PAPER 2

QUANTITATIVE FLOOD RISK ASSESSMENTS FOR THREE TOWNSHIPS IN JOHANNESBURG USING HIGH-RESOLUTION MODELLING

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ABSTRACT

This project focused on the widespread illegal dumping in river floodplains which predominantly comprises of building rubble and fill material for creation of platforms and development of shacks. The proliferation of these informal developments is no longer sustainable as it is already resulting to encroachment of the floodplains, unsafe living conditions, damage to existing infrastructure and possible increase in flood risk due to changes in the river hydrology. These impacts are expected to worsen if no interventions are taken. The objective of this study was to assess the flood risk increase due to illegal dumping along the water courses in Alexandra, Kaalfontein and Diepsloot. This project was commissioned by City of Johannesburg and implemented by Johannesburg Road Agency.

Six state-of-the-art, cloud-based, two-dimensional flood models were developed using Digital Terrain Models with 1m horizontal resolution. For each area, two flood models were generated; one representing the 2012 (pre-dumping) situation and one representing the 2019 (post-dumping) situation. An extreme value analysis of the rainfall events of the three areas was done to determine the normative rainfall durations and depths which were required to force the hydraulic models. A total of 28 modelling scenarios were simulated using combinations of different time horizons (2012 and 2019), different areas and different return periods (ranging from 5 to 100 years). Not only were the flood lines derived for each scenario, but also water depth maps, water level difference maps and flood hazard rating maps were generated. This gave a good first insight how the response of the river system changed as a result of the illegal dumping of building material in the floodplains.

A quantitative flood risk assessment was performed to gain a deeper understanding of the economic impact of floods and how the flood risk changed between 2012 and 2019. This assessment was performed using a Global Flood Risk Tool which is a cloud-based platform that quickly and accurately calculates flood damages and flood risk as a product of the modelled flood hazard maps, land use maps and vulnerability functions of the exposed assets. The study found among others that during a 100-year return period event water level increases of up to 1.8m could occur as a result of the illegal dumping. Also, the economic flood risk (i.e., expected annual direct flood damage) increased by 12-15% for Kaalfontein, 33-34% for Diepsloot and 8-10% for Alexandra between 2012 and 2019.

Keywords: 3Di, Flood hazard modelling, Flood risk assessment, Hydrological analysis, Johannesburg, Rivers

INTRODUCTION

Several watercourses, floodplains and wetland areas across the City of Johannesburg are currently experiencing widespread illegal dumping, particularly of building rubble and fill material. The large-scale dumping of builder's rubble by both small operators and large formal waste contractors has been ongoing for years at some sites. The builder's rubble

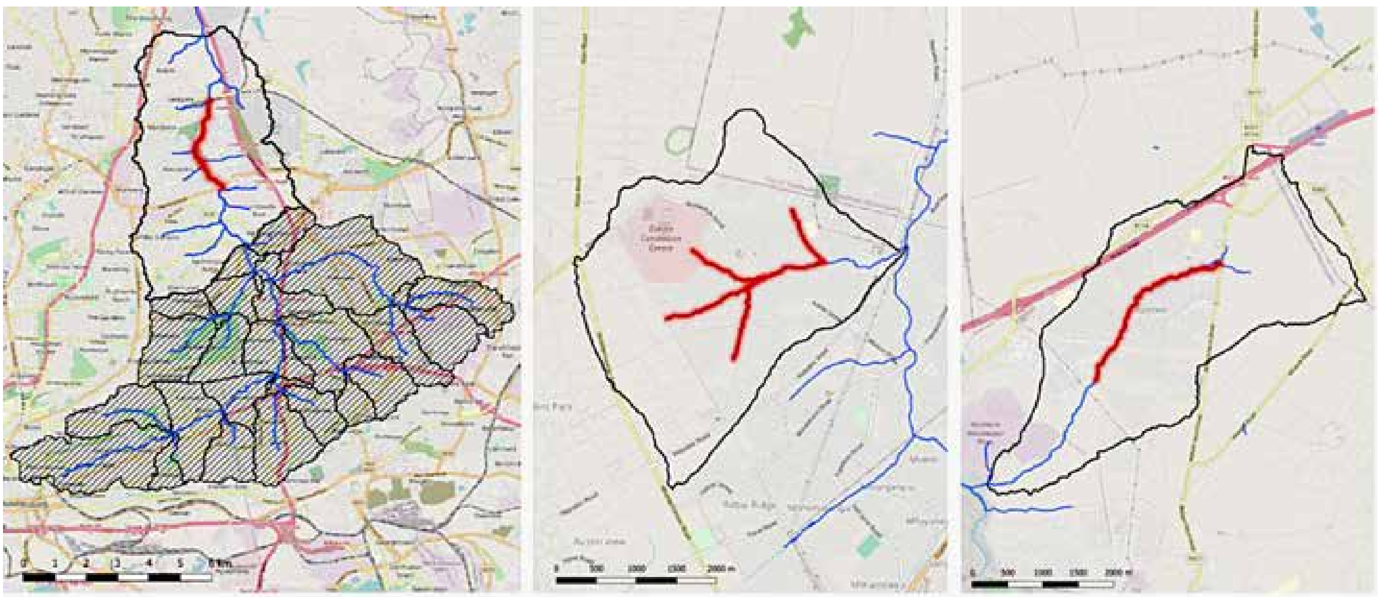

FIGURE 1: *Overview of the Alexandra catchment (left), Kaalfontein catchment (center) and Diepsloot catchment (right). Blue lines are streams and red lines are streams in the areas of interest.*

is then flattened to create a platform and shacks are being built on the newly created 'stands'. According to the City of Johannesburg, these are being sold by self-appointed developers. Structures are also built over pipelines, servitudes and adversely impact storm water infrastructure.

The areas which are currently of greatest concern are areas in Alexandra along the Jukskei River, in Kaalfontein along the Kaalspruit, and areas in Diepsloot along a tributary which feeds into the Jukskei River. The City of Johannesburg initiated a study to deal with the environmental degradation which has occurred because of the dumping, illegal encroachment, and related pollution. The goal of City of Johannesburg is to prevent the further infilling and erection of shacks within the watercourse and to rehabilitate the water courses to an acceptable environmental standard and thereby reducing the existing flood risk. The existing situation is not sustainable and causes major problems if no interventions are taken. It causes unsafe living conditions, it encroaches the floodplain, causes river pollution, threatens existing infrastructure near the rivers and could possibly increase the flood risk by the changed hydrology.

The main research question that this study answers is 'What is the increased flood risk due to illegal dumping along the water courses in Alexandra, Kaalfontein and Diepsloot?' The Environment and Infrastructure Services Department of City of Johannesburg appointed Johannesburg Roads Agency as the implementing agent for the determination of certified flood lines and quantitative flood risk assessment for Alexandra, Kaalfontein and Diepsloot areas of the City of Johannesburg.

STUDY AREA

The focus areas for this study encompass areas along the Jukskei River and its tributaries which are located within the Alexandra, Kaalfontein and Diepsloot catchments. The Kaalfontein and Diepsloot catchments are much smaller in size than the Jukskei catchment (which is relevant for Alexandra). Based on catchment delineation using a 1m Digital Elevation Model (DEM), the relevant catchment sizes derived for Alexandra, Kaalfontein and Diepsloot are 110.6km^2, 9.7km^2 and 11.1km^2, respectively. Kaalfontein and Diepsloot catchments are sufficiently small that all hydrological and hydraulic processes can be captured in the model instrument used for the study. Figure 1 shows the three catchments that are analyzed in this study.

DATA

The development of accurate flood lines and sound flood risk assessment are both dependent on the availability and quality of relevant site-specific data. There are four key processing modules required to develop the flood models which are a high-resolution digital terrain model (DTM), infiltration and roughness grids and infrastructure data. An overview of the data required (and adopted) to drive the model is presented per module in Table 1.

Other information that does not necessarily form part of the model development process but is critical in forcing the flood models relate to the historical rainfall, water level and discharge records characteristics of the three areas of interest. However, for this study, the historical water level and discharges were not available for model verification purposes.

MODEL AND RISK TOOL

Hydrodynamic modelling software

The model software used for this study is 3Di which is a hydrodynamic simulation software for pluvial, fluvial, and coastal floods and can be applied in both urban and rural areas. The software is a cloud-based solution that combines accuracy, robustness, speed, interactive modelling, and capabilities to model hydrological and hydrodynamic processes. These processes can be integrated in one model using 0D, 1D and 2D components. This approach is particularly suitable for surface runoff, river flows, channel and sewer flow, levee and dam breaches and coastal water systems. The computational core solves the full St. Venant equations with conservation of mass and momentum using subgrid and quadtrees as described in Casulli 2008, Casulli & Stelling 2013 and Volp et al. 2013. The subgrid methodology has the advantage that the high detail of the schematization is used without the need for extra computational power. The computational core handles dryfall in cells well, while the subgrid approach greatly reduces the need for extra time step iterations. This allows for the use of high-resolution topographic data, such as LiDAR surveys.

Global flood risk tool

For the quantitative flood risk assessment performed in this study, a cloud-based platform was used to run high-performance flood risk calculations using parallel computing performance. The Global Flood Risk Tool automates a wide range of calculations, such as allocating damage functions, economic land values and investment costs. The flood risk analysis tool visualizes economic flood damage, affected people and economic risk. It allows for inclusion of risk reduction measures and compares the costs of such measures with the financial benefits of reduced risk. This cost-benefit analysis supports any strategic appraisal framework and assists in building a business case whether to invest in flood risk reduction measures. The tool uses water depth maps, land use or population maps and flood depth-damage curves as input

METHODOLOGY

Hydrological analysis

The hydrological analysis was undertaken using an extreme rainfall analysis which was aimed at estimating the rainfall depths for the three areas of interest. To this end, a design-event approach was implemented using the Design Rainfall Estimation Software (Smithers & Schulze 2012) which executes the Regional L-Moment Algorithm and Scale Invariance (RLMA&SI) procedures developed by Smithers & Schulze 2002.

The Design Rainfall Estimation Software was used to obtain rainfall depths for different storm durations (30-min, 1-hr, 2-hr, 4-hr, 8-hr, 12-hr and 24-hr) and different return periods (10, 20, 50 and 100 years) from representative rainfall stations within each of the three catchment areas.

TABLE 1: *Overview of the data required for model development*

Module	Data required/used in this study
DTM	• LiDAR survey (2012 and 2019) converted to DTM with 1m horizontal resolution • Bathymetry information (or typical cross-sections) of natural rivers/channels with clear geographic projection • Aerial imagery
Infiltration grid	• Soil type classification • Land use data for both pre-dumping and post-dumping situations
Roughness grid	• Land use data for both pre-dumping and post-dumping situations • Manning's friction coefficients (corresponding to land use)
Infrastructure	• Information on the existing drainage systems, and road and rail networks at each area of interest - Location - Dimensions - Shapes - Invert levels - Type of structures and channels - Road center lines and polygons

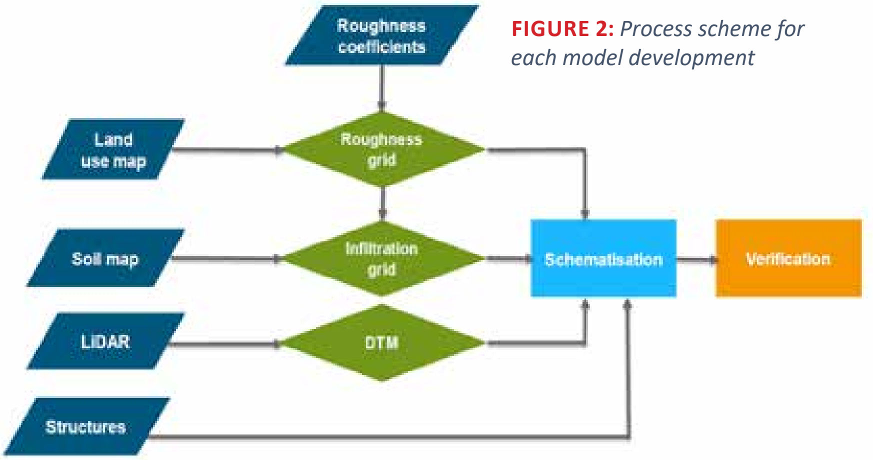

FIGURE 2: *Process scheme for each model development*

The software uses a 1 arc minute grid to provide its outputs. All grid points in Alexandra (11 points), Upper Jukskei (26 points), Kaalfontein (3) and Diepsloot (4 points) were extracted. All grid outputs were averaged for each area to determine the average catchment rainfall at different storm durations and return periods.

After obtaining the rainfall depths for the predefined storm durations and return periods, triangular-shaped rainfall hyetographs were developed (for each storm duration and return period) to force the hydraulic models developed for each catchment area. Given the small size of the Kaalfontein and Diepsloot catchments, no areal reduction factor (ARF) was applied on the rainfall depths. Simulations with the flood model of Diepsloot and Kaalfontein were performed to determine the normative storm duration (based on flood extent and level) for each catchment area.

The Kaalfontein and Diepsloot models include the complete catchment, so the normative storm duration is determined by the rainfall that is forced directly on the model grid. A different approach was required to determine the normative storm duration for the Alexandra catchment, because the Alexandra flood model only includes the area of interest but still receives discharges from the upper Jukskei catchment which is about 78km^2 in size as depicted in Figure 1. The upstream discharge from the Upper Jukskei is much (50-100 times) larger than the lateral inflow in the area of interest in Alexandra and will thus be determining the normative storm duration of the area of interest.

For the Alexandra area, a hydrological analysis for the upstream catchment (which is about 78km^2) is performed. The idea is to capture the upstream discharge from the Upper Jukskei and translate it to an inflow on the upstream boundary of the flood model that includes the Jukskei transect between the R25 and where the Jukskei crosses the N3 near Buccleuch. A detailed understanding of the flood hydrology of the Upper Jukskei area is therefore required in determining the normative storm duration of the Alexandra catchment and hence establish which upstream boundary discharge should be adopted. The T100 (1-hr, 2-hr, 4-hr, 8-hr, 12-hr and 24-hr) hyetographs for the Upper Jukskei area were used to simulate rainfall events in an existing PCSWMM model. The discharges obtained from rainfall-runoff simulations in PCSWMM were thereafter used to perform test runs in the 3Di hydraulic model to determine the normative storm duration for the Alexandra area.

Flood model development

A flood model is created for each area which results in three models. Figure 2 presents the 3Di process scheme (framework) that guides the development of flood models for the three areas of interest in this study. Each model has a 2012 and 2019 schematization which gives 6 model schematizations. The 2012 schematizations differ from the 2019 schematization, because it uses the 2012 topography and land use. Hence, the 2012 schematization also has different infiltration and roughness grids, because these are dependent on the land use.

Table 2 captures the main model settings that are used.

Sensitivity analysis

Several tests with the numerical model were performed to help understand the sensitivity of the areas to certain parameters. Based on the analysis of these tests choices in applied model settings could be made. The following aspects of the models were subjected to sensitivity test and analysis:

(i) Calculation grids: a fine calculation grid size was adopted within the river channels and area of interest and a coarse calculation grid size in the remaining area.

(ii) Boundary conditions: a 2D energy slope boundary condition is used as downstream boundary in all three models. The energy slope is estimated based on the slope observed in the surface level and tested based on how far its effect travels upstream. An upstream boundary condition in form of a hydrograph for applied only to the Alexandra model.

(iii) Infiltration: For all areas it was found that infiltration is not an important model parameter as it accounts for <5% of the rainfall volume. This aligns well with the theory that for short extreme events, in which rainfall intensities exceed infiltration capacities, infiltration is negligible.

TABLE 2: *Overview of main model settings*

	Diepsloot and Kaalfontein	Alexandra
Model extent	Complete catchment	Only area of interest. Upper Jukskei catchment is not included in the 3Di flood model.
Hydrological processes	Yes, captured	Yes, captured for the model extent. Hydrology of the catchments upstream of the model extent are not solved by 3Di, but are captured by using an upstream discharge boundary
Hydraulic processes	Yes, captured in 2D (structures in 1D)	Yes, captured in 2D (structures in 1D)
Upstream model boundary	No	Yes, time-varying discharge
Downstream model boundary	Yes, constant water level slope	Yes, constant water level slope
Rainfall on model grid	Yes, time-varying rainfall	Yes, time-varying rainfall
Computational grid	Structured, staggered with refinement (cell sizes vary between 4m and 32m)	Structured, staggered with refinement (cell sizes vary between 4m and 32m)
Subgrid	Yes, resolution is 1m	Yes, resolution is 1m

(iv) Roughness: For all models, various friction values were tested and applied to the whole model domain to better understand the sensitivity. It was found that the models are relatively sensitive to roughness values
(v) Storm duration: a range of events with different durations and a return period of once every 100 years were tested for the three areas. The critical rainfall durations tested are 15 minutes, 30 minutes, 1 hour, 2 hours and 4 hours. The critical rainfall duration (duration resulting in the highest water levels near the AOI) are then selected based on the maximum flood depths. The normative storm durations of the areas of interest in Alexandra, Kaalfontein and Diepsloot are 2 hours, 30 minutes, and 30 minutes, respectively.
(vi) Structure discharge coefficients: The riverbeds and floodplains in the three areas are characterized by a lot of waste and natural debris. Clogging of hydraulic structures has a great impact on its hydrodynamics and causes adverse backwater effects. Sensitivity tests were performed to determine the influence of clogged structures by varying the discharge coefficients of the structures in the model. The discharge coefficients values were calculated following the method proposed by Ollett et al. 2017.

Flood simulations

Following the development of flood models, simulations were performed to determine the 1:100-year flood lines for the three areas of interest. A total of 24 simulations were run comprising three areas of interest, four return periods (10-year, 20-year, 50-year and 100-year) and two time horizons (2012 and 2019). Simulations at return periods less than 100 years were run to serve as a basis for the flood risk assessment. It is assumed that 100-year rainfall events also lead to 100-year flood lines.

Flood hazard rating

A flood hazard rating is typically developed based on spatial analysis of flood depths and flow velocities. In the three study areas, flood hazard ratings were obtained for the pre- (2012) and post-dumping (2019) of rubble and fill material. A matrix developed by the Environment Agency & HR Wallingford (2008) was adopted in determining the flood hazard ratings for this study. The matrix provides flood hazard ratings and thresholds for development planning and control purposes and is useful for a range of applications such as an initial indication of risk to people. The "Hazard to People Classifications" is derived as a function of depth, velocity, and debris factor and useful for a range of application as an initial indication of Risks to People. The 'hazard rating' based primarily on consideration to the direct risks of people exposed to floodwaters, is expressed as:

$$HR = d \cdot (v + n) + DF \quad (1)$$

where, HR = (flood) hazard rating;
d = depth of flooding (m);
v = velocity of floodwaters (m/sec);
DF = debris factor (0, 0.5 or 1 depending on probability that debris will lead to a hazard); and
n = a constant of 0.5

Flood risk assessment

The study performed a quantitative flood risk assessment which means that the flood impacts are quantified in actual costs which finally results in an economic flood risk value. Flood risk is the product of two components: flood hazard and flood impact. The flood impact is a result of the exposure of assets and the vulnerability of these assets. The flood hazard refers to the probability, extent, and water depths of a certain flood event. The flood impact describes the consequences as a result of vulnerability of exposed objects (or land uses) to flood hazard. It is dependent on the vulnerability of an object to flooding, its resistance to the impact of a flood and capacity to recover to the state prior to a flood event. This vulnerability is described in terms of a flood depth-damage function which is a method that is often used (Du Plessis & Viljoen 1997, Du Plessis & Viljoen 1998, Huizinga et al. 2017).

As empirical data on flood vulnerability is limited in South Africa, the majority of existing damage functions are empirical ones. Depth-damage functions from literature were used and the maximum damage value per land use was corrected for price year, currency difference and GDP difference between countries as explained in Huizinga 2017. Only direct damages were considered, so indirect damage such as reduced economic activity, individual financial hardship, adverse impacts on the social well-being of a community, lost trading time, loss of market demand for products, clean up, emergency response and emergency accommodation for evacuees were excluded. Indirect damages may vary between regions and flood events but are estimated to add 25% to 40% to the direct damages.

When flood hazard and flood impacts are assessed for different event probabilities (or return periods) the Damage Probability Function (DPF) can be prepared (see Figure 3). Then the economic risk becomes clear by integrating the DPF. This results in an Estimated Annual Damage (EAD) value (in ZAR/year) that can be considered an annual cost to compensate for flood losses of all possible flood events. In this study, the economic direct damages were calculated for four return periods, being 10, 20, 50 and 100 years, for both 2012 and 2019 situations.

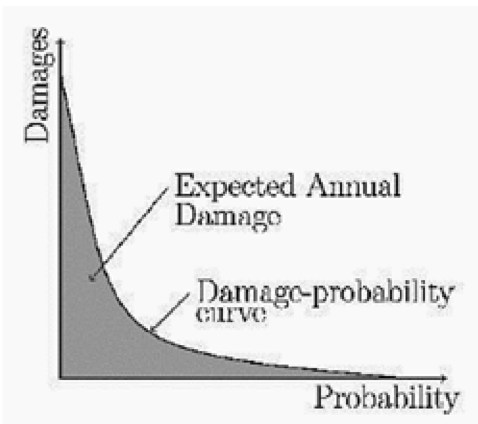

FIGURE 3: *Damage-probability curve and expected annual damage (Foudi et al. 2015)*

RESULTS

100-year flood lines and influence of dumping

Following the model runs executed using 3Di, the 100-year flood lines were generated for the post-dumping scenario (2019) for the three areas of interest are presented in Figure 4. Local stormwater ponding is also part of the model result, but the maximum water depth maps have been post-processed to ensure that all flooded areas smaller than 1 hectare are removed from the result. The flood lines are thus also partly including pluvial stormwater runoff as long as it is connected to the main channel, or the area of flooding is bigger than 1 hectare. The change in flood lines varies per location when looking at the 2019 and 2012 flood lines. In areas where the floodplain has been encroached (or raised), the flood line has moved closer to the river, while in other areas (most likely where the water

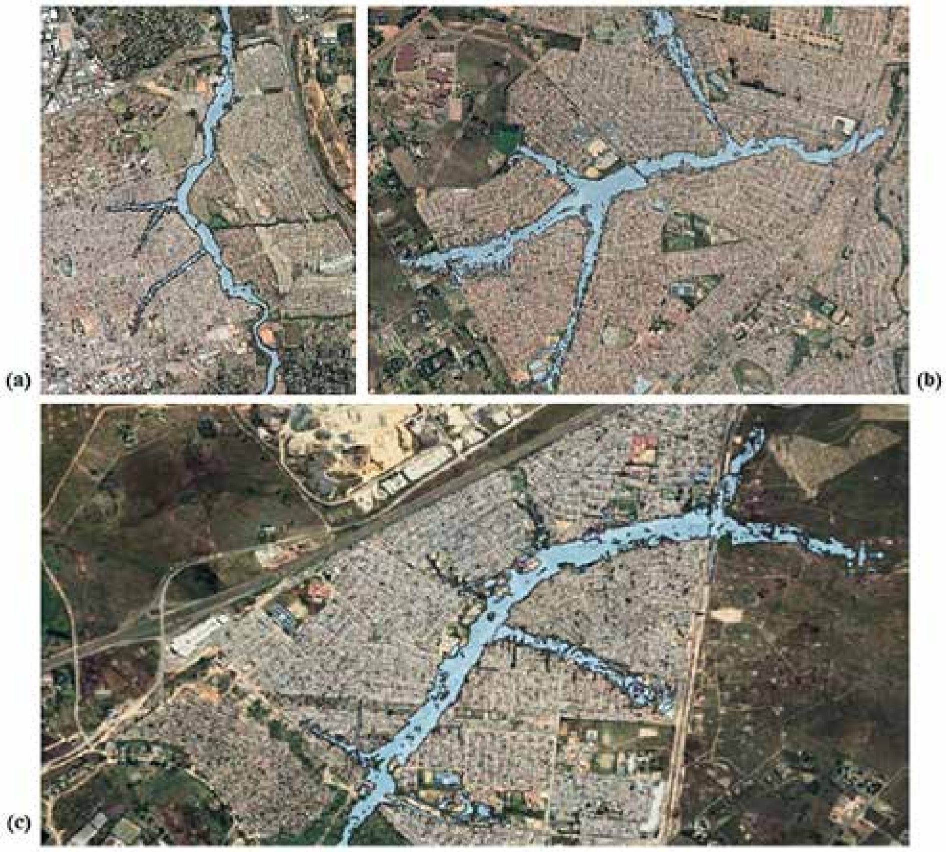

FIGURE 4: *100-year flood lines for the post-dumping scenario (2019): (a) Alexandra; (b) Kaalfontein; and (c) Diepsloot*

level increases occur) the flood line moves further away from the river.

The influence of dumping and land use change on the three catchment areas, considering both the pre-dumping (2012) and post-dumping scenarios (2019) during a 100-year return period flood event are represented as a function of changes in water levels via water level maps. The water level difference maps for Alexandra, Kaalfontein and Diepsloot are presented in Figure 5.

Significant changes can be observed for Alexandra between Florence Mofosho Street and Marlboro Road. This significant change in water level (up to 1.8m) can be attributed to high level of dumping and encroachment of the flood plains around the area of Seswetla. A clear backwater curve can be seen that affects the water level up to 1.5km upstream. A clear water level increase can also be seen upstream of London Road where the East Bank has been raised for several meters which has seriously encroached the floodplain. The water level increase is almost 1m. The water level changes between Roosevelt Street and 600m downstream are also an effect of encroachment of the floodplain. The water level increase is up to 0.5m.

FIGURE 5: *Differences in 2019 and 2012 water levels as a result of encroachment of the floodplain in (a) Alexandra; (b) Kaalfontein; and (c) Diepsloot*

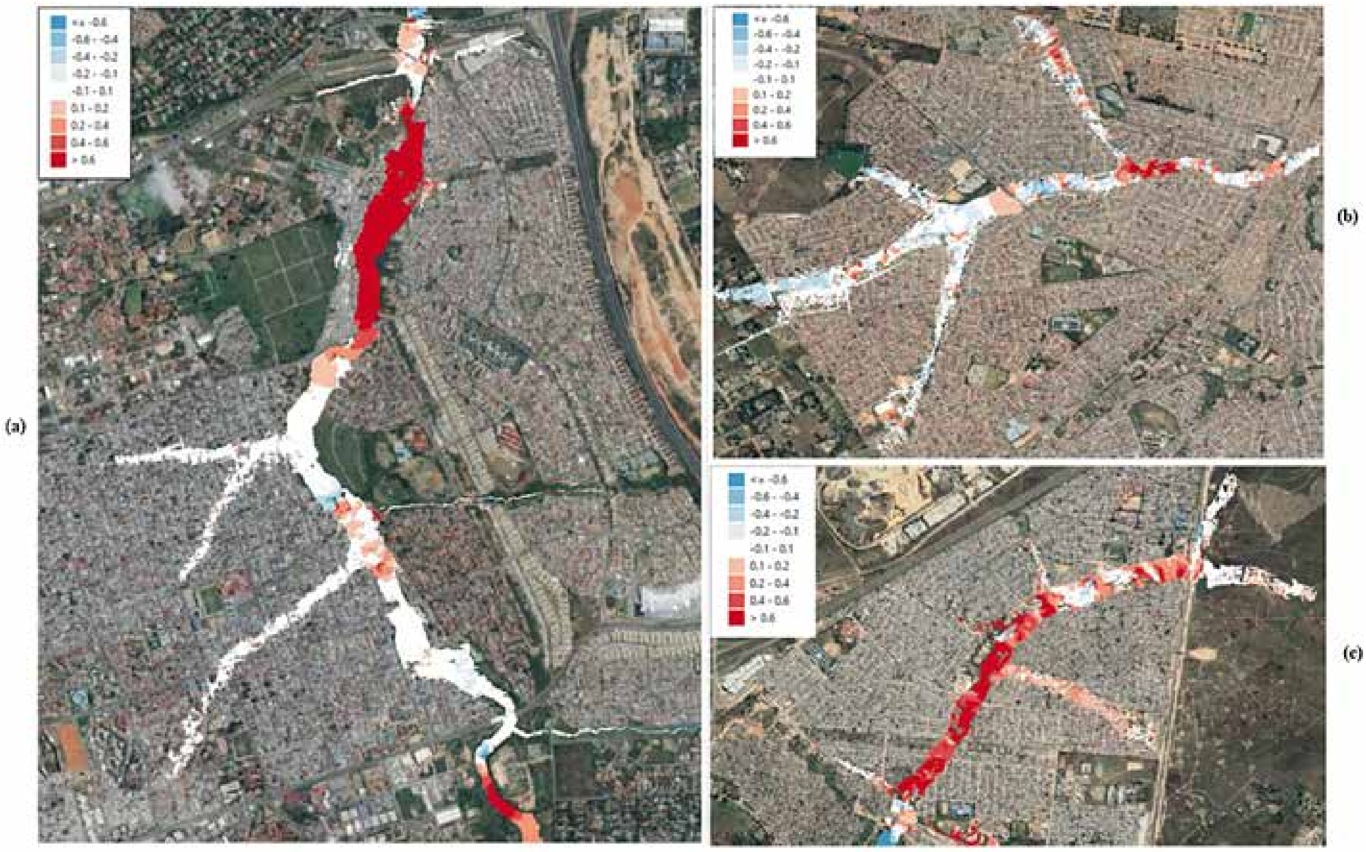

TABLE 3: *Overview of estimated direct flood damages*

Return period (years)	2012 situation (millions ZAR)	2019 situation (millions ZAR)	Difference (millions ZAR)	Difference (%)
Kaalfontein				
10	5.4	5.9	0.5	10%
20	8.0	9.8	1.8	23%
50	12.0	15.5	3.5	29%
100	16.1	21.4	5.3	33%
Diepsloot				
10	19.5	26.1	6.6	34%
20	25.6	35.1	9.5	37%
50	35.5	47.8	12.3	35%
100	43.8	59.5	15.7	36%
Alexandra (between London Road and Marlboro Road)				
10	41.6	44.5	2.9	7%
20	49.3	54.3	5.0	10%
50	61.3	71.1	9.8	16%
100	71.9	87.6	15.7	22%

TABLE 4: *Economic flood risk values (i.e., EAD) for all three townships, for both time horizons and with sensitivity around the start of damage*

Location	Return period of event from which damage starts (years)	EAD (million ZAR/year)		Difference EAD (million ZAR)	Difference EAD (%)
		2012	2019		
Kaalfontein	1	2.7	3.1	0.3	12
	2	1.9	2.2	0.3	15
Diepsloot	1	10.3	13.8	3.4	33
	2	6.7	9.0	2.3	34
Alexandra	1	24.0	26.1	2.0	8
	2	13.6	14.9	1.3	10

Significant changes in water levels can be observed in and around the main channels in Diepsloot. This is again a clear result of the encroachment of the floodplain. The 2019 DTM shows a clear encroachment in almost the entire floodplain. The most extreme section is between the bridge near Thorn Street and 100m downstream of the bridge at Lemon Street where water level increases vary between 1 and 2m in both the main channel and sections of the flood plain.

Flood hazard rating

Based on spatial analysis of flood depths and flow velocities in the 3 areas of study, the flood hazard ratings obtained for the pre- (2012) and post-dumping (2019) of rubble and fill material are presented in Figure 6.

The flood hazard rating shows that the flash flood events are dangerous events for all. The ratings are higher than 2 for most areas. This would mean that crossing rivers should always be avoided and that people living in the flood line area need to be warned and evacuated in time to prevent loss of life. This is a challenge since these events occur very quick.

Flood risk assessment

The estimated economic damages in the 2012 (pre-dumping) and 2019 situation (post-dumping) are reported in Table 3 for all three areas. In absolute damage values and for similar probability events, Alexandra is facing the largest damage, Diepsloot the second largest damage and Kaalfontein the least amount of damage between the three areas of interest.

For Kaalfontein, significant changes in water level are not as pronounced as observed in Alexandra, but significant water level increases up to almost 1m can be observed 200m up- and downstream of Glassnose Street bridge. This is a clear result of encroachment of the floodplain on both sides of the river. Another point of attention is the Main Road bridge. Upstream there is encroachment of the banks which results in local water level variation that can be significant.

In Kaalfontein, the impact of dumping increases with more extreme events; from 10% at a 10-year storm to 33% for a 100-year storm. Also in Alexandra, the impact of dumping increases with more extreme events; from 7% at a 10-year storm to 22% for a 100-year storm. In Diepsloot, the impact of dumping increases with more extreme events in absolute terms, but relatively there is a stable increase ranging between 34% and 37. Both in absolute and relative terms, Diepsloot is experiencing

(a)

(b)

(c)

FIGURE 6: *Flood hazard ratings for the post-dumping scenario 2019): (a) Alexandra; (b) Kaalfontein; and (c) Diepsloot*

the largest increase in flood damage between 2012 and 2019 because of dumping.

The damage values in Table 4 form the basis for different DPFs. These curves assume damage is 0 ZAR at an event with a probability of once per year and that damage occurs at any extremer event. This is an assumption that is not verified, since no data was available. Damage may already occur with less extreme events or could only occur at a lower probability event (e.g., a storm with a 2-year return period). Since the high probability (or low return period) events have a large influence on the economic risk computation it is important to consider this uncertainty. To deal with this uncertainty, the economic flood risk, calculated by integrating the DPF, is presented by including a sensitivity around the return period event at which damage starts: a once per year event as well as once per two years event. The results are presented in Table 4 below and show a wide range in the EAD values. The results show that despite the uncertainty when damage starts exactly, the relative increase of the flood risk is in the same order of magnitude: 12-15% for Kaalfontein, 33-34% for Diepsloot and 8-10% for Alexandra.

CONCLUSIONS

As result of this study several conclusions were drawn. The normative storm durations differed between the three townships and were 2 hours, 30 minutes, and 30 minutes for Alexandra, Kaalfontein and Diepsloot, respectively. Alexandra had a longer normative storm duration, because it has a much larger catchment upstream of the area of interest.

It became apparent that the three flood models were relatively sensitive to roughness values and discharge coefficients of the structures. The seasonal change in vegetation could therefore greatly influence the water levels. Also, litter, garbage and/or environmental waste (e.g., branches) is expected to severely impact the discharge capacity of the structures. Since the structures constrict the flow by definition and hence cause for backwater effects, proper waste management of this type of garbage is important to reduce flood risk.

The flood lines varied spatially when looking at the 2012 and 2019 model results. In areas where the floodplain was encroached (or raised), the flood line was situated closer to the river, while in other areas the flood lines moved further away from the river. In Alexandra, the biggest water level increases as a result of encroachment of the floodplains could be found between Florence Mofosho Street and Marlboro Road (up to 1.8m), upstream of London Road where the East Bank (up to almost 1m) and between Roosevelt Street and 600m downstream (up to 0.5m). In Kaalfontein, these increases were found 200m up- and downstream of Glassnose Street bridge (up to almost 1m) and near the Main Road bridge (Local water level variation can be significant). In Diepsloot, encroachment in the floodplain caused water levels to increase in the entire main channel. Especially between the bridge near Thorn Street and 100m downstream of the bridge at Lemon Street water level increases were between 1 and 2m.

The flood hazard rating shows that the flash flood events are dangerous events for all. The ratings are higher than 2 for most areas. This would mean that crossing rivers should always be avoided and that people living in the flood line area need to be warned and evacuated in time to prevent loss of life. This is a challenge since these events occur very quick.

Logically, the direct flood damages increased with flood events with more extreme return periods. In Alexandra, direct flood damage for flood events with a 10- to 100-year return period increased relatively with 7% for a 10-year storm to 22% for a 100-year storm. In Kaalfontein, the relative increase varied between 10% for a 10-year storm and 33% for a 100-year storm. In Diepsloot, the relative increase varied between 34% for a 10-year storm to 36% for a 100-year storm. The 100-year return period flood events in Kaalfontein, Alexandra and Diepsloot are expected to cause 5.3 million ZAR, 15.7 million ZAR, 15.7 million ZAR more direct damage for the post-dumping situation (2019) than prior the encroachment of the floodplain (2012). Relatively, the economic flood risk increased by 12-15% for Kaalfontein, 33-34% for Diepsloot and 8-10% for Alexandra between the period of 2012 and 2019.

RECOMMENDATIONS

The results of this study have been conclusive and show an increase of flood risk in all three areas of interest. The quality of this study could be further improved by calibration and validation of the three flood models. There was no data made available within the City of Johannesburg that could be used to verify the simulated flood levels and extent. Any information on historical flood extents or water level and discharge data from river gauges should be used in future studies to further optimize the performance of the flood models.

Another recommendation to improve both the flood model as well as the flood risk assessment is the use of a more detailed and accurate land use dataset. The dataset was an aggregate of various sources and has been improved in the areas along the river during this study using high-resolution satellite imagery. A more detailed and accurate land use dataset would improve the roughness and infiltration layers in the flood model and would allow for a more accurate flood damage assessment.

The flood risk assessment in this study has shown the benefits of a quantitative risk analysis. This assessment can be improved in two ways. Firstly, the current assessment only considers direct economic costs while, ideally, a more comprehensive risk assessment is performed that also includes the indirect flood damages, social welfare, loss of life and other non-tangible impacts. Secondly, the damage estimates could not be verified with damage estimates of historical events. Any additional data on flood damage would assist in the validation of the simulated damage estimates and in the finetuning of the flood depth-damage functions for the different land use types.

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