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Research Article

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Gis-Based Estimation of Land Subsidence Impacts on Water Resources Infrastructures: A Case Study in the Nile Delta, Egypt

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Abstract This paper aims to investigate and quantify the hazardous impact of the vertical land movements phenomenon on water resources infrastructures in Egypt probably for the first time. It depends on the results of the Global Navigation Satellite Systems (GNSS)-based estimation of that natural hazard over 2012-2019 previously carried out by the Surrey Research Institute (SRI). The geospatial analysis and interpolation of the land subsidence/uplift have been performed within a Geographic Information System (GIS) environment and a novel danger factor has been proposed. Based on available datasets and accomplished results, it has been found that the average factors over main canals and main drains equal 43% and 37% respectively. Furthermore, it has been found that danger factors on barrages range between 11% and 63% and those over pump stations range between 4% and 71%. The attained findings could be considered primarily due to the short time of the GNSS-based datasets used to quantify the vertical land movements in the Nile delta region. However, they should be considered by decision makers in the operation, maintenance, and development of water resources infrastructures in Egypt. It is recommended that other data collection techniques, such as the radar remote sensing imageries, should be utilized along with GNSS data for monitoring and quantifying the land vertical movement phenomenon more accurately. Also, it is highly recommended that the presented approach should be carried out over the overall water resources infrastructures in the entire territories of Egypt.

Keywords GIS, GNSS, Vertical Land Movements, Water Resources, Natural Hazards

1. Introduction

Natural hazards affect human, economic, and environmental activities worldwide. Such hazards include Sea Level Rise (SLR), land subsidence, landslides, storm surges, drought, flash floods, desertification, and seawater intrusion among many types of hazards. Geospatial techniques, particularly the Geographic Information Systems (GIS) and satellite-based Remote Sensing (RS), provide significant state-of-the-art approaches for monitoring, analysis, and risk assessment for natural and man-made hazards. For an instant, GIS has been utilized in delineating areas subject to severe droughts in Ethiopia [1]. Also, Abdelkarim et al. [2] (2020) have applied GIS to assess flood hazards in Saudi Arabia. In Kuwait, GIS has analysis has been carried out to assess coastal inundation due to future SRL [3] (Neelamani et al. 2021). Parallel research has been conducted in Alexandria, Egypt for coastal vulnerability assessment using GIS [4]. On another scene, GIS is used to evaluate economical vulnerability due to a natural hazard such as land subsidence [5].

Land subsidence constitutes one of the vital environmental hazards that causes physical, human, and economic risky impacts globally, mainly in low-land areas and coastal areas. Fundamentally, land subsidence could be attributed to both natural and human-induced reasons such as geology structures, soil characteristics, withdrawal of groundwater and natural gas and other factors. A number of geodetic approaches have been applied in monitoring land subsidence, particularly the Global Navigation Satellite Systems (GNSS) [6], the Differential

Synthetic Aperture Radar Interferometry (DInSAR) [7], satellite altimetry and tide gauges data [8], and levelling data [9]. A combination of several observing techniques would be more efficient in monitoring land subsidence. GIS-based analysis of topographic and geological could be utilized to model land subsidence over a specific spatial area [10]. It is to mention that the absolute SLR is the result of both relative SRL as measured at Tide Gauge (TG) stations and the land subsidence. In Egypt, the relative SLR at the Nile delta from two TG stations equals 3.5 and 1.9 mm/year at Alexandria and Port Said respectively [11]. Regarding the recent results of GNSS-based vertical land movements in the Nile delta, it is estimated that the absolute SRL rate at Alexandria and Port Said equal 6.0 and 7.6 mm/year respectively [12].

The evaluation of natural hazards' risks is a principal aspect in efficient decision making and the development of strategic policies and plans. This paper investigates the utilization of GIS in estimating the risky impacts of land subsidence in the Nile delta region. It aims to quantify the hazardous impact of that phenomenon on canals, drains, and water resources structures, within the study area, probably for the first time in Egypt.

2. Study Area and Available Data

The Nile delta (Fig. 1) extends from longitude 29.7° E to longitude 32.6° E, and from latitude 29.8° N to latitude 31.6° N, and its overall area equals approximately 35,000 square kilometers.

GNSS raw data of 23 stations of the Virtual Reference Stations (VRS) belonging to the Egyptian Survey Authority (ESA) over 2012-2019 have been utilized to estimate recent precise trends of the vertical land movements over the Nile delta [12]. The Arc GIS package has been applied to construct a 3D spatial surface of vertical land movements. It has been found that the land motion range from subsidence of -5.49 mm/year to uplift equals +4.66 mm/.year, with an average of +0.32 mm/year (ibid). That spatial model has been, in the current research, for further investigations particularly for estimating the impacts of vertical land movements on water resources infrastructures in the Nile delta region.

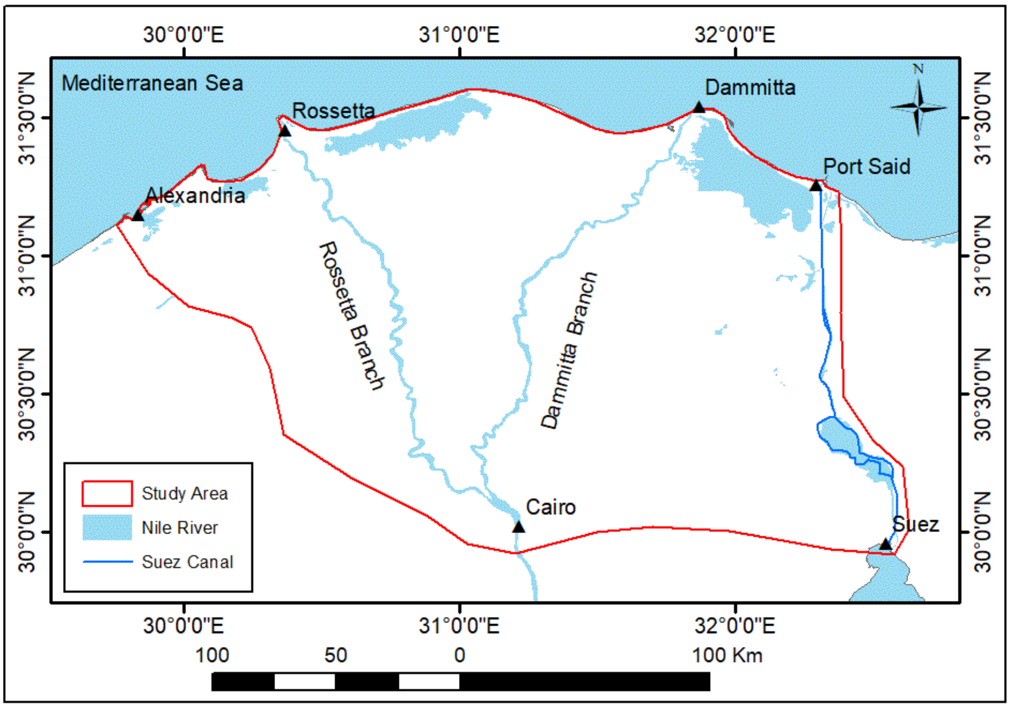

Figure 1: The Study Area

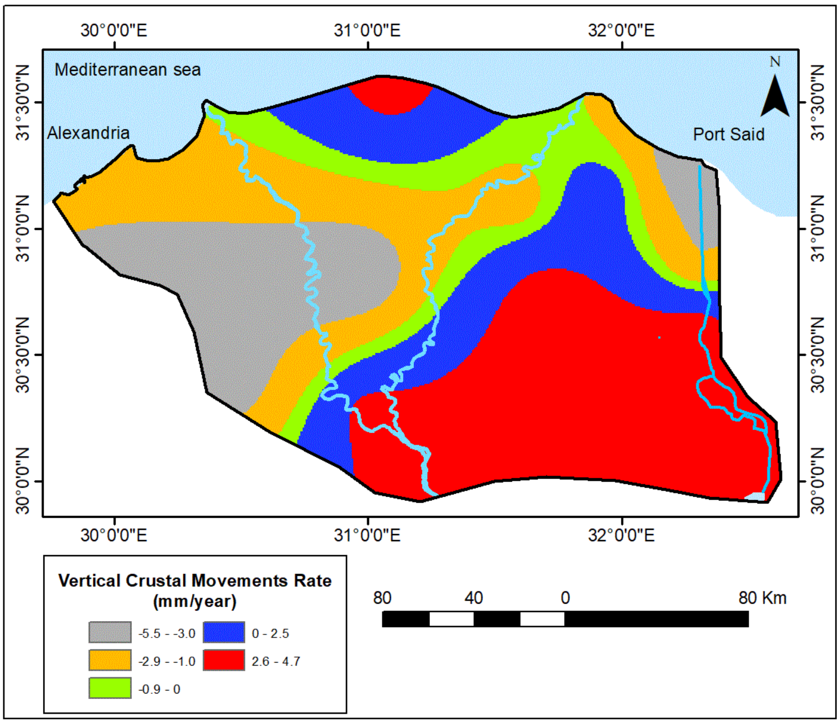

Figure 2: Vertical Land Movements in the Nile Delta over 2011-2019 (after SRI 2022)

3. Methodology

The processing strategy starts with developing an integrated geodatabase of water resources infrastructures in the study area. Several datasets have been collected from various sources and four layers have been assembled to represent the canals, drains, barrages, and water pumping stations (Fig. 3). Since the constructed geodatabase consists of thousands of features, the current study focuses only on canals and drains whose lengths are greater than 20 and 40 kilometers respectively. Next, the krigging interpolation method, within the Arc GIS 10 package, has been performed to interpolate the vertical land movement (Fig. 2) at each pump station, and barrage directly. However, because a specific canal or drain might pass by different categories on the vertical land movements, a novel indicator has been proposed, that consists of the following steps:

- Interpolate the minimum land movement trend (R_{min}) on a specific canal or drain,
- Interpolate the maximum land movement trend (R_{max}) on a specific canal or drain,
- Interpolate the average land movement trend (R_{mean}) on a specific canal or drain,
- Compute the Dangerous Factor (Dang1) for each canal or drain by dividing its average land movement rate by 5.5 (that is the maximum value of land movements, mm/year, in the study area) multiplied by 10 (to be on a scale of 10):

$$Dang1 = \left(R_{mean} / 5.5\right) * 10 \qquad (1)$$

- Since some canals and drains, as polyline features, would cross different categories of vertical land movements (subsidence and uplift as noticed from both R_{min} and R_{max} values), another Dangerous Factor (Dang2) is proposed to consider such a situation by adding a constant equals 5 to represent such a more risky case:

$$Dang2 = Dang1 + 5 \quad \text{(if there exist both +ve and –ve movements)}$$

$$Dang2 = Dang1 \quad \text{(if there exist even +ve or –ve movements)} \qquad (2)$$

- Re-classify the attained dangerous factors, of both canals and drains, into percentages by dividing it by 15 (that equals the maximum dang2 factor) and multiplying it by 100 just to be easier for interpretation and comparisons:

$$Dang\% = {Dang2 * 100}/{15} \quad (3)$$

- For pumping stations and barrages as point features, re-classify the attained dangerous factors, as similar to Eq 1, but directly to percentages (Dang11) as:

$$Dang11 = (R_{mean}/5.5) * 100 \quad (4)$$

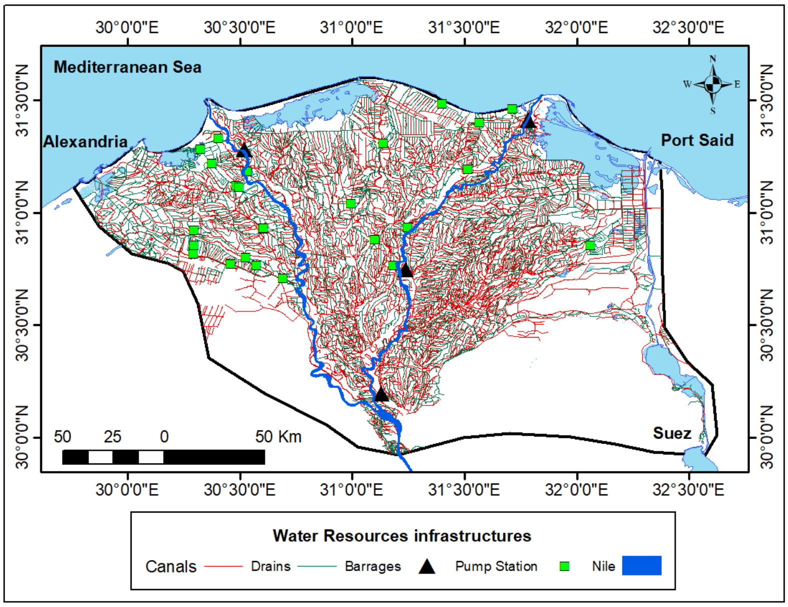

Figure 3: Water Resources Infrastructures in the Nile delta Area

4. Results and Discussions

The GIS-based developed geodatabase consists of 3270 canals with variable lengths between 0.04 km and 132.35 km, and 1997 drains whose lengths range between 0.01 km and 105.76 km, 27 pumping stations, and 4 barrages. The danger factor (Eq. 3) has been computed for the 16 main canals (Table 1). It has been noticed that this factor range between 26% for Meet Tazeed canal and 61 % for El-Bagoryia canal, with an overall average equals 43%. Fig. 4 depicts the categories of danger factors on main canals where it has been divided into three groups: low danger (26%-34%), medium danger (35%-47%), and high danger (48%-61%). Comparing Fig. 2 and 3, it can be realized that the high-danger main canals exist primarily in the middle and the east of the Nile delta where maximum vertical land movements occurred.

Table 1: Land movements' Danger Factors on Main Canals

No	Canal Name	Canal Length (km)	Danger Factor %	No	Canal Name	Canal Length (km)	Danger Factor %
1	El-Neanayia	91.2	52%	9	El-Ryaah El-Tawofekey	66.1	53%
2	Meet Yazeed	63.3	26%	10	El Hager	87.2	42%
3	El Mahmoudyia	75.5	31%	11	El Nobaryia	119.2	42%
4	Bahr Shebeen	113.2	51%	12	El-Esmaliyai	132.4	47%
5	El-Bagoryia	91.6	61%	13	Suez	91.2	49%
6	Bahr Tiyara	69.3	43%	14	Port Said	74.8	53%
7	El-Rayah El Nasrey	84.3	34%	15	Bahr Mowis	68.3	30%
8	El Rayah El Beheri	95.1	39%	16	El-Salam	89.1	42%

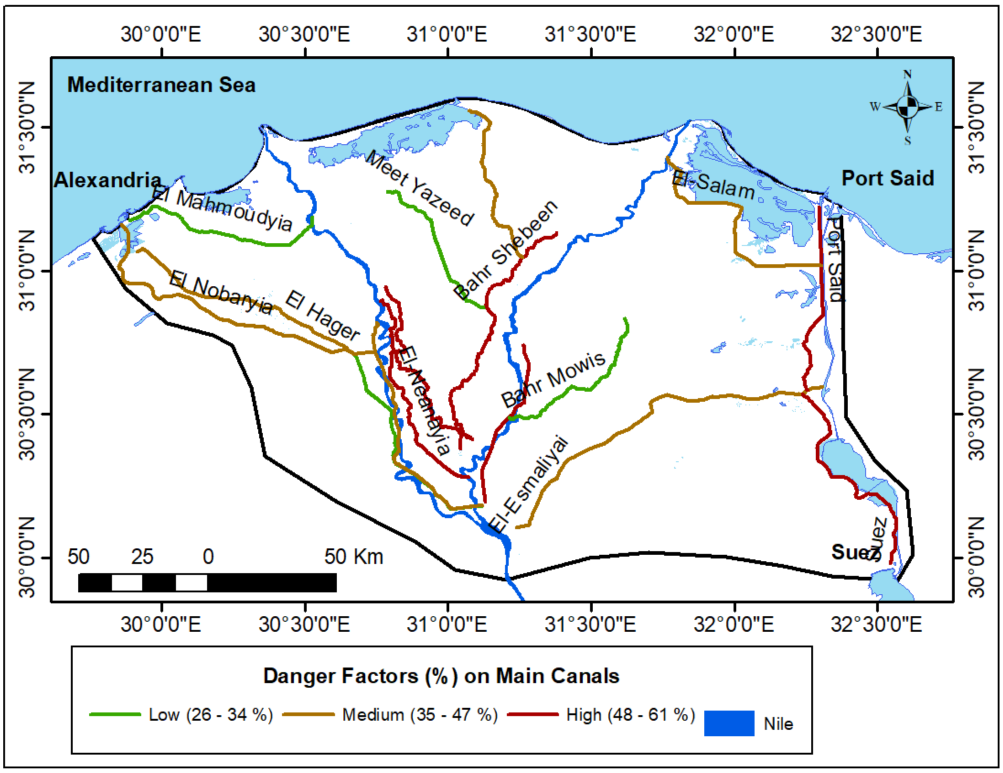

Figure 4: Land movements' Danger Factors on Main Canals

Similarly, the danger factor has been computed for the 13 main drains (Table 2). It has been noticed that this factor range between 16% for Nemra 1 High drain and 49 % for Al Mhsma drain, with a mean of 37%. Fig. 5 depicts the categories of danger factors on main drains where it has been grouped into three categories: low danger (16%-19%), medium danger (20%-40%), and high danger (41%-49%). Comparing Fig. 2 and 5, it can be realized that the high-danger main canals exist, as expected, principally in the east and the middle of the study area where maximum vertical land movements occurred.

Table 2: Land movements' Danger Factors on Main Drains

No	Drain Name	Drain Length (km)	Danger Factor %	No	Drain Name	Drain Length (km)	Danger Factor %
1	Shobrakheit Wamtdada	45.7	40%	8	West Al-Nubaria	59.0	38%
2	Al Qrnein	43.6	47%	9	Al Amoum	40.0	34%
3	Al Aarein	42.9	42%	10	Al Gharbiya Main	69.0	40%
4	Belbis	65.9	44%	11	Bahr Sft Southern	75.5	19%
5	Bahr Hadous	57.5	38%	12	Al Mhsma	40.0	49%
6	Al Qalioubiya Main	73.5	33%	13	Bahr Al Bqr	105.8	46%
7	Nemra 1 High	45.2	16%				

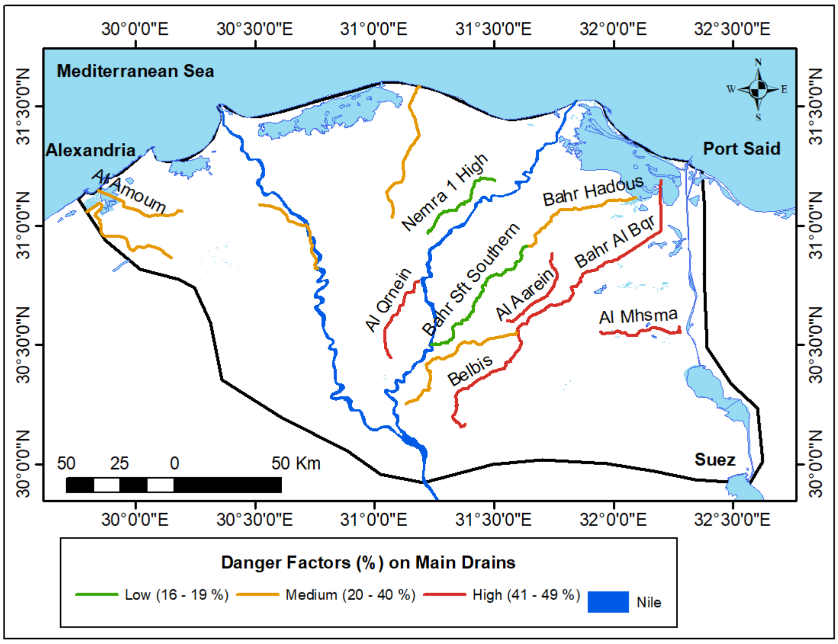

Figure 5: Land movements' Danger Factors on Main Drains

Next, Eq. 4 has been applied to estimate the danger factors of barrages and pumping stations. Danger factors on barrages, within the study area. Have been found to be 11%, 20%, 26%, and 63% for Farskoor dam, Zifta, Edfina, and Delta barrages respectively. From Fig. 2, it is noticed that the delta barrage exists in the region with maximum uplift, thus its danger factor is the highest one.

Next, the danger factors have been estimated at the 27 pump stations within the study area (Fig. 6). The accomplished danger factors range between 4% and 71%, with a mean of 42%. Fig. 7 depicts the frequency histogram of the danger factors on pump stations, where it is noticed that 11% of the stations have danger factors less than 10%, 7% stations of have factors between 10-20%, 33% of stations got factors between 20-40%, 15% of stations have danger ranging from 40% to 60%, and 33% of stations got high danger factors between 60%-71 %.

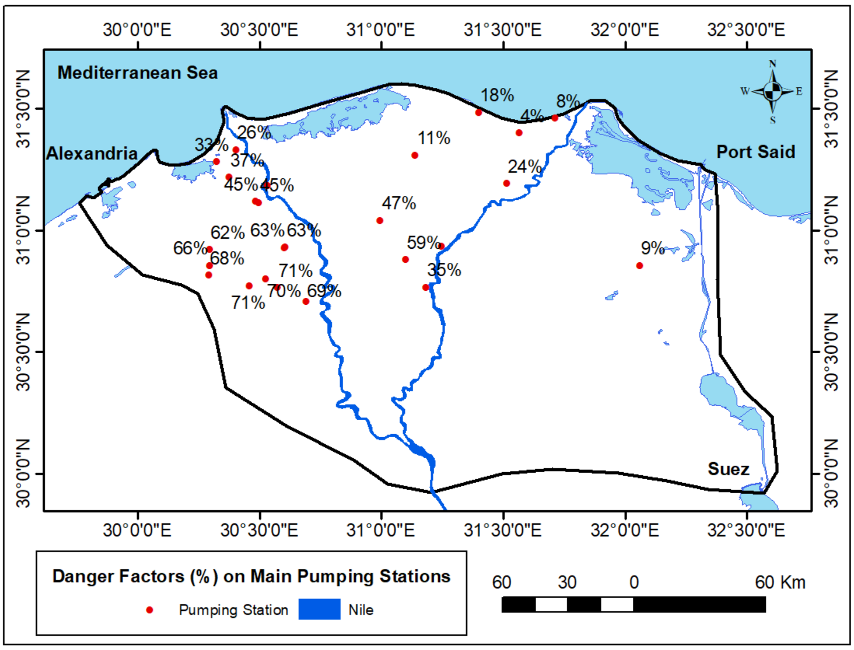

Figure 6: Land movements' Danger Factors on Main Pumping Stations

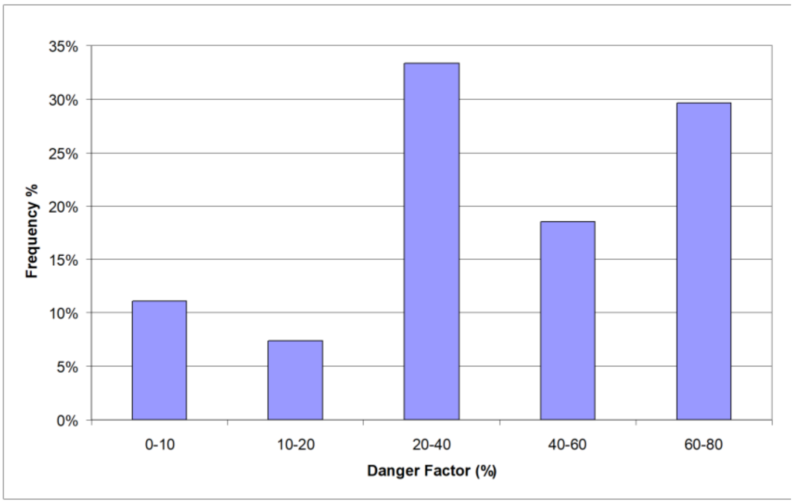

Figure 7: Frequencies of Land movements' Danger Factors on Main Pumping Stations

5. Conclusions

Estimating the risks of natural hazards represents a significant feature in decision making and the development of strategic plans. The current study examines the utilization of GIS in estimating the risky impacts of land subsidence, in the Nile delta region, particularly on canals, drains, and water resources structures possibly for the first time in Egypt as far as the authors' concern. The study depends basically on the GNSS-based vertical land movements determination, over 2012-2019, carried out by SRI in 2022. The GIS has been applied to construct a 3D spatial surface of vertical land movements and interpolates its dangerous effects on water resources infrastructures through a few proposed novel indicators.

Based on available datasets and accomplished results, it has been found that the danger factors over main canals range between 26% and 61 %, with an overall average equals 43%. In the same way, it has been concluded that the danger factors over main drains range between 16% and 49 %, with a mean of 37%. Moreover, it has been realized that the high-danger main canals and drains occurred, as expected, mostly in the east and the middle of the study area where maximum vertical land movements exist. Furthermore, it has been found that danger factors on barrages range between 11% and 63%. Also, it is noticed that the delta barrage exists in the region with maximum uplift, thus its danger factor is the highest one. Finally, the accomplished danger factors over pump stations range between 4% and 71%, with a mean of 42%. The attained findings could be considered primarily due to the short time span of the GNSS-based datasets used to quantify the vertical land movements in the Nile delta region. However, they should be considered by decision makers in the operation, maintenance, and development of water resources infrastructures in Egypt.

6. Recommendations

Few recommendations could be drawn, based on the achieved outcomes, for future works such as:

1- The vertical land movements natural phenomenon significantly affect water resources infrastructures, and thus it is recommended to monitor such hazard continuously.
2- GNSS data should be collected over a longer time in order to estimate more reliable estimates of vertical land movements.
3- Other data collection techniques, such as the radar remote sensing imageries, should be utilized along with GNSS data for monitoring and quantifying the land vertical movement phenomenon more accurately.
4- The approach presented in the current study should be carried out over the overall water resources infrastructures in the entire territories of Egypt.
5- Multi-disciplines research studies should be carried out to understand the nature of the vertical land movements phenomenon, its causes, and its physical, human, and environmental risks in Egypt.

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