dramatically reduced the productivity of the land. Although growing rice is advantageous in reducing salinisation, avoiding seawater intrusion, and increasing profit (compared with other crops), rice cultivation can only be a limited proportion under the necessary rotation policy of growing different crops in response to the high water consumption of rice cultivation, as well as the increasing eutrophication condition of water system due to fertilisation pollution.

2.1.2. Solid Waste Pollution and Flood

Although solid waste management (SWM) and related pollution issues of Egypt have long been discussed and researched for decades, plus considerable efforts made by the government, the SWM is still inadequate and remains a principal environmental issue of Egypt [13–18]. As climate change and the building of the Aswan dam have gradually changed the flooding pattern of Egypt, the adverse interactions between flood and SWM issues in Egypt have just emerged; it is still largely neglected in the research literature. As this study considers that extreme hydrological events will increasingly have adverse interactions with solid waste that harms the food security of Egypt in the future, the study seeks to address this unfavourable nexus for Egypt when the nexus is still prone to be overlooked at the present.

Egypt annually generated 89.03 million tons of solid waste, including 30 million tons of agricultural waste, 25 million tons of waterway cleaning waste, and 21 million tons of municipal solid waste at the top three portions respectively (in 2014) [19]. Driven by population growth and changing consumption patterns, waste generation is expected to increase at a rate of 3.4% per year. What really shocks people is the fact that there is around 28% solid waste coming from waterway cleaning [19]. As a river does not produce solid waste, it means the solid waste in the watercourses is caused by inappropriate and massive dumping. Besides, with financial difficulty in continuously conducting SWM in the country, it seems not sensible in allocating financial resource in collecting solid waste from the watercourses rather than initially from the real generators, which has actually become a negative cycle and a dilemmatic effort. So far, only around 60% of the waste is collected across the country, namely less than 30% collection coverage in rural areas and 50–65% in urban areas; merely less than 20% of the collected waste is properly disposed of or recycled [19]. Only part of public spaces in major cities can be kept clean, and the rest of the country is unbelievably overwhelming. The uncollected solid waste indiscriminately exists and heaps up in unauthorised places, such as roadsides, supply canals, irrigation drainages, the Nile River and its flood plains, and open areas. Even at authorised dumping sites, amongst the municipal waste, 80–88% of it is openly dumped, meaning without proper sanitary cover and infiltration prevention. The solid waste circumstance creates odour almost everywhere and destroys landscapes and townscapes, not to mention it noticeably causes adverse effects on tourism and cultural economy.

With increasing extreme hydrological events since recent decades, solid waste is expected to cause much more pollution and harm to crops, farm soil, surface water, and groundwater and to cause diseases and health issues to humans, livestock and aquatics, which directly and indirectly affect the food security of the nation. Solid waste heaps and garbage-soil-mixed banks along watercourses is one of the most representative views in Egypt, which reveals how water resources could be considered polluted by waste due to extreme rainfall and flood. Regardless of absent exploration as to how much water pollution is caused by the waste heaps along the waterways, we can still have a bit of sense by the fact that one metric ton of landfill municipal solid waste would generate 0.2 m^3 of leachate, which often contains a considerable amount of heavy metals and toxic substances [20]. In terms of the food aspect, Egypt has the largest aquaculture industry in Africa with a market value of over $2.18 billion, which provides about 75.46% of the country's fish production [21]. The lower areas in Nile Delta are the primary place for the country's aquaculture, whilst they are also flood-prone areas. Extreme rainfall is prone to cause strong runoff and flood, which brings pollutants and leachate from solid waste heaps and dumping sites to aquaculture farms. Even without direct flood intrusion to the farms, due to the pressure in water resource, aquaculture is only legally allowed to use the water from irrigation drainages rather than from supply canals and the Nile, whereas the water quality in the irrigation drainages is generally very poor due to the pollution from wastewater, solid waste, fertilizers and pesticide [21]. Similarly, as for fishery, lake fishery contributes about 52% of the fish produces, which is mostly produced at four lakes of northern Nile Delta, namely Lake Manzala, Lake Burullus, Lake Edko and Lake

Mariout, which rely on water from the drainage canals to maintain their freshwater lake status and are also flood-prone areas [22]. Regardless of supposedly without direct contact of wastewater, fertilizers and pesticide, the supply canals and the Nile are still facing an increasing threat of solid waste pollution due to interactions with extreme hydrological events; fishery and agriculture are hence affected in food safety and production.

Through the discussions of this section regarding the nexus between solid waste pollution and flood, we pointed out that the nexus is significantly associated with all the complex environmental issues described in Section 2.1.1, including seawater intrusion, water reuse problems, soil salinization and contamination, planting rotation and improper groundwater exploitation that are decisively influencing food security which has never been brought into discussion with the waste issue.

2.2. Study Design

Egypt has a unique feature in the water system that is the whole country relies on the Nile River for supplying water for drinking and simultaneously collecting stormwater and wastewater to be discharged to the sea. To fulfil the multiple purposes, the water system has developed into three subsystems, namely the Nile and its branches, supply canals, and drainage canals. Principally, the supply canals are built to distribute clean water from the Nile to reach a wider area for domestic drinking, industry consumption, and irrigation, whereas the drainage canals are built to collect all the discharged water, including irrigation drainage water, wastewater and surface drainage water. With the building of wastewater treatment works, wastewater is supposed to be treated before discharging into the drainage canals, which means ideally the water quality in the drainage canals should be mainly attributed to agricultural activities, and hence it would be sensible to be reused for irrigation. The reuse measure was hence practised since 1970 in the Lower Egypt with a national policy established in 1975 for drainage water reuse in an attempt to improve water use efficiency and to expand the agriculture area and production [22]. However, with the impact from solid waste, plus the notable difference in collection coverage of solid waste between urban and rural areas, as well as the difference in economic activities and environmental awareness, the working principle of the three subsystems seems to be facing challenges and confusion, which will exacerbate the adverse nexus with extreme hydrological events. Despite international support and several national strategies conducted by the government, waste collection and disposal are still not performing properly [19].

Therefore, the research questions regarding solid waste are as follows: To what level does the solid waste pollute the three water subsystems, from rural to urban areas in the Nile Delta? What are the obstacles of pollution control in terms of the existing legal framework and administration? How do people recognise the issue of the unfavourable nexus? Apart from the financial difficulty that is attributed as the main obstacle, the authors also want to figure out whether the allocation of responsibilities and policing enforcement, for both governments and people, remain unclear and inadequate. To explore these questions, this research relies on field investigation and interviews with local people, to obtain further understanding covering regional differences. The recommendations in Section 3 are based on the results of field investigation and interview. The interview is non-directive and for qualitative analysis, which consists of a questionnaire with common unstructured questions for understanding essential information and status of every investigation spot, as well as specific questions for individual local context, which are subject to what the authors find and what they seek to explore. The interviewees cover local people who are the residents of the place, as well as outsiders so that we can figure out how Egyptians of different places view towards the same issue. In addition, the secondary data is obtained through statutory publications for further analysis. This study seeks to end up with a recommendation of policy through investigating the pollutant front line—the water system—to accommodate the environmental problems in terms of the adaptation of climate change for food security.

3. Research Results and Adaptation Recommendations

3.1. Research Results

We conducted a field investigation with a questionnaire survey on 16 September 2019 for four consecutive days. The investigation started from Alexandria (Figure 2), the second-largest city of Egypt at the downstream end of the Nile water system as well as the most important city in the West Nile Delta. The field survey was conducted to investigate 16 spots covering some important water-supply canals (thereafter called canals), drainage canals (thereafter called drainages), and drainage reuse pump stations all the way upstream to Cairo where is located at the end of the Nile Delta, to cover the main project domain (i.e., the West Nile Delta).

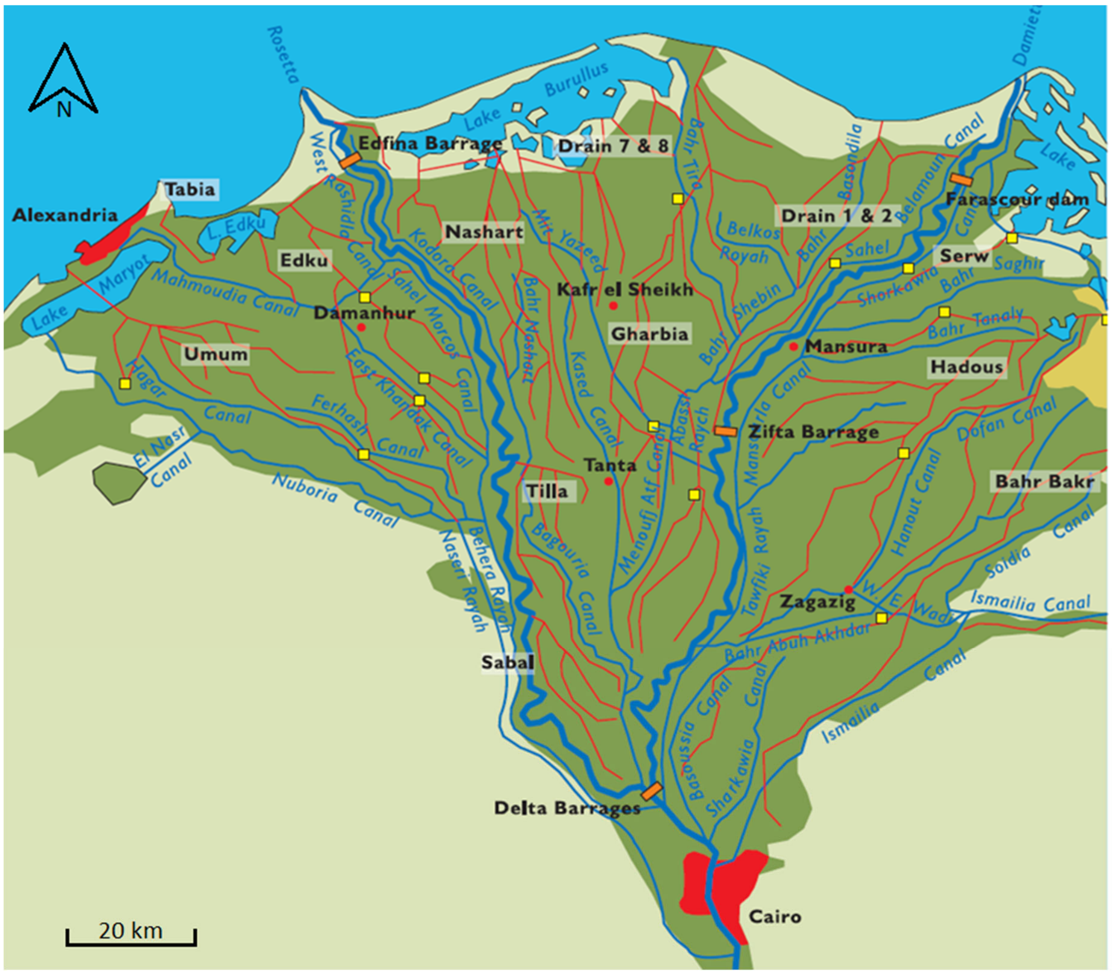

Figure 2. The Nile water system. Legend: The Nile River (thick blue lines), the supply canals (thin blue lines), and the irrigation drainage canals (red lines). Source: Reproduction from [23].

The first downstream spot was the Mahmoudia Canal, which is an important canal supplying water to Alexandria's 5,200,000 population for drinking and other economic activities, as can be seen in Figure 3. The left photo shows one end of the canal in Alexandria's city centre close to the Mediterranean Sea and particularly a police station, which is surrounded by garbage. As the water was not moving at the end, the high level of eutrophication of the water can easily be seen, which means the water has been polluted by irrigation activities. The middle and right photos were shot a bit upstream of the canal in Alexandria, which is located nearby the canal in front of the main water plant of the city (the right photo). The middle photo shows the bank earth of the canal is also mixed with garbage and shows the poor-quality water being taken in the water plant that produces portable water. It is notable that these two locations of the canal, one near the police station and the other near the intake of the water plant, were not expected to see this level of garbage existence. In response to the question, How do the law and police enforcement perform against the waste issue? The following responses were given:

"I have no idea whether Egypt has a law for solid waste management or not, but I know there are some laws with expensive penalties against littering garbage around or into waterways. However, I think the littering is just too much for police to manage by issuing the fines, and it does not seem to bother them."

(R3, male, 40–45, local resident, at the Mahmondia Canal in Alexandria)

"I have never heard any fine issued to people breaking laws for littering. I think police will not do it as they understand government is not cable of coping with waste management."

(R4, male, 25–30, local resident, at the Mahmondia Canal in Alexandria)

Moreover, in response to the question, Do people understand the difference between supply canals and irrigation drainage canals? The following responses were given:

"People living in city generally do not know which one is supply canal and which one is irrigation drainage canal, they look the same anyway. The water in both canals also look the same (dirty) as well. Farmers in the country probably know the difference because they need to operate the canals for irrigation."

(R1, male, 45–50, resident of Cairo, at the Mahmondia Canal in Alexandria)

"I have no idea whether this canal is a supply canal or irrigation drainage canal. It has nothing to do with me."

(R3, male, 40–45, local resident, at the Mahmondia Canal in Alexandria)

"I can see the water plant behind me intakes water from this canal, so I guess this is a supply canal. The water is too dirty for drinking purpose. People generally drink bottled water instead of tap water."

(R4, male, 25–30, local resident, at the Mahmondia Canal in Alexandria)

Figure 3. The Mahmoudia Canal in Egypt. Source: Author. Legend: The downstream end of the canal, located nearby a police station, is surrounded by garbage heaps (**left**); the bank earth of the canal is mixed with garbage, located in front of the water plant of Alexandria (**middle**); the water plant viewed from the canal (**right**). Location: 31°11'05.6" N 29°52'55.4" E (**left**), 31°13'14.6" N 29°59'27.4" E (**middle** and **right**).

Figure 4 shows the Lake Mariout, which is one of the four most important freshwater lakes in the northern Nile Delta. It used to be an important place for fishery production as aforementioned, whilst it has been severely polluted by drainage water, industrial wastewater, municipal solid waste, agricultural waste, and even construction waste. The lake is mainly supplied by the Umum drainage, which is also the drainage shown at the right photo. A high level of eutrophication of the lake water is expected, as the water is discharged from Umum drainage, which is the end of the drainage canal. The right photo was shot a bit upstream of the Lake Mariout. The photo shows some poor locals living near the drainage to fulfil the demands of accommodation and water, which is not a rare scene in the rural area. Notably, the earth bank is also occupied by garbage heaps. As aforementioned, the Lake Mariout, as well as most of the other main lakes featuring lake fishery, rely on water from the drainage canals to maintain their freshwater lake status, in response to the question, What happened to the lake? The following responses were given:

> *"There used to be lots of fish in the lake, whilst no one wants to fish here nowadays. Over the latest decade, the water (from the Umum drainage) flowing into the lake was getting dirtier and dirtier, with more and more algae and garbage. Also, the population has been hugely increasing, so have the housing developments in Alexandria. The water looks like there is something else in it, probably domestic wastewater."*
>
> (R5, male, 45–50, local resident, at the Lack Mariout in Alexandria)

> *"The government is not doing well in waste management in recent decades, so there are lots of illegal dumping happening around and into the lake, with domestic, agricultural, and construction waste. The lake is a big place and surrounded by roads, so it is very difficult for police to prevent illegal dumping. The government is working on digging the garbage out of the water, but will probably leave them on the bank as the way as the waterway cleaning."*
>
> (R6, male, 50–55, local resident, at the Lack Mariout in Alexandria)

Figure 4. The Lake Mariout and Umum drainage. Source: Author. Legend: The lake is seriously polluted by different kinds of solid waste, as well as wastewater. It also contains high level of eutrophication (**left**); the government is implementing cleaning work by excavators (**middle**); residents living adjacent to the drainage and garbage heaps (**right**). Location: 31°09'18.2" N 29°55'26.6" E (**left** and **middle**) and 31°09'52.5" N 29°59'40.8" E (**right**).

Figure 5 is another drainage canal system called Edku, which supplies water to Lake Edku. The lake is also one of the four most important freshwater lakes in the northern Nile Delta for the fishery. The left photo is the drainage right in front of a wastewater treatment plant (the right photo), which shows massive municipal and agricultural solid waste laid on the banks of the drainage. According to the locals, most of the solid waste was generated by waterway cleaning. However, they have been increasing as people kept dumping solid waste to the existing garbage heaps. The middle photo shows an example of unofficial reuse of drainage water for irrigation. This kind of reuse happens when water demand could not be met through canal water. The reuse has negative impacts on the irrigation systems and management though they solve the problem of deficit irrigation [22]. Through the interview with the locals, they expressed doubt about what was the point to spend money treating wastewater, as the drainage seems to be the purpose to send the foul things away. We could see the worrying fact of the confusing perception learnt from the existing environment. In response to the question, How is the wastewater treatment performing? The following response was given:

> *"I guess wastewater treatment is only happening in the main cities, and the coverage is still rather low. The household connection is slower than the increase in population. I do not know how clean the effluent water from the wastewater plant can be. It seems to be cleaner than the water of the drainage anyway. In the place where there is no*

wastewater treatment, the foul water goes to the drainage like this one, so do other wastes you do not need."

(R7, male, 25–30, local resident, at the Edku drainage near Damanhour)

Figure 5. The Edku drainage. Source: Author. Legend: The drainage in front of the WWTP is seriously polluted by different kinds of solid waste, as well as wastewater. It also contains high level of eutrophication (**left**); unofficial reuse of drainage water for irrigation (**middle**); the WWTP adjacent to the drainage (**right**). Location: 31°01'09.1" N 30°27'05.8" E (**left** and **right**) and 31°05'15.4" N 30°25'20.0" E (**middle**).

Figure 6 is another drainage canal system called Tilla, which is located in the middle of the Nile Delta. We thought the water and solid waste condition should be better than the previous ones as it is relatively upstream. We were shocked by the fact that the level of pollution was not any lighter. The level of pollution seemed worse, probably because the population of the town was higher than the previous rural areas. We selected the Tilla drainage to investigate further because it is one of the few cases that a drainage canal directly discharges into the Nile, rather than discharging into the Mediterranean Sea as most drainage canals do in this area. It was unclear what was the original reason for the design for discharging the drainage water back to the Nile; probably the long distance to the Mediterranean Sea was the main concern. However, the original plan did not foresee that the water in the Tilla drainage canal would be polluted to this level, such that the drainage would contaminate the Nile that was planned to be kept clean for supplying drinking water. The middle photo shows solid waste was directly transported to the Nile through the discharge of the Tilla drainage. In response to the question, Do you know the drainage connects and has adverse effects on the Nile River? The following responses were given:

"I have never noticed that the drainage connects to the Nile River. I have no idea how much effect would be and whether it relates to the tap water I am using. I guess people are like me thinking drainage is the place for foul stuff to go, and they would not think where the drainage is flowing to and through."

(R8, male, 35–40, local resident, at the Tilla drainage in Kafr El-Zayat)

"I have never thought about the question that whether there are some drainages connecting to the Nile or supply canals; I supposed it should not happen. The drainage will definitely pollute the Nile River. The government should know this issue and do something."

(R2, male, 30–35, resident of Minya, at the Tilla drainage in Kafr El-Zayat)

Figure 6. The Tilla drainage. Source: Author. Legend: The drainage is seriously polluted by different kinds of solid waste, as well as wastewater (**left**); the drainage discharges to the Nile river (**middle**); the drainage contains high level of eutrophication (**right**). Location: 30°49'00.8" N 30°48'48.6" E (**left** and **middle**) and 30°48'46.6" N 30°50'31.0" E (**right**).

Figure 7 is a supply canal system called Kased, which mainly supplies clean water to Tanta, a major city in the middle of the Nile Delta. The left photo is a water reuse pump station in Tilla drainage, for pumping water from Tilla drainage to Kased Canal to increase the water supply capacity. However, the high level of eutrophication of the water reveals the worrying fact that whether the reuse deteriorates the water quality of the Kased Canal that supplies water not only for irrigation but also for domestic drinking demand. Moreover, the middle photo shows the Kased Canal itself cannot be kept clean due to the same solid waste issue. We were shocked by viewing even right at the intake of the water plant of Tanta, the intake was surrounded by massive garbage heaps. The more worrying thing is, most of the garbage does not seem to be from river cleaning, meaning deliberate dumping onto the existing river cleaning garbage heap. In response to the question, Do you have any concern about the pumping station pumping water to the Kased Canal? The following response was given:

> *"As I know supply canals are to supply water to irrigation whereas drainages are to collect excessive water from irrigation. The pumping station is to pump water from drainage to canal when the canal is short of water for irrigation. I cannot see any concern about it."*
>
> (R9, male, 40–45, local resident, at the Tilla drainage near Damanhour)

On the other hand, in response to the question, Why there are lots of dumping near the intake of water plant? The following responses were given:

> *"Dumping tends to happen where there is already waste heap, no matter it was from waterway cleaning or previous dumping. I guess that makes people think the increased part would not be noticeable. The government must have done waterway cleaning near the intake area, so it just happened that way."*
>
> (R10, male, 30–35, local resident, at the Kased Canal in Tanta)

> *"I am from a big city so I do not know clearly about the functions of supply canals and drainages. I was shocked by seeing garbage problem affecting not only drainages, but also supply canals, particularly water plant intaking water from supply canal."*
>
> (R1, male, 45–50, resident of Cairo, at the Kased Canal in Tanta)

Figure 7. The pump station of Tilla drainage, Kased Canal, and the water plant in Tanta. Source: Author. Legend: The water in the drainage for pumping contains high level of eutrophication (**left**); the bank of canal is covered by solid waste (**middle**); the intake of the water plant is surrounded by garbage heaps (**right**). Location: at 31°06'49.9" N 30°29'51.4" E (**left**), 30°47'02.9" N 30°58'24.0" E (**middle**), and 30°47'02.9" N 30°58'24.0" E (**right**).

On the other hand, the research seeks to obtain a better understanding of the causes of solid waste existence along and within waterways through reviewing the current statutory and administrative frameworks. After field investigation, we cannot help but ask, does Egypt lack statutory requirements in banning garbage dumping in unauthorised areas, particularly along and in waterways? We hence review relevant legislation regarding solid waste and waterways, as Egypt has never had SWM law. Environmental law No.9 of 2009 regulates the prohibition of dumping garbage and solid waste in waterways (including banks), whilst it is mainly dedicated to pollution control in air quality aspect [24]. It also regulates the cleanliness of garbage collection and transportation with fines and penalties. Although the cleanliness requirement is regulated mainly from the air pollution and odour aspect, unmindful garbage drop during the transportation is clearly not allowed, not to mention dumping on the road deliberately. As there is usually a road built alongside the waterways in Egypt, dumping garbage on the side of a road will result in garbage heaping up or falling into the waterway. From another law legislation, law No. 48 of 1982 on the protection of the Nile River and waterways from pollution, it clearly prohibits discharging or dumping solid, liquid, or gaseous waste in the waterways and on banks [25]. Furthermore, another law legislation, law No.12 of 1984 on irrigation, also regulates similar prohibitions with fines and penalties [26]. We can at least conclude that it is illegal to dump waste alongside the waterways and banks, of which the disobedience will result in a fairly high fine. From the interview, the locals expressed that most people know that disobedience is illegal, even though few people are actually clear about how much the fine would be, a few cases are being caught and fined. We can see the police enforcement for this regard is not realistic, as the lengths of waterways of Egypt are too long to guard and monitor, particularly at nights when there is often a lack of lighting along waterways and adjacent roads.

3.2. Adaptation Recommendations

So far, Egypt does not have SWM law in place. The parliament just approved the draft law in August 2020 [27]. The new law particularly addresses the solid waste issue in waterways and open-air burning; it also forbids carrying out integrated non-hazardous waste management activities without a licence, which is highly related to the deliberate dumping to waterways and adjacent roads, as the service providers collect garbage with charge and sell the recyclable part and dump the rest at unauthorised areas. The law even significantly raises the penalties and fines to a relatively high level. We sincerely hope the new law will transform the country, whilst we acknowledge there still exist many unchanged aspects that might fail the effectiveness of the new law. Some recommendations are proposed in terms of the unfavourable nexus of SWM and extreme hydrological events through the foregoing findings supported by field investigation and interview, as follows:

- The framework of the existing national laws is reactive-based rather than proactive-based. The reactive-based framework relies on bans on people's disobedience, as well as police enforcement, whilst it is apparent that the police enforcement regarding solid waste in waterways or adjacent spaces is not available and achievable for most of the watercourse areas. However, the proactive-based framework features conveying jurisdiction to local governments whilst simultaneously giving the obligation to local governments to conduct SWM effectively, which is absent in the existing statutory framework. These two statutory frameworks are two different philosophies in legislation. The obligation given to local governments is, by all means, necessary, which will then be supervised by the pubic and Egypt's central government through political means. This absent element may strengthen the collaboration, the distribution of responsibilities, and the allocation of resources, between the central and local governments. It is expected to be one of the decisive points in the successfulness of the new SWM law.
- Regardless of the establishment of the new strict SWM national law and relevant programmes, the awareness of the health and pollution of the public is one of the key elements to achieve good SWM performance, which is still rather weak. Environmental neuroscience approaches are recommended to be applied, particularly for Egypt’s context. A well-known theory of it, the broken windows theory [28], is critical in dealing with the overwhelming solid waste heaps in watercourse areas. The theory basically describes that if a window in a building is broken and is left unrepaired, all the rest of the windows will soon be broken, as it is a signal that no one cares, and so breaking more windows costs nothing. Similarly, the waterway cleaning waste laid on the banks of the waterway is by no means appropriate handling, as it will result in "the broken windows" effect, which weakens the environmental moral of the public and reduces the hope of a clean Egypt of the future. Moreover, with increasing extreme hydrological events, the waterway cleaning waste is very likely to be flushed back into the water, causing an endless cycle of wasting efforts and resources. Once the heaps disappear, the different view will create a positive recognition and attitude in people's mind that an improving cycle is ongoing; any effort will be recognised to be able to make positive change and contribution to the environment, rather than the original recognition that one personal good practice will not make any difference. More approaches in environmental neuroscience can be developed for environmental education and policy awareness building as the accessibility of the internet and mobile phone are getting rather common in Egypt.
- A recommendation to review the relationship between the three water subsystems, namely the Nile, the supply canal, and the drainage canal, as our research has found that the current utilisation does not match the original expectation, namely the shocking fact that the Tilla drainage discharging back into the Nile (Figure 6). We strongly recommend that the Egyptian government should comprehensively examine the pollution of this kind of convergence of different subsystems. Besides, the national drainage water reuse policy through pumping stations should also be reviewed, as the drainage water is mostly severe eutrophicated and polluted, which seriously affects the safety of raw water taken in to water plants at supply canals. In addition, regardless of the ongoing development of wastewater treatment coverage (approximately 65% coverage of drinking water supply and only 24% sewage service coverage), decentralised wastewater treatment and on-site treatment should be considered for wastewater treatment as well as for waterway purification, which could be an ideal strategy for Egypt’s special water system, particularly with relatively low cost overall [22,29,30]. The decentralised strategy will also substantially contribute to the base flow of the river/canals in between WWTPs along the

waterways, which enhances not only the water quantity in the waterways but also the quality. However, how to remove the nutrition from the water with acceptable costs, such as nitrogen and phosphorous by fixing them in the loop, as well as the removal of pathogens, are the critical tasks demanding more research and discussions in the future.

- Notwithstanding a recommendation for urgently enhancing stormwater drainage seems to be merely a common sense without research need, the authors want to emphasise that tackling the solid waste issue must be achieved simultaneously as we can foresee the possibility of flooding events caused by blocked drainage due to garbage. An example in Surat in India in 1994 showed a major flood caused by garbage-blocked drainage, which resulted in an outbreak of a plague-like disease with more than 1000 people infected and 56 dead [31].

On the other hand, apart from the recommendations regarding the nexus of SWM and extreme hydrological events, we can see another point from foregoing findings that there is an urgent demand in the improvement of the technical sphere in Egypt, i.e., flood early warning tools, particularly for pluvial flood management. As we know flood forecasting with lead time from hours to days mainly relies on two parts of precipitation input, namely present observations (e.g., rain gauges radars and satellites) and future rainfall predictions (e.g., nowcasting from remote sensing and forecasting from numerical weather prediction models) [32]. However, the former input part involves the aforementioned obstacle of Egypt that is the scarcity of ground rainfall observation, whilst the latter input part reflects the current status of lack of capability in precipitation forecasting for pluvial flood management in Egypt. Therefore, we also attempt to provide feasible resolutions with some practical recommendations in these two regards, which is to enhance the practical applicability and capability, by introducing NWP and satellite-based precipitation observations and employing the integration of nowcasting and numerical weather prediction (NWP) approach in precipitation forecasting.

The recent decades can see the development of remote sensing technologies; satellite precipitation products started to emerge in the 1990s. To cope with the issue of a sparse rain gauge and non-existent radar observations, airborne and satellite-based datasets may work as a complement or even substitute. So far, there are quite a few datasets with coverage of Africa region. For satellite-based products, they include the Tropical Rainfall Measuring Mission (TRMM, by NASA), Global Satellite Mapping of Precipitation (GSMaP, by JAXA) [33,34], Precipitation Estimation from Remote Sensed Information Using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS, by the University of California) [35], Multisensor Precipitation Estimate (MPE, by EUMETSAT) [36–39], and NASA's Global Precipitation Measurement Mission (GPM, IMERG product, by NASA and JAXA) [40]. Besides, there are also the Climate Hazards Group Infrared Precipitation (CHIRP) and CHIRP combined with station observations (CHIRPS) (by the University of California and U.S. Geological Survey) [41,42], the Global Precipitation Climatology Project (GPCP) [37], the Climate Prediction Centre (CPC) Merged Analysis of Precipitation (CMAP) [43], African Rainfall Climatology version 2 (ARC2) [44], and the Tropical Applications of Meteorology using SATellite and ground-based observations (TAMSAT) [45], whilst these latter products featuring relatively coarse spatial and temporal resolutions even though with long-term time series, are not adequate for rainfall forecasting but are more appropriate for climate variability analysis [46]. Therefore, the former satellite-based observation products are suggested for further investigation for overcoming ground observation scarcity (Figure 8 left). In addition, the use of numerical weather prediction (NWP) models driven by global analysis datasets, such as those from the European Centre for Medium-Range Weather Forecasts (ECMWF) or global forecasts by the National Centre for Environmental Prediction (NCEP), which are reanalysis products that can be applied for real-time rainfall forecasting in attempt to meet the demands of flood early warning (Figure 8 right). The above two types of the airborne and satellite-based dataset have different performances and characters in accuracy, resolutions, time series, regional coverage, and minimum latency (e.g., real-time), which are the factors of constraints in rainfall forecasting worthwhile being further explored in the future.

Meanwhile, on the other hand, for the improvement of rainfall forecasting capability of Egypt, we recommend enhancing the practical applicability and capability by introducing and employing the integration of nowcasting and numerical weather prediction (NWP) approach. It is generally known that extrapolation-based nowcasting approach and NWP have different strengths and weaknesses, whilst the integration of the two approaches has shown its merit in weather forecasting, as nowcasting has the advantage in short term performance (i.e., a few hours) whereas NWP has the advantage in mid/long term performance (i.e., from several hours ahead to a few days). Therefore, there is a large body of research exploring how to combine the two approaches for better performance in forecasting. So far, there is still a lack of application of satellite observation in nowcasting aspect, which is worthwhile further exploring particularly for Egypt's context.

Apart from exploring the improvement in the integration, overcoming local practical constraints (e.g., finance) is also a priority concern, which is the reason why open source models (i.e., nowcasting and NWP) are recommended for the Egyptian context in this matter as they are free, easy to use, modular, and community-driven initiatives for further developing and maintaining by the users, i.e., national and local authorities. For nowcasting, there are different models such as STEPS, INCA, PySteps [47–50], whilst for NWP the weather research and forecasting model (WRF, by National Center for Atmospheric Research) has had much popularity [51]. Furthermore, it has been indicated that NWP models feature regional characteristics in configuration combination of physical, dynamical, and computational parameters [52]. So far, there is still an absence of research identifying suitable configuration exclusively for Egypt's context. Therefore, considering the research potential and demand of the aforementioned two absent research topics, the authors are conducting two explorative pieces of research: one is to explore the applicability of satellite rainfall products in nowcasting modelling, whilst the other seeks to apply the well-developed and open-source NWP model—WRF—for downscaling and localising parameters through the use of reanalysed data ERA5 (Figure 8 right), for the common purpose of enhancing integration with nowcasting approach for improvement of flood early warning capability in Egypt. These two types of research will be presented in another article.

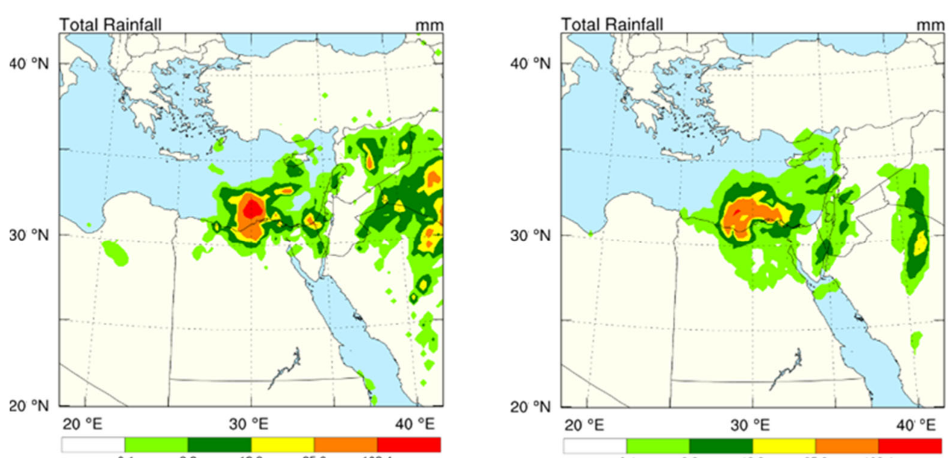

Figure 8. GPM satellite rainfall observations (**left**) and WRF NWP simulations (**right**) for an extreme hydrometeorological event on 4 November 2015. Legend: The two figures show the estimation difference between two approaches.

4. Conclusions

The complexity of environmental issues in the West Nile Delta, along with the impacts of climate change and human-induced evolvements, have become the main national challenges towards food security in Egypt. There has been an emerging issue in the adverse nexus between solid waste hazard and extreme hydrological events, as the nexus has significant potential to affect national food security particularly in Egypt's context, whilst it is still overlooked at the moment. The findings provide a holistic lens to further understand the nexus whilst the effects of climate change make it even worse. Through extensive field investigation, practical and novel recommendations in policy and statutory respect are proposed based on the findings. On the other sphere, the technical aspect, the research provides insight into the application of satellite precipitation observations in rainfall forecasting, aiming for contributing to the integration of nowcasting and NWP approaches for enhancing the technical capability of flood early warning tools of Egypt. The paper hopes to assist the stakeholders and the public to assimilate the extreme weather system, as well as how to accommodate the interrelated issues, through interdisciplinary discussions and a distinct lens.

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