Agricultural runoff and urban flooding in Mauritius: evidence, methods and mitigation measures

July 2013

Author
J.E. Hunink, P. Droogers

Client
Ministry of Public Infrastructure, Mauritius

Report FutureWater: 130

FutureWater
Costerweg 1G
6702 AA Wageningen
The Netherlands

+31 (0)317 460050

info@futurewater.nl

www.futurewater.nl

Preface

Mauritius has experienced several severe flooding events over the last years. Urban areas were hit, but also some of the rural areas were affected. To combat this flooding structural remedial measures are often selected as these have been proven to be effective and show direct and concrete results. The project includes topographical surveys and field reconnaissance and engineering studies that are separated in a feasibility study, the preliminary design and the detailed design with preparation of tender documents.

In this report we explore options to reduce peak flows by effectively managing the upstream areas where in fact the source of the flooding is located. Focus will be on looking at international experiences and potential translations into the Mauritius case. The objective is to evaluate evidence, methods and possible mitigation measures for flood control by targeting the source areas where the agricultural runoff originates.

The report starts with describing the impact of agricultural catchments and catchment degradation on flooding, providing some international experiences. This is followed by a discussion relevant to the specific case of Mauritius and finally options for mitigation measures in upstream agricultural areas to reduce flood risk are discussed.

This report was developed as part of the project called “Consultancy Services for Land Drainage and Watershed Management” commissioned by the Ministry of Public Infrastructure, the National Development Unit (NDU) - Land Transport and Shipping, Mauritius. The Contract between the Ministry and the Consultants was signed on the 18th of March 2013 and the project is led by the Z&A P. Antonaropoulos And Associates S.A., Athens, Greece.

Summary

The rural areas of Mauritius are increasingly subject to flooding problems due to the rapid developments that took place over the last decades. In recent times, the problem has become so acute in some areas resulting in fatal accidents and damages to households. The government has intervened by taking some ad hoc measures to relieve the problem but no long term sustainable schemes have been developed taking the overall watershed area into consideration.

The critical situation in the identified emergency locations requires structural measures to be implemented as soon as possible. However, in the medium to long-term these structural measures should be accompanied by measures that reduce peak runoff at source: the rural catchments. In fact the real problem of flooding starts at this level and mitigation options should be considered at these locations for sustainable flood protection. These measured can be viewed as ´prevention at source´, or sometimes referred to as ‘green infrastructure”.

This report discusses the links between agricultural runoff and urban flooding in Mauritius and summarizes global evidence, possible impacts, and methods for its analysis and summarizes possible mitigation measures for flood control. A first-order modeling exercise is carried out to show how this type of at-source measures delay or attenuate the runoff generation, having a positive effect on the catchment flood hydrograph. To assess the overall effect, it is necessary to take into account the hydrological functioning of the catchment as a whole. Therefore, it is recommended to carry out a more detailed analysis to estimate the potential of these measures in each of the catchments draining to the critical locations. This will provide a detailed proposal that guarantees the sustainability in the long run of the immediate investments to be made in infrastructural works for flood protection.

Table of contents

Tables

Figures

1 Impact of soils and land use on flooding

1.1 Context

There is a general concern in many parts of the world that the increase in the incidence of urban flooding by runoff from upstream areas is related to changing agricultural practices and agricultural intensification (Boardman et al., 1994; O'Connell et al., 2007; Wheater and Evans, 2009). This is also an issue in Mauritius, given the high and intensive agricultural occupation of the island (Mamoun et al., 2013). Also the possible effects of climate change, growing populations, the continuing development in flood-prone areas, and poorly maintained infrastructure are factors affecting the flooding risk of urban areas. However, the continuous changing agricultural sector and corresponding farming practices are most likely explaining part of the changes in runoff and flooding regimes.

The generation of runoff affects both upstream as well as downstream parts of a basin. Surface runoff from agricultural areas may cause erosion and the transport of sediments and contaminants. When it concentrates into gullies and streams, runoff may cause peak flows and flooding downstream. Excess water generated by surface runoff has therefore several negative impacts, both upstream (loss of fertile soil, sustainability of livelihoods, etc) as downstream (related to flood risk).

From a management point of view it is more practical to focus flood protection on measures downstream (flood-plain management, emergency plans, early warning systems, infrastructure, awareness raising), than to target mitigation measures in agricultural areas upstream. However, in many studies it was demonstrated that from a holistic point of view, upstream measures to reduce the sources of runoff may be very cost-efficient for flood protection. Recent projects related to ´payment for watershed services´ recognize this fact and aim at connecting the upstream and downstream benefits through a financial management scheme.

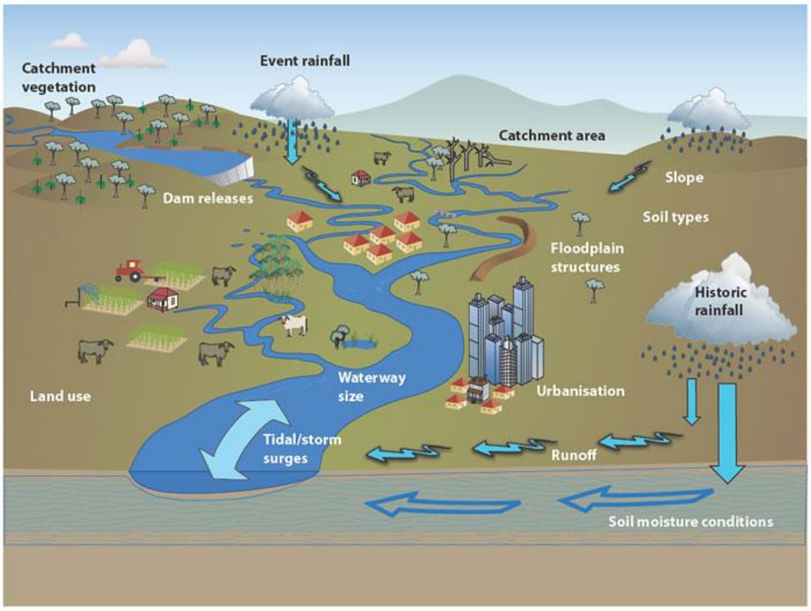


Figure 1. An illustration of the factors that contribute to floods, emphasising the role of land use and infrastructure (Source: http://www.chiefscientist.qld.gov.au).

1.2 Processes

When rain falls, the first amount of water is intercepted by the leaves and stems of the natural vegetation or crop. This process is usually referred to as interception. The part of the rain that reaches the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall (intensity) exceeds the infiltration capacity of the soil (*infiltration-excess runoff,* also sometimes called *Hortonian overland flow*). Thereafter, surface puddles, ditches, and other depressions are filled (depression storage), after which runoff is generated. Also, the soil can become saturated, and runoff occurs because the soil has no capacity to absorb any additional water (*saturation-excess runoff,* also sometimes called *Dunne overland flow*).

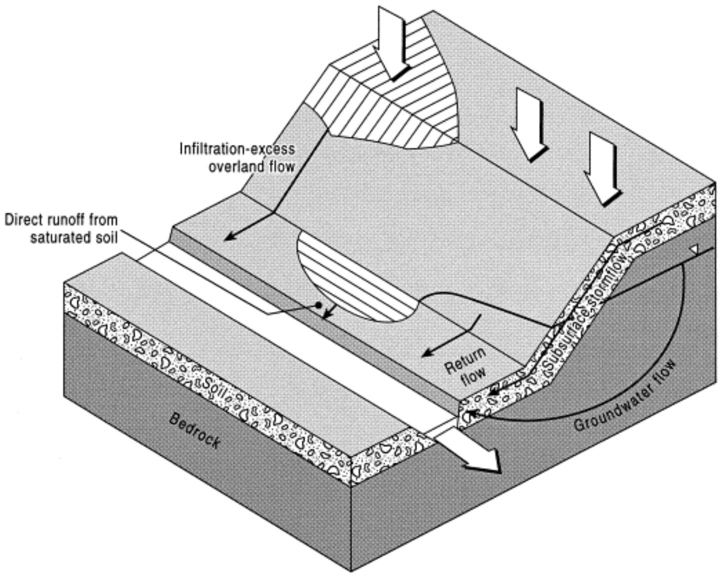


Figure 2. Sources of flooding. (1) infiltration-excess overland flow. (2) saturation-excess overland flow; (2a) direct runoff from saturated soil; (2b) return flow; (3) subsurface stormflow; (4), groundwater flow (source: Burt, 2001)

The generation of runoff depends on three major factors: (i) the intensity, duration and distribution of the rainfall event, (ii) the antecedent soil moisture condition which is a function of preceding rainfall events, and (iii) the surface characteristics, including slope, cropping structure, soil management, and others. The first factors cannot be managed, but the last one depends to a large extent on land use and management practices. These practices determine the terrain conditions and therefore the concentrations of runoff volume and the runoff velocities.

Within the same type of crop, different farming and land management practices may cause totally different runoff regimes. A common method to calculate the rainfall-runoff partitioning is the SCS Unit Hydrograph Method (see elsewhere in report). Several studies carried out for this calculation method provided reference tables on the relationships between management and the runoff curve number. As can be seen, the type of conservations and farming practice causes large differences in runoff curve number, and thus in the amount of generated runoff. The runoff concentrates in gullies and streams and may result in peak flows downstream which cause flooding.

Table 1: Runoff curve numbers according to different types of land cover (USDA-SCS, 1972). High values indicate more surface runoff.

Land Use Type	Conservation Practice	Hydrologic Condition	Hydrologic Group A	B	C	D
Row Crops	None(0)	Poor	72	81	88	91
		Good	67	78	85	89
	Contour (1), Strip (2) or Terrace (4)	Poor	70	79	84	88
		Good	65	75	82	86
	Two or more of Contour, Strip and Terrace	Poor	66	74	80	82
		Good	62	71	78	81
Small Grains	None(0)	Poor	65	76	84	88
		Good	63	75	83	87
	Contour (1), Strip (2) or Terrace (4)	Poor	63	74	82	85
		Good	61	73	81	84
	Two or more of Contour, Strip and Terrace	Poor	61	72	79	82
		Good	59	70	78	81
Close Seeded Legume	None (0)	Poor	66	77	85	89
		Good	58	72	81	85
	Contour (1), Strip (2) or Terrace (4)	Poor	64	75	83	85
		Good	55	69	78	83
	Two or more of Contour, Strip and Terrace	Poor	63	73	80	83
		Good	51	67	76	80
Pasture or Range	None (0)	Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contour, Strip or Terrace or combination of two or more	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	6	35	70	79
	None (0)	Poor	45	66	77	83
Meadow (not used)		Fair	36	60	73	79
Woods		Good	25	55	70	77
	All	All	77	86	91	94
Fallow						

1.3 Evidence

Many studies have been carried out on reducing the interrelated processes runoff and erosion. Most studies have been focusing on the benefits on the upstream agricultural areas, quantifying the effects on crop yields and economic sustainability of these areas (Gafur et al., 2003; Valentin et al., 2008). Downstream benefits of runoff reduction in upstream agricultural areas have been taken into account to a lesser degree but are widely acknowledged (e.g. Evrard et al., 2007; Posthumus et al., 2008).

In humid tropical regions, a wide range of experiments and studies have demonstrated the relevance of farming practices upstream for the flow regime downstream in the basin. Here a summary of studies is provided that provide evidence for the relevance of land management for runoff generation and downstream flood reduction, focusing on humid tropical regions.

- Wohl et al. (2012) provides an overview of how anthropogenic changes in land use affect the hydrology of humid tropical regions, striking the importance of agricultural land use conversions for the hydrology at the basin level.
- Porras et al. (2013) provides a review of so-called “Payment for Watershed Services” schemes in the world, including several in tropical basins, in which upstream-downstream interactions are integrated, often focusing on flood protection.

- Hunink et al. (2012) summarizes work done for the Green Water Credits project, in which the downstream benefits were quantified of the implementation of different farming practices in upstream parts of the basin, focusing on downstream water availability and reservoir sedimentation rates.
- Lambin et al. (2003) summarizes recent estimates on changes in cropland, agricultural intensification, tropical deforestation, pasture expansion, in tropical regions and identifies possible basin-wide impacts, as also flooding risk.
- Sturdevant-Rees et al. (2001) discusses the importance of the spatial variability in land use and soil moisture capacity on runoff production over the basin, based on data of several tropical storms.
- Jothityangkoon et al. (2013) describes how climate and land use change affect the occurrence of extreme floods in a large tropical catchment in Thailand
- Kramer et al. (1997) investigated how land conversions and changes affect hydrological patterns in Madagascar.
- Santillan et al. (2011) studied long-term land use change and impacts on runoff and flooding in a tropical watershed on the Phillipines and found a direct relation between land use and runoff volumes.
- Salazar et al. (2012) provide evidence from different hydro-climatic regions in Europe on the effectiveness of flood management measures based on the concept of “retaining water in the landscape” and found that they are most effective for the more frequent and medium flooding events.

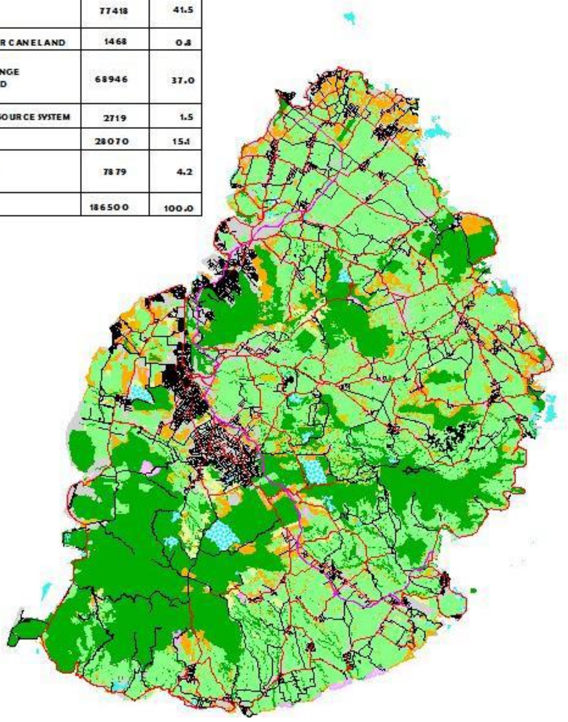
In summary, there is an increasing attention in watershed management throughout the world on soil and water management in rural areas, because of their relevance in the catchment-level hydrologic response and their importance for flooding. Also for stormwater management in the urban setting there is a general trend throughout the world to implement so-called ´source control measures´ (Petrucci et al., 2013). The principle of these measures is to implement measures and develop facilities that manage stormwater locally and close to the source, to prevent catchment-scale stormwater problems.

The principal barrier to the adoption of source control measures both in rural as in urban areas, is the difficulty to distinguish their gradual beneficial effects from those of the structural interventions in the catchment (O’Connell et al., 2007; Petrucci et al., 2013). However, field data, remote sensing and detailed hydrological modeling can provide sound evidence and guidance for policy design supporting the implementation of this type of measures in rural areas to reduce flood risk in urban areas.

2 Runoff and landuse in Mauritius

2.1 Determining factors

It is reported that on average around 60% of rainfall in Mauritius is converted into runoff. This percentage is an average and highly depends on the rainfall distribution patterns and soil and land management in specific locations. In general, physical conditions on the Island are favourable in terms of rainfall-runoff processes and flood mitigation. The elongated shapes of many catchments lead to a comparatively large time of peak flow concentration. Also the incised and clearly defined river channels with steep slopes increase the hydraulic capacity ensuring that peak runoff can be effectively routed to the sea.



LEGEND	MAJOR LAND USE	AREA (Ha)	% TOTAL
SUGAR CANE OTHER CROPS LIVESTOCK PRODUCTION (POULTRY, FODDER)	AGRICULTURE	77418	41.5
ABANDONED SUGAR CANE LAND	ABANDONED SUGAR CANELAND	1468	0.8
RESERVES (MOUNTAIN & RIVER) WASTE LAND ROCK HEAP LEISURE (BEACH, PUBLIC GARDEN,ETC)	FOREST, SHRUB, RANGE AND GRAZING LAND	68946	37.0
WATER BODY & MARSH	INLAND WATER RESOURCE SYSTEM	2719	1.5
BUILT-UP AREA	BUILT-UP AREA	28070	15.1
HIGHWAY MAIN ROAD SECONDARY ROAD/PIVOT PARKING	INFRASTRUCTURE	7879	4.2
TOTAL AREA (Ha)		186500	100.0

Figure 3. Mauritius - Land Use map (Source: MSIRI Occasional Paper No. 41).

However, changes in landcover has created more unfavourable hydrological conditions resulting is higher flood risks in downstream areas. In the past much of Mauritius was covered with forests, which has been exploited heavily resulting in almost no forest left in the last century (Figure 3). Land was converted to agriculture or was just left barren resulting in soil degradation with associated poorer soil water holding capacity and lower infiltration capacity (Figure 4).

In technical terms, the runoff coefficient is now relatively high due to the humid conditions of the island, the poorly developed soils in some areas and the intensive agriculture occupation. The principal factors determining the runoff patterns in Mauritius are discussed in the following sections.

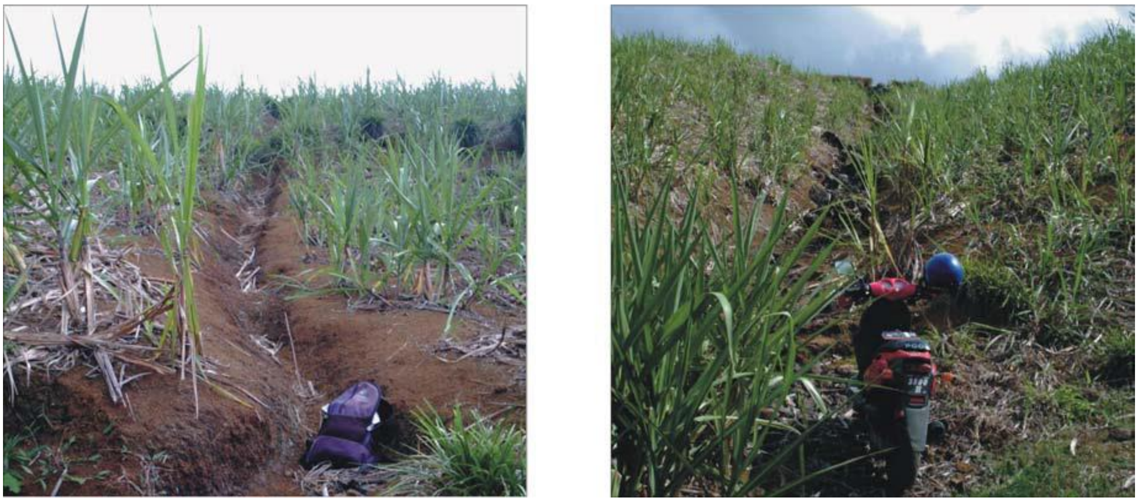


Figure 4. Runoff gullies in sugarcane cultivation on Mauritius (Le Roux, 2005)

2.2 Rainfall and cyclones

The climate in Mauritius is tropical maritime with two seasons, a rainy summer from November–April and a dry winter from May–October dominated by frontal systems and the southeastern trade winds. About 70% of mean annual rainfall is received during summer, with February being the wettest and hottest month and October the driest month.

Mean annual rainfall is 1400 mm on the eastern coast, 4000 mm in the central uplands and 600 mm on the western coast (Nigel and Rughooputh, 2010). The central uplands are the most humid regions due to orographic effects caused by the south-eastern mountain range and the 'ridge' of the central uplands.

Figure 5. Storm approaching sugarcane field (source: http://captainkimo.com)

On average, Mauritius has one cyclone approach annually (Mauritius Meteorological Services). The highest historical values of rainfall intensity have been recorded during cyclone passages, that can reach up to around 90 mm/h. Rainfall intensity during normal rainfall shows a spatial variability similar to rainfall depth, where typically 30mm h^{-1} is recorded at the coast and 50 mm h^{-1} recorded in the central uplands (Le Roux, 2005).

Studies have also highlighted the impacts of climate change on Mauritius (Mysiak et al., 2013; Senapathi et al., 2009). Dore and Singh (2013) found that historically wetter months are likely to become wetter while drier months could become even drier than currently observed, but the net annual precipitation is likely to decline. This would certainly have its impact on runoff and flooding patterns on the island.

2.3 Soils

The soil characteristics determine to a large extent the amount of generated runoff and the portion of rainfall retained in the root zone and available to the plant. For example, soils with abrupt horizons can be more prone to runoff generation as uniform soils as downward percolating water tends to accumulate at the abrupt interface, leading to runoff when the topsoil is filled with water.

Besides the inherent soil properties, soil surface properties can also be altered positively or negatively by farming practices. Changes in soil surface properties by mechanized traffic in for example sugarcane cultivation plots can lead to surface crust formation, reduced water infiltration, and increased runoff (Meyer et al., 2011).

The soils used for agriculture in Mauritius have a basaltic origin, and can be subdivided in two main groups: mature ferralitic soils, or latosols, and immature latosolic soils. Latosolic soils are still in the process of weathering, and are less developed. Le Roux (2005) studied a sugarcane cultivated catchment in Mauritius and found large variabilities in soil infiltration rates, ranging between 5 and 60 mm/h, determined by soil structure, texture and land management factors.

As a conclusion, soil structure and soil surface characteristics are key factors for runoff generation. As they are dependent to some level on the farming practices, they can be positively influenced, protecting the soil and reducing runoff.

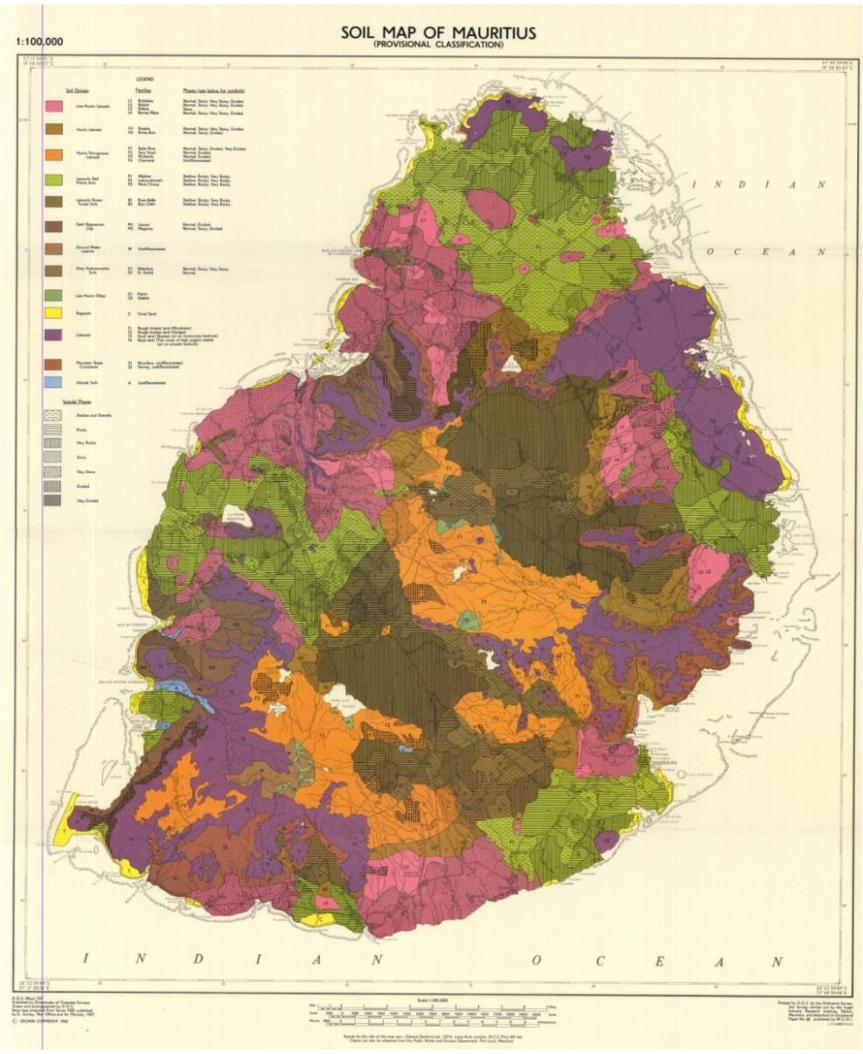


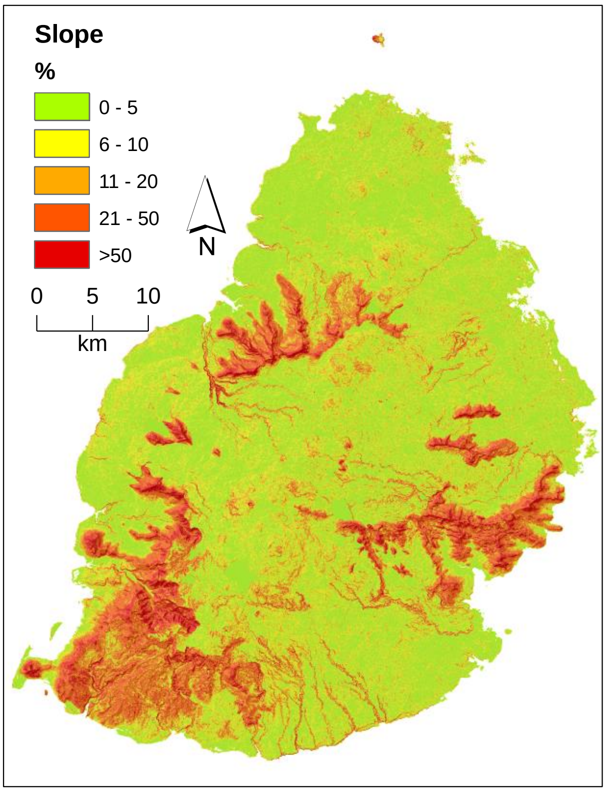
Figure 6. Soil map of Mauritius (Directorate of Overseas Surveys, 1962)

2.4 Slopes

The slope determines to a large extent the runoff patterns and velocities. Several studies in sugarcane cultivations have highlighted the importance of slope (Meyer et al., 2011):

- Mauritius: Soil loss from bare plots of 37.6, 14.3, 9.5, 4.1 and 0.5 t/ha/y were obtained on five soils in Mauritius on various slopes. Sugarcane was shown to reduce erosion by 80 to 99 % compared to a bare fallow.
- Australia: Soil losses of 42-227 t/ha/y were recorded on conventionally cultivated slopes of up to 8 %, and 47-505 t/ha/y (average148 t/ha/y) on conventionally cultivated slopes of 5-18 %.
- Fiji: Research into soil loss through erosion showed a soil loss of 16 t/ha/y from cane planted up and down the slope on an 8° slope but only 0.2 t/ha/y in trashed ratoons[1] planted across the slope.

[1] Ratooning is a method of harvesting a crop which leaves the roots and the lower parts of the plant uncut to give the *ratoon* or the *stubble crop*.



7. Slope map of Mauritius

2.5 Crops and cultivation practices

Sugarcane is the principal crop cultivated in Mauritius. In 2011, the area harvested was around 57,000 hectares, according to the Mauritius Sugar Syndicate, which is 85% of the cultivated area of the island (67,000 in 2011 according to FAOSTAT). Due to economic conditions currently a conversion has started towards a more diversified cropping structure, including vegetables, pineapple and forestry (Le Roux, 2005).

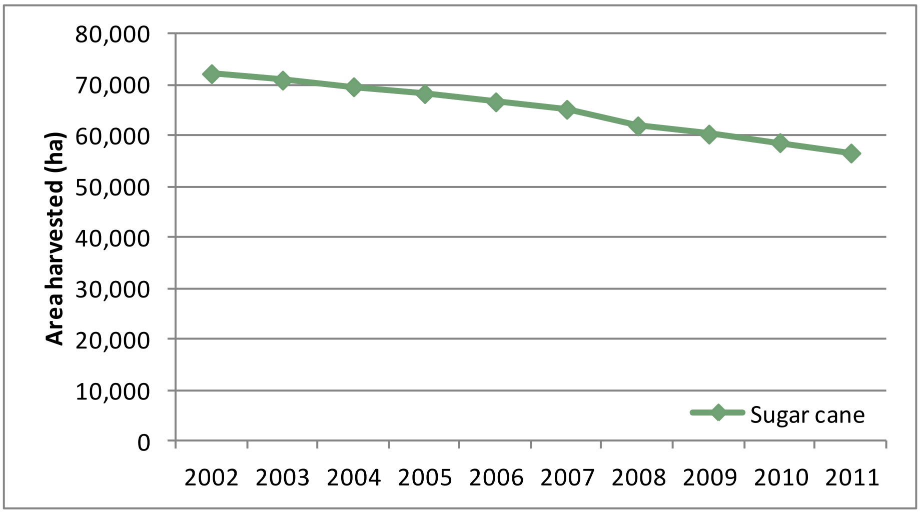


Figure 8. Area harvested of sugar cane in Mauritius from 2002 to 2011 (source FAOSTAT)

The following figures show the downward trend in the total area harvested in Mauritius in sugar cane, and the trends in the other significant crops from 2002-2011 (FAOSTAT). This conversion is however only partly successful the increase in other crops does not compensate the decrease in sugar cane cultivated areas. Generally, there is an increase in abandoned lands in Mauritius. This is likely to affect the runoff and erosion coming from these areas which a higher risk of flooding events in urban areas.

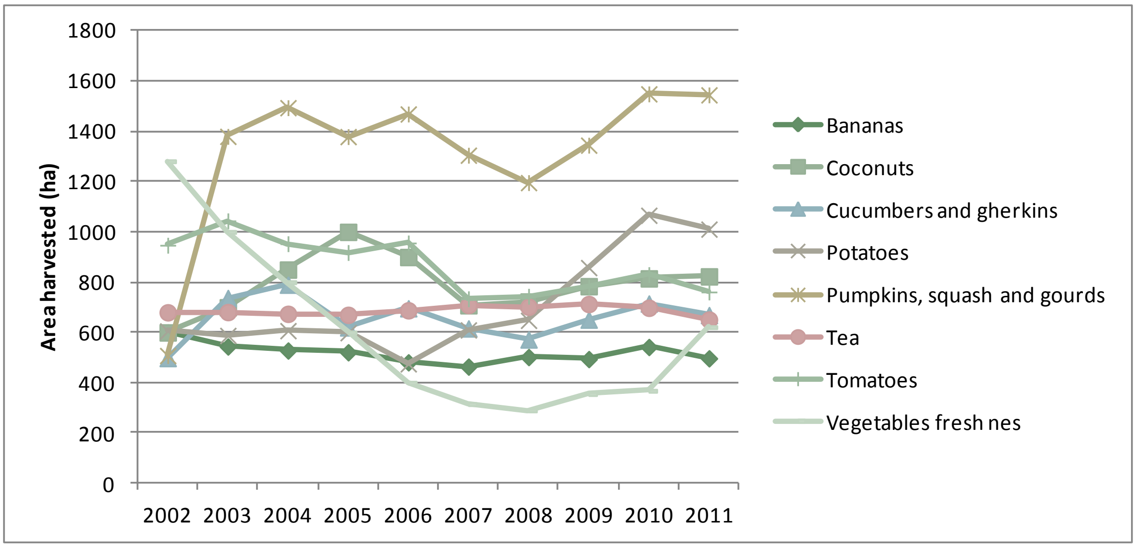


Figure 9. Area harvested of other crops in Mauritius from 2002 to 2011 (source FAOSTAT)

The sugarcane crop is harvested once a year. When mature, it provides a very good ground and aerial cover, protecting the soil for erosion and reducing runoff considerably compared to bare fallow grounds (soil loss reduction around 80%, according to Seerutun et al (2007)) .

After harvesting, the ground cover is low. During this period the plots are highly sensitive to erosion and may generate lots of runoff when strong rainfall occurs. Soil protection for erosion is therefore highly variable through the year, but is concentrated during the post-harvest period. Normally the crop is replanted every 5–7 years, which requires tillage. The majority of soil loss from sugarcane fields occurs at the time of replanting (Meyer et al., 2011).

Figure 10. Sugarcane cultivation in Mauritius, first growth stage (left) and after harvest (right), (Le Roux, 2005)

Quite clearly, sugar cane cultivation may generate important amounts of runoff and are sensitive to soil loss and erosion, mostly post-harvest and during replanting. The potential to reduce these negative impacts is high, as with some management practices such as trashing and minimum tillage and strip cropping, runoff and soil loss can be considerably reduced (see following sections).

Since 2011 agreement has been reached on the setting up common Best Management Practices (BMP) for sugar producers in Mauritius (2012 annual report of Mauritius Sugar Industry). The purpose of developing regional BMP standards is to respond proactively to the new market trends and requirements for adoption of best practices in supplying countries. They should include practices that will minimize the impact on the environment.

3 Assessment tools and methods

3.1 Observations

Observations on runoff and flooding are the standard approaches to evaluate flood risk, frequency and intensity. In case sufficient observations have been made statistical analysis can be undertaken to evaluate the risk and severity of flooding. Such so-called Flood Frequency Analysis is based on maximum observed flood events in the past. Based on these observations probability distributions can be fitted (e.g. GEV Type-I, Log Normal, Gumbel, Log Pearson Type III) and subsequently flood peak discharges for various recurrence intervals can be assessed. Such analysis can be done at different scale levels ranging from fields to entire river basins.

However, observations and the derived distributions reflect only the current state of the system and do not take into consideration recent changes. Moreover, impact of proposed flood mitigation measures cannot be evaluated since no observations exist. Therefore, models are often used to explore the expected impact of interventions to reduce flood risk. These models can also be used to understand the full hydrological processes in high level of spatial as well as temporal scale in order to support decision making (Droogers and Bouma, 2013).

3.2 Rainfall-runoff modeling for flooding studies

Typical empirically based approaches are the equations proposed by Kostiakov (Kostiakov, 1932), Horton (Horton, 1941), and the Holtan (Holtan, 1961). It is convenient to calibrate these equations with measured data from field experiments in the watershed of interest or similar watersheds.

An alternative empirical approach is the SCS curve number approach (USDA, 1972), used very often in watershed modeling. This equation can be used for basins where no field data is available and can be parameterized based on soil and land use data. However, its accuracy is limited and its conceptual basis are discussed in literature (Ponce and Hawkins, 1996; Van den Putte et al., 2013).

One of the major limitations of the runoff curve number method is that the runoff is not related to time or in other terms runoff is not related to rainfall intensity or duration of the storm. This may present a major limitation for discontinuous or storms of duration larger than one day. Furthermore, as implemented in most models, the curve number does not change with variation in vegetal cover or management practices. For flooding studies however it is the most straightforward and useful modeling approach. Most hydrological models use this approach, as for example HEC-HMS and SWAT.

Infiltration can also be modeled using a physically based approach. The physically-based infiltration equations include the Green-Ampt (Green and Ampt, 1911), the modified Green-Ampt (Mein and Larson, 1971), and the Philip equations (Philip, 1957). Physically-based equations have the advantage that their parameters can be determined from soil properties and vegetal cover information and do require less calibration.

Besides, infiltration can also be modeled using numerical solutions to the physically-based differential equation that governs water movement in and within the soil, also referred to as the Richards' equation (1931). For watershed assessments and flooding studies, these approaches are difficult to implement due to the large data and computer resources required.

To assess runoff on a watershed-scale, different rainfall-runoff modeling approaches and modeling codes can be used. For small homogeneous watersheds, a lumped modeling approach is sufficient, as for example the "rational method", that relates discharge (usually peak discharge) directly to a measure of rainfall inputs, catchment area, and a runoff coefficient

For large watersheds, the heterogeneity of the watershed characteristics and climatology require a (semi-)distributed approach. Distributed models attempt to take account of the spatial patterns of hydrological response within a catchment area. This section summarizes the most commonly used distributed models for evaluating downstream impacts of runoff management techniques.

4.1.1.1 SWAT - Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. SWAT is a public domain model actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA. SWAT can be downloaded from the internet and is free of charge

SWAT is a process-based continuous daily time-step model which evaluates land management decisions in large ungauged rural watersheds. It is used in many studies to evaluate the impacts of runoff and erosion management techniques on downstream water availability.

4.1.1.2 MIKE SHE

MIKE-SHE is a dynamic, user-friendly modeling tool that can simulate the entire land phase of the hydrologic cycle and can be summarized as an integrated modeling environment that allows components to be used independently and customized to local needs. It also includes powerful preprocessing and results visualization tools.

For flooding studies, the hydrograph output of MIKE SHE is often coupled with the MIKE 11 model to study flooding risk in the drainage network and assess the effects of structural interventions.

4.1.1.3 HSPF

HSPF (Hydrological Simulation Program) is a public domain software program distributed by the U.S. EPA's Center for Exposure Assessment Modeling (CEAM). HSPF first version originates from the 1960's and was called Stanford Watershed Model, one of the first hydrological models. It has been used in a wide range of studies to assess runoff and catchment response of land use changes.

4.1.1.4 HEC-HMS

HEC-HMS is a product of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers. It is designed to simulate the precipitation-runoff processes of dendritic drainage basins. It is used in a wide range of geographic areas for solving a very wide range of problems, including flood hydrology, and small urban or natural watershed runoff.

Hydrographs produced by the program are used directly or in conjunction with other software (as for example HEC-RAS) for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

4.1.1.5 VIC

The Variable Infiltration Capacity (VIC) model is a semi-distributed grid-based macroscale hydrology model which solves the full water and energy balances. It was developed at University of Washington and Princeton University.

The VIC model in its various forms has been applied to many basins in the US, and other large river basins around the world. Currently, VIC is one of the main hydrological models being used within climate change studies, often with a principal focus on flooding risks.

4 Flood control measures in catchments

4.1 Approaches

Reduced downstream flooding and peak flows can be accomplished by runoff management techniques in the upstream agricultural areas. The techniques to be applied are site specific and depend on the existing soil and water conservation problems, and on current farming practices. The various types of runoff management techniques may be classified follows (FAO, 1993):

- increase water intake and storage and so reduce runoff,
- control water movement over the soil surface,
- dispose safely of the excess rainfall as runoff or concentrate inadequate rainfall runoff.

In the arid and semi-arid regions, the choice of management is clear; all rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. In humid and sub-humid areas as in Mauritius a balance has to be struck between conservation of soil and water by runoff control and the avoidance of surface waterlogging, so the options are not as straightforward. In general, runoff is best minimized by ensuring high infiltration of rainwater into the soil through biological conservation measures, mulching and similar techniques.

Where biological conservation measures cannot be implemented, for example in areas of high-intensity storms or where there are periods of poor crop cover, earth works (physical control measures) can provide surface protection by holding water to give it time to soak through the surface. Such physical conservation measures involve land shaping, the construction of contour bunds, terraces and ridges.

Physical conservation measures require considerable technical design, supervision, proper construction and maintenance. In contrast, the biological methods include some soil management and agronomic cultural practices that are normally the companion of profitable agriculture such as appropriate land use and preparation, fertility maintenance, crop residue management, the use of cover crops and appropriate crop husbandry.

A selection of potential practices that might be considered to be implemented in Mauritius is described in the following section.

4.2 Flood mitigation options in Mauritius

Much research on rainfall-runoff management and its potential on-site benefits (erosion reduction, enhanced soil water availability, etc) and off-site benefits (reduction of pollution of surface waters, reduction of peak flows and flooding, etc) has been accumulated over the years. They have been gathered in many ‘Best Management Practices’ guides, specific for certain crops or crop types, and in databases and reports summarizing these type of experiences and techniques.

The most extensive database on farming practices that reduce runoff and erosion is maintained by the World Overview of Conservation Approaches and Technologies (WOCAT) initiative

(Liniger and Critchley, 2007). It aims to promote the integration of successful soil and water conservation approaches and techniques into land use systems world-wide.

From the WOCAT database and best management guides for sugarcane cultivation, the following practices were selected that result in a significant reduction in erosion, when implemented in the key source areas:

- Green can trash blanket
- Grass buffer strips
- Contour barrier hedgerows
- Artificial on-farm wetlands
- Periodic flooding
- Minimum tillage
- Strip intercropping

The following sections detail these selected options for runoff management to reduce downstream peak flows. These flood mitigation options are all very well suitable to be applied in the Mauritius situation.

4.2.1 Green can trash blanket

Title:	Green can trash blanket 
Source:	WOCAT (reference T_AUS003), www.wocat.net
Summary:	Elimination of burning as a pre-harvest treatment of sugar cane, and managing the resultant trash as a protective blanket to give multiple on and off-site benefits
Positive effects on runoff:	- Control of dispersed runoff - Enhanced infiltration - Increased surface roughness
Description:	Under conventional production systems, sugar cane is burnt before being harvested. This reduces the volume of trash - comprising green leaves, dead leaves and top growth - making harvesting of the cane simpler, and subsequent cultivation of the soil easier. The ‘green cane trash blanket’ (GCTB) technology refers to the practice of harvesting non-burnt cane, and trash blown out behind in rows by the sugar cane harvester. This trash forms a more or less complete blanket over the field. The harvested lines of cane re-grow (‘ratoon’) through this surface cover, and the next year the cycle is repeated: the cane is once again harvested

	and more trash accumulates in the inter-rows. Generally the basic cropping cycle is the same, whether cane is burnt or not. This involves planting of new cane stock (cuttings or 'billets') in the first year, harvesting this 'plant crop' in the second year, and then in years three, four, five and six taking successive 'ratoon' harvests. Studies showed (Meyer et al., 2011) that using runoff plot measurements show that trash mulch reduced runoff with around 60% compared to plots where burnt trash had been spread. A recommendation following from this study was to apply this practice on slopes greater than 15 % during the wet season, to reduce the impact of raindrop action, if insufficient crop cover has developed. The marked reduction in surface runoff and erosion is beneficial for the growers - but has also a major beneficial impact off-site, related to the downstream impacts of runoff (peak flows and pollution).

4.2.2 Grass buffer strips

Title:	Grass buffer strips 
Source:	WOCAT (references: HON03, KEN21, PH13, RSA04), www.wocat.net
Summary:	Within individual cropland plots, strips of land are marked out on the contour and left unploughed in order to form permanent, cross-slope barriers of grasses and herbs.
Benefits in terms of runoff and peak flows:	- Runoff velocities slow down - Enhanced infiltration - Increase surface roughness
Description:	Vegetative barriers are considered to be a cheap and effective 'green' alternative to terracing. Vegetative barriers (sometimes called 'live barriers' or 'bio-terraces') impede soil and water movement downslope. Such barriers are living and semi-permeable, and these can be advantages over cut-and-fill terraces. Sediment builds up above each contour strip while runoff is slowed down and drains through.

4.2.3 Contour barrier hedgerows

Title:	Contour barrier hedgerows 
Source:	WOCAT (references: NICO02, THA01), www.wocat.net
Summary:	Within individual cropland plots, strips of land are marked out on the contour and left unploughed in order to form permanent, cross-slope barriers of agroforest species.
Benefits in terms of runoff and peak flows:	- Runoff velocities slow down - Enhanced infiltration - Increase surface roughness
Description:	Over the last decade or so, contour barrier hedgerows of tree species have become the favoured conservation system for conservation projects in the humid steeplands. This development has been fuelled by agroforesters, keen to promote a system that combines trees and crops in an environmentally beneficial way. Contour barrier hedgerows normally comprise multipurpose, leguminous trees, densely planted in double rows and pruned for fodder or mulching.

4.2.4 Artificial on-farm wetlands

Title:	Artificial on-farm wetlands 
Source:	Meyer et al. (2011)
Summary:	Artificial wetlands are constructed to store excess runoff coming from the plot or farm before released to the watershed drainage network.
Benefits in terms of	- Reduction of runoff

runoff and peak flows:	- Reduction of pollution
Description:	Artificial wetlands are shallow ponds where the runoff can be stored before final release. They inevitably support vegetation that helps to remove nutrients and to add oxygen. Artificial wetlands are constructed such that applied effluent is caused to percolate through a permeable matrix (e.g. sand) that supports plant growth.

4.2.5 Periodic flooding of sugarcane cultivation

Title:	Periodic flooding of sugarcane cultivation 
Source:	US Agricultural Research Service (ARS) , Agronomy Journal https://www.agronomy.org/publications/aj/abstracts/96/3/0832
Summary:	Drainage is limited of sugarcane fields during heavy rainfall in order to retain the water for a short period, reducing peak flows, and reducing phosphorus runoff.
Benefits in terms of runoff and peak flows:	- Less runoff - Enhanced infiltration - Less peak flows
Description:	Normally growers try to drain their flooded fields immediately during heavy rains. A study by the US Agricultural Research Service (ARS) scientists shows that sugarcane can tolerate flooded conditions for up to two weeks. This fact allows the retention of water for a longer period on the fields, without affecting negatively crop yields.

4.2.6 Minimum tillage

Title:	Minimum tillage 
Source:	WOCAT Ref HUN1; CHL01; THA01 and Meyer et al. (2011)
Summary:	Crop operations are focused on minimizing the amount of tillage.
Benefits in terms of runoff and peak flows:	- Less runoff - Enhanced infiltration - Less peak flows
Description:	The negative effects of disturbing the soil in sugarcane cultivation have been recognized with a loss of organic matter and breakdown in soil Structure (Meyer et al., 2011). Minimum tillage is a term used to describe systems which attempt to reduce the conventional amount of soil tillage associated with growing a crop. The concept is to carry out crop operations with attention to minimizing the amount of tillage.

4.2.7 Strip intercropping

Title:	Strip intercropping 
Source:	WOCAT, Ref TAJ03;TAJ07;TAJ08 and Meyer et al. (2011)
Summary:	Strip intercropping is the cultivation of symbiotic crops such as potato, mustard, green gram and lentils, planted in alternate rows with sugarcane
Benefits in terms of runoff and peak flows:	- Better soil structure - Enhanced infiltration - Less land abandonment
Description:	Intercropping with cash food crops may provide additional income to the growers, preventing actual land abandonment occuring in Mauritius and

	their impacts on runoff. At the same these practices are known to while improve organic carbon content in the soil and soil structure, improving their water retention capacity.

4.3 Assessment of potential benefits of flood mitigation measures

Based on the previous sections it was decided to undertake an explorative assessment of the benefits of introducing flood mitigation options in agricultural areas upstream of flood prone areas. For this the HEC-HMS model, as described in the previous section, was set up to demonstrate and quantify the mitigation benefits. To this aim a so-called reference catchment was constructed. Such a reference catchment is often used to demonstrate the benefits of certain measures. Since results are presented in percentages change, it can be translated into the selected study areas for this particular study. The following assumptions were made for this representative catchment:

- Catchment area of 50 km^2
- Soils mixture of latosols and lithosols
- Land use sugarcane
- Slope classes between very steep and gradual, nearly flat
- A standard rainfall event of a total of 200 mm in 3 hours: 50 mm in one hour, 100 mm in the second hour, 50 mm in the third hour.
- Flood mitigation measures: combination of green can trash blanket, grass buffer strips and contour barrier hedgerows.

The above information was translated into input parameters for HEC-HMS and the model was run for 25 combinations of soil slope and flood mitigation measures. These flood mitigation measures were assumed to be implemented at 0%, 25%, 50%, 75% and 100% of the catchment area.

A typical screenshot of the output of one HEC-HMS run is presented in Figure 11. Combining the results of the various model runs, rainfall-runoff responses can be drawn. Figure 12 presents the runoff curve resulting from the 200 mm rainfall for a steep catchment and a rather flat catchment with gradual slopes. It is clear that peak runoff for the steep catchment is almost double compared to the gradual one. For both situations it was also assessed what the impact of flood mitigation measures would be. The runoff curves indicated that especially for the steep catchment quite a substantial reduction in peak runoff can be obtained of more than 30%. For the less steep catchments benefits will be in the order of 10%.

By combining the range of slopes in the catchment and the percentages of fields where the flood mitigation measures would be implemented, total reduction in peak flow is assessed. Figure 13 demonstrates that especially for catchments where high runoff occurs, the implementation of flood mitigation measures can be very effective. Also for the more flat gradual catchments, reductions of more than 10% in peak runoff can be achieved. Finally, the time to peak runoff (time of concentration) will be longer if these mitigation measures will be taken (Figure 14). Especially in areas where flooding is originating from various catchments, changes in time to peak runoff can be very effective in flood mitigation.

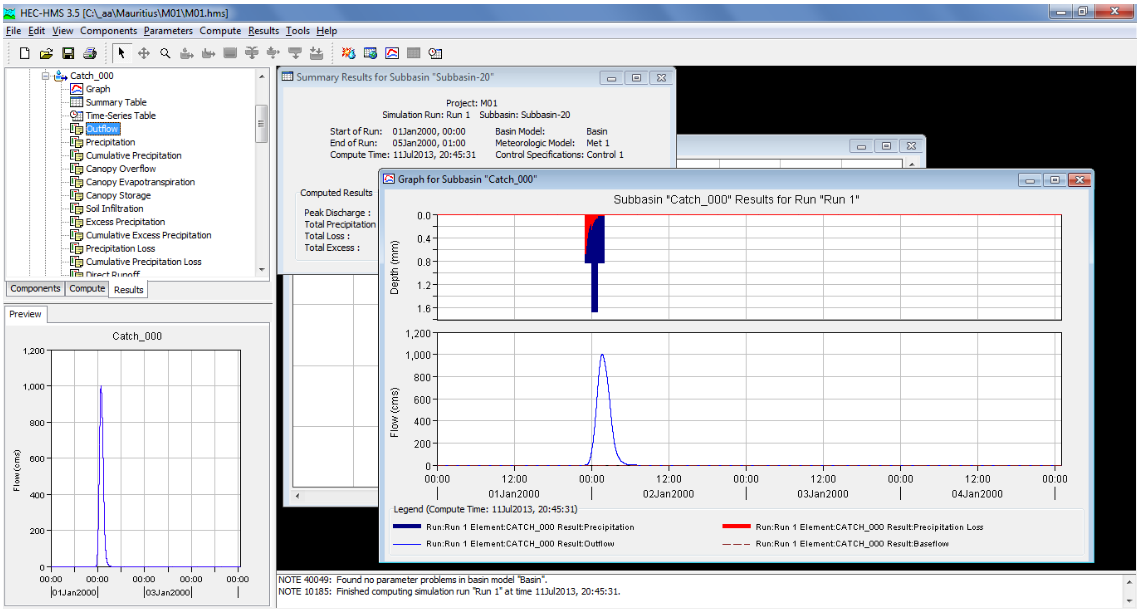


Figure 11. Typical screenshot from a HEC-HMS run to explore the potentials of flood mitigation options in upstream areas.

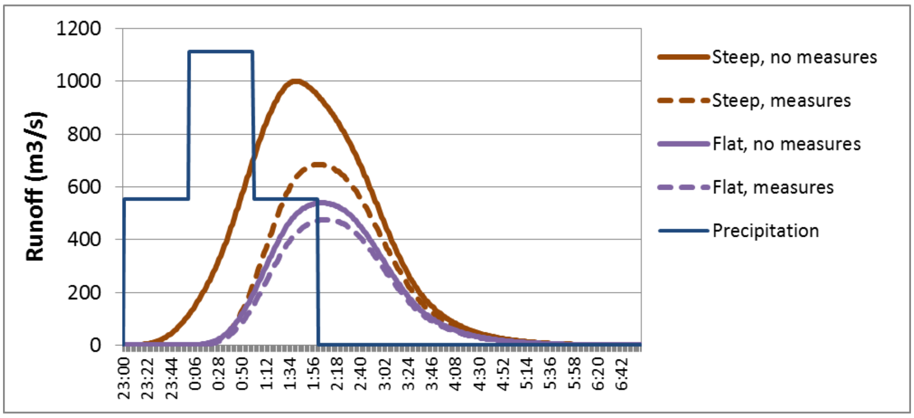


Figure 12. Example of four rainfall-runoff events as simulated using HEC-HMS after a rainfall event of 200 mm.

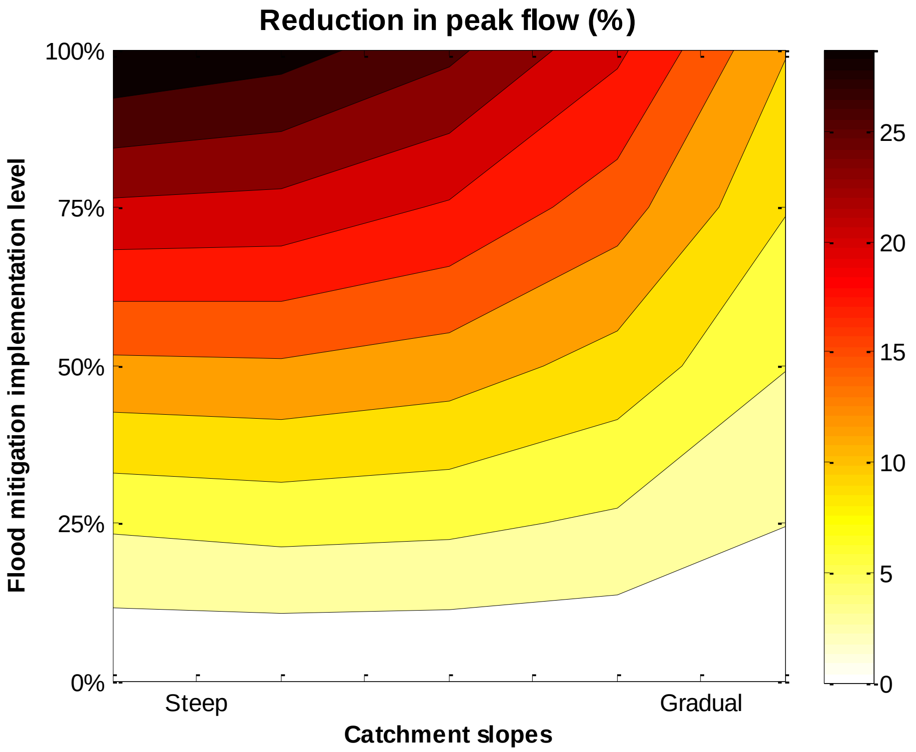


Figure 13. Expected reduction in peak flow for steep and shallow catchments as a function of the percentage of fields where flood mitigation options are implemented. Result based on multiple HEC-HMS runs.

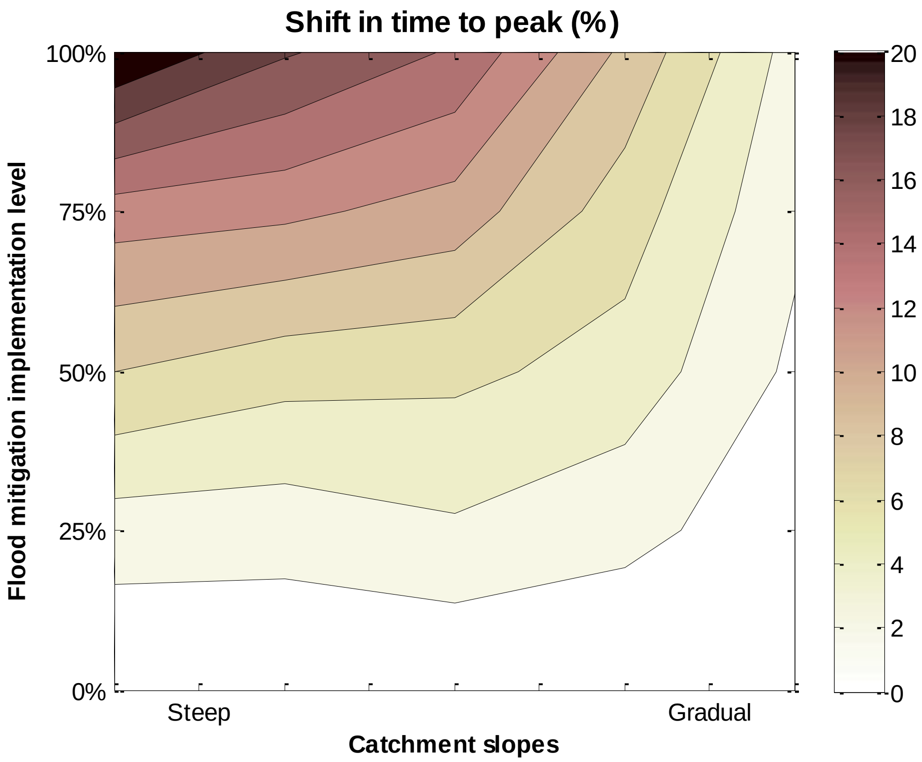


Figure 14. Same as Figure 13 but for the relative shift in time to peak of the hydrograph, percentages indicating the relative reduction in time between start of rainfall event and peak flow.

5 Conclusions and Recommendations

The critical situation in the identified emergency locations in Mauritius requires structural measures to be implemented as soon as possible. However, in the medium to long-term these structural measures should be accompanied by measures that reduce peak runoff at source: the rural catchments. In fact the real problem of flooding starts at this level and mitigation options should be considered at these locations for sustainable flood protection. These measured can be viewed as ´prevention at source´ or ‘green infrastructure’.

The local-scale at source measures delay or attenuate the runoff generation, which has a positive effect on the catchment flood hydrograph. To assess the overall effect, it is necessary to take into account the hydrological functioning of the catchment as a whole. Therefore, a more detailed analysis is necessary to estimate the potential of these measures in each of the catchments draining to the critical locations.

The following recommendations are proposed:

- Fine-tune the modeling reference catchment to the catchments draining to the 7 critical emergency localities
- Assess the potential and effectiveness of each of the source control flood mitigation measures in the 7 catchments
- Assess effectiveness of possible combinations of mitigation measures
- Precise targeting of mitigation measures (design)

This assessment should determine in which rural areas it is most effective to implement source control mitigation measures and how this reduces flood risk in the critical points and the urban area. This will provide the Ministry of Infrastructure in Mauritius with a concrete and detailed plan that ensures that infrastructural investments will accompanied by long-term sustainable flood protection measures at source.

6 Bibliography

Boardman, J., Ligneau, L., de Roo, A., Vandaele, K., 1994. Flooding of property by runoff from agricultural land in northwestern Europe. Geomorphology 10, 183–196.

Burt, T.., 2001. Integrated management of sensitive catchment systems. Catena 42, 275–290.

Dore, M.H.I., Singh, R.G., 2013. Projected Future Precipitation Scenarios for a Small Island State: The Case of Mauritius, in: Younos, T., Grady, C.A. (Eds.), The Handbook of Environmental Chemistry, Volume 25. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 47–66.

Droogers, P., Bouma, J., 2013. Scenario Tools for Integrated Water Resources Management in Basins. International Journal Water Resources Management submitted.

Evrard, O., Bielders, C.L., Vandaele, K., van Wesemael, B., 2007. Spatial and temporal variation of muddy floods in central Belgium, off-site impacts and potential control measures. CATENA 70, 443–454.

FAO, 1993. Soil Tillage in Africa: Needs and Challenges. FAO Soils Bulletin 69. Food and Agriculture Organization of the United Nations.

Gafur, A., Jensen, J.R., Borggaard, O.K., Petersen, L., 2003. Runoff and losses of soil and nutrients from small watersheds under shifting cultivation (Jhum) in the Chittagong Hill Tracts of Bangladesh. Journal of Hydrology 274, 30–46.

Green, W.H., Ampt, G.A., 1911. Studies on soil physics, 1. The flow of air and water through soils. J. Agric. Sci 4, 1–24.

Holtan, H.N., 1961. A Concept for Infiltration Estimates in Watershed Engineering. Agricultural Research Service, U.S. Department of Agriculture.

Horton, R.E., 1941. An approach toward a physical interpretation of infiltration-capacity. Soil Science Society of America Journal 5, 399–417.

Hunink, J.E., Droogers, P., Kauffman, S., Mwaniki, B.M., Bouma, J., 2012. Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures : Supporting policy making in the Green Water Credits program of Kenya. Journal of Environmental Management 111, 187–194.

Jothityangkoon, C., Hirunteeyakul, C., Boonrawd, K., Sivapalan, M., 2013. Assessing the impact of climate and land use changes on extreme floods in a large tropical catchment. Journal of Hydrology 490, 88–105.

Kostiakov, A.N., 1932. On the dynamics of the coefficient of water-percolation in soils and on the necessity for studying it from a dynamic point of view for purposes of amelioration. Trans. Com. Int. Soc. Soil Sci 6, 17–21.

Kramer, R.A., Richter, D.D., Pattanayak, S., Sharma, N.P., 1997. Ecological and Economic Analysis of Watershed Protection in Eastern Madagascar. Journal of Environmental Management 49, 277–295.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annual Review of Environment and Resources 28, 205–241.

Le Roux, J.J., 2005. Soil erosion prediction under changing land use on Mauritius. MSc dissertation, University of Pretoria, South Africa.

Liniger, H., Critchley, W., 2007. Case studies and analysis of soil and water conservation initiatives worldwide. Earthprint.

Mamoun, C.M., Nigel, R., Rughooputh, S.D.D. V., 2013. Wetlands' Inventory, Mapping and Land Cover Index Assessment on Mauritius. Wetlands.

Mein, R.G., Larson, C.L., 1971. Modeling the infiltration component of the rainfall-runoff process. Water Resources Research Center, University of Minnesota.

Meyer, J.H., Rein, P., Turner, P., Mathias, K., 2011. Good management practices manual for the cane sugar industry. Johannesburg, South Africa.

Mysiak, J., Galli, A., Amadio, M., Teatini, C., 2013. Multi-hazard risk assessment of the Republic of Mauritius. EGU General Assembly Conference Abstracts 15, 13203.

Nigel, R., Rughooputh, S., 2010. Mapping of monthly soil erosion risk of mainland Mauritius and its aggregation with delineated basins. Geomorphology 114, 101–114.

O'Connell, P.E., Ewen, J., O'Donnell, G., Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? Hydrology and Earth System Sciences 11, 96–107.

Petrucci, G., Rioust, E., Deroubaix, J.-F., Tassin, B., 2013. Do stormwater source control policies deliver the right hydrologic outcomes? Journal of Hydrology 485, 188–200.

Philip, J.R., 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil science 84, 257–264.

Ponce, V.M., Hawkins, R.H., 1996. Runoff Curve Number: Has It Reached Maturity? Journal of Hydrologic Engineering 1, 11–19.

Porras, I., Alyward, B., Dengel, J., 2013. Monitoring payments for watershed services schemes in developing countries. London.

Posthumus, H., Hewett, C.J.M., Morris, J., Quinn, P.F., 2008. Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire. Agricultural Water Management 95, 787–798.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1, 318–333.

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A., Blöschl, G., 2012. A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. Natural Hazards and Earth System Science 12, 3287–3306.

Santillan, J., Makinano, M., Paringit, E., 2011. Integrated Landsat Image Analysis and Hydrologic Modeling to Detect Impacts of 25-Year Land-Cover Change on Surface Runoff in a Philippine Watershed. Remote Sensing 3, 1067–1087.

Seeruttun, S., Koon, D.A., Ismael, F.M., Cheong, R.N., 2007. Sugarcane reduces soil erosion by more than 80% in five major soil groups of Mauritius., in: XXVI Congress, International Society of Sugar Cane Technologists, ICC, Durban, South Africa, 29 July - 2 August, 2007. International Society Sugar Cane Technologists (ISSCT), pp. 384–387.

Senapathi, D., Underwood, F., Black, E., Nicoll, M.A.C., Norris, K., 2009. Evidence for long-term regional changes in precipitation on the East Coast Mountains in Mauritius. International Journal of Climatology 30, 1164–1177.

Sturdevant-Rees, P., Smith, J.A., Morrison, J., Baeck, M.L., 2001. Tropical storms and the flood hydrology of the central Appalachians. Water Resources Research 37, 2143–2168.

USDA, 1972. National Engineering Handbook. Hydrology Section 4, chapter 4-10. US Department of Agriculture, Soil Conservation Service.

Valentin, C., Agus, F., Alamban, R., Boosaner, A., Bricquet, J.P., Chaplot, V., de Guzman, T., de Rouw, A., Janeau, J.L., Orange, D., Phachomphonh, K., Podwojewski, P., Ribolzi, O., Silvera, N., Subagyono, K., Thiébaux, J.P., Vadari, T., 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. Agriculture, Ecosystems & Environment 128, 225–238.

Van den Putte, A., Govers, G., Leys, A., Langhans, C., Clymans, W., Diels, J., 2013. Estimating the parameters of the Green–Ampt infiltration equation from rainfall simulation data: Why simpler is better. Journal of Hydrology 476, 332–344.

Wheater, H., Evans, E., 2009. Land use, water management and future flood risk. Land Use Policy 26, S251–S264.

Wohl, E., Barros, A., Brunsell, N., Chappell, N.A., Coe, M., Giambelluca, T., Goldsmith, S., Harmon, R., Hendrickx, J.M.H., Juvik, J., McDonnell, J., Ogden, F., 2012. The hydrology of the humid tropics. Nature Climate Change 2, 655–662.