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ORIGINAL PAPER

In the aftermath of the October 2015 Alexandria Flood Challenges of an Arab city to deal with extreme rainfall storms

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Abstract The October 2015 storm in Alexandria led to flooding of historical proportions. Although this October storm was a rare event ($\approx$1:50 year), it could have been predicted at least 1 week in advance. If an appropriate warning system had been in place, measures could have been taken to alleviate its consequences. Therefore, the use of rainfall forecasting in storm water modelling can be one of the first useful and cheap mitigation measures. This forecasting system may further allow employing Anticipatory Water Management. The latter would imply that a large extra retention reservoir would be made available by pumping the water out from lakes of the city (Lake Maryot and Airport Lake) before it rains. Further research will be required to assess the technical and economic aspects of this option. The high variability and uncertainty of rainfall call for a robust and flexible strategy for Alexandria, which considers a portfolio of measures able to absorb the negative consequences of extreme events (designed for exceedance). This strategy should enable the responsible authorities to map out the future of the drainage system across the city over the next two or three decades and to identify the tipping point when upgrading of the existing drainage and irrigation system will be required. It will also provide the required evidence base on which a long-term wastewater and sewerage plan for Alexandria City should be implemented.

Keywords Urban floods · Extreme events · Rainfall forecasting

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1 Introduction

On 25 October and 4 November 2015, Alexandria City and the neighbouring region of Egypt experienced an unexpected severe rainfall event (more than 100 mm in 2 h was recorded in some places) causing severe flooding of these areas. This devastating flood has been described as "the worst flooding of Alexandria City over the past decades in terms of the number of people affected and the amount of economic damage" (Egyptian Streets 2015). The long duration of the Alexandria storm event was not expected. The existing urban hydraulic network of canals and drainage infrastructure has not been designed to accommodate the large volumes of water resulting from prolonged and heavy rainfall such as this. About 60% of the city area was flooded from 0.5 up to 1.0 m, and in some low lying areas stagnant flood water on the roads remained for more than 15 days (HCWW 2015). The huge and unexpected water volumes were beyond the pumping capacity of the city.

The Middle East is host to fast growing urbanized regions which are major sources of economic and human development. Many cities in these regions are also of historical and cultural significance. Disasters pose a serious threat to these regions in general and to urban centres in particular. There are a variety of risk factors across Arab cities. The rising urban population coupled with the poor quality of infrastructure and services, being the key drivers of these risks. Poor land-use planning against hazards, absence of building construction standards (or their application), urban poverty, rural–urban migration, immigrant population in Arab cities, and the impact of climate change are some contributing factors to urban vulnerability. Additionally, city governments in these regions have limited authority for city planning and the implementation of local level actions, due to the centralized nature of the states. Policies and institutions for disaster risk reduction in most Arab cities are weak. The awareness amongst communities and authorities of disaster and climate risks disaster preparedness is extremely low (UNDP 2014).

As a response to the Alexandria flood event an assessment study has been carried out to better understand the underlying causes. The results of this study aim to support the development of a Stormwater Management and Mitigation Program for Alexandria City to reduce casualty numbers, damages to infrastructure and economic losses resulting from future rainstorms. This paper summarizes the main findings of the study. The first section briefly outlines the background and general context of Alexandria, followed by a presentation of the results and analysis. The conclusions and recommendations, which are described in the final section of this paper, may have significance for up-scaling to other cities across Egypt and the Arab region, as Alexandria City is considered a "model"city for many (coastal) Arab cities.

2 Background and context: the City of Alexandria, Egypt

Egypt is now in a critical period of economic and social transformation. Egypt's macroeconomic figures have shown some improvements, since the 2011 revolution, but economic growth has been moderate and insufficient to absorb the rapidly growing population (6% a year) and labour force. In addition, political instability has diminished tourism and foreign investment over the past 5 years. Far-reaching structural reforms are needed to transform Egypt's economy into a dynamic one that can alleviate poverty, create productive employment opportunities and maintain social and political stability (Hallegatte et al. 2013). The new government has developed a medium-term strategy and national priorities for promoting macroeconomic stability and private sector-led job creation, strengthening service delivery and fostering social justice and inclusion.

Alexandria is an ancient city which has periodically been reclaimed from the sea. Records from 45BC show that a canal from the River Nile at Shedia supplied the city with water. The city was almost abandoned twice in its history, once due to volcanic activity and the second time due to the development of an alternative port close by.

Alexandria is the second largest city of Egypt, and its biggest port hosts about 40% of its industry. It serves the wider Alexandria Region (total surface area of 2210 km^2) which has a 70-km coastline. The population of Alexandria is about 4.8 mln. The only potable water source for Egypt is the River Nile, and as a consequence, the national water development plan has great importance and water infrastructure issues influence most governmental decisions. The city has to cope with considerable population fluctuations associated with tourism: the total population may rise up to 7 mln in summer due to an influx of tourists. Since the revolution the city has implemented political, economic and social reforms, but significant challenges still remain.

With a Mediterranean climate Alexandria experiences long dry summers (March–October) and mild short winters (November–February). The temperature during the summer varies between 14 and 45 °C. The winter temperature varies between 9 and 33 °C. The summer is usually dry with about 30 mm of rainfall on average, whereas the winter is wet with 166 mm of average rainfall. The average annual rainfall in Alexandria is about 196 mm. As regards the characteristics of climate and rainfall patterns, run-off is managed using a combined drainage system. Although the capacity of the system has been upgraded, it still remains insufficient. Overflowing of manholes and pumping stations, with the consequent damages, has been observed during heavy rainfall in the recent past (HCWW 2015).

The three institutions responsible for flood risk management in Alexandria are the Ministry of Irrigation and Water Resources, the Ministry of Housing and the Holding Company for Water and Waste Water (HCWW). The Ministry of Irrigation and Water Resource is responsible for water distribution, coast line protection, irrigation canals (16.000 km) and subsurface drainage, of which 85% serves the agricultural sector.

HCWW was established in 2004 and produces a 5-year master plan, which prioritizes future projects and is based on an assessment of the projected demands for the decade ahead. In Alexandria, HCWW has two separate companies: one for water and one for wastewater. The tasks and responsibilities of the companies are operation and maintenance, infrastructure construction, and research and development. They have capacity to produce 20.5 mln m^3 of drinking water per day and treat 13 mln m^3 wastewater per day. The average coverage of drinking water supply in the region is about 50% (80% in urban areas and 15% rural). The ambition of HCWW to cover 100% will cost about 100 mln EGP. Hence, two main challenges of HCWW are to manage Egypt's shortage of water and to maintain adequate sanitation. The latter is lagging behind, causing extensive contamination of raw water provided by the channel drains. This results in a reduction in raw water availability.

Alexandria has nine low-income, peri-urban areas that are poorly served with water and sanitation services. In addition to supplying water to the city population, water is also supplied to neighbouring areas outside the city. The city currently lacks a storm water management plan.

3 Methodology

The study presented in this paper is based on a (1) rainfall analysis, (2) remote sensing analysis and (3) field work. These analyses and research activities were carried out in the period of December 2015 to April 2016.

3.1 Rainfall analysis

In this study, we have used rainfall forecast data from the European Centre for Medium Range Weather Forecast (ECMWF). ECMWF provides 6-hourly rainfall forecast of 15 days. The Egyptian Meteorological Organization provides rainfall forecast of three days (ASDC 2015). During this study, the rainfall forecast from the Egyptian Meteorological Organization was not readily available. The rainfall forecast from the ECMWF website was downloaded for the months of October and November of 2015.

3.2 Remote sensing analysis

A land-use analysis of Alexandria has been conducted for the period 2001–2015. This analysis (based on Landsat satellite images) provides quantitative information about the urban growth rate and features such as densification, infill and leap frogging. Land cover maps have been constructed for 25 September 2001 and 24 September 2015, using the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and the Landsat 8 Operational Land Imager (OLI), respectively. Band 5 (near infrared, 0.88–0.85 μm), band 4 (red, 0.64–0.67 μm) and band 3 (green, 0.53–0.59 μm) of the Landsat 8 sensor and band 4, 3 and 2 of the Landsat 7 sensor provided daytime images with a 30-m resolution. Erdas Imagine 14 (Hankerson et al. 2012) has been used for conducting a supervised classification (maximum likelihood), and the changes in area have subsequently been analysed in ArcGIS (version 10.3.1).

3.3 Field work

Fieldwork was carried out in order to inspect the flood affected areas and to collect additional data regarding flood features (duration, extent and damages), to review existing policies and strategies at local and national level on flood risk management and to discuss the conclusions and recommendation of this study with stakeholders. The latter activities comprised of meetings and interviews with technical experts and managers from HCWW, Alexandria Sanitary and Drainage Company (ASDC) and representatives of the Ministry of Water Resources and Irrigation.

4 Results

4.1 Features of the 2015 flood

During the devastating October and November flooding in 2015 the flooding persisted in some areas for more than 10 days, resulted in a total of seven deaths and affected millions of people. The largest number of affected people consisted of the urban poor living in slum areas covering over 26% of the total city area. The responsible national and local authorities did not anticipate this extreme flood event, and hence no protective and emergency measures were taken in advance, nor were citizens forewarned (HCWW 2015).

Economic impacts on properties (direct damage to buildings and contents due to flood water entering homes and buildings), alongside social impact such as an increase in anxiety and stress due to waterborne diseases as well as the disruption of services such as of electricity, water supply and sanitation, and food supply were perceived as the most severe consequences of the flooding.

In the district of El Mandara alone, 400 buildings showed severe structural damages and in the district of Wadi El Kamar the lives of 100,000 people were threatened by destruction of their homes, waterborne diseases and damaged infrastructure (HCWW 2015). Major concerns also included the danger of electrocution: at several locations (restricted to poor areas) of Alexandria the overhead power supply line of the tram line snapped and electrocuted four people due to the collapse of the supporting pillars. As a response to these electrocutions, the city government had cut the electric supply for 10 days, and as a consequence some tunnels were closed (such as tunnel 45) causing great anxiety and inconvenience amongst the citizens.

During the flood, the Army and Ministry of Housing provided assistance. Actions to alleviate the impact of floods included the installation of extra pumps and the removal of parts of the flood protection wall along the coast. There is no detailed information to what extent the water supply was affected by flooding (e.g. risk of contamination of drinking water through diffusion and/or leakage of pollutants into the network).

Major roads in and around Alexandria, which play an essential role for transport of people and goods and thus for the economy of the region, were inundated for several days (such as the Cornish Road). Apart from the direct impacts to the local economy, the flood also indirectly affected business activities (such as tourism) through supply chain disruptions. Many factories had to stop production due to the shortage of raw material affected by the flooding. There are no data available regarding these indirect damages. Moreover, detailed maps of the flood extent, depth, and duration are also still lacking.

4.2 Hydraulic infrastructure of Alexandria and wider region

Traditionally, storm water management in cities uses grey infrastructure to move water away from the city as soon as possible through a series of underground pipes (Brown et al. 2009; Ashley et al. 2013). Very often, these conveyance systems have insufficient capacity, which causes flooding during storm events. This was also the case for Alexandria.

A large fraction of the city's drainage and sanitation infrastructure dates back to the 1980s and is currently in a poor condition. In the existing and newly built-up areas, investments in infrastructure have not kept pace with its rapidly growing demand. A significant part of the buildings in newly built-up areas are deemed illegal. These illegal houses lead to further densification of the city and result in an increase in impervious areas and direct run-off of rainfall falling on that area. The extra run-off provides an extra load on the pipe network and puts additional strain on the pumping stations. Moreover, this urbanization causes the run-off peak to come early. Hence, if uncontrolled, this growth trend is likely to have serious adverse effects on the hydrology. Alexandria has a combined storm water conveyance systems. This combined system transmits storm water and sewage water in the same pipe sending it to the waste water treatment plant before it reaches the water receiving body. During high rainfall events, combined sewer overflows (CSO) occur, and considerable amounts of sewage water is released into waterways, which represents serious environmental concerns and constitutes a public health threat. Next to the inability to meet its original purpose during storm events and obvious inflexibility, grey infrastructure also implies high capital and maintenance costs.

According to ASDC (2015), the capacity of the drainage system is about 1.6 million m^3/day. There is an irrigation drain which brings a much higher discharge (up to about 11 m^3/day). The combined system as well as the irrigation drain brings the water under gravity to a location known as the Max Point. The pumping station at the Max point pumps to lift the water to drain off in the Mediterranean Sea through a canal of about 800 m in length. This canal currently must have a reduced conveyance capacity due to the presence of vegetation and debris within it. An assessment of the drainage capacity, particularly in view of the clogging of the drains and gutters and the reduced conveyance capacity of the drain off the Max Point, may be carried out in the future.

4.3 Hydro-meteorological analysis of the flooding in October 2015

A frontal depression in the eastern Mediterranean region caused torrential rainfall together with strong wind in the morning of Sunday, 25 October 2015. Due to the very high rainfall, the city's drainage system was unable to drain the resulting volume of storm water run-off to the Mediterranean Sea.

Alexandria has three rainfall stations where daily rainfall is measured with rain gauges. The daily total rainfall on October 25 from the three rainfall stations was:

(a) Rainfall station Ras El Teen (west of Alexandria, 31.19 N and 29.88E): 40 mm.
(b) Rainfall station Abu Kir (west of Alexandria, 31.33 N and 30.08E): 40 mm.
(c) Rainfall station Nozha (south of Alexandria, near the airport, 31.19 N and 29.95E): 12 mm.

Based on this data the daily rainfall in Alexandria on October 25 has been estimated as 32 mm. The monthly rainfall at Alexandria during the last 3 years is presented in Fig. 1.

In the absence of rainfall data from gauges, the rainfall data from the Tropical Rainfall Measuring Mission (TRMM) have been used (Huffman et al. 2007a; Arias-Hidalgo et al. 2013). In particular the 3B42, version 7 daily data were used. Figure 2 shows the variation of daily TRMM rainfall for the months of October and November during the period 2007–2015. The TRMM rainfall estimate clearly shows that the rainfall on both October 25 and November 4 was extremely high (~60 mm) (Fig. 2). The excessive rainfall caused the flooding. However, the gauge rainfall on October 25 was 32 mm. There is a considerable

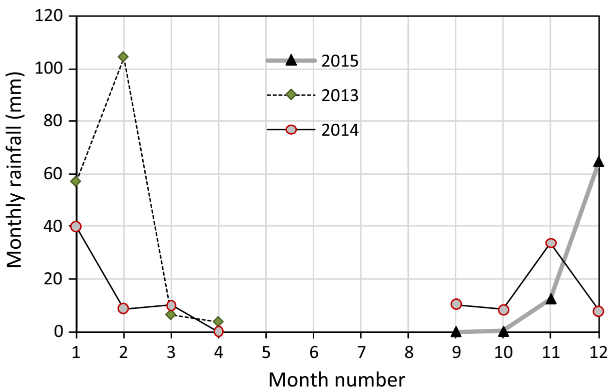

Fig. 1 Monthly rainfall in Alexandria during 2013 to 2015. The month number 1 corresponds to January and 12 corresponds to December. Rainfall data for the months May to August are not available. However, during this period Alexandria does not experience a lot of rainfall

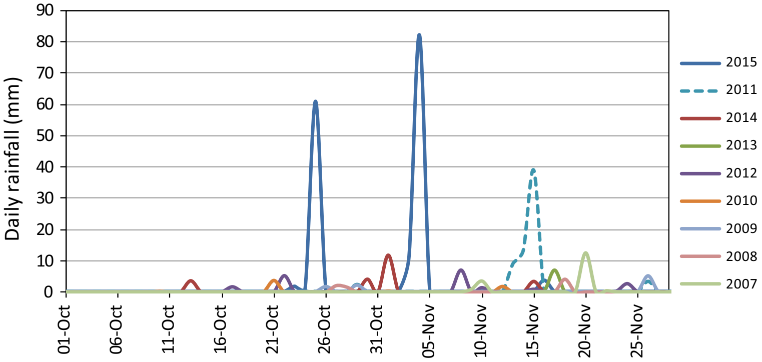

Fig. 2 Comparison of TRMM rainfall at a daily time scale in the month of October and November at Alexandria from different years

difference between the satellite rainfall and gauge rainfall data. If the gauge rainfall data are available over a longer period of time, then it can be used to correct the satellite rainfall data (Tesfagiorgis et al. 2011; Arias-Hidalgo et al. 2013; Hughes 2006; Huffman et al. 2007b). At this stage, there are not enough rainfall data available to correct the satellite rainfall data.

Figure 2 also shows that the rainfall on November 4 was very high. ASDC reported that this rainfall event had also caused flooding, but it was less severe compared to the one in October 2015 (ASDC 2015) mainly because the rainfall intensity was less. It may also be noted that the rainfall in 2011 was also high, which led to flooding in Alexandria, however, to a much lesser extent compared to the flood in 2015.

As the city had not experienced floods with significant impacts in the recent past and as no previous flood event data was available (e.g. 2011 flood), it was not possible to compare the 2015 flooding (extent, depth, velocity, etc.) with any previous flood. The historical rainfall data of Alexandria was not yet available at the time this study was conducted. Figure 2, which is prepared with the satellite rainfall data, provides relevant information regarding the extremity of the rainfall event in October/November 2015. The intensity–duration–frequency (IDF) chart of Alexandria is shown in Fig. 3. For the 32 mm of rainfall in 30 min on October 25, the frequency could only be estimated by extrapolation and the frequency of this rainfall seemed to be of the order of 50 years. The meteorological data revealed that the individual storm events in October and November 2015 were low probability events. Additionally, the persistence and clustering of the observed two consecutive peaks of extensive rainfall storm was exceptional, leading to flooding in Alexandria of historical proportions. The probability of occurrence of this type of clustered storm event is hard to predict and associated with large uncertainties.

4.4 Rainfall forecast

The medium range rainfall forecast data from the European Centre for Medium Range Weather Forecast (ECMWF) (de Roo et al. 2003) was downloaded for the study period. The comparison of the mean forecast rainfall from ECMWF with the TRMM and gauge rainfall is shown in Fig. 4. From Fig. 4 it can be concluded that the October 2015 flood could have been predicted with up to 10-day forecast lead time. The high values of the forecast rainfall at all forecast lead times are discernible. The forecast amount matched

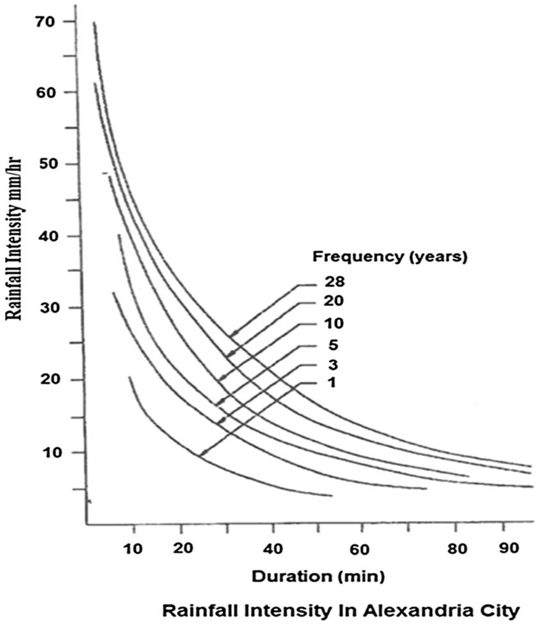

Fig. 3 Intensity–duration–frequency chart of Alexandria (*Source*: Alexandria Sanitary and Drainage Company)

more or less the satellite rainfall. The gauge rainfall was less than the forecast rainfall and satellite rainfall by about 50%. This is not completely unusual. The standard procedure that is used to update the forecast rainfall data is known as quantile-to-quantile mapping (see, for example, Hopson and Webster 2010). This procedure requires historical gauge rainfall data. With this method the sample probability of a forecast rainfall may be computed and the gauge rainfall data with the same sample probability is assigned to the forecast rainfall data. Unless the time series of rainfall data is available, the forecast rainfall data (and the TRMM rainfall data) cannot be corrected. However, even with the uncorrected forecast rainfall data Fig. 4 clearly shows that the high rainfall event of October 25 could have been predicted 10 days ahead of the event.

4.5 Land-use changes

The changes in land use were studied using Landsat images of 2011 and 2015, and the results are presented in Fig. 5. A summarizing overview is presented in Table 1.

The results show that the urban area of Alexandria has grown almost 40% during the past 15 years. A striking feature resulting from the RS analysis is that this increase is mostly a result of infill and further densification of the existing urban neighbourhoods. The total urban growth is estimated to be 43,305 km^2 and more than half of this growth (55%, or 23643 km^2) is due to urban infill. This unfortunately results in a staggering loss of unpaved, green or open areas and to a lesser extent loss of water bodies (such as ponds/lakes and canals) within the city. The reported average population has grown between 2 and 3% annually in the past two decades (CAPMAS 2016). Hence, the enormous pressure on the existing urban areas to accommodate this growth has resulted in an increase of the urban population density. The absence of affordable housing in Alexandria will likely further aggravate this process of densification due to uncontrolled, informal settlements in the future (Sušnik et al. 2015).

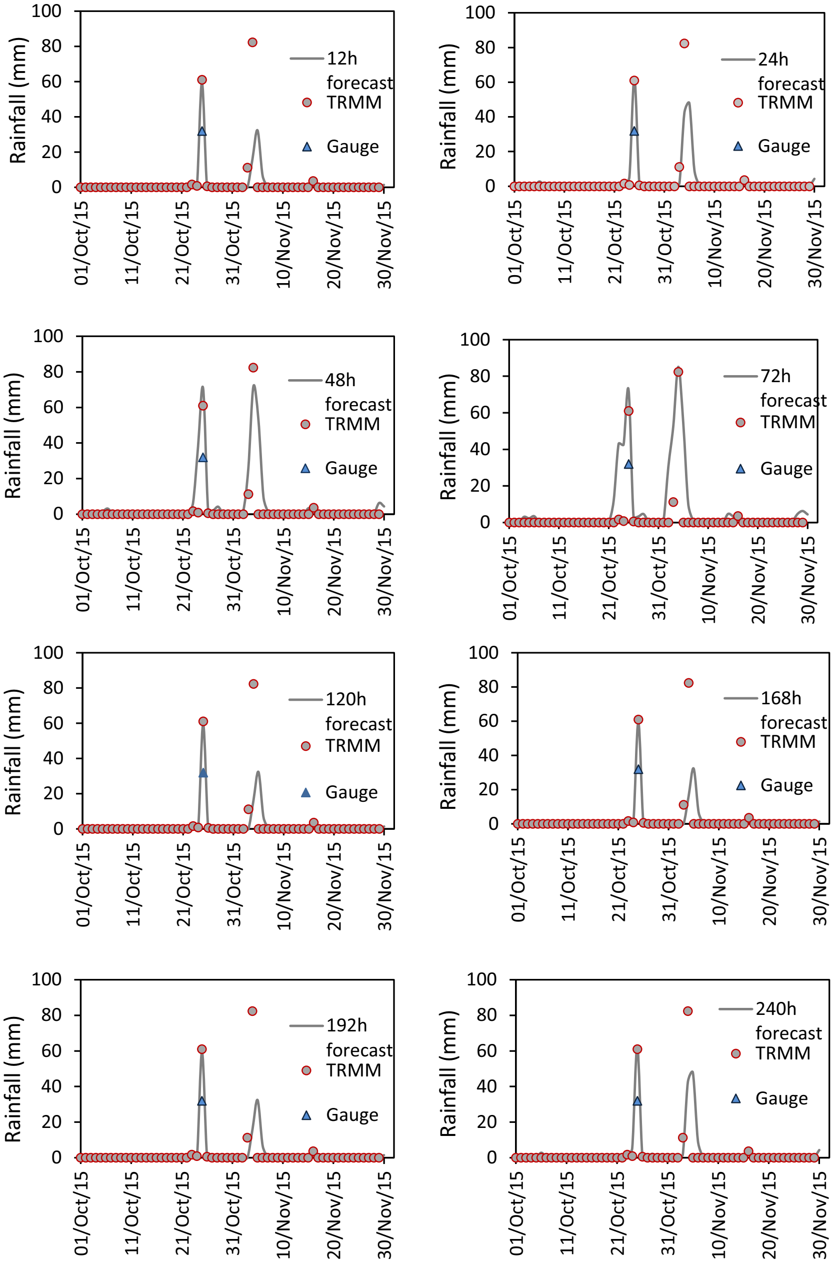

Fig. 4 Forecast rainfall for the October and November 2015 flood event in Alexandria with forecast horizon of 240 h. Gauge measurements and estimates of actual rainfall from TRMM are also presented

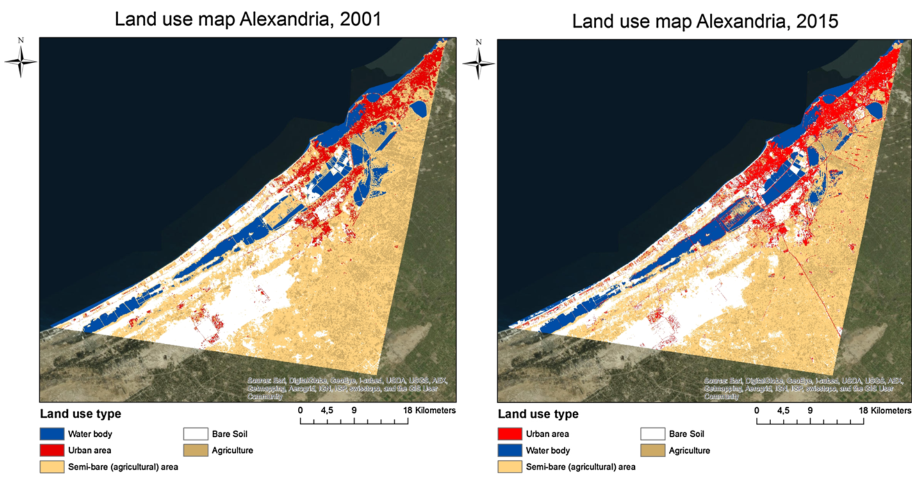

Fig. 5 Land-use map Alexandria 2001 (*left*) and 2015 (*right*)

Table 1 Summarizing overview of land-use changes in Alexandria

Class name	Area in 2001 (in km^2)	Area in 2015 (in km^2)	Percentage change
Water body	162,800	161,087	−1.05
Spars vegetation	630,459	597,383	−5.25
Agriculture	200,478	160,325	−20.03
Urban area	114,283	157,588	37.89
Bare soil	365,457	386,229	5.68

5 Identification of mitigation measures

5.1 General

The high variability and uncertainty of rainfall call for a robust and flexible strategy that considers a portfolio of measures to reduce both the *chance* and the *consequences* of flooding (Zevenbergen et al. 2008; Samuels et al. 2010; Sayers et al. 2012). These measures aim to influence the source (by capturing and storing rainwater) as well as the exposure and the vulnerability of people and assets to flood water. An effective and flexible strategy should therefore consist of a mixture of measures addressing (e.g. Zevenbergen et al. 2012):

- Flood preparedness (soft measures) such as flood emergency measures (flood forecasting and warning, evacuation and recovery plans);
- Flood protection such as building controls (minimum flood levels and flood proofing);
- Flood prevention (hard measures and land-use planning controls) such as flood mitigation works (construction of levees) and zoning requirements.

To identify and select these measures, and to decide when to implement and how best to distribute resources, requires a strategic approach acknowledging that future conditions may change. A strategic approach typically consists of a sequence of actions (implementation of measures or strategies) and potential pathways indicating when to transfer from one measure or strategy to another (Sayers et al. 2012; Gersonius et al. 2012). Figure 6 presents an overview of potential measures and an illustration of how strategies for managing (storm water) flood risk in Alexandria could involve multiple options and pathways.

These potential measures include short-term flood mitigation actions, which ease the discharge of run-off water to the sea, such as the removal of the flood protection walls and the installation of extra pump capacity and drains at some low lying sections in the city along the coastal road (Cornish Road). As an immediate response to the October flood, some of these measures have already been implemented. The effectiveness of these short-term actions is unknown as a detailed hydraulic analysis has so far been lacking. Other short-term actions include cleaning the urban drainage and irrigation systems and protecting critical infrastructure (power supply lines). Actions belonging to this category (often referred to as "no- or low-regret measures") together with the enlargement of the capacity of the waste water treatment plant have already been identified as a major target by the Ministry of Irrigation and Water. Upgrading of capacity should also include the conversion to a system for separate treatment of sewage and storm water. At present it is unclear when this upgrading will take place.

The much needed longer-term upgrading of drainage and irrigation system capacity will require major investment. The extent of this investment will be dependent on the agreed

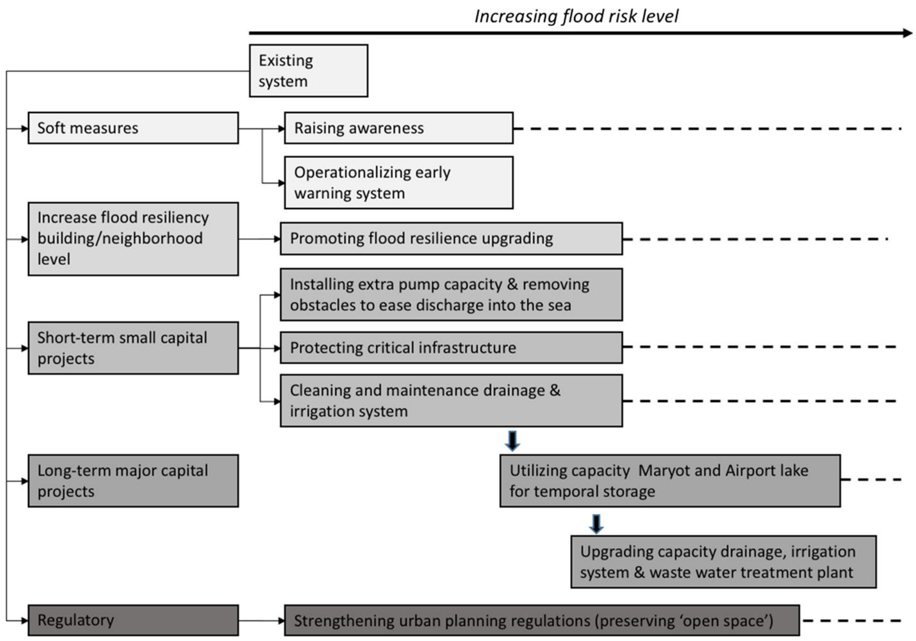

Fig. 6 An overview of potential measures and an illustration of how strategies for managing (stormwater) flood risk in Alexandria could involve multiple options and pathways (*arrows in bold* indicate a change in strategy)

upon (tolerable) risk levels used as a basis for the design of the new drainage and irrigation system. Hence, the implementation of this measure marks a transfer from one strategy (of relatively small interventions leading to incremental improvements) to another more radical and systemic change. Reaching the "tipping point" which leads to change depends upon both socio-economic and climatic factors. Finally, strengthening urban planning regulations to stimulate the development of affordable housing and stimulating infrastructural development (delivery of urban services such as roads and electricity networks) are urgently needed as they will guide urbanization.

It follows from our hydro-meteorological analysis that flood forecasting is likely to be an effective, short-term, no or low-regret measure, which will require very limited investment. Unfortunately, the city of Alexandria has not used any flood forecasting system. From the previous analysis, we may conclude that if Alexandria would have been using this system to forecast rainfall, then the October–November 2015 flooding could have been predicted. With an expanded forecast, horizon measures also could have been taken to minimize damage. As the city is not flooded on a regular basis, a flood forecasting system would be a very cost-effective solution for the city. A forecasting system would enable the city to be better prepared for a storm water event. This approach also allows the city time to carefully consider the design and investment in hard engineering structures, such as upgrading the current drainage systems.

5.2 Anticipatory water management

As shown in Sect. 4.5 the uncontrolled process of urbanization in Alexandria has resulted in a further densification and infill of the existing urban areas at the expense of open, green and unpaved areas in the city. This loss of permeable, green areas has further reduced the capacity of the city to retain storm water resulting in more peak run-off during heavy rainfall. This process need to be stopped or at least better managed. This will require policies in place that enforce development control and the preservation of green, unpaved areas in the city.

An effective flood forecasting and warning system will help reduce the loss of life, the number of people affected and to some extent the economic damage. However, other mitigation measures are required to reduce the risk of flooding. The water bodies situated at the border of the city can be used to store flood water. In particular, Lake Maryot and Airport Lake have been identified for this purpose (Fig. 7). If the forecasting system predicts heavy rainfall over successive forecast times, then water from Lake Maryot and Airport Lake may be pumped out before it starts raining. Subsequently, when it starts raining then the lakes would have headspace to accommodate the extra water from the rainfall. This is typically known as anticipatory water management (Kok et al. 2011).

During initial discussions with HCWW and the Ministry of Water Resources and Irrigation the above-mentioned lakes were identified as suitable repositories for the temporary storage. In the future, more accurate analysis of the lakes' capacities, vis-à-vis the storage requirement, will needed. If required, there are alternative lakes to the west of Lake Maryot. These lakes are not used for irrigation. An inaccurate forecast, which may cause lowered lake water levels, without subsequent rain, would not be a major problem. However, the impact on the water quality and ecology does need to be assessed. This mitigation measure will make use of the existing canals and drains and will need only one or two inlets and minimum engineering works such as strengthening the embankments of some irrigation canals. The drainage organization ASDC needs to collaborate with the Irrigation Department as the latter administers these lakes.

Fig. 7 Location map showing Lake Maryot and Airport Lake

5.3 Designing for exceedance

In the literature the so-called ALARP principle ("as low as reasonable practicable") is being widely applied in various domains to define acceptable risks levels. This principle assumes that our capabilities for risk reduction have their limits (HSE 2002). Flood risk is being addressed in contemporary approaches along these lines, as they explicitly acknowledge that these systems may fail (van de Ven et al. 2011; Fratini et al. 2012). Hence, the excess rainfall, which the drainage system cannot cope with, should be managed. In these contemporary approaches, the excess storm water, which occasionally may occur, is stored within the existing urban environment. These approaches are based on the principle of "designing for exceedance in urban drainage" (Digman et al. 2006). These approaches help to manage extreme water flows to reduce their impact on vulnerable assets by using roads to channel and convey flows to less vulnerable areas and by creating multifunctional, shared spaces to retain and store exceedance rainfall (Zevenbergen et al. 2012; Liao 2012; Fletcher et al. 2014). Applying these measures in newly developed areas is easier than in pre-existing built-up areas. As the current problems of Alexandria are in the existing city, adapting (c.q retrofitting) the urban fabric to enhance flood resilience in order to cope with exceedance will be a slow process (Veerbeek et al. 2010). It will be dependent on the pace of implementation of regular renewal and upgrading projects in the city. This process calls for an integrative, long-term planning approach in which storm water management and land use, urban design, and urban renewal planning processes are aligned. This integrated approach also allows for the identification of multiple benefits. The responsible authorities (HCWW, the Ministry of WR&I and the City Government and Public Works) should jointly develop a comprehensive, integrated urban retroffiting plan that links wider drainage issues and rainwater harvesting and recycling to urban (renewal) planning and design.

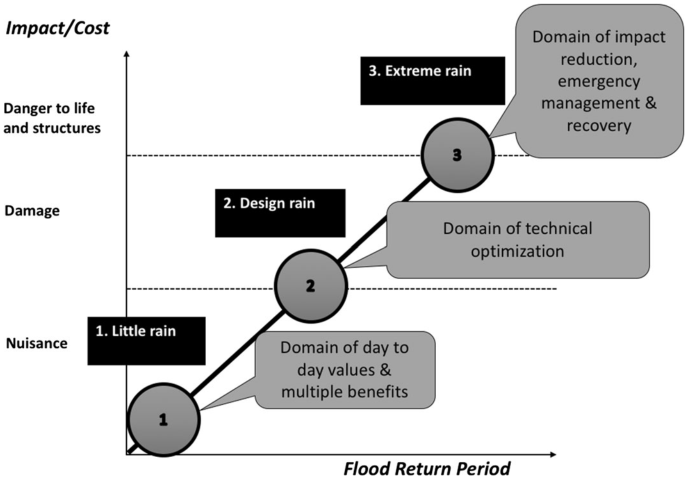

Fig. 8 Three-point approach (3PA). The horizontal axis represents the flood return period and the vertical axis represents the magnitude of the rain event in terms of cost of maintenance and damage of the urban infrastructure (Fratini et al. 2012)

The three-point approach (3PA) is an emerging approach in urban flood risk management which may provide practical guidance to facilitate the above-mentioned process. It aims to achieve maximum value from the synergies between surface water and other urban systems (Fratini et al. 2012). The 3PA encompasses three domains (see Fig. 8) which should be addressed in any renewal and upgrading project in the city: (1) the day-to-day rainfall events which are typically beneficial. This is the domain of day-to-day values and multiple benefits. (2) The “design” events; this is the domain of technical optimization dealing with standards and guidelines for urban drainage systems. (3) The extreme events; this is the domain of exceedance and flood resilience. Figure 8 is used to help understand how and why the domains are interrelated. Each domain is important in the way in which urban areas are laid out and managed to utilize their potential benefits and manage adverse impacts across the full range of rainfall frequencies (Salinas Rodriguez et al. 2014). The 3PA may therefore offer a practical framework to explore, identify and communicate in a structured way the synergies resulting from the above-mentioned strategic (and integrated) approach for Alexandria.

It is widely assumed and reported that Alexandria is highly vulnerable to the potential impacts of climate change (e.g. Sušnik et al. 2015). These impacts concern increased frequency and intensity of flooding due to changing rainfall patterns and associated sea level rise (SLR). The above-mentioned comprehensive, integrated urban retroffiting plan should therefore also take SLR into account.

6 Conclusions and recommendations

Flooding cannot always be prevented and this certainly holds true for the October 2015 flooding of Alexandria. However, Alexandria should be better prepared for flooding as it is likely that this type of events will happen more frequently due to climate change (Sušnik et al. 2015).

An analysis of the meteorological data reveals that the observed consecutive individual storm events are low probability events and that the persistence and clustering of this extensive rainfall storm events have been exceptional. This storm has led to flooding in Alexandria of historical proportions. The probability of the occurrence of this type of clustered storm event is hard to predict: they are associated with large uncertainties. The risks of these clustered storm water events cannot be properly managed using traditional approaches as they have not been designed for exceedance or failure. Although this October storm was a rare event, it could have been predicted at least 1 week in advance. Hence, if an appropriate warning system had been in place, measures could have been taken to alleviate its consequences. The use of rainfall forecast in stormwater modelling can be one of first short-term and cheap mitigation measures. The October flood could have been predicted with forecast rainfall. Instead of opting for high investments in upgrading the current drainage system, the forecasting would be a cheap, and short-term no- or low-regret risk mitigation measure. The forecasting system may further allow employing Anticipatory Water Management. The latter would imply that a large extra retention reservoir would be made available from lakes of the city (Lake Maryot and Airport Lake) by pumping the water out before it rains. Initial estimates suggest that the two identified lakes would provide adequate storage space in case of excessive rainfall events. This mitigation measure, however, needs more thorough analysis. The Alexandria Drainage and Sanitation Company needs to collaborate with the Irrigation department as the lakes are managed by them.

Based on these findings, the following recommendations can be made. The responsible authorities should ensure that a comprehensive flood study of the Alexandria region is undertaken. Advanced remote sensing techniques would likely be particularly useful here to further understand and detail the flood extent and behaviour of the October 2015 flood, as no monitoring data seem to exist. It will also require the development of a suitable hydraulic model that is able to determine flood heights, extents of inundations, rate, rise and duration of inundation for floods of different probabilities representing the actual conditions and future scenarios. These future scenarios should be based on plausible futures, taking into account the various drivers such as urbanization, climate change and other factors mentioned in this paper.

The high variability and uncertainty of rainfall call for a robust and flexible strategic approach that considers a portfolio of measures to reduce both the *chance* and the *consequences* of flooding. This approach should enable the responsible authorities to map out the future of the drainage system across the city over the next two or three decades and to identify the tipping point when upgrading of the existing drainage and irrigation system will be required. It will also provide the required evidence base on which to build a long-term wastewater and sewerage plan for Alexandria City which is essential to the strategy.

Towards this end, it is recommended that all water stakeholders in the Alexandria Region, engage in a broad discussion, leading to an agreement on the level of acceptable flood risk. This communication would entail a better understanding of the risks, the costs of failure and inaction and the multiple benefits to accrue from integrated mitigation measures.

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