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Evaluating the hydraulic capacity of existing drain systems and the management challenges of stormwater in Addis Ababa, Ethiopia

Dagnachew Adugna[a,c,*], Brook Lemma[b], Marina Bergen Jensen[c], Geremew Sahilu Gebrie[d]

[a] Ethiopian institute of Architecture, Building Construction and City Development, Addis Ababa University, Ethiopia
[b] College of Natural & Computational Sciences, Addis Ababa University, Ethiopia
[c] Department of Geosciences and Natural Resource Management, Copenhagen University, Denmark
[d] Addis Ababa institute of Technology, Addis Ababa University, Ethiopia

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ABSTRACT

Study region: Addis Ababa, Ethiopia.
Study focus: Addis Ababa is undergoing rapid urbanization with unprecedented high rate of road and building constructions, resulting in a sudden upsurge of sealed surfaces and generation of significant amounts of stormwater. The present study therefore aims to investigate the hydraulic capacity of existing drains and stormwater management challenges using detailed field surveys, and stakeholders' interview. 469 road segments (74 km) and 202 drain segments (42.76 km) in two representative case sites confined in 564.54 ha boundary areas were physically surveyed.
New hydrological insights for the region: Results showed that 14% of the drains in new city parts and 28% in old city parts were in conditions inadequate for removal of stormwater, resulting in flash flooding and infrastructure degradation in the associated watersheds. Further, although more than 72% of the surveyed drains were oversized, stormwater overtopping reoccur as a season-to-season problem, ascribed to illegal dumping of waste into drains, reducing their hydraulic capacity. The challenges of stormwater management were related to lack of city-wide drainage master plan, absence of hydrologic data considerations during designing drains, and weak enforcement on solid and liquid waste dumping into drains. The present study recommends that building practices that minimize surface sealing and critical hydrologic and hydraulic considerations during designing drains, and educating the local community and stakeholders regarding waste management.

1. Introduction

Urbanization is characterized by a marked increase in built structures (Koehn et al., 2011), such as streets, walkways, parking lots and rooftops creating sealed surfaces. Compared to the pre-urban conditions these sealed surfaces result in increased stormwater runoff and a reduction in infiltration capacity (Gill et al., 2007; Miller and Hess, 2017). This is resulting in stormwater related flash flooding where most global cities are facing (Price and Vojinovic, 2008). This phenomenon is manifested by infrastructure and properties damage and the hindering of traffic movement. The causes are poorly developed stormwater management system, improper waste management and increasing impervious surface cover (Miller et al., 2014; Hoang and Fenner, 2015). To protect the

* Corresponding author at: Ethiopian institute of Architecture, Building Construction and City Development, Addis Ababa University, Ethiopia.
E-mail address: dagnachew2@gmail.com (D. Adugna).

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costly built up areas from flooding and degradation and sustain the service life of infrastructure stormwater management is needed (Barbosa et al., 2012). Most developing countries like Ethiopia have low coverage of urban stormwater management systems (Abeje, 2004), providing neither on-site management nor safe removal and discharge to natural receiving environments. In Ethiopia, most municipalities assume that the majority of the road networks, usually the arterial and collector roads should have drain (FUPCoB, 2008). However, this goal is not realized beyond the planning level, assumable due to high financial requirements, lack of focus of city administrations, and its single-purpose approach to only collect & convey stormwater out of the boundary of the city. Conversely, some developed countries combine the conventional approach with the multiple-purpose stormwater management alternatives such as stormwater management using green infrastructure, rainwater harvesting, retaining and detaining stormwater on-site, green roofing and porous pavements at streets and parking lots (Hoyer et al., 2011; Hamel et al., 2013; Hoang and Fenner, 2015; Niu et al., 2015).

Addis Ababa, the capital of Ethiopia and the seat of the African union, is experiencing a high rate of urbanization (Mazhindu and Gondo, 2010) with a population rise from 0.684 million in 1967 to 3.434 million in 2017 (CSA, 2013), increasing more than five-folds in fifty years. Like other developing countries (Parkinson and Mark, 2005), stormwater management is given less emphasis when compared with other urban development activities, resulting in flash flooding, and degradation of urban infrastructure. The coverage of the unsystematic traditional piped drains together with their hydraulic capacity in Addis Ababa is largely unknown, apart from few data collected in a small neighborhood in the oldest part of the city (Belete, 2011). Consequently, the actual state of drainage in Addis Ababa including the hydraulic capacity and map of the constructed drains are anonymous.

Understanding the contribution of wastes in reducing the hydraulic capacity of drains and causing flash flooding will help engineers, urban planners and city decision-makers to effectively prioritize responsive strategies. Taking Addis Ababa as case, the present study was conducted to:

- evaluate the hydraulic capacity of the existing drains by taking two representative case studies, and
- investigate the management challenges of stormwater.

2. Review of stormwater management practices

To control the historical urban grown stormwater problems, various stormwater management systems have been developed by various researchers and applied in different countries. Some of these include Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Integrated Urban Water Management (IUWM), Sustainable Urban Drainage System (SUDS), Best Management Practices (BMPs), Source control, Green Infrastructure (GI) and Landscape Based Stormwater Management (LSM).

Currently these sustainable stormwater management systems are opted to deal with the limitations of traditional stormwater drainage systems. The traditional system often focuses on collecting and conveying stormwater runoff (Burns et al., 2012) directly to water bodies resulting in an exacerbating pollutant concentrations and hydrologic disturbance which ultimately degrading ecosystem structure and function (Roy et al., 2008). Conversely, these sustainable stormwater management systems are with the objective to retain, infiltrate, and harvest stormwater at or near the source. This is enhancing evapo-transpiration and groundwater recharge, and re-use of stormwater may lead to a more sustainable solution to stormwater. The practices of stormwater management solutions are reviewed as follows:

2.1. LID

It has been most commonly used in North America and New Zealand since the 1970s (Fletcher et al., 2014) to minimize the cost of stormwater management through integrating design with nature approach. LID is characterized by smaller scale stormwater treatment devices such as bio-retention systems, green roofs and swales, located at or near the source of stormwater runoff (Barlow et al., 1977).

2.2. WSUD

This system was started in the 1990s in Australia (Fletcher et al., 2014) to manage the water balance, maintain and where possible enhance water quality, encourage water conservation (minimizing import of potable water supply through harvesting stormwater and the recycling of wastewater, and reductions in irrigation requirements), and maintain water-related environmental and recreational opportunities.

2.3. IUWM

It combines the management of water supply, wastewater and stormwater (Fletcher et al., 2007) and considers the roles and interactions of the various institutions involved in urban water cycle management (Rogers, 1993). IUWM considers all parts of the water cycle, natural, constructed, surface and subsurface (Mitchell, 2006). IUWM recognizes the water cycle as an integrated system both for human needs and ecological, consider the local context, accounting for environmental, social, cultural and economic perspectives.

2.4. SUDS

It was started to habituate in the UK in the late 1980s and in 1992 due to developments changing the approach to stormwater and the change of the scope for control of urban runoff (Fletcher et al., 2014). It consists of a range of technologies and proficiencies used to manage stormwater which is more sustainable than conventional solutions (Hoang and Fenner (2015). SUDS is based on the rationale of retroflexing the natural, pre-development drainage from a site.

2.5. BMPs

It was primarily drafted in 1972 as part of the Clean Water Act in the US and Canada to prevent pollution using structural approaches. It has a historical basis in the management of centralized wastewater treatment systems (Fletcher et al., 2014) until it was matured to pollution prevention activities. BMPs encompasses both non-structural and structural measure including schedules of activities, prohibitions of practices, maintenance procedures and practices to control plant site runoff, leaks, and sludge disposal (USEPA, 2011).

2.6. Source control

It was initiated in North America in the 1990s to mitigate increased runoff. Initially it was used to make a distinction between on-site stormwater systems and practices, to be used at or near to the source of stormwater generation, contrary to larger detention ponds that are constructed at the downstream of a drainage system (Whipple et al., 1983). Moreover, it focuses on stormwater pollution control with a strong focus on non-structural or semi-structural techniques (Ellis, 2000).

2.7. GI

It goes far beyond stormwater management as its concept influences urban planning to maximize the benefits of green spaces (Center for Neighborhood Technology, 2010). Of the many functions, the potential usage of GI to assist stormwater management was realized throughout the US (USEPA, 2012). GI is used interchangeably with LID and BMPs (Struck et al., 2010). It is a sustainable stormwater management practices (e.g. green roofs, rain gardens, permeable pavement) that can detain and infiltrate rain where it falls, resulting in reducing stormwater runoff and improving the quality of water bodies (Foster et al., 2011). In contrast to single-purpose piped based grey stormwater infrastructure, GI uses vegetation and soil to manage stormwater at or near the source of generation. The widespread adoption of GI is likely to take stormwater management towards a more distributed and at-source application (Keeley et al., 2013).

2.8. LSM

It relates the natural system with the hydrological features that encompass the landscape. LSM considers the environmental context of a specific site within the matrix of the larger landscape. It also recognizes the importance of temporal, seasonal and microclimatic factors on ecological function (Sameer and Zimmer, 2010). The goal of LSM is to maintain the ecological integrity of healthy sites and watersheds. The application of LSM requires a comprehensive understanding of natural and hydrologic features and functions. This includes biophysical, hydrological, and hydro-geological features and their interrelated functions, modifying factors (e.g. climate) and temporal factors (e.g. seasonal changes) (Sameer and Zimmer, 2010).

These nature based stormwater management solutions have substantial contributions to attain sustainable urban development. In contrast, in Addis Ababa, the introduction and use of such sustainable stormwater management is absent, though they are fundamental to efforts to improve the well-being of the residents. Moreover, the high density of structures, improper open spaces management, lack of enforcement, complex social and political dynamics, and limited available resources pose major challenges to the city's development. The study discusses that the implementation of IUWM principles by most urban planners and decision makers is acute with respect to stormwater management, which is also a case in Addis Ababa.

Despite continuous investments by the city of Addis Ababa, traditional stormwater management system is challenged by impervious structures, poor waste management, and increasing frequency and intensity of rainfall events. Besides, the poor understanding of the stakeholders to meet the urgent challenges of flash flooding for the city's (nearly) four million dwellers complicates the issue.

3. Materials and methods

3.1. Study area

The study was conducted in two case studies, locally known as “wereda” that are the lowest local government administrative units in Addis Ababa. It comprises of the new “wereda” 3 located in Nefas Silk-Lafto sub-city with a boundary area of 461.72 ha, and the old “wereda” 4 which is located in Arada sub-city with a boundary area of 102.82 ha (Fig. 1).

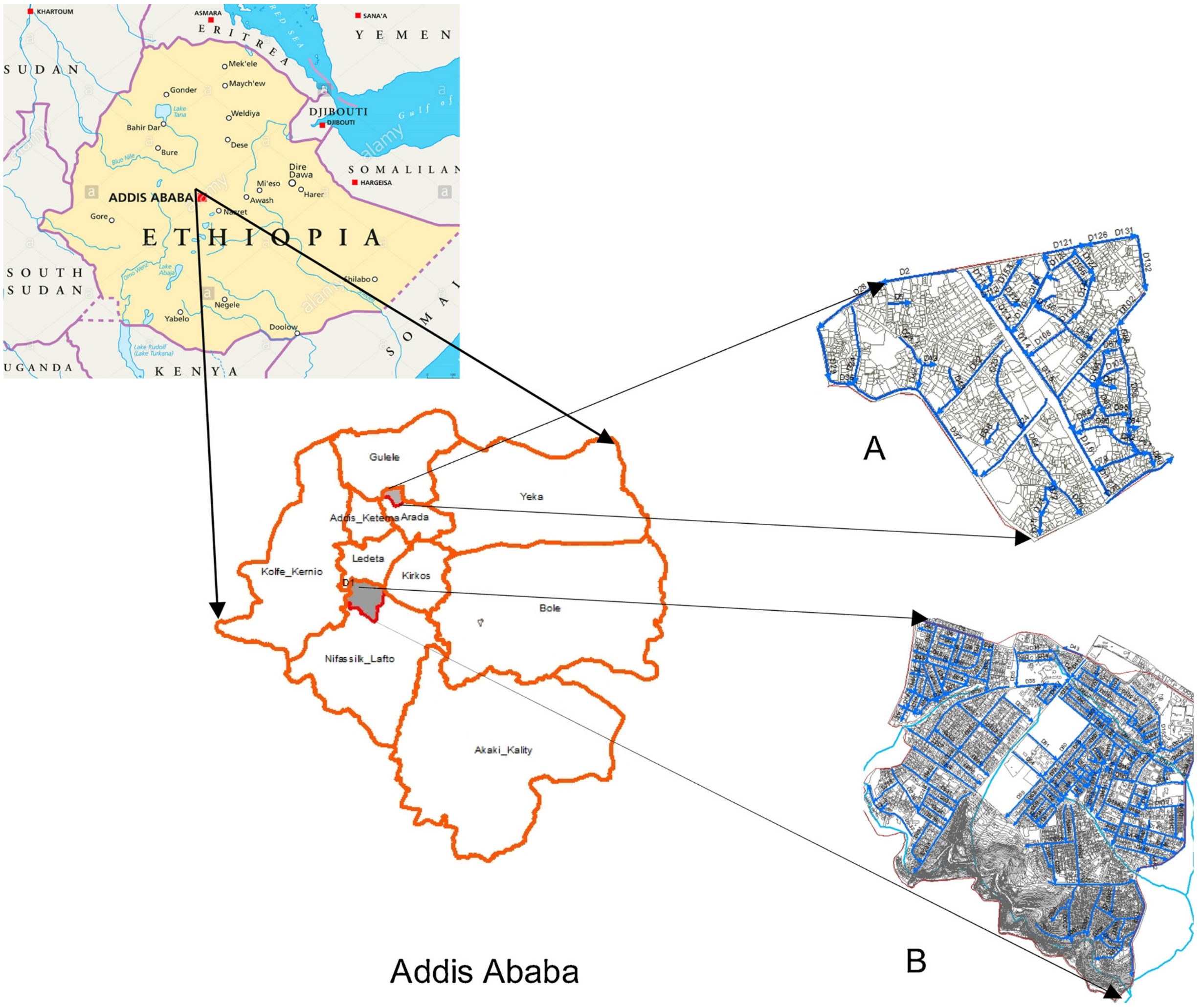

Fig. 1. The two case studies; "wereda" 4 (A) and "wereda" 3 (B), with surveyed and mapped constructed drains network (blue arrow), in Addis Ababa, Ethiopia.

3.2. Selection of the case studies

The case studies were selected to represent the new and older parts of the city, which in total covers an area of 530 km^2. They were also selected to evaluate whether the hydraulic capacity of the existing drains in the old (greater than 100 years old) and new (less than 30 years old) parts of the city have similar trends, and to conclude if improvement towards the new case site has been made. In addition, they were used to identify the key causes of flash flooding through linking with the hydraulic capacity of the drains. The coverage of drains per given boundary area of the case studies and integration with the available road surfacing types were also the other reason to consider the two "weredas".

3.3. Field survey

Digital base maps were obtained from the corresponding local administrations of the two studied “weredas” in 2017. The maps were engaged as a guide to follow the routes to be measured and to locate roads and drains to be surveyed. The maps show all physical infrastructure and natural features (e.g. rivers, buildings, open spaces).

Prior to data collection ten data collectors (fifth year undergraduate Architecture internship students) were trained about technical issues related to road pavements, widths, road network, geometry and types of drains, surveying instruments, reading maps and encoding data into data collection sheets, developed by the researchers. Then, before the data collectors did the actual survey, they practiced with the researchers at a pilot case site. Moreover, as quality control, the data collectors were supervised by the researchers, and once a week there was a discussion among the data collectors chaired by the lead researcher. Data collectors transferred the data into a computer on a daily basis.

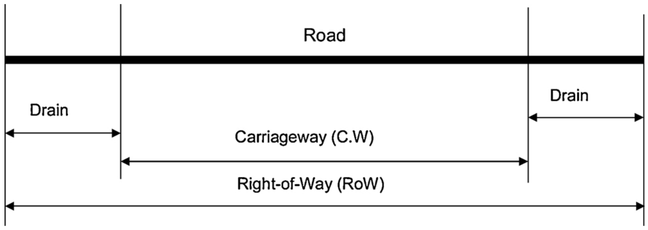

Fig. 2. Profile of measured road and drain section.

All roads and corresponding pavement types in the study sites were physically surveyed (or measured) including length, width, pavement type & cross-sectional profile of roads, as illustrated in Fig. 2. In parallel, the length (as marked on the base maps), type (open/closed), geometry (trapezoidal, rectangular or circular/pipe), dimensions and construction materials of drains were physically measured. The registrations were supplemented with photos. Both the road and drains data were analyzed using ArcGIS 10.3.1. All data in the present study were collected in three dry months from November 2016 to January 2017.

3.4. Questionnaires

To investigate the challenges of stormwater management, the extent of integration and understanding among the different stakeholders working directly or indirectly in stormwater management in Addis Ababa, common and customized questionnaires were distributed. The interviews were performed with 25 interviewees ranging from experts to head of organizations, representing five organizations (Table 1). The stakeholders were selected purposively based on their competencies in stormwater management and the activities they are performing. The questionnaires provided insight on challenges and gave information on the current stormwater management practices. All were interviewed about the challenges of stormwater management and to what extent they collaborate.

Each participant was asked three common questions including "is your organization involved in stormwater management"? How do you collaborate with other organizations to manage stormwater? What are the major challenges in stormwater management?

3.5. Evaluation of the hydraulic capacity of drains

The hydraulic capacity of the existing drains was evaluated based on the corresponding contributing watershed delineation using PCSWMM (Version 2013 EU 2D), and areas and elevation of each drain using ArcGIS (version 10.3.1). Based on the length, discharge, slope and velocity of stormwater and contributing watershed area of each drain the dimension of the hydraulic capacity of each surveyed drain was evaluated (Tables 4). First the hydraulic capacity of the existing drains was designed and then the designed hydraulic capacity (or discharge) was compared against the existing drains' hydraulic capacity which was actually surveyed from the field.

3.6. Stormwater runoff quantification

Stormwater draining from contributing watersheds into each of the surveyed 202 segments of drains (42.76 km in length) was computed using the models (Eqs. (1) through (4)) adopted by the Ethiopian Federal Urban Planning Institute (FUPCoB, 2008). Each of the computation was performed using a design sheet developed by the researchers.

3.6.1. Stormwater runoff, Q (m^3/s)

Stormwater drained into each surveyed drain was computed based on the contributing watershed area, A (m^2), rainfall intensity, I (mm/h) and runoff coefficient, C (dimensionless) (Eq. (1)).

$$Q = C \times I \times A \quad (1)$$

3.6.2. Rainfall intensity

It was computed based on rainfall depth of a 'T' years return period in 't' minute duration and time of concentration (T_c).

3.6.3. Rainfall depth, RtT (mm)

It was quantified using the formula (Eq. (2)) based on return period, T (years), rainfall duration, t (minute), and rainfall depth in millimeter of one hour duration and 10 years return period, R_{10}^{60} (Eq. (2)); where, $2 \le T \le 100$ Years and $5 \le t \le 120$ min.

$$R^t T = (0.21 \times lan\ T + 0.52) \times (0.54 \times t^{0.25} - 0.5) \times R^{60}10 \quad (2)$$

3.6.4. Time of concentration, T_c (h)

It was computed using the Airport or Federal Aviation Administration methods (1970) (Eq. (3)) based on flow length from the remotest point to the point of interest, L (m), elevation difference, H (m) and C.

Table 1
Overview of interviews conducted in terms of stakeholders (interviewees) and questions.

No	Organization	Role of interviewee in the organization	Number of interviewee	Relation of the organization to stormwater management	Customized questions presented to each organization
1	Addis Ababa City Roads Authority (AACRA)	Road and Bridge department head Civil engineers	1 3	Provide drains as road side ditches and maintains whenever a need arises	● Which stormwater management principles your organization follows? ● What major criteria and procedures you follow to design drains? ● Does your organization assign a responsible professional to work only on stormwater?
2	Addis Ababa Urban Planning Institute (AAUPI)	Deputy manager Urban planners	1 3	Locate places on map where drains can be provided	● How do you plan drains? ● What major criteria do you use in planning drains? ● Which profession makes the plan?
3	Addis Ababa Beautification, Parks and Cemetery development Agency (AABPCDA)	Deputy manager Greening process owner Experts	1 1 2	Greening road medians, parks, squares and cemeteries	● What is the purpose of greening road medians, squares, parks and cemeteries? ● Does your organization have a plan to harvest rainwater to irrigate the greeneries rather than using potable water?
4	Addis Ababa Environmental Protection Authority (AAEPA)	Manager Deputy manager Natural resources department head Experts	1 1 1 4	Greening the upstream mountains, river buffers and provision of flood protection walls	● What is the purpose of soil and water conservation activities on upstream mountains? ● Does your organization have a plan to harvest rainwater to irrigate the greeneries rather than using potable water?
5	Addis Ababa Water Supply and Sewerage Authority (AAWSA)	Water resources and quality department head Ground water department head Water experts Sewerage experts	1 1 2 2	Water resources development, water supply and sewers provision & infrastructure management	● Did you consider the use of stormwater management to supplement the potable water directly or indirectly? ● Do you have any controlling mechanism to prevent the dumping of wastewater in to drains?

$$\mathrm{Tc} = 3.64 \times (1.1 - C) \times \mathrm{L}^{0.83}/\mathrm{H}^{0.33} \quad (3)$$

3.6.5. *Mean velocity of stormwater runoff flow, V (m/s)*

The mean velocity of the stormwater discharge of each drain was quantified by Manning's formula (Eq. (4)), using the Manning's roughness coefficient (n), hydraulic radius, R (m), and the slope of the energy grade line, S (m/m).

$$\mathrm{V} = (\mathrm{R}^{2/3} \times \mathrm{S}^{0.5})/n \quad (4)$$

3.7. *Digitalizing the roads and drains*

The process of digitalization was followed after Shape files were created on ArcCatalog in ArcGIS 10.3.1 using the standard methods of Environment Systems Research Institute (ESRI). After digitalization, under the attribute tables of roads layer and drains layer fields containing roads code, pavement and length of roads, and drains code, geometry and type of drains, dimensions of each drain type and length of drains were added. Subsequently, to evaluate the hydraulic capacity of drains and coverage of roads by drains, the lengths of all roads and drains together with their pavement types were calculated separately using the Calculate Geometry tool from ArcGIS 10.3.1.

4. Results

4.1. *Current stormwater management practices*

Drains are provided as road side ditches commonly with road construction. According to the interview made with the AACRA which frequently works on stormwater management and related issues (August 2017), and triangulated with field survey (September 2017) drains are provided through traditional approaches by installing the largest possible drains size to accommodate worst scenarios. The present study also revealed that there was no assigned engineer who only works on stormwater management. Moreover, the respondents reported the nonexistence of drains net-work map for the case studies and the entire city.

4.2. *Drains, roads and paving materials*

The paving materials and lengths of roads and the types, length and geometry of drains together with their corresponding dimensions are reported in Table 2. Photos, captured during data collection, of representative road pavements and drains are presented in Fig. 3.

The results in Table 2 revealed that in "wereda" 3 only 59% of the roads were covered by drains; the remaining 41% of them were without drains. Of the various types of road pavements, 58% of asphalt, 63% of cobblestone, 43% of gravel and 87% of earthen roads were covered by drains. From the total drains in "wereda" 3 nearly 45% of them were found open.

In parallel, the results in Table 2 revealed that in "wereda" 4 only half of the roads were covered by drains; the remaining half of the roads were without drains. Of the total road pavement types, 54% of asphalt, 66% of cobblestone, 51% of gravel and 50% of earthen roads were covered by drains. From the total drains in "wereda" 4 nearly 36% were found open.

4.3. *Hydraulic capacity of existing drains in "wereda" 3 and "wereda" 4*

The hydraulic capacity of the 130 drain segments equivalent to 30.12 km in length in "wereda" 3 and 72 drain segments equivalent to 12.64 km in length in "wereda" 4 are presented in Tables 3 and 4. In these Tables, only the existing capacity of the drains (column 2 and 7) and the stormwater draining into these drains (column 3 and 8) are presented to evaluate the hydraulic capacity of the existing drains against the potential stormwater draining into each existing drain from contributing watersheds.

Based on Table 3, the result of evaluation of the hydraulic capacity of drains in "wereda" 3 showed that only 14% (equivalent to 4.324 km of the total surveyed 30.12 km) of the drains were undersized. This revealed that the drains are inadequate to convey the stormwater generated from the corresponding contributing watersheds resulting in flash flooding and infrastructure degradation. Conversely about 86% (25.796 km) of the drains were found oversized.

From Table 4, the result of evaluation of the hydraulic capacity of drains in "wereda" 4 showed that about 28% (3.522 km of the total surveyed 12.64 km of drains) were undersized resulting in flash flooding and infrastructure degradation. While more than 72% (9.118 km) of the drains were oversized.

4.4. *Stakeholders involvement in stormwater management*

The responses of stakeholders and the existing stormwater management practices in Addis Ababa are reported in the following sub-sections.

4.4.1. *AACRA*

According to AACRA stormwater is managed through traditional systems and drains are commonly provided as road side ditches

Table 2
Summary of surveyed roads and drains in “wereda” 3 and "wereda" 4.

“wereda” 3						
Road pavement	Measured road segments and Road length		Drain types and average length of drains (m)			
	Segments	Road length (m)	Concrete pipe (closed)	Rectangular (open stone masonry)	Trapezoidal (open stone masonry)	Sum
Asphalt	126	25,851	8638	3404	3019	15,061
Cobble stone	63	11,444	4560	1826	843	7229
Gravel	80	11,414	1200	2636	1072	4908
Earthen road	32	5031	3083	1177	125	4385
Sum	301	53,740	17,481	9043	5059	31,583
“wereda” 4						
Road pavement	Measured road segments and Road length		Drain types and average length of drains (m)			
	Segments	Road length (m)	Concrete pipe (closed)	Rectangular (open stone masonry)	Trapezoidal (open stone masonry)	Sum
Asphalt	42	8692	3308	–	1401	4709
Cobble stone	35	3286	879	256	1033	2168
Gravel	81	7326	2798	–	917	3715
Earthen road	10	1177	205	–	383	588
Sum	168	20,408	7190	256	3734	11,180

Fig. 3. Common road pavements, in addition to asphalt: Gravel (A) (8°59′19.901″N & 38°43′33.453″E), Cobblestone (B) (8°59′9.81″N & 38°43′51.904″E), and stone paver (C) (9°3′0.519″N & 38°44′33.77″E) and drain types along Gravel (D) (9°2′58.893″N and 38°44′37.087″E), Cobblestone (E) (8°58′57.67″N and 38°43′54.859″E) and stone paver roads (F) (9°3′4.414″N and 38°44′52.087″E) in the case studies.

to accommodate the stormwater from road surfaces. Addis Ababa practices a separate sewer system; nevertheless residents illegally dump wastes into drains that commonly reduce the hydraulic capacity of drains. Drains collect stormwater from various land uses and dump into rivers. During designing drains, generally, the hydrologic and hydraulic features of the contributing watersheds to each drain were not considered. AACRA also reported that there was no a single professional who appointed to work with stormwater management, rather stormwater is one of more activities.

4.4.2. AAUPI

It is the only urban planning institute in the city; however it only leaves space on plan for the provision of drains, based on the road network map of the city, as is done for all other utility lines.

4.4.3. AABPCDA

According to AABPCDA, the purpose of greening road sides and parks is to increase the aesthetics of the city and for ecosystem functions (e.g. climate regulation, carbon sequestration), and thus not for stormwater management. AABPCDA reported that GI is not integrated with stormwater management due to the fact that the stakeholders who directly or indirectly working with stormwater management have no integrated plan to work together; each follows its own customary plan.

4.4.4. AAEPA

According to AAEPA, the primary purpose of soil and water conservation activities at the upstream mountains, which are the main sources of stormwater generation in Addis Ababa, is to rehabilitate the mountains and prevent soil erosion and the occurrence of flooding on the city. However, mountain rehabilitation and soil conservation practices are not well integrated with stormwater management.

4.4.5. AAWSA

According to AAWSA, rainwater harvesting would be an alternative water supply for the city, but the treatment method needs advanced technologies as stormwater in Addis Ababa is highly polluted. There are regulations to prevent the dumping of waste into

Table 3
Evaluation of the hydraulic capacity of the existing drains against the potential stormwater flows into each existing drain in "wereda" 3.

Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison	Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison
D1	1.9	2.1	− 1.1 folds[a]	Us[b]	D102.1	1.5	0.8	+ 1.8 folds	os
D2	2.3	0.5	+ 4.6 folds[c]	Os[d]	D102.2	1.0	0.4	+ 2.8 folds	os
D17.1	2.7	0.4	+ 6.4 folds	os	D105	0.6	0.1	+ 6.4 folds	os
D17.2	3.3	0.2	+ 18.5 folds	os	D106	1.0	0.1	+ 7.5 folds	os
D18	4.3	0.4	+ 10.2 folds	os	D107	1.6	0.7	+ 2.4 folds	os
D19	3.7	0.3	+ 11.5 folds	os	D108	0.5	0.2	+ 3 folds	os
D22	1.4	0.1	+ 14.3 folds	os	D109	0.8	0.3	+ 2.3 folds	os
D23	5.3	0.8	+ 6.4 folds	os	D110	0.5	0.1	+ 8.2 folds	os
D24	2.1	0.2	+ 11.2 folds	os	D111	1.4	0.7	+ 2 folds	os
D25	0.9	0.2	+ 4.2 folds	os	D112	0.4	0.2	+ 2.1 folds	os
D26	0.5	0.1	+ 3.4 folds	os	D116	1.0	0.3	+ 3 folds	os
D28	0.3	0.3	slightly less	us	D117	0.5	0.1	+ 8.4 folds	os
D29	1.3	0.4	+ 2.9 folds	os	D118	1.3	0.5	+ 2.7 folds	os
D30.1	0.1	0.3	− 2 folds	us	D119	0.4	0.1	+ 2.6 folds	os
D30.2	0.2	0.3	− 1.4 folds	us	D120	0.8	0.4	+ 2 folds	os
D30.3	0.2	0.2	slightly less	us	D121	1.3	0.5	+ 2.5 folds	os
D31	0.6	0.4	+ 1.3 folds	os	D124	0.9	0.1	+ 7.2 folds	os
D32	2.2	1.1	+ 2 folds	os	D125	0.8	0.2	+ 4.6 folds	os
D35	1.5	0.8	+ 2 folds	os	D126	4.4	0.4	+ 12.4 folds	os
D38	1.6	0.8	+ 2.2 folds	os	D128	0.9	1.9	− 2 folds	us
D39.1	1.0	0.1	+ 8.3 folds	os	D129	2.4	1.1	+ 2.2 folds	os
D39.2	1.1	0.2	+ 7.3 folds	os	D130	2.6	1.2	+ 2.1 folds	os
D40	0.8	0.2	+ 4 folds	os	D139	1.6	1.5	+ 1.1 folds	os
D41.1	0.9	0.3	+ 3.6 folds	os	D140	0.3	0.8	− 2.7 folds	us
D41.2	1.0	0.2	+ 5.3 folds	os	D141	2.3	1.4	+ 1.6 folds	os
D54	1.7	1.1	+ 1.5 folds	os	D142	1.5	0.2	+ 6.1 folds	os
D55	0.4	3.3	− 7.4 folds	us	D143	1.6	0.1	+ 12.8 folds	os
D56	0.7	0.2	+ 3.1 folds	os	D145	2.7	1.0	+ 2.8 folds	os
D57	1.4	0.8	+ 1.7 folds	oos	D146	1.4	0.4	+ 3.2 folds	os
D58	2.2	2.7	− 1.2 folds	us	D147	1.2	0.2	+ 5.4 folds	os
D59	1.2	0.8	+ 1.6 folds	os	D148	1.3	0.4	+ 3.1 folds	os
D60	0.7	0.2	+ 3.1 folds	os	D149	0.5	0.6	− 1.2 folds	us
D61	1.1	1.7	− 1.5 folds	us	D150	0.4	0.2	+ 2.4 folds	os
D62	1.1	0.9	+ 1.2 folds	os	D151	0.7	1.7	− 2.5 folds	us
D63	0.9	0.5	+ 1.9 folds	os	D153	0.4	0.5	− 1.3 folds	us
D64	0.9	0.2	+ 4.2 folds	os	D154	9.8	2.0	+ 5.2 folds	os
D65	3.2	2.2	+ 1.5 folds	os	D155	12.7	1.5	+ 8.4 folds	os
D66	2.1	0.5	+ 4.1 folds	os	D156	1.2	0.1	+ 9.1 folds	os
D69	0.8	0.3	+ 3.1 folds	os	D157	3.4	0.8	+ 4.3 folds	os
D70	0.9	0.3	+ 3.2 folds	os	D160	1.1	0.2	+ 7 folds	os
D71	2.1	0.2	+ 10.4 folds	os	D161	4.3	1.9	+ 2.2 folds	os
D72	0.7	0.02	+ 32.3 folds	os	D163	0.4	0.0	+ 8.4 folds	os
D75	0.9	0.2	+ 4.5 folds	os	D164	0.3	0.1	+ 4.4 folds	os
D76	0.7	0.6	+ 1.2 folds	os	D165	1.0	1.8	− 1.8 folds	us
D78	0.6	0.5	+ 1.2 folds	os	D166	6.9	0.8	+ 8.5 folds	os
D77	1.5	1.2	+ 1.2 folds	os	D204	5.8	2.1	+ 2.8 folds	os
D79	0.5	0.5	+ 1.2 folds	os	D213	1.5	1.2	+ 1.2 folds	os
D80	1.9	2.4	− 1.3 folds	us	D231	2.5	1.6	+ 1.5 folds	os
D81	1.9	1.6	+ 1.2 folds	os	D233	1.6	0.6	+ 2.7 folds	os
D83	0.7	0.3	+ 2.2 folds	os	D235	1.5	1.1	+ 1.3 folds	os
D85	1.1	0.5	+ 2 folds	os	D237	2.7	3.0	− 1.1 folds	us
D86	0.7	0.2	+ 4 folds	os	D239	3.6	0.3	+ 13 folds	os
D87	0.7	0.3	+ 2.3 folds	os	D242	3.9	1.0	+ 4 folds	os
D88	1.9	0.6	+ 3.2 folds	os	D263	10.3	1.4	+ 7.1 folds	os

(*continued on next page*)

Table 3 (*continued*)

Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison	Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison
D89	1.2	0.2	+ 6 folds	os	D264	1.6	0.4	+ 3.8 folds	os
D90	0.4	0.2	+ 1.7 folds	os	D265	3.8	0.6	+ 6.6 folds	os
D91	1.0	0.1	+ 9.4 folds	os	D300	8.0	2.7	+ 3 folds	os
D93	1.0	0.1	+ 8.2 folds	os	D302	2.5	0.8	+ 3.2 folds	os
D94	1.1	0.2	+ 6.4 folds	os	D304	0.7	0.6	+ 1.2 folds	os
D95	1.6	0.1	+ 12.8 folds	os	D305	3.6	0.9	+ 3.8 folds	os
D97	1.0	0.8	+ 1.3 folds	os	D308	5.1	1.7	+ 3.1 folds	os
D98	7.7	0.5	+ 16.4 folds	os	D309	2.9	0.4	+ 7.4 folds	os
D99	1.8	0.2	+ 10.2 folds	os	D311	1.6	0.8	+ 1.8 folds	os
D100	0.8	0.9	− 1.2 folds	us	D334	2.6	0.7	+ 4 folds	os
D101	0.9	0.1	+ 12 folds	os	D335	4.1	2.0	+ 2.1 folds	os

[a] The negative sign shows as the existing hydraulic capacity of drains which is less by the indicated folds when compared with the potential stormwater flows into each drain (column and 9).

[b] us refers under sized drains.

[c] The positive sign shows as the existing hydraulic capacity of drains which is in excess by the indicated folds when compared with the potential stormwater flows into existing drains(column 4 and 9).

[d] os refers oversized drains.

drains, but the absence of enforcement coupled with low level of awareness among the residents and stakeholders causes dumping of waste to continue.

4.5. Stormwater management challenges

The identified challenges can be grouped as planning, design and construction, monitoring and evaluation, collaboration and regulatory challenges, as discussed below.

4.5.1. Planning challenges

The process of drains planning is not led by a master plan, as Addis Ababa has no city-wide stormwater network master plan. Consequently, drains planning is based on traditional and fragmented approaches. The option of integrating other sustainable stormwater management systems (e.g. rainwater harvesting, retention and detention based solutions) is absent. In addition, the focus on expanding GI is minimal where most industries, institutions and residences prefer to increase impermeable surfaces. Additionally, following longer roads most drains are installed from upstream (initial point of a road) to downstream (final point of a road) without distributing into nearby receiving system which would reduce the volume of stormwater travelling downstream.

Moreover, Addis Ababa has no integrated planning approaches from the context of stormwater management. For example, integrating stormwater management with urban land-use planning, GI development and other landscape plans is absent at any level. The components of urban water (water supply, waste water & stormwater) managed separately by separate institutions. Landscape and urban planning instruments therefore don't offer possibilities to integrate stormwater management concerns and to promote sustainable stormwater management on a range of spatial scales.

4.5.2. Design and construction challenges

Based on field survey and questionnaires response, the design of drains in Addis Ababa is carried out through segmental or fragmented approaches resulting in flash flooding. It was found that drains are usually designed without hydraulic and hydrologic analysis.Most of the drains were found older than fifty years. The largest parts of the drains especially in the older parts of the city were old and found filled with solid and liquid waste resulting in flash flooding. Moreover, the respondents' reported that the designers are less experienced to design drains due to inadequate exposure to such practices.

4.5.3. Monitoring and evaluation challenges

Drains are commonly provided by AACRA, but regarding monitoring and evaluation the city has no responsible institution. This shows that the city focuses only on provision than on the management of the provided drains and associated facilities. Moreover, no monitoring and evaluation on the hydraulic performance and need of stormwater management facilities. Reactive measures are taken mainly based on complaints. It was also investigated that the number of studies in Addis Ababa related to stormwater is few which become a challenge to know the status and operation condition of drains. There is no scheduled drains' clearing time table.

Table 4
Evaluation of the hydraulic capacity of the existing drains against the potential stormwater flows into each existing drain in "wereda" 4.

Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison	Drain code	Existing designed capacity of drains (m^3/s)	Potential stormwater flows into existing drains (m^3/s)	Status of the existing drains	Comparison
D1.1	5.0	0.5	+ 10.2 fold	*os*	D87	0.8	0.2	+ 4.6 folds	*os*
D1.2	7.1	1.1	+ 6.2 folds	*os*	D88	0.2	0.1	+ 2 folds	*os*
D1.3	7.9	3.0	+ 2.6 folds	*os*	D89	0.2	1.1	− 5.4 folds	*us*
D1.4	10.0	6.5	+ 1.5 folds	*os*	D91	0.8	0.1	+ 5.3 folds	*os*
D1.5	10.0	6.8	+ 1.4 folds	*os*	D92	1.3	0.4	+ 3.5 folds	*os*
D1.6	11.1	8.9	+ 1.4 folds	*os*	D93	1.7	1.14	+ 1.5 folds	*os*
D1.7	8.6	17.0	− 2 folds	*us*	D94	1.4	0.3	+ 5.4 folds	*os*
D2	0.9	1.0	− 1.1 folds	*us*	D95	0.8	1.5	−1.8 folds	*us*
D5	1.2	0.6	+ 1.9 folds	*os*	D96	1.5	0.1	+ 11.8 folds	*os*
D22	3.0	0.9	+ 3.2 folds	*os*	D102	1.2	0.9	+ 1.4 folds	*os*
D23	1.5	0.5	+ 2.8 folds	*os*	D104	0.4	0.5	− 1.3 folds	*us*
D24	2.4	1.5	+ 1.6 folds	*us*	D105	1.8	0.5	+ 3.7 folds	*os*
D24.1	1.5	1.6	− 1.1 folds	*us*	D108	1.3	0.8	+ 1.6 folds	*os*
D28	1.3	1.8	− 1.4 folds	*us*	D110	1.2	1.9	− 1.7 folds	*us*
D28.1	2.2	2.1	− 1.1 folds	*us*	D112	0.3	1.6	− 5.3 folds	*us*
D29	3.8	2.7	+ 1.4 folds	*us*	D114	0.4	0.2	+ 1.5 folds	*os*
D36	4.4	2.8	+ 1.5 folds	*os*	D115	0.4	0.2	+ 4.3 folds	*os*
D37	6.8	4.7	+ 1.5 folds	*os*	D119	1.5	0.3	+ 4.3 folds	*os*
D42	9.3	10.8	− 1.2 folds	*us*	D121	1.5	1.4	+ 1 folds	*os*
D43	3.8	1.2	+ 3.2 folds	*os*	D122	0.9	0.6	+ 1.5 folds	*os*
D48	3.0	1.3	+ 2.3 folds	*os*	D123	1.0	0.2	+ 4 folds	*os*
D58	3.8	1.2	+ 3.2 folds	*os*	D124	1.7	0.9	+ 1.8 folds	*os*
D64	13.3	0.8	+ 16 folds	*os*	D126	1.6	0.5	+ 3.2 folds	*os*
D71	0.1	1.2	− 16.5folds	*us*	D131	1.0	0.7	+ 1.4 folds	*os*
D72	1.9	1.4	+ 1.3 folds	*os*	D132	0.9	2.0	− 2.2 folds	*us*
D74	2.1	1.5	+ 1.4 folds	*os*	D136	4.5	0.6	+ 7 folds	*os*
D75	3.3	2.2	− 1.5 folds	*os*	D138	1.8	0.7	+ 2.8 folds	*os*
D70	4.3	1.8	+ 2.4folds	*os*	D140	1.0	0.2	+ 4.3 folds	*os*
D78	4.6	0.4	+ 11 folds	*os*	D142	0.3	0.6	− 1.9 folds	*us*
D80	5.6	3.4	+ 1.7 folds	*os*	D146	2.9	1.5	+ 1.9 folds	*os*
D79	3.3	1.0	+ 3.5 folds	*os*	D152	0.2	0.1	+ 1.8 folds	*os*
D81	5.8	3.4	+ 1.7 folds	*os*	D153	0.5	0.1	+ 4 folds	*os*
D82	1.0	0.4	+ 2.6 folds	*os*	D153.1	0.1	0.5	− 3.4 folds	*us*
D83	3.7	3.6	+ 1 folds	*os*	D155	1.6	0.1	+ 21.6 folds	*os*
D84	1.6	0.1	+ 14.8 folds	*os*	D156	0.4	0.0	+ 9.4 folds	*os*
D86	2.4	0.9	+ 2.5 folds	*os*	D157	1.1	0.0	+ 52 folds	*os*

4.5.4. Collaboration challenges

The present study, generally, investigated that the five organizations (Table 1) which are assumed to work with the city's stormwater have no collaboration, creating redundancy of activities and resources, no clear roles and responsibilities, and no defined activity performed by each of the institutions regarding stormwater management. Subsequently, sustainability in stormwater management is unlikely due to the absence of monitoring and evaluation. These institutions have no integrated plans.

4.5.5. Regulatory challenges

The present study revealed that demolished construction materials were dumped inside drains and on flood plains, reducing the hydraulic capacity of drains & river through obstruction and silting up. Besides, small scale auto garages dumping wastes from repairing and washing of cars directly into drains, blocking the hydraulic capacity of drains.

The absence of legal instruments (or policies) to manage stormwater at household, institutions, commercial and industrial levels represent additional stormwater management challenge. Every one collects & conveys stormwater from own compound to anywhere else without borders.

5. Discussion

5.1. Existing stormwater management practices

The traditional stormwater management practice in Addis Ababa complicates stormwater management because all the piped drains are planned to remove stormwater out of the boundary of the city. This cumulates stormwater while draining from upstream at an elevation of 3100 m to 2100 m downstream, joins the city's river water without treatment. A study conducted by Parkinson and

Mark (2005) in developing countries reports as stormwater often enters surface drains. The unsystematic and fragmented provision of drains by different actors without collaboration further worsens stormwater management. Such practices failed to update the available stormwater management systems which might help to foresee stormwater related problems arising from rapid urbanization and increasing densification in Addis Ababa. Addis Ababa doesn't consider the existing drains as assets implying that options are rarely unlock to design new drains or revise existing drains based on hydrologic and hydraulic data. Moreover, Addis Ababa hasn't attempted to move to sustainable stormwater management systems. While substantial cities, especially in the global north, are promoting sustainable stormwater management because of the unsustainable feature of conventional or piped stormwater management (Cettner et al., 2014).

Furthermore, such uncoordinated activities became a barrier to understand the spatial distribution as well as the coverage of the existing drains, the gaps and the needs for future plans. According to Marsalek et al. (1993) for 'sustainable stormwater planning and management' the existing drains network map including the area coverage should be known. Because it is a basis for planning and identifying the existing gaps. However, in Addis Ababa it was unlikely to get such data.

5.2. Hydraulic capacity of existing drains in the studied case sites

The findings of the present study revealed that the key cause of flash flooding in the case studies was not due to undersized drains. But, dumping of wastes into drains as more than 72% of the existing drains in both case studies were found oversized. This is apparent evidence to the unsystematic and fragmented approach and the lack of critical hydraulic and hydrologic related data analysis during designing drains, as revealed from the interviewees' response. Moreover, in "weredas" 3 and 4, of all the roads only 59% and 50% of the roads were covered by drains respectively revealing that the corresponding 41% and 50% of the roads were without drains; which is still unsatisfactory in both cases. This coupled with the noteworthy quantity of the unmanaged 25% of solid and 55% of liquid wastes, where only 10% of the residents are connected to existing sewer lines, are expected to enter existing drains as significant portion of the drains were found open (Fig. 3). This together with the nonexistence of scheduled drains clearing time might further reduce the hydraulic capacity of the drains resulting in flash/fluvial flooding.

5.3. Comparison of the two case studies

When comparing the older and newer part of the city more drains were found on asphalt roads followed by gravel roads. Conversely, the least coverage was found on earthen roads suggesting that the city administration was aware with the most susceptible type of road pavement to degradation, as asphalt roads require significant drains concentration. Unlike "wereda" 4, more of the drains in" wereda "3 were found open (Table 2) which could result in reduced hydraulic capacity of the drains due its vulnerability to dump wastes inside it (Murtaza, 2001). Thus, in both "weredas" scheduled clearing time table is required before the beginning of the rainy season to maintain the designed hydraulic capacity of drains. Pertaining this, the respondents reflected the nonexistence of scheduled clearing time table instead blocked drains are cleared based on complaints. This could suggest that it is because of the blocked drains that more stormwater overtops during the rainy season leading to flash flooding. In conformity with this, studies conducted in Mumbai (Arunachalam, 2005), Bangladesh (Murtaza, 2001) and Nigeria (Sridhar et al., 2001) report that open drains filled with wastes were the major drivers of flooding due to reduced hydraulic capacity.

In both case studies the issue of sustainable stormwater management was lacked which is pertinent to cities like Addis Ababa which receives rainfall only for a maximum of 121 days (NMA, 2016) implying that drains remain idle for the extended 245 dry days. For example, a study conducted by Freni et al. (2010) discusses that minimizing stormwater at-source through nature-based solutions can reduce the cumulative impact of stormwater draining downstream; proportionally the size of drains which need to be constructed could be minimized. Consistently, this could have significant contributions in promoting at-source stormwater management in Addis Ababa.

In summary, although the majority of the drains are oversized, flash flooding is a major problem in Addis Ababa. The findings of the present study revealed that in the new part of the city the undersized drains dropped to 14% when compared with the 28% undersized drains in the older part of the city. This indicated that the customary and fragmented drains installation might be the root causes of over sizing the drains. Moreover, due to the nonexistence of the original drains design models (or equations) from the responsible organization; the present study employed the models which often used by the then Federal urban planning institute of Ethiopia to design drains, which might be the other reason.

Therefore, understanding of the hydraulic capacity of drains is central to evidentially identifying the causes of flash flooding recurring every rainy season. The hydraulic capacity of drains is evaluated whether to collect the stormwater from the contributing watershed and safely conveying to receiving systems or not. Drains are constructed to collect and safely convey stormwater commonly occupied by wastes leading to the reduction or total blockage of the hydraulic capacity of drains. Thus, to prevent the obstruction of drains from solid and liquid wastes, establishing clear waste management measures need to be integrated with stormwater management. Moreover, to append the costly investment on conventional management systems municipalities need to integrate GI development (e.g. road side greening, parks development) with stormwater management.

5.4. Stormwater management challenges

The interview responses were proved by the field surveyed data and evaluation of the hydraulic capacity of the drains. One of the articulated challenges was the flowing of stormwater over road surfaces and sides, causing flash flooding and obstructing traffic movement. Most of the stormwater challenges could be simplified, if the city administration gives special emphasis on stormwater management as they can be corrected easily. For example, timely clearing of the drains, and focusing on sustainable stormwater management have imperative hand-outs to Addis Ababa where it receives rainfall for a maximum of 121 days (NMA, 2016) with an average annual rainfall of 1100 mm. The absence of legal instruments to manage stormwater near or at-the source opened a gap for significant stormwater to be conveyed from sources to receiving systems. Consistent with the present study, Goldenfum et al. (2007) report that lack of legal instruments in Brazil is a major challenge of stormwater management.

The deficiency of collaboration among stakeholders participating directly or indirectly in stormwater management further worsens stormwater management in the city. This results in redundancy of resources and undermines the balance between the green and grey drainage approaches which is assumed to be the primary move toward sustainable stormwater management (Pauleit et al., 2011; Hamel et al., 2013) than conveying through piped drains into downstream environment. Therefore, besides establishing a single responsible institution which can only engage in stormwater management, the city should establish a steering committee that could build collaboration among the five organizations. In agreement with this, Jiusto and Kenney (2015) report the significance of stakeholder collaboration to manage stormwater sustainably. Equally, the city should integrate the different greening, soil conservation and flood prevention activities with stormwater management. Promoting rainwater harvesting and retaining stormwater from upstream to downstream at smaller scales will significantly minimize volume of stormwater cumulating downstream. The traditional piped stormwater management systems and the absence of existing drains' plan reviews further worsen the challenges of stormwater management. A study by Marsalek et al. (1993) reports the significance of contemporary and integrated planning for stormwater management which can be of helpful for Addis Ababa.

Thus, identifying the management challenges of stormwater is key to formulate appropriate management tools which can accommodate the rapid urbanization and increasing densification of cities in developing countries. This is a roadmap for urban planners and engineers to consider the significance of stakeholder collaboration and community participation from planning to monitoring and evaluation. Furthermore, integrated land-use planning and institutional setup arrangements help to realize the need for minimizing the challenges of stormwater management.

6. Conclusion

Stormwater management in Addis Ababa is purely traditional, with no additional purpose than collecting and conveying stormwater from source to rivers. In terms of stormwater drains coverage, the system is inadequate to manage stormwater within the boundary of the city, as revealed from the two case studies. The older parts of Addis Ababa has a stormwater drains coverage of 50% and the newer part a coverage of 59%, showing unmanaged stormwater likely to create problems including flash flooding, and degradation of other infrastructure. Of the total surveyed drains it was 63% and 81% of them were found open stone masonry in the older and newer part of the city respectively where piles of waste dumped into drains illegally. The elevation of the city drastically decreases from 3100 to 2100 m.a.s.l which complicates the management of stormwater as the volume of stormwater cumulates draining downstream with potentially reduced on-site infiltration.

Evaluation of the hydraulic capacity of the existing drains in the case studies showed that more than 72% of the drains were oversized, though flash flooding is a major challenge during the rainy season in Addis Ababa. This could be attributed to the obstructed hydraulic capacity of drains from dumping of portion of the uncollected 25% of solid and 55% of liquid wastes. Thus, it can be concluded that illegal dumping of wastes into drains coupled with undersized drains (14% in “wereda” 3 and 28% in “wereda” 4 of the total existing drains) reduces the hydraulic capacity of drains. This proved that the lack of hydraulic and hydrologic characterization during designing drains by the concerned organization might be the major causes of over sizing and under sizing drains capacity, as also triangulated from the stakeholders’ responses.

Generally, stormwater challenges are associated with planning, design and construction, monitoring and evaluation, and regulatory issues. The drains were planned and designed unsystematically through segmental approach as the hydrological and hydraulic analyses were not properly considered. Besides, the performance and ill-functioning of the drains were not monitored timely. Furthermore, the city does not have legal instruments that promote on-site stormwater management and prevent the dumping of wastes into drains. The poor collaboration among the different stakeholders is expected to widen the gap which might have rather reduced stormwater challenges. Equally important, Addis Ababa should focus on stormwater management monitoring and evaluation to signalize the coverage and performance of drains city-wide which are key parameters to identify the gaps for decision making and planning.

The present study highlights that Addis Ababa should focus on linking nature-based solutions (e.g. GI, LID, LSM, WSUD) with the traditional piped system to promote sustainable stormwater management in practice. A first step could be to address the challenge of the dichotomy between nature and structural techniques in engineering culture. In parallel, participating and considering influential persons including celebrities, elders, youths, and women as frontrunners will assist to strengthen the efforts to move to sustainable stormwater management.

Declaration of Competing Interest

We confirm that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2019.100626.

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