

TRANSPORT GLOBAL PRACTICE

FLOOD-RESILIENT MASS TRANSIT PLANNING IN OUAGADOUGOU



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ABBREVIATIONS AND ACRONYMS

ANAC	National Civil Aviation Agency
AOI	Area of Interest
cm	centimeter
GFDRR	Global Facility for Disaster Reduction and Recovery
DGTTM	General Directorate of Land and Maritime Transport
DTM	Digital Terrain Model
DSM	Digital Surface Model
IDF	intensity-duration-frequency
IRD	Institut de Recherche pour le Developpement
mm	millimeter
OPTIS	Ouagadougou Public Transport Implementation Study
POI	Point of Interest
RP	Return Period
UAV	Unmanned aerial vehicle
US\$	United States Dollar
VTOL	Vertical take-off and landing

GLOSSARY OF KEY TECHNICAL TERMS

bathymetry	The measurement of depth of water in oceans, seas, or lakes
bioswale	Vegetated, shallow, landscaped depressions designed to capture, treat, and infiltrate stormwater runoff and convey stormwater at a slow, controlled rate; the flood-tolerant vegetation and soil act as a filter medium, cleaning runoff and allowing infiltration. Bioswales are generally installed within or near paved areas (e.g. parking lots, roads and sidewalks).
canals	Large open conduits conveying water on the surface; they form the primary drainage network, collecting water from secondary structures and channeling it to the natural outlet
channels	Structures that form the secondary and tertiary drainage networks; typically rectangular section concrete structures, with dimensions ranging from 50cm to a few meters wide; channels are generally used to collect rainwater along the road surface. When playing this function of longitudinal drainage, they are generally called “caniveaux” in French (open rectangular street gutters). Larger channels collecting water from several smaller ones and leading to a canal may be called “collecteurs”. In this report, both types will be referred to as channels, since they are represented by similar rectangular concrete structures. In Ouagadougou, longitudinal channels are often partially covered with concrete slabs.
culverts	Buried structures, either circular (pipe culverts – “buses” in French) or rectangular (box culverts – “dalots” in French), whose function is to ensure hydraulic transparency of a road by channeling water under the road surface. They are also referred to as transverse/cross-section structures.
design storm	A rain event, either observed or synthetic, which is chosen as the basis for the design of a hydraulic structure
Digital Elevation Model	A representation of the bare ground (bare earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects; it is as a subset of the Digital Terrain Model, which also represents other morphological elements.
Digital Terrain Model / Digital Surface Model	Both models are three-dimensional models representing, in digital form, the relief of a portion of land. But, while the DSM represents the altitude of the first surface observed from the sky (tree top, roofs, ground, etc.), the DTM aims at representing the altitude of the ground. To elaborate a dynamic hydraulic model, one needs a DTM (to model water circulation on the ground). The result obtained from an aerial topographic survey, whether LIDAR or photogrammetric, is a DSM, which requires data treatment to access a digital model offering information as close as possible to the ground elevation.
dynamic hydraulic model	A dynamic hydraulic model simulates the evolution of flows/heights/speeds over time, during the whole duration of the design storm. Such a model requires more input data and more calculation capacities than a stationary model, but in return offers more information on the hydraulic system functioning. Dynamic models are necessary when the simple information on peak flows is not sufficient, and in complex situations which exceed the capabilities of stationary models: when water storage/retention occurs, or when a downstream condition exists for example (when the outlet of the hydraulic system is a lake or ocean, for example).
Gray solutions	Solutions based on hard, human-engineered infrastructure that uses concrete and steel
Green solutions	Solutions that use soils and vegetation to utilize, enhance and/or mimic the natural hydrological cycle processes of infiltration, evapotranspiration and reuse
greenbelt	A policy and land-use zone designation used in land-use planning to retain areas of largely undeveloped, wild, or agricultural land surrounding or neighboring urban areas

hydrograph	A graph showing the rate of water flow in relation to time, given a specific point or cross section; often used to evaluate stormwater runoff on a particular site
hyetograph	A graphical representation of the distribution of rainfall intensity over time
intensity-duration-frequency curve	A mathematical function that relates the rainfall intensity with its duration and frequency of occurrence
non-dynamic / stationary hydraulic model	Hydraulic model aiming only at calculating the peak situation caused by the design storm (peak flow / water height / velocity). Such models use simplification hypotheses, by considering the rainfall as stationary during a given duration corresponding to the highest sensibility of the watershed. Stationary models generally offer enough information for simple scenarios.
rain garden	A garden of native shrubs, perennials, and flowers planted in a small depression, which is generally formed on a natural slope; designed to temporarily hold and soak in rain water runoff that flows from roofs, driveways, patios or lawns; dry most of the time and typically holds water only during and following a rainfall event; unlike bioretention swales, they do not convey stormwater runoff.
pocket parks	Smaller public parks (generally occupying less than one acre of land) that represent ideal locations for green infrastructure (vegetated bioretention cells) that treats and captures stormwater through bio-filtration and infiltration. Pocket parks are opportunistic, often sited on whatever land is available, and might be constructed to revitalize unused or underused land (e.g. decommissioned railroad tracks).
return period	An average time or an estimated average time between events such as earthquakes, floods, landslides, or a river discharge flows to occur; also known as recurrence interval or repeat interval. A storm intensity with a return period of 10 years has a 1 in 10 chance of being observed each year. Return periods are used to define the level of risk that a project owner can accept, depending on the criticality of the infrastructure to be protected. For example, a road is typically designed to be protected against flooding of its surface by storms with a 10 year return period, whereas a large dam or a nuclear plant would have to be designed to cope with extreme events with return periods of several hundreds or even thousands of years.
runoff coefficient	Also referred to as drainage ratio, it is the ratio between the height of water runoff at the exit of a specific surface (called "net rain") and the height of water precipitated (called "gross rain"). This ratio is affected by factors such as evapotranspiration, impermeability of surfaces, soils infiltration capacities. It has a lower value for permeable, well vegetated areas (forest, flat land).
Soft solutions	Solutions that use institutions and technology services
watershed	The watershed / catchment area of a watercourse is defined by the area receiving the waters feeding this watercourse. In a broader use, a watershed can be defined for any point in space: it is formed by all the areas receiving water that runs off to that point (all the areas located upstream of that point).
wetlands	Areas where water covers the soil, or is present either at or near the surface of the soil all year or for varying periods of time during the year, including during the growing season

EXECUTIVE SUMMARY

Ouagadougou, the largest city in Burkina Faso, is growing rapidly, with the annual rate reaching 9 percent by some estimates, and with commensurate challenges for ensuring efficient mobility for its residents. Like many urban areas in Sahelian West Africa, **Ouagadougou is also highly vulnerable to extreme hydro-meteorological events.** In Sahel countries, the frequency of extreme storms tripled in the last 35 years; between 1991-2009 alone Burkina Faso experienced 11 major floods. The flooding events of the last few decades directly affected the functionality of Ouagadougou's transport system, especially considering the sparsity of the climate-resilient (paved) road network and the dominance of poorly maintained dirt roads. Moreover, urban growth, extreme weather events, and climate change are expected to continue to drive an upward trend in flooding risk in the future, highlighting the urgent need for flood-resilient infrastructure development in Ouagadougou.

In the context of the plans to develop an efficient, bus-based mass transit system in Ouagadougou in the medium term, **the study aimed to characterize the spatial distribution and severity of flood risk affecting the planned system; and to identify, evaluate and prioritize interventions that would increase its resilience.** The study focuses on a pilot sector of 67 km², covering a large part of central Ouagadougou and its strategic infrastructures, at the intersection of the future planned mass transit system and the areas of the city *a priori* considered more flood prone (e.g., near the major dams).

By working with a local drone operator and an international flood modelling firm, **the study constructed high spatial resolution Digital Elevation and Digital Terrain Models for the area of interest (AOI), which served as inputs for developing a hydrological model.** The main output of the flood modeling are maps showing maximum water heights and speeds in the AOI, under four return periods, summarized as follows:

- Frequent stormwater event (2-year return period)
- Rare stormwater event (10-year return period)
- Very rare stormwater event (50-year return period)
- Exceptional stormwater event (historical flood of September 1st 2009, with a return period higher than 100 years)

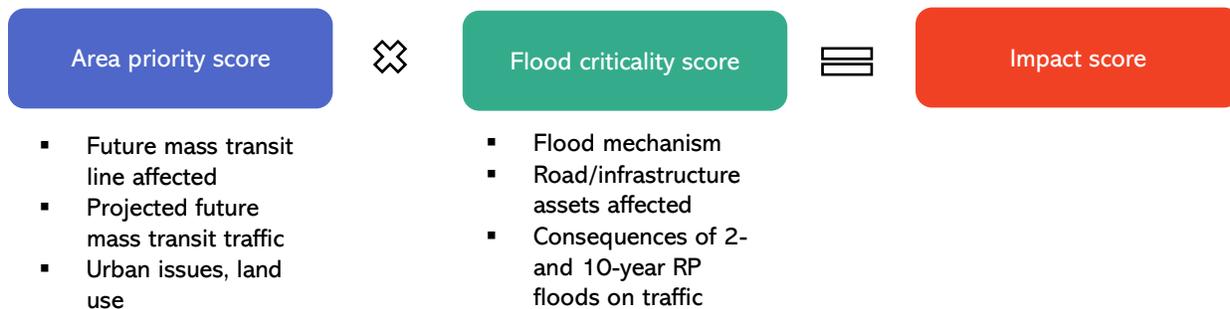
In general, axes 2, 3, 6 and 8 of the future planned mass transit network are not found to be subject to high flood hazards, as compared to axes 1, 4, 5, and 7. To further understand the flood risk affecting the planned layout of the bus system, a set of points was selected

in the AOI representing different flood types, for which hydrographs were generated showing the evolution of water height over time during the 2-year return period (RP) flood and the 2009 flood. The analysis of the ramping up and down of water heights associated with rainfall intensities allowed to characterize the type of flooding associated with various situations and causes. This analysis helped characterize the severity of floods in the set of points, from which the insights were extrapolated to other areas presenting the same characteristics (areas next to a canal flooded by overflow, street parallel to the slope, street perpendicular to the slope and flooded by transverse streets, low points / basins).

To further classify the road and future mass transit sections in order to prioritize interventions, the analysis applied the criteria of an “area priority score” and a “flood criticality score”, which together combine into an overall “impact score”:

- The **area priority score** was assigned based on the projected mass transit traffic and urban issues. For example, the section of 28.257 St. on Line 4 was assigned a low priority score because this section is at the end of a future planned bus line, where the travel demand and therefore the impacts of service disruptions would be limited. On the contrary, the sections of Avenue du Capitaine Thomas Sankara and Avenue Nelson Mandela shared by most future bus lines were given a high score because they serve the City Centre and attract the highest travel demand of the planned mass transit system.
- The **flood criticality score** was assigned based on the flood mechanism and consequences (flood depth and duration); sections flooded for an extended period with a high depth of water were given the maximum criticality score.

The analysis allowed concluding that the **traffic on Avenue Nelson Mandela and the Nations Unies roundabout, used by most future bus lines, could be interrupted by the 2-year RP rainfall.** This area is the most critical in terms of not only flood criticality (flood depth and duration) but also urban area priority (presents the highest projected mass transit traffic and serves the city center). Outside of this area, the traffic on the roads used by several lines could be interrupted by the 2-year RP rainfall at specific locations of their respective itinerary.

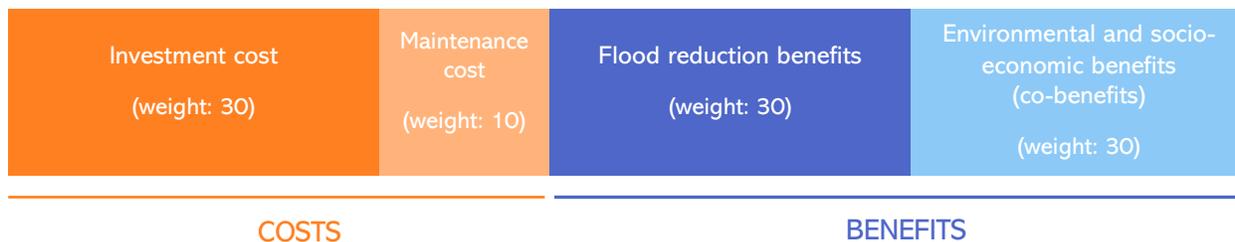


Next, a methodology was developed to identify solutions for improving the flood resilience of the planned transport system of Ouagadougou. First, a “long list” of solutions was identified based on preliminary criteria of relevance for Ouagadougou and considered vis-à-vis the specific sections of the planned transport system exposed to flood risk. The analysis explicitly considers not only structural infrastructure (“gray” measures) but also ecosystem-based approaches (“green” measures), hybrid measures, and non-structural, or “soft”, measures (e.g. risk monitoring, territorial planning, etc.).

The analysis focused on the main streets, intersections and obstacles (e.g. canals) used by the planned transit system. The analysis considered the consequences of

the 2- and 10-year-return-period models to find structural solutions that would protect the infrastructures and bus operation against such events. The use of structural solutions to protect the infrastructures and bus operation against the 50-year RP floods and floods such as the one that occurred in 2009 (whose RP is superior to 100 years) would be costly and ineffective as these events are rare. Instead, soft adaptation solutions (e.g. development of pre-disaster and business continuity action plans) could be used to reduce the impacts on the transport operation.

To compare and rank the measures and arrive at a “short list”, the team developed a multicriteria-analysis methodology. To this end the following criteria and weights were selected in the base scenario:



The multicriteria analysis was used to compare the performance of the different types of measures (green, gray, soft). To this end, the 26 measures were classified into groups of measures applying similar solutions.

Soft measures are associated with the lowest investments and maintenance costs. Gray measures are associated with medium upfront costs and low maintenance costs. In contrast, the initial costs of green measures greatly vary. Finally, the highest upfront and maintenance costs are associated with hybrid measures that mix green and gray elements.

In terms of the flood-impact-reduction benefits, soft solutions tend to be associated with medium to very high benefits as they generally apply to the whole AOI. The flood-impact-reduction-benefit score of the gray solutions is generally medium to high, as these measures are effective in reducing flood impacts but

apply to limited sections. Finally, as expected, **green and mixed solutions are associated with the highest environmental and socio-economic benefits (co-benefits).**

The multicriteria analysis allowed the identification of the top measures that should be prioritized based on the total score. However, **to evaluate how the choice of weights impacts the rank of the measures, we performed a sensitivity analysis by considering three scenarios, each representing a different set of priorities for the decision makers.** These different sets of priorities are represented by different sets of weights attached to the criteria used in the analysis.

Scenario 1 is the base scenario, with a balanced distribution of priorities between costs, flood impact reduction benefits and environmental and socio-economic co-benefits.

Scenario 2 represents a situation where the decision-makers consider the reduction of flood impacts as the absolute priority and the other criteria as secondary.

Scenario 3 puts higher priority on the maintenance cost, and a relatively high priority on co-benefits. This could represent the preoccupations of the Ouagadougou Municipality, who could more easily obtain external funding to pay for the investment but will be in charge of the maintenance of the infrastructure and have to consider the acceptability of the measures.

The top-10 rankings resulting from the three scenarios are close, as they tend to mostly include the same measures although in different order. For example, the first seven measures of the base scenario also appear among the ten highest ranked measures of scenarios 2 and 3. **All in all, seven measures rank among the ten highest ranked measured in all three scenarios and should therefore be prioritized (see Figure 1):**

21: Set up a dedicated maintenance plan and team in charge of the periodic and systematic cleaning and maintenance of flood related structures (canals, culverts, rain gardens, pockets parks, etc.) dedicated to the mass transit system, in particular before the rainy season

25: Reinforce the solid waste collection system: organize awareness-raising activities, and most importantly, provide an efficient collection system, concrete baskets at the bus stops, garbage collection

points at strategic locations collecting trucks, landfill / incineration sites

17: Build a rain garden on the Nations Unies roundabout

24: Develop a flood monitoring and disaster prevention system for the city: Pre-disaster action plan (timeline) that aims to prevent damage and allow public transport to resume operation at an early stage. The actions should be triggered depending on the information provided by a flood monitoring tool (considering current and predicted rainfall and water level in the dams) — the system should be managed by the city authorities and the relevant information passed on to the bus operating company

22: Enforce regulations aiming at limiting water run-off generated by new constructions. A simple way is to impose a limit on the flow a newly developed area can discharge to the drainage network. This engages developers to integrate stormwater management in their design and implement solutions to reduce flows sent to the network (e.g. green roofs, permeable pavement over parking lots).

11: Build a drainage system to protect Ave Oumarou Kanazoe and Place du Rail roundabout

2: Install a bioswale in the median of the road on Ave Kwame Nkrumah and Ave de l'UMOA

Figure 1: Location of the proposed flood-resilience and adaptation measures

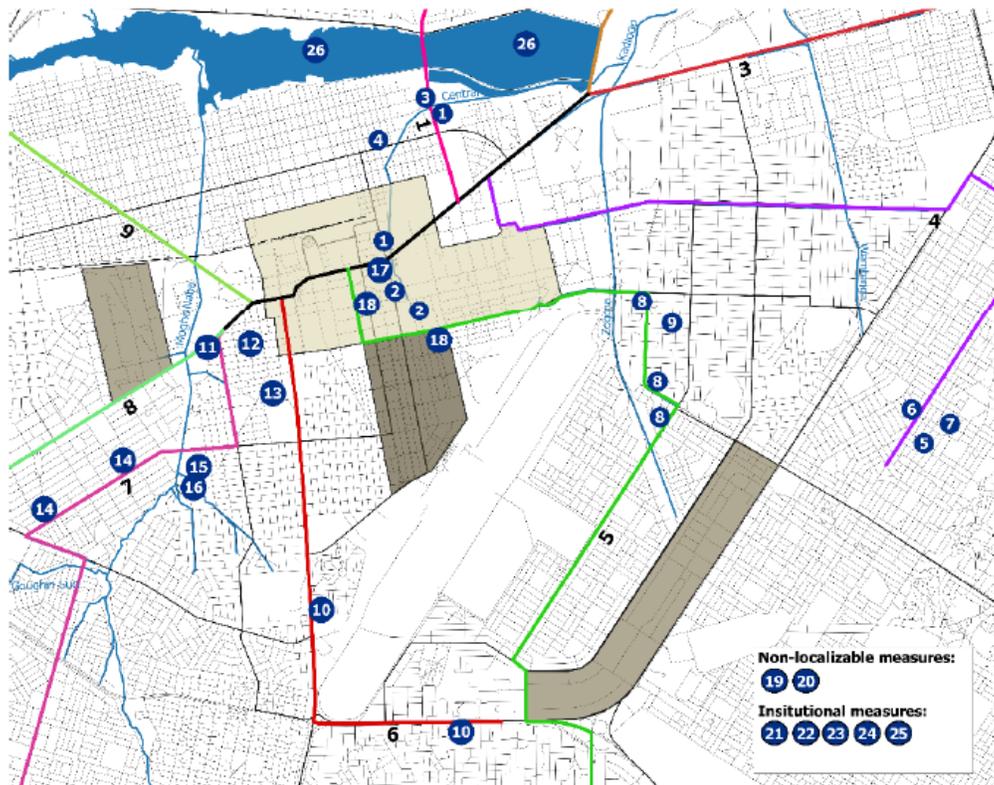
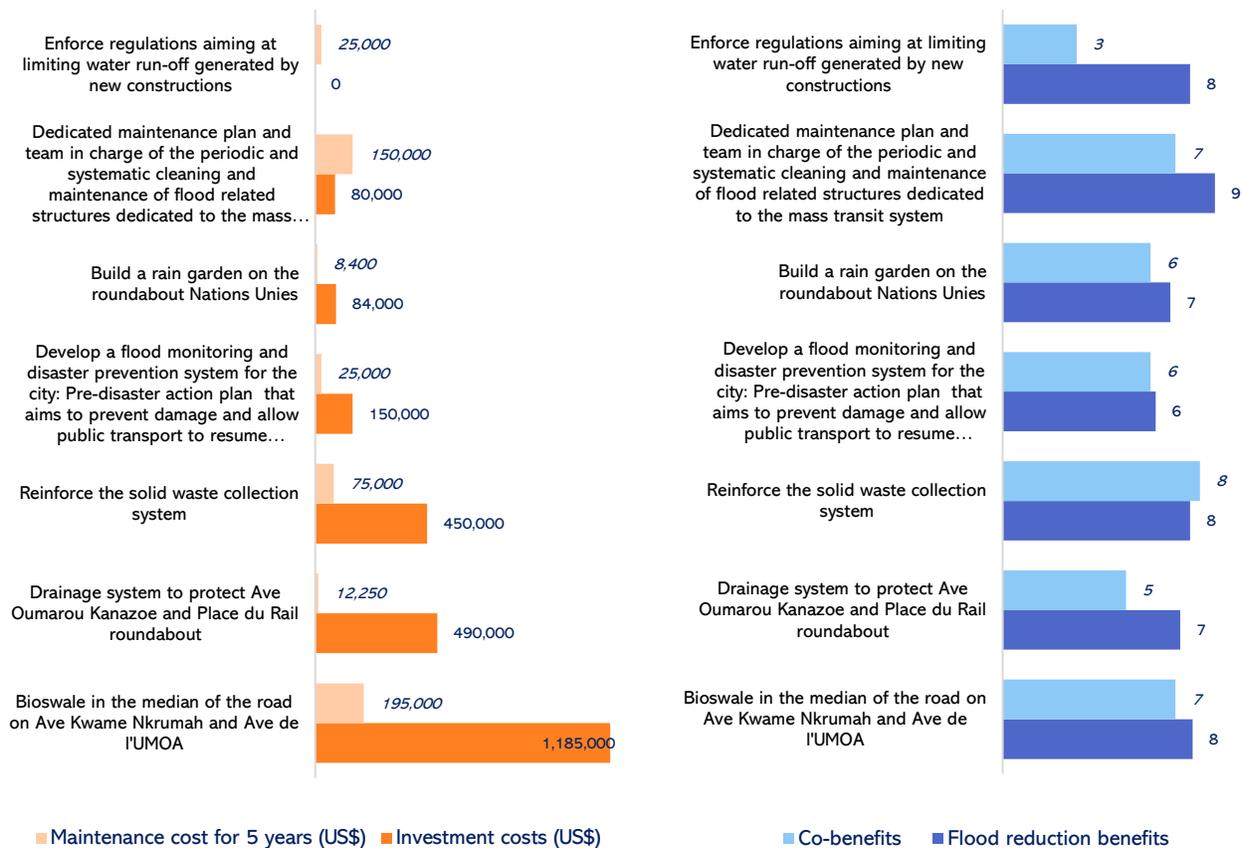


Figure 2 summarizes the investment and maintenance costs associated with each priority measure, as well as the flood reduction benefits and co-benefits. The graphs illustrate much greater relative range in terms of costs than benefits, albeit the benefits have not yet been monetized at this stage and are assessed on a qualitative scale. The variation in co-benefits is somewhat greater, with measures such as the reinforcement of the solid waste collection system having the highest score, due to the benefits it would generate also in terms of job creation in waste

collection, beautifying the surrounding landscape, and improving stormwater retention efficiency of existing infrastructure and natural ecosystems. In contrast, the enforcement of regulations aiming at limiting water run-off generated by new constructions is deemed to have relatively low co-benefits (albeit also very low costs), given that this measure would increase the cost of construction projects in the city. To ensure the acceptability of this measure, therefore, a first step might be to apply it only to development projects by professionals, excluding individual owners.

Figure 2: Comparison of the costs and benefits of the prioritized measures



Moreover, several caveats apply to the prioritized measures and should be considered in the actual design and implementation process. For example, with respect to measure 17, it should be noted that creating green spaces is not in itself sufficient to improve infiltration but that efforts should also be made to increase the presence of absorbing soil (e.g., using underground structures such as rainwater collection systems¹). Hence, rain gardens and other green spaces should be specifically designed with technical specifications to maximize absorption and soil water retention. Similarly, regarding measure 2, it should be noted that a bioswale

in the Sahelian climate might require irrigation for part of the year, and a follow-up study might be necessary to determine what plant species would be best adapted to the climate in Ouagadougou.

Which of the measures prioritized above are strictly technical and which ones are more a matter of good urban planning and political will? As noted in the study, flooding in Ouagadougou is more a result of unplanned urban growth rather than the frequency of extreme rainfall. Hence, good urban planning and integrated policies across sectors are crucial. Among others, the

¹ The underground rainwater collection systems, in turn, could also provide the benefit of mitigating drought impacts in

Ouagadougou by allowing the collected water to be reused for agricultural purposes or be purified and used as potable water.

city's urban mobility plan should not be segregated from the flood risk management strategy and should include measures to counteract the impacts of flooding. An example that emphasizes the links between the mobility plan and stormwater management is the potential development of much needed bicycle and motorcycle lanes that could be implemented along with the recommended permeable pavement.

The importance of good planning and policy and regulatory actions vis-à-vis more structural engineering solutions is underlined by the fact that the top two measures singled out by the multicriteria analysis are so-called "soft" solutions – related to the maintenance and cleaning of the flood-related structures and the reinforcement of the waste collection system. These solutions are ranked highly because they would effectively contribute to the flood resilience of the entire future mass transit system, are associated with large long-term environmental and socio-economic benefits, and require limited initial and maintenance investments. In addition to these, several other "soft" measures rank

in the top: the development of a flood monitoring and disaster prevention system for the city, the enforcement of regulations aiming at limiting water runoff generated by new constructions, and the development of a risk awareness culture in the bus management company to manage the residual flood risk.

Their actual ranking notwithstanding, some of the soft measures – such as developing a flood monitoring and disaster prevention system for the city – should likely be implemented in parallel to infrastructure investments under any scenario, given their role in reinforcing the sustainability and commitment of the local authorities to a long-term vision.

Note: An [interactive online tool](#) was prepared along with this report to allow stakeholders and decision-makers to more closely interact with the data and the findings.

1. Context

1.1. Ouagadougou's growth patterns

Ouagadougou currently has 3 million inhabitants with a population growth rate of 7-9 percent per year due to the natural growth rate and migration, and the population is expected to reach nearly 4 million by 2025. The city is composed of 12 districts and 55 sectors. The average density of the conurbation is low, around 50 inhabitants per hectare, but can exceed 100 inhabitants per hectare in the non *lotis* (non-parceled, precarious) districts (AFD, 2019). In terms of governance, Ouagadougou is an "urban commune with special status" led by an elected central mayor and 12 district mayors.

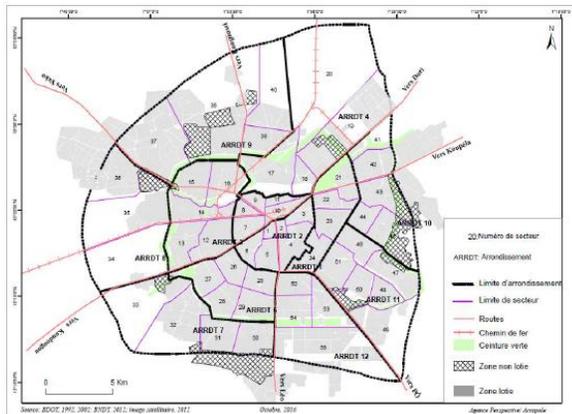
Greater Ouaga covers an area of 3,300 km² within a 30 km radius of Ouagadougou. It includes the urban commune of Ouagadougou and seven rural communes around Ouagadougou: Pabré, Tanghin-Dassouri, Komki-lpala, Komsilga, Koubri, Saaba and Loubila.

Figure 3: View of an outlying neighbourhood, traditional housing



Source: Google Earth

Figure 4 Ouagadougou structure



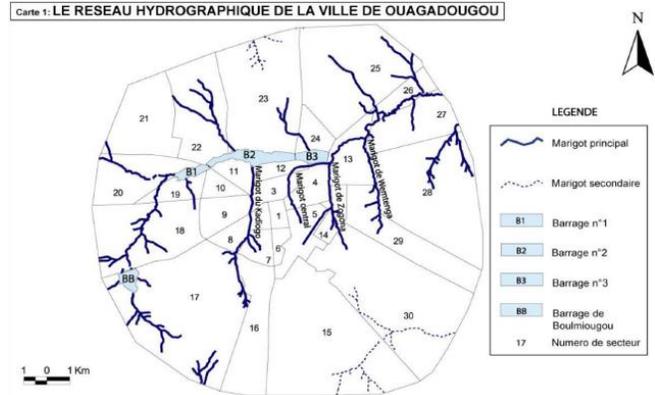
Source: AFD (2019)

This territory is planned by means of a master plan for the development of Greater Ouaga (SDAGO) of 2010.

The urban area of Ouagadougou has different types of land use but is dominated by built-up areas of varying density, constrained by roads and waterways. Some rare areas are still little built-up or covered with vegetation. The built-up areas are dominated by the traditional housing estates, forming rectangular blocks in which the building stock is very dense. The houses are located in enclosed concessions, with openings at the base of the walls to ensure rainwater drainage. The concession yards are either concreted or natural. The roads that delimit the blocks are generally unpaved, except for the main roads. Undeveloped housing is also very present in the peripheral areas, with a lower density of buildings and an irregular structure. The network of structuring urban roads takes a radial form from the city center, and only the main road network is paved.

The morphological elements that characterize the urban territory of Ouagadougou are the three dams located to the north of the city center as well as the greenbelt that is delimited across a horizontal plane and which includes the Bangr Weogo urban park to the northeast, commonly known as "The Forest". However, this greenbelt is regularly threatened by various developments (housing, quarries, landfills, household waste). Its role in terms of urban agriculture must also be stressed: approximately 5,000 people work in over 100 agricultural sites within an area of 750 ha. This ecosystem is fragile and vulnerable because it is threatened by various types of pollution: industrial waste, household waste dumps, massive digs, etc.

Figure 5 Ouagadougou water system



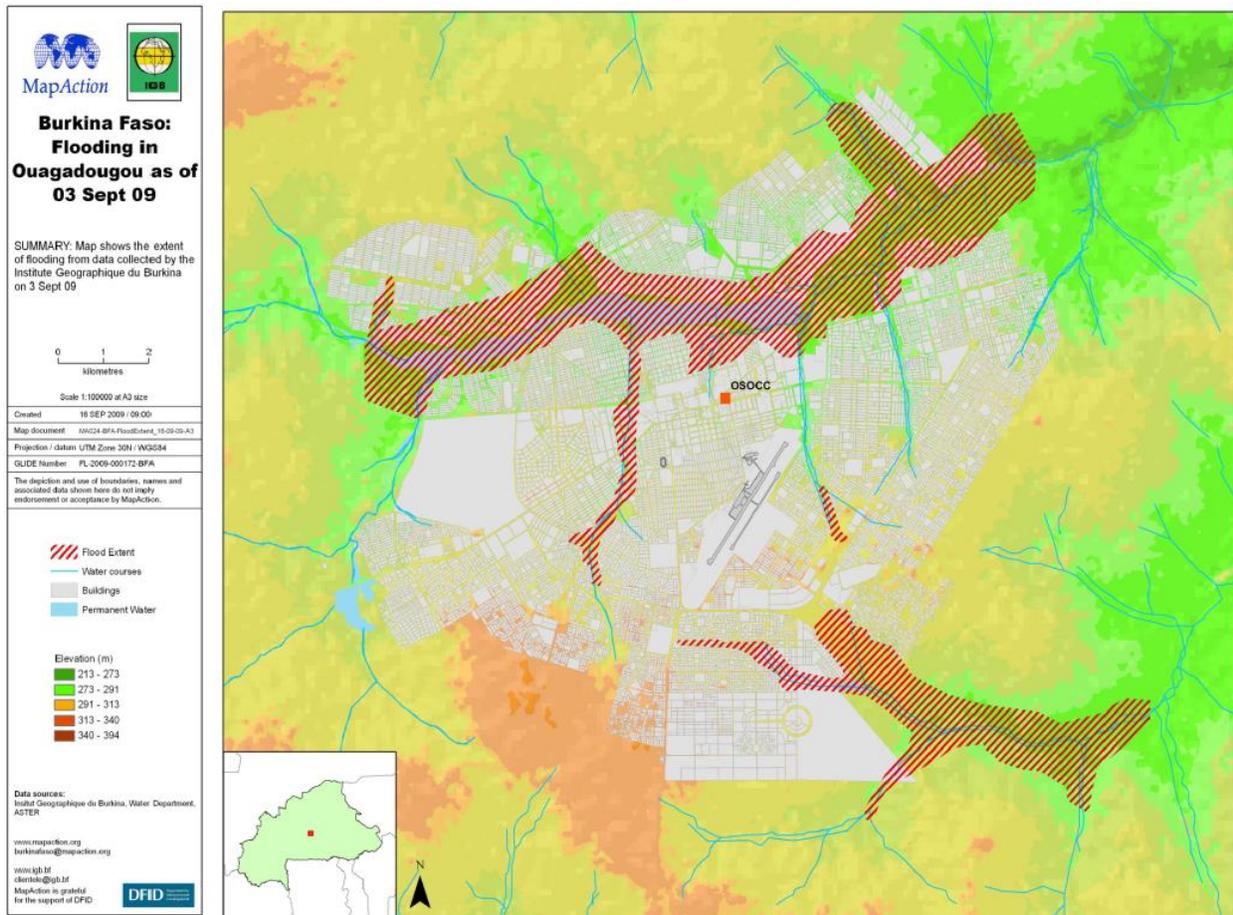
1.2. Major flooding events of this century

Like many urban areas in Sahelian West Africa, Ouagadougou is highly vulnerable to extreme hydro-meteorological events. In the region the frequency of extreme storms tripled in the last 35 years; between 1991-2009 alone, Burkina Faso experienced 11 major floods. During the September 2009 West Africa floods, Burkina Faso was one of the most affected countries: 150,000 people fled their homes, mostly in Ouagadougou, where a record-breaking 263 mm rainfall was recorded in less than 12 hours, affecting around half of the city's territory. According to evaluation by Traoré (2012), who analyzed the record

of one part (the most intense) of the rainfall, the return period of this rainfall is more likely to be of the order of 100 years. The flood most severely affected neighborhoods near the dams and marigots crossing the city, notably Kouritenga, Pissy, Dapoya, Paspanga, Ouidi, Larlé, Tanghin, and Bissiguin.

Heavy flooding in Ouagadougou in August 2015 affected 20,000 people, destroyed several thousand homes, and left parts of the city under water for days. In July of 2018, heavy rains resulted in significant flooding and caused road traffic disruption throughout the capital.

Figure 6: Floods extent map in September 2009



Source: Cited in Bazoun et al. (2010)

Hangnon et al. (2015) list the major floods that occurred between 1983 and 2012, between June and September. The results show that the rainfall that causes flooding is often normal, with a return period of less than 6 years. Flooding in Ouagadougou is therefore a result of unplanned urban growth and uncoordinated planning rather than just the frequency or intensity of extreme rainfall. A review of press articles and other documents shows that after 2012, floods occur almost every year:

24 June 2015: Heavy rain fell on Ouagadougou and some localities in Burkina Faso. With a volume of between 67 millimetres and 79.8 millimetres, this rainfall caused four deaths, including three children, as well as extensive material damage.

10 July 2016: Heavy rain fell on Ouagadougou and several regions of Burkina Faso. At the Yalgado Ouédraogo University Hospital and the

General Directorate of Land and Maritime Transport (DGTMM), this rain caused enormous material damage. In several other areas of the capital, 1,488 people were forced to abandon their homes invaded by rainwater.

19-20 July 2016: Heavy rain fell on Ouagadougou and some localities in Burkina Faso, causing extensive damage. 51.4 mm was recorded in Ouagadougou Airport, 55.3 mm in Somgandé and 97.6 mm in Pô (~150 km from Ouaga).

9 August 2016: 88 mm in less than 12 hours; most affected districts were 1, 2, 3, 4, 6, 9, 12, and Rimkieta neighborhood

18 May 2017: 96.7 mm in less than 12 hours; affected districts 4 and 12 and the Kouritenga, Bissighin, and Rimkieta neighborhoods

25 July 2018: Around 100 mm of water fell on Ouagadougou in the space of 24 hours; eight secteurs (1, 2, 3, 6, 7, 10, 11 and 12) were affected by flooding

July 4, 2019: 89 mm in Ouaga Aero, 75 mm in Somgandé, 2-hour episode

Flooding poses a recurrent threat to Ouagadougou for a number of reasons: (i) the city is naturally prone to seasonal flooding, given its flat topography, its network of riverside channels, and the soils' poor water retention and infiltration capacity; (ii) the three dams that contribute so much to the identity of the city are silted up and can no longer fulfil their role as an outflow, buffer as well as potable water supply for the conurbation; in addition, the drainage system is poorly maintained, while the uncovered gutters tend to be used as waste disposal, and clogging by litter reduces the network drainage capacity; (iii) rapid settlement growth and soil sealing are additionally straining the drainage capacity, while uncontrolled urban development results in an increase in direct flood hazard exposure, especially in *non-lotis* neighborhoods, whose population accounted for two-thirds of victims during the most recent floods. In sum, the frequency of flooding in Ouagadougou has increased since 2000, due to the effect of exceptional rainfall but also because of rapid and poorly controlled urbanization. Floods occur every year, after rains of only a few dozen millimeters.

Stormwater is another threat. The city was built on a site that could be described as marshy (the presence of marigots, or river side channels, was a natural protection against invaders), with a series of flat areas that slope gently (between 0.5% and 1%) from south to north, without any elevated points. The soil has a limited capacity for water infiltration and conservation. In addition, rainfall episodes, while generally decreasing over the last 30 years (due to the phenomenon of dry spells), can also be particularly intense (up to 180 mm/h), especially with the lack of upkeep and

maintenance of rain collectors, an accumulation of solid deposits (waste, load products) and an inherently low water carrying capacity which increases flood risk.

The city's rainwater drainage network is essentially limited to the main collectors, which drain water to the dams' reservoirs, and to a secondary network bordering the main secondary roads. Almost all of the network is open on the surface, sometimes covered with slabs. The collectors are often very clogged or deteriorated.

The evolution of rainfall under the effect of climate change has been addressed at the Sahel scale, including in Ouagadougou (Panthou *et al.*, 2014). The main results show that the annual number of rain storms tends to decrease over the whole Sahel, and that the intensities of the heaviest showers tend to increase. Climate change scenarios based on the CP4 regional model have also been provided for Ouagadougou, as part of the AMMA 2050 project, led by CEH (UK) with the collaboration of Institut de Recherche pour le Développement (IRD) based in Burkina Faso. In the same project, Taylor *et al.* (2017) show that the frequency of heavy rainfall has tripled since 1982 in the Sahel, based on cloud surface temperature measured by Meteosat.

Analysis rainfall for the prediction period 2021-2050 in comparison with the 1971-2000 baseline period shows various trends for the evolution of *annual rainfall*: a significant downward trend for two models and a significant upward trend for two other models. Across five climatic models comparing the reference period and the prediction period, also the anticipated increase in *daily maximum rainfall* in Burkina Faso varies widely depending on the model, from 0.7 to 17.4%. Thus, although the literature indicates that climate change is very likely to cause an increase in rainfall intensities in the next decades, the results of climate models show significant differences from one model to another, and these predictions apply to maximum daily rainfall, whereas the concentration time of the watersheds composing the Area of Interest (AOI) spans from 30 minutes to 3 hours. There is thus not enough evidence to generate an estimation of the increase in rainfall intensities for short, intense events.

1.3. Impacts on the transport system

The flooding events of the last few decades directly affected the functionality of the city's transport system, especially considering the sparsity of the climate-resilient (paved) road network and the dominance of poorly maintained dirt roads. Physical impacts of the floods, with the associated operational and maintenance impacts, are summarized in Table 1. An illustration of the impacts of floods on the traffic in Ouagadougou is illustrated in Figure 7, showing the Nations Unies roundabout in Ouagadougou city center under normal versus flooded conditions.

Urban growth, extreme weather events, and climate change are expected to continue to drive an upward trend in flooding risk in the future, highlighting the

urgent need for flood-resilient infrastructure development in Ouagadougou.

Figure 7: The Nations Unies roundabout in Ouagadougou: under normal versus flooded conditions



Sources: © Tiphaine Brunet, 2013; ©RFI, 2009

Table 1: Impact of past floods on the transport system

Past flood event	Rainfall classification ²	Impacted areas ³	Physical impacts	Operation impacts	Maintenance impacts
1st September 2009	Very exceptional i.e. return period > 100 years	Mostly impacted districts: 1 (Kouritenga); 2 (Dapoya, Ouidi, Larlé, Paspanga); 4 (Tanghin), 6 (Pissy); 8 (Bissighin)	Flooded roads, bridges and scuppers Major damage observed on over 15 structures (mainly embankments and covering of bridges and scuppers) ⁴	Public and private transport delays and disruptions due to speed reductions and impassable roads (the delays and disruptions lasted for several days - and even weeks in some areas)	Serious maintenance operations required for inspecting, cleaning and planning repair and reconstruction works Repair and reconstruction work required for over 15 structures
24 June 2015 10 July 2016 19-20 July 2016 9 August 2016 18 May 2017 25 July 2018	Normal to severely abnormal i.e. return periods between 1 and 50 years	Certain districts are always impacted (e.g. 12), while others are more or less impacted depending on the flood events (e.g. 7 and 11)	Flooded roads, bridges and scuppers Minor damage of structures	Public and private transport delays and disruptions due to speed reductions and impassable roads	Maintenance operations required for inspecting, cleaning and planning repair works

² Tazen et al. (2018)

³ SEPIA Conseils. (2021)

⁴ World Bank. (2010)

2. Addressing the flood risk to improve the resilience of Ouagadougou's transport system

2.1. The planned mass transit system

Over the medium- to long run, a bus-based mass transit system (possibly a Bus Rapid Transit, or BRT, network with feeder services) is planned to be developed in the city to improve urban mobility along high priority corridors. Figure 8 shows the planned layout of the

transit system as well as the location of key urban zones in Ouagadougou. The proposed system is expected to carry about 150,000 passengers per day, with the busiest segments of the system – located in the city center – carrying over 14,000 passengers per day per direction (Transitec, 2021).

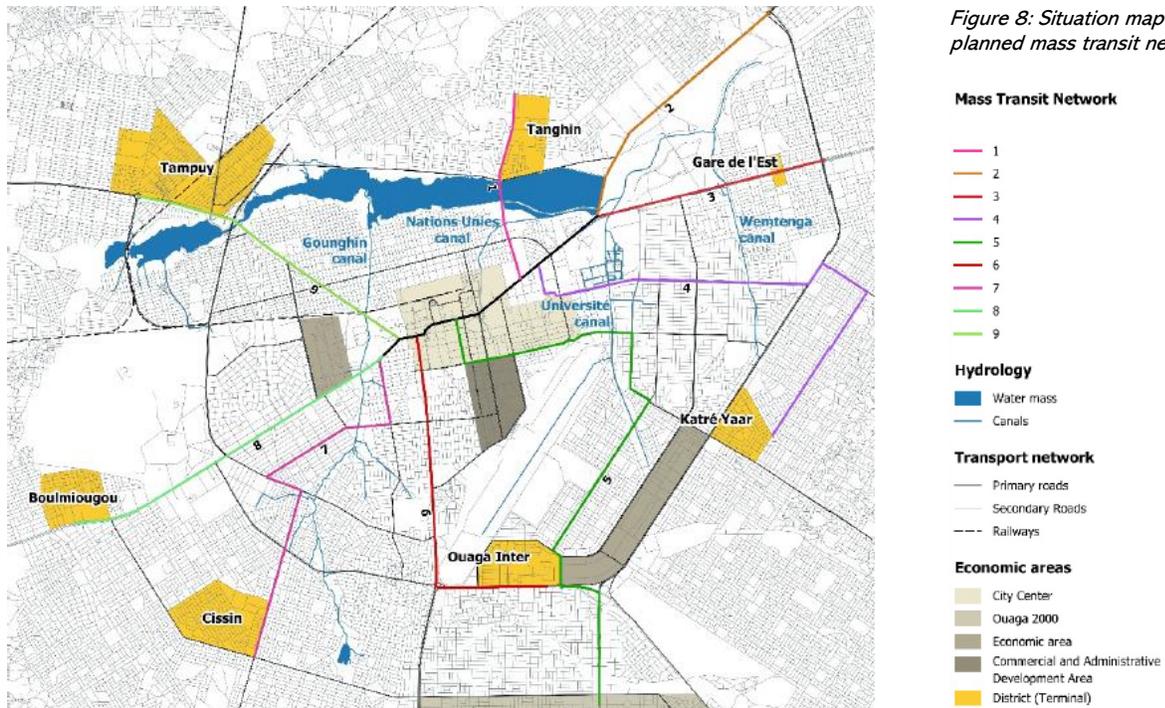


Figure 8: Situation map of the planned mass transit network

Source: Elaborated by authors, based on Transitec (2021)

In light of the past extensive flood damage to the city's transport connectivity and the potentially growing severity of flood risks in the future, there is a need for applying a "climate lens" to prioritizing the future planning of the public transport system in Ouagadougou, through a comprehensive, life-cycle approach to risk that addresses the following aspects, as detailed in the guidance developed by the Global Facility for Disaster Reduction and Recovery (GFDRR) (Figure 9):

Systems Planning: Shifting deployment of long-lived infrastructure away from disaster-prone areas to avoid development lock-in; consideration of integration and redundancy on critical infrastructure to offer alternatives

Engineering & Design: Improving design standards of transport infrastructure to maintain connectivity and reduce disaster risk; use of innovative materials and

design specifications that enhance robustness and flexibility of infrastructure

Operations & Maintenance: Inventory and mapping of transport infrastructure, development and implementation of sound asset management and maintenance systems, improving institutional and financial arrangements for infrastructure maintenance; integration of climate and disaster risk considerations in the prioritization of investments in new infrastructure, rehabilitation, and restoration

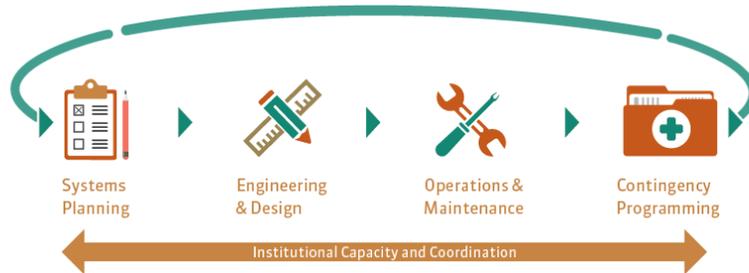
Contingency Planning: Developing policy and institutional frameworks, communication protocols, and investments in emergency preparedness and response; alignment of transport systems and flows with local and regional evacuation, response, and recovery needs

Institutional Capacity & Coordination: Centralizing of disaster risk information and data comprehensively by enhancing strong coordination among central

governments, line ministries and agencies, and local municipalities; upstream planning of transport systems to reduce the hazard exposure of the infrastructure that results in greater disaster risk; mitigation of institutional and regulatory challenges, which are crosscutting in nature, to utilize the life cycle approach effectively

The current study focuses primarily on the first two aspects of the life-cycle approach with the objective to improve the resilience of the future urban transport system in Ouagadougou.

Figure 9: The Life-cycle approach to addressing risk



Source: GFDRR

2.2. Flood modelling analysis

Building on the available rainfall data and past flood modeling studies available for Ouagadougou, the current study focuses on a pilot sector of 67 km², covering a large part of Ouagadougou city center and its strategic infrastructures. The flood risk modeling conducted for the purposes of the current study was based on aerial imagery collected by an unmanned aerial vehicle (UAV, or “drone”) with vertical take-off and landing (VTOL) capability over the period of several weeks in July-August 2020. The imagery was then used to construct a Digital Elevation Model (DEM) at a resolution of 10 cm covering the study area, a key input into the flood risk modeling. The detailed description of the process and the challenges encountered in the process, including in developing the DEM, is provided in Annex 1.

In addition to the drone imagery collection, a field campaign was undertaken to survey the dimensions of the main canals in the city: Gounghin (Moro Naba) canal, University canal, United Nations canal, Wemtemga canal, and Somgandé canal. Four of the five canals (Gounghin, University, United Nations, Wemtemga) are within the AOI (part of the city crossed by the planned future mass transit system). A geomorphological rule was then adopted to estimate channel dimensions (Bouvier et al., 2017), relating the width of flow sections to the slope and area of the upstream basin. Depths were estimated at 1 meter.

The flows are regulated by three dams as they pass through the city. Bathymetry and water levels are available for dam 3. The water level in this dam is particularly important for estimating the possible downstream influence of the flows in the study area. In

this dam, the water level varies every year with an amplitude of up to 4 meters between the minimum and the maximum level.

The average annual rainfall in Ouagadougou over the 1983-2012 period was 733 mm. RainCell data acquired in 2016 and 2017 on a set of fourteen rain gauges give an overview of the rainfall characteristics leading to floods on 9 August, 2016, and 18 May, 2017. Rainfall totals varied from 40 to 140 mm, with a duration of about 2h30 for the intense part of the rain. The episode was centred on the south-eastern part of Ouagadougou, where the rainfall exceeded 100 mm. According to the local IDF curves, the rainfall corresponds to a return period of more than 50 years if we refer to an accumulation of 120 mm in 3 hours, and to a return period of much less than 1 year if we refer to an accumulation of 20 mm in 15 minutes. These examples can be used as project rainfall associated with return periods of between 2 and 10 years. Indeed, although daily rainfall in excess of 100 mm was observed in both 2016 and 2017 at least at one of the measuring stations, it should be considered that the probability of observing such rainfall at a given point is more rare.

The runoff coefficients for Ouagadougou tend towards values around 0.70 for the two basins monitored in 1979, around 0.40 for the two basins monitored in 1992-1993, and around 0.10-0.20 for the three basins monitored in 2016-2017. For the study area, considering that the urbanization is relatively dense, it was considered best to adopt runoff coefficients of the order of 0.7-0.8 for rainfall reaching 50 mm. These coefficients are reduced to 0.40-0.50 for any areas still undergoing urbanization.

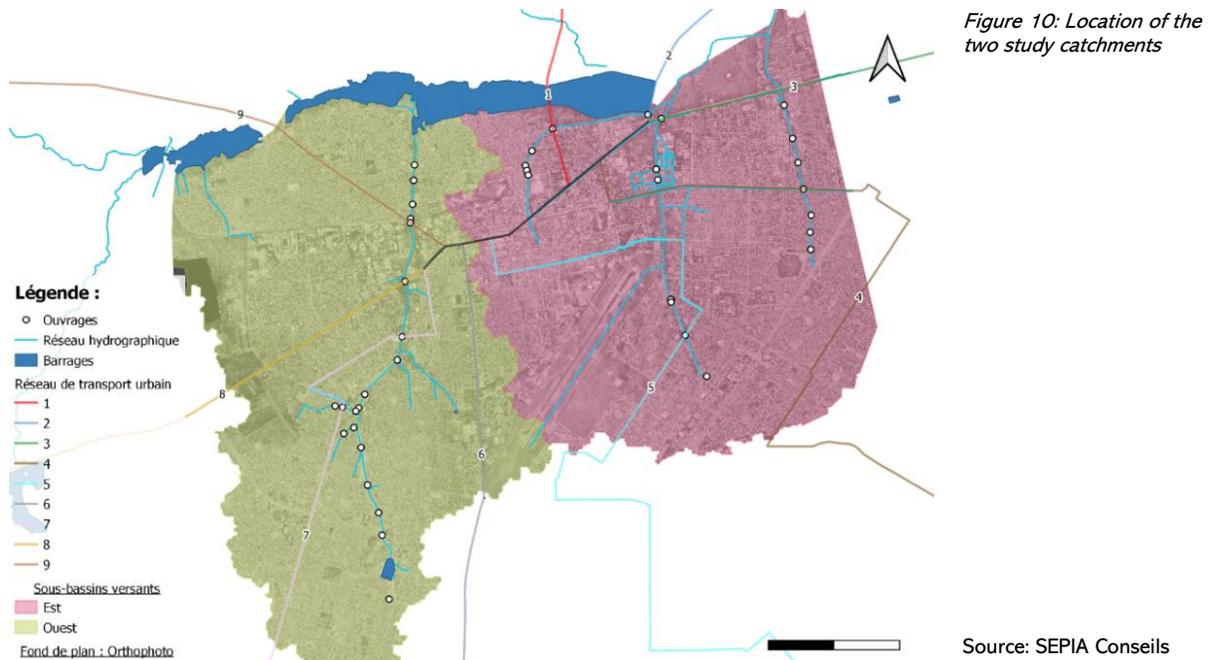


Figure 10: Location of the two study catchments

The study area is divided into two sub-catchments (Figure 10). The river system in the West is mainly composed of the Gounghin Canal, which is the longest canal in the study area. Its upstream part has long remained undeveloped, and was a natural gully. However, since 2016, strong urbanization has taken place, and this canal is now fully developed. The hydrographic network in the East is denser, composed of three main canals: Nations-Unies, University, and Wemtenga. The Nations-Unies canal is partly buried. Together with the University canal, they meet at the entrance to Bagr Weaogo Park. In this area the canals are no longer developed. The University, Wemtenga, Gounghin and United Nations canals are partially built of concrete, and their depth and width increase as one moves downstream of the canals. They are often very congested or deteriorated. These main canals are fed

by the network of secondary canals, coming from the districts or bordering the main roads. Along the tarmac roads, the canals are built, while on the dirt roads, gullies are dug naturally. These storm drains are also often deteriorated and clogged with rubbish, which prevents them from functioning properly.

Numerous structures ensure the hydraulic continuity of flows within the canals under roads, railways and paths. They vary in size from small passage structures on secondary canals to large structures on the main canals, particularly downstream. The latter are often made up of several pillars, which favors the retention of waste and the creation of logjams. Thus, they are often in poor condition and obstructed, reducing the flow and thus increasing the frequency and risk of channel overflows.



Figure 11: Examples of rainwater collectors in Ouagadougou

Source: Louis Berger

Figure 12: Structure located on the Gounghin canal (Rue 17.250) on the left obstructed by a lot of rubbish and structure on the university canal on the right with congestion at the bridge piers.

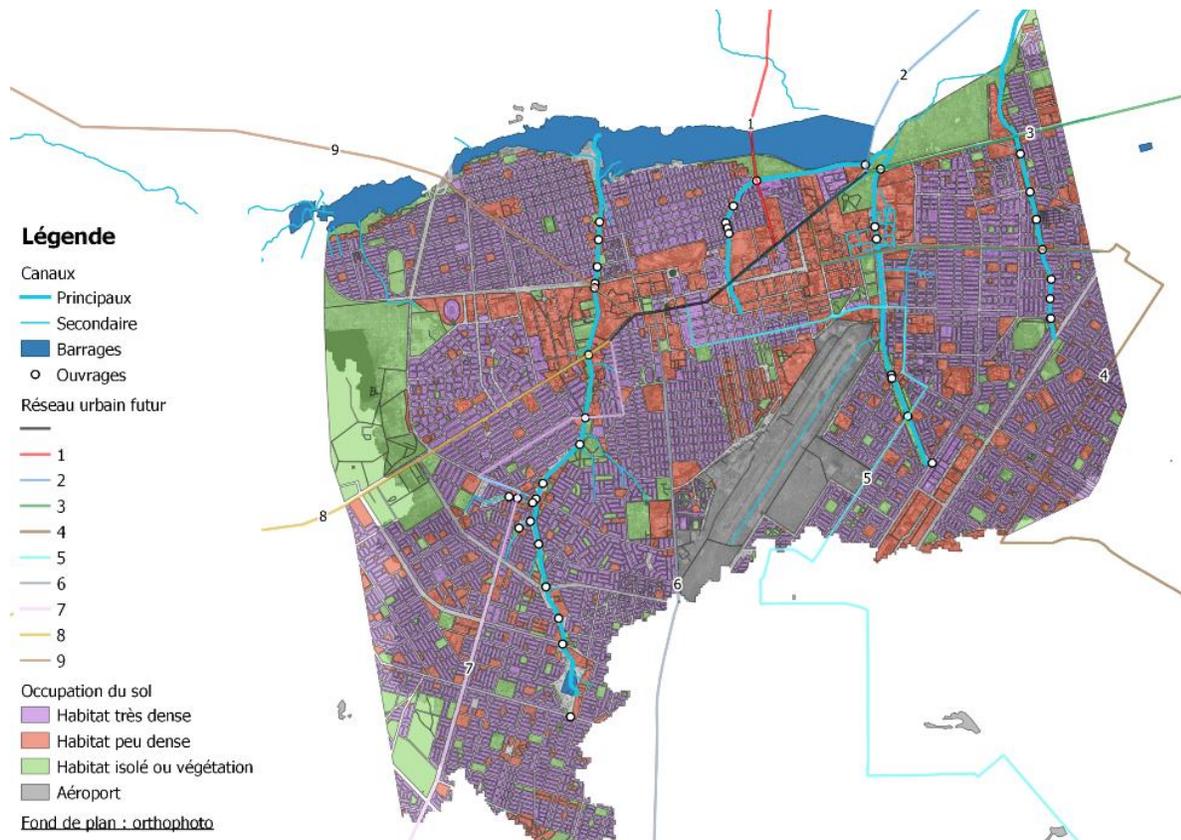


Source: Louis Berger

The study area is almost completely urbanized. In order to determine the current land use, the work carried out in this study is based on data from Bonnet and Nikiema (2013) which provide contours of the built-up areas,

supplemented by systematic work based on aerial photographs in order to take into account the changes that have taken place since 2013. Overall, most land use corresponds to dense grouped housing (Figure 13).

Figure 13: Land use



Source: SEPIA Conseils

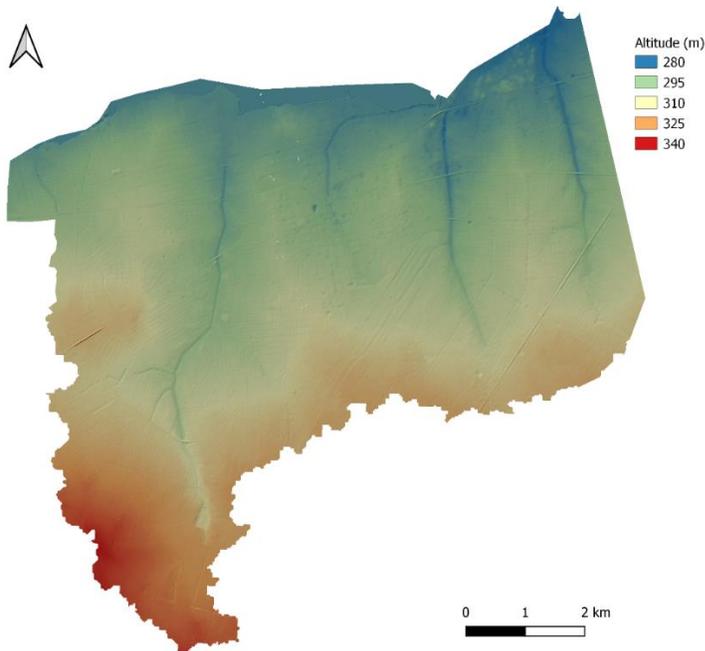


Figure 14: Relief of the studied territory made from the DTM

Source: Espace Geomatique

The elevation of the study area varies between 285 and 340 m in altitude. The low points of concentration of the flows are found at the level of the canals and dams downstream. The water of the agglomeration is drained towards the latter, then towards their outlets to the north. In the south-west of the study area there are areas that reach altitudes of over 340 m.

The study area is characterized by low slopes, generally between 1 and 5%. Only a few embankment roads and the banks of the canals have slopes of over 5%. As a result, rainwater runoff can take a long time to drain away to the canals and dams.

The main output of the flood modeling are maps showing maximum water heights and speeds in the AOI, under four return periods, summarized as follows:⁵

- Frequent stormwater event (2-year return period)
- Rare stormwater event (10-year return period)
- Very rare stormwater event (50-year return period)
- Exceptional stormwater event (historical flood of September 1st 2009, with a return period higher than 100 years)

Table 2: Characteristics of the reference rainfall events

	2-year return period	10-year return period	50-year return period	Historical rain storm of 2009
Occurrence	Frequent	Rare	Very rare	Exceptional
Cumulative intensity in 1 hour (mm)	54	70	97	112
Cumulative total in 3 hours (mm)	70	106	142	173

Source: SEPIA Conseils

The two-dimensional (2D) modelling of flows carried out in this study makes it possible to:

- Evaluate the impact of the occurrence of different rainfall ranges, from a frequent rainfall with a return period of 2 years to an exceptional rainfall of the September 2009 type with a return period of more than 100 years;
- Delimit the main risk areas for people and property: flow axes and main accumulation areas with an estimate of the order of magnitude of the potential submersion heights and flow speeds;
- Understand the flooding dynamics at the block/neighborhood scale: taking into account the general urban topography, the obstacle effect of buildings, and the preferential drainage axes on roads;
- Provide useful information for crisis management: identification of cut-off traffic routes in particular;
- Evaluate the stakes at risk exposed to runoff phenomena.

On the other hand, this model does not allow to simulate the functioning of underground drainage axes within built-up areas; accurately represent flooding at

⁵ All the stormwater events were simulated over a few hours period, with a 5-second time step.

the scale of a building; or simulate the dynamic interactions between the three dams downstream of the study area.

The study modeled three scenarios for the four reference rainfall events (2-year, 10-year, 50-year) and the historical rainfall of 2009:

- **Scenario 1** is the reference scenario. The downstream condition of the model corresponds to the average level of the dams, i.e., a height of 286.5 m. Hydraulic continuity is ensured at the various hydraulic structures. For the canals that are in water all year round, only the effective hydraulic capacity is taken into account.
- **Scenario 2** is scenario 1, to which is added the hypothesis of a total obstruction of the flows at the level of the canal passage structures under the

roads and railways, i.e., the presence of bulky items and rubbish trapped at the level of the bridge piers, creating logjams. The purpose of this scenario is to assess the risk of overflow in the event of obstruction of these structures.

- **Scenario 3** is based on the reference scenario but with a high downstream condition. It corresponds to the hypothesis of dams being overflowed, with a water level of 289.5 m. In this scenario, hydraulic continuity is ensured at the level of the structures.

The comparison of the floodable areas for the 2-year return period for Scenario 1 vs. Scenario 3 is shown in Annex 3. A comparison of the size of the area within the study area of interest that is flooded with a height of more than 3 cm under scenarios 1 and 3 is summarized in Figure 15.

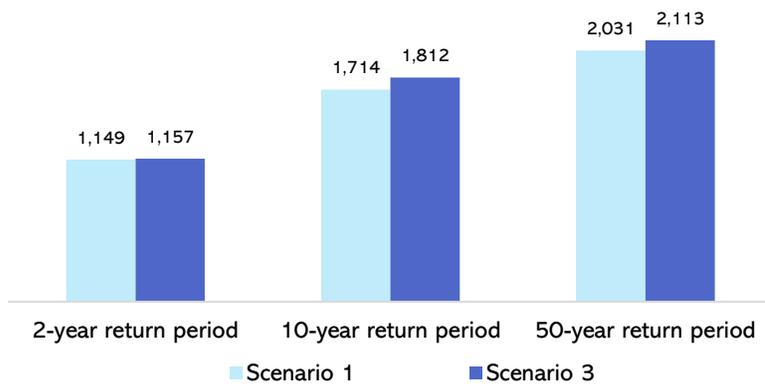


Figure 15: Flooded area for scenarios 1 and 3 and for different return periods (hectares)

Source: SEPIA Conseils

The comparison of the modelling results with existing historical data, such as on the spatial distribution of the 2009 flood events and the less dramatic 2016 and 2018 flood events, allows checking the capacity of the model to reproduce past floods, as well as to highlight its strengths and weaknesses. Overall, the modelling results reproduce the main flood and disaster areas observed in 2009 and even allow refining them and understanding the flood origin mechanisms (overflowing of the canals, formation of a basin or runoff on the road).

Looking at the surface and point disorders observed during the 2016 and 2018 rainfall events, secteur 12, for example, appears to have been affected during each intense rainfall episode, while others are affected more occasionally, such as secteurs 7 and 11. In turn, for each affected secteur, more detailed analysis was carried out, focusing in on the overlaps between flood risk and the future mass transit network.

Flood risk was conceptualized along two main axes, namely flood height (in cm) and flow velocity (in meters per second). Thus, the flood risk analysis distinguishes between :

- **Low risk areas** with water heights < 15 cm
- **Zones at risk** with water height between 15 and 50 cm and velocity below 0.5 m/s.
- **Strong hazard zones** due to the presence of significant water heights (> 50 cm) which induce a risk of drowning
- **Strong hazard zones** due to the presence of significant velocities (>0.5 m/s) which induce risk of being washed away
- **Very strong hazard zones**, with both high submersion heights and velocities (H > 50 cm and V > 0.5 m/s), associated with very high risk of drowning and being swept away.

Figure 16: Areas flooded by the 10-year return period storm in the downstream Mogho Naaba watershed



Source: SEPIA Conseils

3. Identifying and prioritizing interventions to mitigate flood risk

3.1. Flood risk vis-à-vis the future mass transit system

Prior to proposing a specific set of solutions and weighing their relative costs and benefits, the potential vulnerability of the planned future mass transit network was analyzed based on the results of the modelling of scenario 1 (the reference scenario) in order to determine in detail the degree of exposure of each branch of the future network. The analysis focuses on the main streets, intersections and obstacles (e.g. the canals) used by the planned transit system. The analysis considers the consequences of the 2- and 10-year-RP models to find structural (or hard) solutions that would protect the infrastructures and bus operation against such events.

The use of structural solutions to protect the infrastructures and bus operation against the 50-year RP rain and 2009 flood (whose RP is superior to 100 years) models would be costly and ineffective as these events are rare. Instead, soft adaptation solutions (e.g. development of pre-disaster and business continuity action plans) could be used to reduce the impacts of rare events on the transport operation.

Axes may be subject to high water levels, high flow velocities, or a combination of both. In general, future axes 2, 3, 6 and 8 are not subject to high flood hazards, as compared to axes 1, 4, 5, and 7.

The flood modeling results, further, allow to identify the areas along the projected bus lines where floods would slow down traffic and where traffic would become impossible. Based on the existing literature, the potential water heights were related to vehicle speed (see Pregolato et al., 2017), allowing to define 15 cm as the threshold water height leading to an interruption of traffic when it is reached or exceeded. It is considered that below this threshold, for areas where heights are between 3 cm and 15 cm, traffic would be slowed down and traffic speed reduced, resulting in a reduced operation of the transport network.

To better understand the flood events affecting the planned bus system, a set of points was selected in the AOI, representing different flood types, for which hydrographs were generated showing the evolution of water height over time during the 2-year RP flood and the 2009 flood. The analysis of the ramping up and down of water heights associated with rainfall intensities allowed to characterize the type of flooding associated with various situations and causes. The detailed findings from the individual points-of-interest are presented in Annex 4.

This analysis helped characterize the severity of floods in the set of points, from which the insights were extrapolated to other areas presenting the same characteristics (areas next to a canal flooded by overflow, street parallel to the slopes, street perpendicular to the slope and flooded by transverse

streets, low points / basins). The results of the analysis are summarized in Table 4.1. in Annex 4.

The analysis led to the following conclusions concerning the flood impacts on the future mass transit system:

- The traffic on Avenue Nelson Mandela and the Nations Unies roundabout (in the city center), **used by most future bus lines** could be interrupted by the 2-year RP rainfall.

Outside of this area, the traffic on the roads used by several lines (except lines 2, 3, 6 and 9) could be interrupted by the 2-year RP rainfall at specific locations of their respective itinerary. More specifically:

- The operation of **line 1** could be interrupted in Nongremasson St. due to an overflow of the canal.
- The operation of **line 4** could be interrupted on 28.257 St., Ave de l'Indépendance and Blvd Charles De Gaulle.
- The operation of **line 5** could be interrupted in multiple locations, i.e. 14.09 St., Ave des Arts, Ave Houari Boumediene and Ave de la Grande Mosquée.
- The operation of **line 7** could be interrupted on Ave Oumarou Kanazoe, Ave Ouezzin Coulibaly and Simon Compaoré St.
- The operation of **lines 7 and 8** could be interrupted on the roundabout de la Bataille du Rail.

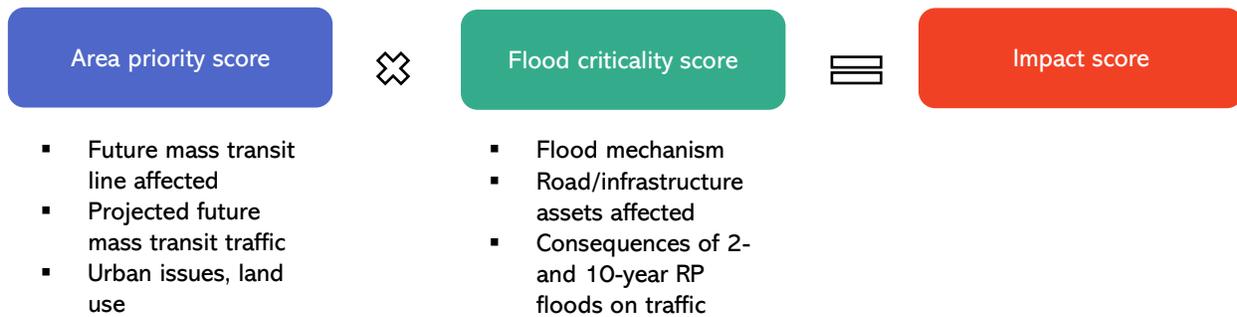
To further classify the road/future mass transit sections in order to prioritize interventions, the following criteria were applied:

- Future mass transit network line affected
- Projected future mass transit traffic – extracted from the OPTIS Study (2021)
- Urban issues for transport system (transit area vs. catchment area, land use, etc.) – assessed using land-use data (including from Google Maps) and the knowledge of the local consultants.
- **Area priority score** (from 1 to 3, with 3 representing a section on which it is crucial to

maintain transport services), assigned based on the projected mass transit traffic and urban issues. For example, the section of 28.257 St. on Line 4 was assigned a priority score of 1 because this section is at the end of the bus line, where the travel demand (5,506,893 passengers per year) and therefore the impacts of service disruptions would be limited. On the contrary, the sections of Avenue du Capitaine Thomas Sankara and Avenue Nelson Mandela shared by most bus lines were given a score of 3 because they serve the City Centre and attract the highest travel demand (16,400,643 passengers per year) of the planned mass transit system.

- Road/intersection and infrastructure assets affected by the 2- and 10- year RP rain events
- Consequences of the 2-year RP rainfall model and consequences of the 10-year RP rainfall model - whether the traffic would be unimpacted, slowed (water height below 15 cm) or blocked (water height above 15cm) under these conditions.
- Description of the flood - the probable cause and characteristics of the flood in the sections. For example, Nongremasson street on Line 1 is flooded because of an overflow of the Canal central (or Nations Unies) while 25.257 St. on Line 4 is flooded because of the run off from the perpendicular streets in the south-east, which act as canals and convey water to the north-west.
- **Flood criticality score**, assigned based on the flood mechanism and consequences (from 1 to 4, depending on the flood depth and duration); the section flooded for an extended period with a high depth of water were given the maximum criticality score (4).
- **Impact of flood issues on the planned mass transit system**: this score combines the area priority score and the flood criticality score. To this end, the area priority score and the flood criticality score were multiplied, and the resulting number scaled in [0,4] and rounded to the nearest 0.5 number. Hence the lowest non-zero score is 0.5, identifying sections that are neither critical in terms of urban transit issues nor in terms of flood criticality (flood depth and duration). The maximum score of 4 indicates areas that are critical both in terms of the flood criticality (flood depth and duration) and urban issues priority (high projected mass transit traffic and service to critical urban areas).

Figure 17: Approach to prioritizing transport infrastructure segments



3.1. Developing a “long list” of potential solutions

In order to identify priority solutions for improving the flood resilience of the planned transport system, first, a long list of solutions was identified based on preliminary criteria of relevance for the case of Ouagadougou. Next, the analysis focused on the specific sections of the planned transport system exposed to floods. Finally, a multicriteria analysis was developed to prioritize among the flood resilience and adaptation measures. The analysis explicitly considers not only structural infrastructure (“gray” measures) but also ecosystem-based approaches (“green” measures), hybrid measures, and non-structural, or “soft”, measures (e.g. risk monitoring, territorial planning, etc.).

To gather a list of possible solutions, the different experts of the project team (i.e. hydraulic engineer, urban planner, green Infrastructure and nature-based solutions expert, etc.) relied on their experience from past projects and on the literature. To analyze and classify the possible solutions, the project team selected the following criteria:

- Solution type
- Advantages
- Disadvantages
- Implementation scale (street, neighborhood, or watershed)
- Adaptability to Ouagadougou
- Situations for which the solution is adapted

The solution type refers to whether the solution is green (uses soils and vegetation to utilize, enhance and/or mimic the natural hydrological cycle processes of infiltration, evapotranspiration and reuse), gray (hard, human-engineered infrastructure that uses concrete and steel) or soft (use institutions and technology services). The project team ensured that the long list of solutions included different types and implementation scales, as different solutions should be combined to effectively improve the flood-resilience of the future transport system and city.

The adaptability to Ouagadougou was assessed using three levels: high (for solutions already implemented in Ouagadougou), medium (solutions already implemented in a similar context (African or other developing countries) and low (solutions only implemented in developed countries, with a low readiness level and adaptability to the local context).

The long list of solutions is presented in a Table 5.2. in Annex 5, where they are ordered depending on the implementation scale. There are 23 solutions in the list, including preserving flood expansion areas, using permeable pavements and building rain gardens, amongst others. The list includes six soft, four gray and eight green solutions but also solutions that mix green, gray and soft elements.

Table 5.1. in Annex 5 shows a breakdown of the sources for the tentative costs. The costs included in the present report are indicative and a more detailed assessment would be required to reduce the uncertainty around those costs.

3.2. Learning from global best practices

Combining green and gray infrastructure can provide lower-cost, more resilient, and more sustainable infrastructure solutions (Browder et al., 2019). A noteworthy example of such integration of the water cycle with city infrastructure is China’s sponge cities (State Council of China, 2015). Under this ambitious program, the country seeks to reduce the effects of flooding through a mix of low-impact development measures and urban greenery and drainage infrastructure, and to have 80 percent of urban areas reuse 70 percent of rainwater by 2020. This approach is similar to what Australia’s Cooperative Research Centre for Water Sensitive Cities calls its vision of the “city as a water catchment” (Hallegatte et al., 2019).

Based on the flood risk assessment, the study analyzed technical solutions that could be applied to reduce the vulnerability and exposure of the planned future mass transport routes. This analysis was guided by the global

experience on the topic. The team reviewed the literature to identify case studies of cities (outside Burkina Faso) that successfully implemented design improvements of urban transport systems to strengthen their climate resilience. The chosen criteria for selecting the case studies resulted from the team's experience and knowledge of Ouagadougou, other cities in Africa, and other countries, where climate risks and mobility are challenging. These included:

- Mobility (transport system, its operation and intramodality)
- Physical geography (geographic location, hydrology and typology of floods)
- Urban environment (demographic and socioeconomic, urban morphology, infrastructures)
- Mobility governance and disaster risk management

Five cities, covering both high- and low-income contexts, were selected based on these criteria and due to their best practices in flood risk management:

Singapore, which highlights nature-based solutions on the scale of a city-state subject to flooding issues with impacts on its public transport systems. Like Ouagadougou, Singapore has also experienced rapid urbanization in recent years and has a very high population density. Moreover, the city's preferred means of public transport is a surface rail system combined with a dense bus network. Concerned about the flooding issues, this city has been working for several years on innovative technologies for flood risk management: new technologies, use of nature-based solutions, etc. It is a particularly flood-resilient city.

Toyooka (Japan), exemplifying the Japanese disaster preparedness and business continuity approach. This approach is specific because it relies on the principle that despite all protection measures aiming at avoiding natural hazards, uncontrollable natural disasters will happen, and the society should be prepared to adapt to these events in order to minimize disruptions and destructions.

São Paulo (Brazil). This city also faces frequent flooding during the wet season and shares with Ouagadougou the problem of maintaining rivers and canals that receive diffuse pollution from storm water run-off and solid litter. São Paulo has also experienced rapid urbanization

to the point of reducing vegetated areas to only a few parks, located mainly in the peripheral areas. It is precisely through the development of "linear parks" that allow vegetation to be reinstated in the city and water infiltration to be increased that São Paulo can be interesting as an example for Ouagadougou. At the same time, São Paulo's public transport network is complex and dense. The demand for public service has been growing for several years. The main modes of transportation are buses, which are also impacted by the flooding phenomena.

Shanghai (China). The rapid urbanization of Shanghai has created complex impacts on the water cycle and hydrology. For this reason, the city is strongly exposed to urban flooding characterized by runoff, just as in Ouagadougou. The limitation of permeable spaces and the problems of pollution of urban water bodies are also issues addressed by the authorities and can be inspiring for Ouagadougou. This city is one of the Chinese "sponge cities" whose integrated approach to flood management can serve as a good practice. Thus, all sectors, including transport (buses, cabs, metro, etc.) benefit from this strategy.

Nairobi (Kenya): The city has developed different types of transports (bus, train, local bus) to respond to the rapid population growth. The city faced recurrent flash floods during the last years that are more and more intensive because of climate change. During the flooding periods, all the transports stop in some neighborhoods. Nairobi shares the same challenges as Ouagadougou. The lack of sanitation infrastructures and the insufficient maintenance of the existing canal system due to solid waste, the urban morphology of the city led to devastations in the city during a flash flood.

Moreover, urban sprawl (whose main component is informal settlements like in Ouagadougou, and increase of residential neighborhoods in the suburbs), has reinforced the need to manage and mitigate floods. Therefore, concerned about the issue, public and private stakeholders have developed resilient initiatives such as: governance tools, green infrastructures, urban policies, etc.

Case Study 1: Bio-swales and rain gardens in Singapore

Similarities with Ouagadougou

- Public transport affected by flooding events
- Projected increase in the intensity of weather variability
- Densely-populated city
- Rapid urbanization despite its land constraints
- Water-related vulnerabilities ranging from flooding to supply scarcity
- Population growth and biophysical limitations.

Urban transport system

The railway network can be regarded as the backbone of the public transport network, and is supported by the bus services.

The Singaporean government has prioritized railway system over bus services as bus services could not be the solution for a compact city like Singapore.

Climate hazards affecting the city

- Singapore receives about 2,400 mm of rainfall annually
- Increase in occurrence of flash flooding coinciding with localized storm events
- Floods caused by a combination of heavy rainfall, high tides and drainage problems, especially in low-lying area
- Many impervious surfaces (e.g. roofs, parking lots, and streets) prevent stormwater from infiltrating into the ground and generate increased runoff that enters the stormwater drainage system
- Singapore has experienced several major floods that have resulted in widespread devastation, as well as destruction to life and property



Orchard Road (2010)



Upper Changi Road (2018)

Solutions implemented to enhance the system's resilience

Context. In the 1960s and 1970s, Singapore witnessed frequent flooding (especially in the low-lying city center), which caused widespread disruption and damage. To reduce the risk of flooding, Singapore traditionally relied on a network of canals and rivers to channel water into reservoirs and the sea. The city launched major projects to enlarge natural waterways (e.g. the Kallang River) and line riverbanks with concrete to improve conveyance of water and reduce bank erosion. Singapore's national water agency (PUB), launched in 2006 the Active, Beautiful, Clean Waters (ABC Waters) Programme.

This programme proposes to manage storm water runoff in a more sustainable manner via the implementation of ABC Waters design features⁶, natural systems (i.e. plants and soil) able to detain and treat rainwater runoff before discharging the cleansed runoff into the downstream drainage system. There are various types of ABC Waters design features, this case study focuses on **bioretention systems including bioswales** (vegetated and bioretention swales) **and rain gardens**.

⁶ [ABC Design Guidelines 4th Edition](#)

Bioswales convey stormwater at a slow, controlled rate, and the flood-tolerant vegetation and soil act as a filter medium, cleaning runoff and allowing infiltration. Bioswales generally are installed within or near paved areas (e.g. parking lots, roads and sidewalks). In locations with low infiltration rates, underdrains can be used to collect excess water and discharge the treated runoff to another green infrastructure practice or storm sewer system. The difference between vegetated and **bioretention swales** is that the latter have a bioretention systems located within the base.

Bioretention basins or rain gardens are vegetated land depressions designed to detain and treat stormwater runoff. Their treatment process is the same as bioretention swales; the runoff is filtered through densely planted surface vegetation and then percolated through a prescribed filter media (soil layers). Unlike bioretention swales, they do not convey stormwater runoff.



Vegetated swale in carpark at the Singapore Botanic Gardens



Bioretention swale along a road with standard kerbs (with slots) in Faber Hills Estate



Rain garden captures stormwater runoff from adjacent Holland Plain Road.

Financial & organizational arrangement. Stormwater management often entails a municipal-level program of infrastructure development and coordination. Revising building codes to encourage green infrastructure approaches can facilitate their adoption. Their implementation can benefit from collaboration between communities, designers, climate scientists and governments to ensure sustainability in design, management and maintenance. Government incentives can also encourage landowners to install bioswales on their land.

Design & construction. Bioswales should be carefully designed to integrate with the characteristics of the surrounding landscape. Vegetation plays a key role in maintaining the porosity of the soil media of the bioretention system and also in the taking up of nutrients from the percolating surface runoff. The plants selected must be able to withstand wet and dry conditions. Infiltration-based design features for bioretention swales should be sited at least 1 m above the seasonal high groundwater table. A study showed that underground gravel layers for storage and orifice outlets significantly improve the runoff control effectiveness of rain gardens and bioswales.

Economic cost (design, construction & maintenance). Design features are green infrastructures that mimic natural systems. They are cost effective, sustainable, and environment friendly. Costs vary greatly depending on size, plant material, and site considerations. Bioswales are generally less expensive when used in place of underground piping. Maintenance costs and time are higher initially and then taper off once established. The estimated cost of a bioretention area is between \$5 and \$30 per square foot⁷.

Maintenance:

- Maintain good vegetation growth (remove weeds, prune vegetation, etc.)
- Routine inspection of vegetation
- Inspect inlet and outlet points for scour and blockage, etc.
- Remove litter and debris
- Maintenance should be conducted after major storm event

Benefits & co-benefits (economic, environmental, social):

- Reduce stormwater volume and flow velocity and increase groundwater recharge
- Settles coarse sediments^[1]_[SEP]
- Encourages habitat creation and promotes biodiversity^[1]_[SEP]
- Filters and cleanses water naturally without the use of any chemicals
- Ease of design
- Provide aesthetic appeal

⁷ [Massachusetts Clean Water Toolkit](#)

Case Study 2: Renaturing the city with Linear Parks and Pocket Parks in São Paulo

Similarities with Ouagadougou

- Climate projections indicate a likely increase in the number of days with heavy storms
- Public transport affected by flooding events
- Rivers and canals receive diffuse pollution from stormwater run-off and solid litter
- Intense and rapid urbanization over the landscape with the eradication of the original ecosystems
- Nature is restricted to some parks, mainly in the peripheral areas
- Occupation of risky areas such as slopes and banks of watercourses
- Lack of urban planning
- Water shortages

Urban transport system

São Paulo's surface transport suffers from slow speeds and long commute times, due to heavy congestion. The modal share for public transport has remained constant over the years, despite growth in passenger numbers. São Paulo's immense public-transport system, run by

SPTrans, is arguably the world's most complex, with over 14,500 buses, 1300 lines and 500km worth of exclusive bus lanes. Public transport options: Commuter rail, light rail including metro and monorail, bus, bike.

Climate hazards affecting the city

- São Paulo is vulnerable to urban heat-island effects and recurrent severe floods
- Strong storms caused by land-cover change
- Climate change could lead to increases in the intensity of rainfall events, potential floods and landslides, as well as an increased tendency towards periods of drought
- Reservoirs and watercourses encounter severe damage, as they are not designed to exclude garbage and other forms of contamination



A metropolitan train is stuck at a flooded rail track running along the Pinheiros river. Feb. 10, 2020



Heavy rains flooded the city, causing its main river to overflow its banks. Feb. 10, 2020

Solutions implemented to enhance the system's resilience

Context. In Brazil, nature-based solutions (the re-naturalization of rivers with greenways, rain gardens and bio-swales, green roofs and walls, urban forests, detention and retention naturalized basins, pervious pavements, as well as linear parks) are used to concurrently solve multiple challenges. This case study focuses on **linear parks and pocket parks**.

Linear parks offer a wealth of pervious surface that can be used to absorb rainwater and runoff from adjacent developed landscapes that currently drain directly to piped collection systems. The city of Sao Paulo municipal green plan proposes 49 linear parks. The Tiquatira Linear Park (320,000 m²) was the first linear park in the city of São Paulo, built along the river Tiquatira to assist in the preservation and conservation of stream bed, and to provide a safe range of landscaping and greening between the stream and urban roads. The Tietê River Valley Park (currently under construction) will be the largest linear park in the world stretching for roughly 75 km to the source of the Tietê River.

Pocket parks are smaller public parks (generally occupying less than one acre of land) that represent ideal locations for green infrastructure (vegetated bioretention cells) that treats and captures stormwater through bio-filtration and infiltration.

Pocket parks are opportunistic, often sited on whatever land is available, and might be constructed to revitalize unused or underused land (e.g. decommissioned railroad tracks). In Sao Paulo, Araucárias Square is a pioneer public pocket garden (which includes a rain garden) that collects, filters and infiltrates the run-off of impervious land cover.



Linear Park Tiquatira between the stream and the road



Araucárias Square: pocket garden and rain garden and

Financial & organizational arrangement. The Taubaté and Santa Lúcia linear parks, are being implemented by the municipality with funds from a federal government programme. Forty-three parks are in the final phase of the preliminary study, financed by the municipal fund for the environment. The Araucárias Square was a community planting effort which included several green grassroots movements with basic support of local city administration. The Tiete Park is being built with the support of the state government, as an environmental offset to the reconstruction of Marginal Tiete, an important highway along the Tiete River that crosses the urban area.

Maintenance: • Include all the work necessary to keep the park's natural ecosystems functioning and ensure that the area is safe, clean, and operating efficiently to serve the needs of its visitors • For example, maintaining good vegetation growth (remove weeds, prune vegetation, etc.), routine inspection of vegetation, removal of litter and debris, maintaining signage and fencing, etc.

Design & construction. The city developed an index of social green areas to identify the regions that had more or less accessibility to green areas, mapping the priority neighborhoods. The mapping indicated where new linear parks should be planned, designed and implemented.

Benefits & co-benefits (economic, environmental, social): • Green space in urban areas has a role in balancing the water cycle system, reducing heat, providing habitats for wildlife, and controlling the local climate • Increase biodiversity of flora and fauna • Contribute to urban climate by reducing air temperature and urban heat • Improve air quality • Decrease air pollution and carbon sequestration • Contribute to social and human wellbeing • Mitigate the production of GHG emissions

Economic cost (design, construction & maintenance). The costs vary greatly depending on the characteristics of the green space and planned intervention. The spatial system of the urban green space may require conservation, restoration, maintenance, improvements and protection of existing and planned spatial forms. Creating partnerships for urban green spaces offers opportunities for coordination of environmental regeneration programs at potentially low financial costs. Among the different categories of expenditure (maintenance, operating and capital costs), maintenance costs constitute the major part of the total cost, ranging from 75% to 95%⁸.

⁸ Tempesta (2015)

Case Study 3: China's Sponge Cities an Integrated Approach: The case of Lingang in Shanghai

Similarities with Ouagadougou

- Rapid urbanization has had complex impacts on the regional hydrological cycle • Changes in natural hydrological processes on natural river basins
- Increased risk of urban flood disasters • Limited green spaces • Water stress • Serious pollution of urban water bodies.

Urban transport system

Extensive public transport system, largely based on buses, trolley buses, taxis, and a rapidly expanding metro system.

It is the longest metro system in the world with more than 673 km of lines.

Climate hazards affecting the city

- Shanghai is one of the top 20 cities exposed to flood disasters • The geological and climatic conditions of Shanghai make it sensitive to flooding risks during heavy rainfall events • Exposed to typhoon induced storm surges
- Threat is posed by tidal waves, storms caused by monsoon winds, as well as fluctuations in the level of the rivers flowing through the city (the Yangtze and Huangpu)



People get on the bus at a flooded section of the Xietu Road in Shanghai, July 30, 2009.



Typhoon Fitow brought heavy rain to the city, flooding more than 50 roads in October 2013.

Solutions implemented to enhance the system's resilience

Context. China is investing nearly US\$300 billion through 2020 to create 30 “sponge city” projects in Beijing, Shanghai, Shenzhen, Wuhan, and other areas. A **sponge city is an integrated approach** that involves a broad range of concepts such as multi-scale conservation and water system management, multi-function of ecological systems, urban hydrology and runoff control frameworks, and impacts of urbanization and human activities on the natural environment. By 2030, China aims to install sponge city projects in 80 % of urban areas across the country and reuse at least 70 % of rainwater.

Lingang, Shanghai's “sponge city”, is the largest city among the 30 pilot cities. Its wide streets are built with permeable pavements, allowing water to drain to the soil. Central reservations are used as rain gardens, filled with soil and plants. The manmade Dishui Lake helps control the flow of water, and buildings feature green rooftops and water tanks. A total of 36 km of roads have been renovated and concrete sidewalks replaced with water-absorbent bricks to reduce water pooling during heavy rainfall. Instead of going directly to drainage, the bulk of the rainwater is absorbed by the soil in grass ditches alongside the roads. Retrofits have been completed in Lingang at 26 residential neighborhoods covering 200 hectares. The city has also implemented pocket parks.



Permeable pavements in Lingang help stop buildup of surface water during heavy rain.



Wetland areas help to absorb rainwater in Lingang

Financial & organizational arrangement. The central government is providing US\$59 to US\$88 million per year to each of its 30 pilot cities for 3 consecutive years as start-up capital to help them devise and construct nature-based solutions. This investment is intended to inspire the creation of public-private partnerships (PPP). China's Ministry of Finance created a strategy to support the PPP model by soliciting private investment in construction projects and formalizing its procurement process for PPPs.⁹ For those cities by which PPP are introduced that reach a certain scale, additional subsidies of up to 10% of the initial funding are added as a bonus. However, this subsidy is far from enough to accomplish the whole project and most funds are expected to be raised by local municipalities. The commitment of funding from local municipalities is one of the preconditions to apply for a sponge city project.¹⁰

Design & construction. Unlike traditional cities, where impermeable roadways, buildings and sidewalks interfere with the natural water cycle, sponge cities mimic and support the natural water cycle. A Sponge City is more than just its infrastructure. It is a city that makes urban flood risk management central to its urban planning policies and designs. Constructions and renovations should be carried out in an integrated way. Since 2015, all newly planned urban districts, all types of industrial parks, development zones and living community should be designed and built according to the new standard.

Economic cost (design, construction & maintenance). China's central government is providing a significant amount of funding for the pilot cities, but the subsidies are far from enough to fully fund sponge city construction. Estimates vary but suggest that sponge city construction could require investments of 100 to 150 million yuan (US\$15 to US\$23 million per km²). The total area under construction in the first 16 pilot cities is more than 450km².¹¹

Maintenance. There must be planning and legal frameworks, and tools in place to implement, maintain, and adapt the infrastructure systems to collect, store, and purify excess rainwater.

Benefits & co-benefits (economic, environmental, social).

- Absorb and reuse flood water
- Improve flood and sediment control as well as water purification
- Minimize the burden on the city drainage and water networks reducing water treatment and equipment maintenance costs
- Create better quality of life in the areas
- Mitigate the production of GHG emissions

⁹ Ozment et al (2019)

¹⁰ Embassy of the Kingdom of the Netherlands, I&M department (2016)

¹¹ World Resources Institute (2018)

Case Study 4: Nairobi's green and hybrid infrastructures and participative risk management approach

Similarities with Ouagadougou

- Urban sprawl and rapid urbanization have affected the hydrological cycle and reduced the nature in the city
- Lack of drainage infrastructures and blockage of existing drains due to solid waste
- Poor solid waste and wastewater management
- Informal settlements

Urban transport system

Large choices of urban transport system (private) based on buses, Matatus (minibus), Commuters train

as well as taxis, taxi moto, cycle taxi and tuktuk

Climate hazards affecting the city

- Intensive rainfalls thereby to flood
- “flash” floods and extensive flooding for days.
- Exposed to the phenomenon of El Nino, which affected the intensity of rainfalls. Climate change could reinforce the intensity of rainfall periods and landslides in informal settlements
- Nairobi has experienced several major floods and drought pockets during the last years, which led to widespread devastation, as well as destruction to life and property



Nairobi CBD after the severe rainfalls, October, 2018.



Flooding along the railway in the slum of Kibera, Nairobi, 2015.

Solutions implemented to enhance the system's resilience

Context. Nairobi County Council in conjunction with the national government has decided to invest in structural and non-structural measures to tackle flooding risks. The government has decided to expand its strategy of **green infrastructures** to the entire city, to **use technology** to alert the inhabitants, and to **design and maintain resilient solutions using participative methods.**

Green Infrastructures are hybrid public spaces along the Nairobi River such as the restored Michuki Memorial Park. The park now provides locals with pavement and plants for water retention and infiltration, recreational space, while also improving the microclimate and habitat quality. Other projects such as Green corridors along Ngong Road or urban forests are projected. Green infrastructures are implemented differently in slums: in Kibera, one of the world's largest informal settlements, they implement sustainable drainage techniques (planted revetments, bamboo plantation for erosion control, structured detention and infiltration, using soft drink crates instead of expensive “stormblocs”, and rainwater harvesting).

The use of the technology: The government has enhanced the use of telecommunication and social network to alert and share the information of rainfalls. The Trilogy Emergency Relief Application SMS platform works across the country and helps communities to be better prepare for potential floods (advice, safety rules).

Pedagogy and design of green solutions through a bottom up approach: Various participative actions have been held by the City Council, the Kenya Red Cross Society, and international stakeholders:

- Pedagogy by raising awareness among the inhabitants



Michuki Memorial Park, 2020

- Promotion of and Participation in regular clean-ups, thereby freeing the drains of garbage
- The Participatory flood modelling, e.g. in Kibera slum in Nairobi: in 2015 a program named 'Building Integrating Community Perspectives' was undertaken, to involve residents in flood risk management, get information during workshops and support the design of the flood model, but also involve and train institutional stakeholders. This collaboration between the inhabitants, experts and institutional actors allowed the prioritization of needs in the slum.



At Andolo in Kibera, green public space combined hard soft and social solutions, in 2017

Financial & organizational arrangement. The national government and the Nairobi city council, experts of Kenya Red Cross Society, Kenya's Meteorological department, National Disaster Operational Centre work together. There is not a city organization. Other stakeholders get involved for local study, NGOs, International institutions and academics. Nairobi takes part into international programs such as Resilient Cities Network.

Design & construction. The green infrastructures are built in critical areas of the city that could be affected by hazards (settled along the rivers). They are composed of endogenous plants and infiltrating pavements. In the slum, the green infrastructures are hybrid. The solutions combine hard (e.g. drains), and soft and social aspects. They use local materials and distinct techniques. The flooding problems were resolved thanks to wire mesh gabions filled with rocks collected by residents, porous drainage channels made from recycled perforated plastic pipes, bioswales that allow water to drain naturally, and by reclaiming and refilling land by the river bank. They built a pavilion, used as offices for a local finance program, craft co-operative and compost businesses. Its roof captures rainwater used on the garden dedicated to the production of vegetables.

Maintenance: Different actors are mobilized, depending on the situation. Social initiatives are suggested: inhabitants and unemployed inhabitants can contribute to the cleaning and maintenance at the request of the Nairobi City Council. In Kibera, the community actively contributes to the maintenance. The government and the Nairobi City Council allocated a budget to clean drains and canals.

Benefits & co-benefits (economic, environmental, social). • Improve the water cycle system and the air quality • Support the city drainage system • Participate in solid waste management • Green spaces in dense urban areas • Inclusive projects that raise awareness among the population • Mitigate the material destruction and the production of GHG emissions

Economic cost (design, construction & maintenance). In 2018/2019, the government allocated 60.4 billion Kenyan shillings (around US\$607 million as of March 2019), 2.4% of the national budget, to environmental protection, water harvesting and flood control. For the Michuki Memorial Park, the rehabilitation cost 30 million Kenyan shillings (US\$278,000).

Case Study 5: Japan's disaster preparedness and business continuity approach

Similarities with Ouagadougou

- Public transport affected by flooding events • Projected increase in the intensity of weather variability • Densely-populated cities

Urban transport system

- Japan has a modern and efficient public transportation network, especially within metropolitan areas and between the large cities • The urban transport systems include buses, trains, subways, trams, taxis, ride-sharing apps, etc.
- Due to land constraints and congestion, subways are usually the fastest and most convenient transport system in major cities

Climate hazards affecting the cities

- Heavy rains, high wind and typhoons leading to floods, overflowing rivers and landslides • Large-scale water-related disasters caused by typhoons are becoming more frequent and severe • Japanese cities (e.g. Toyooka in October 2004 and Hiroshima in July 2018) experienced major floods that resulted in widespread devastation, service disruptions, as well as damage to property and loss of lives • Flood vulnerability is increasing due the increased concentration of population and socio-economic functions, as well as the advanced use of underground space.



A parking flooded in Toyooka (2004)



Flooded road in Hiroshima (2018)

Solutions implemented to enhance the system's resilience

Context. Japanese cities (such as Toyooka) that were severely damaged by typhoons decided not only to implement structural resilience measures (e.g. excavating river channels and strengthening levees), but also to implement **soft measures**. The soft measures implemented include the preparation of **pre-disaster action plans (timelines)**, and more generally measures towards the creation of "**flood prevention and disaster awareness society**".

Timelines: The timeline of Toyooka city was developed to strengthen crisis management capabilities in the event of a large-scale flood disaster to help prevent and mitigate disasters. A total of 17 organizations, including Toyooka City, Hyogo Prefecture, Kobe District Meteorological Observatory, Hyogo Prefectural Police, local railroad and bus operators, telephone companies, and electric power companies, participated in the meeting to discuss "what will be done, when, and by whom" in case of a large-scale disaster, and to formulate a timeline to clarify each entity and person's actions¹².

¹² http://www.bousai.go.jp/kohou/kouhoubousai/h29/87/special_01.html

This timeline was developed with the assumption that typhoons and rainfall can be predicted using **monitoring tools**. The latter combine information about the accumulated rainfall, the forecasted accumulated rainfall for the next six hours and river levels (the main river in Toyooka is the Maruyama River). The timeline includes three scenarios composed of different stages defined according to the amount of rainfall (current and projected rainfall), taking into consideration the characteristics of the Maruyama River, and the probable location, level and evolution of the water.

When the cumulative rainfall plus the projected cumulative rainfall for the next 6 hours exceeds a planned threshold, the disaster prevention and mitigation actions corresponding to this threshold is triggered.

In the transportation sector, a system was put in place to ensure that station staff and crew are informed and that standards are set for suspension and post-hazard recovery of service. Bus companies also prepared relocation plans and parking spaces to evacuate their vehicles to areas with higher elevations, which allowed the vehicles to escape the damage and resume operation at an early stage.



Buses evacuating from a flooded area (Nagano, 2019)¹³



Emergency Sandbag Storage Area on Itabashi Ward Station (Tokyo, 2017)¹⁴

Flood prevention and disaster awareness society: The Japanese authorities seek to rebuild a "**flood prevention and disaster awareness society**" in which the entire society is always prepared for floods by sharing goals for disaster mitigation and promoting structural and soft measures in an integrated and systematic system that involves neighboring municipalities, prefectures, the national government, etc., in preparation for large-scale flood damage. Toyooka City not only **distributed flood hazard maps to all households**, but also conducted **proactive educational programs** such as visiting lectures to directly reach out to residents. To complement the conventional disaster prevention radio system, the city has established a system to send faxes simultaneously to community leaders and people with hearing disabilities.

Design & construction: There must be planning and legal frameworks, and tools in place to implement, maintain, and adapt soft measures. In general, the developments of **local emergency plans and timelines** involves a wide range of stakeholders from the public sector (the national government, local governments, meteorological office, police and fire department) but also the private sector (bus, telecommunication and electricity companies) as well as the inhabitants of the areas prone to flooding.

Maintenance: The plan should also be regularly reviewed and tested for continuous improvements.

Benefits & co-benefits (economic, environmental, social): Raise awareness among inhabitants • Soft measures are cheaper and faster to implement than structural measures • Complement structural measures.

¹³ https://www.mlit.go.jp/unyuanzen/content/torikumi_jirei177.pdf

¹⁴ https://www.mlit.go.jp/river/bousai/shinsuihigai/pdf/171225_zentai_lo.pdf

3.3. Prioritizing measures for Ouagadougou through multi-criteria analysis

The results of the analysis of the flood-exposed sections were used to propose appropriate measures (i.e. application of one or several solutions to a flood-prone area). To this end, the project team associated each section with an appropriate solution based on the type of flood in the section and availability of land in the area. For example, the flood in Nongremasson Street on Line 1 is due to an overflow of the canal Central, causing floods in the adjacent areas and perpendicular streets, such as Nongremasson St. In this case, several solutions can be considered:

- Solutions aiming at increasing the canal's capacity (next to the bridge and downstream): clearing obstructions, refurbishment, removing silt, improving the outlet;
- Solutions aiming at reducing the peak flows in the canal (targeting the upstream watershed): retention basin, local storage, parks, swales.
- Solutions aiming at preventing overflows from the canal: dyke
- Elevating the road profile (which implies replacing the bridge)
- A temporary diversion through Ave Kiendrebeogh Moryamba

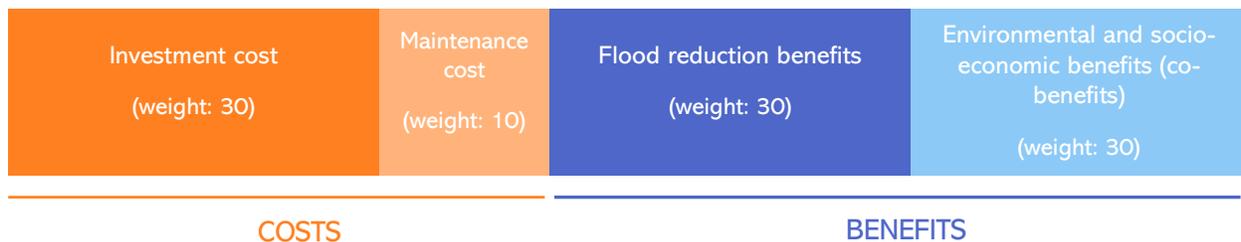
All these solutions appear in the list of proposed measures except the dyke that would not be effective in protecting Nongremasson street that is perpendicular to the canal.

Another example is 28.257 St. on Line 4, which is flooded due to runoff from the perpendicular streets in the south-east that acts as canals and convey water to the north-west. This area is located at the top end of the watershed, with relatively high slopes, and the perpendicular streets lack proper drainage. Hence, the solutions that can be considered are:

- Solutions aiming at improving the drainage capacity of the perpendicular streets: build a drainage system;
- Solutions aiming at improving the water retention capacity of the area: permeable pavements, porous asphalt, and rain gardens.

Both types of solutions were included in the list of proposed measures. In particular, it is proposed to implement a rain garden in the open space close to Saint Paul chapel. A set of soft and city-wide measures was also included to address the residual flood risk related to rare and more extreme flood events.

To compare and rank the measures, the team developed a multicriteria-analysis methodology. To this end the following criteria and weights were selected:



Investments costs were marked using a continuous rating scale designed to allow a good dispersion of marks between 0 and 10. For investment costs, unit costs and estimated quantities were used whenever possible. The cost estimates included in the present report are indicative and a detailed design of the solutions would be required to reduce the uncertainty around those costs. The use of the cost classification in more qualitative terms (from very low to very high) reduces the impact of the uncertainty around the costs on the results of the multicriteria analysis.

Maintenance costs were marked using a continuous rating scale designed to allow a good dispersion of marks between 0 and 10. Many of the proposed measures include the construction of new hydraulic structures, whether channels, culverts, canals or alternative solutions such as swales, porous pavement,

rain gardens. All these solutions require proper routine and periodic maintenance to maintain their initial effect in the long term. In a few particular cases, it was possible to use unit costs to estimate maintenance costs, but in most cases, other methods had to be employed.

One specific measure (measure 21) proposes to create a team dedicated to the standard maintenance of the structures contributing to flood protection of the whole bus system. This standard maintenance would consist of cleaning of the structures after rain events and before the beginning of the rainy season. This would be the best way to ensure that the proposed structures are kept in good working conditions. The long-term cost of this team was estimated by assessing the required staff composition and considering local labor costs.

Since all proposed measure need to be evaluated separately, maintenance costs still needed to be assigned to each measure, including the construction of new structures, although routine maintenance of these structures would actually be covered by the maintenance team proposed in measure 21.

Maintenance operations would typically be divided in routine maintenance (simple and cheap tasks to be performed every year) and periodic maintenance (heavier work, to be planned every 7 to 10 years). In order to assess the maintenance costs applicable to the proposed structures, the following ratios were used, including for both routine and periodic maintenance:

- Maintenance of road surface: 1% of the investment per year
- Maintenance of hydraulic structures (channels, canals): 0.5% of the investment per year
- Maintenance of green structures (bio swales, rain gardens, etc.): 2% of the investment per year

These ratios illustrate the fact that a road surface is subject to more wear than hydraulic channels, and that green surfaces require more frequent maintenance than concrete structures.

The **flood impact reduction benefits** were assessed using two criteria:

- The impact of the current flood issues on the planned transportation system (marked from 0 to 5).
- The effectiveness of the proposed measure to reduce these flood impacts on the transportation system (marked from 0 to 5).

The overall flood impact reduction benefit mark on a scale from 0 to 10 is calculated by combining the two above sub-marks. The rationale behind this evaluation method is that technical efficiency should not be the only parameter considered when evaluating the flood reduction benefits of the proposed measure. A measure providing full protection to an area that has a very low importance in the transportation system should not get the maximum grade. On the contrary, a solution that provides limited protection may prove valuable if it allows flood impact reduction on critical sections of the transportation system.

The impact of the current flood issues is quantified as follows:

- For measures targeting a single area, the score is taken from the Table 4.1. in Annex 4 where this score was computed from 0 to 4.
- Measures targeting several areas were assigned the highest impact score given to either of these areas (still from 0 to 4).

- Measures targeting the entire AOI were assigned the maximum score of 5.

The effectiveness of the proposed measure in reducing the flood impacts on the transportation system was assessed using experts' judgment. In a few occurrences, proposed measures have already been studied in previous works, mostly the Ouagadougou Drainage Master Plan, in which case the measures have been designed in detail to ensure protection against a specific return period storm. In most other cases, the proposed measures have been pre-dimensioned based on experts' judgement, and more detailed design including hydraulic modelling would be necessary to determine the exact required dimensions. The maximum score of 5 represents a measure allowing guaranteed full protection against a design storm. Solutions that do not fully prevent flooding of the section but decrease the recovery time or reduce the flood height received lower scores. The minimal score of 1 corresponds to measures that have no impact on flood reduction, but help minimize the consequences of the floods (diversion scheme to a non-flooded itinerary, for example).

The choice of a relevant formula to combine the two marks into an overall flood impact reduction benefit score required several tests.

In the formulas that were considered, the following notation was applied:

I for the Impact of current flood issues, scored from 0 to 5

E for the effectiveness of the proposed measure to reduce the impacts, scored from 0 to 5

FIRB for the Flood Impact Reduction Benefit, marked from 0 to 10

C for the conversion factor, a number allowing to adjust for each calculation method the range of the results to the 0-10 scale.

The tested formulas were as follows:

Simple addition:

$$FIRB = I + E$$

This formula has the advantage of being straightforward, and provides good dispersion and reasonable average of the scores. However, this formula had a major inconvenience: a measure that has no impact on flood reduction would still get a mark of 5/10 if it targeted the most critical areas. Conversely, a measure with good hydraulic efficiency would also get 5/10 even if it targeted an area with no current flooding issues. Ideally, these two extreme and theoretical situations should lead to a score of 0/10.

Simple multiplication:

$$FIRB = \frac{I \times E}{C} \text{ with } C = 2.5$$

This formula fixed the above-mentioned issue: by using multiplication instead of a sum a measure with a 0 mark at one of the two sub-criteria would get a 0 score in flood impact reduction benefits. However, this came with a serious drawback: the resulting scores were very low, on average, and the dispersion limited (most scores were under 5/10). Thus, the flood impact reduction criteria lost much of its weight in the evaluation.

Weighted multiplication:

$$FIRB = \frac{I^a \times E^b}{C} \text{ with } C = 5^a \times 5^b / 10$$

This formula is a generalization of the previous formula, allowing to apply different weighing on the two sub-criteria of flood impact and effectiveness. By changing the values of the coefficients, a and b , it was possible to adjust the dispersion and average of the resulting scores, as well as the relative importance of the two sub-criteria.

After several tests, we selected the weighted multiplication formula, with values of $a=0.5$ and $b=0.3$ (resulting in $C=0.36$). This formula gave satisfying results: good dispersion of scores, average around 5/10, and slight preponderance given to the flood impact sub-criteria.

Environmental and socio-economic benefits were assessed for each measure, and a score from 0 to 10 was given with the following scale: 0 for very negative impacts, 5 for no impact, 10 for very positive impacts. Since the proposed measures have been designed to take advantage of available space (right of way of the road, existing canals, public spaces), they do not involve major negative impacts such as demolition of buildings requiring resettlement of population. Four of the proposed measures have negative impacts. Measure 6 (temporary diversion of Line 1 through Avenue de la Liberté and Avenue du Barrage if Nongremasson St. is blocked) and measure 10 (temporary diversion of Line 5 through the itinerary of future Line 6) have minor

negative impacts related to the resulting extra cost of travel time, fuel consumption and CO₂ emissions. Measure 3 (elevation of the road profile of Nongremasson street north and south of Canal Central — future Line 1) would make pedestrian traffic between the road and the surroundings difficult. Measure 26 (enforcement of regulations aiming at limiting water run-off generated by new constructions) that concerns the whole AOI would increase the cost of construction projects in the city.

Implementing a measure that is already recommended in the Ouagadougou Drainage Master plan has been considered to have a significant socio-economic benefit, since it would be consistent with the investment plan already targeted by the municipality.

3.4. Results of the multicriteria analysis

The multi-criteria analysis ranked 26 different measures, including gray, green and soft measures that are applied to specific flood-prone areas or to the entire layout of the planned transport system (see Table 3). The map in Figure 18 shows the location of the measures in the AOI.

Certain solutions included in the initial long list were not directly included in the list of measures as they appeared ineffective at protecting the planned mass transit system or difficult to implement. For example, the construction of green roofs in areas that are already constructed is difficult as it requires complex interactions between the city council and homeowners. This solution is more suitable for new developments. However, even if this solution has not been used on the list of proposed measures, one should note that the enforcement of regulations aiming at limiting water run-off generated by new construction projects (measure 22) would in practice strongly incite developers to implement such solutions.

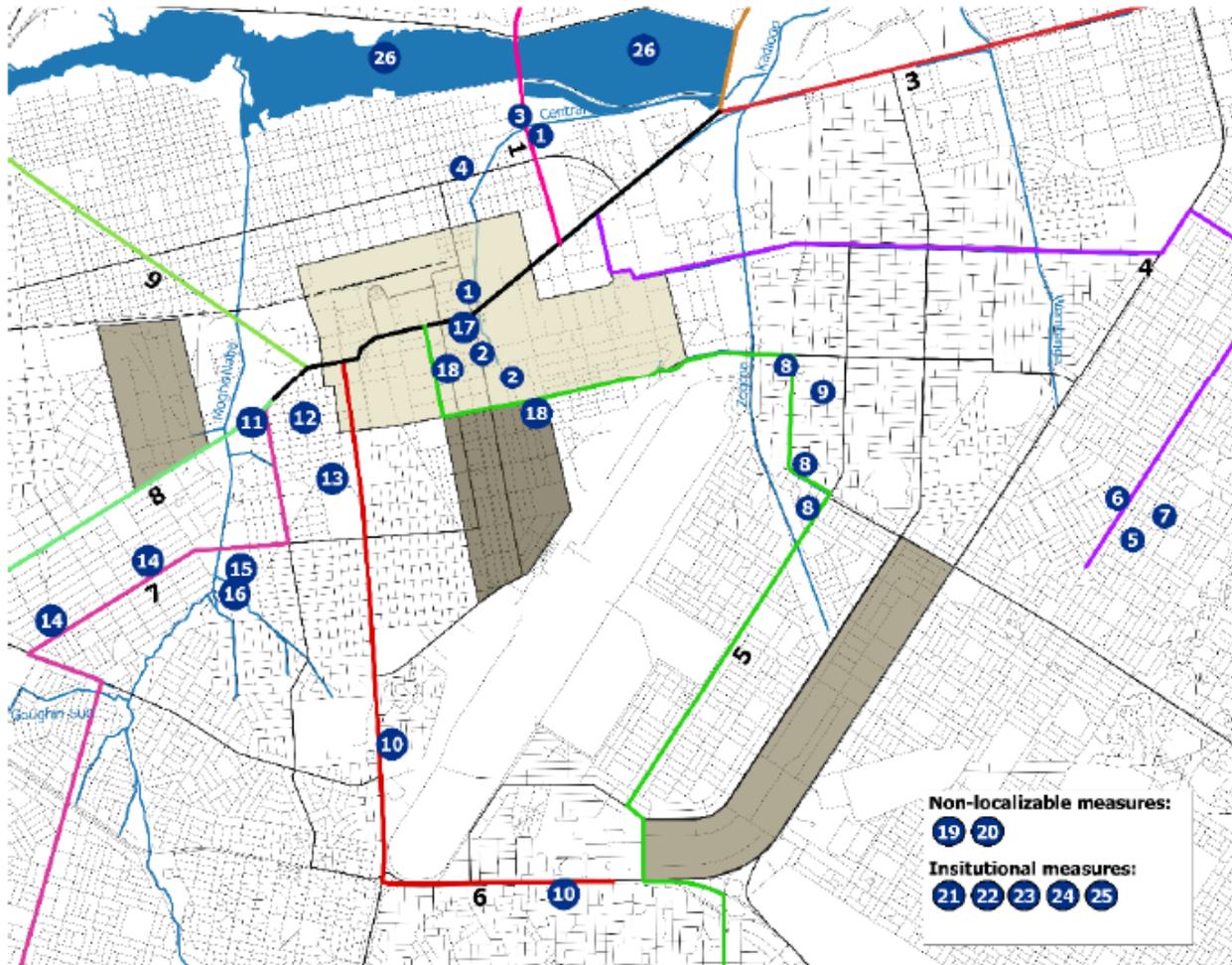
Some of the proposed measures are described in more detail in Table 5.3. in Annex 5.

The multicriteria analysis was used to compare the performance of the different types of measures (green, gray, soft). To this end, the 26 measures were classified into groups of measures applying similar solutions.

Table 3: Proposed flood-resilience and adaptation measures

Gray measures		Green measures		Soft measures	
No.	Description	No.	Description	No.	Description
1	Rehabilitation of upstream part of the Canal central and development of its downstream part	2	Install a bioswale in the median of the road on Ave Kwame Nkrumah and Ave de l'UMOA (that are large and have a descending slope)	4	Put in place a temporary diversion through Ave de la Liberté and Ave du Barrage if Nongremasson St. is blocked
3	Elevate the road profile of Nongremasson street north and south of the Canal Central (implies replacement of the existing bridge)	9	Rain gardens in the open space surrounding the house lots between 14.09 St. and Ave Babanguida (the design should include parking spaces for the inhabitants)	10	Put in place a temporary diversion of Line 5 through the itinerary of Line 6, which uses an elevated road (Ave Bassawarga) if Ave des Arts is blocked
5	Build a drainage system to collect run-off water for the neighborhood south-east of 28.257 St. and channel them until the flood control basins of Wemtenga canal	12	Water retention solution for the neighborhood east of Avenue Oumarou Kanazoe: Permeable pavements/porous asphalt for the unpaved roads	21	Set up a dedicated maintenance plan and team in charge of the periodic and systematic cleaning and maintenance of flood related structures (canals, culverts, rain gardens, pockets parks, etc.) dedicated to the BRT (in particular before the rainy season).
6	Build a drainage system focusing on protection of the 28.257 St.	13	Water retention solution for the neighborhood east of Avenue Oumarou Kanazoe: pocket park in Mogho Naba Palace and rain garden or floodable sports field in the 8 Mars garden and Lycée Bambata	22	Enforce regulations aiming at limiting water run-off generated by new constructions. A simple way is to impose a limit on the flow a newly developed area can discharge to the drainage network. This engages developers to integrate stormwater management in their design and implement solutions to reduce flows sent to the network (e.g. green roofs, permeable pavement over parking lots, bioswales etc.).
7	Drainage system to protect 28.257 street, combined with water retention solutions for the neighborhood to the south-east: permeable pavements and rain garden in the area in front of Chapelle St Paul				
8	Build a drainage system to protect 14.09 St. from transverse flows and ensure longitudinal drainage of Ave des Arts North of Canal de l'université	17	Build a rain garden on the roundabout Nations Unies	23	Develop a risk awareness culture in the bus operating company to manage the residual flood risk: Develop a: pre-disaster action plan; a business continuity plan, identifying the sections of the lines that should be maintained in case of extreme storms; a communication plan to inform users based on mobile technologies (SMS)
11	Build a drainage system to protect Ave Oumarou Kanazoe and Place du rail roundabout	19	Install stormwater retention trees (street trees combined with an underground structure and above ground plantings which collect and treat stormwater using bioretention) along the roads of the future transit system that will be paved or improved to allow the bus to pass (e.g. 28.257 St. on future Line 4, which is unpaved)	24	Develop a Flood monitoring and disaster prevention system for the city: Pre-disaster action plan (timeline) that aims to prevent damage and allow public transport to resume operation at an early stage. The actions should be triggered depending on the information provided by a flood monitoring tool (considering current and predicted rainfall and water level in the dams) — the system should be managed by the city authorities and the relevant information passed on to the bus operating company
14	Build a longitudinal drainage system on Simon Compaoré street	20	Plant trees along the roads of the future transit system that will be paved or improved to allow the bus to pass (e.g. 28.257 St. on Line 4, which is unpaved)	25	Reinforce the solid waste collection system: organize awareness-raising activities, and most importantly provide an efficient collection system, concrete baskets at the bus stops, garbage collection points at strategic locations collecting trucks, landfill / incineration sites
15	Cleaning / rehabilitation of the Moogho Naaba canal downstream of Avenue Ouezzin Coulibaly, as recommended in the Drainage Master Plan				
18	Build a new drainage network to protect Ave Houari Boumediene and Ave de la Grande Mosquée				
26	Cleaning of the reservoir lakes north of the area study and modification of the spillway to lower the water level in the lakes and improve outlet conditions of the canals				

Figure 18: Location of the proposed flood-resilience and adaptation measures



Soft measures are associated with the lowest investments and maintenance costs. Gray measures are associated with medium upfront costs and low maintenance costs. In contrast, the initial costs of green measures greatly vary (from very high for permeable pavements/porous asphalt to relatively low, on average, for street- and stormwater-retention trees). The average maintenance costs associated with green measures are slightly lower than those of gray and soft measures. Finally, the highest upfront and maintenance costs are associated with the measures that mix green and gray elements.

The flood impact reduction benefits of the green and mixed solutions vary greatly, and it is difficult to identify specific trends. In contrast, soft solutions tend to be associated with medium to very high benefits as they generally apply to the whole AOI. The flood impact reduction benefits of the gray solutions are generally medium to high, as these measures are effective in reducing flood impacts but apply to limited sections. Finally, as expected, green and mixed solutions are associated with the highest environmental and socio-economic benefits (co-benefits).

Table 4: Scoring the proposed measures according to the four criteria

Groups of similar measures	Measures no.	Type of measure	Mean [min, max] scores, by criteria (/10)					Total score (/100)
			Investments costs	Maintenance costs	Flood impact reduction benefits	Environmental & socio-economic benefits		
Dedicated maintenance team and reinforcement of solid waste collection system	21; 25	Soft	8.5 [8, 9]	8.5 [8, 9]	8.1 [7.6, 8.6]	7.5 [7, 8]	81 [80, 82]	
Enforce regulations aiming at limiting water run-off generated by new constructions.	22	Soft	10	9	7.6	3	71	
Risk awareness culture in the bus and City flood monitoring and disaster prevention system	23; 24	Soft	9 [9, 9]	7 [4, 9]	6.2 [6.2, 6.2]	6 [6, 6]	70 [68, 73]	
Bioswale	2	Green	6	8	7.7	7	70	
Temporary diversion of bus lines	4 ;10	Soft	10 [10, 10]	10 [10, 10]	4.3 [3.9, 4.8]	3.5 [3, 4]	64 [61, 66]	
Cleaning of the reservoir lakes and modification of the spillway to lower water level in the lakes and improve outlet conditions of canals	26	Mix of gray and green	2	0	9.4	10	64	
Street trees and stormwater retention trees	19; 20	Green	6.5 [5, 8]	8.5 [8, 9]	2.2 [2.0, 2.4]	9 [9, 9]	62 [57, 66]	
Rehabilitation and development of the canals	1; 15	Gray	5 [3, 7]	8.5 [7,9]	5.9 [3.4, 8.4]	7 [7, 7]	62 [59, 64]	
Build a drainage system	5; 6; 8; 11; 14; 18	Gray	5.3 [4,8]	9 [9, 10]	4.6 [3.0, 7.2]	5.5 [5, 7]	56 [48, 71]	
Permeable pavements/ porous asphalt	12	Green	1	8	6.6	8	55	
Rain gardens and pocket parks	9; 13; 17	Green	4.3 [1, 9]	8 [6, 10]	5 [3.4, 6.8]	6 [6, 6]	54 [37, 75]	
Elevate the road profile of Nongremasson street north and south of the Canal Central (implies replacement of the existing bridge)	3	Gray	5	10	6.3	1	47	
Drainage system combined with green water retention solutions	7	Mix of gray and green	0	7	3.2	10	46	

Highest ranked individual measures

The multicriteria analysis allowed the identification of the top ten measures that should be prioritized (based on the total score):

- **Measure 21:** Set up a dedicated maintenance plan and team in charge of the periodic and systematic cleaning and maintenance of flood related structures (canals, culverts, rain gardens, pockets parks, etc.) dedicated to the mass transit system (in particular before the rainy season).
- **Measure 25:** Reinforce the solid waste collection system: organize awareness-raising activities, and most importantly provide an efficient collection system, concrete baskets at the bus stops, garbage collection points at strategic locations collecting trucks, landfill / incineration sites
- **Measure 17:** Build a rain garden on the Nations Unies roundabout
- **Measure 24:** Develop a flood monitoring and disaster prevention system for the city: Pre-disaster action plan (timeline) that aims to prevent damage

and allow public transport to resume operation at an early stage. The actions should be triggered depending on the information provided by a flood monitoring tool (considering current and predicted rainfall and water level in the dams) — the system should be managed by the city authorities and the relevant information passed on to the bus management company

- **Measure 22:** Enforce regulations aiming at limiting water run-off generated by new constructions. A simple way is to impose a limit on the flow a newly developed area can discharge to the drainage network (e.g., in France it is 3l/s/ha max for the 10-year return period rain). This engages developers to integrate stormwater management in their design and implement solutions to reduce flows sent to the network (e.g., green roofs, permeable pavement over parking lots, bioswales, etc.).
- **Measure 11:** Build a drainage system to protect Ave Oumarou Kanazoe and Place du rail roundabout
- **Measure 2:** Install a bioswale in the median of the road on Ave Kwame Nkrumah and Ave de l'UMOA (that are large and have a descending slope)
- **Measure 23:** Develop a risk awareness culture in the bus management company to manage the residual flood risk: develop a pre-disaster action plan; develop a business continuity plan, identifying the sections of the lines that should be maintained in case of extreme storms; and develop a communication plan to inform users based on mobile technologies (SMS)
- **Measure 4:** Put in place a temporary diversion through Ave de la Liberté and Ave du Barrage if Nongremasson St. is blocked
- **Measure 20:** Plant trees along the roads of the future transit system that will be paved or improved to allow the bus to pass (e.g., 28.257 St. on future Line 4, which is unpaved)

The top two measures (measures 21 and 25) are solutions related to the maintenance and cleaning of the flood-related structures and the reinforcement of the waste collection system. These solutions are highly ranked because they present a very high score for all criteria. In other words, they would effectively contribute to the flood resilience of the entire future mass transit system, are associated with high long-term environmental and socio-economic benefits, and require limited initial and maintenance investments.

In addition to these, the highest ranked measures include four other soft measures: the development of a flood monitoring and disaster prevention system for the city (measure 24), the enforcement of regulations aiming at limiting water runoff generated by new constructions (measure 22), the development of a risk

awareness culture in the bus management company to manage the residual flood risk (measure 23), and the implementation of a temporary diversion through Ave de la Liberté and Ave du Barrage if Nongremasson street is blocked (measure 4).

The ten highest ranked measures include three green measures (17, 2 and 20). Measures 2 and 17 score relatively high on all criteria. Measure 20 (planting trees along the roads of the future transit system that will be paved or upgraded) presents very high environmental and socio-economic benefits as well as very low investments and maintenance costs, which compensate for its modest ability to reduce flooding impacts.

Measure 11 (build a drainage system to protect Ave Oumarou Kanazoe and Place du Rail roundabout) is the only gray measure ranked in the top ten. This measure scores relatively high on most criteria except in terms of co-benefits.

Further, the measures ranked 11th and 12th are a mix of gray and mixed structural measures. For example, the rehabilitation of upstream part of Canal Central and development of its downstream part (measure 1) and cleaning of the reservoir lakes north of the area study and modification of the spillway to lower the water level in the lakes and improve outlet conditions of the canals (measure 26) present very high flood impact reduction benefits because they are both effective and would be applied to critical areas of the planned future mass transit system. However, the associated upfront costs are very high.

3.5. Sensitivity analysis

To evaluate how the choice of weights impacts the rank of the measures, we performed a sensitivity analysis by considering three scenarios, each representing a different set of priorities for the decision makers. These different sets of priorities are represented by different sets of weighing of the criteria used in the analysis. The proposed scenarios are defined by the following weighing:

Scenario 1 is the base scenario, with a balanced distribution of priorities between costs, flood impact reduction benefits and environmental and socio-economic co-benefits.

Scenario 2 represents a situation where the decision-makers consider the reduction of flood impacts as the absolute priority and the other criteria as secondary.

Scenario 3 puts higher priority on the maintenance cost and a relatively high priority on co-benefits. This could represent the preoccupations of the Ouagadougou Municipality, who could more easily obtain external funding to pay for the investment but will be in charge of the maintenance of the infrastructure and has to consider the acceptability of the measures.

Table 5: Weighing of the criteria used in the three scenarios for multicriteria analysis

Criteria	Weighing criteria scenarios		
	Scenario 1	Scenario 2	Scenario 3
Investment costs	30	10	10
Maintenance costs	10	10	30
Flood impact reduction benefits	30	60	30
Environmental & socio-economic benefits	30	20	30
Total	100	100	100

The results of the sensitivity analysis are shown in Table 6, which lists the ten highest ranked measures depending on the scenario considered. The top-10 rankings resulting from the three scenarios are close, as they tend to mostly include the same measures although in different order. For example, the first 7 measures of the base scenario also appear among the 10-highest ranked measures of scenarios 2 and 3.

Measures 21 (setting up of a dedicated maintenance team in charge of the cleaning of flood related

structures protecting the bus routes) and 25 (reinforcement of the solid waste collection system) are ranked first or second in all 3 scenarios due to their high marks in all criteria.

The three measures that were not included in the top 10 of the base scenario but are included in the top 10 of scenario 2 are measures 1, 26 and 12. These measures clearly see their ranking improve because of the lower priority on investment cost (they each cost more than US\$3 million).

Table 6: List of the 10 highest ranked measures depending on the multicriteria analysis

Rank	Scenario 1		Scenario 2		Scenario 3	
	Measure Nr.	Investment cost ('000 US\$)	Measure Nr.	Investment cost ('000 US\$)	Measure Nr.	Investment cost ('000 US\$)
1	21	80	21	80	25	450
2	25	450	25	450	21	80
3	17	84	26	3,300	17	84
4	24	150	1	3,100	1	3,100
5	22	0	2	1,185	11	490
6	11	490	17	84	2	1,185
7	2	1,185	11	490	24	150
8	23	80	22	0	12	4,600
9	4	40	24	150	22	0
10	20	474	12	4,600	8	980

All in all, seven measures rank in the top 10 in all three scenarios and should therefore be prioritized:

21: Set up a dedicated maintenance plan and team in charge of the periodic and systematic cleaning and maintenance of flood related structures (canals, culverts, rain gardens, pockets parks, etc.) dedicated to the mass transit system, in particular before the rainy season

25: Reinforce the solid waste collection system: organize awareness-raising activities, and most importantly provide an efficient collection system, concrete baskets at the bus

stops, garbage collection points at strategic locations collecting trucks, landfill / incineration sites

17: Build a rain garden on the Nations Unies roundabout

24: Develop a flood monitoring and disaster prevention system for the city: Pre-disaster action plan (timeline) that aims to prevent damage and allow public transport to resume operation at an early stage. The actions should be triggered depending on the information provided by a flood monitoring tool (considering current and predicted rainfall and

water level in the dams) — the system should be managed by the city authorities and the relevant information passed on to the bus operating company

22: Enforce regulations aiming at limiting water run-off generated by new constructions. A simple way is to impose a limit on the flow a newly developed area can discharge to the drainage network (e.g. in France it is 3l/s/ha max for the 10-year return period rain). This engages developers to integrate stormwater management in their design and implement solutions to reduce flows sent to the network (e.g. green roofs, permeable pavement over parking lots, bioswales etc.).

11: Build a drainage system to protect Ave Oumarou Kanazoe and Place du rail roundabout

2: Install a bioswale in the median of the road on Ave Kwame Nkrumah and Ave de l'UMOA (that are large and have a descending slope)

Table 7 shows a comparison of the cumulative costs of the highest-ranked measures, depending on the preferred scenario. Scenario 1 privileges measures with lower investment costs compared to scenarios 2 and 3. As one could expect from its focus on solving flood issues, Scenario 2 favors more expensive measures. Scenario 3 is only more expensive than Scenario 2 if the 15 highest ranked measures are implemented. This is due to measure 16 (construction of a new flood retention basin for the Mogho Naaba canal), whose cost is estimated at US\$ 9 million.

Table 7: Cumulated investment cost of the highest-ranked measures

	Investment cost of the X highest-ranking measures ('000 US\$)		
	<i>Scenario 1</i>	<i>Scenario 2</i>	<i>Scenario 3</i>
X = 3	614	3,830	614
X = 5	764	8,115	4,204
X = 10	3,033	13,439	11,119
X = 15	10,968	18,039	24,133
X = 26		49,080	

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ANNEX 1: DRONE-BASED IMAGERY COLLECTION TO CONSTRUCT A DIGITAL ELEVATION MODEL

Flight authorizations: The locally-based drone company, Espace Geomatique, organized a meeting with the HYDROMET Project Coordinator to ask for the support to obtain the flight authorizations. He then informed the National Civil Aviation Agency (ANAC) which is the ultimate authority to give the final authorization after authorizations are received from the Ministries of Defense and Security. Espace Geomatique sent flight authorization requests on June 10, 2020, to the Ministries of Defense and Security. From then on, Espace Geomatique was contacted several times, mostly due to the fact that drone regulations in Burkina Faso are very new. Thus, there is not yet a specified and organized office within the Ministries of Defense and Security that is in charge of giving the requested authorizations. Espace Geomatique received the official authorizations from the Ministries of Defense and of Security mid-July and transmitted them to ANAC for flight organization purposes. A demonstration flight with ANAC took place on July 17, 2020.

Ground data collection involved carrying out ground surveys at the level of the crossing structures along the watercourses / canals of the AOI. Espace Geomatique identified around 60 structures to be measured and pictures were taken of each structure. The ground topographic measurements were completed in July 2020.

Summary of challenges associated with drone imagery collection:

- Espace Geomatique were notified by ANAC that they needed to get authorization from all the embassies and medical centers located in the AOI. This caused more than 2 months delay in the overall work, as it was not possible to fly without these official authorizations.
- Espace Geomatique had to start its drone flights during the rainy season, and this led to delays of several days. Because the rainy season had been exceptional in 2020, it had some consequences on the flights. Indeed, the rains had begun in Ouagadougou by June and terminated by September. Because of this and the fact that it was not safe to fly in rainy and cloudy weather, some flights had to be cancelled and rescheduled.
- Flights were organized in coordination with the Ouagadougou International Airport's control tower, which at times asked Espace Geomatique to change flight plans at the last moment. To avoid collision risks or electromagnetic influences between the drone and other flying aircrafts, it was imperative to coordinate the flights with the airport control tower. Before each flight, it was obligatory to call the control tower and to give its staff the place and the drone flight conditions (altitude, duration, area to be covered). Moreover, the control tower could call Espace Geomatique and request to wait, to fly back, and to cancel or interrupt the flight depending on the airport traffic and knowing that all other aircraft were prioritized above the drone. For those reasons, several drone flights had to be cancelled at the last minute. Espace Geomatique was also obligated to inform the airport control tower when each drone flight was terminated.
- Espace Geomatique discovered that the geodesic requirements needed more densified ground control points. Despite the fact that the drone was carrying a real-time kinematic positioning system which was calibrated with the national geodetic system and the fact that each flight plan was covering an area of less than 2x2 kilometers, it was necessary to measure and put additional ground control points when processing the aerial imagery.
- The collected photos were very big in terms of memory size, about 1 To, and the results had to be delivered at a high resolution. Therefore, the data processing operations were very slow even when using two powerful computers of 128 Gb RAM each. Because of the required resolutions, these operations were implemented many times to find the best filter's parameters and to generate the best results. Individual steps of data processing took 10 continuous days.

ANNEX 2: FLOOD RISK MODELING

BACKGROUND DATA AVAILABILITY

Several studies have already been carried out in urban hydrology in Ouagadougou, establishing the intensity-duration-frequency (IDF) curves. Spatial variability of rainfall can be estimated from radar rainfall measurements made in Ouagadougou in 1992 and 1993, coupled with a network of 17 rain gauges within a 50 km radius of the radar (Kacou, 2014) deployed as part of the MeghaTropiques project. Data are also available from a network of 14 rain gauges in 2016 and 2017 (Bouvier et al., 2017).

Rainfall-flow measurements are available on three experimental urban basins monitored from 1977 to 1979 in the Moro-Naba/Airport sector (Le Barbé, 1982), and on two urban basins monitored from 1992 to 1993 in the Wentemga sector (Lamachère, 1993). These basins, moderately urbanized, nevertheless present high runoff coefficients, due to the low permeability of the unpaved soils, compacted by human activity (Bouvier and Desbordes, 1990). They can still be used as a reference for the calibration of models in urban areas. More recently, three peri-urban basins were monitored from 2016 to 2017 within the framework of AMMA 2050, and made it possible to characterize the contribution of these peripheral zones and, by comparison with measurements on urban basins, the impact of urbanization on runoff.

There is no reliable map of the building or sealing coefficients in Ouagadougou. The reason for this is that the notion of waterproofing is ambiguous, insofar as many surfaces are unpaved (roads, concession yards), but correspond to very low permeability compacted soils. What should be considered as sealed or permeable? The various authors do not necessarily speak of the same objects. Bouvier and Desbordes (1990) find low coefficients (10 to 25%) for traditional housing areas in Ouaga, based on an exhaustive count of paved surfaces. Simulated rainfall runoff measurements showed that unpaved soils were very low in permeability, with lower infiltration intensities after a few minutes of intense rain.

REFERENCE RAINFALLS

Four synthetic reference rainfall events were selected for the study. Three are theoretical double triangle project rainfall events: (i) A frequent rainfall with a 2-year return period, (ii) A rare rainfall with a 10-year return period, and (iii) A very rare rainfall with a 50-year return period. The last rainfall, exceptional, is the historical rainfall of 2009.

The theoretical double triangle rainfall was calculated from the times of concentration of the various sub-catchments of the study area. These times of concentration were estimated between 1 and 3 hours for the largest sub-catchment (Gounghin canal), and between 30 minutes and 1h30 for the other sub-catchments of the territory. Thus, the synthetic project rainfall was constructed using the double triangle method, with a total duration of about 3 hours and an intense period of 1 hour. This makes it possible to model the maximum contribution of all the sub-catchments in terms of peak runoff flow without underestimating the volumes of runoff which also condition the levels of flooding reached in the topographical depressions.

The major flood of recent years (or even decades) is that of 1 September 2009, when the rainfall reached 263 mm locally in less than 12 hours, which according to the reference statistics gives it a return period well in excess of 100 years over 12 hours (cumulative 100 years over 12 hours = 175 mm).

The reconstruction of the hyetogram of the rain between 04h37 and 07h35 according to Traoré 2012 allows to estimate the return period of the rain over different durations:

- 5 min: 25 mm return period between 20 and 50 years
- 15 min: 52 mm return period between 20 and 50 years
- 30 min : 72 mm return period between 20 and 50 years
- 1h : 136.5 mm return period >> 100 years
- 2h : 176 mm return period >> 100 years
- 3h : 178 mm return period >> 100 years

Thus, the data of this rainfall was used to model the effect of a real exceptional rainfall.

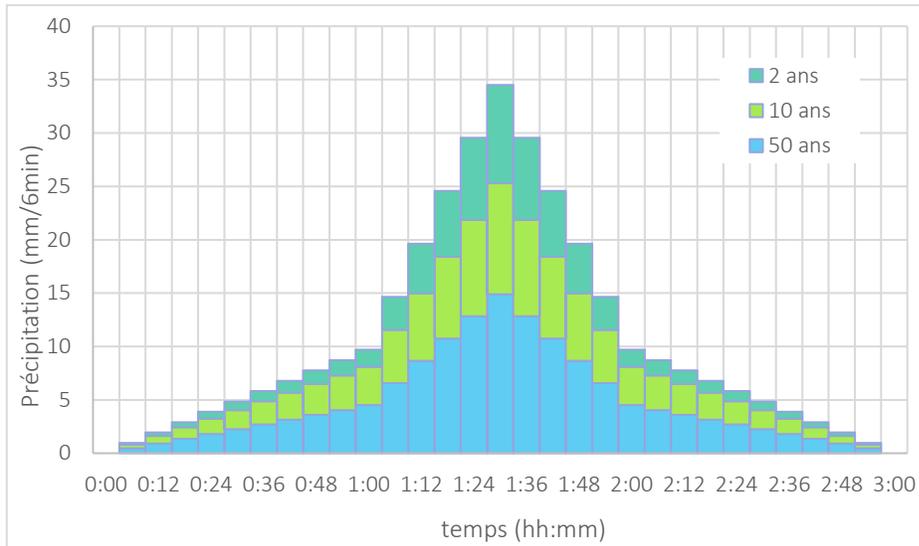


Figure 2.1: Hyetograph of project rainfall

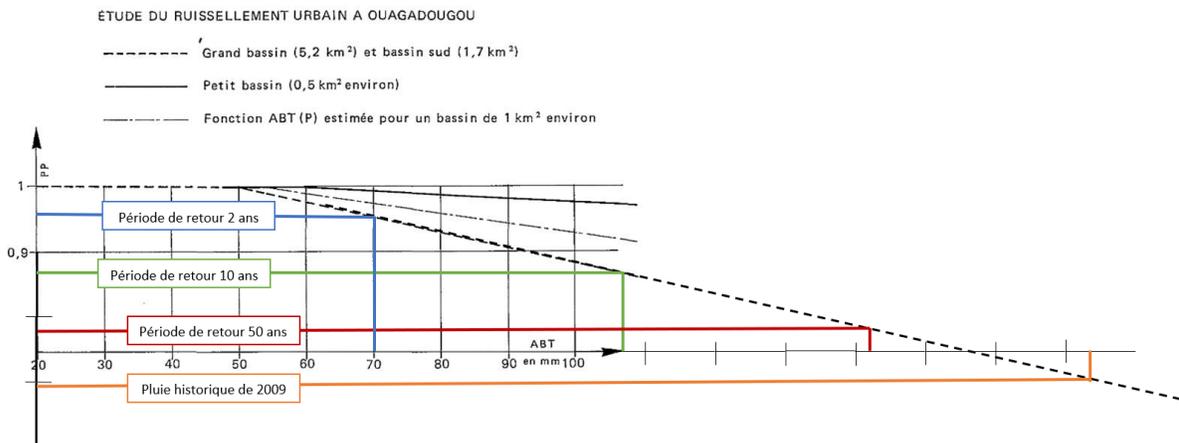
SPATIAL ABATEMENT AND RUNOFF COEFFICIENTS

The various reference rainfall events were applied uniformly to all the catchment areas. Nevertheless, in order to take into account the spatio-temporal distribution of rainfall, a global abatement coefficient was evaluated for each of the four selected rainfall events, allowing for the transformation of point rainfall into surface rainfall.

Le Barbé (1982) proposes spatial attenuation coefficients established in Ouagadougou for daily rainfall. Although the rainfall distributions may have changed compared to the period 1954-1977, the relationships between the distributions of point rainfall and surface rainfall probably remain unchanged.

Assuming that the spatial attenuation coefficients calculated at the daily time step are also applicable to the sub-daily time steps, the values of these coefficients in Ouagadougou were used to calculate the spatial attenuation coefficient. In the absence of abacuses for catchment areas larger than 5 km², this curve was used and extrapolated to calculate the spatial attenuation coefficients for each rainfall.

Figure 2.2: Spatial attenuation coefficient as a function of point rainfall



Source: Le Barbé (1982)

Given the high and relatively dense urbanization of the study area and the fact that unpaved areas have low infiltration, it was considered best to apply runoff coefficients of the order of 0.7-0.8 for rainfall of up to 50 mm. The four project rainfall events have accumulations above 50 mm. Each raw rainfall is reduced by the spatial reduction coefficient, then by the runoff coefficient.

Table 2.1: Description of the four reference rainfalls used in modeling

Rainfall event	2-year return period	10-year return period	50-year return period	2009
Spatial abatement coefficients	0.95	0.87	0.78	0.7
Runoff coefficients	0.7	0.75	0.8	0.8
Total gross accumulation (mm)	70	106	142	173
Total net accumulation (3h)	47	69	89	97
Gross accumulation over the intense period (1h)	54	70	97	/
Net accumulation over the intense period (1h)	36	46	61	/

CONSTRUCTION OF 2D HYDRAULIC MODEL

The modelling approach chosen for this study is a two-dimensional (2D) modelling of flows over the entire study area. The US Army Corps of Engineers' HECRAS 2D software was used to construct the 2D model. This modelling approach allows constructing a single model allowing the representation of all the flooding mechanisms of the sector: urban runoff, runoff in the undeveloped areas, overflow of the canals, blocking of the flows behind the embankments, etc. The results of the model thus allow a detailed understanding of the genesis of the flows, the areas drained by the canals, etc.

The Digital Terrain Model (DTM) was further refined to represent the cross-sectional profile of the canals and thus realistically reproduce their respective real hydraulic capacities. Certain canals are in particular in water all year round, these particularities were also taken into account during the construction of the model in the calculation of the hydraulic capacities. The calculation mesh of the hydraulic model is based on the topography of the terrain from this DTM.

COMPUTATIONAL MESHING

The model was meshed in several stages:

- Producing a first regular mesh (5 to 10 m) of the entire study area. Within each of these meshes, the software reproduces a height-volume law from the sub-mesh topography, calculated on the basis of the DTM with a resolution of 50 cm (there are therefore 400 calculation points per mesh);
- Refining this grid by forcing the boundaries of the grids on the routes of canals, roads, built-up areas and on the route of road and rail infrastructures in embankments. This forcing thus makes it possible to take into account with greater precision these characteristic elements of the territory.

In total, the study perimeter is represented by 680,000 2D calculation meshes structured by 6,000 forcing lines.

CONSIDERATION OF BUILDINGS AND LAND USE

The different land uses in the study area were taken into account in the form of differentiated roughness in the model in order to distinguish between dense and loose built-up areas, vegetation, roads and canals.

Table 2.2: Roughness according to land use

Roughness	Strickler ($m^{1/3} / s$)	Manning
Dense building	10	0.1
Loose building	20	0.05
Vegetation and isolated buildings	7.5	0.133
Watercourses and canals	30	0.033

CONSIDERATION OF PASSAGE STRUCTURES

The main structures present along the canals (scuppers, bridges, nozzles) were identified (42 in total) and were the subject of a land survey. These structures were integrated at full capacity in the model of the reference scenario in order to ensure the hydraulic continuity of the flows on both sides of the crossed infrastructure embankments (road, railroad). However, as some canals are partially filled with water throughout the year, the hydraulic capacity of these structures was adapted locally in order to simulate the effective capacity of these structures in the event of a rainfall event in the study area.

To take into account the risk of jams and floatation entrapment, and the current state of obstruction and deterioration of some of the structures, a specific scenario was also simulated (scenario 2). This scenario assumes that jams completely obstruct the flow section of the structures.

The safety spillway of dam no. 3 is located at the 287 m level. In order to take into account in the models a normal downstream condition at the outlet of the sub-catchment areas, a water level 50 cm below the level of the safety spillway, i.e. 286.5 m, was applied at the three dams for the reference scenario with and without jams.

At the level of Bangr Weogo Park in the north-east of the study area (outside the influence of dam n°3), a normal level was retained as the downstream condition allowing the evaluation of flows outside the model. In order to measure the impact of a high level of the dams (at the end of the rainy season for example) on the drainage of runoff and the overflowing of the canals in the event of a concomitant rainy episode, a specific scenario was developed (scenario 3), with a high downstream condition of the dams. In this scenario, the elevation of the three dams is set at 289.5 m. This level corresponds to the average level of the N3 road overhanging the safety spillway of dam n°3.

POST-PROCESSING OF RESULTS

The raw results of the simulations have been filtered and simplified: (i) Precipitation is applied to the whole territory. In order to improve the visibility of the results, and to see the preferential paths of runoff, a minimum threshold of 3 cm of water height has been set up for the display of the results; and (ii) a filtering of the isolated hazard polygons with a surface of less than 500 m² (average size of a plot in urban area) is applied to concentrate the analysis on the main risk areas. Thus, all polygons smaller than this size are filtered.

CAVEATS

Simplification of the runoff coefficients: The run-off coefficients used in the model have been considered identical over the whole project area, varying only with the rain intensities. In reality, this coefficient is higher in densely urbanized areas than in mildly densified neighborhoods. With the growing urbanization, run-off coefficients would remain high in already developed areas, and would increase in newly developed parts. This impact of urbanization cannot be simulated with the assumption of homogenous coefficients. This simplification was imposed by the absence of reliable data on soils occupation at small scale. The impact of the simplification is also limited by the fact that most of the AOI is already densely occupied, and due to the type of soils, even the non-paved surfaces show a high run-off coefficient. We thus consider that the selected coefficients (0.7-0.8) are on the safe side, and that this simplification does not significantly impact the model's ability to simulate future floods.

Impact of climate change: The design storms used as inputs in the simulations are based on intensity-duration-frequency curves built from past hydrological records, covering a period ranging from 1950 to 2014. The length of the period where meteorological data are available is satisfying with regards to the return periods the model aim at simulating. However, the design storms do not take into consideration the potential impact of climate change, which, as noted earlier, will have an impact on rainfall intensity that is quite difficult to predict in Burkina Faso.

Modeling of hydraulic structures: The hydraulic model is based on a DTM created from data collected during an aerial survey. By definition, such a model includes all hydraulic structures visible from the sky (such as channels) but cannot reflect the presence of underground hydraulic structures (such as pipes and culverts). The main structures observed on site have been manually added to the models, but small-scale culverts, mostly in the upstream parts of the watersheds, are not simulated in the model. This means that in some cases, the maps resulting from the model show flooding where part or all the flow would actually transit under the street through a culvert that is not simulated in the model. However, the impact of this simplification is limited because the culverts that are not implemented in the model are small and quickly overflowed anyway.

Moreover, the DTM produced by the local firm contains several unexpected low points on road surface which appear to be due to error rather than reflect the reality on the ground. Therefore, the flood maps resulting from the hydraulic model based on this DTM indicate several individual small flooded areas (“false positives”). However, despite these localized limitations of the flood model, it is considered able to represent the hydraulic system as a whole (in particular flooding areas caused by an overflow of canals).

Figure 2.3: Origin of a DTM anomaly: local low point in the Digital Surface Model in the area next to Sainte Camille hospital

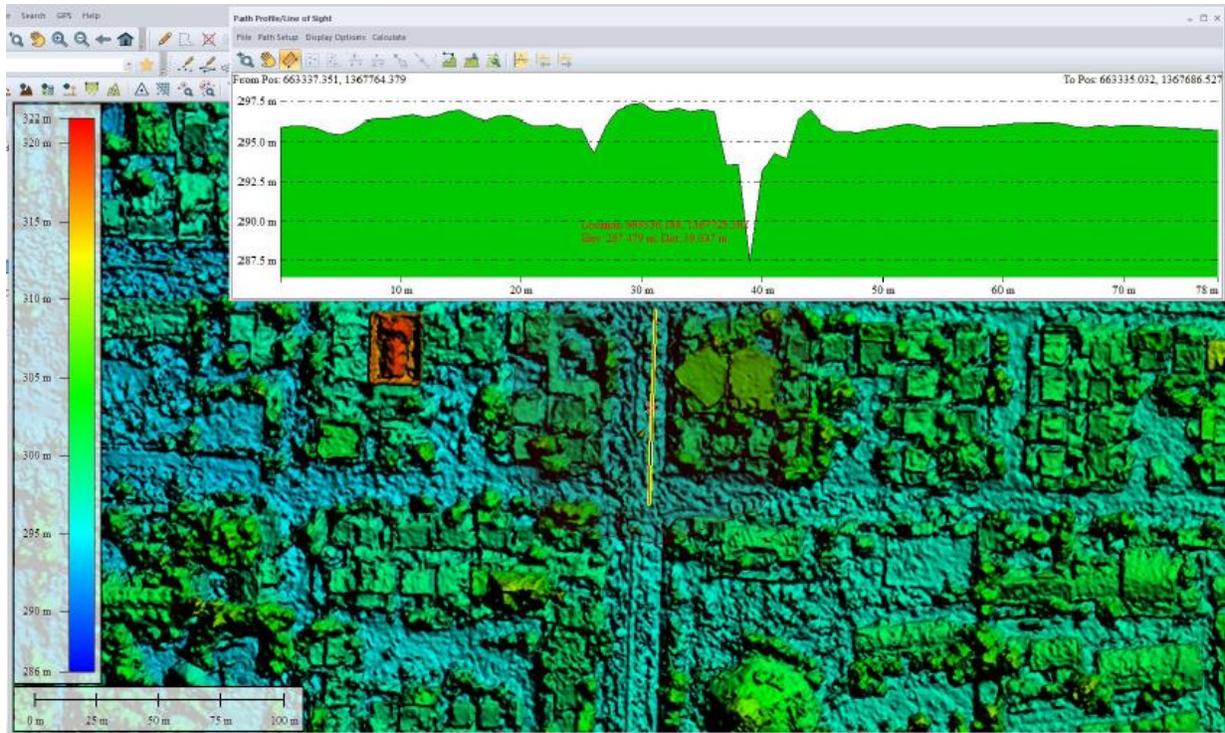


Figure 2.4: DTM anomaly caused by the incorrect low point: 7 m deep “hole” in the road surface

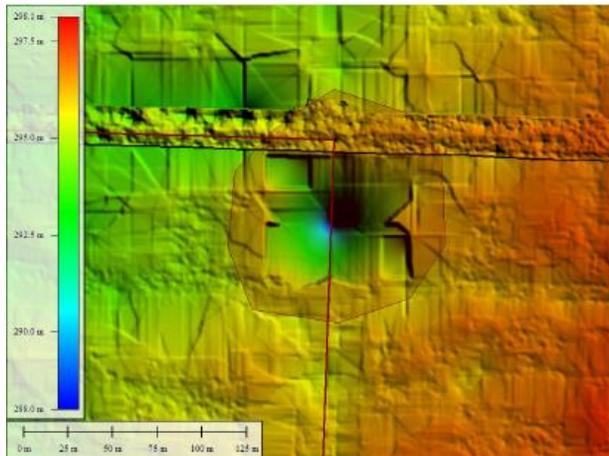
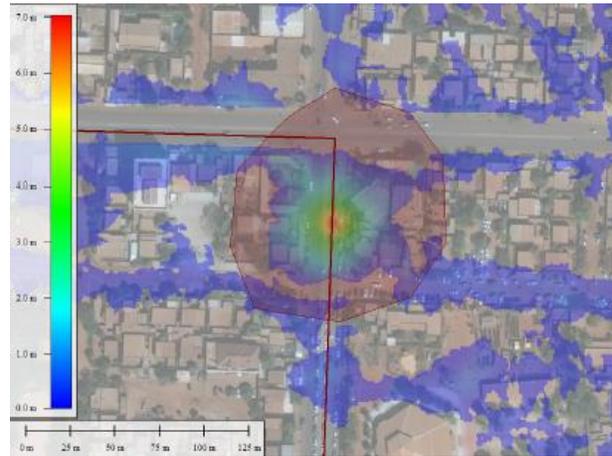


Figure 2.5 Consequence of the DTM anomaly in the hydraulic model: very localized “false positive” flood result



The above points highlight some limitations of the model resulting from low availability of input data. These limits do not fundamentally challenge the results of the hydraulic model.

ANNEX 3: COMPARISON OF FLOOD RISK

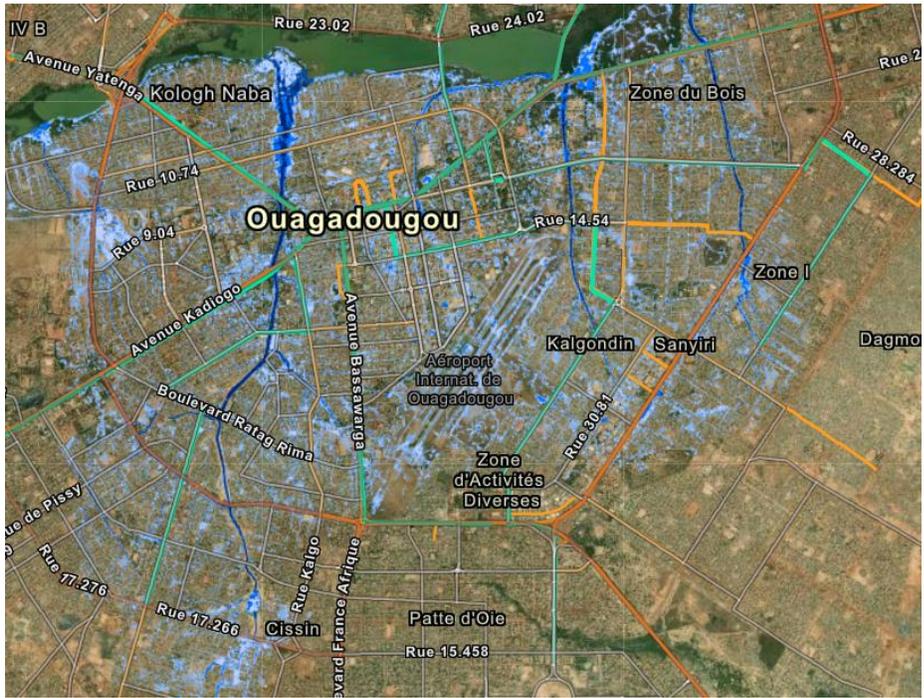


Figure 3.1: 2-year return period, with low water level in dams (Scenario 1)

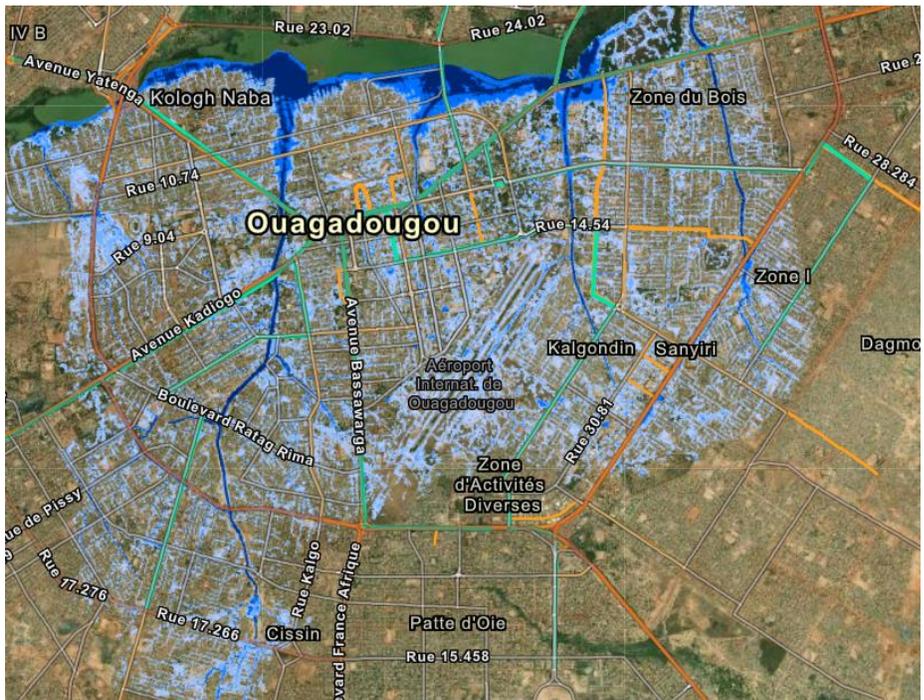
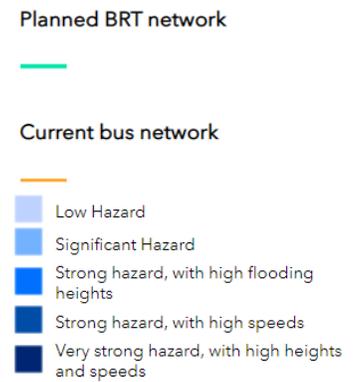


Figure 3.2: 2-year return period, with high water level in dams (Scenario 3)



Source: SEPIA Conseils

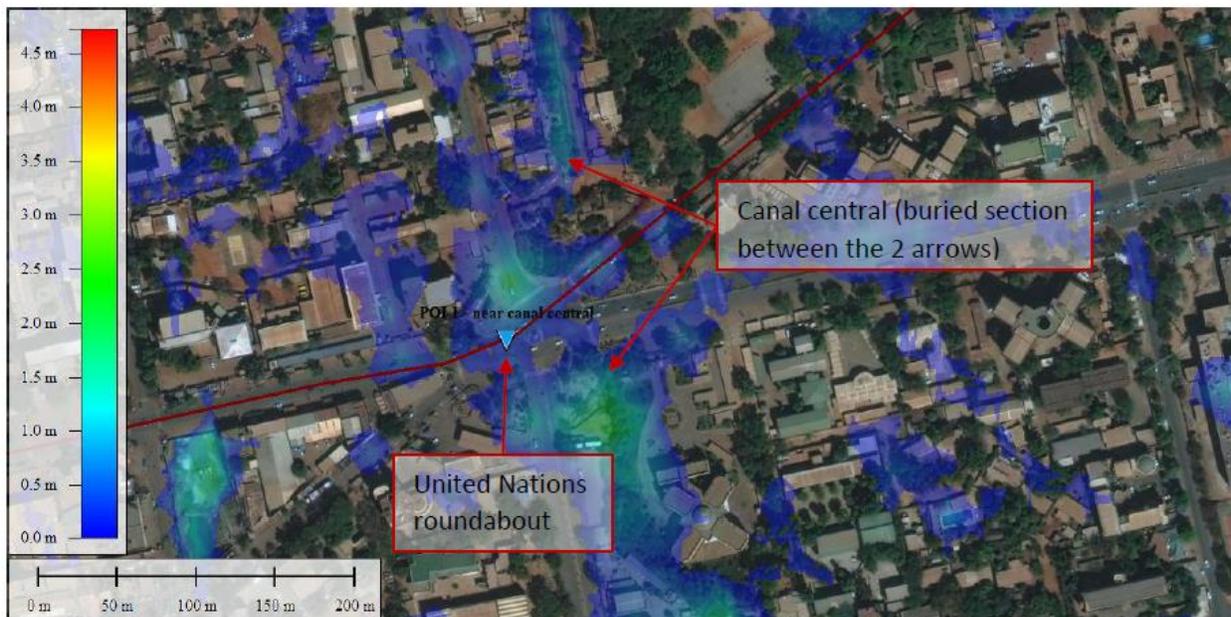
ANNEX 4: IMPACT OF FLOOD HAZARD ON TRAFFIC FLOWS

To better understand the flood events affecting the planned layout of the bus system, it was necessary to analyze the results of the models with more detailed information than the information on peak flows and heights. A set of points was thus selected in the area of interest, representing different flood types, for which hydrographs were generated showing the evolution of water height over time during the 2-year RP flood and the 2009 flood. The analysis of the ramping up and down of water heights associated with rainfall intensities allowed us to characterize the type of flooding associated with various situations and causes.

Point of interest 1

This point of interest (POI) is located on the United Nations roundabout (“rond-point des nations unies”), which is crossed by most bus lines. A few meters east of the roundabout there is a 130m-long section of the canal central, which is buried. The entire area undergoes flooding caused even by 2-year return period storms.

Figure 4.1: Areas flooded by the 2-year return period storm around POI 1

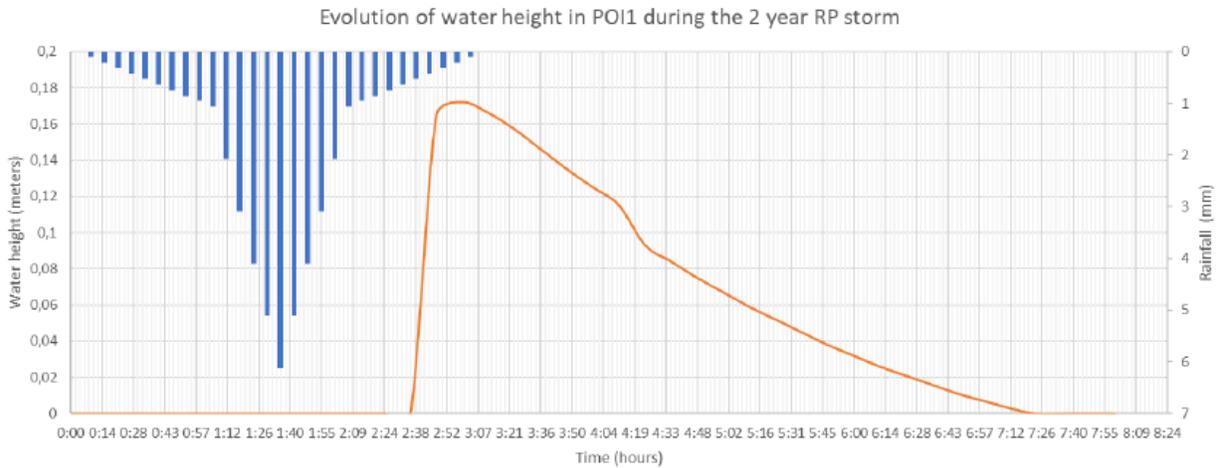


Source: Results from the SEPIA hydraulic model

The profile of the hydrograph, too, confirms what could be inferred from the map: the floods in this point are caused by an overflow of the canal central. Floods appear almost one hour after the peak of rainfall intensities. This duration is in the order of magnitude of the watershed's concentration time. We observe a sudden rise in water level, corresponding to the moment when the canal overflows to the neighboring areas, and then a slow decrease (more than 4 hours to return to normal conditions). It is very likely that this slow decrease is the consequence of the canal central's capacity being reduced in its downstream part, due to obstruction and to the high-water level at the outlet, which both affect the canal's capacity to evacuate water.

Solving floods in this area will involve solutions focusing on improving the hydraulic capacity of the canal central's downstream part, or increasing storage capacities of the upstream areas.

Figure 4.2: Hydrograph in POI 1 under the 2-year RP storm



Source: Results from the SEPIA hydraulic model

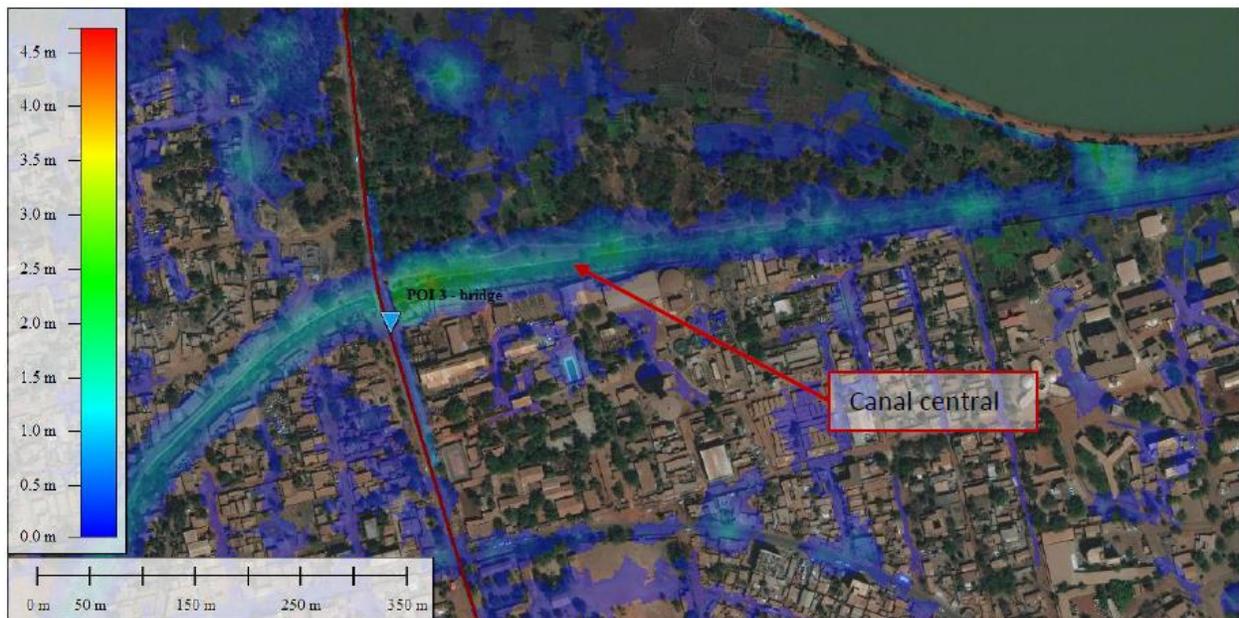
Point of interest 2

This point is located on rue Nongremasson, a few meters south of a bridge over the downstream part of Canal Central. The 2-year RP storm causes the canal to overflow in all its downstream part, where its section is reduced by silt, aquatic plants and market gardening activities. The overflow is important enough for the water to flood perpendicular streets, including Nongremasson street used by line 1, which is flooded on more than 200 meters to the south.

The profile of the hydrograph is very similar to the one in POI 1. This is not surprising since both points are located next to the same canal central, POI 2 being approximately 1500 meters downstream compared to POI 1.

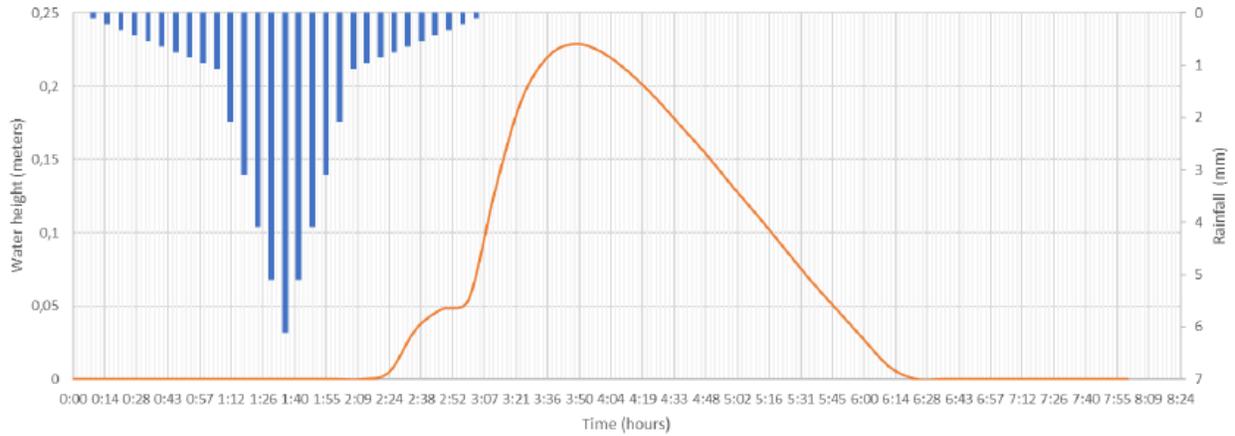
The solutions adapted for these areas are the same as POI 1, improving the hydraulic capacity of the canal central's downstream part, or increasing storage capacities of the upstream areas.

Figure 4.3: Areas flooded by the 2-year return period storm around POI 2



Source: Results from the SEPIA hydraulic model

Figure 4.4: Hydrograph in POI 2 under the 2-year RP storm



Source: Results from the SEPIA hydraulic model

Point of interest 3

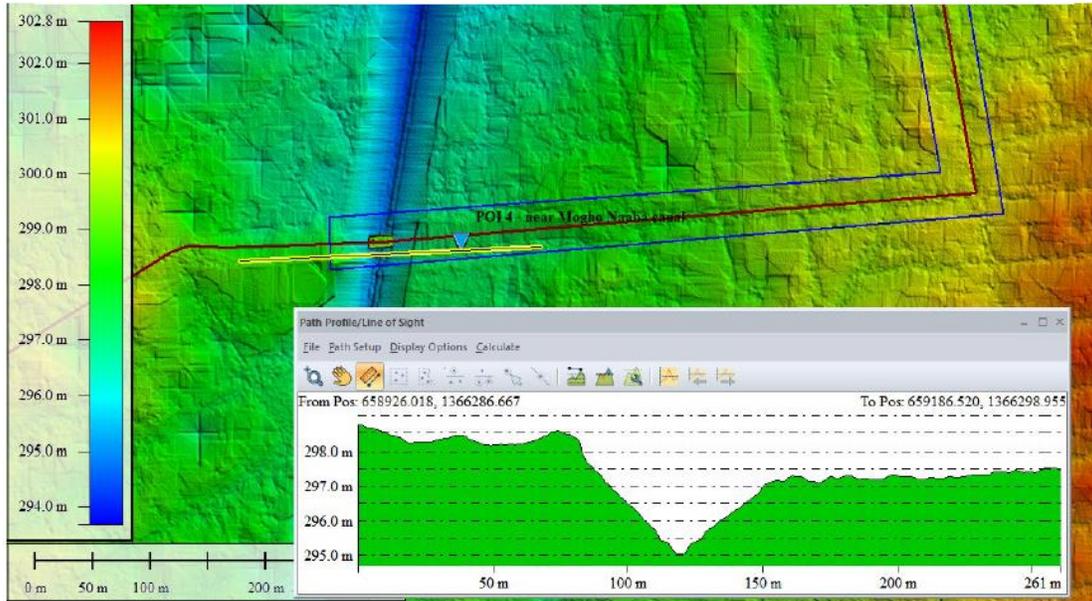
This point is located on Avenue Ouezzin Coulibaly, 60 meters east of the bridge over the Mogho Naaba Canal. This bridge is located 300 meters downstream a reduction of the canal's section, transitioning from a newly constructed portion of 25 m width to an older reach of only 11 meters width. The capacity of this ancient section of canal is clearly insufficient, which causes overflows on the east bank, which in this part is lower than the left side.

Figure 4.5: Areas flooded by the 2-year return period storm around POI 3



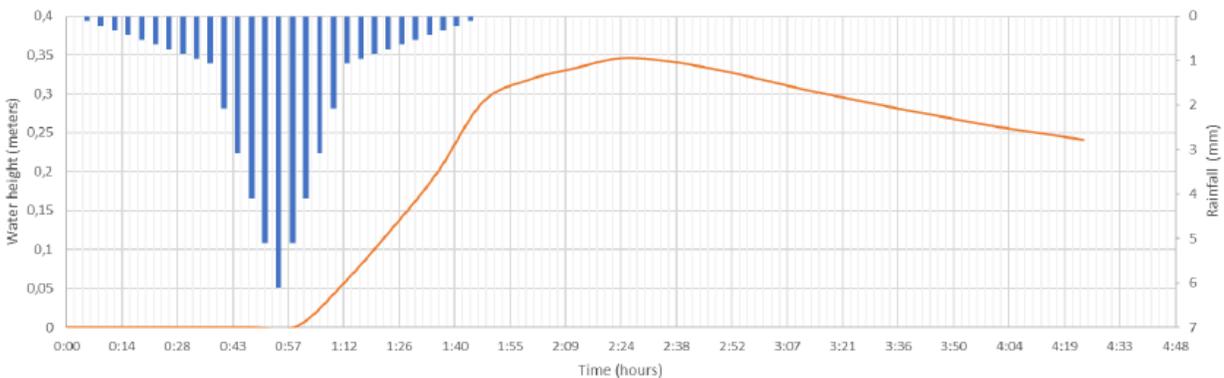
Source: Results from the SEPIA hydraulic model

Figure 4.6: Terrain elevation and cross section of the Mogho Naaba canal and its surroundings near POI 3



Source: Results from the SEPIA DEM/DTM

Figure 4.7: Hydrograph in POI 3 under the 2-year RP storm



Source: Results from the SEPIA hydraulic model

The hydrograph of the 2-year return period storm in POI 3 shows that the water level rises quite slowly, reaching its peak in more than one hour, and takes even longer to get back return to its normal level (more than 4 hours). This hydrograph can be interpreted as follows:

- The ramp up of the flood is relatively slow because the flat area on the east side before the bridge (including René Monory stadium) acts as a flood expansion zone.
- The very slow ramp down is due to the limited capacity of the downstream part of the Mogho Naaba canal, whose section is reduced and outlet in the lake is partially obstructed by silt and market garden activities. This causes large volumes to overflow all along the canal during the peak of the storm, and these volumes take time to be evacuated by the canal when the rain stops.

Solving the flood issues around the Mogho Naaba canal has been studied in detail in Ouagadougou's Drainage Master Plan, which proposed two variants:

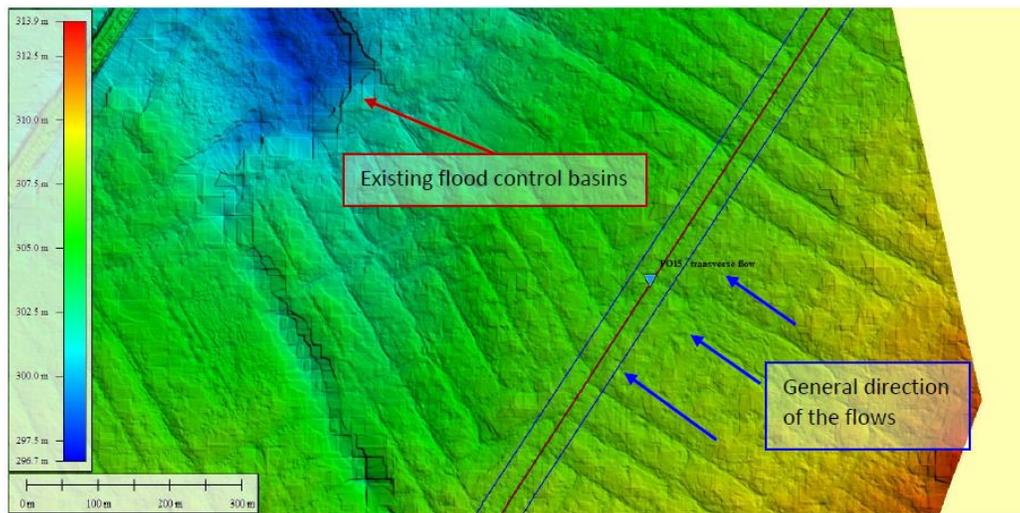
- Enlarging the 3.5km downstream section of the canal from until the lake.
- Building a new flood control basin south of avenue Ouezzin Coulibaly

This second option has been selected by the municipality and is under study. The identified area for the basin being just upstream POI 3, it would fix the flood issue there and thus protect this section of bus line 7.

Point of interest 4

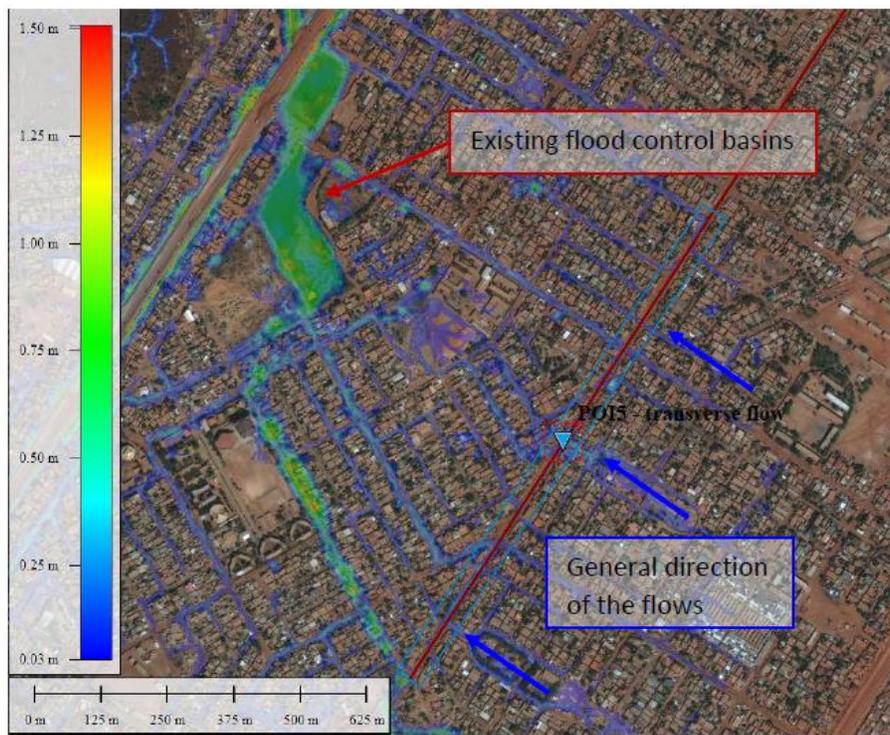
This section is at the very end of future bus line 4, in the upper part of the Wemtenga watershed (the most eastern watershed of our area of interest). The DTM shows that this section of street 28.257 used by future line 4 is perpendicular to the general slopes of the terrain. Two flood control basins exist in the area, but they are located west (downstream) of the 28.257 stream, and thus does not protect this street. Besides, the neighborhood located south-east of the street lacks a drainage network. Therefore, the perpendicular streets act as channels carrying run-of water straight through the surface of 28.257 street.

Figure 4.8: Terrain elevation of the area around POI 4



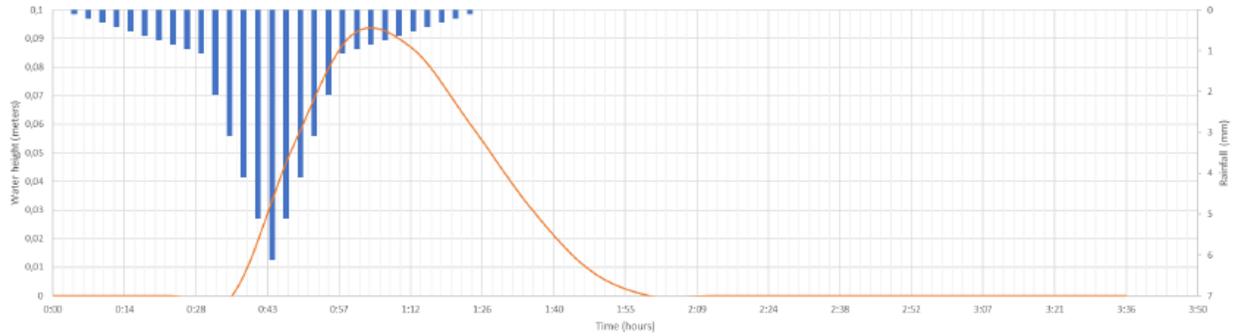
Source: Results from the SEPIA DEM/DTM

Figure 4.9: Areas flooded by the 2-year return period storm around POI 4



Source: Results from the SEPIA hydraulic model

Figure 4.10: Hydrograph in POI 4 under the 2-year RP storm



Source: Results from the SEPIA hydraulic model

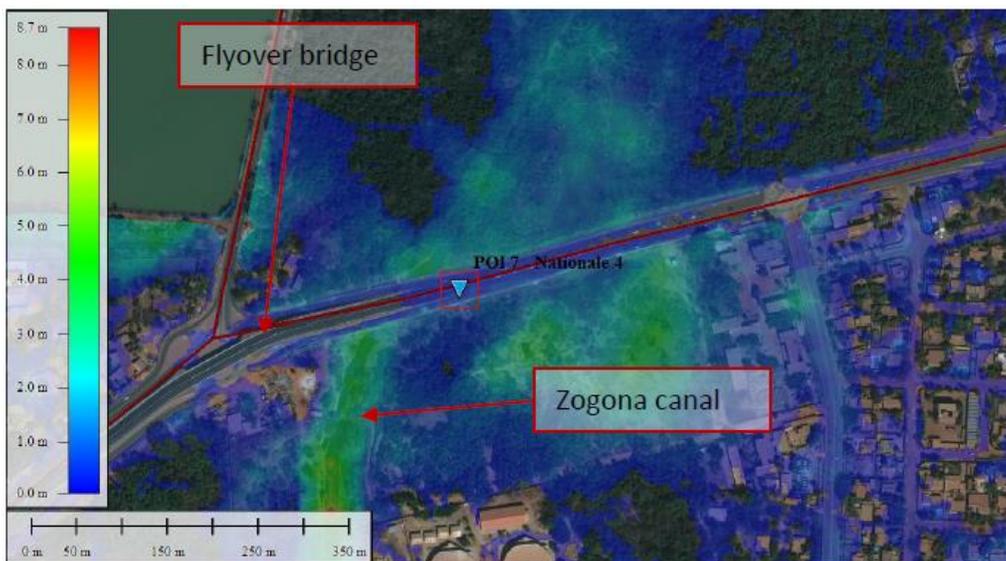
The hydrograph shows that the water height in POI 4 during the 2-year storm follows the same profile as the rainfall intensities, with a short response time and limited flood height. This is due to the fact that the area is very close to the upper part of the watershed: 28.257 street receives the run-off water from a small (a few ha) and short (400 meters) area, thus run-off gets to the street soon after the beginning of the rain and stops soon after its ending.

The obvious solution to fix this type of flooding caused by lack of drainage of lateral streets is to create a proper drainage network in the area to intercept run-off flows from the perpendicular streets and convey them (under the axis to protect) until a natural outlet. In this case, it would mean intercept water from south-east streets and direct them to the downstream basins. An alternate solution (which would not remove the need for a drainage network, but allows for smaller dimensions works), would be to retain as much as possible run-off water in the upstream neighborhood, thus flattening the hydrograph. Here one could imagine implementing permeable pavement in the south-east streets, pocket parks or even a rain garden in the area next to the Saint-Paul church (if available). A newly developed street parallel to the 28.257 street, 700m to the south-east, is not affected by flood risk, and could thus constitute an alternate path for the bus line.

Point of interest 5

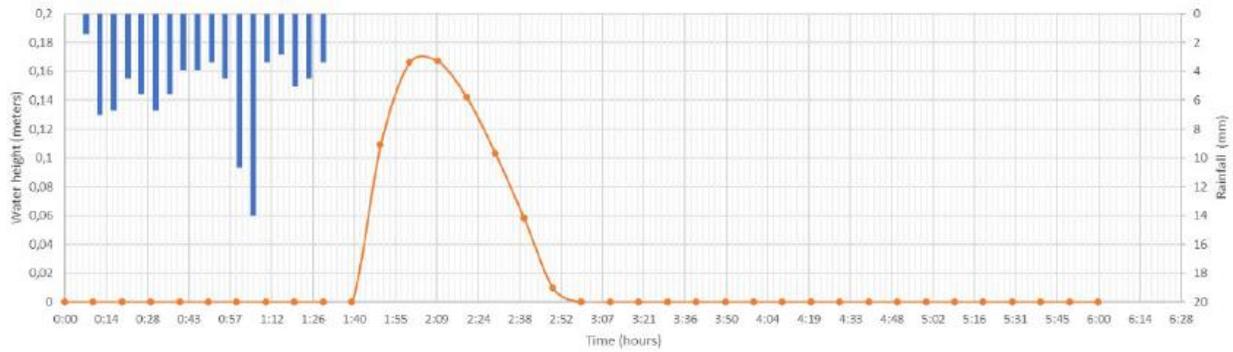
This point is located on a critical axis on the Nationale 4 road to the East of Ouagadougou. It is not affected by 2 and 10 years return period events, but this area was severely flooded during the 2009 flood when the lake overflowed the dam. In 2009, the peak of rainfall intensities lasted about 10 minutes. Flooding over POI 5 area started 40 minutes after the beginning of that peak, and lasted one hour, with a maximal height of flooding of 17cm.

Figure 4.11: Simulation of the maximum water heights caused by the 2009 storm event



Source: Results from the SEPIA hydraulic model

Figure 4.12: Hydrograph in POI 5 under the 2-year RP storm



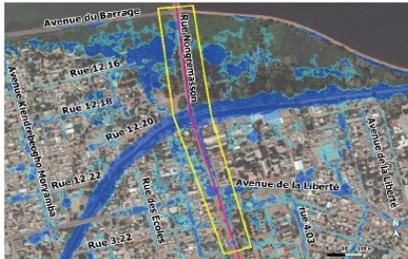
Source: Results from the SEPIA hydraulic model

From the hydrograph and the location map, flooding in POI 5 is caused by overflow from the Zogona canal, and only during the highest intensities (higher than 140mm/hr). When intensities remain lower, the Zogona canal's capacity seems sufficient to evacuate the flow.

In this area, floods can be prevented with solutions focused on the Zogonal canal: increasing its capacity, improving the outlet conditions, or creating retention areas upstream.

Since the flooded section is only 300m long, and does not cross populated areas, it would also be feasible to elevate the road in this section to protect it from floods. However, since a flyover bridge has recently been built just west of the flood-prone area, it seems unlikely that new earthworks will be executed here soon, since it would require to modify the profile of the access ramp to the overpass.

Table 4.1: Exposure of the planned mass transit lines to flood risk: Flood criticality score and Impact of the current flood issues on the planned mass transit system

Map	Bus line affected	Projected BRT traffic (annual no. of passengers in both directions)	Urban issues for transport system (transit area vs catchment area, land use, etc.)	Area priority score (from 1 to 3, 3 meaning that it is crucial to maintain services in this area)	Road/intersection affected (Ave = Avenue, street = St., Blvd = Boulevard)	Assets affected	Overall impact of the 2-year return period rainfall model on the traffic	Overall impact of the 10-year return period rainfall model on the traffic	Description of the flood	Flood criticality score from 1 to 4, depending on the flood depth and duration. Areas where field observations do not confirm flooding issues (probable local errors of the DTM) are marked 0.	Impact of the current flood issues on the projected BRT system (area priority multiplied by flood criticality, marked on 4 points)	Picture/map of the flood
Zoom 1	Line 1	5 662 500	Mostly a residential area. However, Line 1 is crucial because it allows reaching a semi-private Medical centre on the north side of the lake which provides a good level of service and is frequented. The city plans to build an alternative path in a few years.	2	Nongremasson St.	<ul style="list-style-type: none"> Multiple road sections between Ave du Barrage and Ave du Capitaine Thomas Sankara Bridge (over the Nation Unies canal) 	Blocked traffic	Blocked traffic	<p>Overflow of the canal central, causing floods in the adjacent areas and perpendicular streets, such as Nongremasson St.</p> <p>South of the bridge, the road is lower than the local terrain, which favours flooding from the canal to go through the road.</p> <p>Limited flood height (17cm with the 2 year storm but slow decrease).</p> <p>North of the bridge, the road is higher than terrain, and no flood from the canal has been observed.</p>	3	2	 Zoom1_Line1_Nongremasson St
	Line 2 & Line 3	5 231 250	Mostly a residential area. Close to the University Hospital. Line 2 is important because it serves the bus depot (north of the Bangr Weogo park)	2	<p>Intersection of Nongremasson St. & Ave du Capitaine Thomas Sankara</p> <p>Ave du Capitaine Thomas Sankara</p>	<ul style="list-style-type: none"> Intersection 0,021 km of road <p>Multiple road sections between Nongremasson St. and the interchange with N3 & N4 highways</p>	Blocked traffic	Blocked traffic	<p>According to the DTM, the intersection is located 50cm lower than the surrounding streets, which creates a basin where ponds form. Field data does not confirm this result. DTM error suspected.</p> <p>The DTM shows local low points on the road, which creates basins where ponds form. Field data does not confirm this result. DTM error suspected.</p>	0	0	 Zoom1_Line2_3
Zoom 2	Line 4	5 506 893	Unpaved road. This section is at the end of Line 4, hence the impact of a flood on transit would be limited.	1	28.257 St.	<p>3 sections between 25.150 St. and 29.100 St. (line 4 terminus)</p> <p>10 sections between 25.150 St. and 29.100 St. (line 4 terminus)</p>	Blocked traffic	Blocked traffic	<p>This road is flooded due to run off from the perpendicular streets in the south-east, which act as canals and convey water to the north-west. This area is located at the top end of the watershed, with relatively high slopes, and the perpendicular streets lack proper drainage. As a result, all run-off from these streets spills on the 28,257 St. The flood has limited depth and lasts approximately one hour during the 2-year storm.</p>	1	0,5	 Zoom2_Line4

Zoom 3	Line 5	3 534 566	Close to the city centre. Important to connect this area to the city centre	2	<p>Ave Houari Boumedienne</p> <p>Place de la femme pour la Paix roundabout</p> <p>14.54 St.</p>	<ul style="list-style-type: none"> Roundabout Multiple road sections on the west and east of the roundabout Place de la femme pour la Paix 	Blocked traffic	Blocked traffic	<p>The DTM shows local low points on the road, which create basins where ponds form.</p> <p>Field data does not confirm this result. DTM error suspected.</p>	0	0	
				2	14.09 St.	Multiple road sections affected between 14.54 St. and the roundabout joining Av des Arts, Av Babanguida & 14.09 St.	Blocked traffic	Blocked traffic	<p>This section is flooded by run-off coming from the streets to the east. The general slope of the terrain in this area is east to west, and lack of tertiary drainage causes surface run-off to flow over the roads and spill on the 14.09 street.</p> <p>Flood depth reaches 15-20cm with the 2 year storm. Due to the flood mechanism, flood is expected to be limited in time. Longitudinal channels exist along 14.09St, but drainage of the transverse streets is missing.</p>	2	1,5	 <p>Zoom3_Line5_14-09</p>
				2	Roundabout joining Ave des Arts, Ave Babanguida & 14.09 St.	Roundabout	Blocked traffic	Blocked traffic	Same causes as street 14,09 above, but flood depth beyond 30cm	3	2	
			2	Ave des Arts (= Ave Babanguida)	Multiple sections between the crossing with Université canal and the roundabout joining Av des Arts, Av Babanguida & 14.09 St.	Blocked traffic	Blocked traffic	3		2		

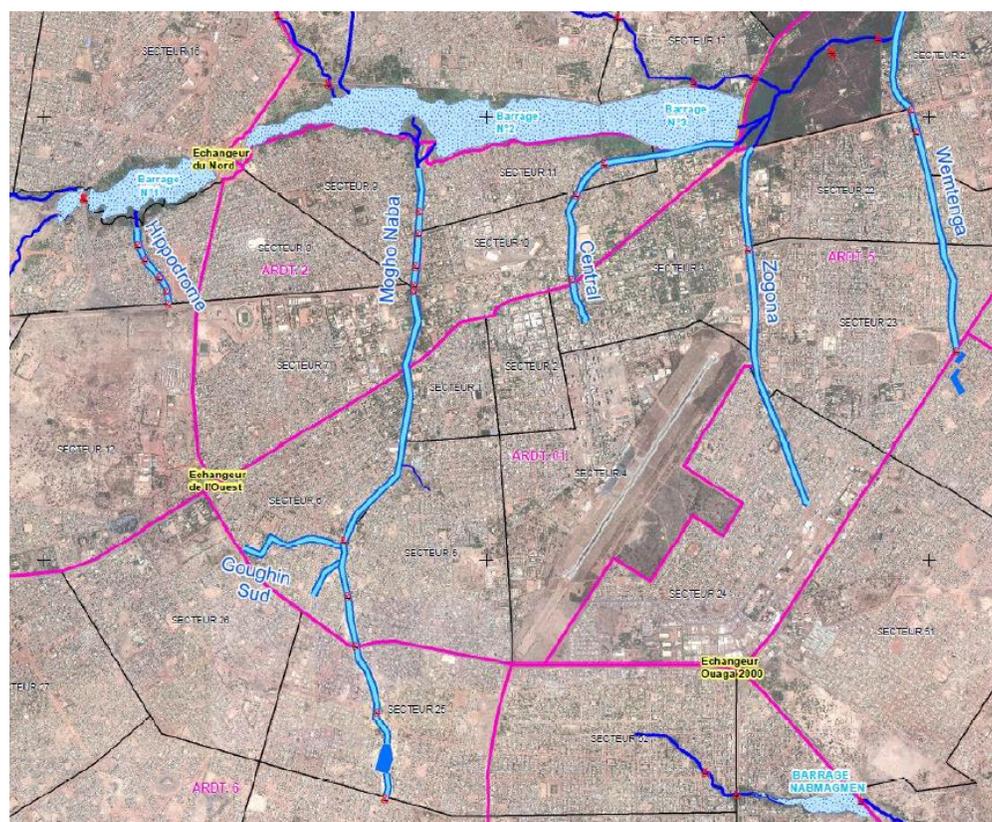
Map	Bus line affected	Projected BRT traffic (annual no. of passengers in both directions)	Urban issues for transport system (transit area vs catchment area, land use, etc.)	Area priority score (from 1 to 3, 3 meaning that it is crucial to maintain services in this area)	Road/intersection affected (Ave = Avenue, street = St., Blvd = Boulevard)	Assets affected	Overall impact of the 2-year return period rainfall model on the traffic	Overall impact of the 10-year return period rainfall model on the traffic	Description of the flood	Flood criticality score - from 1 to 4, depending on the flood depth and duration. Areas where field observations do not confirm flooding issues (probable local errors of the DTM) are marked 0.	Impact of the current flood issues on the projected BRT system (area priority multiplied by flood criticality, marked on 4 points)	Picture/map of the flood
Zoom 4	Line 5	3 534 566	Mostly a residential area. This section serves the end of Line 5, which can be reached from the city centre using the itinerary of Line 6.	1	Ave des Arts	Multiple road sections affected between the crossing with Université canal and 15.22 St.	Blocked traffic	Blocked traffic	The direction of this section follows the general direction of the slopes. This street thus acts as a canal collecting surface run-off from neighbouring areas, and conducting it to the Zogona canal below. The hydraulic model shows flood depths over 40cm, on a long section of road, and for an extended duration. However field reconnaissance shows the presence of drainage channels on both sides of the road, in good conditions, which have not been taken into account in the hydraulic model. We suspect the actuals floods are much more limited, if any.	1	0,5	 Zoom4_Line5
Zoom 5	Line 7 and Line 8	9 247 244	Commercial and residential area (shops and market next to the road, private facilities, stores, banks). Line 8 serves the national road N1 towards Bobo-Dioulasso	3	Ave Oumarou Kanazoe and Ave Kadiogo	Roundabout de la Bataille du Rail - Interchange joining Ave Kadiogo & Ave Oumarou Kanazoe	Blocked traffic	Blocked traffic	Avenue Oumarou Kanazoe is perpendicular to the direction of the slopes and receives surface run-off from the streets to the east. The results of the model indicate that there is no clear path for water coming to the Avenue Kanazoe to the Mogho Naaba canal, which increases floods on the avenue, and thus on the roundabout (place de la bataille du rail). Flood depth reaches 30cm.	3	3	 Zoom5_Line7_8_Kanazoe_Kadiogo_Coulibaly
	Line 7	3 891 303	Serves residential areas. Line 7 is the least important line of the BRT system for transit and accessibility.	1	Ave Oumarou Kanazoe	Multiple road sections between Ave Ouezzin Coulibaly and the interchange joining Ave Kadiogo & Ave Oumarou Kanazoe	Blocked traffic	Blocked traffic		3	1	
					Intersection of Ave Ouezzin Coulibaly & Ave Oumarou Kanazoe	Intersection	Blocked traffic	Blocked traffic		3	1	
					Ave Ouezzin Coulibaly	Multiple road sections affected between 7.01 St. And the intersection joining Ave Ouezzin Coulibaly & Ave Oumarou Kanazoe	Blocked traffic	Blocked traffic	Same as above	3	1	

Map	Bus line affected	Projected BRT traffic (annual no. of passengers in both directions)	Urban issues for transport system (transit area vs catchement area, land use, etc.)	Area priority score (from 1 to 3, 3 meaning that it is crucial to maintain services in this area)	Road/intersection affected (Ave = Avenue, street = St., Blvd = Boulevard)	Assets affected	Overall impact of the 2-year return period rainfall model on the traffic	Overall impact of the 10-year return period rainfall model on the traffic	Description of the flood	Flood criticality score from 1 to 4, depending on the flood depth and duration. Areas where field observations do not confirm flooding issues (probable local errors of the DTM) are marked 0.	Impact of the current flood issues on the projected BRT system (area priority multiplied by flood criticality, marked on 4 points)	Picture/map of the flood
Zoom 5	Line 7	3 891 303	Same as above	1	Ave Ouezzin Coulibaly	<ul style="list-style-type: none"> • Bridge (over the Gounghin canal) • Road section affected on the east of the canal 	Blocked traffic	Blocked traffic	<p>Overflow from the Mogho Naaba canal causes floods on the adjacent areas. The capacity of the canal is insufficient to evacuate peak flows caused by storms with return periods of 2 years and higher. Reasons for this include:</p> <ul style="list-style-type: none"> - degradations of the canal itself - obstruction by silt and waste under bridges/culvert - obstructed outlet at the lake <p>Flood depth over 35cm, and with a very slow decrease.</p>	4	1,5	
			Same as above	1	Simon Compaoré St.	Multiple road sections between Ave Ouezzin Coulibaly and Gounghin St.	Blocked traffic	Blocked traffic	<p>Floods in those neighborhoods crossed by line 7 are caused by a lack of tertiary drainage system. Flood depth is limited.</p>	1	0,5	

Zoom 7	Line 4	5 506 893	Serves Charles de Gaulle hospital. Close to several government buildings. Close to the city centre. This section is important for connecting Line 4 to the other BRT lines	2	Ave de l'Indépendance	Multiple sections between Ave du Capitaine Thomas Sankara and Ave Général Bila Zagré	Blocked traffic	Blocked traffic	The DTM shows local low points on the road, creating basins where ponds form. Field data does not confirm this result. DTM error suspected.	1	0,5	 <p>Zoom7_Line4</p>
					Intersection of Ave de l'Indépendance & Ave Général Bila Zagré	Intersection	Blocked traffic	Blocked traffic	Field reconnaissance shows the road is in good condition, with no low points or holes, and existing drainage. The existing channels are in good structural condition, but are partially filled with silt, waste and vegetation in some places.	1	0,5	
					Blvd Charles De Gaulle	Multiple sections east of the intersection between Ave du Burkina & Blvd Charles De Gaulle	Blocked traffic	Blocked traffic	Talks with local residents have confirmed limited water stagnation during heavy rains near the intersection with Ave Sankara.	1	0,5	
	Section shared by most lines	16 400 643	City centre Administrative district. Central market, schools, public services, embassies, military camps. Ave Nelson Mandela is the main east-west axis.	3	Ave du Capitaine Thomas Sankara	Multiple road sections between Nongremasson St. and Ave Kwame Nkrumah	Blocked traffic	Blocked traffic	The DTM shows local low points on the road, which creates basins where ponds form. The area next to Lycée Philippe Zinda Kaboré seems to be a general low point lacking proper drainage to an outlet.	0	0	 <p>Zoom7_All_sections</p>
					Nation Unies roundabout	Roundabout	Blocked traffic	Blocked traffic	A few meters east of the roundabout is a 130m long buried section of the canal central. Flooding of the roundabout is caused by overflow of the canal, which with 2 year return period storms and higher. This is caused by insufficient capacity of the canal central.	4	4	
					Ave Nelson Mandela	0,039 km of road section between Nation Unies roundabout and Ave Yennenga	Blocked traffic	Blocked traffic	Flood depth over 40cm, and takes several hours to decrease.	4	4	
	Line 5	3,534,566	City centre, serves Ouaga 2000	2	Ave Houari Boumedienne	Multiple road sections between the roundabout Place de la Femme pour la paix and Ave du Général Sangoulé Lamizana	Blocked traffic	Blocked traffic	These streets intercepts water coming from the upper parts of the watershed (to the south and west) and lack proper drainage. The profile of Ave Boumedienne shows a low point near its crossing with Ave de l'UEMOA and Rue du PNUD, which aggravates flooding.	2	1,5	
					Ave de la Grande Mosquée	Multiple road sections between Ave Houari Boumedienne and Ave de la Nation	Blocked traffic	Blocked traffic		2	1,5	

ANNEX 5: IDENTIFYING SOLUTIONS TO ADDRESS FLOOD RISK

Figure 5.1. Canals crossing the area of interest



Source: AGEIM (2020)

Table 5.1. Reference of the unit costs considered to estimate the investments and maintenance costs of the proposed flood resilience and adaptation measures

Bioswales	<p>Construction: A Better City (ABC). (2015). Enhancing Resilience in Boston, A Guide for Large Buildings and Institutions. February.</p> <p>Maintenance: Osouli, Abdolreza & Akhavan Bloorchian, Azadeh & Grinter, Mark & Alborzi, Aneseh & Marlow, Scott & Ahiablame, Laurent & Zhou, Jianpeng. (2017). Performance and Cost Perspective in Selecting BMPs for Linear Projects. Water. 9. 302. 10.3390/w9050302.</p>
Cleaning of the reservoir lakes north of the area study	SCET Tunisie and AGEIM. (2019). Drainage Master Plan of Ouagadougou.
Communication plan based on mobile technologies	Orange. (2019). Le SMS, nouveau Commerciale votre entreprise en 2019.
Permeable pavements	<p>Construction: Ellwood, N. (2012). "A Detailed Look at Costs Associated with Green Stormwater Controls." Proceedings from Water Environment Federa on Stormwater Symposium.</p> <p>Maintenance: WisDOT Southeast Region. (2012). Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost, Prepared by CTC & Associates LLC WisDOT Research & Library Unit, January 13.</p>
Rain Garden	Construction: Malaviya, P. et el. (2019). Rain Gardens as Storm Water Management Tool. Estimated cost of rain garden in Greece to be "less than 50E per m2".
Reinforcement of the solid waste collection system	Purchase and installation of concrete baskets; and construction of concrete garbage collection points: Drainage Project of Louis Berger in Douala, Cameroun Organization of awareness raising campaigns: Projects of RESALLIENCE and Louis Berger

Retention basins	Installation & maintenance: The IGNITION Project. (2020). Nature-based Solutions to the Climate Emergency: The benefits to businesses and societies. June. Installation: SCET Tunisie and AGEIM. (2019). Drainage Master Plan of Ouagadougou.
Tree planting	o Street trees: Installation: Project of Louis Berger in Cameroon Installation & maintenance: The IGNITION Project. (2020). Nature-based Solutions to the Climate Emergency: The benefits to businesses and societies. June. o Stormwater retention trees (or SuDS-enabled street trees): Installation & maintenance: Charles River Watershed Association, Low Impact Best Management Practice (BMP) Information Sheet www.charlesriver.org
Urban parks and green spaces	Maintenance: The IGNITION Project. (2020). Nature-based Solutions to the Climate Emergency: The benefits to businesses and societies. June.
Wetland creation or restoration	Construction & maintenance: Charles River Watershed Association. (2008). Low Impact Best Management Practice (BMP) Information Sheet: Constructed Stormwater Wetlands, August.

Box 1: Illustrations of terminology

The following terms are used to characterize hydraulic structures, whether existing or projected:

Culverts: buried structures, either circular (pipe culverts – “buses” in French) or rectangular (box culverts – “dalots” in French), whose function is to ensure hydraulic transparency of a road by channeling water under the road surface. They are also referred to as transverse/cross-section structures.

Canals: large open conduits conveying water in the surface. They form the primary drainage network, collecting water from secondary structures and channeling it to the natural outlet, which in the area of interest are the reservoir lakes and the Kadiogo river north of the AOI. In Ouagadougou, existing canals are generally formed by large trapezoidal section concrete structures, but some undeveloped parts still exist with earth bottom and sides. Their dimensions range from a few meters wide to 20m wide in the area of interest, which includes 4 main canals, one per watershed.

Channels: they form the secondary and tertiary drainage network. They are typically rectangular section concrete structures, with dimensions ranging from 50 cm to a few meters wide. Channels are generally used to collect rainwater along the road surface. When playing this function of longitudinal drainage, they are generally called “caniveaux” in French (open rectangular street gutters). Larger channels collecting water from several smaller one and leading to a canal may be called “collecteurs”. In this report, both types will be referred to as channels, since they are represented by similar rectangular concrete structures. In Ouagadougou, longitudinal channels are often partially covered with concrete slabs.



Box culverts in the AOI



A typical canal in the AOI



A typical open channel in the AOI

Table 5.2. Long list of solutions

Nr.	Name	Short description	Solution type	Advantages	Disadvantages	Implementation scale	Adaptability to Ouagadougou	Situations for which the solution is adapted
1	Preserving flood expansion areas	Enforce interdictions to build in the right of way of the primary network (rivers, main channels, reservoirs, lakes) and within a few meters along the channels. Preserve non-urbanized areas along the channels that can be used as flood expansion areas. Since unoccupied spaces will quickly be filled with informal constructions, these areas should be used to build public spaces such as floodable sports facilities, pedestrian paths/health trails, socialization spaces.	Soft, Grey & Green	<ul style="list-style-type: none"> Reinforce the urban rules and land uses plan Allow the densification along the BRT outline, and create spaces Do not create empty spaces or corridors Protect inhabitants and users from floods and the lack of facilities accesses 	<ul style="list-style-type: none"> Might take time to implement Entailed demolition of existing houses or informal settlements 	Street level	Medium - there are not many available areas suitable for flood expansion in the area of interest	This solution has similarities with the construction of water retention basins. However, it offers less impact on flood control, but is easier to implement and has more co-benefits;
2	Construction of an embankment for the road platform for the bus routes	Construction of an embankment allowing the road to be placed higher than the water level of floods, with a longitudinal and transversal drainage system to ensure the hydraulic transparency of the system.	Grey	<ul style="list-style-type: none"> Strong protection of the bus lanes 	<ul style="list-style-type: none"> Disruption of the urban fabric and cross-cutting movements Makes access difficult Protects bus lanes but not their surroundings High cost 	Street level	High - standard civil engineering, applicable everywhere.	This solution should be reserved for very particular cases where no other solution is practical and where the impact on the surroundings will be limited. Example: in a low point / basin where drainage is not practical, and over a limited length to avoid the "barrier effect".
3	Bio-swales (vegetated swales, bioretention swales)	Bioswales are vegetated, shallow, landscaped depressions designed to capture, treat, and infiltrate stormwater runoff convey stormwater at a slow, controlled rate, and the flood-tolerant vegetation and soil act as a filter medium, cleaning runoff and allowing infiltration. Bioswales are an effective type of green infrastructure facility in slowing runoff velocity and cleansing water while recharging the underlying groundwater table. Bioswales are generally installed within or near paved areas (e.g. parking lots, roads and sidewalks).	Green	<ul style="list-style-type: none"> Ease of design Cost effective, sustainable, and environment friendly solution Reduces flow velocities and filters and cleanses water naturally Beautifies surrounding landscape 	<ul style="list-style-type: none"> They may be a potential source of odor and mosquitoes if water is left stagnant. May require irrigation to maintain vegetation They cannot be used on in areas with steep slopes. 	<ul style="list-style-type: none"> Street level Neighborhood level 	Medium - requires available space. Best suited in regions where rainfall is regular over the year. Can be adapted by using local species.	Bioswales can be widely applied and are particularly useful along streets or in parking lots where they can redirect water from the curbside. Bioswales have flexible siting requirements, allowing them to be integrated with medians, cul-de-sacs, bulb-outs, and other public space or traffic calming strategies.
4	Construction of new drainage works in poorly drained areas	Development of natural primary drains in flood-prone areas. Construction of secondary network when missing.	Grey	<ul style="list-style-type: none"> Solving local flooding problems Securing the infrastructure Improving accessibility in all seasons 	<ul style="list-style-type: none"> High cost : long linear length of new works may be necessary to connect the new networks to an acceptable outlet Disturbances to 	<ul style="list-style-type: none"> Street level Neighborhood level 	High - standard civil engineering, applicable everywhere.	Adapted in flood-prone areas (neighborhoods with no drainage system or in an embryonic stage). In particular, the outlying districts.

					road traffic during construction works			
5	Permeable pavements/ porous asphalt system	Precipitation falling on the surface of the structure (and possibly other surfaces) is directly infiltrated by a permeable pavement and percolates to the underlying granular structure. These structures increase the time delay of run-off, and favor infiltration capacities. Porous concrete, asphalt, or interlocking pavers allow water to percolate through their surfaces to be treated and stored in soils and rock beds below. Some applications have demonstrated a 90% reduction in run-off volumes.	Green	<ul style="list-style-type: none"> • Ease of design • Effective to improve drainage of the run-off from road surfaces • Once installation costs are factored, it can cost as much as 50 % less than conventional pavement systems, and can be cheaper in the long run to maintain • Permeable pavements can help reduce the concentration of some pollutants 	<ul style="list-style-type: none"> • Cost 	<ul style="list-style-type: none"> • Street level • Neighbor hood level 	Medium – Porous pavement is more sensitive to lack of routine maintenance than standard pavement. Might be an issue in developing countries where maintenance is often overlooked.	Can be used in most situations. At small scale (on a street, portion of street), effective to improve drainage of the run-off from road surfaces, but offers little protection against flows coming from outside the right-of-way. At large scale, a large number of streets equipped with porous pavement will act as a water retention basin and contribute to reducing peak flows.
6	Rain gardens	Vegetated land depressions designed to detain and treat stormwater runoff. The runoff is filtered through densely planted surface vegetation and then percolated through a prescribed filter media (soil layers). Unlike bioretention swales, they do not convey stormwater runoff.	Green	<ul style="list-style-type: none"> • Flexible layout to fit into landscape • Cost effective, sustainable, and environment friendly solution • Beautifies surrounding landscape • Detains and cleans stormwater runoff 	<ul style="list-style-type: none"> • They may be a potential source of odor and mosquitoes if water is left stagnant. • May require irrigation to maintain vegetation • They cannot be used in areas with steep slopes. 	<ul style="list-style-type: none"> • Street level • Neighbor hood level 	Medium - grass areas are best suited in regions where rainfall is regular over the year. Can be adapted by using local species.	Rain gardens can be installed in various scales and shapes: in planter boxes or integrated with streetscapes. They can also act as 'standalone' soil filtration systems within residential areas, parklands, schools, car parks and other developments.
7	Planting trees	Trees provide a natural stormwater management system by intercepting precipitation in their leaves and branches. Many cities have set tree canopy goals to restore some of the benefits of trees that were lost when the areas were developed. A mature deciduous tree can capture as much as 700 gallons of rain a year, while a mature evergreen can absorb up to 4,000 gallons annually.	Green	<ul style="list-style-type: none"> • Reduce slow stormwater runoff • Beautifies the city • Purifies the air • Create shade 	None	<ul style="list-style-type: none"> • Street level • Neighbor hood level 	High – no issue to grow local tree species, which are already numerous in the city.	Trees can be planted strategically throughout the city. Homeowners, businesses, and community groups can participate in planting and maintaining trees throughout the urban environment.
8	Green roofs	Green roofs are covered with growing media and vegetation that enable rainfall infiltration and evapotranspiration of stored water. Rooftop vegetation enables rainfall infiltration and evapotranspiration of stored water, which helps slow stormwater runoff by reducing the rate at which water reaches the drainage system.	Green	<ul style="list-style-type: none"> • Reduce slow stormwater runoff • Beautifies the city • Purifies the air • Insulates the building • Increases lifespan of the roofing 	<ul style="list-style-type: none"> • Underlying structure may have to be strengthened to cope with the extra load • Requires extra maintenance 	<ul style="list-style-type: none"> • Street level • Neighbor hood level 	Low - Low compatibility with the standard architecture in Ouagadougou.	Green roofs can be retrofitted onto existing buildings and can be located strategically in buildings located in highly exposed flooding sections of the road as well as bus stations and bus stops (e.g.

		Green roofs can retain on average 75 % of the stormwater they receive.			Higher cost than traditional roof			this was done in Holland in the cities of Wageningen and Utrecht)
9	Hybrid infrastructure	Hybrid embankments or small levees covered by vegetation (plants, communal gardens) along the canals, sidewalks and public spaces (rows of seats), with porous pavement along the embankments	Green & Grey	<ul style="list-style-type: none"> • Combine grey and green approaches to maximize water absorption and infiltration in the long term • Ease of design • Improve quality of life • Limited costs 	<ul style="list-style-type: none"> • Requires lands and organization of uses of public spaces 	<ul style="list-style-type: none"> • Street level • Neighborhood level 	Medium - grass areas are best suited in regions where rainfall is regular over the year. Can be adapted by using local species.	Adapted to slightly increase flood protection along primary channels, with limited costs, and environmental and wellbeing co-benefits
10	Awareness raising on waste management (education in local neighborhoods, in conjunction with the city council and a crisis unit per neighborhood)	Development of an awareness campaign (e.g. awareness day) tackling waste management and participative clean-up of canals in informal settlements (94% of the city), and neighborhoods along the BRT line will help recover the full drainage capacity of the infrastructures. To include civil society and local stakeholders in the management of the resilient infrastructures.	Soft	<ul style="list-style-type: none"> • Easy to implement • Contribute to the maintenance of infrastructures • Include the civil society and makes people more accountable • Low cost 	<ul style="list-style-type: none"> • Only effective in the long term • Requires the coordination of several actors and the organization of local committees /neighborhoods 	Neighborhood level	High – no specific constraints	To maximize the positive impact on flood reduction, this action should target areas generating significant quantities of solid waste likely to end up in the drainage system: markets, areas missing formal waste collection systems, and informal settlements. Should be combined with improvements of the collection system, as awareness raising will have a limited impact on littering if the inhabitants are not provided with more suitable alternatives to evacuate waste.
11	Changes in the use of dams downstream of the study area	The urban dams of Ouagadougou are no longer essential for the water supply of the city's inhabitants. It is thus possible to consider reorienting their function towards flood prevention:- Preventive emptying before heavy rainfall, so that it does not coincide with a high lake filling level;- Integration of sluice gates;- Lowering of overflow weirs;	Soft & Grey	<ul style="list-style-type: none"> • Reduce the risk of the lakes overflowing to the area of interest • improve the outlet condition of the primary channels which emerge into the lakes. 	<ul style="list-style-type: none"> • change of approach in the management of the lakes • requires institutional arrangements 	Areas close to the lakes	High — The dams are not necessary anymore for drinking water supply. The only issue is cost.	This solution is relevant to improve the protection of the areas located next to the reservoir lakes against rare to exceptional storms (similar to the 2009 storm which caused the lakes to overflow).
12	Cleaning of the reservoir lakes north of the area study	The basins of dams No. 1, 2 and 3 have silted up as a result of solid deposits and the height filled by silt has been determined at 1.5m, 2m and 1.5m respectively. This situation considerably reduces the retention capacity of these basins (estimate of 3,9M of m3	Green	<ul style="list-style-type: none"> • Significantly increase the efficiency of the previous solution. 	<ul style="list-style-type: none"> • High one-time cost for the cleaning works • Requires complete emptying of the dams 	Areas close to the lakes	High — Only cost is an issue.	This solution is relevant if combined with the previous one. It would allow further reduction of water height in the reservoir lakes, and thus improve flow conditions in the downstream parts of the

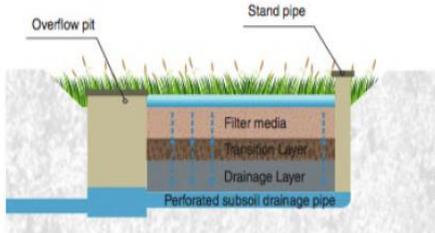
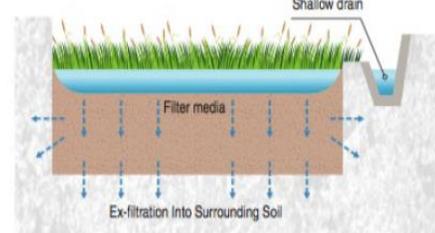
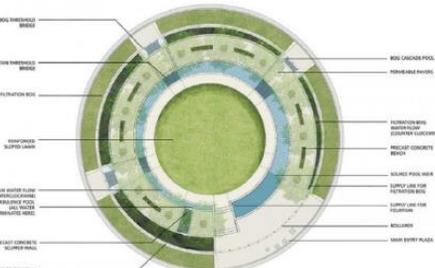
		corresponding to the quantities of silt). Cleaning this silt would thus increase the storage capacity of the lakes and reduce the risk of overflow towards upstream areas.						primary channels. To improve its efficiency, it should be combined with long-term efforts to reduce the quantities of silt and waste getting to the lakes.
13	Improvement of existing hydraulic structures & construction of dykes to prevent overflow onto the road	Creation of elevated lanes on both sides of the main collectors; Widening of certain sections of collectors; Widening of crossing structures on the main collectors	Grey	Waterproofing of tracks and securing of surrounding infrastructure	<ul style="list-style-type: none"> • Cost (higher than maintenance or repairs) • Technical complexity • Requires acquisition of new land, and potential expropriations 	Watershed level	High — already implemented in Ouagadougou	Suited along primary drains already developed into lined canals: Mogho Naaba Canal, Zogona Canal, Wemtenga Canal. For example, some sections of the Mogho-Naaba canal are smaller than upstream sections, causing a constriction which increases flooding risks.
14	Construction of new flood retention basins / flood control areas	Flood control areas are filled during storms and progressively emptied after the storm, thus reducing the peak flows and limiting floods downstream. They can take the form of concrete retention basins, natural flood expansion areas or multiple-uses flood control areas.	Grey & Green	<ul style="list-style-type: none"> • Positive impact on flood protection in all downstream areas • Reduces the need for new works downstream • Different types available: from concrete retention basin for maximum flood reduction, to full natural area or shared uses area to foster co-benefits. 	<ul style="list-style-type: none"> • Requires significant land • Significant construction and maintenance costs 	Watershed level	High – already exists in Ouagadougou	When land is available upstream of a catchment basin, this solution offers great opportunities to reduce floods in all the downstream areas. A suitable 10 hectares area was identified along the Mogho Naaba canal in the 2020 Drainage Master Plan.
15	Maintenance / improvement of existing water retention basins	Cleaning of existing retention basins; Equipping existing basins with water level control devices	Grey & Green	<ul style="list-style-type: none"> • same advantages as new basins • possibility to modify existing basins to allow for shared uses (park, urban agriculture) 	Less disadvantages than creating a new basin: does not require new land (but may require some evictions if areas of the retentions basins are illegally occupied)	Watershed level	High – already exists in Ouagadougou	Restoring the hydraulic capacity of existing water retention areas has one of the best cost/efficiency ratios. Of course, it is limited to watersheds where flood control area already exist. Two such basins exist upstream of the Wemtenga canal. They are partially filled with silt, and should be cleaned and refurbished.
16	Repairs of existing canals and clearing of invaded structures	Rehabilitation or reconstruction of degraded sections to restore their hydraulic capacities, including restoration of natural systems of flow and vegetation.	Grey & Green	Rapid solution for potentially severe flood issues in localized areas	<ul style="list-style-type: none"> • Sometimes requires evictions of activities illegally established in the right of way of 	Watershed level	High – already exists in Ouagadougou	Well suited in areas where flooding of the road is caused by damages to the neighboring hydraulic structures.

					the hydraulic structures • Cost			
17	Reinforcement of the solid waste collection system	The most effective way to reduce the filling of hydraulic structures by solid waste is to act on the source of waste, either through awareness-raising activities, but mostly by ensuring an efficient collection system is in place: street litter bins, collecting trucks, landfill / incineration sites.	Soft	<ul style="list-style-type: none"> • Co-benefits on pollution reduction, water quality and quality of life • Reduces the need for cleaning actions 	Needs actions on a large scale, since a structure can be affected by waste coming from upstream areas.	<ul style="list-style-type: none"> • Watershed level • City level 	High — the current solid waste system is insufficient, but access to proper waste collection system is a growing concern concerning African major cities.	Improvement in flood protection is a secondary effect of an efficient waste collection system, which should be implemented for health reasons first. Should be combined with awareness raising measures.
18	Restoration and creation of green urban spaces (e.g. linear parks, pocket parks)	Park spaces offer a wealth of pervious surface that can be used to absorb rainwater and runoff from adjacent developed landscapes. Green urban parks can act as a sponge to absorb excess stormwater. Green spaces design that may also be considered includes: linear parks to create green areas along the watercourses through riverbank naturalization to dampen flood peaks and bring green space; and pocket parks which represent small public parks (generally occupying less than one acre of land) and can be sited strategically to revitalize unused land.	Green	<ul style="list-style-type: none"> • Opportunistic solution, often sited on whatever land is available • Increases interception and storage capacity of stormwater in urban spaces, reducing pressures in the urban drainage system • Contribute to social and human wellbeing 	Requires land	<ul style="list-style-type: none"> • Street level • Neighborhood level • City level 	Medium - in Ouagadougou such green urban spaces will be relevant only in areas where water is available nearby.	In Ouagadougou there is potential to restore the ecological integrity and retention capacity of the urban Parc Bangr, experiencing increased environmental pressures. Linear parks are strategically built along the river/canal banks to assist in the preservation and conservation of stream beds. Pocket parks are opportunistic, often sited on whatever land is available, and might be constructed to revitalize unused or underused land (e.g. decommissioned railroad tracks).
19	Flood monitoring and disaster prevention system	Pre-disaster action plan (timeline) that aims to prevent damage and allow public transport to resume operation at an early stage. The actions should be triggered depending on the information provided by a flood monitoring tool (considering current and predicted rainfall and water level in the rivers)	Soft	<ul style="list-style-type: none"> • Low cost • Can be rapidly implemented 	Requires the collaboration and coordination of public authorities, private companies, and inhabitants	City level	High - can be applied anywhere.	This measures does not reduce the flooding risk, but aims at being better prepared when extreme floods occur.
20	Wetland restoration or creation	The use of wetlands for stormwater management is widely adopted in many urban areas. The wetland needs to be restored or constructed such that system hydraulic efficiency is optimized, healthy vegetation is sustained and a balance of ecosystem maintained. In Ouagadougou, the Complexe du Parc Urbain Bāngr – Weoogo et du lac des trois barrages has been designated as Wetland of	Green	<ul style="list-style-type: none"> • Filters and cleanses water naturally • Encourages habitat creation and promotes biodiversity • Beautifies landscapes • Detains and cleans stormwater runoff 	Requires lands and organization of uses of public spaces	City level	Low - the areas where this solution would be applicable (such as the Bangr Weogo park) are outside of the Area of Interest.	In Ouagadougou, the Complexe du Parc Urbain Bāngr – Weoogo et du lac des trois barrages has been designated as Wetland of International Importance (Ramsar Site no. 2367) is suffering from increased degradation and restoration efforts combined with

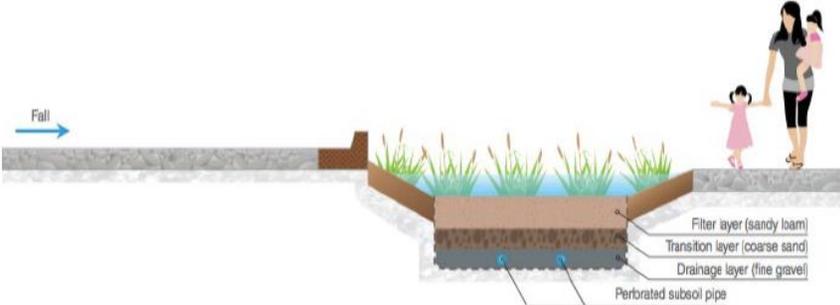
		International Importance (Ramsar Site no. 2367).						integrated nature-based solutions could greatly enhance the stormwater infiltration capacities of this important urban wetland. The site, located in the heart of Ouagadougou, covers 945 hectares including two linked areas: the Bāngr – Weoogo Urban Park, and the three reservoirs and dams of the city.
21	Develop a risk awareness culture in the bus system management company (SOTRACO, future mass transit system)	Although protection measures will be implemented, the residual flood risk should be taken into account in the management of the bus operating company. Risk awareness includes measures such as: - Develop a pre-disaster action plan - Develop a business continuity plan, identifying the sections of the lines that should be maintained in case of extreme storms, - Develop a communication plan to inform users based on mobile technologies (SMS)	Soft	• Cost-effective solution to reduce flooding impacts on bus operation • Allows users to adapt • Can be used to signal other disruptions	• Does not reduce flood risks • May take time to implement a functional system • Requires coordination between institutional stakeholders, bus operating company and network operators at the city level	City level	Medium — mobile technologies are well adopted in Burkina Faso (90% of the population and 75% of women) — similar solutions were implemented in Nairobi, for example	Suppressing all natural hazards would require unlimited resources. Any infrastructure is designed to be protected against a given level of risk, associated with a return period, and is not protected against more severe events. The idea of this solution is to accept that this residual risk will cause disruptions to the bus service and plan measures to limit the impact of these disruptions. One can imagine that network operators would send such notification messages to all mobile phones connected to the antennas of the city, or of specific areas. This solution doesn't solve any problem, but avoid users waiting in vain for a bus that will not come due to a flood in another part of the city.
22	Maintenance of existing structures (canals, culverts) whose current capacity is reduced	Develop institutional arrangements to plan periodic and systematic cleaning and maintenance works (before the rainy season).	Soft	• Low cost • Ease of execution	Efforts need to be maintained in the long term in order to keep their efficiency	City level	High - can be applied anywhere.	This measure provides an immediate improvement of flood protection in the areas where floods are caused or aggravated by obstruction of the hydraulic structures with silt and waste.

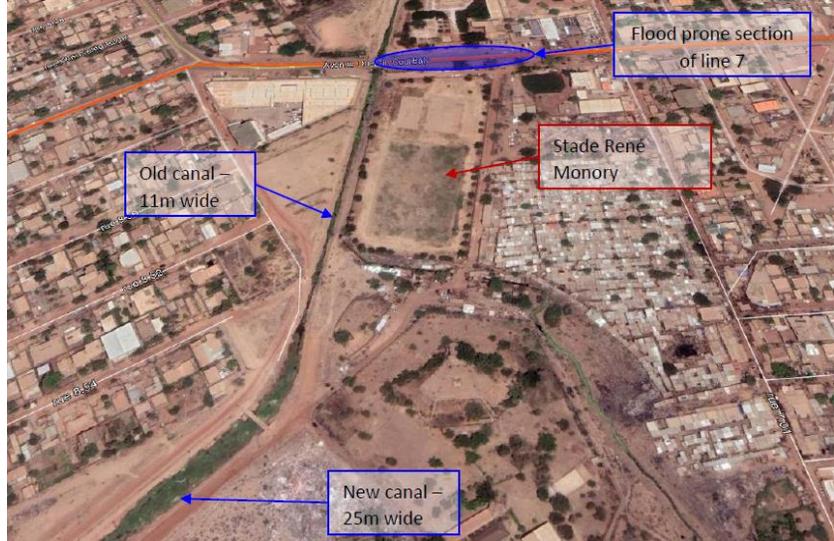
23	Implement regulations on construction projects	Enforce regulations aiming at limiting water run-off generated by new constructions. A simple way is to impose a limit on the flow a newly developed area can discharge to the drainage network (e.g. in France it is 3l/s/ha max for the 10 year return period rain). This engages developers to integrate stormwater management in their design and implement solutions to reduce flows sent to the network.	Soft	<ul style="list-style-type: none"> • No cost for the city • Reduction of peak flows arriving to the drainage network → reduces the need for grey infrastructure 	<ul style="list-style-type: none"> • Additional constraints and costs for project developers → acceptability issues • Applies only to new constructions → takes time to have a significant impact 	City level	Medium - efficiency of this measure would depend of the ability of the municipality to enforce it and make sure that new development projects meet the new requirements.	As a first step, such regulations could be applied only to construction projects by companies and real estate developers. It would limit aggravation of soils impermeabilization, by imposing alternative techniques such as porous pavement in parking lots or bio-swales.
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Table 5.4: Explanations and sketches of some of the proposed measures

Technical solution	Relevance	Description	Depiction	
Rain gardens and pockets parks	Included in measures 7 (protecting future Line 4), 9 (Line 5), 13 (Line 7) and 17 (protecting the road section in city center shared by most lines)	Rain gardens are proposed as water retention solutions in several measures (i.e. 7, 9, 13 and 17). The open space situated in the land of the Mogho Naaba Palace would be suitable to install a rain garden. However, the Mogho Naaba being the monarch of Wogodogo (Ouagadougou), one of the Mossi Kingdoms located in present-day Burkina Faso, there may be some cultural barriers and land ownership issues related to the installation of a rain garden in this area. Therefore, we propose instead to install a pocket park to green this space, which will require less design and construction works. It is worth noting that the rain garden and pocket parks should be designed to include resilient and endemic species.	<p><i>Typical cross-section of a conventional rain garden</i></p>  <p><i>Typical cross-section of a soak away rain garden</i></p>  <p><i>Roundabout rain garden</i></p> 	

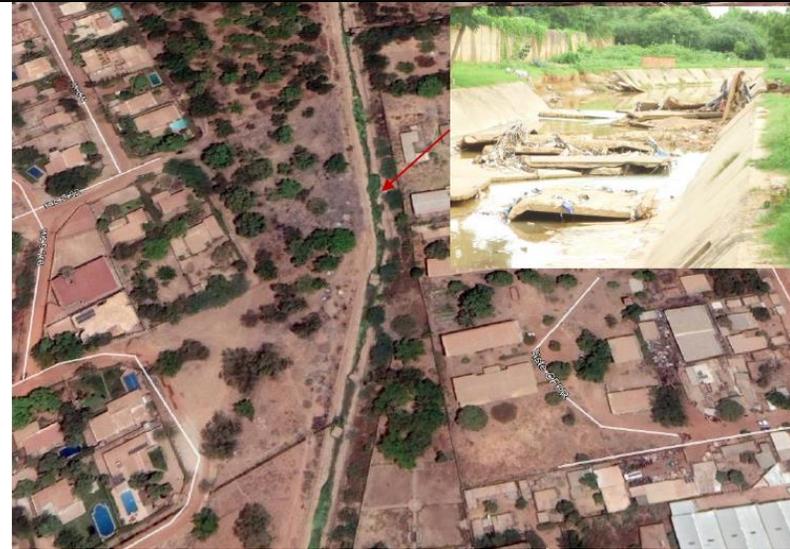
Sources: *Top sketches:* Public Utilities Board (PUB) Singapore (2018); *Bottom left sketch:* © Hoerr Schaudt. <https://nl.urbangreenbluegrids.com/projects/normals-uptown-water-circle-waterrotonde-in-normal-illinois-us/> *Bottom right sketch:* Sfbetterstreets.org. www.sfbetterstreets.org/find-project-types/greening-and-stormwater-management/stormwater-overview/bioretenion-rain-gardens/

<p>Install a bioswale in the median of the road on Ave Kwame Nkrumah and Ave de l'UMOA (that are large and have a descending slope)</p>	<p>Measure 2 (protecting the section in the city centre shared by most future mass transit lines)</p>		 <p>Source: Public Utilities Board (PUB) Singapore (2018)</p>
<p>Put in place a temporary diversion through Avenue de la Liberté and Avenue du Barrage if Nongremasson St. is blocked</p>	<p>Measure 4 (protecting future Line 1)</p>	<p>The itinerary of the proposed temporary diversion is shown in the sketch on the right. Ave de la Liberté and Avenue du Barrage appears unimpacted by the 2-year RP storm event (scenario 1). Although, it seems that Avenue du Barrage could be flooded (the area next to the lake), the road is elevated and therefore unimpacted.</p>	
<p>Rehabilitation of upstream part of the Canal central and development of its downstream part</p>	<p>Measure 1 (protecting future Line 1 in Nongremasson St and the section shared by most lines in the city centre)</p>	<p>The first 1.8km of the canal are built in concrete and in good structural condition, but needs cleaning since its bed is partially obstructed with waste and vegetation. The downstream part of the canal (after the crossing with line 1 of the bus on Nongremasson street) is in earth, with variable sizes, and is largely filled with silt, with the presence of vegetation and solid waste of all kinds. On this downstream section, the canal behaves like a "dustbin" due to the discharges of the riparian populations directly into the canal and market gardening in the vicinity of the canal.</p> <p>The obstruction of the downstream part of the canal causes water level to be permanently high in this section of the canal. This water is used for gardening activities on the shores of the canal. It should be noted that the canal</p>	 <p>Canal central (Avenue de la liberté bridge) Canal central (Nongremasson street bridge)</p>

		<p>receives wastewater from nearby buildings, thus posing health concerns. The current condition of the canal central, especially its downstream part, causes frequent floods during the rainy seasons, including in the upper part of the canal, up to the bridge of Nongremasson street used by line 1 of the planned bus system. This situation is clearly identified in Ouagadougou's Drainage Master Plan, which recommends the following measure (page 150): "To remedy this situation, we propose to convert the existing earthen section (Reach No. 3) until the RN3 road crossing structure into a trapezoidal concrete channel. A canal 14m wide at the base and 19.4m wide at the top and 1.8m high is proposed. The development of the downstream section of the central canal will make it possible to eliminate the flooding of the 10-year return period. In addition, it is necessary to plan cleaning and rehabilitation work on the existing concrete reaches."</p>	 <p>Downstream section of Canal Central Culvert at the end of canal central – fully obstructed</p> <p>The cost of cleaning / rehabilitation of existing concrete sections has been estimated at US\$100,000 in the Drainage Master Plan. The construction cost for developing the downstream part into a concrete canal (19.4 m wide and 1.8 m deep) is estimated at US\$2,031 per meter for a length of 1,480 meters, resulting in a total construction cost of US\$3,005,319.</p>
<p>Construction of a new flood retention basin along the Mogho Naaba canal</p>	<p>Measure 16 (protecting future Line 7)</p>	<p>The upper part of the Mogho Naaba canal (upstream from its crossing with avenue Quezzin Coulibaly, and until its beginning next to Lycée Universalis) has been recently developed, with the construction of a flood control basin near its beginning, and a new trapezoidal concrete canal 10 to 25m wide. This newly developed part is connected to an older section of the canal which is only 10.5m wide. This very significant narrowing of the section causes a rise in the water line and overflows in the vicinity of the canal and the districts drained towards Mogho Naaba. Flooded areas include a section of the Quezzin Coulibaly Avenue, where line 7 of the bus system crosses the canal.</p> <p>Two possible solutions have been proposed in the Ouagadougou Drainage Master Plan to solve these floods caused by overflow of the Moogho Naaba canal:</p> <ul style="list-style-type: none"> - Rebuild and enlarge the downstream part of the canal - Create a new flood control basin 	 <p>Limit between the newly constructed canal (upstream), and the old existing part (downstream)</p>

The second option has been selected by the municipality of Ouagadougou. It consists in the construction of a new flood control basin of 10ha on the east bank south of Avenue Ouezzin Coulibaly. With a depth of 4.7m, this basin would offer a 410 000m³ storage capacity, enough to prevent overflow of the downstream part of the canal against a 10-year return period storm. This solution also includes construction of 120m of new concrete canal in the downstream part of the canal, to reach the lake, and rehabilitation of the damaged section of canal between Avenue Ouezzin Coulibaly and Avenue Kadiogo.

Being located just upstream of the flood-prone area on future bus line 7, this flood control basin designed to avoid floods during storms up to the 10-year return period would thus be enough to protect the targeted area of the mass infrastructure system on line 7. This is a minor part of the benefits that this basin would bring since its main impact would be to reduce floods in the downstream part of the canal.

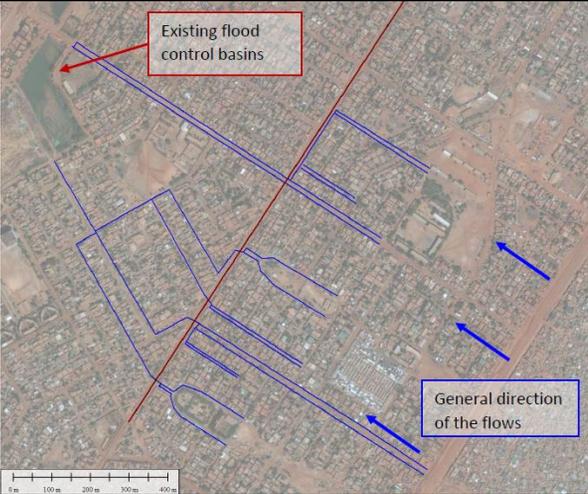
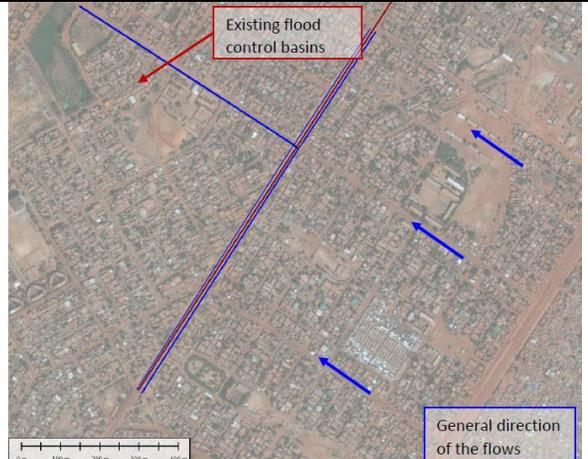


Damaged section of the canal between Avenue Ouezzin Coulibaly and Avenue Kadiogo. The Drainage Master Plan reports these damages as being caused by recent overflows. Inlet photo: SCET-Tunisie and AGEIM (2019)



Area identified for the construction of a new flood control basin (Source – Actualisation du schéma directeur de drainage des eaux pluviales de la ville de Ouagadougou, p 155)

<p>Cleaning of the reservoir lakes north of the area study and modification of the spillway to lower water level in the lakes and improve outlet conditions of the canals</p>	<p>Measure 26</p>	<p>Two reservoir dams are located north of the AOI. They were initially designed for water storage in order to supply drinking water to the city. This role is now largely obsolete since much larger dams were built further north, to face growing needs in the water supply. While there was initially a need to store as much water as possible in these dams, their current situation has adverse impacts on flood control:</p> <ul style="list-style-type: none"> - The high altitude of the spillways (elevation 287.35m for lake 3) results in a high water level in the lakes, which creates a downstream condition for the canals that flow into the lake, thus limiting their capacity and causing water level to rise in the canals (particularly the Mogho Naaba canal, whose downstream region is continually underwater). - These dams have been partially filled by the accumulation of silt, thus reducing their storage capacity. <p>These issues are well described in the Drainage Master Plan: "The basins of dams N° 1, 2, and 3 have silted up as a result of solid deposits and the excavation heights determined are 1.5m, 2m and 2m respectively. This situation considerably reduces the retention capacity of these basins and 3,801 418 m3 of water, corresponding to the amount of silt, threaten the banks every year."</p> <p>The Master Plan indicates the Mogho Naaba canal is the most affected by these issues: "The canal on its section between the Kadiogo bridge and the N°2 dam is constantly under water over almost its entire section, due to the significant silting up of the dam downstream of the canal".</p> <p>"For the proper hydraulic functioning of the Mogho Naaba canal, it is imperative to find a mechanism to lower the water level in the dam (by adjusting the spillway's level) and also to provide for a local cleaning of the dam in the basin area adjacent to the canal. Total cleaning of the dam is necessary in the long term."</p>	<div data-bbox="1045 235 1879 706" data-label="Figure"> </div> <p style="text-align: center;">Location of Lake 2, Lake 3, the SOTRACO bust depot and road N3</p> <p>The Drainage Master Plan recommends lowering the water level in the dams through the construction of new spillways for dams 2 and 3, with the flowing characteristics:</p> <ul style="list-style-type: none"> - New 60m long spillway at elevation 286.2m for the Ouaga 3 dam - New 70m long spillway at elevation 286.2m for the Ouaga 2 dam <p>According to the Drainage Master Plan, these new spillways would ensure the water level in the lakes does not go above 288m, even during 50-year return period floods. This would avoid overflow of the lake on the Nationale 3, and on the south bank which is protected by a levee reaching the 289m elevation).</p> <p>This lowering of the lakes level would also improve the flow in the Mogho Naaba canal, thus solving some of the flooding issues of the surrounding areas of the canal as well as stagnant water issues. Although these impacts do not affect the bus system, they are significant co-benefits. The construction of the new spillways has been estimated in the Drainage Master Plan at 1.8 billion FCFA (US\$3.3 million).</p> <p>To be fully effective, the construction of the spillways should be completed by the cleaning of the basins of dams 2 and 3. Due to the volume of silt accumulated over the years (more than 2 billion m3), the cost of fully cleaning the basins of all silt appears prohibitive (over 40 million \$). For this reason, it seems more reasonable to consider at least yearly cleanings of a smaller scale, aiming at least at removing more silt than accumulated over the past year.</p>						
<p>Construction of secondary and tertiary</p>	<p>Relevant for several measures</p>	<p>Construction of drainage systems comprises longitudinal channels and transversal hydraulic structures (box culvert or pipe culvert). The construction cost of these</p>	<table border="0"> <thead> <tr> <th style="text-align: left;">Hydraulic structures</th> <th style="text-align: left;">Unit price</th> </tr> </thead> <tbody> <tr> <td>Small concrete channel (60x60cm), covered with concrete slabs</td> <td>\$240/m (130 000 FCFA/meter)</td> </tr> <tr> <td>Medium concrete channel (80x100), covered with concrete slabs</td> <td>\$510/m (280 000 FCFA/meter)</td> </tr> </tbody> </table>	Hydraulic structures	Unit price	Small concrete channel (60x60cm), covered with concrete slabs	\$240/m (130 000 FCFA/meter)	Medium concrete channel (80x100), covered with concrete slabs	\$510/m (280 000 FCFA/meter)
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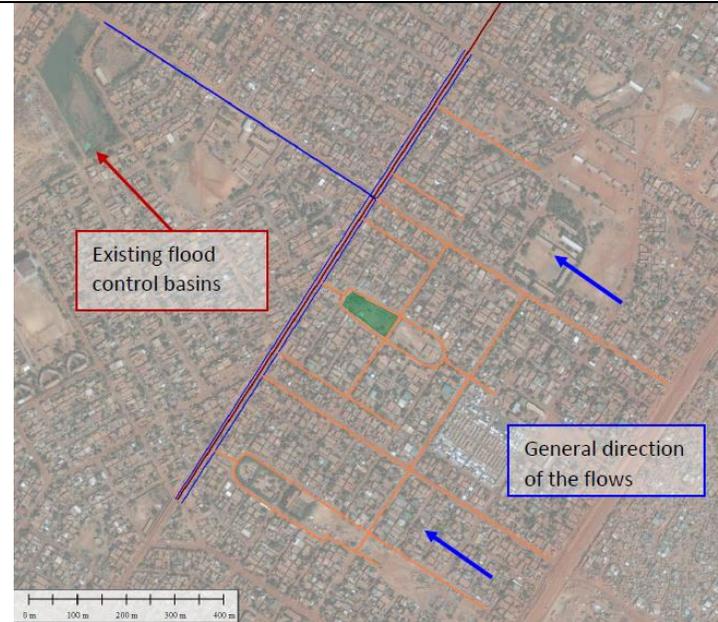
<p>drainage systems</p>		<p>structures has been assessed by drawing a scheme of the necessary networks and using average unit prices provided by the local member of our consortium or taken from quotations of construction projects in Africa supervised by Louis Berger.</p>	<p>Large concrete channel (150x120), covered with concrete slabs \$880/m (480 000 FCFA/meter) Pipe culvert (concrete, diameter 800mm) \$730/m (400 000 FCFA/meter) Pipe culvert (concrete, diameter 1200mm) \$1,100/m (600 000 FCFA/meter) Box culvert (concrete, 2mx2m) \$4,760/m (2 600 000 FCFA/meter)</p>
<p>Build a drainage system to collect run-off water for the neighborhood south-east of 28.257 street and channel them until the flood control basins of the Wemtenga canal</p>	<p>Measure 5 (protecting future Line 4)</p>	<p>There is currently no existing drainage system in this flood prone area. This measure includes small channels and pipe culverts to ensure hydraulic transparency of the 28.257 St used by line 7: run-off water in the streets to the south east is collected in these streets, passed under the street 28.257 with several culverts, and carried until the retention basins to the west with several channels.</p>	
<p>Build a drainage system focusing on protection of 28.257 street</p>	<p>Measure 6 (protecting future Line 4)</p>	<p>This measure is an alternative to measure 5, to solve the same flooding issue in this area which has no existing drainage system. This measure includes a simple drainage system: run-off water coming from perpendicular streets is collected by a channel running all along the 28.257 street, and carried away to the flood control basins through a single large channel following Naaga Loada street. This measure focuses on protecting against flood the 28.257 street used by line 7. It does not improve the situation of the upstream streets to the south-east.</p>	

Drainage system to protect 28.257 street, combined with water retention solutions for the neighborhood to the south-east: permeable pavements and rain garden in the area in front of Chapelle St Paul

Measure 7
(protecting future Line 4)

This measure is an alternative to measures 5 & 6, to solve the same flooding issue in this area which has no existing drainage system. It follows the same principle as the previous measure, with a channel on the right side of the 28.257 street to intercept run-off water coming from the south. In this option, the channels are smaller than in the previous one, because the streets to the south east are equipped with porous pavement used to slow down run-off and thus reduce the peak flows. A rain garden in the area in front of Saint Paul church reinforces the upstream storage of water.

This solution can be implemented in two steps:
 - Build the main channels
 - When the streets to the south-east will be paved, use porous pavement.



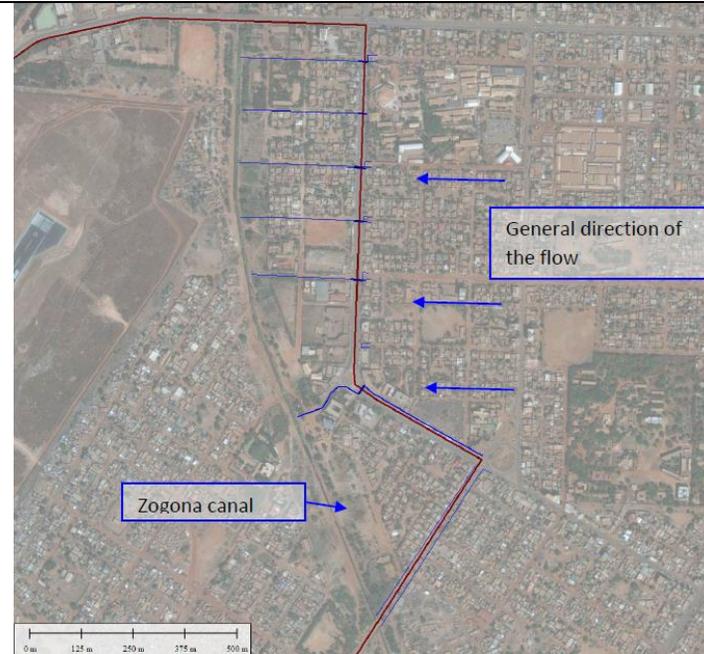
Proposed drainage system to collect run-off water on the side of street 28.257 apply permeable pavement (orange) on the main streets to the east and build a rain garden (green) in the administrative reserve in front of Saint-Paul church

Hydraulic structures	Unit	Unit price (USD)	Estimated quantity Measure 5	Cost (USD) Measure 5	Estimated quantity Measure 6	Cost (USD) Measure 6	Estimated quantity Measure 7	Cost (USD) Measure 7
Small concrete channel	m	240	8 827	2 118 480	1 097	263 280	2 178	522 720
Medium concrete channel (80x100),	m	510	210	107 100	1 081	551 310	649	330 990
Large concrete channel (150x120),	m	880	-	-	649	571 120	-	-
Pipe culvert (concrete,	m	730	219	159 870	16	11 680	16	11 680
Pipe culvert (concrete,	m	1 100	-	-	16	17 600	16	17 600
Box culvert (concrete, 2mx2m)	m	4 760	-	-	-	-	-	-
Permeable pavement	m ²	130	-	-	-	-	50 967	6 625 710
Rain garden	m ²	200	-	-	-	-	442	88 400
Total cost				2 385 450		1 414 990		7 597 100

Build a drainage system to protect 14.09 St. from transverse flows and ensure longitudinal drainage of Ave des Arts North of Canal de l'université

Measure 8
(protecting future Line 5)

Small channels already exist along street 14.09, but they seem to collect only run-off from the 14.09 street surface, and they do not intercept water from the perpendicular streets. Field data confirms that this area suffers from floods coming from the streets to the east. We thus propose to keep the existing channels, add portion of new channels to intercept run-off from the east, and create several outlets to the Zogona canal.



Hydraulic structures	Unit	Unit price (USD)	Estimated quantity	Cost (USD)
Small concrete channel (60x60cm), covered with concrete slabs	m	240	2 524	605 760
Medium concrete channel (80x100), covered with concrete slabs	m	510	516	263 160
Large concrete channel (150x120), covered with concrete slabs	m	880	-	-
Pipe culvert (concrete, diameter 800mm)	m	730	122	89 060
Pipe culvert (concrete, diameter 1200mm)	m	1 100	24	26 400
Total cost				984 380

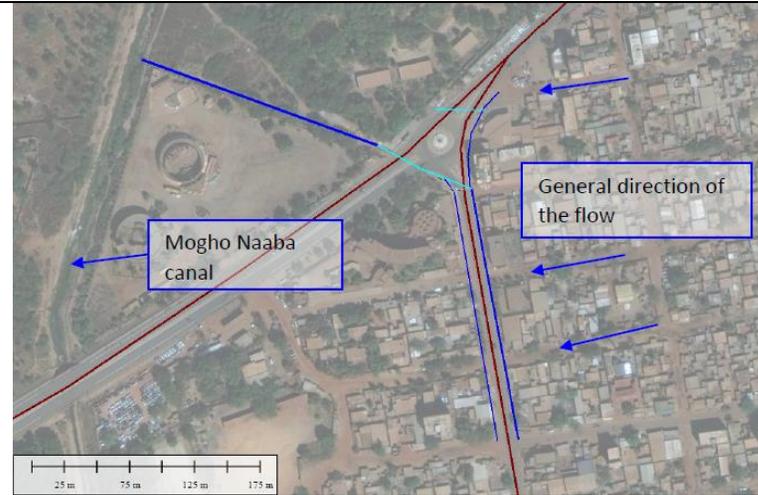
Build a drainage system to protect Ave Oumarou Kanazoe and Place de la bataille du rail roundabout

Measure 11
(protecting future Line 7)

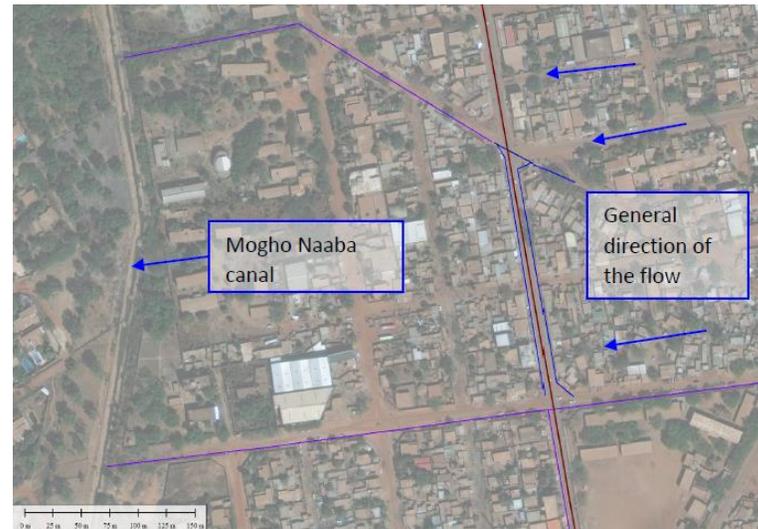
Some existing channels are visible on avenue Kanazoe, between its intersections with avenue ME/ Pacere and with Ave Coulibaly, draining part of the avenue Kanazoe to the Mogho Naaba canal to the west. No such channel is visible in the northern part of the street, but 2 culverts have been observed under the Place de la bataille du Rail intersection (light blue in the map). Only the outlet of the existing culvert could be observed. Further inspections would be necessary to make sure the whole culvert is in good structural condition.

The proposed measure includes a new network in the north of Avenue Kanazoe, including a branch of channel collecting run-off east of the Place du Rail roundabout. The existing culvert would be kept in place to convey the flow under avenue Kadiogo, to a new large channel towards the Mogho Naaba canal.

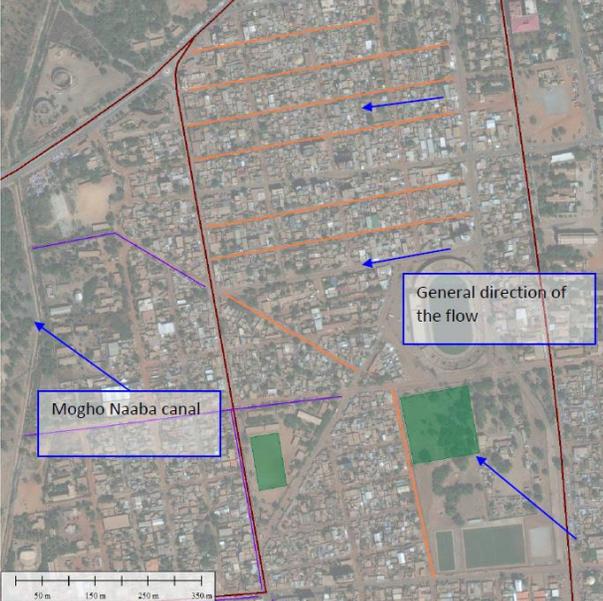
In the southern part of the street, the proposed measure uses the existing channels and outlets to the canal, simply adding missing sections of channel on both sides of the street.

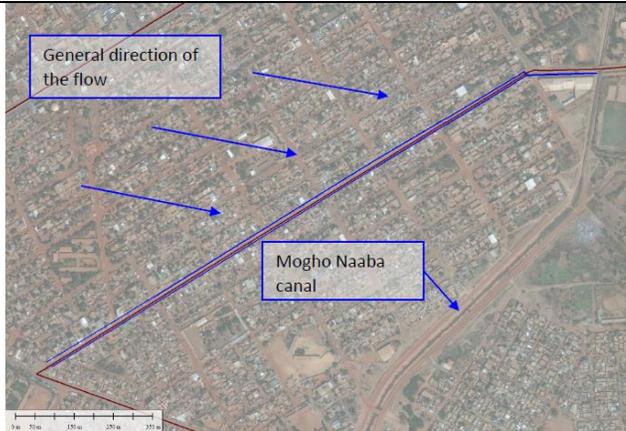
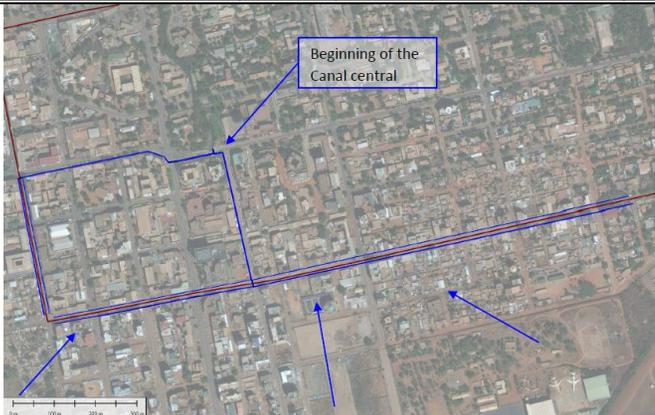


Sketch of proposed drainage network to drain the northern part of Ave Kanazoe



Sketch of the drainage network proposed to drain the southern part of Ave Kanazoe. Existing channels are shown in purple

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<p>Water retention solutions for the neighborhood east of Avenue Oumarou Kanazoe</p>	<p>Measures 12 and 13 (both protecting future Line 7)</p>	<p>As an alternative or supplement to the previous measure, one can consider improving water storage in the upper areas upstream of Avenue Kanazoe, using permeable pavement on the currently unpaved streets and creating water storage areas on the open space Bambata high school and the palace of the Mogho Naaba. These water retention areas could either take the form of rain gardens, pocket parks or floodable sports fields. However, access to the grounds of the Mogho Naaba palace might prove difficult. The Mogho Naaba is the traditional chief of the Mossi people. Although he has no legal power, he represents a highly respected moral authority in the country. Expropriation of his property to build a water storage facility is thus unthinkable, and such development would require prior consultation to build it by mutual agreement.</p>	 <p>Sketch of the proposed retention solutions to reduce peak flows towards Ave Kanazoe. channels are shown in purple, permeable pavement in orange, pocket parks / rain gardens in green</p> <table border="1"> <thead> <tr> <th>Hydraulic structures</th> <th>Unit</th> <th>Unit price (USD)</th> <th>Estimated quantity</th> <th>Cost (USD)</th> </tr> </thead> <tbody> <tr> <td>Permeable pavement</td> <td>m²</td> <td>130</td> <td>35 080</td> <td>4 560 400</td> </tr> <tr> <td>Rain garden</td> <td>m²</td> <td>200</td> <td>21 540</td> <td>4 308 000</td> </tr> </tbody> </table>	Hydraulic structures	Unit	Unit price (USD)	Estimated quantity	Cost (USD)	Permeable pavement	m ²	130	35 080	4 560 400	Rain garden	m ²	200	21 540	4 308 000															
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<p>Build a longitudinal drainage system on Simon Compaoré street</p>	<p>Measure 14 (protecting future Line 7)</p>	<p>There are no drainage system along this axis. We propose a simple longitudinal system to protect Simon Compaoré street.</p>	 <p>Sketch of the network proposed to drain Simon Compaore street towards Mogho Naaba canal</p> <table border="1" data-bbox="1075 669 1854 954"> <thead> <tr> <th>Hydraulic structures</th> <th>Unit</th> <th>Unit price FCFA</th> <th>Unit price (USD)</th> <th>Estimated quantity</th> <th>Cost (USD)</th> </tr> </thead> <tbody> <tr> <td>Small concrete channel (60x60cm), covered with concrete slabs</td> <td>m</td> <td>130 000</td> <td>240</td> <td>1 287</td> <td>308 880</td> </tr> <tr> <td>Medium concrete channel (80x100), covered with concrete slabs</td> <td>m</td> <td>280 000</td> <td>510</td> <td>1 558</td> <td>794 580</td> </tr> <tr> <td>Large concrete channel (150x120), covered with concrete slabs</td> <td>m</td> <td>480 000</td> <td>880</td> <td>175</td> <td>154 000</td> </tr> <tr> <td>Pipe culvert (concrete, diameter 800mm)</td> <td>m</td> <td>400 000</td> <td>730</td> <td>-</td> <td>-</td> </tr> <tr> <td>Pipe culvert (concrete, diameter 1200mm)</td> <td>m</td> <td>600 000</td> <td>1 100</td> <td>11</td> <td>12 100</td> </tr> <tr> <td colspan="5">Total cost</td> <td>1 269 560</td> </tr> </tbody> </table>	Hydraulic structures	Unit	Unit price FCFA	Unit price (USD)	Estimated quantity	Cost (USD)	Small concrete channel (60x60cm), covered with concrete slabs	m	130 000	240	1 287	308 880	Medium concrete channel (80x100), covered with concrete slabs	m	280 000	510	1 558	794 580	Large concrete channel (150x120), covered with concrete slabs	m	480 000	880	175	154 000	Pipe culvert (concrete, diameter 800mm)	m	400 000	730	-	-	Pipe culvert (concrete, diameter 1200mm)	m	600 000	1 100	11	12 100	Total cost					1 269 560
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<p>Build a new drainage network to protect Ave Houari Boumedienne and Ave de la Grande Mosquée</p>	<p>Measure 18 (protecting future Line 5)</p>	<p>Some channels have been observed in this area, but they do not seem to form a coherent and sufficient drainage system, as field data reports frequent floods. Avenue Boumedienne crosses the valley of the canal central watershed. It has a low point around its intersections with Avenue de l'UEMOA and Avenue du PNUD. We thus propose to intercept waters coming from the south with a channel on the side of Ave Boumedienne, and to convey them to the canal central which starts 300 meters to the north, using a channel through avenue de l'UEMOA. Another channel along Avenue de la Grande Mosquée would collect run-off water from the west, and channel it to the canal central through Patrice Lumumba street.</p>	 <p>Sketch of the proposed drainage network to avoid floods on Avenue Boumedienne and Avenue de la Grande Mosquée</p>																																										

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<p>Set up a dedicated maintenance plan and team in charge of the periodic and systematic cleaning and maintenance of flood related structures</p>	<p>Measure 21 (protecting the road section shared by most future mass transit lines in the city center)</p>	<p>In several instances, the extent of the flood simulated by the hydraulic model initially led to the conclusion that a street / area was completely lacking drainage system, and that the obvious measure to implement to solve flood in this area was to build gutters, or bioswales when possible. In situation where a drainage system exists but is not included in the hydraulic model, the simulated floods are thus exaggerated, and the construction of new channels is not relevant. However, also the existing channels are often partially filled with solid waste, silt, or even vegetation, which hampers their drainage capacity. This led to proposing a measure consisting of the maintenance of all flood-protection structures. The best way to estimate the cost of this measure was considered to be not to use linear costs for the cleaning of a channel or a canal, but to propose the dimensioning of a team that would be specifically assigned to the task of maintaining all the hydraulic structures related to the flood protection of the bus system layout.</p> <p>It is proposed that this team could be tasked with the routine maintenance of all hydraulic structures, including channels but also culverts, that are regularly obstructed by solid waste, as well as canals and flood retention basins which get progressively filled with silt when left without proper maintenance. Green solutions such as bioswales or rain gardens, if selected and built, will also require frequent maintenance to remove waste and invasive plants and also cut excess grass.</p>	<div style="display: flex; flex-wrap: wrap;"> <div style="width: 50%;">  <p>Example of channels partially filled with waste, silt or vegetation</p> </div> <div style="width: 50%;">  </div> <div style="width: 50%;">  <p>Example of partially obstructed box culvert</p> </div> <div style="width: 50%;">  <p>Example of canal to be cleaned</p> </div> </div>																																								

The activities of the team would vary along the year:

- During the rainy season, they would focus on daily tours after significant rain events to identify and remove newly formed obstructions.
- During the dry season, they would follow a pre-established plan focusing on larger scale activities, such as clearing the banks and bottoms of the canals, removing silt accumulated in flood retention basins, cleaning the surface of permeable pavements or maintaining green areas.

Considering the number of structures involved in protecting the bus routes against flooding, we have estimated the required size for this dedicated team to be around a dozen workers, split into two teams, with two trucks and small equipment (shovels, gloves, protecting equipment, etc). A manager would be added to plan and organize the team's activities, based on regular inspections of the structures included in the scope of the maintenance team, in order to detect sections requiring cleaning. It is to be noted that cleaning and maintenance of all hydraulic structures in cities is part of the standard responsibilities of the municipalities. However, in Ouagadougou as in many other large African cities, maintenance is often insufficient, leading to decreases in the efficiency of the structures. The analysis and solving of the reasons for this recurrent issue of insufficient maintenance is out of scope of the present study. However, one should consider this factor when proposing the development of a dedicated maintenance team. Without proper planning, it is to be feared that lack of maintenance would also rapidly affect the newly developed rapid bus system. The idea of having a team dedicated to the structures protecting the bus routes partially reduces that risk: instead of relying on the ability of the municipality to ensure maintenance of the whole city (which is not very likely due to resources shortage) the development of a small team dedicated to specific sections increases the chances of having maintenance correctly performed in this limited scope. One should still define the institutional arrangements that would be put in place to manage this team. We have identified two options:

- The maintenance of urban infrastructures belonging to the city being a standard responsibility of the municipality, the most obvious measure would be to include this team among the municipality staff, as a sub-team among the municipal employees in charge of urban cleaning.
- The proposed team being dedicated to the maintenance of structures protecting the bus network, one could also imagine transferring this responsibility by contract to the bus system operator.

Since the municipality of Ouagadougou currently struggles to ensure maintenance of the existing network, it seems appealing to entrust maintenance of the structures contributing to the protection of the bus system to its operator. However, this solution also shows some serious drawbacks:

- While cleaning of channels along the bus routes and culverts under it seems accessible for a team employed by the bus operator, it is worth noting that many structures contributing to the protection of the bus routes are actually far from these routes: the proposed measures include upstream retention basins, portions of canals and bridges downstream the bus route, bioswales, rain gardens and permeable pavement that are located outside of the right-of-way of the roads used by the buses.
- Putting the bus system operator in charge of the maintenance of some hydraulic structures, and the municipality in charge of the same type of structures just a few meters away may generate coordination issues.
- While the main function of longitudinal drainage is to prevent flooding of the road surface, other structures like the proposed flood retention basin or canals are designed to protect larger areas of the city. Asking the bus system operator to maintain these structures is very far from the typical activities of such entities.
- Adding maintenance activities to the bus system operator's scope of work would increase its exploitation costs. Since the financial analyses included in the OPTIS report show that the financial balance of the operation is already fragile, adding cost to its operation would involve an increase in the tariffication, which is not desirable.

For the above reasons, we consider the "standard" solution of having the municipality manage the maintenance of the structures involved in the prevention of floods on the bus route to be better suited. However, a mechanism should be established to make sure that the municipality takes ownership of the need for such maintenance, otherwise it will likely be diluted within its many other urgent needs.

One of the key issues of a similar initiative in Cameroon was to help the urban communities improve their own resources (human, technical and financial resources) to make sure that they are able to properly manage and maintain the new infrastructures built under the program and transferred to them. Sustainability of the investments also relied on "City contracts", which are written agreements between the Ministry in charge of Urban Development and the cities benefiting from the investment program. These contracts covered the following aspects:

- an investment framework program aimed at meeting the economic and social development objectives of the cities, specifying the sources of financing;
- a road maintenance framework program, aimed at providing a road maintenance account with sufficient funds to guarantee the sustainability of the works carried out;
- a management improvement program, allowing the settlement of cross-debts between the State and the urban communities. This program also includes measures to strengthen the financial services of the cities in order to improve the transparency and legibility of the preparation and execution of urban communities' budgets.

Similar arrangements could be implemented in Ouagadougou, and a contract or convention could be signed with the municipality, specifying what investments the municipality will receive, and what efforts it is committed to making, including in terms of maintenance of the existing or new structures.