Source: (Roads for water, 2015)

FROM A PROBLEM TOWARDS POTENTIAL

IMPROVING RURAL ROAD DESIGN IN DRYLANDS, A MODELLING CASE STUDY FOR A CATCHMENT IN THE TIGRAY REGION, ETHIOPIA.

A thesis presented to the Utrecht University, Faculty of Geosciences. In partial fulfilment of the requirements for the degree MSc. Water Science and Management

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ECTS: 37,5
Date: 10-12-2015
Academic year: 2015-2016

Content

Abstract

The Ethiopian government aims at the improvement of rural road systems in the Tigray region, situated in the Ethiopian Highlands. Road systems currently cause alterations in local hydrology which result in erosion related problems. Farmer communities living along the road are affected and the road authorities invest a substantial amount of their budget in road maintenance. There is a high potential for improved rural road design, including a further integration of the concept of road water harvesting into road system design. Improved rural road design would reduce the current observed problems and enable an extra water source for agricultural purposes to promote regional food security.

This research was of an explorative character and aimed at an improved understanding of the combined effect of road alignment and culvert design on local hydrology and erosion patterns at a catchment scale. A model was developed in the PCRaster environment to facilitate the execution of a scenario study focussing on a road system in the Tigray region, taking into account the low data availability and quality. A set of 28 road system scenarios was formulated, based on three different road alignments and different techniques for culvert positioning. The study aimed at a further development of concepts on improved road alignment and culvert allocation. The formulated scenarios were evaluated through the application of a Multi Criteria Analysis which was developed to address three objectives of rural road performance: Erosion, costs and the potential of water harvesting practises.

The most important contribution of this research towards improved rural road design is the newly developed method for road design analysis on a catchment scale, the integration of both process-based modelling and a post-hoc analysis by a MCA has a potential for further investigation and eventual extension when the encountered model shortcomings are addressed. It enables an integration of a range of aspects with a different character towards a balanced design which includes a certain degree of flexibility by the adjustable criteria weighting system applied in the MCA. The model results revealed that the model is able to identify the general impacts of a road system on local hydrology and erosion. The impact of road alignment on the formulated indicators is mainly related to the size of the upstream area and was supported by applied statistics (one-way ANOVA and Tukey test). An estimation on the enhanced food production enabled by integrating a water harvesting aspect into road design, showed at least a doubling of the current cultivated irrigated area in the region and is able to produce a substantial amount of the annual food demand. The modelling process revealed an event related to culvert positioning, which might impede the actual differences between culvert scenarios. Discharge is being cross-drained forth and back caused by an increased number of cross-draining opportunities for the road system scenarios with a higher number of installed culverts or culvert scenarios being align with natural discharge patterns. An adequate evaluation of road system performance and the potential formulation of improved rural road design concepts, requires a reformulation of more adequate indicators and a better integration of the erosion objective.

1. Introduction

1.1 General

The Ethiopian Road Authority (ERA) has been extending its national infrastructure since it launched The Road Sector Development Program (RSDP) in 1997. This program is supposed to be one of the key strategies and pillars in Ethiopian's development policy. The last of four project phases covers five years until the end of the year 2015, it focuses on so-called all-weathered *'Universal Rural Road Access Program'* (URRAP) roads to improve and enhance mobility around the different regional centres located in the abundant rural areas of Ethiopia (Demenge et al, 2014). The URRAP program aims at over 70,000 km of new roads on a national level, which will provide 80% of the population with all year road access, currently 40% of the aimed total has been built. One of the target areas is the Tigray region, a relatively poor and agrarian region in the northern part of Ethiopia, bordered by both Sudan and Eritrea. The RSDP planned about 5000 kilometres of new infrastructure in this region, of which 2500 kilometres will be all weathered URRAP road (ERA, 2013).

Increased economic resilience and food security of these communities are of high priority in national policy. This positive relation between infrastructure and development is best clarified by the fact that an improved rural road network enables an increased market integration of previously isolated communities, it provides access to health care, education, administration, increases mobility and thereby contributes to welfare development and improved quality of livelihoods. However, the link between road construction and development is rather complex and not of a bilateral character, rural road construction can actually result in negative consequences for local development due to an insufficient integration of the local needs (Demenge et al, 2014).

Road systems can also cause negative impacts on their surroundings. Roads can be badly designed, resulting in increased risks for road overtopping and flooding. Road networks do act as artificial structures in the landscape and can be major interventions in the local hydrology. Roads may connect catchments, obstruct or change natural (sub)surface flow patterns. The higher volume, concentrated and diverted flows cause higher chances for erosion, flooding or waterlogging to occur (van Steenbergen et al, 2014). These hydrologic changes often harm farmer communities along the road (Demenge et al, 2014). Observed negative consequences of road networks in Tigray are the occurrence of severe erosion along the roadsides and culverts, gully formation, sedimentation of (farm)land, waterlogging of both the up- and downstream side of the road, changed soil moisture patterns and an increase in road maintenance costs (Demenge et al, 2014; Van Steenbergen et al, 2014; [1]Wolderagay et al, 2014). Nyssen et al (2002) revealed that road building in the Tigray region caused the loss of fertile soil and crop yield, decreased the land holding size and the creation of obstacles for tillage operations. The costs of annual road maintenance in the Tigray region is taking up 35% of the ERA's annual budget, the majority is spend on repairing damages to the road system caused by water (World bank, 2006).

Community driven initiatives show that road networks also hold a potential for harvesting rainwater and sub sequential storage or infiltration of rainwater. Using rainwater harvested from roads for shallow groundwater development or direct irrigation purposes will potentially improve drought resilience among farmers, prolong the growing season and enable the cultivation of an extra crop cycle. Road water harvesting is promising for Ethiopia when one notices that about 85 per cent of the population depends on the agricultural sector for their livelihoods. Agriculture covers about 50 per cent of the Ethiopian GDP (Worku, 2011). Moreover, only 2% of the current Ethiopian cropland is irrigated. The altered runoff patterns also change the direction and degree of sediment transport which have an effect on the receiving soils. Road related problems could actually be reversed, changing a problem into a potential for agricultural development. Future consequences of road damage caused by runoff but also water harvesting potentialities could already be addressed during the stage of road planning. An elaborate study by Kubbinga (2012) on the performance and potential up-scaling of road water harvesting practises for small-scale farmers, showed good practises in Kenya and predicted large potential of road water harvesting practises for Sub-Saharan countries. However, not much research has been done on systematically integrating this potential into road planning programs.

1.2 Project context

The application and further up scaling of water harvesting from road systems in drylands is promoted and extensively researched by the Roads for Water Initiative, a consortium led by MetaMeta Research[1]. The consortium is aiming at an integration of the water harvesting potential for half of the roads on the continent of Africa by the year 2025, key strategies are a further upscaling and development of water harvesting techniques based on current findings and maintaining road water harvesting in road asset management by collaborating with the International Road Federation[2]. The Roads for Water Initiative started in 2013-2014 with a case study along a pilot route in the Tigray region, Ethiopia. A collaboration between Meta Meta Research and the Mekelle University executed a regional survey on the performance of all weathered URRAP roads ([1]Woldereagay et al, 2014). The main focus was to examine the potential of rainwater harvesting from road networks. The research revealed the current problems related or caused by current road development, the present applications of road water harvesting and the formulation of institutional reform and policy recommendations for further integration of road water harvesting principles. From this survey several important conclusions can be drawn:

- Current road development is not characterised by an integrated design approach.
- Road safety is an issue due to the occurrence of flooding and waterlogging, which are caused by alterations of the local hydrology related to the road system presence.
- There is a large potential to include water harvesting principles into the road planning process to further promote more integrated and safer road design.
- There is a large potential of water harvesting practises.

1.3 Previous work and research

The relationship between road systems and their effects on alterations in natural drainage patterns and sediment production and transport patterns has been subject to numerous studies. Most of the early research on this topic is based on experimental field plots, executed in several regions in the north western part of the United States. Especially the effects of forest (logging) roads on sediment production, input to streams and sediment pathways has been studied extensively. Forest (logging) roads turn out to be significant sources of sediment (Megehan and Kidd, 1972; Janda et al, 1975; Luce and Black, 1999*),* which was quantified by Best et al (1995) through a sediment budget study. Megehan and Kidd (1972) executed a field experiment in the state of Idaho, studying the effects of logging and associated roads on sediment production and transport. Their research revealed that roads associated with the logging system increased average sediment production by 750 times compared to the natural rate. The individual effect of the different road parameters (e.g. slope and segment length) was studied by Luce and Black (2001) in the state of Oregon. Comparable studies on logging forest roads can (among others) be found for catchments in Malaysia (Sidle et al, 2004), Thailand (Ziegler et al, 1999) and Spain (Arnaez et al, 2004). Sidle et al (2004) found that three quarter of the total sediment production by road systems is transported into streams on lower elevations. This increased connectivity to streams facilitates a faster runoff, therefore it might alter discharge patterns in the lower-lying streams (faster peak flows and larger discharge volumes) and might enhance bankside erosion due to increased velocities and volumes.

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[1] http://metameta.nl/research/

[2] http://roadsforwater.org/

McCashion and Rice (1983) found that erosion on logging roads in the north western part of California could be avoided by 24% by applying conventional engineering methods. Road-related erosion covered 40% of the total erosion in the catchment. The majority of the erosion was caused by site specific or landscape factors. Madej (2001) studied the same region in California and revealed the effectiveness of control treatments (e.g. excavating culverts) on abandoned logging roads, with the aim of reducing road-related sediment input to streams and minimise disturbances of the natural drainage patterns or even restoration when possible. The research concluded that controlling treatments on the road system can substantially reduce sediment yields, thereby also showing that road-related disturbance along forest roads can actually be minimised to acceptable levels when appropriately addressed in the stage of design or planning.

Channel initiation and gully triggering caused by road drainage is a topic frequently researched. The road causes an increased risk for gullying by an enhanced concentration of runoff, diversion of runoff to other catchments and an increased size of the contributing catchment(Montgomery, 1994; Nyssen et al, 2002; Crocke and Mockler, 2000). The enhanced gully erosion risk caused by the construction of new roads is described in Kenya (Jungerius et al (2002)), Australia (Crocke and Mockler, 2000), United States (Katz et al, 2011) and Ethiopia (Nyssen et al (2002)). The latter executed an extensive case study for the northern Tigray region. Threshold values can be determined for channel initiation to occur, which might result in sub sequential gully triggering. Montgomery (1994) studied three different regions in the United States, he formulated site specific thresholds values for both channel initiation and the risk for landslides to occur. The slope-area relationships are based on local slope values and contributing catchment size. The accuracy of several slope-area relationships were studied by Takken et al (2008), by the application of a regression analysis on three different sets of field data from south east Australia.

Both exploratory and analytical studies have been accompanied with a small number of modelling studies concerning the processes of road drainage and their effect on local hydrology and sediment transport. The Washington Road Surface Erosion Model (WARSEM) us an empirical model which estimates long-term average road-related sediment transport discharged to the stream network. This model was applied in, for instance, a study on sediment transport caused by forest roads in southeast Australia (Fu et al, 2009). Another physically based model is the Water Erosion Prediction Project (WEPP): Road, which is a model developed by the USDA forest Service as an extension to the general WEPP model. The model can describe numerous road erosion conditions. The use of the WEPP:Road model requires a calibration of the input parameters for regions outside the United States. The WEPP: Road model was adjusted by Cochrane et al (2007) to facilitate forest road planning specifically (FORECAST model). A disadvantage of the abovementioned models is that only individual road segments can be parameterised and evaluated, hydraulic structures (e.g., culverts) are not incorporated but evaluated as the end of a modelled road segment.

The X-DRAIN Cross Drain Spacing and Sediment Yield Model is another extension based on the WEPP model, it has been developed to determine the optimum drain spacing of both planned and existing roads. A specific tool for sediment delivery from culverts has been developed by Damian (2003), CULSED is an interactive decision support tool which can assist in the optimisation of road planning (Schiess et al, 2004). CULSED is implemented as an ArcGIS extension which makes it a conventional application. The tool has been applied by Abdi et al (2012) to study the sediment delivery to a stream from a road network in Iran, its contributing parameters and further optimised the current road design.

Several of the abovementioned models were reviewed by Fu et al (2010). It was concluded that most models work with a scope of a single road segment, which can have a limited transect length and exclude processes happening further downstream along the road. The spatial patterns of runoff and sediment transport cannot be represented, which is of importance when aiming on the spatial integration of water harvesting practises. No model could be found which integrates both road segments and hydraulic structures.

2. Problem statement

2.1 General

The Ethiopian Road Authority states in its technical guidelines that drainage systems encompassing roads are designed to keep road networks safe and prevent road damage during usual floods and also minimise modifications in the local hydrology ([1]ERA, 2011). The URRAP project aims primarily at the upgrading of existing trails or tracks. The current development of all weathered URRAP roads turns out to be not sufficiently incorporating the effect on flow patterns, potential erosion, waterlogging and flooding ([1]Woldereagay et al, 2014**.** Moreover, the technical guidelines provide example measures which manage or address erosion caused by roads (e.g. rip-rap, mitre drains, etc.), but do not include clear guidance on the spatial integration of these measures. The ERA uses a specific culvert design software (HYDRAIN) for the design of highway drainage systems (ERA, 2002). However, this is not applicable for the design of rural road systems. High data input and relatively high costs of the design process do not make this a feasible option for the design of unpaved rural road systems.

Improved rural road planning and design for drylands should integrate the risk of road flooding and erosion and avoid or minimise road related problems for surrounding farming communities by optimising the interception, concentration and deviation of runoff. Techniques must be applied to spread concentrated runoff in space and time and focus on infiltration measures (Nyssen et al, 2002; Steenbergen and Tuinhof, 2010). There is a high potential for the application of road water harvesting practises while taking the often limited available infrastructural budget, data availability and data quality into account. Road alignment, culvert locations and culvert discharge capacity are the most important parameters in the improvement of road design. Culverts are among the most important aspects of the drainage system and cover a more than substantial amount of the overall costs in unpaved road systems (ERA, 2013). General rules on the number of culverts per kilometre or spacing are difficult to formulate, this is strongly depending on factors like the weather conditions, local topography and surrounding catchment characteristics. In order to get more insight in the effects of road alignment and its culvert design, a more in depth study is required focussing on the intertwined effect of road alignment, culvert number and their positioning along an unpaved rural road system.

2.2 Objectives

This research aims at an improved understanding of the combined effect of road alignment and culvert design on local hydrology and erosion patterns at a catchment scale. It aims at a further development of concepts on improved road alignment and culvert allocation for the remaining duration of the roads for water project focussing on road networks in drylands. This research contributes to the general project objective of a fundamental reversal of the current problems related to road networks in the Tigray region, scaling up the principles of water harvesting from road systems, and contribute to regional welfare development by an increase in productive land use through the spatial integration of road water harvesting practises and the reduction of future road maintenance costs. A model is developed which can potentially assist in the further application of improved rural road design concepts, providing insights on effects caused by road systems on runoff and erosion patterns. The model is primarily developed to facilitate a scenario study on a range of road system designs at catchment scale, focussing on a road in the Tigray region, situated in the Ethiopian Highlands. The insights from the modelling study are expected to contribute in a further formulation of rural road design concepts. The application of a Multi Criteria Analysis (MCA) for the evaluation of road system scenario is an attempt to enable a prioritisation between the road system scenarios and explores its potential assistance in future decision making on rural road development. The development of a model for road system analysis and a (MCA) method for the evaluation of alternatives are both of an explorative character. The outcomes from the model and MCA are used to address the potential for increased regional food production by integrating water harvesting practises.

The following section presents the main research question, which is divided into 5 sub research questions.

3. Main research question

How can the design of rural road systems be improved regarding costs, erosion and the integration of water harvesting practises?

3.1 Sub research questions

- How does the current road system affect the local hydrology and erosion pattern?
- What is the effect of road alignment on runoff and erosion patterns at the study site?
- What is the effect of the number of culverts and their positioning technique on runoff and erosion patterns at the study site?
- How can an optimal road system be developed for the selected study site using a Multi Criteria Analysis, regarding costs, erosion and water harvesting potential?
- What is the potential for the application of water harvesting practises at the study site under these optimal road system conditions?

These questions will be answered using the insights from a case study in the Tigray region, Ethiopia.

4. Study area description

4.1 General

This study area is situated in the Tigray region which is located in the Northern part of Ethiopia on the border with both Eritrea and Sudan, the capital of the region is *Mekelle*. The total area covered is approximately 50 thousand square kilometres and is often referred as most degraded part of the country. The Tigray region has a population of about 4.5 million inhabitants; most of the people are living in rural areas (CSA, 2007). Figure 1 shows the Tigray region, its zones and smaller *woredas* (districts).

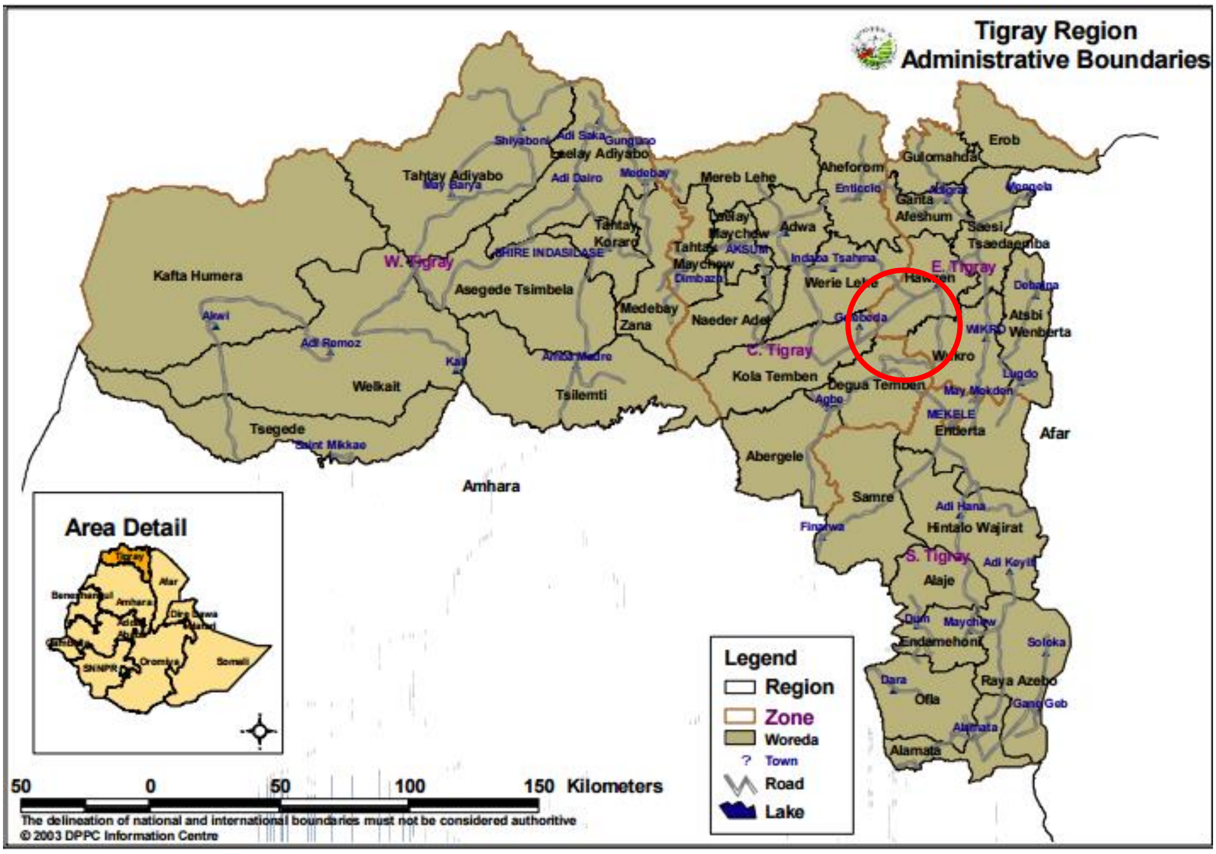


Figure 1: The Tigray region and indicated study area (DPPC Information centre, 2015)

The study area is a catchment located in East-Tigray, more specifically in the Hawzen district. The region counts approximately 230,000 people. The main livelihood of its inhabitants is mixed crop and livestock agriculture ([1]Woldearegay et al, 2014). The valley has altitudes of 1900-2000 meters and is bordered by steep slopes and sharp cliffs which show elevation values up to 2450 m a.m.s.l. The well-known ancient rock churches of Abraha Atsbeha point out the long history of this region. The Suluh river is the only river with a continuous annual flow. It flows in a north south direction just west of Abreha Atsbeha towards the south of the first catchment, discharging the East-West oriented seasonal flows collected in the north resulting in high peak flows during the more intense events. The Suluh river is part of the Geba catchment, which has a drainage basin of approximately 5200 km^2 and discharges in the Tekeze river which is an important tributary of the Blue Nile (Baert, 2010). Several villages are located along the road, still about 75% of the people are living in rural areas outside the urban centres ([1]Woldearegay et al, 2014). A typical landscape of the study area is shown in figure 2.

Figure 2: Typical landscape in the central Tigray region (photo taken by author, November 2014).

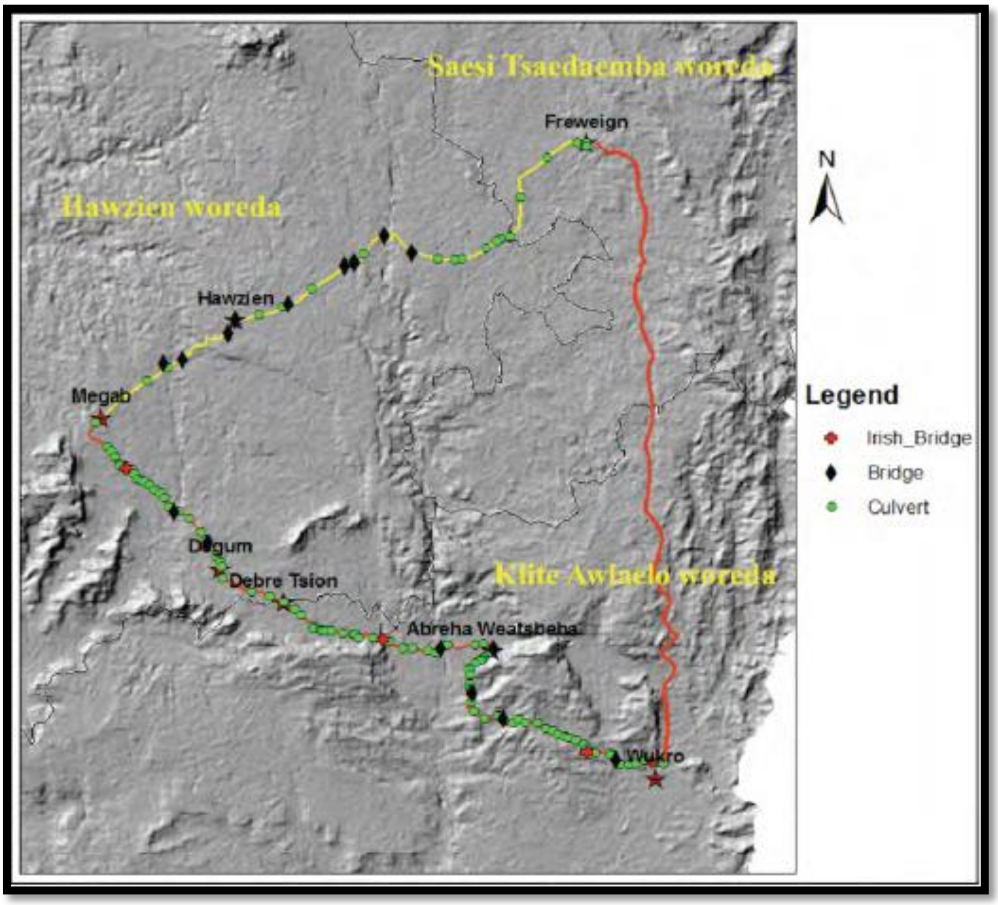


Figure 3: The surveyed pilot route from the study by [1]Woldareagay et al (2014). The figure shows the road alignment and culvert positions along the road.

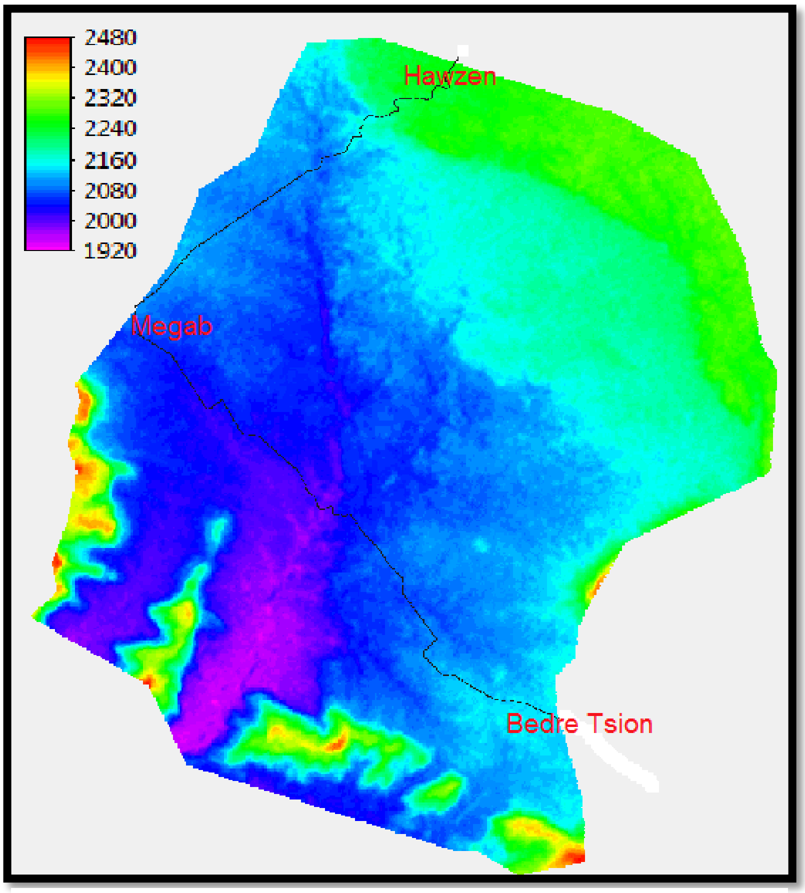


Figure 4: The DEM of the study area and the current road alignment. The three main villages are Bedre Tsion, Megab and Hawzen.

The road surveyed by the roads for water collaborative ([1]Woldearegay et al, 2014) covers a total distance of approximately 40 kilometres and is aligned through the valley bottom which results in easy grades and no large elevation differences. Abreha Atsbeha is the starting point of the surveyed route and is situated in the south east. The road follows a north west direction until it reaches Megab, which is situated in the outer west. From Megab the road further bends to the north east until it reaches Hawzen. The pilot route covers two large closed catchments which are divided by a mountain ridge. The second catchment will be analysed in this explorative research and covers the road from the village of *Debre Tsion* until *Hawzen.* The size of the catchment is approximately 140 km^2, the DEM is shown in figure 4 including the current road alignment.

4.2 Climate

The climate of the Tigray region is semi-arid and the rainfall can be described as erratic and torrential. The annual rainfall has a bimodal shape, with the main events occurring during the months June to September. This rainy season is called Kiremt and covers over 80% of the total amount of rainfall. The second rainfall occurs in the months March until May and is called Belg. The average annual rainfall is about 700 mm. The climate of Ethiopia is strongly depending on the dynamics of the Inter Tropical Convergence Zone (ITCZ). It passes the country twice a year and is causing the onset and withdrawal of winds and it has a strong influence on the rainfall pattern in Ethiopia. The ICTZ is characterised by low pressure and strong convergence between the Tropical Easterlies and Equatorial Westerlies. The Kiremt originates in the South Atlantic and Indian Ocean Westerlies. During winter the ICTZ moves to the south and is under influence of the colder and drier North African and West Asian wind. In spring the ICTZ is situated in the South, causing the development of a cyclical cell above Sudan which causes the offset of the smaller *Belg* rains in some regions of Ethiopia (Alemayehu, 2006). Figure 5 presents the monthly average temperature and precipitation for the meteorological station of Hawzen (NMA, 2015), the used data is enclosed in appendix B. The two rainy season can clearly be distinguished. The average monthly temperature ranges between approximately 16 and 21 degrees Celsius.

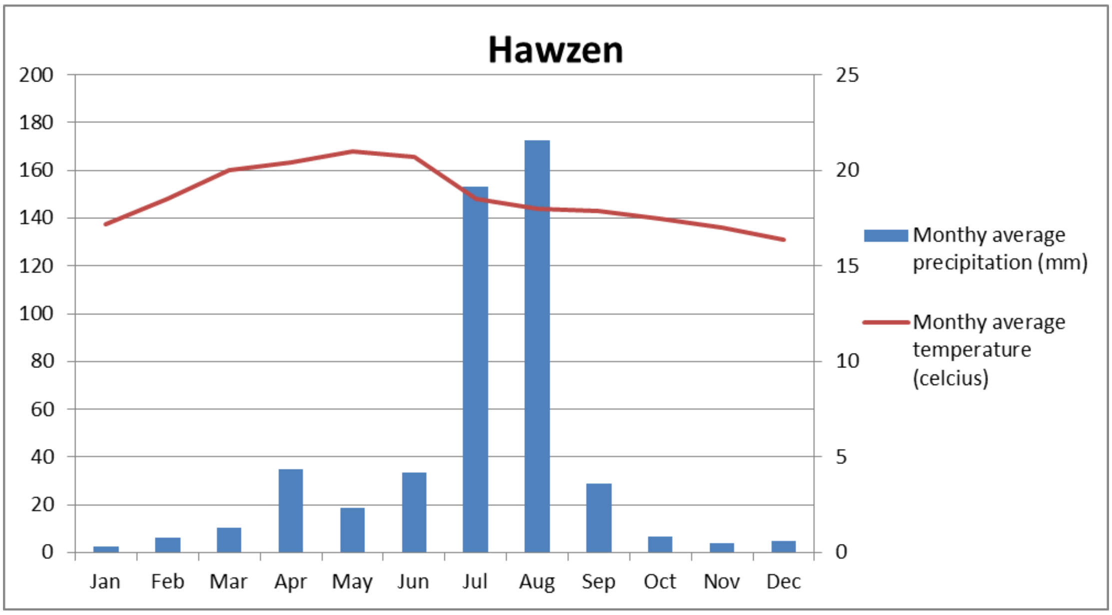


Figure 5: Rainfall and temperature data from the Hawzen meteorological station (NMA, 2015)

The rainfall can vary significantly between different catchments. Nyssen et al (2005) studied the rainfall characteristics of the Ethiopian Highlands. The orientation of the valley and the slopes along longer gradients turn out to play an important role in the spatial distribution of annual rainfall, which causes significant differences on a relatively small scale (up to 80 mm. annually). Daily rainfall almost never falls before noon, which can be clarified by the dominance of convective rains and which build up in the morning due to a fast warming up of the earth surface. The rain intensity during an event shows a very short high peak which can occur in all stages of the event, about three quarters of the rainfall falls within an intensity of 30 millimetres per hour (Nyssen et al, 2005).

4.3 Vegetation and land use

Vegetation has changed significantly due to anthropogenic and climatic forces. The Ethiopian Highlands used to be covered with grass- and woodlands in the lower and moist valley bottoms and thicket on higher altitudes or drier regions. A growing population and intensification of agriculture in combination with a changing climate showing more arid conditions, have caused a significant deforestation and land degradation (Nyssen, 2004). The valley bottoms have been fertile, making them good locations for agriculture. Food insecurity used to be a big problem in these districts. The high variability in rainfall, land degradation and a consequential decrease in soil fertility and the small land sizes of the farmers are important causes. Since the big famines in the eighties an on-going conversion has taken place of natural fields into productive lands, also to keep up with the continuous population growth and subsequent demand for food ([1]Woldearegay et al, 2014). Barely any natural vegetation is left, which makes the land vulnerable for erosion.

In the study area the vegetation cover is little, although some trees have been saved often for religious reasons. Lower vegetation types like bushes and cacti cover the hill slopes, eucalyptus trees have been planted in the wetter areas which also serve the purpose of protection against malaria (Baert, 2010). Some areas (often steep degraded hill slopes) are protected from cropping or grazing because their susceptibility to erosion, these exclosures are recovered by the replanting of vegetation. The most common livelihood is mixed crop and livestock agriculture, about 80% of the people are working in the agricultural sector ([1]Woldearegay et al, 2014).

The agricultural fields are mainly used for rain fed subsistent farming. The main products are teff, sorghum, tomatoes, chillies and beans. Irrigation enables the cultivation of oranges and other fruit trees (Baert, 2010). Groundwater is the main source of water for household purposes, shallow groundwater development for the application of irrigation practises is increasing over the last decade. The flat plains and valley bottoms which are crossed by the road are sufficient for groundwater development (serving water supply and irrigation) because of their porous character. Hand-dug wells increased in number since the year of 2000, about 3000 hand dug wells were constructed in three districts between 2011 and 2013 solely (Woldearagay, et al, 2014). Locations close to these wells enable cultivation throughout the year, while drier areas are restricted to the rainy season (Baert, 2010). At the moment about 30% of the land can be cultivated, this is restricted by the availability of water([1]Woldearegay et al, 2014). Supplemental irrigation has a large potential to increase food security and welfare for this region.

Figure 6: Left: Farmer working on his land. Right: Hand dug well for irrigational purposes (Roads for water, 2015).

4.4 Geology and soils

The two districts are dominated by a few rock and soil types. Metamorphic rocks are present in just a few areas, most around deep rivers. This rock material is characterised by a low permeability, due to a weathering process these soils contain fractures which increase the capacity for shallow groundwater development which is the case for large areas situated in the valley bottom. Paleozoic sediments which can be characterised by the Enticho sandstone which is of a glacial origin. It is forms flat plateaus or dome shaped hills (Baert, 2010), do have good aquifer properties. Fine to medium grained and moderately weathered rock material facilitate shallow groundwater development, these areas are preferred for the construction of wells. Antalo limestone is a rock type which is present along the studied road, it consists of hard limestone and has only moderate aquifer properties. The unconsolidated deposits vary considerably in permeability and suitability for groundwater development. The main soil types observed along the road are: different types of Cambisols, Luvisols, Leptosols and Vertisols. The silty sand soils make up the majority of the present soils and are valued as good aquifers, which results in the extensive use of shallow groundwater ([1]Woldearegay et al, 2014).

5. Theory

This chapter elaborates on the concepts used in the method section and integrated into the revised Morgan, Morgan and Finney model.

5.1 Rural road systems

5.1.2 General

A rural road, or low-volume road, logging roads or roads which connect rural communities are all a significant part of any infrastructural system, they will be referred to as unpaved rural roads in this study. In sub-Saharan countries the unpaved road system made up 85% of the total infrastructure in 2008 (Faiz, 2012). Infrastructure development in the Tigray region focuses to a large extent on the unpaved rural road systems as was documented in the URRAP program. The aim is to construct approximately a total of 70,000 kilometres of new roads which will provide 80% of the total population with all year road access. A total of 2500 kilometres of unpaved rural road is planned for the Tigray region ([1]ERA, 2011; [1]Woldearegay et al, 2014). These unpaved rural road systems are essential in providing public services, they improve the flow from goods or services and thereby promote welfare development (Keller & Sherar, 2008). An unpaved rural road is defined as a road that serves an average daily traffic of less than 300 vehicles per day and is constructed for design speeds less than 70 km/h ([2]ERA, 2011). These roads often evolve from existing tracks or trails, they follow logical routes across the landscape and are built with locally available construction materials, which can vary significantly in texture, erodibility and trafficability (Zeedyk, 2006). A minimum impact unpaved rural road, is well drained, has a stable driving surface, is aligned along stable slopes and is satisfactory for its traffic purpose.

Unpaved rural road systems are accompanied by often simple and low cost drainage systems. The general objective of a drainage system is to protect the road system from being damaged by runoff. The main purpose is to reduce the energy of runoff and protect the road surface, its embankments and installed hydraulic structures. Reducing the energy can be done either by reducing the conveyed volume through for instance spreading mechanisms or reduce the flow velocity. An effective road drainage system needs to comply with two main criteria: It must secure a minimum disturbance of the natural drainage pattern and it needs to drain surface and subsurface water away from the roadway while avoiding excessive collection of runoff which might cause downstream erosion (FAO, 1998). Road drainage can be divided into internal and external drainage systems. The first one describes the drainage of the road surface itself, all other drainage measures are referred to as the external drainage system. Internal drainage can easily be secured by simple and relative cheap solutions (eg. rolling dips). Numerous techniques are mentioned in the work by Zeedyk (2006). This study focuses on external drainage system, which includes the hydraulic structures integrated for both roadside- and cross drainage. Culverts or drifts are generally required at every low point along the road alignment, when runoff should be cross-drained or when a watercourse is crossed. The following pictures give an impression of the unpaved rural road systems in the Tigray region, which are studied in this research.

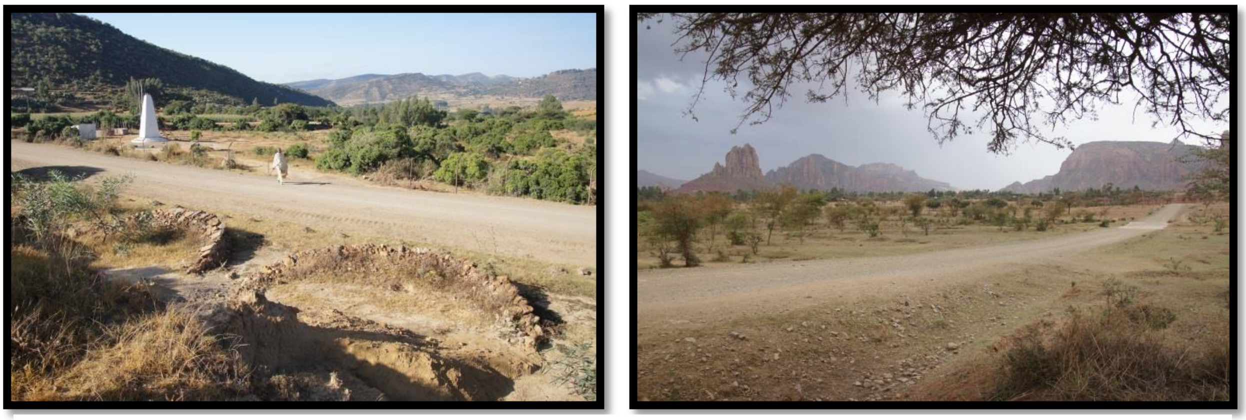
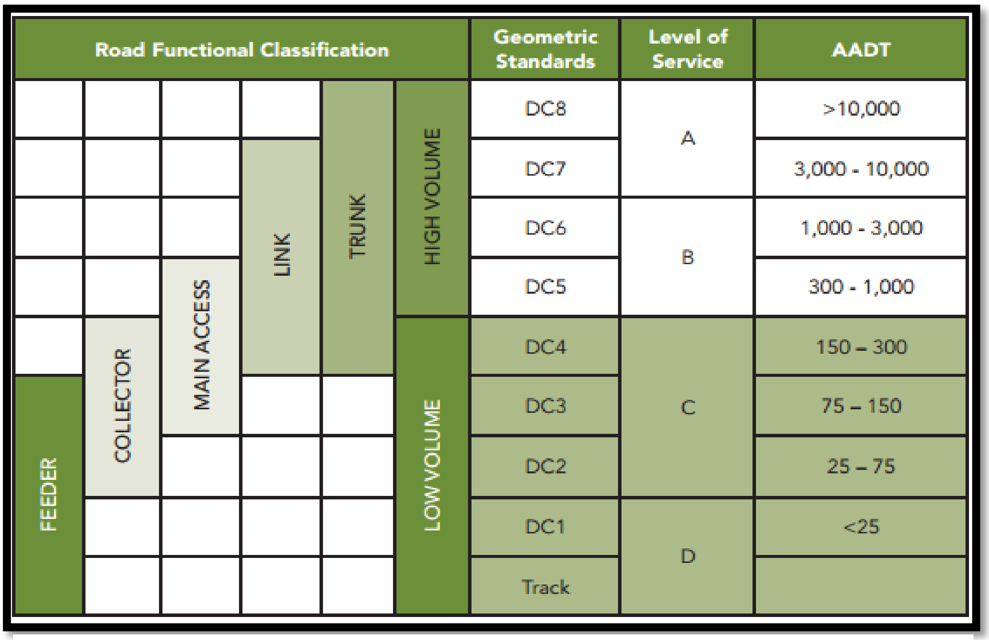


Figure 7: Representative rural road systems in the Tigray region (Roads for water, 2015).

5.1.3 ERA design manuals

The ERA provides a set of design manuals for the development of different types of road systems, the manuals can provide assistance during the planning procedure of future road systems. It addresses policy and legislative considerations, design parameters like climate and terrain, pavement materials, drainage and erosion control measures but also traffic signs and road markings. The prescribed procedure for road design follows a step-by-step approach and is elaborately described by the different manuals. The ERA guidelines prescribe detailed geometric road design standards per different road category. Figure 8 shows the different categories distinguished by the ERA, it defines low volume roads into four different categories which can be categorised based on their traffic volumes, they are further defined by other factors, for instance population size of surrounding communities or landscape features. Low-volume roads are defined by the ERA as roads that carry up to about 300 vehicles per day ([2]ERA, 2011)



Road Functional Classification						Geometric Standards	Level of Service	AADT
				TRUNK	HIGH VOLUME	DC8	A	>10,000
			LINK			DC7		3,000 - 10,000
						DC6	B	1,000 - 3,000
		MAIN ACCESS				DC5		300 - 1,000
	COLLECTOR				LOW VOLUME	DC4	C	150 – 300
FEEDER						DC3		75 – 150
						DC2		25 – 75
						DC1	D	<25
						Track		

Figure 8: Road classification scheme constructed by the Ethiopian Road Authority (ERA) ([2]ERA,2011)

The design manuals define the most suitable geometric road system standard by their traffic load, general topography and socio-economic context. Much of these data is not available for the study area. Moreover, the described data in the ERA manuals is of a rather detailed character (quality and scale) compared to the available data. Following the ERA guidelines on the design of an adequate drainage system, one evaluates the future performance of single hydraulic structures. A design storm with a particular return period is used to determine the dimensions of individual structures (eg. culverts), nomographs (will be explained in section 5.4 on culvert hydraulics) are then used for the actual dimensions. Analysing every structure individually is too time consuming and does not fit the explorative character of this research. The ERA manuals are considered relevant background information in the formulation of improved road design guidelines which also integrate the potential of road water harvesting practises. However, the ERA manuals also enclosed some standardized guidelines on culvert spacing, sizing and the type of culvert. The contributing catchment size of a potential culvert location can be used in the determination of a minimum required culvert diameter. The spacing intervals between the positioned culverts can be based on the average road gradient along longer grades. These standardized guidelines will be used to develop a road system scenario based on the ERA guidelines, in order to evaluate the design guidelines’ appropriateness. The development of the ERA based scenario is elaborately described in the section on scenario formulation in the method chapter.

5.2 Water harvesting practises

Runoff harvesting from road systems is a relatively new concept to researchers and development NGOs, it can shortly be defined as 'the collection of runoff from roads and roadsides for productive uses (Kubbinga, 2012). Runoff harvesting from roads is often the result from small-scale farmer initiative, a wide array of different small-scale applications can be found (Kubbinga, 2012; Nissen-Petersen, 2006; [1]Woldearegay et al, 2014). The basics of runoff harvesting from road system follow the normal steps of rainwater harvesting: 1) The collection of runoff by concentration. 2) Storage (optional). 3) Using the runoff for agricultural or other purpose (Kubbinga, 2012).

Supplemental irrigation enabled by runoff harvesting from roads has a large potential to improve conventional rain fed agriculture and provides a source of water during the dry season. The runoff can directly be used to irrigate cultivated land via a simple diversion system, runoff can be collected in (a network of) retention ditches or reservoirs which occur in a wide array of designs (borrow-pits, water pans, earth dams) (Nissen-Petersen, 2006, Wolderaregay et al, 2014). Storage of runoff in percolation ponds or high permeable zones can make a significant contribution to groundwater development and lead to an increase in the groundwater level (Steenbergen et al, 2014). The construction of hand-dug wells are an effective technique to make use of the increased groundwater source, in the region of the study area over 3000 wells were dug in the years 2011-2013 with the purpose of supplemental irrigation (Puertes et al, 2014).

Two different types can be distinguished in road water harvesting. Runoff harvesting with a roadside drain which mainly focus on the runoff generated by the road surface. This research focuses on harvesting discharge from culverts. Rainwater is collected from the uphill catchment, the road is used as a diversion structure until it can be drained to the downslope side of the road through an (culvert) outlet. The application of runoff harvesting from roads fits into the 3R-approach (recharge, retention and Reuse), an approach aiming at maximising the use of both groundwater and rainwater to 'give people the means and confidence to protect and strengthen their livelihoods in response to climate changes, ensure a reliable access to water, economic development and the integrity of their environment (Steenbergen, van. and Tuinhof, 2010).

The impact of a road system to farmer communities was researched through a survey in the Tigray region, executed by the roads for water collaborative last year (Demenge et al, 2014). The identified impacts contain multiple applications of water harvesting principles. Table 1 summarises the encountered positive aspects, the table is illustrated with figure 9 and 10 showing road water harvesting applications along the surveyed pilot route.

Table 1: Observed positive aspects of a road system for farmer communities in the Tigray region (Demenge et al, 2014).

Observed positive aspects
• **Road runoff and groundwater recharge through ponds and shallow wells**
• **Increased groundwater recharge resulting in more water available in wells for irrigation**
• **Increased runoff from the road and adjacent areas is canalised to the fields and pastures: as a result fields benefit and grazing land downstream is enriched**
• **Increased availability of fodder for livestock**
• **Increased moisture downstream (in some cases)**
• **The water table downstream is more stable throughout the year**
• **Borrow pits can be used to store the water**
• **Diversion of rainwater from erosion gullies to the fields**
• **Sand concentrating at gullies**
• **Yields at the hand pump increase**
• **Possibility to cross the river during heavy rains**

Figure 9: Road ponds are installed along the road to capture runoff and recharge groundwater (Roads for water, 2015).

Figure 10: Culvert discharge is channelled and spread into farmlands, without adjustments the gully would most likely cause gully formation (Roads for water, 2015)

5.3 Land degradation and soil erosion

5.3.1 General

Land degradation is caused by three main processes: physical, chemical and biological degradation. Physical degrading processes consist of a decline in soil structure (eg. decrease in porosity), amount of soil, infiltration capacity and thereby increase the generation of runoff and susceptibility for wind or water erosion (FAO, 1965; Lal, 2001; Toy et al, 2002). Chemical or biological weathering changes the composition of the soil material, the interaction with water, oxygen or acids (often produced by biological agents) and the soil material can cause various chemical reactions to occur. These chemical reactions affect the stability of the soil aggregates, decreases particle size or organic matter content and increase the susceptibility to detachability which results in an increase in soil erosion. Soil erosion exacerbates land degradation and vice versa (Lal, 2001; Tefera et al, 2002). Agricultural practises are an important anthropogenic driver of soil erosion because they cause soil disturbance (tillage and compaction) and reduce ground cover (bare fallow or burning practises). Accelerated soil erosion decreases farmer income because of land productivity losses and decreased soil quality. Loss of topsoil depth in soils with root-restrictive layers is the most severe effect, a process which is enhanced by the practise of tillage on cultivated lands. (Lal, 2001). There are limited estimates about the actual productivity losses. Lal (1995) estimated yield losses due to past erosion in Africa, and came up with a percentage between 2 and 40 %, with a mean loss of 9 per cent for the continent. Soil erosion rates were founded to be highest on the African continent, showing average rates of 30 to 40 tons of soil loss per hectare per year (Pimental et al, 2004).

Soil erosion is caused by the process of soil being worn away by either wind, water or ice. Soil erosion results in a decrease of the soil quality. These degrading processes can lead to a reduction in biomass productivity of the soil, potential contamination of water and subsequential eutrophication and a reduction in air quality. Different soil erosion driving factors can be distinguished. Environmental factors which are primarily of a climatic character (e.g. drop size distribution, rainfall intensity and amount and velocities), chemical factors leading to enhanced weathering of the soils, topography of the terrain and the susceptibility of the soil. The susceptibility of the soil depends on soil properties like texture, structure and organic matter content. The erodibility of a soil is dynamic and can be influenced by management, all factors can potentially be influenced by anthropogenic forces (eg. soil conservation management) (Lal, 2001).

5.3.2 Runoff generation

This research addresses erosion caused by water, which has two components: the impact of raindrops and runoff. Runoff is the biggest driver of water caused erosion. A brief description of run-off generation will be given after which the consequential erosion process will be explained more elaborate. Several types of rainfall-runoff responses can be distinguished, two main types are Hortonian overland and saturated overland flow (Dingman, 2002):

- Hortonian overland flow: This is runoff driven by the saturation from above, which occurs when the water input rate is larger than the infiltration capacity of the soil for a time exceeding the time of ponding.
- Saturation overland flow: This is runoff that occurs due to a process of saturation from below, the runoff consists of both rainfall from the saturated area as well as a return flow from the groundwater.

Hortonian overland flow is considered responsible for the flashy rainfall-runoff response of catchments in (semi-) arid areas and for high rainfall intensities (Hendriks, 2010), the Tigray region can be characterised as an (semi-)arid area and faces a short erratic and torrential rainy season. Hortonian overland flow is caused by the temporal exceedance of the rainfall intensity compared to the infiltration capacity of an unsaturated soil, which depends on the soil characteristics and initial conditions (e.g. moisture content). The infiltration capacity equals the rainfall intensity during the beginning of the event, due to increased saturation and subsequential processes like packing of the soil surface by rain, swelling of the soil and washing of fine particles into soil-surface openings the soil porosity and thereby infiltration capacity decreases gradually. From the moment the infiltration capacity is exceeded by the rainfall the water starts ponding, on sloping land surfaces this results in the downstream flow of water. After the event, restoration of the infiltration capacity starts (Dingman, 2002; Hendriks, 2010).

5.3.3 Erosion process

The process of erosion contains three stages. Detachment of the soil relates to the breakdown of aggregates by either the impact of raindrops or when the impact of shearing or drag forces by the water become larger than the resistance of the soil to detachment. The detached particles are transported by either water or wind; detachability tends to increase for coarser sized particles (FAO, 1965; Lal, 2001; Toy et al, 2002). Transportability of the sediment depends on both the shear stresses applied by the runoff, which are strongly depending on velocity and the size of the particles to be transported (Toy et al, 2002). A process of deposition takes place when velocities decreases (e.g. lower local slope values or higher surface resistance) and thereby the transport capacity of the runoff. Soil erosion is limited by the magnitude of either the process of soil detachment or transport capacity. Soil erosion limited by erosion occurs in soils with a heterogeneous soil structure and aggregate strength is higher than the impact of raindrops, drag or shear forces. Steeper slopes which do not allow for an accumulation of sediment show a process of soil erosion limited by detachment (Lal, 2001).

5.3.4 Gully initiation and development

A special case of soil erosion is the formation of gullies. A gully is a ravine formed by water, it is a process depending on a certain local threshold. The formation of gullies is affected by multiple factors and processes, their formation is often triggered by land use change and they can develop rapidly to dramatic proportions. Gullies divert and concentrate runoff and tend to enlarge drainage volumes of inter-gully areas which cause a process of land aridification (Nyssen et al, 2002; Poesen et al, 2003; Valentin, 2005), sediment production studies showed that 60-95% of total sediment production could be traced back through gullies (Valentin, 2005). Once gullies developed they increase the connectivity of the landscape and thereby cause higher runoff volumes, larger peak flows and shorter concentration times (Poesen et al, 2003). Gully development leads to enhanced hill slope erosion via a feedback loop, it can cause significant losses in crop yield and land area on cultivated lands. Gullies are often triggered by agricultural practises, by the application of irrigation systems or wrong cultivation methods, overgrazing, road construction or urbanization (Poesen et al, 2003; Valentin, 2005).

Figure 11: The photo shows the outlet from a cross-draining culvert. In the centre of the picture one can clearly see a previous developed gully. The culvert outlet is adjusted by stone bunds to reduce the runoff energy by diverting the flow in two parts, the gully can now be recovered (Roads for water, 2015).

Hydraulic thresholds for gully triggering are difficult to determine because they depend on the surpassing of the boundary flow shear stress, which depends on a wide array of variables (eg. soil type and compaction) (Poesen et al, 2003). Zevenbergen (1989) described five factors of influence for gully formation, 1) overland flow and duration, 2) slope and flow depth which both influence the boundary shear stress exerted by the flow, 3) planform curvature which determines the flow convergence or divergence and thereby the magnitude of the flow 4) Soil characteristics controlling infiltration and erodibility 5) Vegetation characteristics influencing processes of interception and flow resistance. A more recently studied topic is the occurrence of 'piping', a factor which in certain occasions turns out to be a very important factor in the process of gully triggering. It is related to the sudden occurrence of a gully due to subsurface soil instabilities (Faulkner, 2006).

Parker et al (2010) formulated a method of automated gully mapping, based on a Compound Topographic Index (CTI) score to determine the risk of gully triggering. The CTI score is based on a proxy value for total stream power, which describes the first three factors mentioned by Zevenbergen (1989) and can be calculated using the local slope and the contributing drainage area of that particular location. A third factor accounts for the effect of either the convergence or divergence of flow, this is represented by a value for planform curvature. The CTI score is validated by field data to obtain a local critical CTI threshold. The spatial resolution of a DEM was found to be a crucial factor in the accuracy in the prediction of gully formation (Parker et al, 2010). A different method for the prediction of gully formation are so-called critical area-slope relationships, a graph distinguishes between higher scores which show a risk of gully formations and lower scores which are evaluated as stable locations. These so-called slope-area relationships are found by field experiments, they differ per region and type of land use (Katz et al, 2011; Montgomery, 1994). Nyssen et al (2002) found a relationship for the Tembien' highlands district in the Tigray region, this relationship is shown in figure 12.

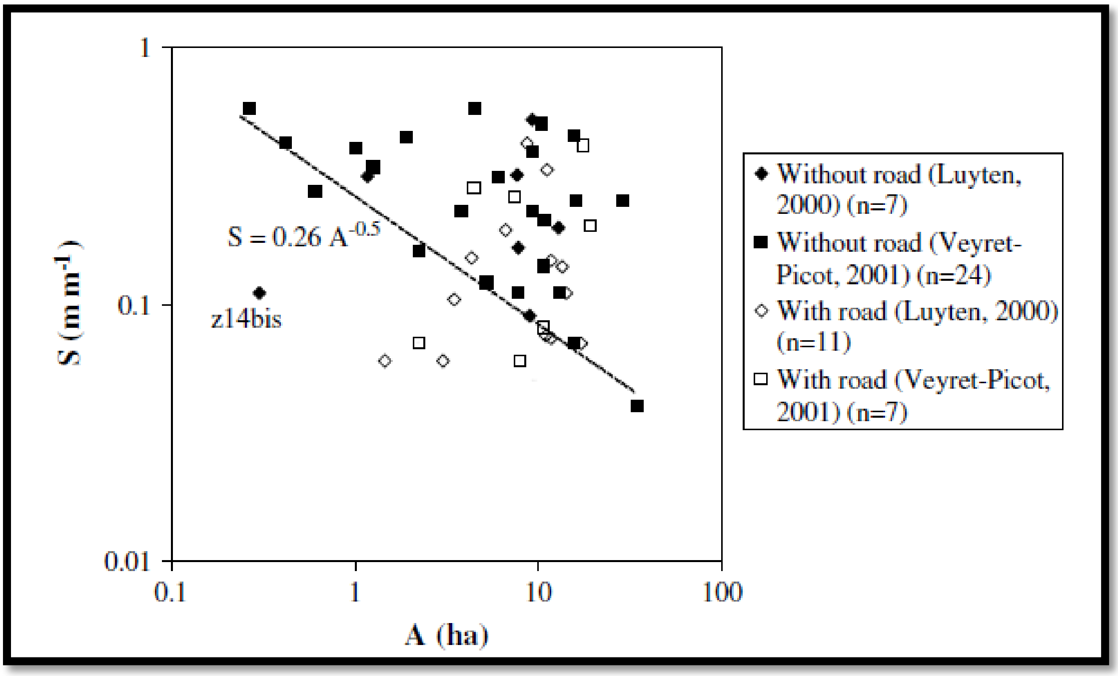


Figure 12: Example of a slope-area relationship by Nyssen et al (2002).

The obtained threshold graph by Nyssen et al (2002) shows relatively high values compared to other slope-area relationships, which can be clarified by the relative low values for soil erodibility in the region. However, due to the presence of steep slopes these thresholds are often surpassed.

5.3.5 Erosion from road systems

Road systems intercept and concentrate surface and shallow subsurface runoff, the relatively dispersed runoff gets blocked along the impermeable road side and transferred to the first cross-draining (pipe) culvert. Natural drainage networks are altered in their patterns, extent and underlying processes. The concentrated discharge might contribute to slope instability on the downstream of the road (Montgomerey, 1994). The road system alters the size and shape of natural catchments, the runoff can be diverted by the road to nearby catchments (Montgomerey, 1994; Nyssen et al, 2002; [1]Wolderaregay et al, 2014). The size of catchments can change considerably due to the construction of roads. Nyssen et al (2002) found an increase in catchment size after the construction of a road system close to Mekelle, Tigray region. The study used several gully heads as reference points to study the effect of road construction on catchment size. The initial catchment size increased for almost all studied locations, the most significant impacts were shown by an increase of 0.09 to 8.6 ha, 2.3 to 6.6 and 5.8 ha to 8.5 ha.

Culverts are constructed to avoid the flooding of roads by cross-draining the discharge from the upstream to the downstream side of the road. Although culverts are built to prevent roads from being flooded, they often cause damage at the downstream side of the road. Bad drainage design can concentrate discharge to an extent that even gullies and severe erosion can occur at culvert outlets, susceptibility of the receiving soils to erosion is an important aspect ([2]ERA, 2011; Kubbinga, 2012; Montgomerey, 1994; Nyssen et al, 2002). In case of lack of discharge capacity, the culvert can get flooded, cause waterlogging on the upstream side or cause severe sedimentation. Culvert diameter and placement interval are two important aspects because the determine the degree of dispersion of runoff and thereby the energy and volume of discharge. The risk for gullies increases when hydraulic structures are wrongly installed, the presence of a hydraulic jump at the outlets (eg. culvert outlets) increases the impact energy and thereby the soil detachment process (Nyssen-Petersen, 2006; Wolderaregay *et al*, 2014). Higher runoff volumes and steeper slopes favour the initiation of channels and sub sequential gullies (Montgomerey, 1994; Nyssen et al, 2002). Fractures in the earth surface or crusted soils can facilitate in starting points for weathering and further gully triggering. Gullying in the Tigray region is mainly related to a general lowering of the infiltration capacity because of a depletion in the vegetative cover and abandonment of fields, especially after conversion to grazing lands. Higher runoff generation can be observed, especially in combination with a weaker soil structure related to the trampling and grazing of cattle (Nyssen et al, 2002). Jungerius et al (2002) reported that 13 out of 24 culverts led to severe downslope erosion along an approximately 40 kilometre road transect in Kenya. Similar problems were described in Kenya by Nissen-Petersen (2006) during a case study. A similar reconnaissance study was executed along the pilot route by the roads for water collaborative ([2]Woldereagay et al, 2014), which will be discussed in the following section. In general, the effects of road construction on gully erosion remain largely unstudied.

5.3.6 Problems along the pilot route

A survey by the roads for water collaborative on the pilot route described in chapter 4 revealed that enhanced soil erosion caused by the road system significantly damaged small-scale farming communities living along the road: increased and accelerated erosion at culvert outlets, loss of fertile land, increased gully formation, siltation of fields, ponds and wells and damage to property because of increased runoff volume ([1]Wolderaregay et al, 2014). Other negative issues caused by the road system and related to erosive processes are the occurrence of severe sedimentation on? (farm)land, waterlogging of both the up- and downstream side of the road, changed soil moisture patterns and the alterations of infiltration and storage zones. On a farm scale this results in unexpected activities like re-ploughing, re-sowing and removal of deposited silt from their lands. Moreover, farmers cultivate more resistant crops (higher stems) but with significant lower value (sorghum, maize and finger)(Demenge et al, 2014). Restoring land or assets requires both financial means and time which are both scarce. A survey focusing specifically on gully erosion was executed along the pilot route by [2]Wolderaregay et al (2014). Over the transect of 40 kilometres a large number of road system caused gullies were found, especially at culvert outlets where the most concentrated volumes are discharged. Dimensions of 1-20 meters depth, 1-15 meters in width and lengths reaching until 1.2 kilometres were found. Soil and water conservation management is applied throughout the region, several techniques are used: stone bunds, grass strips and trenches. Gully restoration is done by the placement of gabions, re-vegetating the gully or check dams. The negative impacts obtained in the reconnaissance are summarized in table 2, followed by figure 13-15 showing illustrative pictures.

Table 2: Observed negative aspects along the surveyed pilot route (Demenge et al, 2014)

Observed negative aspects
• **Flooding and waterlogging upstream**
• **Runoff directed and concentrate in culverts, leading to increased and accelerated erosion, formation of gullies and floods downstream**
• **Siltation of fields, ponds and wells**
• **Elevated road blocking the even flow of runoff**
• **Increased runoff leading to the destruction of crops, and the loss of seeds, fertilizer and seedlings**
• **Waterlogging increases the incidence of malaria**
• **Flooding, waterlogging and siltation of fields, making land less productive and more difficult to cultivate, deposit of clay on the land**
• **Loss of arable land due to road, gullies and infertility**
• **Damage to houses: water infiltration, collapse of walls, soil subsidence, and mortar washed away.**

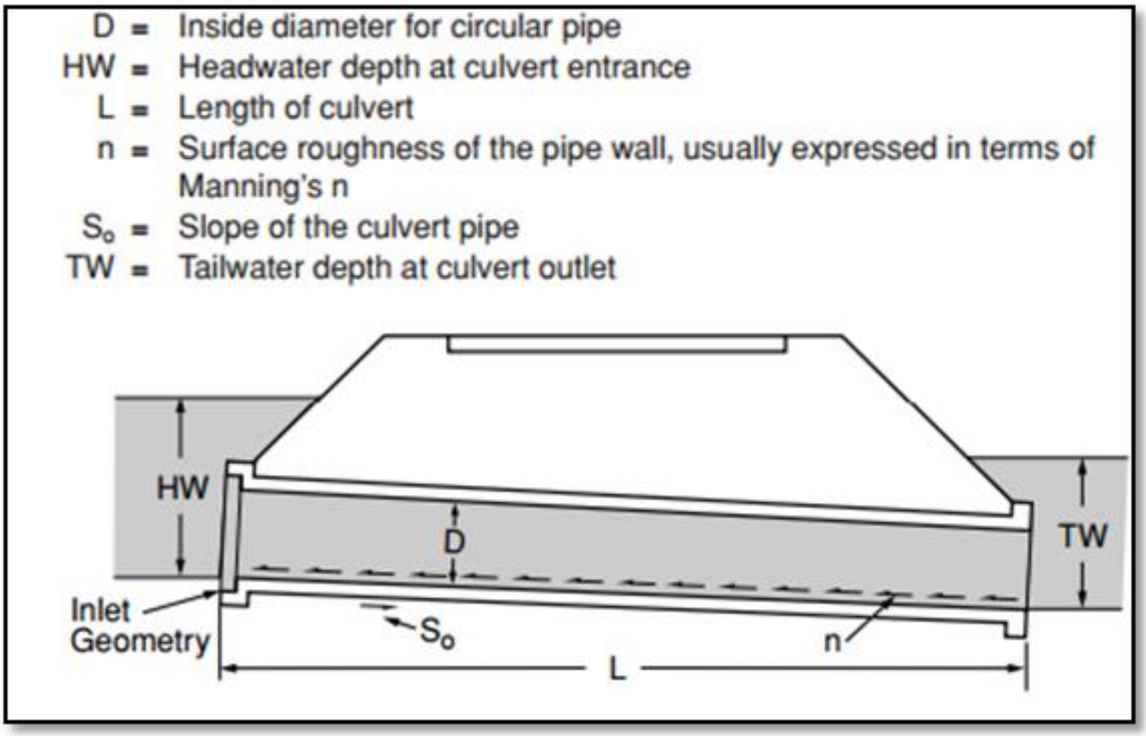
Figure 13: The photo shows part of the surveyed route. The road side Is characterised by a large gully, developed due to a too concentrated flow caused by an insufficient drainage design (Roads for water, 2015).

Figure 14: The photo shows a culvert surpassing a bridge along the surveyed route. The runoff from the culvert outlet and road side merge at this point and cause the development of a severe gully (Roads for water, 2015)

Figure 15: The photo shows a bridge that is completely ‘eaten’ by the high volumes of runoff from the road surface, the installation of an appropriate internal drainage system could have avoided this severe damage (Roads for water, 2015).

5.4 Culvert hydraulics

Culvert hydraulics are complex and require a good insight in actual flow conditions, flow conditions vary per culvert type, location and can change rapidly. A detailed analysis requires backwater and drawdown calculations, energy and momentum balances and eventually results of hydraulic modelling (FHWA, 2012). A detailed analysis of individual culvert hydraulics for culvert planning is time-consuming and requires a lot of data. The Federal Highway Administration, the United States (FHWA) has done extensive laboratory research on culvert performance which led to the development of design capacity charts and nomographs which can assist in culvert planning procedures. Equations distinguishing between (non-)submerged and in- and outlet controlled culverts are used to develop dimensionless design curves, using a range of possible culvert diameters. Both methods start with the formulation of a design event (storm) with a particular return period, this depends on the importance of the road transect and a potential flood damage. Depending on the size and costs of the culvert installations a more in depth hydrologic analysis need to be performed, which can include complete storage routing of flood events. The flow through culverts is determined by distinguishing about whether or not a culvert is submerged and if flow through the culvert is either controlled by the inlet or outlet side. Figure 16 shows a schematised culvert with all important hydraulic factors.



D = Inside diameter for circular pipe
HW = Headwater depth at culvert entrance
L = Length of culvert
n = Surface roughness of the pipe wall, usually expressed in terms of Manning's n
S_o = Slope of the culvert pipe
TW = Tailwater depth at culvert outlet

Figure 16: Main parameters in culvert hydraulics (FHWA, 2012)

Inlet controlled flow conditions hold as long as the water can flow out of the culvert with a greater rate than the water enters the culvert. Since the control section is at the inlet of the culvert, inlet controlled culverts are only dependent on the inlet geometry and the upstream headwater depth. Critical depth occurs at the culvert inlet or close to it, the flow regime downstream is in a supercritical state. Outlet control holds when discharges are dependent on all the hydraulic factors upstream from the culvert outlet, which are described by figure 16. In the case of inlet control, water is able to enter the culvert at a greater rate than water can flow through the pipe, therefore pressure or subcritical flow conditions hold (FHWA, 2012). For the Tigray context one can assume inlet controlled culverts, most culverts discharge freely downstream and are not restricted by the culvert inlet ([2]Woldereagay et al, 2014). Standard concrete pipe culverts are mostly installed along the unpaved rural road networks in Tigray.

The planning procedure of individual culvert capacity is often done by either using culvert capacity charts or by the use of so-called nomographs. The use of culvert capacity charts is a relatively simple method to determine individual culvert capacities, the charts are distinguished based on the agreed value for an allowable headwater depth. An iteration process between allowable and the estimated headwater depth for the design discharge results in optimal culvert dimensions, this is related to both inlet- and outlet controlled curves. The nomograph procedure is often used for submerged, or culverts with special entrance conditions. Different graphs are used for inlet or outlet control conditions. The complete stepwise process is described in the appendices of the hydraulic design manual by the FHWA (FHWA, 2012). Both an example of the design capacity chart and nomograph are presented in figure 17.

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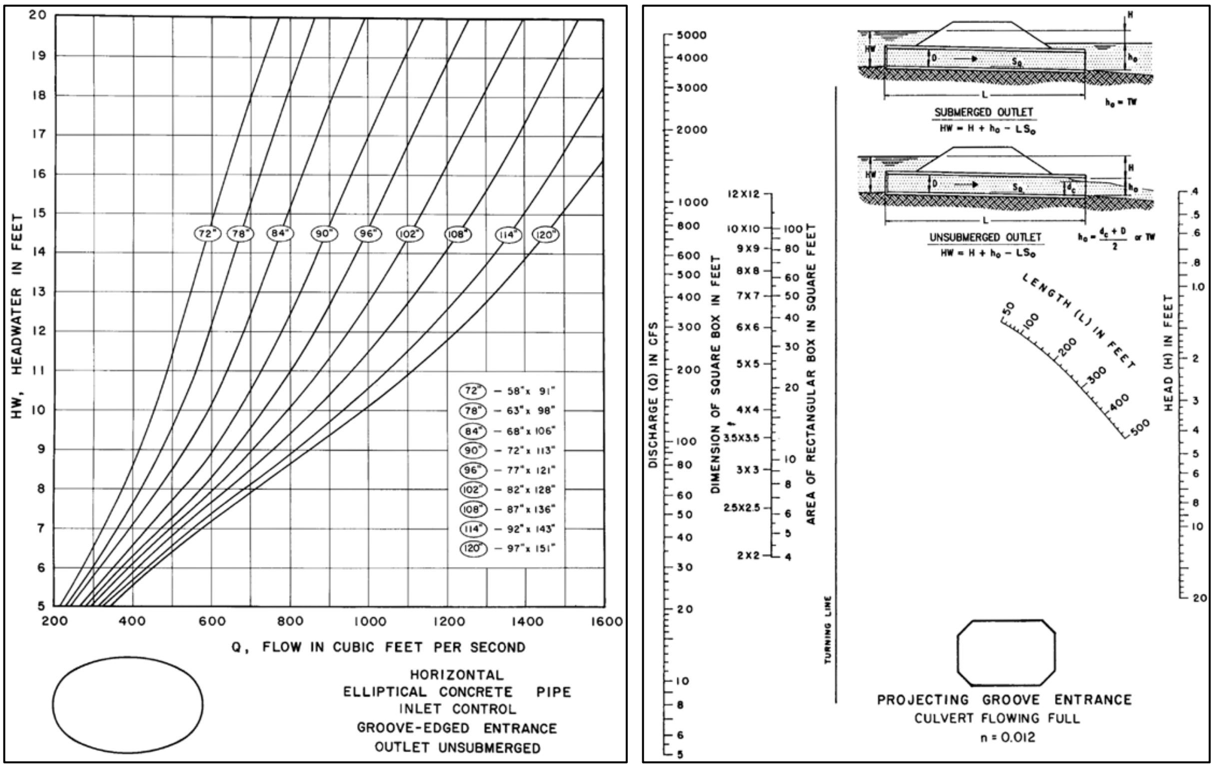


Figure 17: Left: Culvert design chart. Right: Nomograph. (FHWA, 2012)

Both procedures are time consuming, differ per culvert type and focus on individual culvert locations, which does not facilitate the purpose of this study, which focuses on a longer road transect containing multiple culverts and their positioning. To facilitate a fast and easy judgement on culvert capacity, standard tabular data has been developed, which relates head water depth and diameter to an approximation of the maximum culvert capacity. A different way of approximating culvert discharge is to use empirical formulas. However, both methods do not include all factors which influence flow conditions, they are easy to use but do not give very reliable results. This study does not aim at reliable and correct values on culvert discharge, but requires a consistent and relative parameter to enable a fair comparison between different road system design scenarios.

5.5 Multi criteria decision making

The application of the concept of Multi Criteria Decision Making (MCDM) is believed to be the most suitable method for this research in evaluating alternative road system designs and find potential improvements in current rural road system design. Finding an optimal road system scenario is a difficult procedure, the integration of all influencing or affected aspects is prone to subjectivity and therefore needs to be executed very carefully. The MCA technique provides a clear process from problem to potential solutions, it can integrate all aspects determining the overall quality of rural road systems and is able to contribute to a balanced evaluation of alternative designs and eventually prioritise the alternatives based on the decision maker’s preference.

Multi criteria decision making (MCDM) includes two processes, decision making and the application of the multi criteria analysis (MCA) method. Much has been written on the theory of both aspects. Decision making is the process of formulating a solution when a decision problem occurs. A decision problem occurs when an individual or group of people perceive a discrepancy between the current and desired state (Janssen, 1992). The process of making a satisfying decision on a potential solution is a delicate and often complex process, often limited data is available and stakeholders keep different expectations during the process. The process of executing a MCA is a step-wise process which starts with getting a complete overview of the case or problem. To make a decision requires the identification of potential influencing aspects and their underlying structure, which is the most important and creative task. Such a structure provides a good overview of the problem and helps the decision maker with a possibility to study the magnitude of all separate aspects, in the same level separately even if they are described by different scale representations. The different criteria of a problem can be identified or distinguished by the construction of a hierarchy structure, prioritisation between alternatives can be done by applying a weighting system.

Pfeffer (2003) identified important advantages of using the technique of MCDM in the case of spatial planning decision procedures. Firstly, it is difficult to compare aspects in an integrated matter during planning procedures other than with the use of MCA. A MCA provides a technique for the systematic decomposition of a complex system in separate meaningful parts which can be integrated in an effective way towards a balanced decision. Second, in many decision processes only one alternative is presented, a MCA can also show and compare multiple alternatives with the same performance but different features. The applications of the MCA for spatial design problems are numerous. Store and Kangas (2001) integrated the MCA method and expert knowledge into modelling habitat suitability in a GIS environment for a region in Finland. The MCA method was applied for site selection of a local park in the Bergamo Province, Italy (Zucca et al. , 2008), a waste disposal site for the city of Chinchina, Colombia (Sharifi and Retsios, 2004). A different application of the MCA method is its application in risk assessments, Raaijmakers et al (2007) integrated the MCA method into a risk assessment in order to evaluate flood risk in the Ebro Delta, Spain. A landslide risk index map was constructed for the nation of Cuba by using a spatial MCA by Abella & van Westen (2007).

6. Method

This section describes the general research process and used methods to answer the formulated research questions. It describes the decision framework used, the data and its management, the revised Morgan, Morgan and Finney model and its adjustments and the developed Multi Criteria Analysis.

6.1 General research process

The research process is based on the step-by-step decision framework formulated by Simon (1960). Cowlard (1998) extended the framework by adding the term ‘evidence’, which is an essential component during all steps of the decision making process. It consists of all contributing information like: data, knowledge, experience and the set of tools and method used to process or manage the available information (Pfeffer, 2003). The decision framework will be briefly described, its components are shown in figure 18.

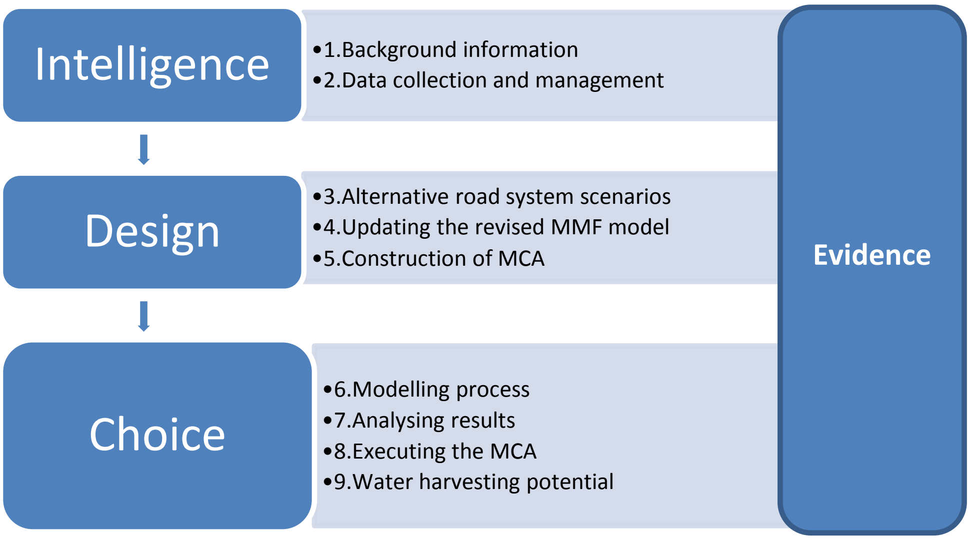


Figure 18: Decision framework based on the work of Simon (1960)

Intelligence

The intelligence component represents the process of getting a good overview of the design problem, the collection and processing of data. This component focuses on the gathering of information which is used in the formulation of research concepts and the theoretical background. This component is described in chapter 5 on background theory and part of the method chapter.

Design

The design component represents the formulation of a set of road system scenarios, the adjustment of the revised MMF model making it suitable for the integration and evaluation of road systems and the development of a sound MCA. All these aspects are described in chapter 6.

Choice

The modelling procedure results in a set of maps and numerical data per road system scenario. The numerical data is saved in an Excel sheet for further analysis. The map material is visually analysed to identify the impact of the current road system. Model outcomes per road system scenario are used to execute the developed MCA. The results are interpreted by making an overall ranking of all road system scenarios. The actual performance of the MCA itself is evaluated by addressing its weighting system by testing its sensitivity. The best performing scenarios are analysed on their potential for water harvesting by estimating their contribution to enhanced food production. All these aspects are described in chapter 7 on results.

6.2 Scenario formulation

In order to study the impact of a road system on hydrology and erosion patterns, a set of road system alternatives were formulated for a scenario study. A road system scenario consists of a specific road alignment and a set of culverts with a particular positioning along the selected road alignment. In this study 28 scenarios were constructed, which differ in road alignment, culvert number and their positioning. This study addresses the impact of road systems on both runoff and erosion processes at a catchment scale, previous studies addressed shorter road transects or a range of single culverts but not a complete road system. No complete set of guidelines could be found for the formulation of a road system at catchment scale. The ERA guidelines were used to formulate two alternative road alignment options, different culvert positioning methods were used for the development of culvert scenarios. Both the formulation of road alignment alternatives and the culvert scenarios will be described in this section.

6.2.1 Road scenario development

The formulation of alternative road alignment scenarios is based on the rural road design considerations described by the ERA. The ERA distinguishes between different road construction projects. These can be categorised into: the construction of a new road following the general alignment of an existing track or trail, upgrade a lower class road or the construction of a completely new road. The URRAP project aims primarily at the upgrading of existing trails or tracks. The ERA formulated a list of best practises which can assist in future road design, most of these are focusing on a preferred road alignment. The best practises are used as reference in the further formulation of alternative road alignment scenarios. Only a limited selection of these best practices can be accounted for, other criteria request more data, data of better quality or of different scale. Table 3 summarises the best practises selected which are divided into four different categories.

Table 3: Best practises for road alignment planning (^{2}ERA, 2011)

Category	Best Practices
Socio-Economic	- The road should be as direct as possible between cities, towns or villages to be linked. - The road should be located as far as possible along properties rather than through them to minimise interference to agriculture and other activities. - When the road follows a railway line or river, crossings need to be minimised and avoided as much as possible, the location should be such as to avoid unnecessary destruction of trees and forests (erosion control mechanism also). - The road should be integrated with the surrounding landscape as much as possible.
Engineering	- The preferred alignment is one that is founded on strong sub-grades. Therefore marshy and low lying areas with poor drainage possibilities need to be avoided. - Problematic and erosion susceptible soils should also be avoided. - The direction of the crossings of major river should be normal to the river flow. - When an alignment passes near to a river, areas liable to flooding and areas likely to be unstable due to toe-erosion by rivers should be avoided.
Mountainous Areas	- The location should facilitate easy grades and curvatures. - High fills should be avoided and attention for the compaction of these fills are important. - Harpin bends should be avoided as much as possible. - Natural terrain features (stable benches, ridge-tops, low gradient slopes) should be utilized. - In crossing mountain ridges, the location should be such that the road preferable crosses the ridge at the lowest elevation. - Needless rise and fall should be avoided, especially when elevation is gained over a distance. - To minimise the adverse effect of moisture on the road environment, an alignment that is predominantly in sunlight should receive priority compared to one which is mostly shaded.
Unstable Terrain	- If possible unstable slopes, areas having frequent landslide problems and benched agricultural fields should be avoided. - Mid-slope locations on long, steep or unstable slopes should be avoided. - It is best to avoid areas with high erosion potential.

Two alternatives were developed besides the current road system. A northern alternative was aimed at for which the alignment in general shows higher elevation levels and is situated more upslope in the catchment. A southern alternative was developed which in general follows lower elevation levels and is further downslope of the current road system. The exact details of the alignment were determined by incorporating spatial restrictions. The higher plateaus were excluded for potential alignments, these regions are out of direction and the slopes connecting the valley and plateaus show too steep slopes (30 - 100%). The ERA states that the steeper slopes (slopes above 25%, mountainous terrain and escarpments) need to be avoided in the construction of road alignment. Avoiding steeper slopes in the formulation of alternative road alignment scenarios, also accounts for other practises like avoiding the construction of too many hairpin bends and facilitate easy grades. The lower lying area in the south where the main river is drained will be avoided too, the preferred alignment is one that is found on strong sub-grades. No real forests occur in the study area, more dense vegetation could be found on the banks of the seasonal rivers. Agricultural areas are not situated in one particular region, but have a rather dispersed character, likewise most present property is only centralized around the existing villages. During the formulation of alternative scenarios, existing paths or tracks which infringed too much with agricultural practices or livelihoods were avoided. Scenarios were formulated while respecting the connectivity between the present villages of the current road system. Start- and endpoint of the current road system were used as fixed points for the alternative alignment options.

6.2.2 Procedure

Alternative alignments were developed by creating a vector map in the ArcGIS software, thereby using the ERA guidelines, produced map material (slope and LS map) and the World Imagery Base map. The satellite imagery was used to address for the following features:

- Starting point and endpoint of the road
- Urban areas
- Agricultural areas
- Rivers and streams
- Forest areas

The DEM was used to create the following maps for the study areas.

- A slope map
- A simplified erosion risk map based on the LS-factor

The original DEM is used to create a slope map. A simplified indicator for erosion risk is the slope length steepness (LS) factor presented in the Universal Soil Loss Equation (USLE). The LS factor describes the influence of topography on soil erosion. This topographic factor is among the most influencing factors for determining erosion in the well-known USLE equation. The slope steepness factor represents the effect of the slope gradient on soil loss (Renard et al, 2000). To calculate the LS factor in the ArcGIS environment, the method described by Pelton et al (2014) was applied. During the formulation of alternative alignment scenarios the regions showing relatively high LS values were avoided, these areas show an increased risk for erosion. The following function was applied to create a LS map in ArcGIS:

$$\mathrm{LS\ factor} = \left(\frac{\mathrm{FA} * \mathrm{R}}{22.1}\right)^{0.4} * \left(\frac{\mathrm{S} * 0.01745}{0.09}\right)^{1.4} * 1.4$$

$\mathrm{FA} = \mathrm{flow\ accumulation}\ \left(\frac{V}{T}\right); \mathrm{R} = \mathrm{resolution\ of\ the\ DEM(L)}; \mathrm{S} = \mathrm{slope}\ (-).$

The alignment vector maps were transformed into a Boolean PCRaster maps. The northern and southern alternative are presented in figure 19.

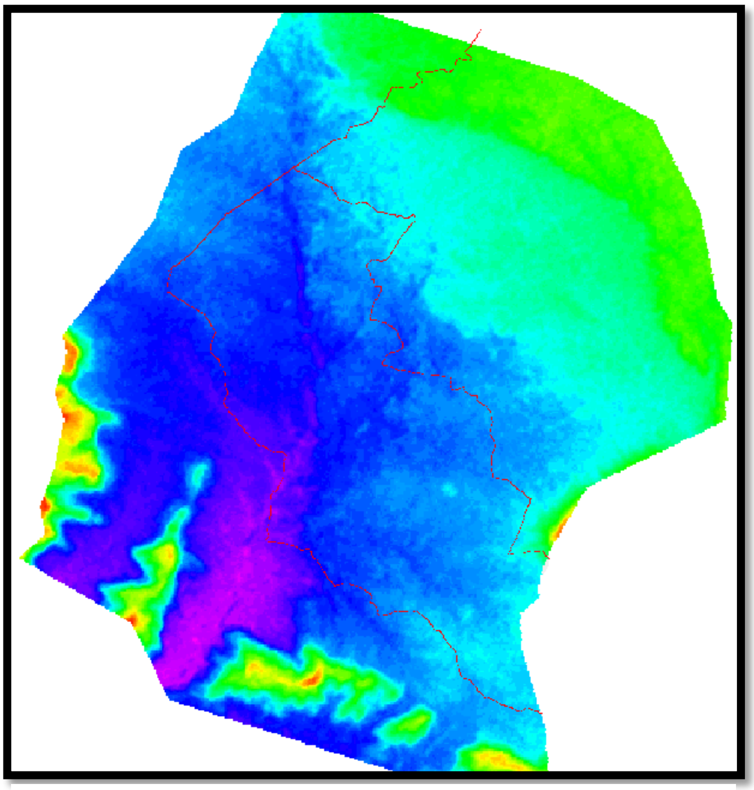


Figure 19: The figure shows the southern and northern alignment alternatives.

6.2.3 Culvert scenario development

The culvert positions of the current road were given in GPS coordinates and loaded into the ArcGIS software and made sure to be align with the current road alignment. The resulting vector map was transformed into a Boolean PCRaster map.

The alternative culvert scenarios are developed in the PCRaster environment. The Boolean alignment map is used to create a map showing a unique ID for all cells representing the alignment (approximately 3000). The road ID map is used together with the natural drainage map to (partly manually) develop new culvert scenarios. Three different methods were formulated to develop new culvert scenarios:

- A fixed culvert interval
- Base the position of culverts on the natural drainage patterns
- Follow the ERA guidelines on culvert spacing

All methods respect the major drainage patterns during the formulation of culvert scenarios. It is assumed that not adjusting for these major streams is unfavourable, a culvert is always installed at these locations. These locations are evaluated as a starting point for determining the position of the next culvert when a fixed culvert interval is applied. Figure 20 gives an impression of the maps used to identify major streams, the image shows three details (enlarged red squares) of three different locations (red circles) for the northern alignment where culvert locations are secured.

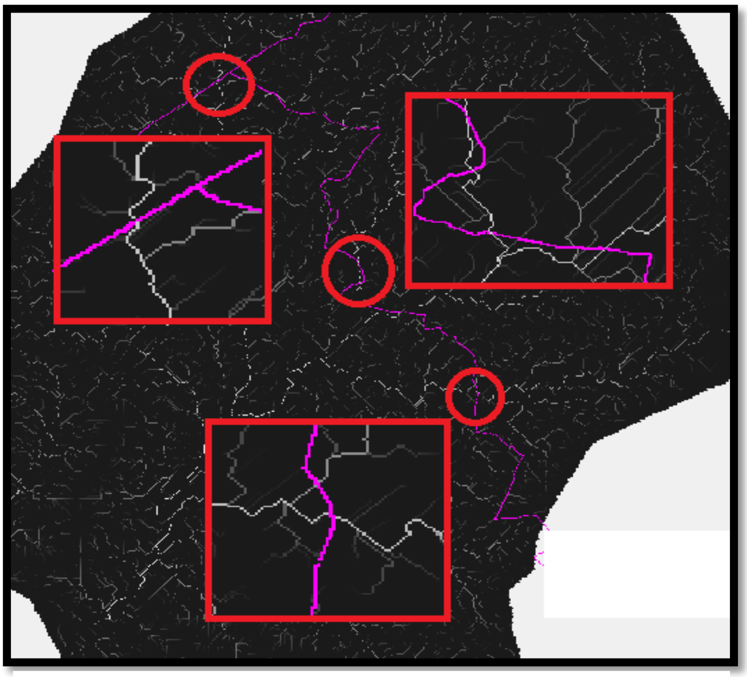
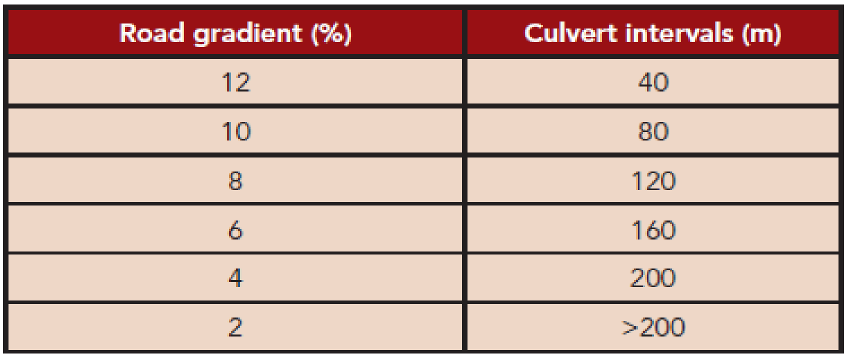


Figure 20: The figure shows the northern alignment option and three locations where culvert locations are secured because of major streams.

A fixed culvert interval is used to define five different culvert scenarios: 100, 250, 500, 750 and 1000 metres. The road ID values are loaded into an excel sheet and used to define culvert intervals based on the reference ID values of the major streams and on the fixed cell size of 10x10 m. An interval of 750 meters is compatible with 75 road IDs. The selected ID values were saved in ASCII-files and loaded from the particular scenario file into the script during the modelling of that particular scenario.

Three culvert scenarios are constructed based on the modelled natural drainage patterns. The drainage map for the situation of road absence is combined with the particular road alignment to identify all streams which would normally cross the road alignment. These road IDs and discharge volumes were extracted and analysed in an Excel sheet. Three threshold values were formulated, which should be evaluated as an expert guess after evaluation of the range in total discharge values of the set. The thresholds are set to: 10, 25 or 50 cubic meters per hour. Three different sets are constructed for every threshold values, a culvert location is set when the modelled values on natural discharge exceed the particular. The culvert locations are also coupled to a particular road ID and are saved as ASCII files.

One scenario is developed to evaluate the prescribed ERA guidelines on culvert positioning. The ERA prescribe a particular interval based on the slope along longer constant grades. Figure 21 presents the prescribed values by the ERA.



Road gradient (%)	Culvert intervals (m)
12	40
10	80
8	120
6	160
4	200
2	>200

Figure 21: guidelines on culvert intervals, prescribed by the ERA ([2]ERA, 2011).

The DEM and road alignment vector maps are combined to identify longer road transects with an approximately average gradient, this is executed in a PCRaster environment. These transects all contain their own interval based on the average gradient. The culvert locations are also coupled to a particular road ID and are saved as ASCII files.

All the formulated culvert scenarios are visually checked upon interval inconsistencies. Table 4 gives an overview of all formulated road system scenarios and their culvert number.

Table 4: Culvert scenario overview, giving positioning method and final culvert number of the scenario.

Scenario	Northern route	Southern route	Original route
Original scenario			36
Fixed culvert interval			
100 m.	295	295	285
250 m.	118	120	114
500 m.	59	58	56
750 m.	40	39	38
1000 m.	29	33	29
Natural drainage position			
>10 m^3/hour	55	52	48
>25 m^3/hour	27	32	29
>50 m^3/hour	20	23	19
ERA culvert positioning	96	94	96
			Total number of scenarios = 28

6.3 Model description

6.3.1 General

The model is built in a Python environment, using the Python PCRaster software including Aguila for visual presentation. The Revised Morgan, Morgan and Finney (MMF) model is used as a base for static modelling, the revised MMF model is a simple model for runoff and soil loss prediction (Morgan, 2001). The model is based on two script components, a part describing hydrology and a another component for soil loss and sediment transport over a raster. All input data and results of individual road system scenarios are stored in separate files. The model script is based on the model described in the appendix of the study by Karssenberg et al (2014). The revised MMF model is further adjusted to integrate and analyse a road system. This section will briefly describe all model components and the important adjustments made.

6.3.2 The road system

A Boolean map representing the particular road alignment is loaded into the model, the Boolean map is used to create an ID map assigning a unique ID to all individual cells representing the road. The culvert scenario is described by an ASCII file in which all culvert locations refer to a specific position (ID value) along the road alignment. The ASCII file is loaded into the script and transformed into a Boolean map. The road system can be described by adjusting the resampled DEM by using Boolean operators and these two maps. The DEM is heightened for the road surface and remains the original elevation values at the location of culverts. Discharge cannot surpass the road alignment but gets diverted to the first downstream cross draining cell which represents a culvert, which can discharge without a maximum.

6.3.3 Runoff

The modelling of runoff is adjusted for the modelling of single events. The original revised MMF model uses annual averages, runoff simulation is based on an exponential function using a mean value for rain per day and soil moisture storage capacity. The updated model integrated a Horton infiltration component depending on local soil texture. Horton infiltration is described by equation 1:

$$1. \quad F_p = F_c + (F_0 - F_c)e^{-kt}$$

$F_p =$ Actual infiltration rate (mm/hr); $H_c =$ Saturated hydraulic conductivity (mm/hr); $F_0 =$ Maximum infiltration rate (mm/hr); $k =$ decay constant ; $t =$ time (sec).

The maximum infiltration rate is based on soil texture and is given by Akan (1993). The saturated hydraulic conductivity is assumed to be equal to the minimum infiltration rate. The decay constant ranges between 2 and 7 according to Akan (1993), in the model it is set to 4.5 which is the median value. The generated runoff is the result of the rainfall depth minus the actual infiltration of each cell. A PCRaster operator is used to calculate the runoff depth per cell for the total event over the LDD map.

6.3.4 Kinetic energy of direct rain and leaf drainage

The kinetic energy caused by direct rainfall is described by the work of Nyssen et al (2005). The equation applies for intensities larger than 0.6 mm of rainfall per hour and is given by:

$$2. \quad E_k = C1 * (1 - (C2/\mathrm{I}))$$

$E_k =$ Kinetic energy of direct rainfall $(\mathrm{J \cdot m^{-2} \cdot hr^{-1}})$; $I =$ rainfall intensity $(\mathrm{mm \cdot hr^{-1}})$; $C1 =$ constant (36.65); $C2 =$ constant(0.6).

The formula for kinetic energy from leaf drainage is described the same way as in the original revised MMF model (Morgan, 2001). The kinetic energy is described by the following formula 3:

$$3. \quad E_k = D1 * \sqrt{PH} - D2$$

E_k = Kinetic energy of leaf drainage ($\mathrm{J \cdot m^{-2} \cdot hr^{-1}}$); PH = plantheight (m); $D1$ = constant (15.85), $D2$ = constant (5.87).

The kinetic energy for direct rainfall and leaf drainage are summed to calculate a total value for the kinetic energy of rainfall. The leaf drainage energy is based on the work of Brandt (1990).

6.3.5 Soil detachment

Soil detachment caused by raindrops is described according to the original revised MMF model, it is calculated by multiplying the total rainfall energy with the erodibility of the soil. Soil erodibility is given by a k-value and depends on soil texture class:

$$4. \quad F = KE_{tot} * K * (1 - SC) * 10^{-3}$$

F = Soil detachment ($\mathrm{kg \cdot m^{-2}}$); KE_{tot} = Total kinetic energy ($\mathrm{J \cdot m^{-2} \cdot hr^{-1}}$) ; K = soil erodibility ($\mathrm{g \cdot J^{-1}}$);

SC = stone cove r (−)

Detachment caused by runoff is described following the original revised MMF model. The process of detachment caused by runoff depends on the amount of runoff flowing through a cell, the fraction of ground cover by both stony material or vegetation, the local slope and a particular z-value depending on the cohesion of the soil. The detachment by runoff component is described by the following formula:

$$5. \quad H = Z * Q^{1.5} \sin S (1\text{-}GC) * 10^{-3}$$

H = Soil detachment ($\mathrm{kg \cdot m^{-2}}$); Z = constant (-); Q = runoff (mm); S = slope(−); GC = Total ground cover (−)

6.3.6 Transport capacity

The transport capacity is modelled as a function of unit stream power, following the method by Govers (1990) which is applied in the EUROSEM and LISEM erosion models:

$$6. \quad T_c = d_s * c * (w - w_c)^d$$

T_c = Volumetric transport capacity ($\mathrm{kg \cdot m^{-3}}$); d_s = material density ($\mathrm{kg \cdot m^{-3}}$); c = coefficient (−);

w = Stream power ($\mathrm{W \cdot m^{-1}}$); w_c = Critical stream power ($\mathrm{W \cdot m^{-1}}$);

d = coefficient (−).

The stream power is calculated by the local flow velocity and energy slope, following the method described by Hessel and Jetten (2007). Flow velocity is calculated by the using an equation based on the general Manning's formula on flow velocity, the formula is based on the work of Morgan and Duzant (2008):

$$7. \quad VS = \frac{Q^{\frac{2}{5}} * S^{\frac{3}{10}}}{n^{\frac{3}{5}} * W^{\frac{2}{5}}}$$

VS = Flow velocity ($\mathrm{m \cdot s^{-1}}$); Q = discharge ($\mathrm{m^3 \cdot s^{-1}}$); S = slope (−); n = Manning's constant; 0.03 (−); W = width of flow(m)

The final formula for transport capacity becomes:

$$8. \quad T_c = 2650 * c * (VS100 - 0{,}4)^d$$

T_c = Volumetric transport capacity ($\mathrm{kg \cdot m^{-3}}$); 2650 = material density ($\mathrm{kg \cdot m^{-3}}$); c = coefficient (−);

$VS =$ Flow velocity $(\mathrm{m \cdot s^{-1}})$; $100 =$ conversion factor; $0{,}4 =$ Critical stream power $(\mathrm{W \cdot m^{-1}})$;

$d =$ coefficient $(-)$.

The formula calculates the transport capacity for every cell on the raster per event, with c and d being coefficients dependent on median grain size. A median grain size is assumed in the calculations to represent the spatial variability of grain sizes. Coefficients are calculated by:

$$9.\quad c = \left[\frac{D50+5}{0.32}\right]^{-0.6}$$

$$10.\ d = \left[\frac{D50+5}{300}\right]^{0.25}$$

c & $d =$ constant; $D50 =$ median grain size (um)

6.3.7 Net deposition and sediment transport

A value for net deposition is calculated for all individual cells and is based on the minimum value between either the soil detachment flux or the actual transport capacity of the cell. The resulting lateral sediment flux is modelled over the LDD map.

6.3.8 Culvert discharge

The road system is evaluated at the selected culvert locations, ideally the model would incorporate a maximum discharge value for these selected cells to integrate the concept of culvert capacity. This would enable the modelling of runoff spreading along the road alignment, which is an important technique in reducing runoff energy and potential erosion. This research did not manage to develop such a component with the set of PCRaster operators. Referring to the theory chapter, culvert hydraulics are very dynamic and do strongly depend on up- and downstream conditions, static modelling of an hourly rainfall event does not provide reliable estimates of these conditions. To illustrate, integrating the modelled headwater height values for a single cell (100 m^2) based on hourly runoff averages, does not result in reliable headwater heights at the culvert inlets. Following the research purpose of providing relative parameters for the comparison of different scenarios, culvert locations are evaluated in a different way. All cells which represent culvert locations can freely discharge to the next downstream cell. A minimum required diameter for the culvert cells is estimated based on the modelled discharge values, which functions as a base for a sub sequent cost estimation. The Federal Highway Administration (FHWA) of the United States describes formulas for culvert discharge capacity, which are used for the development of more detailed design curves. These general formulas are based on extensive experimental research. The formula contains standard coefficients which change according to the culvert characteristics and flow conditions, they are documented in extensive tabular data. This research assumes that all modelled culverts are of a circular and submerged character, constants can be retrieved from tabular data described in the manual by the FHWA (2012). The general formula is given by:

$$11.\ \frac{HW}{D_c} = c * \left[K1 * \frac{Q}{AD_c{}^{0.5}}\right]^2 + Y + K2 * S$$

HW= Headwater height (m); Q= Culvert capacity $(\mathrm{m^3 \cdot s^{-1}})$; D_c = Culvert diameter (m);

Y= 0.67 ; $K2$= slope correction constant(-0.5); S= slope of culvert(0.1); c= constant(0.0398); $K1$= constant(1.811).

For simplicity reasons and the lack of sufficient data regarding up- and downstream flow conditions, the headwater height is assumed to be equal to the diameter of the culvert. This is arbitrary but enables a conversion of the formula, that an estimate can be made of the minimum required culvert diameters, based on the modelled discharge value of the selected cell.

Formula 11 can therefore be rewritten into equation 12:

$$12.\ D_c = \frac{K1^2 \cdot Q^2}{A \cdot \sqrt{\frac{1 - Y - K2 \cdot S}{c}}}$$

D_c = Culvert diameter (m); Q = Culvert capacity ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$);

Y = 0.67 ; $K2$ = slope correction constant(-0.5); S = slope of culvert(0.1); c = constant (0.0398); $K1$ = constant (1.811).

This variable does not give any reliable results on actual diameter estimation, but was assumed to represent a relative mean in road system scenario evaluation. A minimum culvert diameter of 30 centimetres is set for all modelled culvert locations.

6.3.9 Culvert costs

The model estimates a diameter for every selected culvert location, based on the modelled discharge values. Relative differences in costs between the developed scenarios are incorporated by a simplified estimation of costs, an estimate of the real costs and differences between the formulated scenarios are too complex to generate any reliable value. A relative indicator suffices to evaluate and compare the different road system scenarios on their financial performance. A cost curve based on culvert diameter is developed. Cost data from a large US-based culvert manufacturer (Con Cast, 2015) on culvert prices related to diameter were used to develop a general price curve. The diameter – price relationship per culvert can be described by the following formula:

$$13.\ P = 411D^2 + 13D + 26$$

P = culvert price (€); D = Modelled culvert diameter (m)

An estimation of total culvert costs is calculated by summing all cost estimate of individual culvert locations. This parameter is expected to change according to both the different number of modelled culverts and the estimated diameters per modelled scenario.

6.3.10 Gully risk

Gully risk is based on the work of Parker et al (2010), which was already described in the theory section. It is stated that calculated CTI scores need to be validated with actual field data, in order to to determine a specific local critical threshold value. This research does not allow for an actual validation of the modelled CTI score, an actual validation with field data is not possible for several reasons (e.g. time constraints). However, the risk for gully formation generally increases when the CTI score is higher. The CTI score proposed by Parker et al (2010) uses the contributing catchment size as a proxy value for discharge values through a particular cell. The revised MMF model simulates actual discharge values for every cell, which enables the integration of actual discharge values into the equation. A CTI score is calculated for all cells of the catchment to estimate its gully formation risk. The following formula is used (Parker et al, 2010):

$$14.\ CTI = Q \cdot S \cdot PLANC$$

CTI = CTI score($-$); Q = Total discharge volume (m^3); S = local slope ($-$); $PLANC$ = Planform curvature (m^{-1})

The calculation multiplies a discharge map showing the discharge per second, a slope and planform curvature map which can be generated from the DEM using two specific PCRaster operators. This score is expected to fluctuate according to the altered hydrology patterns under different scenarios.

6.4 Data description and management

The revised MMF model uses a range of different input parameters. Table 5 summarises the necessary model input data and its eventual sources. All parameters will be briefly discussed by a short description on how the data is obtained and processed. Most of the data processing of input map material was done in an ArcGIS environment.

Table 5: Parameter overview.

Input parameter category	Parameter	Initial parameter value
General	Duration of time step	1.0
	Seconds per time step	3600
Rainfall	Total hourly rainfall (m). Based on the work of Nyssen et al (2005).	30×10^{-3}
	Through fall fraction (-)	0.5
	Erosive rainfall constants (C1 & C2) (Nyssen et al, 2005)	36.35 & 0.6
	Leaf drainage constants (D1 & D2) (Brandt, 1990)	15.8 & 5.87
Surface cover	DEM (m). (NASA, 2015)	Varies over catchment
	Road scenario (-)	Vector map
	Culvert scenario (initial/alternative)	Vector Map/ASCII files
	Vegetation cover (-)	0.1
	Stone cover fraction (-)	0.1
	Average plant height (m)	5.0
Soil	Soil type (WRLC, 2015)	Varies over catchment
	Detachability of soil by **a)** runoff (z-value) and **b)** raindrops (k-value). (Morgan, 2001)	Based on soil map
	Hydraulic conductivity (Akan, 1993)	Based on soil map
	Soil porosity set as constant over the whole catchment (-)	0.43
	Median grain size, D_{50} ($m*10^{-6}$)	50
	Specific weight of rock (kg/m^3)	2650
	Manning's n	0.03
	Decay constant (-), [2-7]	4.5
Culvert hydraulics	Y, constant	0.67
	C, constant	0.0398
	$K_{1,}$ constant	1.811
	Slope correction, K_s	-0.5
	S, culvert slope	0.10
Transport capacity	Critical stream power (W/m). (Hessel and Jetten, 2007)	0.4

6.4.1 General parameters

The majority of calculations covered by the model are based on hourly averages. The duration of an event is therefore set to a value of 1.0. The 'seconds per time' step parameter changes according to the characteristics of the event one needs to model. The initial value is set to 3600 seconds which is compatible with one hour.

6.4.2 Rainfall parameters

The rainfall input parameters are to a large extent based on the 6 year research (1998-2003) by Nyssen et al (2005). An extensive field survey was executed on the spatial variability of rain depth and erosivity of the rainfall for a region in the Geba catchment, where also the studied catchment is situated. This data is assumed to be representative for the study area of this research, both study sites are situated in the same Geba catchment and show strong similarities in e.g. landscape and climate.

The rainfall input is set as a constant value over the whole catchment. This rainfall input is split into a component of direct rainfall, a part is intercepted which depends on vegetation cover and a through fall fraction. The direct rainfall flux is given by an absolute water flux in vertical meters depending on the rainfall event and compensated for the local slope value, the initial value is set to 30 mm/hr. which is arbitrary. This value represents the maximum recorded rain depth for one hour by Nyssen et al (2005). The through fall fraction is assumed to have a value of 50%. However, the contribution of this factor on total rainfall erosivity is rather small compared to direct rainfall.

6.4.3 Surface cover

The model uses a standard digital elevation map (ASTER GDEM V2), which is online available (NASA, 2015). The DEM has a resolution of 30 meters and is visualised with a geographic projection of Adidan 37N (WGS-84). The ArcGIS software was used to delineate the catchment borders of the catchment. The delineated catchment was used to create polygons to define the extension of the study area and ensure that processed map material all had the same extension which is necessary for further processing in the PCRaster software. The data is converted into an ASCII-file and imported to the software by transforming the ASCII files to a PCRaster format. The resampled DEM is ‘smoothened’ by applying an interpolation using a window of 30 meter, which is done to improve the low quality of the initial LDD and resulting drainage map. The resampled DEM is used to create multiple standard maps (e.g. slope map and local drainage direction map) for model operations.

The ArcGIS software was used to create vector maps of the current road, alternative alignments and culvert scenarios, which is more elaborately described in the section on scenario formulation (6.2). The culvert locations of the current road system are based on GPS coordinates, obtained during the extensive survey executed in 2014 by MetaMeta ([1]Woldearegay et al, 2014). The GPS coordinates are enclosed in appendix A. The GPS coordinates are imported to the ArcGIS software and converted to the right geographic projection and extension. All road system vector maps are rasterized and converted to an ASCII file, the ASCII files are imported to the PCRaster environment and converted to Boolean maps.

The parameters presenting plant height, vegetation and stone cover fraction are set as fixed values over the whole catchments. The values are assumed to be compatible with the initial values described in the revised MMF model (Morgan, 2001).

6.4.4 Soil parameters

A classified soil vector map of Ethiopia was provided by the ‘roads for water’ collaborative and retrieved from a dataset retrieved form the Water and Land Resource Centre in Ethiopia (WLRC, 2015). The vector soil map was used to create several soil parameter maps. The polygon map contains soil codes which refer to specific Ethiopian soil type, an enclosed document is used to relate the Ethiopian soil types to the standard FAO soil type codes and obtain percentages of clay and sand in the topsoil. The standard FAO texture classes of the particular soil types are estimated by using the Soil Water Characteristics (SWC) program (online available at NRCS.com). Which is a free software package provided by the United States Department of Agriculture (USDA) and used to estimate soil parameters based on soil textures. This tool also makes a rough estimate of the hydraulic conductivity per soil texture class.

The obtained soil texture classes per soil type are used to obtain parameter values for the soil cohesion, a soil specific z-value, the maximum infiltration capacity and erodibility. An overview of all soil parameters including references is shown in table 6.

Table 6: Soil parameters.

Soil type code (Ethiopia)	FAO abbreviation	Texture class	Erodibility of the soil K (g/j) (Morgan, 2001)	Cohesion of the soil (kPa) (Morgan, 2001)	Z-value (Morgan, 2001)	Sat. hydraulic conductivity (m/hr) (Akan, 1993)	Max. infiltration capacity (m/hr) (Akan, 1993)
456: (Eutric) Cambisols	Be (31)	Loam	0.8	3	2/3	$25.4 \cdot 10^{-3}$	$26.7 \cdot 10^{-3}$
454: (Chromic) Cambisols	Bc (29)	Clay Loam	0.7	10	1/5	$5.59 \cdot 10^{-3}$	$16.9 \cdot 10^{-3}$
854: (chromic) Luvisols	Lc (84)	Sandy Clay Loam	0.1	3	2/3	$7.87 \cdot 10^{-3}$	$25.4 \cdot 10^{-3}$
700: Leptosols	Lp (82)	Sandy Loam	0.7	2	1	$52.3 \cdot 10^{-3}$	$33.9 \cdot 10^{-3}$
1554: (chromic) Vertisols	Vc (129)	Clay	0.05	12	1/6	$2.03 \cdot 10^{-3}$	$8.5 \cdot 10^{-3}$
955: (dystric) nitisols	Nd (89)	Clay	0.05	12	1/6	$2.03 \cdot 10^{-3}$	$8.5 \cdot 10^{-3}$
164: (Orthic) Acrisols	Ao (6)	Sandy Clay Loam	0.1	3	2/3	$7.87 \cdot 10^{-3}$	$25.4 \cdot 10^{-3}$
1264: (Orthic) Solonchaks	Zo (120)	Clay Loam	0.7	10	1/5	$5.59 \cdot 10^{-3}$	$16.9 \cdot 10^{-3}$
2222: no soil		-	-	-		0	0

Median grain size, Manning's n, soil porosity, Horton's infiltration decay's constant and the specific weight of rock material are set as constant parameter values over the whole catchment.

The different soil parameters are developed into individual soil vector maps using the polygon maps in ArcGIS. The vector maps are rasterised and converted to an ASCII file, the ASCII files are imported and converted to maps compatible with the PCRaster software and the other processed data.

6.4.5 Culvert hydraulics

The input parameters related to culvert hydraulics are based on a tabular data enclosed in the culvert design manual (Appendix A) provided by the Federal Highway Administration of the United States (FHWA, 2012).

6.4.6 Transport capacity

The modelling of the transport capacity requires a value for critical stream power which is based on the work by Hessel and Jetten (2007).

6.5 Multi Criteria Analysis

6.5.1 General

This section describes the construction and application of the Multi Criteria Analysis (MCA), which is an attempt in developing a method for the evaluation of road system at a catchment scale. The MCA method is very useful in solving problems that are characterized as a decision among a range of alternatives. Using a MCA requires the formulation of a complete and sufficient overview of the problem and all its influencing aspects, It enables the user to analyse only a part of the problem but is able to integrate all aspects towards a final balanced decision. The application of a MCA requires a decomposition of the actual problem into smaller parts or criteria, an identification of the right methods or techniques to integrate all relevant problem aspects in the analysis and in this case the formulation of road system scenarios (Malzcewski, 1999; Pfeffer, 2003; Van Herwijnen, 1999). The rural road design problem is decomposed and managed according to the Analytical Hierarchy Process (AHP), a method developed by Saaty (1987). In general, MCA methods either deal with a finite or infinite set of solutions, the range of developed road system scenarios complete a set of finite solutions. The following sections describe the decomposition of the problem according to the AHP technique, the individual components of the constructed hierarchy structure, the standardisation of the criteria, the developed criteria weighting system and a so called decision rule.

6.5.2 The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) developed by Saaty (1987) is an often applied method in MCA decision making. It includes the decomposition of a problem into objectives, 1st (and eventual 2nd level) criteria, measurable indicators and a set of alternatives or potential solutions. In general a hierarchical model representing a problem descend from an aim of the decision, down to criteria, measurable indicators and finally a set of alternatives or potential solutions. The decomposition process is the most creative part of the whole decision making process and is the most determining factor in the effectiveness of a decision making process (Saaty, 1990). The developed hierarchy for the road system design problem is presented in figure 22. The developed structure accounts for three general objectives: Erosion, costs and the potential of water harvesting. These objectives are evaluated by different criteria which are represented by indicators based on different model components. All the individual components of the hierarchy will be described separately in the following section.

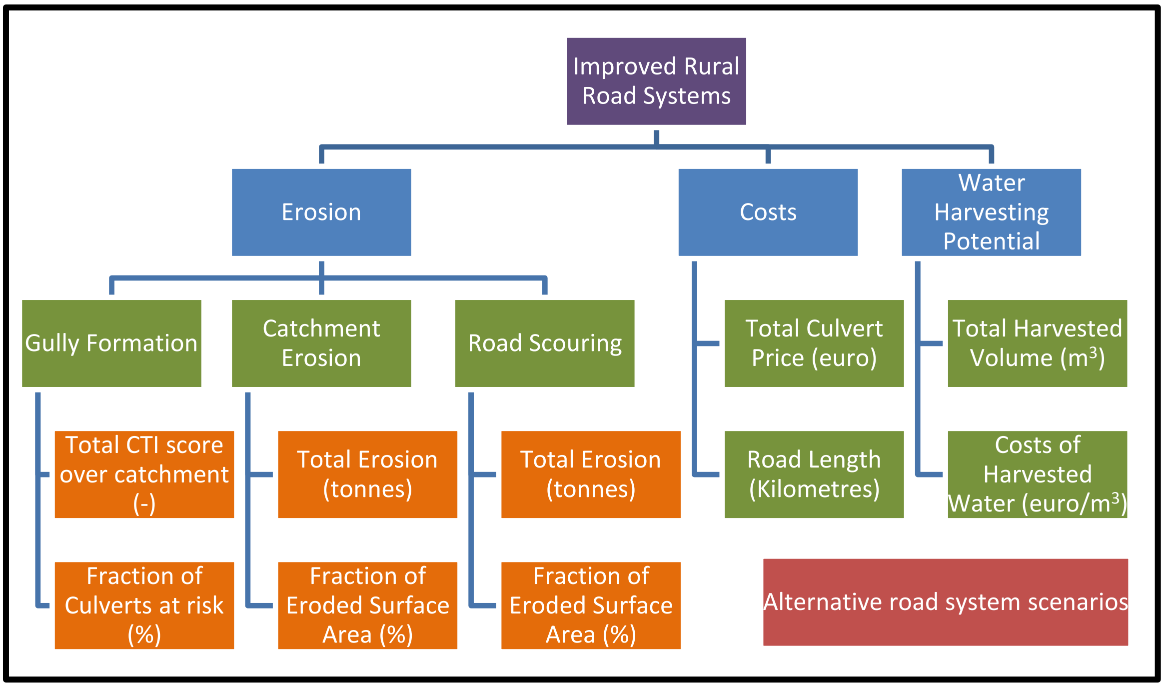


Figure 22: Hierarchy of the improved rural road design. Purple: Aim; Blue: Objectives; Green: 1st level criteria; Orange: 2nd level criteria, Red: Set of alternative road system scenarios.

6.5.3 Erosion objective

The erosion objective is decomposed into three criteria which were formulated to account for the impact of road systems on erosional processes: catchment erosion, road scouring and gully formation risk.

Catchment erosion

The spatial pattern and magnitude of total catchment erosion is believed to be altered by the different alternative road system scenarios. The effects of road systems on runoff and erosion patterns were elaborately discussed in the theory chapter. In general, it is assumed that changing the parameters of the rural road system design (road alignment, culvert positioning and the number of culverts) will alter the surrounding natural hydrology pattern and magnitude by either diversion, concentration or collection of runoff, both up- and downstream of the particular road system. These alterations are believed to affect the occurrence and magnitude of erosional processes on a larger scale than just the scale of the road system. The catchment criterion is described in twofold by two different indicators. It is assumed that these will describe a different impact for a particular road system scenario.

During the preliminary model runs some irregularities were found in the estimation of net deposition, several single cells at fixed locations show negative values for the parameter of transport capacity which results in significantly larger values for deposition of these particular cells. The calculation of net deposition at catchment scale is therefore unreliable, the problem could not be solved during the research and an alternative criterion needed to be defined. The encountered irregularities on transport capacity are more elaborately discussed in chapter 8 and visually shown in appendix F. An alternative criterion was developed by defining ‘erosion’ as a more relative measure between scenarios. The erosion criteria (catchment erosion and road scouring) is described by cells which show a negative value on the modelled deposition map, which basically means a net flux of sediments downstream, this excludes the encountered irregularities and the eventual process of deposition downstream. However, it is believed to represent the effects of a road system on erosion magnitude. The first indicator is total catchment erosion and is evaluated by a summation of all cells showing ‘erosion’. This indicator is expected to represent the alterations in magnitude of erosion caused by the presence of the particular road system. The road system presence is assumed to cause alterations in the surface area undergoing ‘erosion’, due to processes of diversion and concentration of runoff. The second indicator is defined by the calculated fraction of all cells undergoing ‘erosion’ compared to the total catchment surface.

The catchment criterion is evaluated as a cost, improved rural road design incorporates the overall aim of minimising road system related erosion.

Road scouring

The road is assumed to block the runoff from uphill regions and divert the runoff to the first downhill cross draining culvert where it can be discharged to the other side of the road. Changing the parameters of the road system alternative (road alignment, culvert positioning and number) is assumed to alter the natural drainage patterns and magnitude and thereby affect the occurrence of erosion. The road scouring criterion is described by a similar parameter and reasoning as the total catchment erosion indicator but focuses on just the direct surroundings of the road system which was assumed to show a different effect. A specific ‘road zone’ is defined to evaluate the indicators. The road zone is defined as a Boolean map incorporating all cells directly aligned next to the road, excluding the road surface itself and culvert locations. The road scouring criterion is evaluated in a similar way as the total catchment erosion but focuses on this ‘road zone’.

This criterion is evaluated as a cost, improved rural road design has an overall aim of minimising road system related erosion.

Gully formation risk

The risk for gully formation is believed to be altered by the different formulated road system scenarios. The effects of road systems on runoff were elaborately discussed in chapter 5, also the most important aspects which influence the triggering and development of gullies according to Zevenbergen (1989). The road system scenario will alter the runoff patterns and their magnitude which are assumed to affect the number of locations where and magnitude of the boundary shear stress is exerted caused by runoff being concentrated or diverted to locations where gullies might develop. The culvert locations were deemed to be crucial because high discharge volumes need to be conveyed which means an increased risk for gully formation.

The risk on the formation of gullies over the catchment is evaluated by a summation of all calculated CTI scores over the catchment, a higher score represents an increased risk for gullies to form. The CTI method normally includes a critical threshold value, this research applies the CTI score as a relative measure. In order to address the gully formation risk at the culvert outlets another indicator is developed. By distinguishing between these two indicators, a difference might be detected between alterations in direct gully formation risk at culvert outlets and the indirect gully formation risk at catchment scale depending on the particular road system. An indicator representing gully formation risk at culvert outlets between different road system scenarios, needs to consider the different number of culverts per scenario. The second indicator for gully formation risk is given by the fraction of all culvert locations which show a positive CTI score compared to the total culvert number of that particular scenario. It is assumed to show a different pattern between road systems compared to the total CTI score at catchment scale, an increased fraction shows a general increase for gully formation risk at culvert outlets.

This criterion is evaluated as a cost, an improved rural road system aims at a minimum risk of gully formation.

6.5.4 Cost objective

Formulating an objective addressing costs will be incomplete for the majority of evaluations. Costs of a road system are very complex and depend on a lot of variable aspects. These costs do depend on too many factors (topography, material, labour costs, etc.), require much more data and are therefore out of scope for this research. Not a lot of aspects can be accounted for in the constructed model. Two relative indicators are formulated to incorporate the aspects of costs into the evaluation of road system design. The cost objective is divided into two criteria: The total culvert price and the road length of a particular road system scenario.

Total culvert price

The total culvert price is assumed to change under a different road system scenario. The alignment of the road, the number and positioning of culverts will change the runoff magnitude and patterns. It is assumed that runoff will be distributed differently (to a certain extent) among culverts under a changing road system scenario, even though culvert capacity could not be integrated into the model. The conveyed discharge will determine the diameter and sub sequential price of the culvert as described in section 6.3 on model components. The total culvert price is calculated by summing all estimated costs of individual culverts of the particular scenario. The price of a culvert tends to increase exponentially when the estimated diameter increases. It is assumed that a certain optimum exists between the number and positioning of culverts of a particular road system scenario and that eventually patterns can be noticed between the road system scenarios. The cost criterion is evaluated as a cost, an improved rural road system aims at lowering its overall costs.

Road length

The road length of a road system scenario is used as a proxy value for the overall road system. The real construction costs of a road system scenario are too complex and time consuming to estimate. Road length is assumed to correlate with road construction costs, an increased road length results in higher costs because it requires higher investments in both material and labour. It was the only reasonable indicator found which can address the cost aspect of road systems to a certain extent using this model

6.5.5 Water harvesting objective

Formulating an objective addressing water harvesting will always be incomplete. Water harvesting potential is a concept which depends on too many factors which cannot be addressed by the constructed model. Water harvesting is often of an ad hoc character, being very dependent on local factors like e.g. soil type and actual demand for water, these factors require much more data of a different quality and are therefore out of scope for this research. These cannot be taken into account in the process of modelling different scenarios. The comparing of scenarios requires a relative and robust indicator to address the potential of water harvesting between road system alternatives. A first attempt is done to integrate the objective by formulating two indicators, which are of an explorative character. The water harvesting objective is divided into two criteria: The total harvested water through culverts and the costs of harvested water.

Total harvested water through culverts

The total volume of harvested water through culverts is calculated by summing all values for modelled discharge through culverts. It was assumed to represent the objective of water harvesting potential, it is believed to change under a different rural road system scenario. When the road is positioned more upslope within the catchment of interest, the contributing catchment area will be smaller and the captured runoff by culverts of the road system decreases. Lower discharge volumes through culverts enable less possibilities for secondary services e.g. supplemental irrigation or shallow groundwater development. The total discharge through culverts is evaluated by summing all the modelled discharge volumes of the selected culvert locations. The total harvested water through culverts is evaluated as a benefit, increased harvested discharge volumes are beneficiary and represent the characteristics of improved rural road systems.

Costs of harvested water

The indicator covering the actual costs of the harvested water is believed to change under a different road system scenario. The indicator is calculated by dividing the total culvert costs by the total volume of harvested runoff through culverts of a particular road system scenario, this results in a price per cubic meter of harvested water. The distribution of the harvested runoff volume by culverts was expected to change under a different road alignment, culvert number and positioning of a particular road system scenario. The indicator was formulated to explore potential patterns between harvested volumes and their distribution. Increased runoff harvesting is beneficiary for secondary services, however the costs should be minimal taking into account the low budget for road development. This criterion is therefore evaluated as a cost, an improved rural road system aims at minimising the costs of the harvested water it can provide.

6.5.6 Standardisation technique

The described criteria are represented by indicators which do differ in their character and scale (e.g. total catchment erosion and total culvert costs). In order to combine and compare all these different indicators in a MCA, the indicators need to be standardised. This research will standardise to a common scale between 0 and 1. Most convenient is to use the method of linear transformation. Other standardisation techniques are the use of so-called value functions, which are selected depending on the characteristic of the criterion. The increase in benefit can be of an exponential character and thereby follow a concave, convex or s-shaped curve. The process of selecting a value function and determining the necessary mid-value point (which determines the shape of the curve) is based on background knowledge about the behaviour of the indicator and therefore basically an expert guess (Pfeffer, 2003). In this research it is assumed that standardisation techniques other than linear transformation are too subjective and arbitrary. The use of, for instance, value functions in the standardisation of indicator values cannot be sufficiently justified with solid background knowledge. Taking into account the lack of knowledge on the intertwined and complex processes determining the indicator values, the low quality of input data but also the uncertainty of the model's performance in the representation of criteria behaviour, makes linear transformation the most convenient standardisation technique. Two formulas are used to transform the criteria to a common scale.

If X is a benefit criterion:

$$15.\ \bar{X} = \frac{(X - Xmin)}{(Xmax - Xmin)}$$

If X is a cost criterion:

$$16.\ \bar{X} = 1 - \frac{(X - Xmin)}{(Xmax - Xmin)}$$

$\bar{X} =$ The standardised value; $Xmax =$ The maximum indicator value of the total set; $Xmin =$ The minimum indicator value of the total set.

6.5.7 Assignment of priorities

The importance of the different individual criteria in a decision making process can be ensured by assigning different weights to the criteria. Assigning priorities is a very subjective process, which might differ considerably between groups or decision makers. Thurstone (1927) developed a method called pairwise comparison, this technique assists in the construction of a criteria weighting system which enables a possible prioritisation between different criteria. The method of pairwise comparison is relatively easy to apply and aims at giving a consistent judgement by comparing pairs separately instead of all criteria together. In order to make a judgement about the relative importance of different criteria, a fundamental scale of absolute numbers is applied in the comparison of pairs (Saaty, 1990). The scale is presented and explained in table 7.

Table 7: Fundamental scale based on Saaty (1990).

Weight	Interpretation	Explanation
1	Equal Importance	Two criteria contribute equally to the decision goal
3	Moderate importance	Experience and judgement slightly favour one criteria over another
5	Strong importance	Experience and judgement strongly favour one criteria over another
7	Very strong importance	A criteria is favoured very strongly over another
9	Extreme importance	The criteria is of the highest possible importance
Reciprocals of above	If criteria A has one of the above numbers assigned to it when compared with criteria B, then B has the reciprocal value when compared with A.	-

The method of pairwise comparison is based on a pairwise judgement of the decision maker(s). The fundamental scale is used to evaluate all possible criteria pairs within a single hierarchy level, it assigns a relative importance of one of the paired criteria compared to the other. The pairwise comparison constructed for this research is solely based on the judgement of the researcher, the reason for this is twofold. This research is of an exploratory character so is the pairwise comparison, the model's performance is still unknown and has not been proven yet. The outcomes are not yet validated by field data which make them unreliable. The execution of this MCA contributes to a better understanding of the model's behaviour and might contribute to potential improvements. The other reason is that limited time withhold the potential application of a questionnaire among stakeholder, in order to further specify the different views on assigning priorities among the different stakeholders. The following table shows the constructed pairwise comparison matrix for this research, followed by a brief motivation of its numbers.

Table 8: The constructed pairwise comparison matrix.

	Catchment erosion	**Road scouring**	**Gully formation**	**Total culvert costs**	**Road costs**	**Total harvested discharge**	**Costs of harvested discharge**
Catchment erosion		**1/3**	**1**	**1/7**	**1/5**	**1**	**1**
Road scouring	**3**		**3**	**1/4**	**1/4**	**2**	**2**
Gully formation	**1**	**1/3**		**1/7**	**1/5**	**1**	**1**
Total culvert costs	**7**	**4**	**7**		**2**	**7**	**7**
Road costs	**5**	**2**	**5**	**1/2**		**5**	**5**
Total harvested discharge	**1**	**1/2**	**1**	**1/7**	**1/5**		**1**
Costs of harvested water	**1**	**1/2**	**1**	**1/7**	**1/5**	**1**	

The costs of a rural road system are valued as most important objective for this pairwise comparison. The construction of rural road systems cannot rely on large investment budgets in the Tigray region and is actually partly financed by 'voluntary' community work which was explained in the first chapter. The total culvert costs of a road system scenario are evaluated as slightly more important compared to the road length criteria, because it is believed that culvert costs can be most influenced by a changing road system design while the road length can only be influenced to a certain extent. A road still needs to connect certain places without being excessively lengthy and is also more restricted to e.g. topographic features. A bit more emphasize is set on the road scouring criterion because this represents a group of often occurring and surveyed problems along current road systems (e.g. gully formation along the road side). The attempts made in formulating a pairwise comparison by giving more priority to one of the other two remaining objectives (erosion or water harvesting potential), did not result in any valid (*consistent*) pairwise comparison. No further priorities between criteria were made because a lack of solid motivation or reason. Also, in order to minimise the degree of subjectivity, the remaining criteria are evaluated as equally important. The erosion objective also contains second level criteria which also do have assigned weights. However, no pairwise comparison has been formulated for these criteria because of their small number, the weights are based on an 'expert guess'. All formulated criteria weights are presented in the following section.

The actual criteria weights are obtained by the following procedure. All cells of an individual column in the pairwise comparison matrix are summed to a total column value. The initial pairwise comparison matrix is standardized by first dividing all individual cell values by the total summation of all column values. The weight is obtained by averaging every individual row of the standardised matrix which results in a so called priority vector. The consistency of the judgement of the decision maker is evaluated by calculating a consistency ratio of the assigned weights. A calculated consistency index is compared to an appropriate index (a so called random index) which is based on a large sample of purely random judgements. If the consistency ratio is much in excess of a value of 0.1, the inconsistency of the judgement is too large and the whole procedure must be repeated (which was also the case in this research). A too high consistency ratio basically means that the decision maker has been either too random or illogical during the construction of the pairwise comparison (Alonso & Lamata, 2006; Saaty, 1990). The consistency ratio is calculated using the technique described by Saaty (1990), the following matrix equations are applied:

$$17.\ CI = \frac{\lambda\mathrm{max} - \mathrm{n}}{n-1}$$

$$18.\ CR = \frac{CI}{RI};\ CR < 0{,}1.$$

$CI =$ consistency index; $\lambda max =$ the principal eigenvalue of the criteria weights matrix; n $=$ number of weights assigned; $RI =$ A random index (in this case 1.32); $CR =$ consistancy ratio.

6.5.8 The criteria weights

Table 9 summarises the obtained values for the different criteria weights for all criteria within the different levels of the hierarchy. A consistency ratio was calculated for the developed pairwise comparison matrix. A value of 4.5% was calculated which is less than the critical value of 10% making the assignment consistent (Saaty, 1980). The MCA's sensitivity towards its criteria weight system will be evaluated in chapter 7.

Table 9: Criteria weighting system.

Objectives	**Summated value**
Erosion	0.24
Costs	0.65
Water harvesting	0.12
1st level criteria	**Criteria weights**
Catchment erosion	0.06
Road scouring	0.12
Gully formation	0.06
Total culvert costs	0.40
Road costs	0.25
Total harvested discharge	0.06
Costs of harvested water	0.06
2nd level criteria	**Criteria weights**
Catchment eroded area (%)	0.045
Total catchment erosion (tonnes)	0.015
Roadside scoured area (%)	0.03
Total roadside erosion (tonnes)	0.09
Risk of gully formation catchment scale	0.006
Risk of gully formation at culvert locations	0.05

6.5.9 Decision rule

A decision rule needs to be defined to enable a prioritising between all modelled road system scenarios on their overall performance. The overall performance in this case estimates the overall score based on the state of the selected criteria and the assigned priorities. The Simple Additive Weighting (SAW) technique is applied, which assumes the concept of weighted averages. An overall ranking score is calculated by the following formula (Pfeffer, 2003):

$$19.\ A_i = \sum_{j=1}^{n} w_j x_{ij}$$

A_i = overall ranking of road system scenario i $(-)$; $w_j =$ the weight; x_{ij} = the standardised indicator value; n = number of criteria; $j =$ criterion.

For every road system scenario, its individual modelled indicator value is multiplied with the particular criteria weight. This is done for all indicator values after which they are summed to get an overall performance score for the particular road system scenario. The overall performance score per road system scenario enables the construction of an overall ranking.

6.6 Potential for water harvesting

The best performing road system scenarios were analysed on their potential for increased food production and food security in the study area by supplemental irrigation, also the current road system will be analysed. Model outputs on the amount of harvested runoff volume and corresponding total culvert costs are used to compare the different rural road system scenarios regarding their potential for food production. This estimate does not aim to formulate exact and reliable crop water requirements or yield estimates, it rather aims at giving a rough estimate and indication of the potential of integrating water harvesting principles into rural road systems in respect to its current agricultural context. A standard procedure on crop water needs developed by the FAO was applied. These estimates were used to determine the water requirements of a total crop cycle.

6.6.1 Regional context

It was assumed that all the runoff harvested by culverts can be stored in reservoirs or used for shallow groundwater development. The offset of the growing period of an extra crop cycle was set to the end of the rainy season, all stored runoff will be applied as supplemental irrigation. This enables farmers to cultivate an extra crop cycle and not being fully dependent on just the rainy season which is of an erratic character, especially considering the increasing influence of climate change (Gebreegziabher et al, 2011). Barley is set as reference crop, it is one of the main staple foods in Tigray and shows a variety in species (Edwards et al, 2007). Barley provided the basic life necessities for millennia (food, feed, beverages and roof thatching) (Mulatu and Grando, 2011).

Figure 23: Barley fields in Oromiya region, Ethiopia (Farm Africa, 2015)

6.6.2 FAO calculation on crop water needs

The crop water need is defined as the depth of water required to meet the water loss through evapotranspiration. The method on crop water need is based on a multiplication of the evapotranspiration and a particular crop factor. The influence of climate on crop water need is given by a reference crop evapotranspiration, which is the evapotranspiration rate of short green grass, completely shading the ground, uniform height and with an optimal water availability. The relationship between the short green grass and the actual crop grown is given by the crop factor. The actual crop factor depends on climate, growth stage and crop type. The crop factor needs to be determined for all individual stages of the growing period (Brouwer and Heibloem, 1986).

Data on evapotranspiration and rainfall is used from a study by Baert (2010) which used a climate dataset from the meteorological station, a main regional centre close to the study area (*Wukro*), it was considered representative. The evapotranspiration was estimated based on the Thornthwaite method. This equation is based on the mean monthly temperatures and a certain heat index related to this same mean temperature. The different crop growing periods and standard crop factors for the different growth stages are given by tabular data described in the FAO manual (Brouwer and Heibloem, 1986).

The crop factor for the initial growth stage needs to be adjusted for climatic factors like interval of rainfall events and their magnitude. A representative rainfall event needs to be defined for the determination of the crop factor for the initial growth stage. Based on the work of Nyssen et al (2005) and in accordance with model settings, a daily rainfall event of 30 mm/hour is assumed.

Two different FAO graphs (low and high intensity rainfall events) are used as input data to determine the final crop factor for the initial growth stage, both graphs require daily evapotranspiration and the interval in days between events as reference parameters. The two graphs will be used to determine a final crop factor value for every month covered by the growing period of the barley.

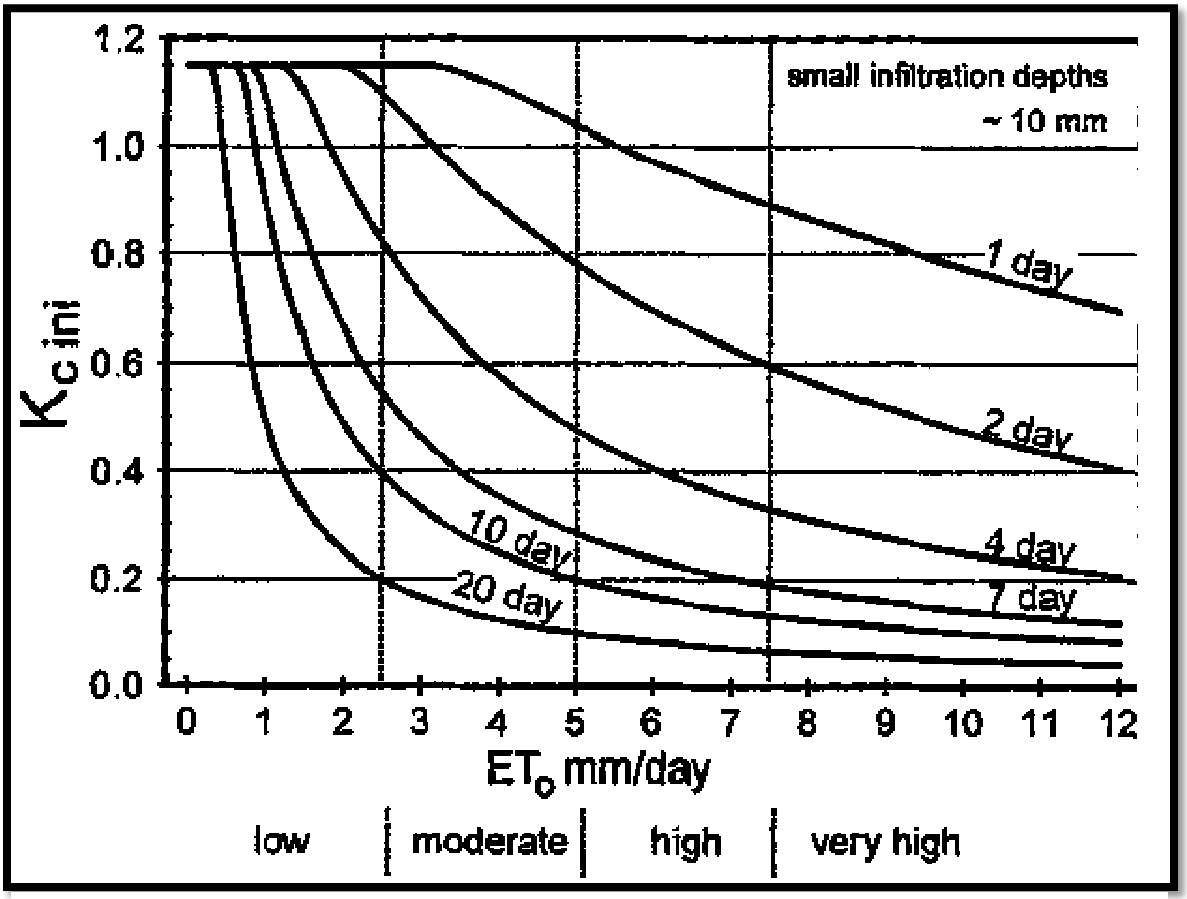


Figure 24: FAO graph for the determination of the crop factor for the initial growth stage, y-axis gives the value for the initial crop factor for low intensity rainfall events (<10mm/hr.). The x-axis gives the reference evapotranspiration in mm/day. The different lines represent the average interval between events (Brouwer and Heibloem, 1986).

The following formula is used to calculate the final crop factor for the initial growth stage, the formula uses the obtained inputs from the two different graphs (figure 24 shows the graph for low intensity rainfall events) (Brouwer and Heibloem, 1986):

$$20.\ K_{c,final} = K_c(A) + \frac{(R-10)}{(40-10)} * (K_c(B) - K_c(A))$$

$\mathrm{K_{c,final}} =$ the initial crop factor (−); R = Typical daily rainfall event (mm); A = $\mathrm{K_c}$ value obtained from 1st graph, low rainfall intensities ; B = $\mathrm{K_c}$ value obtained from 2nd graph, high rainfall intensties.

The crop factor for both the late and mid-season stage can be adjusted for climate situations with increased wind speed. Due to a lack of data on wind speed for the study area, both values are determined by a standard FAO table based on the selected crop type (Brouwer and Heibloem, 1986). The crop factor for the development growth stage is calculated by averaging between the crop values for the initial and mid-season stage.

7 Results

This chapter will present the general model outcome of all road system scenarios. The general impacts and altered hydrology and erosion patterns caused by a road system will be identified by evaluating the current road system, based on the modelled map material. Three pre-defined impact zones will be analysed by comparing drainage maps under road system presence and absence. The impact of road alignment was analysed by evaluating the sets of individual indicators per road alignment option using statistics. The influence of the culvert scenario is evaluated by analysing the modelled outcome sets for potential patterns between either the number of culverts or the applied positioning method for each road systems scenario. The results of the MCA are presented, its performance will be evaluated by testing for its sensitivity towards the applied weighting system. The final section presents the estimates for food production of the best performing scenarios, by using the FAO method on crop water needs.

7.1 The impact of the current road system design

7.1.1 General information

The resulting map material indicates that the impacts of the road system on both hydrology and erosion do mainly occur in the vicinity of the road system, minor impacts or alterations might occur farther away from the road system but seem irrelevant and are therefore not considered in this section. In order to study the impact of the current road system, the current road system scenario was compared to the hypothetical scenario of road system absence. The value for total 'erosion' over the modelled catchment (negative net deposition value, as defined in chapter 6 on methods) after a standard event resulted in $2.22 \cdot 10^8$ tonnes for the scenario with road system presence, compared to $2.02 \cdot 10^8$ tonnes under road absence. These values exclude the process of deposition (because of reasons mentioned in section 6.5), which makes it difficult to compare to other sediment yield studies. However, it does clearly show an increase of the total sediment flux over the catchment because of road system presence.

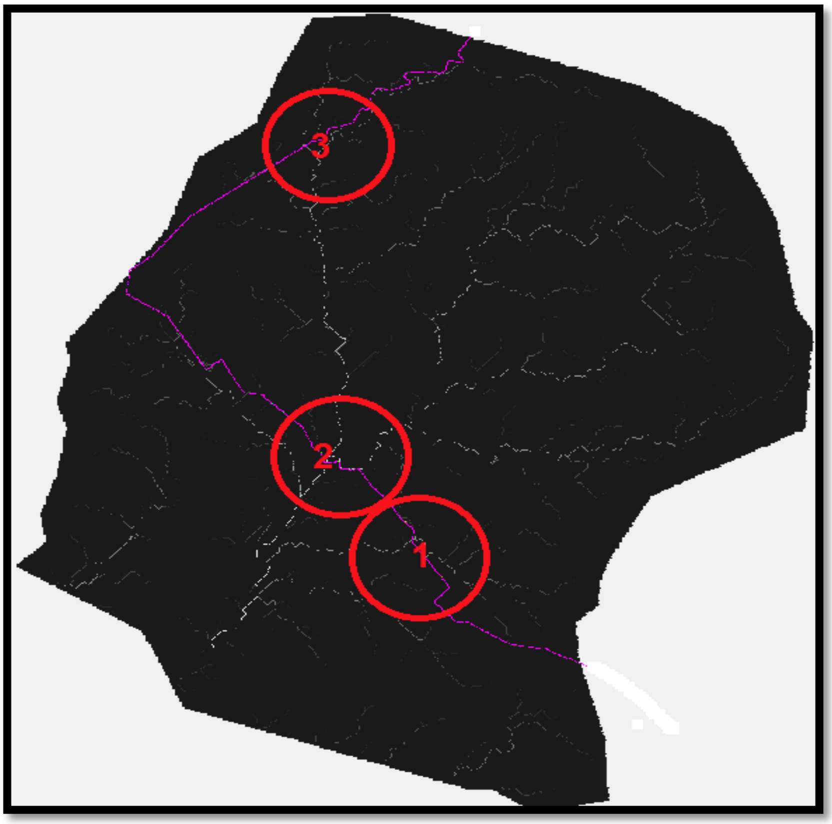


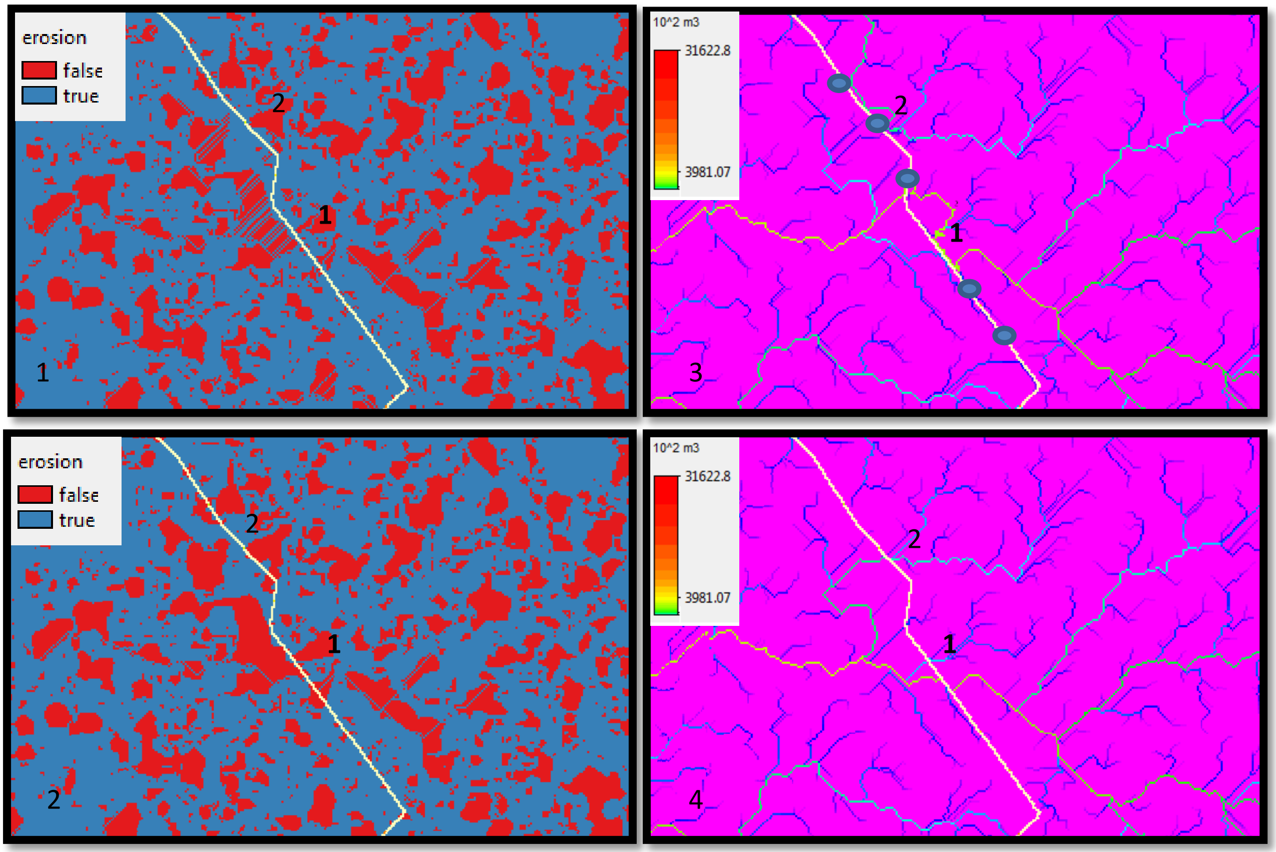
Figure 25: The image shows the general discharge patterns for the study area. The numbered red circles indicate the three predefined zones where the road system impact is most obvious.

The total area of the catchment showing a negative net deposition ('erosion') shows an increase due to the presence of the current road system. The fractional catchment surface area of the whole catchment undergoing 'erosion' shows an increase of about 0.2%, which equals about 2833 hectares.

Comparing the modelled drainage maps for road system presence and the situation of road system absence show that the natural drainage patterns are clearly altered by the current road system at several locations along the road system, three 'impact zones' were identified to illustrate the main alterations. The impact zones are shown in figure 25 and indicated by the red circles. These zones will be described more elaborately by using detailed illustrative map outputs on runoff and fractional surface area undergoing ‘erosion’. Other resulting map material on e.g. sediment transport and gully formation do not allow an easy visual interpretation and will not be presented.

7.1.2 Impact zone 1

The general flow direction over an east-west axis is interrupted by the road system. The two main discharge streams do not follow their natural directions but get circumvented by the road systems which cause more concentrated runoff on the upstream side of the road. Two points are identified to further describe and illustrate the impact of the road system.



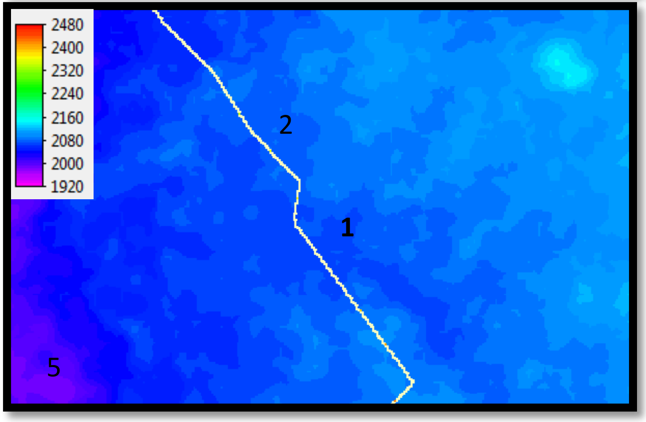


Figure 26: The images present the differences in runoff and sediment transport patterns for the scenarios of road system presence or absence at impact zone 1, locations of interested are notified by a number and discussed in the enclosed text. Map 1 & map 2 show respectively the surface areas where either net transport of sediment occurs (true) or not (false) for the scenario of road system presence (map 1) or absence (map 2). Map 3 & map 4 show respectively the discharge maps using a logarithmic scale for the scenario of road system presence (map 3) or absence (map 4). Map 5 shows elevation levels in metres for the area by the DEM (cell size 10 m.).

At **Point 1** the road system blocks the natural flow lines and causes a diversion along the roadside further northwards. The runoff circumvents due to locally increased elevation levels after it reaches the first possible culvert to get cross-drained to the other side of the road. The natural flow length seems to increase and results in the merging of an extra stream on the northern side of the road, an increase of 8% in the discharged volume at the cross-draining culvert can be observed for this stream compared to the situation of road absence. At the downstream side of the road, the runoff tends to follow the natural flow lines again. The second culvert around **point 2** seems to be wrongly positioned, the runoff gets conveyed further northwards which results in a lowering of 9% in conveyed volume by the main stream on the downstream side of the road. The surface area undergoing erosion seems to increase in the vicinity of the road system, changes seem to coincide with the alterations in runoff patterns, especially at the downstream side of the road close to the formulated first and second points. Based on the modelled map material only the central culvert conveys a significant amount of runoff.

7.1.3 Impact zone 2

The topography shows significant differences in elevation values for the second impact zone, which results in strong natural flow lines. The two major streams would merge just south of the current road system for the situation of road absence. Two points are identified to further illustrate the actual impact of the road system. The conveyed volume of the main stream on the downside of the road does not show significant alterations due to road presence. This might be clarified by the significant drop in elevation levels south west of the current road system which causes all runoff to be drained towards this area.

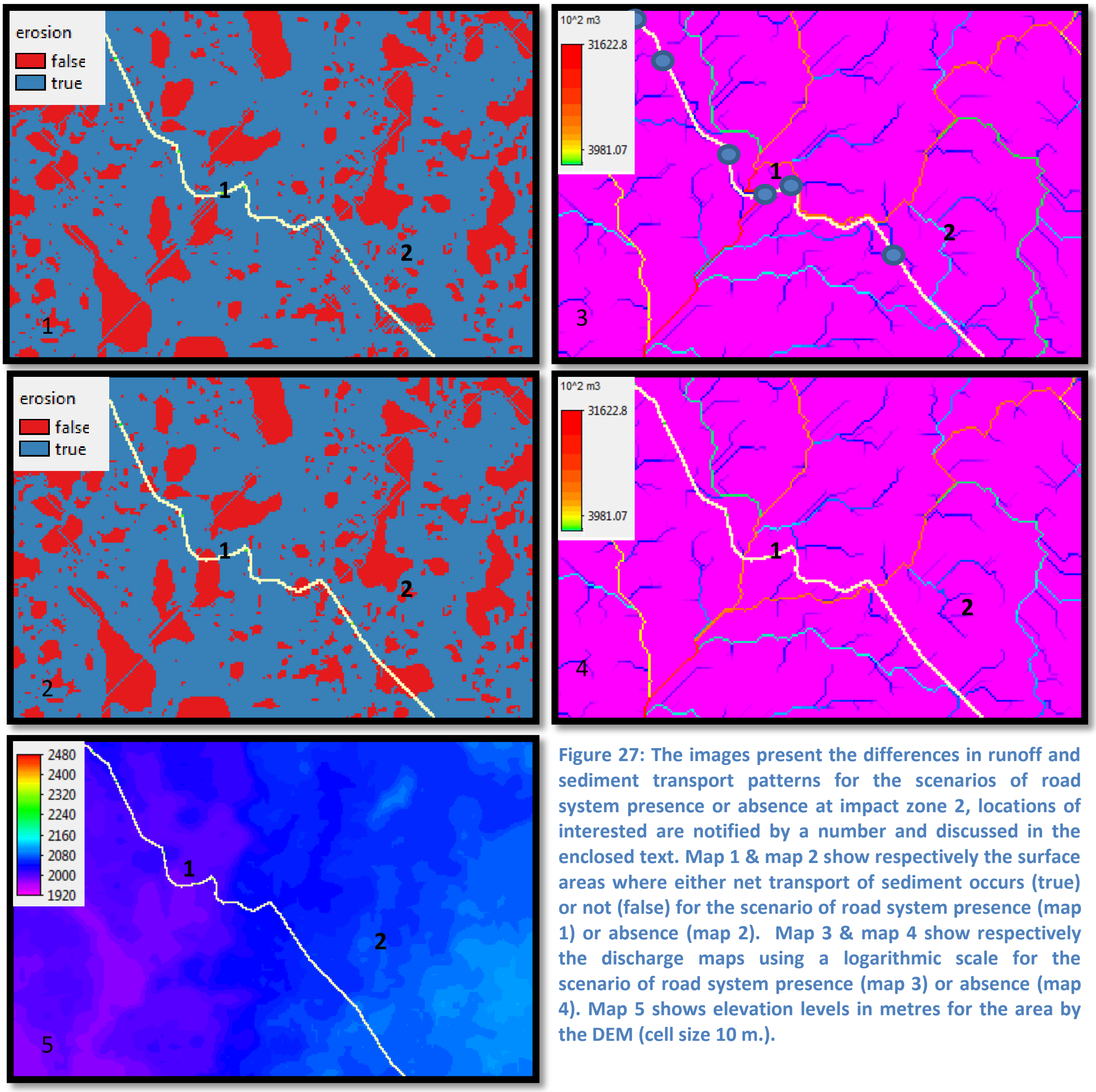


Figure 27: The images present the differences in runoff and sediment transport patterns for the scenarios of road system presence or absence at impact zone 2, locations of interested are notified by a number and discussed in the enclosed text. Map 1 & map 2 show respectively the surface areas where either net transport of sediment occurs (true) or not (false) for the scenario of road system presence (map 1) or absence (map 2). Map 3 & map 4 show respectively the discharge maps using a logarithmic scale for the scenario of road system presence (map 3) or absence (map 4). Map 5 shows elevation levels in metres for the area by the DEM (cell size 10 m.).

Point 1 shows that the presence of the road system causes the natural stream flowing from the north-east, gets blocked by the road embankment and causes a further diversion along the road side westwards. The two main discharge streams merge just north of the road and get cross-drained at the same culvert, which shows an increase of about 140% in conveyed volume compared to conditions of road absence. This culvert could be positioned better aligned with the natural flow lines, especially taking into account that the highest fraction of total runoff within the catchment needs to be cross-drained at this location. One can also see that the area undergoing erosion increases downstream of this culvert. The alterations are not obvious, this is most probably related to the fact that the runoff is highly concentrated here. Alterations seem to mainly follow the changes in flow lines. The other culverts do not seem to make a significant contribution in cross-draining runoff. At **point 2** an extra stream from the south east merges with one of the two big contributing streams, this is diverted runoff originating from the previously described first impact zone.

7.1.4 Impact zone 3

The third impact zone is characterised by increased elevation values in the northern and eastern part. A general north to south drainage direction can be observed. The two main streams are both altered by the road system and do not follow their natural flow lines.

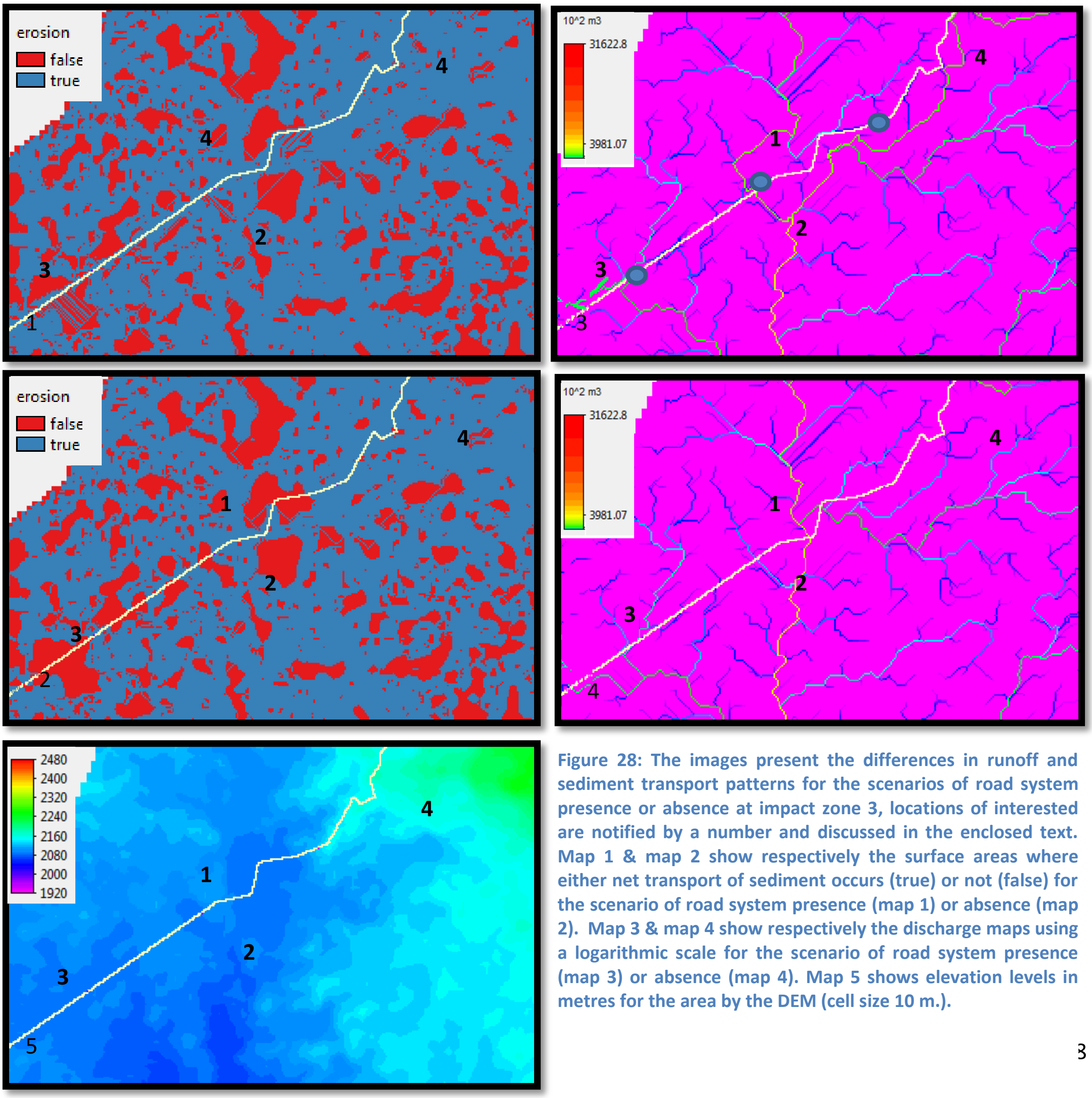


Figure 28: The images present the differences in runoff and sediment transport patterns for the scenarios of road system presence or absence at impact zone 3, locations of interested are notified by a number and discussed in the enclosed text. Map 1 & map 2 show respectively the surface areas where either net transport of sediment occurs (true) or not (false) for the scenario of road system presence (map 1) or absence (map 2). Map 3 & map 4 show respectively the discharge maps using a logarithmic scale for the scenario of road system presence (map 3) or absence (map 4). Map 5 shows elevation levels in metres for the area by the DEM (cell size 10 m.).

At **point 1** the runoff is conveyed further southwest before it is cross drained at a culvert. Close to **point 2** the natural flow lines would allow two streams to merge just north of the current road system, one of the two main streams is not cross-drained further uphill but follows the road alignment on the southern side (see around **point 4**). This causes a separation of one into two contributing streams, which consist of approximately 45% (northwest-southeast) and 55% (northeast-southwest) of the initially conveyed volume by the main stream further southwards. At **point 3** the runoff is diverted along the roadside northwards before it reaches the first culvert, here it is drained to the downstream side of the road.

7.2 Scenario results

7.2.1 Road system scenarios

This section presents a detail of three different road system scenarios, in order to give an impression of the developed road system scenarios and the different culvert positioning methods applied. The area of interest coincides to a large extent with the second impact described in the previous chapter. The different images all show a modelled discharge map (resolution 10 m.) after a 30 millimetres rainfall event of one hour, the runoff is given by a logarithmic scale. The culvert locations are presented by the coloured dots. One can see that the different road system scenarios cause different alterations in runoff patterns to occur. The current road system causes a significant circumvention of the main eastern stream, which does not hold for the culvert scenarios following the ERA guidelines or keeping a fixed culvert interval of 500 m. Furthermore, the culvert scenario with the culvert positioned according to the ERA guidelines seem to contain several culverts which do not make a large contribution in cross-draining.

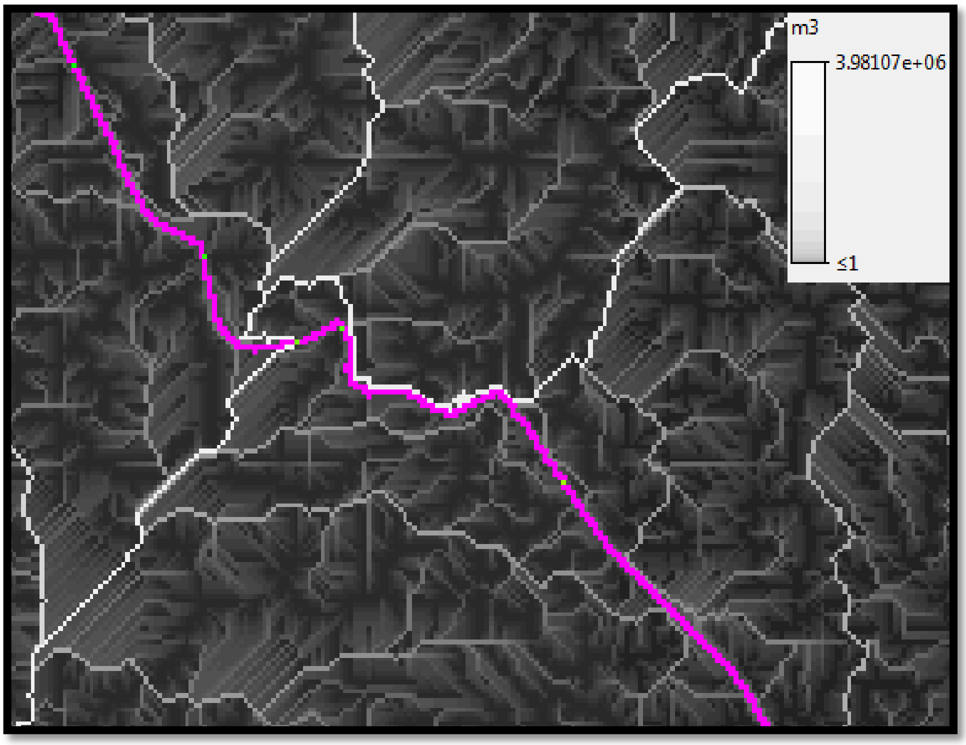


Figure 29: The current road system is presented with its original culvert locations, which are indicated by the coloured dots. The runoff is shown on a logarithmic scale and given in cubic metres. A total of five culverts can be noticed along the selected road transect.

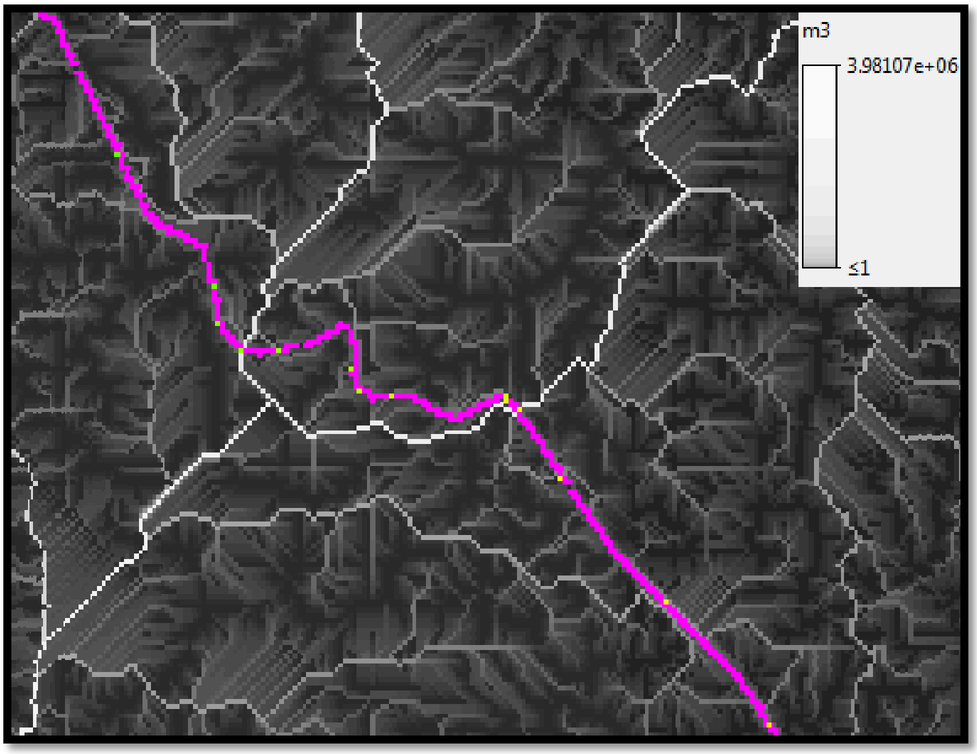


Figure 30: The original road alignment is presented with culvert positioned following the ERA guidelines, the culverts are indicated by the coloured dots. The runoff is shown on a logarithmic scale and given in cubic metres. A total of thirteen culverts can be noticed along the selected road transect.

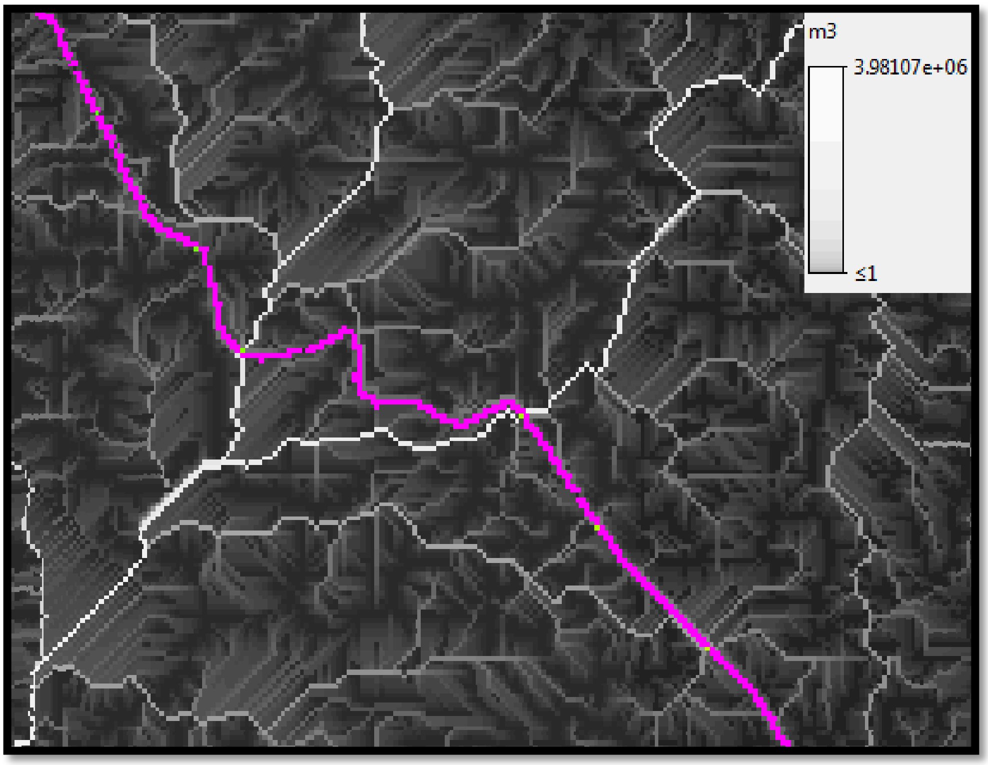


Figure 31: The current road system is presented with a fixed culvert interval of 500 meters, the culverts are indicated by the coloured dots. The runoff is shown on a logarithmic scale and given in cubic metres. A total of six culverts can be noticed along the select road transect.

7.2.2 Erosion indicators

Total catchment erosion

The model outcomes for the indicator representing total catchment erosion are shown in figure 31. A significant lower value can be observed for the situation of road absence ($2.02\cdot10^{8}$ tonnes) compared to all modelled road system scenarios, thereby suggesting an enhancing effect of road system presence on total catchment erosion. The current road system scenario shows a remarkable high value, also the road system scenario following a southern road alignment with a culvert positioned at all locations showing a natural discharge of more than 10 m^{3} per hour. The scenarios following a southern road alignment show increased values for the majority of the culvert scenarios compared to the other road alignment alternatives. No further trends could be noticed looking at total catchment erosion for the rural road system scenarios.

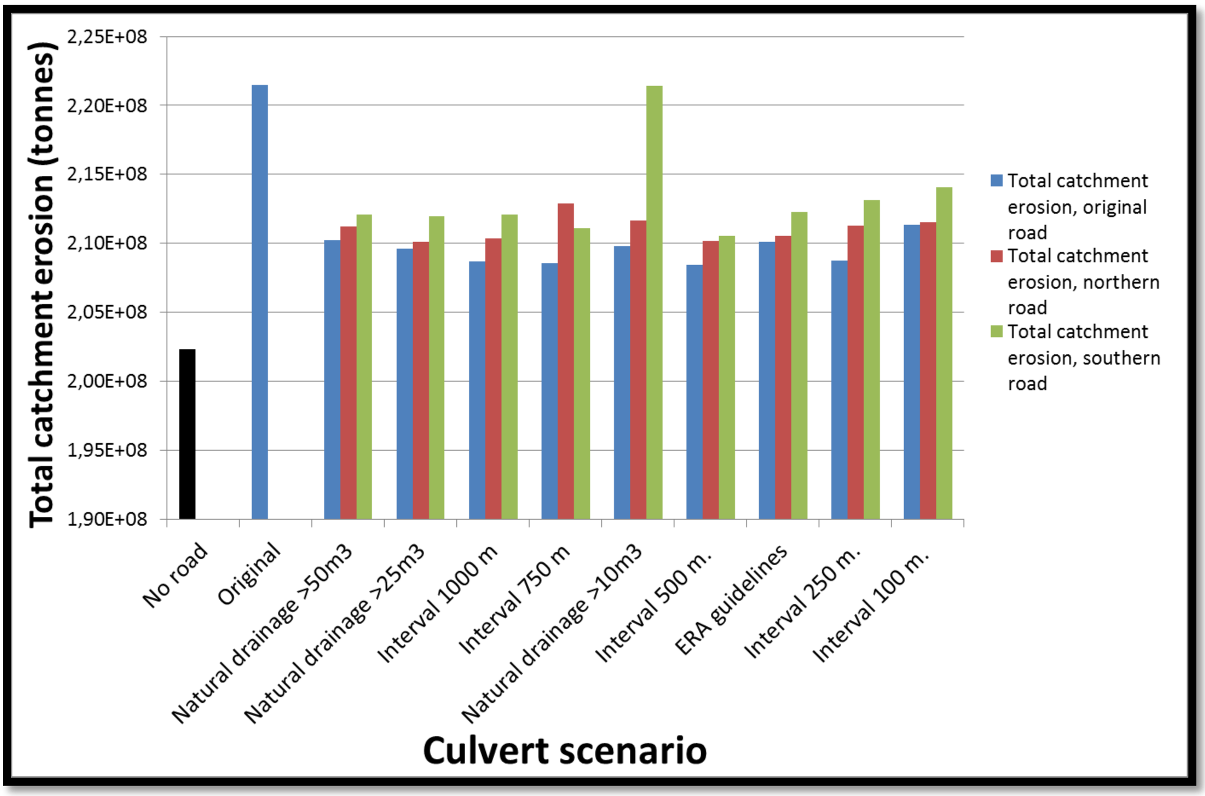


Figure 32: : The figure shows the modelled values for total catchment erosion per road system scenario. The highest value obtained is $2{,}21\cdot10^{8}$ tonnes, it is covered by the scenario following a southern road alignment and culverts positioned at every location showing a natural discharge of more than 10 m^{3} per hour. The lowest obtained erosion value is $2{,}08\cdot10^{8}$ tonnes, it is represented by the scenario following an original road alignment and a fixed culvert spacing of 500 meters.

Catchment surface area undergoing erosion

The range of all modelled values is 0.1% of the total catchment area, which corresponds to approximately 17 hectares. The scenario without road presence does show a considerable lower value of 75.6 %, thereby suggesting an enhancing effect of road system presence on total catchment surface area undergoing erosion. Fractional surface area of the catchment undergoing erosion. The current road system shows the highest fractional area of the catchment of approximately 75.8 %. The lowest fractional area is 75.7 % and can be observed for the scenario following a southern road alignment and having culverts positioned at all locations showing a natural discharge of more than 10 m^{3} per hour. The results do not show obvious differences between alignment alternatives as compared to the indicator on total catchment erosion. The modelled outcomes on the indicator representing the fractional area of the total catchment showing erosion is enclosed in appendix B.

Total road scouring

The scenarios following a southern road alignment show much higher values for the indicator representing total road scouring compared to the original and northern road alignment (approximately four times more), which is shown in the enclosed figure 33. The current road system shows approximately an average value of $3.64 \cdot 10^6$ tonnes. It seems that all scenarios with their culverts positioned according to the natural drainage patterns show increased values, this effect is however not obviously holding for the scenarios following a northern alignment. The magnitude of the values for total road scouring per road alignment strongly correlates with the indicator on total harvested discharge through culverts. This is to an extent based on the total contributing upstream area of the actual road system, which partly determines the energy of the runoff (increased discharge volumes) and consequential erosion along the road. The model outcomes have also been normalised for the different road zone surface areas to compensate for the different road zone surface areas to obtain potential patterns, still the patterns one can observe in figure 32 remain similar.

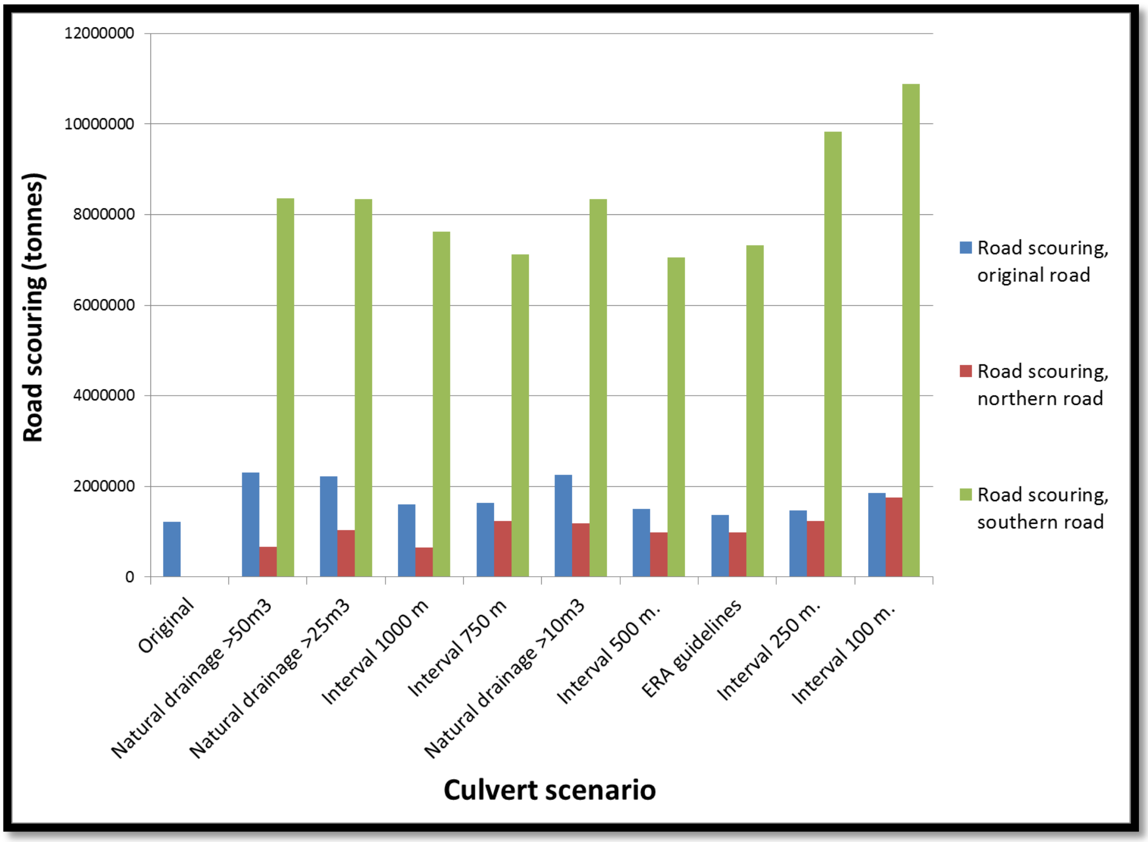


Figure 33: The figure shows the modelled values for road scouring per road system scenario. The highest value counts $1{,}9 \cdot 10^7$ tonnes and can be observed for the scenario following a southern road alignment with a fixed culvert interval of 100 meters. The lowest score is $6{,}52 \cdot 10^5$ tonnes and can be accounted to the scenario following a northern road alignment with a fixed culvert interval of 1000 meters.

Fractional area of road zone undergoing erosional processes

The outcomes on the fractional road zone surface undergoing erosion show high values, all show erosion over more than at least 90% of its total road zone surface. The northern and southern road alignment scenarios show higher values compared to the current road alignment. A decrease can be observed towards higher culvert numbers for the road system scenarios following the current road alignment. This latter trend does not hold for the other road alignment alternatives. The results are shown in figure 34 The model outcomes have also been normalised for the different road zone surface areas to compensate for the different road zone surface areas, the general patterns remain similar.

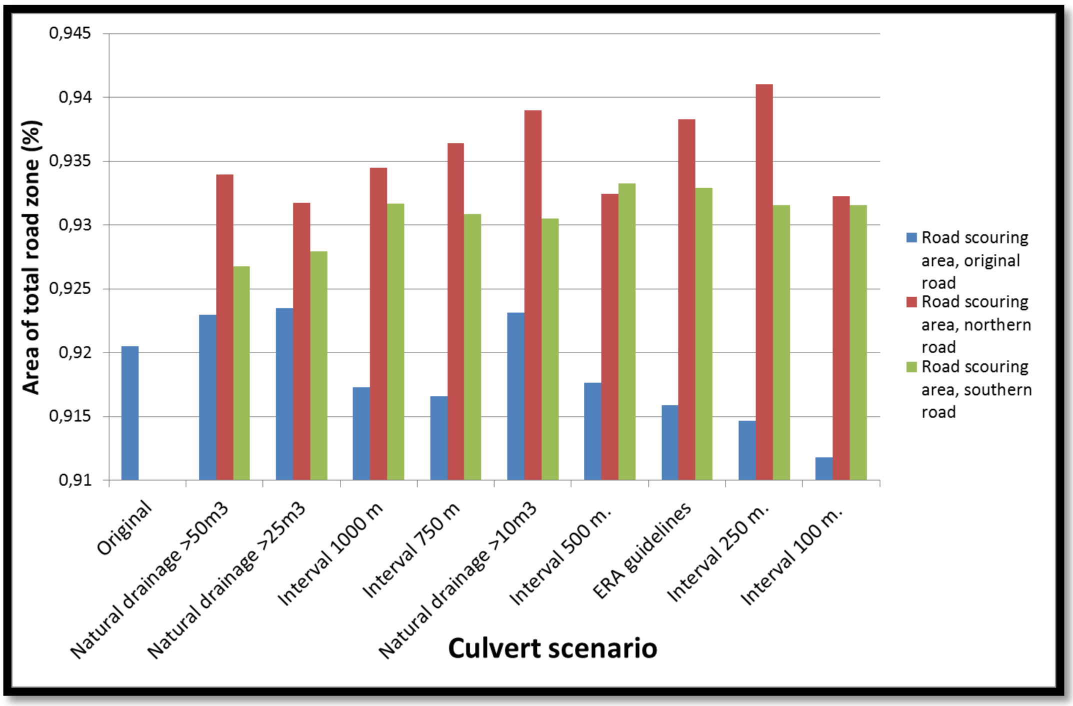


Figure 34: The highest value for the area of the road undergoing scouring processes is 94% and can be observed for the scenario following a northern road alignment and having a fixed culvert interval of 250 meters. The lowest value is 91 % and is covered by the scenario following the current road alignment and having a fixed culvert interval of 100 meters.

Total gully formation risk at catchment scale

The total CTI score per scenario shows relatively lower scores for several scenarios following a southern road alignment even compared to the road absence scenario. This trend does not hold for the other two road alternatives. Other patterns or trends could not be observed between road system scenarios and the total outcome seems of a random character. The highest total CTI score is 212.8 and can be observed for the scenario following a northern road alignment and having a fixed culvert interval of 750 meters. The lowest score is 201.5 and could be observed for the scenario following a southern alignment and a fixed culvert interval of 100 meters. The figure is enclosed in appendix B.

Gully formation risk at culverts

The indicator on gully formation risk at culvert locations shows the modelled fractions cover a range between 20% and approximately 50% of the total number of culverts per road system scenario. No obvious trends could be noticed looking at the risk for gully formation at culvert locations. The highest score is covered by the scenario with a southern road alignment and a fixed culvert interval of 1000 meters. Also the lowest score is covered by a scenario following a southern road alignment but having a culvert positioned at every locations showing a natural discharge of more than 25 m^3 per hour. The current road system seems to score a little above average (34.7%). The figure is enclosed in appendix B.

7.2.4 Water harvesting indicators

Total harvested discharge through culverts

The total harvested volume of water by culverts after one event can be observed in figure 35. It shows much higher scores for the scenarios following a southern road alignment. The high scores for the southern alignment can be clarified by the larger upstream area of the road, all runoff is blocked by the road system and finally discharged through its culverts. The small difference between the northern and original alignment indicate that the different alignment options have an almost equal contributing catchment size. The total harvested discharge volume tends to strongly increase for all road alignment options with either a fixed culvert interval of 250 or 100 meters. The scenarios with an original or southern alignment also show higher scores when the culvert is positioned based on the natural drainage pattern. The lowest value on total harvested discharge through culverts is represented by the current road system. These differences in harvested discharge between culvert scenarios were unexpected and do not follow the assumption that the alignment cause the captured runoff by the road system to be more or less constant for the different road system scenarios of a particular alignment. This event will be further clarified and elaborated in section 7.4.2.

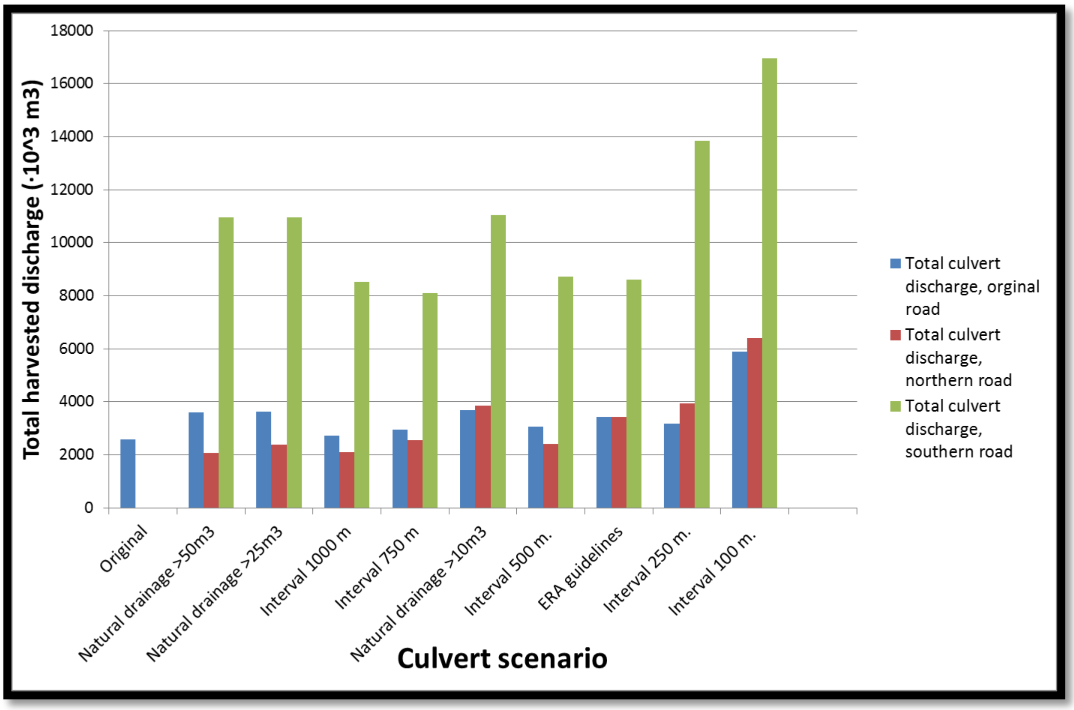


Figure 35: The highest score is approximately $1.7 \cdot 10^7$ cubic meters and can be observed for the scenario following a southern road alignment and a fixed culvert interval of 100 meters. The lowest score is about $2.6 \cdot 10^6$ cubic meters and can be observed for the current road system.

Price of harvested water

The price of the harvested discharge at culvert locations after one event is shown in figure 36, it shows much higher scores for the scenarios following a southern road alignment, much lower scores can be observed for the original and northern alternative. The scenario following the current road alignment and having a fixed culvert interval of 1000 meters shows a very high value compared to the other scenarios following the original road alignment. No obvious trends among the different culvert positioning techniques scenarios can be noticed. The northern road alignment shows the lowest prices per cubic metre of harvested water. This might be clarified by the fact that the road is aligned more uphill were runoff is of a more dispersed character, further downstream it merges into larger streams which results in higher individual culvert prices because of increased required diameters. It might indicate that runoff seems to be better spread among the installed culverts, which makes discharge per culvert and therefore minimum diameter and price of the culvert lower.

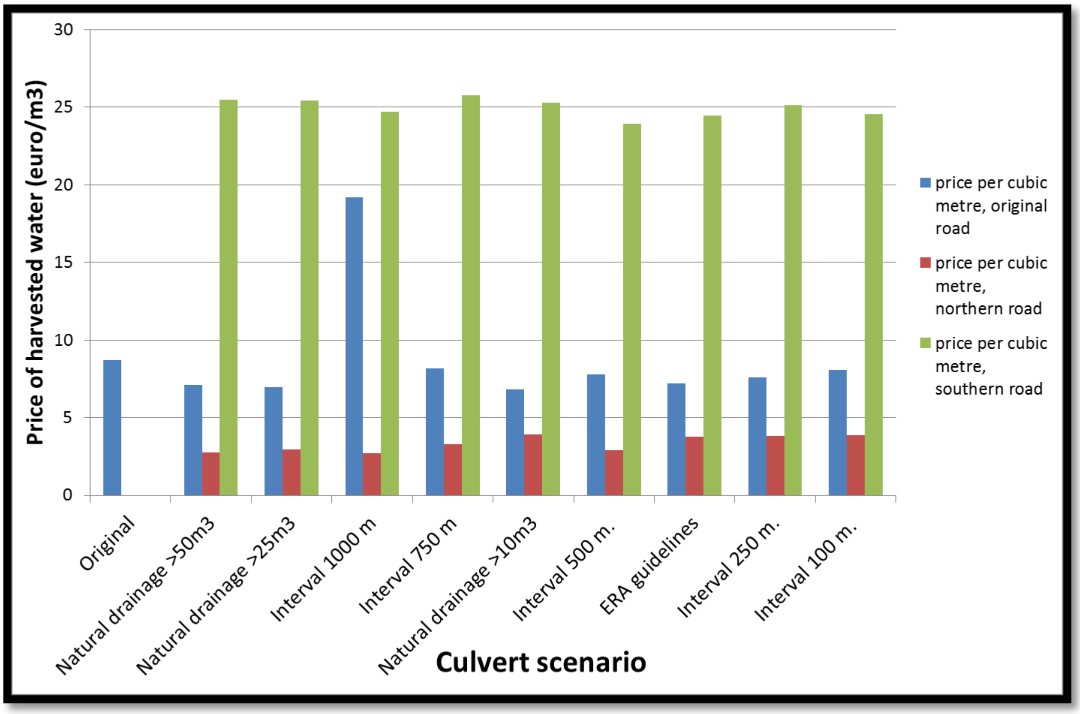


Figure 36: The highest modelled price is 25.8 euro/m^3 and can be observed for the scenario following a southern road alignment and a fixed culvert interval of 750 meters. The lowest price is 2.7 euro/m^3 can be observed for the scenario following a northern road alignment with a fixed culvert interval of 1000 meters.

7.2.3 Cost indicators

Total culvert costs

Important note to make is that all calculated total culvert costs are unrealistic, but by referring to the method in chapter 6 serve as a relative measure for scenario comparison. The scenarios with a southern road alignment show far higher costs than the original and northern road alignment scenarios. The patterns for culvert scenarios within a particular road alignment option, seem to follow a similar pattern discussed for the indicator representing total harvested discharge through culverts. However, the current road system shows relatively increased costs compared to the other scenarios following an original alignment. The high scores for the southern alignment can be clarified by the larger discharge volumes to be conveyed which determine the modelled culvert sizes. The total culvert costs for the northern alignment are significantly lower compared to the original alignment while the values on total harvested discharge through culverts are more alike for these alignments. This might be clarified by the same aspect described for the indicator representing the price of harvested water, the discharge is of a more dispersed character more uphill in the catchment. It might indicate that runoff seems to be better spread among the installed culverts compared to further downslope where runoff already merged into larger streams. Less concentrated discharge causes the discharge per culvert and therefore minimum diameter and price of the culvert to be lower.

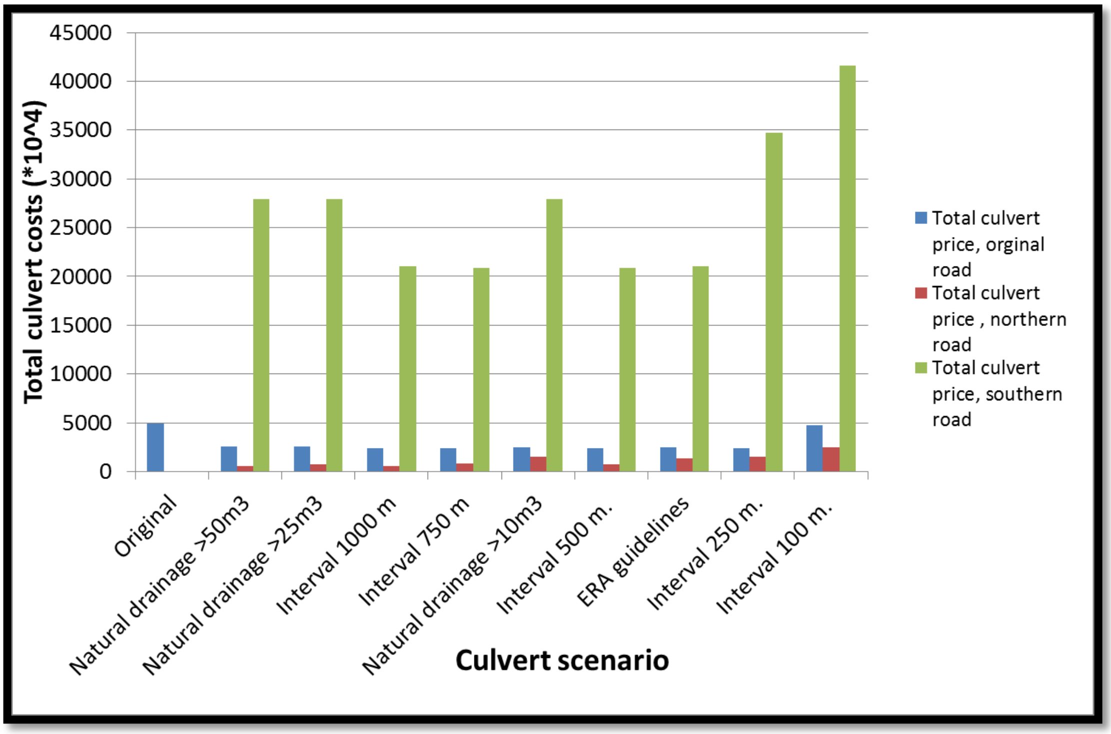


Figure 37: The highest total culvert price is approximately 4.16·10^8 euro and can be observed for the southern road alignment with a fixed culvert interval of 100 meters. The lowest total culvert price is approximately 5.62·10^6 euro and can be observed for the scenario following a northern road alignment and having a fixed culvert interval of 1000 meters.

Road length:

Is a fixed variable per road alignment:

- Original road alignment: 21.5 km.
- Northern road alignment: 21.6 km.
- Southern road alignment: 24.1 km.

7.2.5 Summary scenario results

The indicators representing total erosion at the catchment scale or road zone, show increased scores for the road system scenarios following a southern road alignment. The indicators seem strongly related to the volume captured by the road system. The current road system shows a remarkable high value for the indicator on total catchment erosion compared to the other road system scenarios. When focussing on the indicators representing the surface area showing erosion, no obvious differences between road alignments can be noticed for both indicators. The northern road alignment shows better scores for the cost aspect, what might indicate that runoff seems to be better spread among the installed culverts compared to further downslope where runoff is more concentrated into larger streams. Less concentrated discharge causes the discharge per culvert and therefore minimum diameter and consequential price for the positioned culvert to be lower. The gully formation risk for the different road system scenarios does not show clear trends, not on a catchment scale nor focussing on just the culvert locations.

The assumption that the formulated road alignment options define the delineation the upstream area of the road and thereby capture a more or less constant volume for a single alignment options seems non-valid. Total harvested discharge by culverts influences most of the defined indicators. The performance of most indicators depend on the degree of division taking place along the particular road system, which is disturbed when the total volume to be divided changes between scenarios.

7.3 The impact of road alignment

In order to study the model outcomes more in-depth and to find potential differences related or caused by a particular road alignment, a one-way ANOVA statistic was applied. The one-way ANOVA shows whether or not a significant difference can be found for a multiple of samples or in this case the different sets of indicator values, thereby testing for potential differences in their mean values. This testing for significance can provide insights in the way the factor road alignment has an influence on the formulated indicator. This section aims at exploring potential differences caused by road alignment. Due to the amount of assumptions made in this section and the somewhat questionable reliability of the model outcomes, conclusions will be drawn with utmost care.

The one-way ANOVA requires the practise of random sampling, because it is likely to be representative of the sampled population. When a sample is representative despite being non-random, most statistical tests will still give acceptable outcomes (Lowry, 2006). The model outcomes for the different indicators of the 27 culvert scenarios, were evaluated as three non-random samples from different populations (based on the particular road alignment option). It was assumed that the three different sets per single modelled indicator value (non-random samples) are representative for that particular road alignment option, because their origin is based on the actual alignment of the road which differs considerably for the three alignment options. The null hypothesis states that the indicator values per culvert scenario (non-random samples) are equal, the alternative therefore implies that road had a significant impact on the value of the tested indicator. The one-way ANOVA assumes that samples are independent, follow a normal distribution and that variances among the different samples are fairly equal. However, most of the modelled indicator values did not show an obvious Gaussian distribution, therefore values were transformed by using a natural logarithm. The one-way ANOVA is stated to be robust enough for violations of both a normal distribution and equality of variances among the different populations when the sample sizes are equal (Lowry. 2006), which is the case for the three sets of indicator values because they are based on an equal number of underlying culvert scenarios.

The one-way ANOVA analyses the different sources of variance to estimate whether or not samples originate from a different population or not. It requires the calculation of the mean values of all three separate samples and a total mean value based on the combined samples. The total sum of squares is calculated and the sum of squares inside the samples, a third sum of squares between the samples can be extracted from these tow values. A F-ratio is calculated which compares the aggregated differences among the means of the used samples and the differences of means inside the separate samples, it is compared to a predefined critical F-value depending on a decided level of significance and the degrees of freedom. For the full procedure one is referred to the elaborate work by Lowly (2006).

The one-way ANOVA does not provide any information in what way the samples differ. The Tukey test is applied to test which road alignment scenarios do significantly differ from each other. A Tukey test statistic is calculated based on the difference between means, the variations within groups and the sample size. The Tukey statistic is calculated by the following equation (Lowly, 2006):

$$21.\ Q = \frac{[M_l - M_s]}{\sqrt{{MS_{wg}}/{N_{p/s}}}}$$

$\mathrm{Q} = \text{Tukey statistic}\ ;\ \mathrm{M_l} = \text{larger mean of the pair of indicator sets (based on road alignment option)};\ \mathrm{M_s} = \text{smaller mean of the pair of indicator sets (based on road alignment option)}$

$\mathrm{MS_{wg}} = \text{the mean square within the set of indicator values};\ \ \mathrm{N_{\frac{p}{s}}} = \text{the number of culvert scenarios per set} = 9.$

The Tukey statistic is compared with a critical value provided by tabular data to test for its eventual significance. For the full procedure one is referred to the elaborate work by Lowly (2006). Table 10 summarises the statistical analysis.

Table 10: Statistics summary. green marked cells show indicator values that are significantly different for the two road alignment options represented by the column (Lowly, 2006). The critical value is Qcrit 4.34 with a significance level of 5%. Larger differences between the road alignment scenarios are represented by an increased value of the Tukey test statistic Q.

Indicators	**Original – Northern ($Q_{0.05}$= 4.34)**	**Northern – Southern ($Q_{0.05}$= 4.34)**	**Southern – Original ($Q_{0.05}$= 4.34)**
Catchment erosion	No significant ANOVA	No significant ANOVA	No significant ANOVA
Catchment erosion area	0.50	3.14	3.64
Road scouring	6.28	25.80	19.52
Road scouring area	15.24	4.22	11.02
Gully risk within catchment	2.27	5.87	3.60
Gully risk at culverts	No significant ANOVA	No significant ANOVA	No significant ANOVA
Total culvert costs	8.47	26.25	17.78
Total harvested discharge	1.40	12.85	11.45

The one-way ANOVA resulted in a significant statistic value for all indicator sets, except of the indicators representing the total catchment erosion and the gully formation risk at culvert locations. The indicator representing the fractional catchment surface area undergoing erosion results in a significant ANOVA statistic but does not show any significant Tukey statistic between the road alignment options. This can be clarified by the different origin of both calculated statistics, the ANOVA refers to the whole independent variable and its relation (or lack of it) with the dependent variable. The Tukey test ask about differences among pairs, then the significance level refers to the statistical significance of these. The lack of a significant statistic for these indicator sets would substantiate the statement that the factor of road alignment does not have a significant effect on the indicator outcomes.

The indicator representing total road scouring shows different patterns for its magnitude and occurrence in the fractional road zone surface area. The Tukey statistic for the indicator on total road scouring is significantly different for all road alignment options. Focussing on the indicator on fractional surface area of the road zone undergoing erosion, the northern and southern alignments do not show a significant difference. The modelled CTI scores which represent the overall risk of gully formation at catchment scale only show a significant difference between the northern and southern alignment option. Total culvert discharge is significantly different for the road system scenarios following the southern road alignment compared to the two alternatives. Although the road system scenarios following either a northern or original road alignment do not significantly differ for the indicator describing total culvert discharge, the modelled total culvert costs which are strongly related to the modelled discharge volumes through culverts do show a significant difference between all the alignment options. The calculated statistics generally support the explained patterns in section 7.2.

7.4 The influence of culvert number and positioning

7.4.1 Culvert number

Three indicators are presented in this section by figure 38-40, suggesting a relation between culvert number and the indicator value. The other figures evaluating indicator values per culvert number are presented in appendix C , they do not show a pattern or trend.

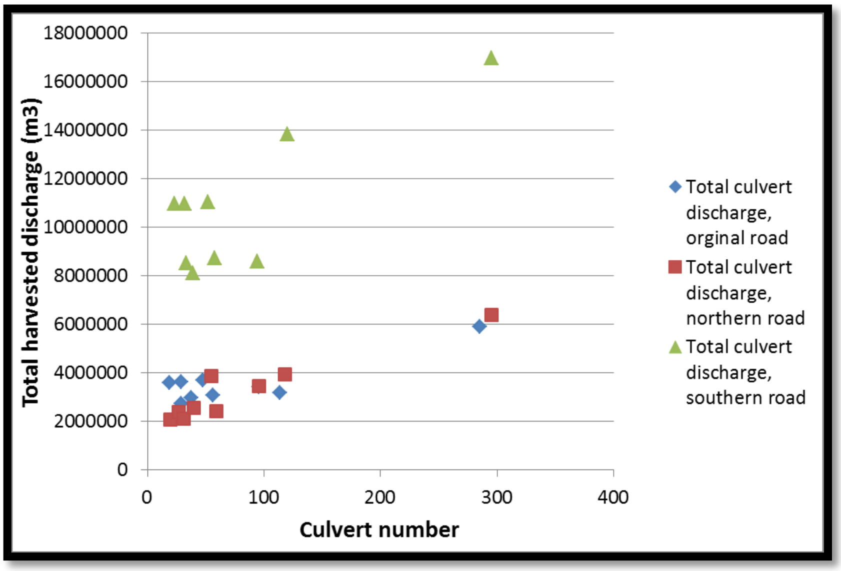


Figure 38: The total harvested discharge through culverts for three alignment options is presented on the y-axis; the x-axis shows the total culvert number of a particular road system scenario.

The figure suggests an increase of the total harvested discharge through culverts when the total culvert number of a road system scenario increases. Which was also addressed in the previous sections. This could not be explained by the modelling process and will be further discussed in chapter 8.

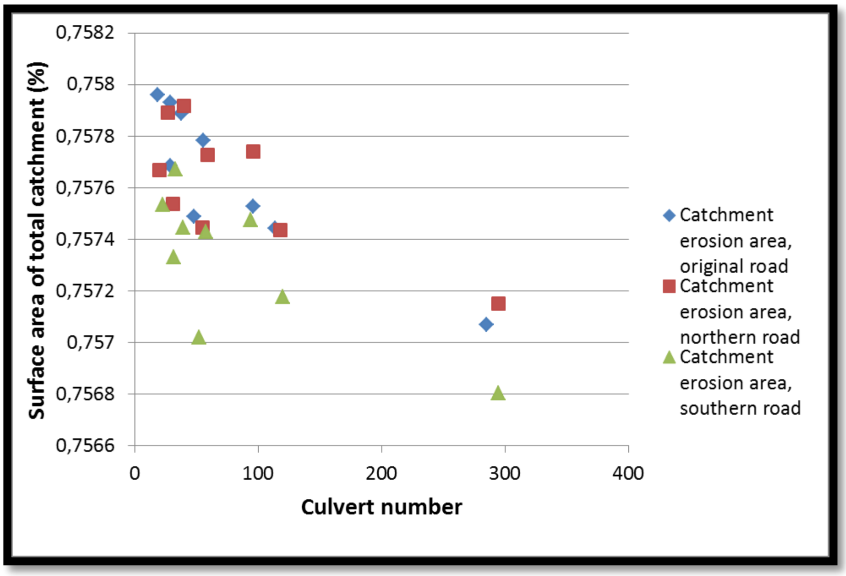


Figure 39:The total fractional catchment surface area undergoing erosion for three alignment option is presented on the y-axis, the x-axis shows the total culvert number of a particular road system scenario.

The total fractional surface area of the total catchment undergoing erosion tends to decrease for road system scenarios with a higher number of culverts installed for all road alignment options. It is important to note that this is a only a very small change (corresponding to a difference of approx. 17 hectares).

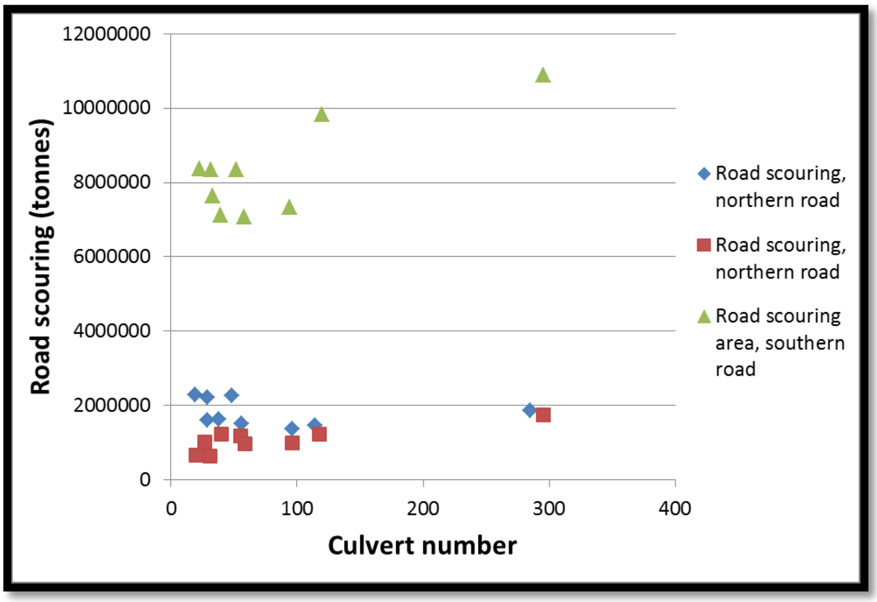


Figure 40: The total road scouring for three alignment options is presented on the y-axis, the x-axis shows the total culvert number of a particular road system scenario.

The slight increase in total road scouring magnitude with increasing culvert number is most probably related to the increased harvested culvert discharge presented in figure 35. The impact of the number of culverts per road system scenario was expected to be related to the ability of the road system to spread discharge among its positioned culverts, thereby reducing the magnitude of the erosion process due to less concentrated discharge volumes and more spreading. The lack of correlations between the modelled outcomes and culvert number per road system scenario, suggests that the process of spreading is actually not occurring or sufficiently integrated into the model. However, a more likely cause is that the alterations in the indicator on harvested culvert discharge cover the potential patterns of reduced erosion due to spreading.

7.4.2 Culvert positioning technique

The model outcomes evaluated in section 7.2 were expected to show relatively lower values for the indicators related to erosion for all scenarios with culverts positioned according to the natural drainage patterns or a small culvert interval. These scenarios were expected to cause less alterations in natural flow line, less diversion and concentration of run-off and therefore decreased values for e.g. total road scouring and fractional surface area undergoing erosion. The model outcomes revealed different results.

A post-hoc analysis on the effect of culvert positioning technique by using the background map material supporting the indicator outcomes, revealed an important pattern caused by culvert positioning technique and the number of culverts per road system scenario. Two small details are shown in figures 41 and 42 of a discharge map and different road system scenarios both following the southern alignment.

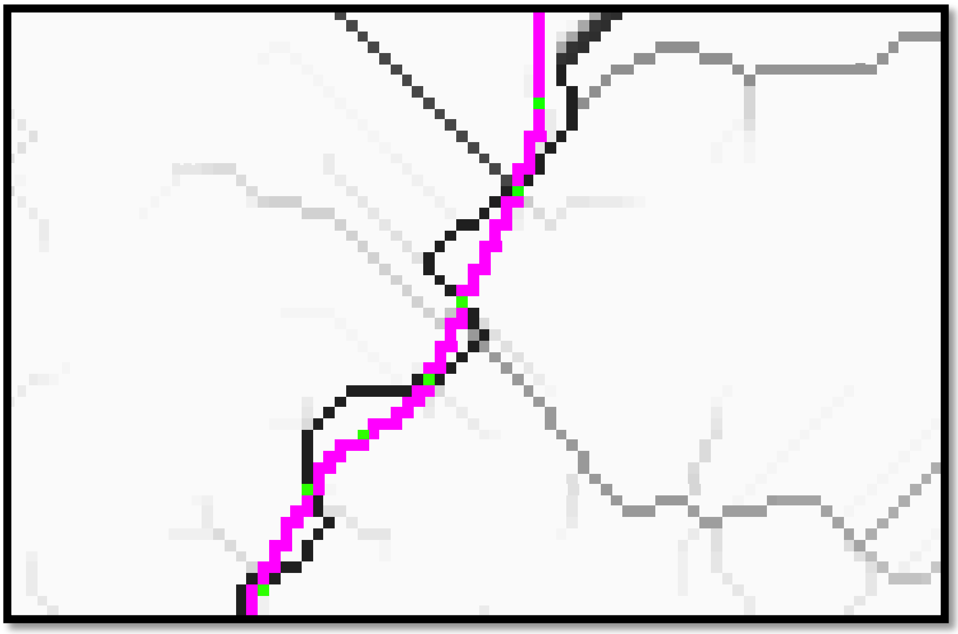


Figure 41: Detail of discharge map, southern alignment with a fixed culvert interval of 100 m.

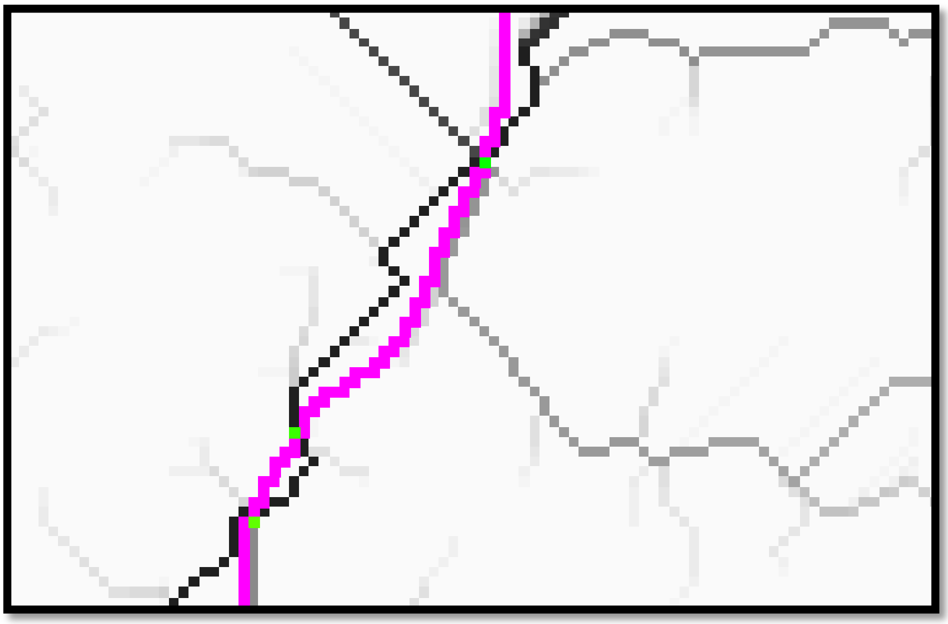


Figure 42: Detail of discharge map, southern alignment with a fixed culvert interval of 1000 m.

The two figures describe a situation which to a certain extent holds for all alignment options. Discharge streams get cross-drained passing the road multiple times. Every cross draining culvert counts a score for the indicator representing harvested discharge through culverts, which results primarily in alterations in the total summated indicator on total harvested discharge through culverts. It was believed that respecting the major streams in culvert positioning would have compensated for this event, but the figures show this was not a valid assumption. The impact of culvert number on this process is clearly described by the two figures, a smaller culvert interval or higher culvert number per road system scenario results in more opportunities for potential cross-drainage of discharge. The culvert positioning technique based on natural drainage patterns is more adapted to natural flow lines and therefore allows the discharge to be cross-drained forth and back to the other side of the road.

7.5 MCA Results

7.5.1 MCA performance ranking

This section shows the outcome of the developed MCA, the ranking of scenarios will be described and interpreted. A sensitivity analysis on the criteria weighting system was used to study the MCA’s performance. In order to obtain a final ranking among the different formulated scenarios, several choices were made which were explained in the method section. Table 11 summarises the selected methods that were applied to each criterion in order to combine and finally prioritise among the scenarios by using the technique of simple additive weighting (SAW). The weights were determined by applying pairwise comparison with a consistency ratio of 0.05 for the criteria, which is lower than the critical value of 0.10.

Table 11: Summary of MCA parameters.

Erosion attribute	**Unit**	**Cost/Benefit**	**Weight = 0.24**
Catchment erosion			0.055
Total erosion	Tonnes	Cost	(75%)
Total eroded surface area	%	Cost	(25%)
Gully formation risk			0.055
Total gully risk over catchment	-	Cost	(12.5%)
Percentage of culverts at risk	%	Cost	(87.5%)
Roadside scouring			0.120
Total erosion	Tonnes	Cost	(75%)
Total eroded surface area	%	Cost	(25%)
Cost attribute	**Unit**	**Cost/Benefit**	**Weight = 0.65**
Total culvert costs	euro	Cost	0.400
Road length	m	Cost	0.250
Water harvesting attribute	**Unit**	**Cost/Benefit**	**Weight = 0.12**
Total harvested discharge	M^3	Benefit	0.060
Price of harvested discharge	Euro/m^3	Cost	0.060

The total performance ranking of all 28 road system scenarios is presented in figure 43. The highest scoring road system scenario is covered by the road system following the northern road alignment and having a culvert installed at all locations where the natural discharge shows a larger value than 25 m^3/hour. The road system scenarios following a southern road alignment show all significantly lower scores compared to the two alignment alternatives, no other patterns in total scenario scores between the original and northern alignment options can be noticed. Focussing at the total score of the road system scenarios in relation to their applied culvert positioning technique does not seem to show a relation or trend. One can for example notice that the culvert positioning technique based on the natural drainage pattern counts 3 out of the 5 highest scoring road system scenarios. However, this pattern does not hold when looking at these culvert scenarios for an individual road alignment option.

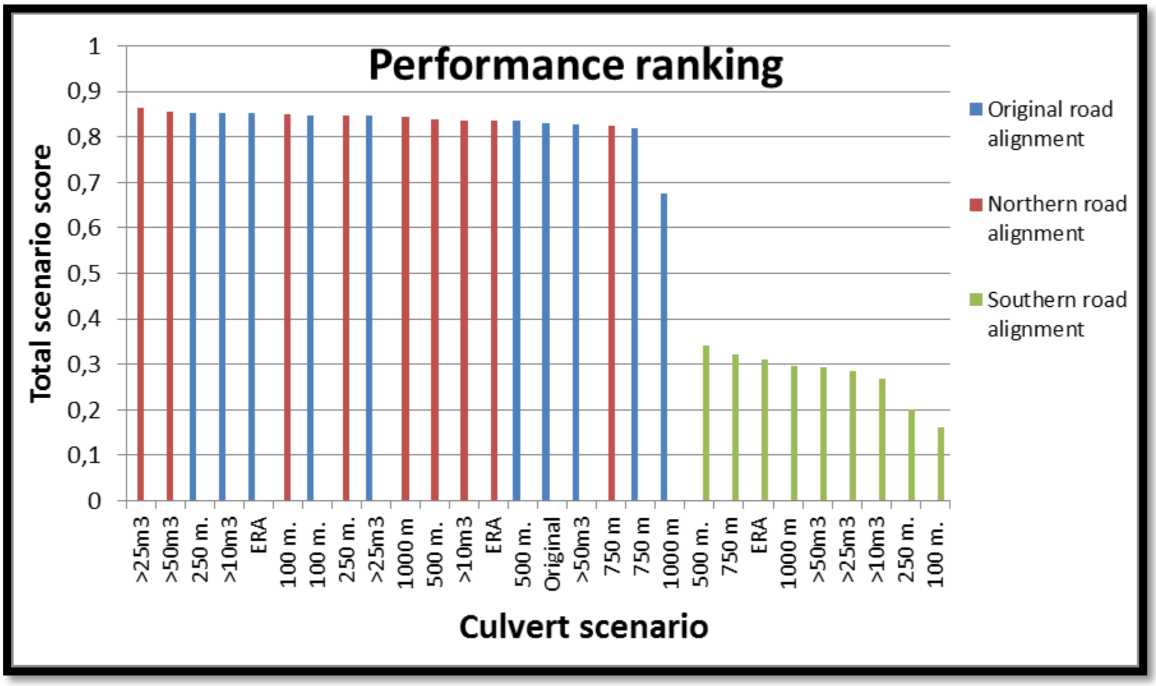


Figure 43: The overall performance ranking of all 28 road system scenarios, the road alignment alternatives are represented by the different colours.

The lower scores of the southern alignment can be clarified by partial MCA scores which are significantly lower than the other alignment options, the indicator values presented in section 7.2 already showed different scores for the following indicators: total road scouring, total harvested discharge through culverts, total road length and total culvert costs. The indicator values were evaluated for the number of installed culverts per scenario, which did not result in any trends. The effect of road alignment on total score seems more relevant to analyse. The following figures (44-46) present the composition of the total MCA scores for all culvert scenarios per road alignment, which provides an easy overview of all individual indicator values per scenario in one figure.

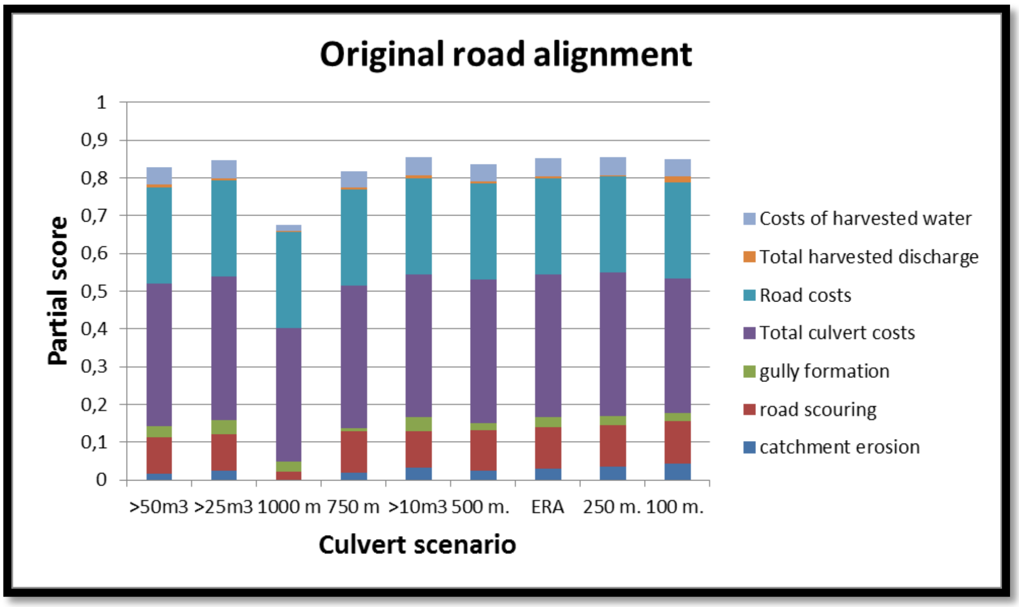


Figure 44: The composition of the total MCA scores for all culvert scenarios following the original road alignment.

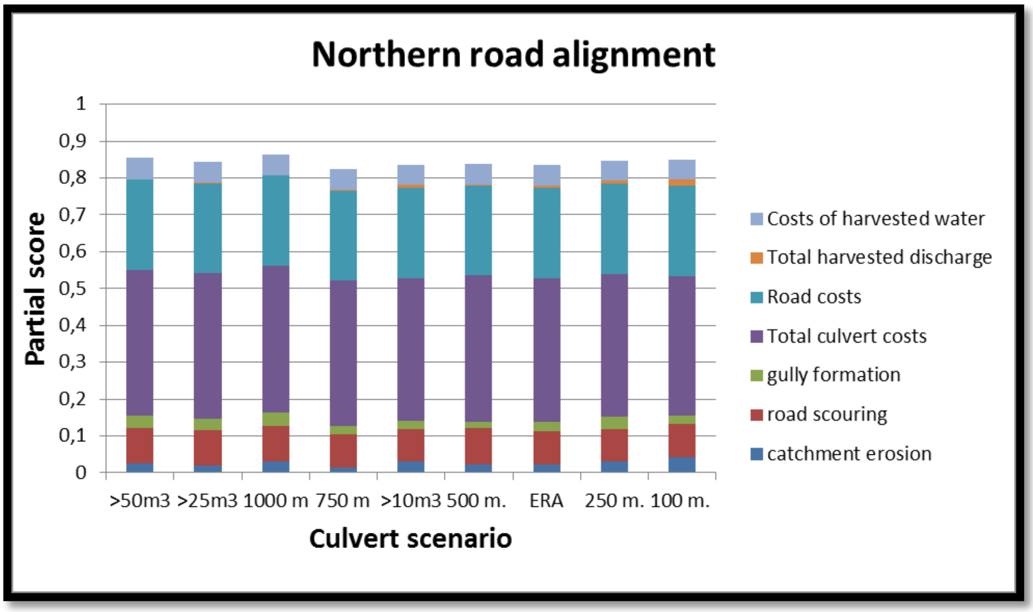


Figure 45: The composition of the total MCA scores for all culvert scenarios following the northern road alignment.

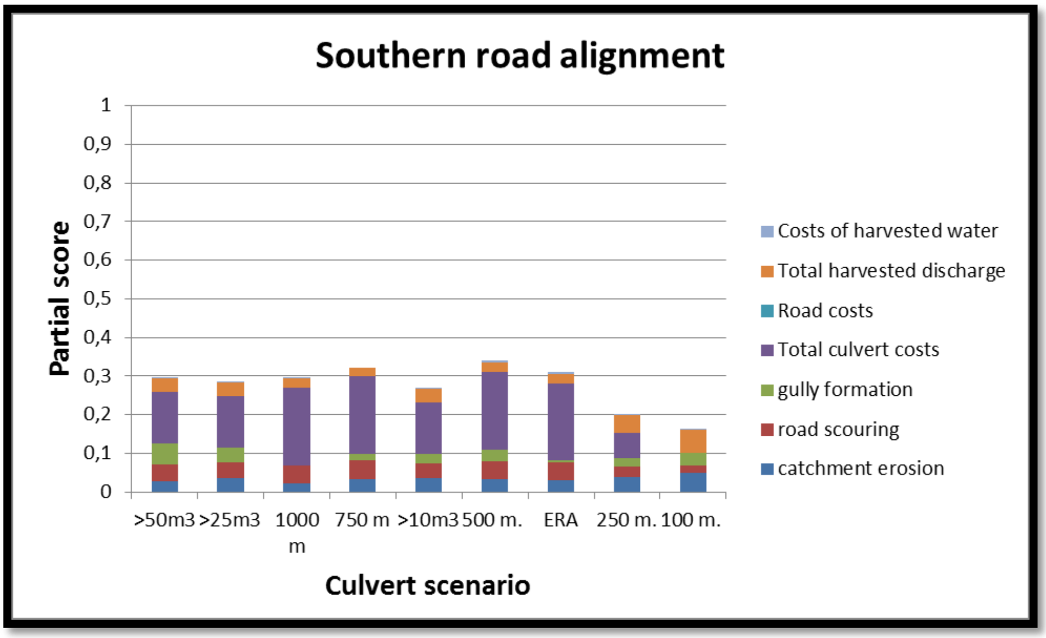


Figure 46: The composition of the total MCA scores for all culvert scenarios following the southern road alignment.

The partial scores for the original and northern alignment culvert scenarios do not show clear tendencies in their composition of the total score. The patterns for the road system scenarios following a southern alignment show a different composition in partial scores compared to the other alignment alternatives. The indicators representing catchment erosion and harvested discharge through culverts show a better performance for all culvert scenarios compared to the other alignment options. The other partial scores all show lower values. A large difference between the alignment options can be noticed for the indicator road length which is caused by the design of the MCA. The MCA is developed on a set of finite design options. This set is used to normalise all scores on a scale of 0 to 1, based on the maximum and minimum value of this particular indicator set. The road length indicator is evaluated as a cost, which result in a zero value for all road system scenarios following the longest southern road alignment.

7.5.2 Sensitivity analysis

In order to evaluate the sensitivity of the MCA regarding the selected criteria weighting system, two other criteria weighting systems are formulated. These alternative weighting systems put more emphasis on a different objective of an improved road system: Minimising road system related erosion is the aim of the environmental weighting system, the promotion of water harvesting practises is secured by the water harvesting weighting system. The original weighting system is evaluated as an economic weighting system, it puts higher emphasis on costs of a road system compared to the other objectives. The alternative weighting systems are constructed changing the total ratio of the objectives while keeping the relative ratios among criteria within one of the three objectives equal. The objectives are altered by applying a division of 60-20-20 %, which is arbitrary but serves the exploratory purpose of this section. Table 12 gives an overview of the adapted criteria weights for the three different criteria weighting scenarios.

Table 12: Three criteria weighting systems.

	Economic (Original)	Environment	Water harvesting
ATTRIBUTES			
Erosion	0.23	0.6	0.2
Costs	0.65	0.2	0.2
Water harvesting	0.12	0.2	0.6
SUM	1	1	1
CRITERIA			
Catchment erosion	0.06	0.15	0.05
Road scouring	0.12	0.3	0.1
Gully formation	0.06	0.15	0.05
Total culvert costs	0.39	0.12	0.12
Road costs	0.25	0.08	0.08
Total harvested discharge	0.06	0.1	0.3
Costs of harvested water	0.06	0.1	0.3
SUM	1	1	1

Figures 47 till 49 show the alternative performance ranking of the road system scenarios. The performance ranking changes considerably when an alternative criteria weighting system is applied. It causes alterations in the total scores of road system scenario but also the rank order of the road system scenarios changes. Looking at the composition of the total road system scenario scores, the effect of the alternative weighting system can be clearly noticed in the magnitude of partial scores. The effect of culvert number on the total road system scenario score was analysed, but also does not show any trends, which might also be related to a lack of modelled scenarios per road alignment alternative.

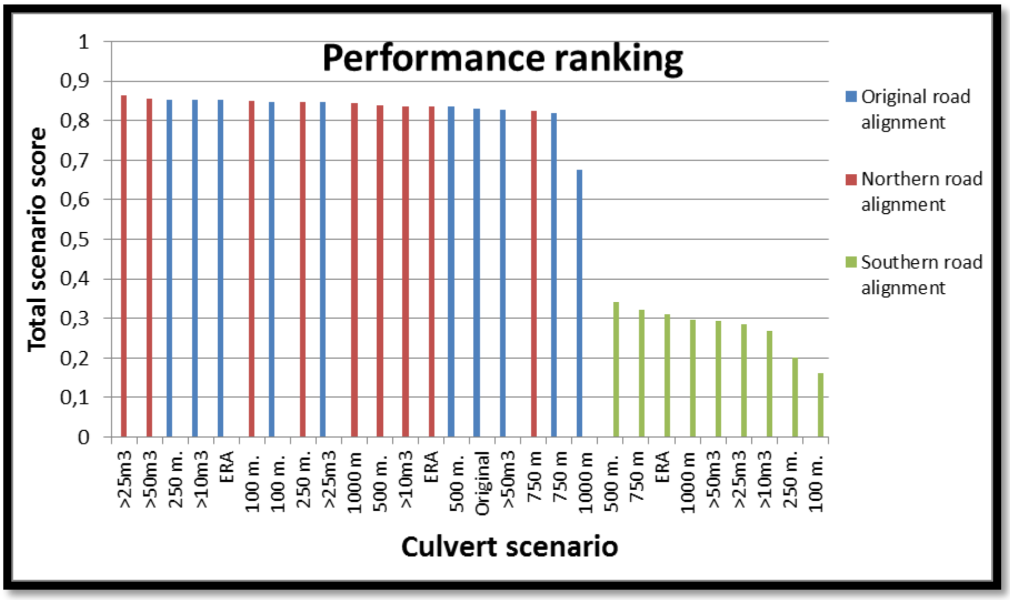


Figure 47: The overall performance ranking of all 28 road system scenarios, the road alignment alternatives are represented by the different colours.

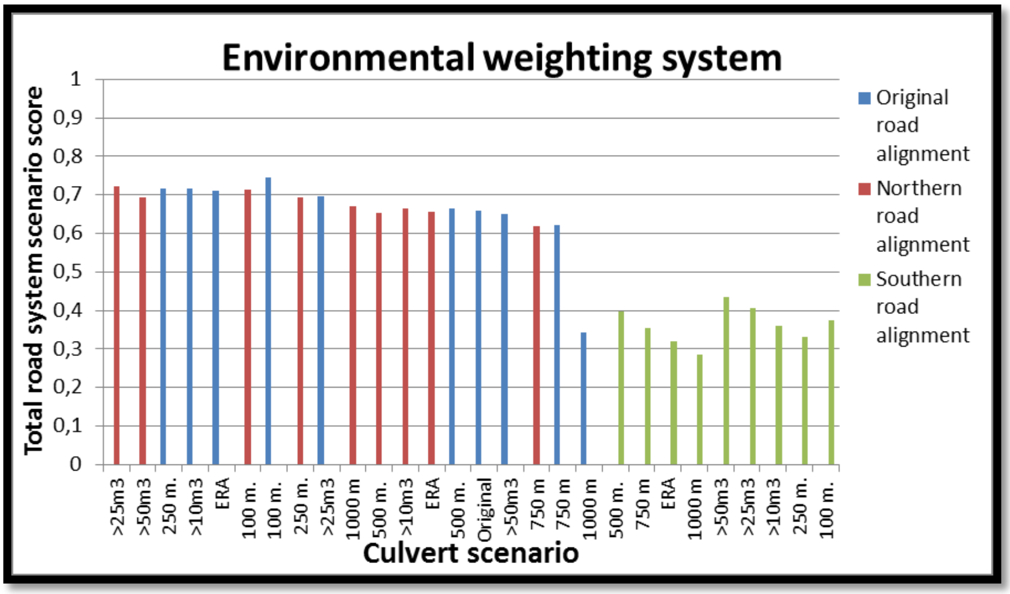


Figure 48: The original order of the culvert scenarios on the x-axis is maintained, The y-axis represents the total scenario scores resulting from the environmental criteria weighting system. The coloured bars represent the different alignment alternatives.

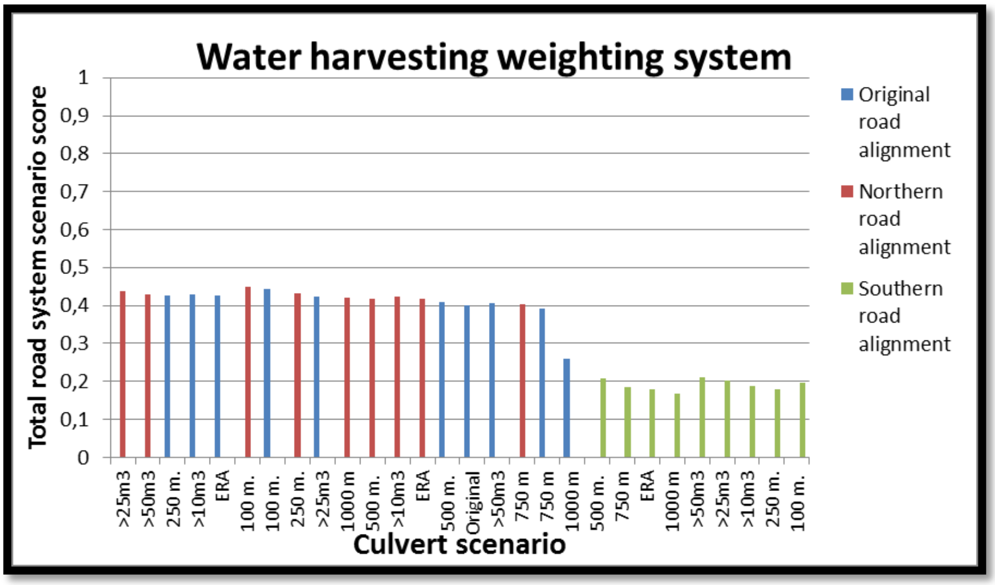


Figure 49: The original order of the culvert scenarios on the x-axis is maintained, The y-axis represents the total scenario scores resulting from the environmental criteria weighting system. The coloured bars represent the different alignment alternatives.

The road system scenarios following a southern road alignment still show the lowest scores for all alternative criteria weighting systems. Both alternative criteria weighting systems show similar alterations in the rank order of the scenarios following a southern alignment. The road system scenarios with a southern alignment and culverts positioned based on natural drainage patterns show an increased performance when costs are less emphasised. The alterations for the ranking of scenarios following either a northern or original alignment do not facilitate an easy interpretation, The range of the initial scores is quite small, which causes significant changes in performance ranking due to small changes in partial scores because of a different weighting system.

7.5.3 Summary

The constructed MCA showed that the road systems following the northern road alignment and having a culvert installed at all locations where the natural discharge shows a larger value than 25 m^3/hour. The scenarios following a southern road alignment show significant lower scores. Studying the applied criteria weighting system of the MCA, one can conclude that the constructed MCA is very sensitive and not well balanced towards its formulated indicators. The cost objective has a too high significance in the total analysis. No clear patterns in overall performance for road alignment, culvert number per scenario or culvert positioning technique could be obtained. The scenarios following a southern road alignment also show a significant lower ranking for all alternative criteria weighting systems. Alterations in the total scores or scenario ranking because of a different weighting system do not facilitate a fair interpretation.

7.6 Potential for water harvesting

This section presents the estimates for food production of the best performing scenarios, by using a FAO method on crop water needs. The assumptions of the calculations and regional context were described in section 6.6.

The 1st of September is assumed to be the onset of a new crop cycle and the date of planting the barley. The total growing period is 150 days, the different growth stages and standard crop factors are described in the table 13. The months September, October and December cover two different growth stages, a monthly average needs to be is therefore calculated.

Table 13: Growth phases of Barley and crop factors.

Planting date	**Sep 1st**	**Kc**
Initial stage, 15 days.	Sep 1st – Sep 15th	0.25
Development stage, 30 days	Sep 16th – Oct 16th	0.75
Mid-season stage, 65 days	Oct 17th – Dec 21th	1.2
Late season stage, 40 days	Dec 22st – Jan 31st	0.25

All parameters needed for the estimation of total crop water requirement were collected and determined. Table 14 presents the most important parameters, a complete overview of all parameters is enclosed in appendix D. The annual patterns for temperature, rainfall and evapotranspiration are given. The calculated crop factors for the different growth stages and the final crop water needs for a complete barley cycle during this period of the year. The total water need of completing the total growing period barley after the main rainy season requires 232.4 millimetres of water.

Table 14: Parameter overview for crop water needs.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
P (mm)	0.5	1.5	9.8	30.6	19.6	53.8	214.4	272	23.1	5.7	0.5	0.9	632.4
Kc_{ini} final	0.25	0.25	0.25	0.15	0.15	0.20	1.05	1.05	0.25	0.25	0.25	0.25	
Kc_{dev}	0.75	0.75	0.75	0.7	0.7	0.7	1.15	1.15	0.75	0.75	0.75	0.75	
Kc_{mid}	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	
Kc_{end}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
Kc_{avg}	0.25								0.5	0.97	1.2	0.89	
ET_{crop} (mm)	15								35.8	62.5	70	49.1	232.4

It was assumed that the total water need of barley can be simplified to 21 standard modelling events which cover a high intensity daily rainfall event of 30 millimetres, which was also used for the modelling of all scenarios (Nyssen et al, 2005).

In order to compensate for factors like evaporation of stored water, transport losses, storage leaking, a safety factor was incorporated in the estimations. This safety factor also incorporates the fact that harvested discharge can actually not be used due to the presence of topographic barriers, that harvested water is located too far from the area of purpose but also for the fact that not all water can be harvested during high intensity rainfall events. In the calculation of the safety factors it was assumed that only 10 % of the harvested water can finally be used as supplemental irrigation. This is highly arbitrary but a conventional estimate based on an expert guess.

Several characteristics from the region can be used to set this rough estimate in a perspective. The survey executed by MetaMeta along the pilot route showed that the region has a population of 236,486, counting a total of 49,574 households. About 34,911 hectares is cultivated land, of which about only 1800 hectares is irrigated. The average yield per hectare was estimated to be 1310 kg/ha. (Steenbergen et al, 2014). An article by Edwards et al (FAO, 2007) made specific estimates for barley yield averages in Tigray, their obtained values are compatible with the values described by Steenbergen et al (2014). Still this productivity is about half of the world average (Mulatu and Grando, 2011). The annual consumption of barley for the Tigray region counts about 60% of the annual calorie intake (Maaza and Lakech, 1996). Average daily calorie intake is approximately 2100 kcal/capita/day, although 40% of the population falls below this daily average (Kahsay, 2014). The calorie content of barley is about 354 kcal/100 gr. (USDA, 2015). Using the nutrition statistics for the Tigray region and the calorie content of barley, one can make an estimation of the annual barley consumption per capita. This results in an annual barley consumption of 129.9 kg/capita/year. The estimates serve as an indication on the magnitude of this potential, not as a reliable estimate on the added value.

Table 15: Estimation of increased food production using discharge harvested by culverts.

	• Extra irrigated area (ha.) • Increase in regional irrigated area (%)	• Barley yield (tonnes) • kg. barley/pp.	Costs of produced barley using modelled costs (euro/kg.)
Scenario: Northern alignment + culvert >25m^3	• 1889 • 105%	• 2475 • 10.5	2.30
Scenario: Northern alignment + culvert >50m^3	• 1870 • 104%	• 2450 • 10.4	2.30
Scenario: Original alignment + fixed culvert interval 250 m.	• 2871 • 160%	• 3761 • 15.9	6.40
Scenario: Original alignment + culvert >10m^3	• 3318 • 184%	• 4347 • 18.4	5.78
Scenario: Original alignment + ERA guidelines	• 3097 • 171%	• 4044 • 17.1	6.1
Scenario: Northern alignment + Culvert interval 100 m.	• 5772 • 320%	• 7561 • 32.0	3.26
Scenario: Current road system	• 2450 • 136%	• 3210 • 13.6	7.35

The table shows the result of the food production estimate for the five best performing road system scenarios and the current road system. The first column shows the increase in irrigated surface area, both in hectares and as a fraction of the current surface area under supplemental irrigation. The second columns shows the barley yield in absolute weight and per capita. The last column represents a cost estimation of the cultivated barley, based on the modelled costs of the particular road system scenario. The potential of integrating road water harvesting practises into road system design for supplemental irrigation is considerable when looking at the rough estimates of increased food production given in table 15. The table will be interpreted in the section on result interpretation (8.3).

8 DISCUSSION

This study was of an explorative character, a model was constructed to study road design parameters on a catchment scale by executing a scenario study. Several remarks can be made about the methods used, the performance of the constructed model, its assumptions and the quality of the used input data. The results will be interpreted by following the formulated research questions. Several recommendations are given for future work.

8.1 Model performance and assumptions

8.1.1 Irregularities in estimation of the variable on net deposition

The variables representing deposition and detachment reveal extreme values for several individual cells, which results in irregularities in the calculation of the variable representing net deposition. The estimated transport capacity shows a negative value at these fixed specific locations and the detachment rate is unrealistically high. The irregularities in the estimation of net deposition were notified during preliminary model runs and could not be solved at that moment. In alignment with the explorative purpose of this study, the erosion objective for road system was described by an indicator of a relative character to enable a comparison of scenarios on their erosion performance and surmount the irregularities, this was more elaborately described chapter 6.

The transport capacity for individual cells is calculated by the following model component:

$$T_c = 2650 * c * (VS100 - 0.4)^d$$

$T_c =$ Volumetric transport capacity $\left(\frac{kg}{m^3}\right)$; $d_s =$ material density $\left(\frac{kg}{m^3}\right)$, 2650; $c =$ coefficient $(-)$;

$w =$ Stream power $\left(\frac{\text{cm}}{\text{s}}\right)$ (calculated as flow velocity $*$ energy slope); $w_c =$ Critical stream power $\left(\frac{\text{cm}}{\text{s}}\right)$, 0.4;

$d =$ coefficient $(-)$.

A negative value must be the result from a very low modelled value for local velocity, the other values are of a constant character. The detachment rate caused by runoff is integrated to the model in the following way:

$$H = Z * Q^{1.5} \sin S(1\text{-}GC) *10^{-3}$$

H = Soil detachment (kg/m^2); Z = constant (-); Q = runoff (mm); S = slope$(-)$; GC = Total ground cover $(-)$

The applied equation reveals that extreme values do occur when the runoff tends to get really high, because the calculated sinus of the local slope component cannot cause such a significant difference in modelled detachment rates. The extreme values could not be clarified through the evaluation of resulting map material, the slope, discharge and velocity map all seem consistent at these locations. No inconsistencies in the used DEM or local drainage direction map could be found. These extreme values could not be clarified during this study but might cause the estimation of sediment transport at these locations (and overall catchment) to be unreliable. Appendix F encloses two PCRaster maps showing the event.

8.1.2 Other studies on sediment loss on a catchment scale…

The applied indicators in the model to describe relative differences between the formulated road system scenarios, do not enable a direct comparison with similar runoff erosion models on their performance in the prediction of actual runoff and soil loss. A post-hoc analysis can be done on model performance by analysing two variables representing the lateral flux of sediments and runoff at the outlet of the catchment. The current road system scenario is evaluated for both variables at the main catchment outlet applying the standard model event (30 mm/hr.):

- Total catchment surface area: $1.41 \cdot 10^4$ hectares.
- Total runoff at catchment outlet: $3.1 \cdot 10^6$ cubic meters.
- Total sediment yield at catchment outlet: $3.0 \cdot 10^5$ tonnes of sediment.

This results in relative values for runoff of 2.1 m^3/ha. and sediment loss of 214.1 tonnes/ha. It is assumed that the standard modelled event is representative and can be converted to an annual average. The sensitivity of the annual averages towards the characteristics of the standard event is roughly tested and summarised in table enclosed in appendix E. Annual patterns of rainfall event intensity are different, based on the elaborate field work on rainfall patterns by Nyssen et al (2005), an 'adapted' event is constructed based on the study of Nyssen et al (2005) on the occurrence of rainfall intensities by a combination of standard events, this was supposed to be more align with the annual rainfall patterns described in this study. The results show a very large range for the estimates on catchment soil loss of 300-$1.7 \cdot 10^6$ tonnes/ha/yr.

Several studies have been done on the estimation of soil loss for the Ethiopian highlands. A general annual soil loss rate for the Ethiopian Highlands was found to be between 200-300 tonnes/ha/yr. (Hurni, 1993). Most studies describe average annual sediment yields for much smaller catchments. Smaller test plots showed increased values of 130 to 170 tonnes/ha./yr. (Hurni, Herweg, Portner, and Liniger, 2008). Soil losses from eroded cultivated fields showed lower values of about 42 tonnes/ha./yr. Analysing a single catchment in the central Tigray region (May zeg-zeg catchment,187 ha.) by Nyssen et al (2009), resulted in a much lower value of 14.3 tonnes/ha./yr. Higher rates were found by Tamene and Vlek (2008), after studying multiple catchments in Tigray, ranging from 3.5 till 50 tonnes/ha./yr. No event based studies on catchment soil loss could be found for the Tigray region.

Comparing these values to the estimates on soil loss obtained in this study shows a large discrepancy, the modelled values in this study are much larger. The assumption of averaging a representative or several rainfall events to obtain a total annual value seems non-valid. Also, increasing the fixed catchment variable representing vegetated cover fraction does not result in very different results. Studies for different catchments are difficult to compare because runoff and erosion processes are non-linear, depend on a large range of local factors and are scale dependent. In general, this causes complications for the estimation of reliable runoff and soil losses at catchment scale. This model excludes the potential influence of local zones where the saturated conductivity might be much lower or micro depressions in elevation do occur, the hydrological connectivity decreases due to these zones as well does area specific runoff and sediment yield (Lesschen et al, 2009). This study describes a very large catchment ($1.41 \cdot 10^4$ hectares) compared to similar runoff erosion studies which often do not have a size larger than 200 hectares, this was decided in order to evaluate a larger and complete road system. This study averaged soil characteristics and cover parameters over larger areas, the original DEM has a resolution of 30 meters which all do not facilitate a fair representation of these local features and thereby influence the modelling results for runoff and erosion.

8.1.3 Discharge and the road system

There are two big shortcomings in the constructed model, which could not be compensated for during this research but make its appropriateness for the purpose of an evaluation or potential planning tool questionable. Both will be briefly described and the consequences for the behaviour of formulated indicators and model outcomes addressed.

This research aimed at the integration of culvert capacity by using the PCRaster software, but did not succeed in formulating such a model component. The integration of a maximum culvert capacity would enable a better integration of the concept of discharge spreading, thereby reduce runoff energy and related processes like e.g. erosion. This would give a much better representation of road system impact on runoff an erosion patterns. If the PCRaster software facilitates the integration of the concept of culvert capacity, it needs to be evaluated through the dynamic modelling of an event which was out of scope for this research. Culvert capacity is depending on the actual upstream headwater depth of the culvert during an event, this cannot be averaged based on coarse hourly averages. An attempt of dynamic modelling would however also enable the integration of the concept of road overtopping, which is one of the surveyed problems along the current roads (Demenge et al, 2014).

No PCRaster function or combination of functions could be developed to describe a maximum discharge for an individual cell, after which it discharges the surplus volumes into a next downstream cell. However, PCRaster provides threshold operators which can allow a particular amount to pass after which the remaining flux is stored in the discharging cells. A first attempt was made to determine maximum capacity (based on the initial formula described in section 6.3.8) for all culverts based on a range of normal diameters (0.5-2.5 meters), the modelled discharge values turned out to be very small and store the majority of the discharge in the cell. This raised questions about the faith of the stored discharge in the cell. Normally this would overtop the road, damage the culvert and cause erosion. The model does not facilitate an interpretation of these latter events, therefore a different approach was chosen which was assumed to be a solid and relative measure in the comparison of different culvert scenarios. Currently, the cells representing culvert locations do always have a large enough diameter to enable unlimited discharge. Culvert scenarios are evaluated based on (proxy) indicators like total culvert costs and harvested discharge instead of actual performance of culvert conveyance.

During the formulation of the road alignment scenarios it was expected that a single alignment would capture a more or less constant volume of water from the upstream side of the road, based on the assumption that the upstream area of the road alignment would be constant for the whole range of formulated culvert positioning scenarios and the road system scenarios would compensate for the major streams encountering the road by fixing culverts. This constant captured volume would enable a fair comparison in performance of the different formulated culvert scenarios for a particular road alignment. As previously addressed in section 7.4.2, the model outcomes show large differences in the amount of harvested discharge volume through culverts because of discharge getting cross-drained multiple times along the road system, this makes both indicators for water harvesting unusable. For the simple reason that water can only be harvested once at a culvert outlet.

8.1.4 Model indicators

All indicators were formulated with the aim of describing relative differences between road system scenarios on a catchment scale to enable a distinguishing on overall performance. No previous and comparable analysis, tool or study could be found, the formulation of indicators should be evaluated as a first attempt and evaluated on their appropriateness and potential improvement. Several indicators will be briefly evaluated.

Total catchment erosion and road scouring

Total catchment erosion and road scouring were described by a summated value of all cells showing a negative value for net deposition, thereby excluding the insurmountable irregularities found in the representation of transport capacity, encountered during the preliminary model runs. The final indicator represents the erosion objective by a summation of all cells showing soil loss but thereby excluding the potential alterations in deposition patterns caused by the road system. It does not describe actual erosion magnitude but seems to capture an effect caused by different alignment options, road alignments with a larger upstream area are faced with an increased erosive energy along the road side due to larger runoff volumes getting blocked by the road system which causes the magnitude of total soil loss to increase. The indicator showing total catchment surface by giving the fraction of all cells in the catchment showing a negative value for net deposition, does not show any response to differences between road system scenarios. Its appropriateness in presenting relative differences between road systems is therefore questionable. The indicators for road scouring follow the same reasoning, but thereby focus on the predefined road zone as described in chapter 6. The total road scouring indicator seems to respond strongly to the formulated road alignment options, which supports the hypothesis of an increased impact through increased volumes along the road side. The appropriateness of the second indicator representing fractional area undergoing road scouring is questionable, it does not show a clear response towards changing scenarios.

Gully formation

A total CTI score for the catchment was set as indicator for the representation of the gully formation risk under different road system scenarios. It was assumed to change according to the occurrence and degree of processes like diversion and sub sequential concentration of runoff due to road system presence and its design. More concentrated runoff at locations with steep concave slopes result in higher CTI scores. The CTI scores seem of a random character and no real patterns can be noticed between culvert scenarios. The impact of the road system seems too little to show any significant difference at catchment scale. For the computation of the CTI score, several remarks can be made. The effect of raster resolution on terrain attributes was described by Thompson et al (2001). It was found that a decreasing raster resolution resulted in lower slope gradients on steeper slope and vice versa. A decreased DEM resolution also caused narrower ranges in calculated curvatures, which has an effect on the calculation of the CTI score. Also Parker et al (2008) showed that grid resolution is an important factor for a good representation of gully development, they concluded that prediction of gullies strongly decreases with DEM resolutions larger than 10 meter. The use of the resampled DEM in the calculation of the CTI score (slope, planform curvature and discharge map), might result in an averaging of topographic extremes, which might cover up the actual risk differences between road system scenarios. For a good integration of gully formation (risk) caused by road system presence, this indicator needs to be further refined or improved. It is recommended to focus on just the vicinity of the road, which was attempted unsuccessfully for this study.

Costs

The cost aspect per scenario was addressed by two indicators describing relative differences between road system scenarios. The determination of total culvert costs was based on an estimation of a minimum diameter per installed culvert and a cost curve. While keeping the purpose of formulating a relative measure for scenario comparison, it was assumed that the ratio between upstream headwater height and culvert diameter always equals one, thereby enabling to solve the equation for the variable culvert diameter. This is highly arbitrary off course. The diameter was calculated based on the modelled discharge values through cells representing a culvert location, which is unlimited due to a lack of the possibility to integrate culvert capacity into the model. The indicator reveals extreme differences between road alignment options, which is caused by the very high values for modelled discharges through the cells representing a culvert. The estimated minimum diameters were used to calculate actual costs based on an exponential cost curve explained chapter 6. The indicator can be refined through updating the cost curve and making it less sensitive for culvert diameter, in order to show a more balanced evaluation of costs between the different scenarios. Using the road length indicator as a proxy for costs seems a reasonable assumption but can also be further worked out.

Water harvesting representation

The formulated indicators have been proven unusable because of the occasion described in chapter 7. Evaluating this indicator at every individual culvert causes water harvesting potential to be addressed multiple times at different culvert locations. Water harvesting is a concept which includes a lot of different aspects, during this research it turned out to be difficult to conceptualise this into a reliable indicator. The total harvested volume through culverts does not capture anything related to the quality of the water through culverts, one can think (among other reasons) that the harvested water can be dislocated from the area of demand or have a too high energy caused by high volumes or flow velocities. Future research can try to formulate an improved indicator which represents a more complete picture of water harvesting to compare different road systems on their performance. This improved indicator needs to include processes related to culvert capacity and spreading, which are not integrated in this model for reasons mentioned before.

8.2 Input data

8.2.1 DEM

The DEM used in this study has a relative coarse resolution (30 m.) compared to the purpose of this study. The landscape of the catchment is characterised by sometimes significant local elevation differences, which are averaged to a cell size of 30x30m. The model resamples and interpolates the initial DEM to a 10 meter resolution using a 30 meter window. It was believed that this will improve the level of detail for several model input maps (e.g. local drainage direction map or slope map) and enable an improved representation of the road system on the DEM raster. However, the resampling most probably also cause the neglecting or *smoothening* of natural topographic features and is quite arbitrary. The effects of a decreasing spatial resolution of a DEM and effects on topographic attributes was described by Thompson et al (2001). The resampled DEM is used as a base for the modelling of small scale processes or features at a much larger scale then they do normally occur (e.g. cross draining through culverts or the representation of a road surface). The modelling of processes which do naturally occur on a scale of only several square meters are after resampling represented by cell sizes of a 100 square meter, which is questionable. The appropriateness of scale representation can be verified by an eventual validation of the model, by using actual field measurements on rainfall and culvert discharges.

The DEM was used in the formulation of road system scenarios, it provided slope maps for the determination of suitable road alignments and the actual culvert positions by following the ERA guidelines. The formulation of road system scenarios based on the applied DEM might have caused the disqualification of potential locations.

8.2.2 Formulation of road system scenarios

The study is of an explorative character, which also holds for the formulation of road system scenarios (as described in chapter 6) The road alignment options were based on design guidelines from the ERA, which prescribed best practises on future road alignment in their design manuals (^{1}ERA, 2011). Alternative routes were formulated to investigate the impact of road alignment and were based on e.g. the occurrence of existing tracks or trails and maximum slope values, a northern (general higher elevation) and southern alternative (general lower elevation) were formulated. These formulated preconditions might not have been the most suitable when aiming at studying the potential alterations in both runoff and erosion magnitude and patterns caused by a road system. The aspect of upstream area from the particular road system determines to a large extent the modelled runoff volumes blocked by the road system, but is not incorporated or used as a base in the formulation of alignment scenarios.

The determination of culvert locations was based on a set of assumptions and placement rules which are arbitrary but were deemed necessary because applicable guidelines for culvert positioning along a road system were lacking. A good example is that major streams discharging the catchment were set as fixed culvert locations for all road system scenarios and used as a reference point, to determine the following culvert positions based on the pre-defined positioning interval. It is deemed important to address the arbitrary character of this formulation procedure. The road system scenarios are constructed on a manual base as was described in chapter 6, this might have entailed errors and is a very labour-intensive process. The culvert scenarios were visually checked upon inconsistencies after construction, but might have still contained faults or be inconsistent when road system scenarios are combined.

8.2.3 Input parameters

A number of input parameters are set as standard values over the whole catchment which neglects local attributes (e.g. vegetative cover and soil porosity), most parameters values are based on the values related to soil texture class given by Morgan (2001). Several input parameters are based on the soil map are also of coarse quality. The standard rainfall event was set to be 30 mm/hr. based on the elaborate field work by Nyssen et al (2005), thereby being align with the time step of one hour. The majority of the events actually show much lower intensities over a shorter period. However, for the explorative character and research purpose of comparing different road systems it does not matter, which focusses on relative differences between scenarios.

8.3 Result interpretation

The model outcomes in section 7.1.1 showed that the current road system causes an increase in the indicators representing total catchment erosion and fractional eroded catchment surface, when compared to the situation of road absence. The modelled map material indicated clear alterations in natural drainage patterns caused by the current road system. The model results showed that flow lengths tend to increase on the upstream side of the road, streams merge due to a lack of cross drainage possibilities which cause discharge to be more concentrated when finally drained at culvert outlets. The eroded surface area shows a small increase under the presence of the current road system and strongly correspond to the modelled alterations in discharge patterns. The map material revealed that some installed culverts along the current road system barely drain discharge, which suggests a potential for improved culvert design. This poses questions about the reliability of the modelled discharge patterns, one might fairly expect that the current installed culverts will drain at least some of the runoff instead of none. The impact of the DEM quality on actual patterns representation might be considerable, this was elaborately described in section 8.2.1. Topographic features within a cell area get averaged over the cell surface. Resampling to a smaller cell size and subsequent interpolation might create a topographic surface which is quite different compared to the actual natural topography. The general modelled runoff patterns can be predicted and used for a further interpretation, but the representations for a smaller scale are unreliable with the current used input data (e.g. culvert locations).

The model outcomes of the 28 formulated road system scenarios showed clear differences regarding the formulated indicators for a particular road alignment. The indicators representing harvested water through culverts, total road scouring and total culvert costs are significantly higher for the southern alignment alternative. The influence of road alignment is obvious when one observes the differences in these indicators values and was supported by the applied statistics. The effect of road alignment seems to be strongly related to the contributing catchment size. The upstream area of the road determines to a large extent the energy of the runoff (higher volumes) which results in increased scores for the scenarios following the southern alignment. The differences between the northern and original alignment are not as obvious, which is most probably related to a more or less equal size of the contributing catchment. The catchment erosion criterion and road scouring criterion apply the same definition for 'erosion'[3], but do not show an equal response to the factor of road alignment. Focussing on just the vicinity of the road (road zone), one can observe considerable changes in the lateral flux of sediments, caused by concentrated discharge along the road system which changes for the particular road alignment. At a catchment scale this difference is not as obvious, an increased lateral flux because of alterations in hydrology patterns is probably compensated with a process of increased deposition at other locations. The remaining indicators do not show any patterns related to the factor of road alignment. The lack of patterns for these indicators might also be clarified by their actual appropriateness, which was discussed in section 8.1.4. referring to e.g. the gully formation criterion.

The impact of the number of culverts per road system scenario was expected to play a role in the ability of spreading runoff among all installed culverts of a road system scenarios, thereby reducing the magnitude of the erosion process due to less concentrated discharge volumes. Analysing the indicator values on the culvert positioning technique applied or the number of culverts per particular road system scenario, showed a pattern related to one common event among alignment options. Total harvested discharge through culverts and road scouring showed increased values for the road system scenarios with a higher number of installed culverts or for the road system scenarios having their culverts positioned based on the natural discharge patterns. This can be clarified by the fact that both facilitate in an increased number of cross-draining opportunities along the road, which was shown in section 7.4.2. The total harvested discharge through culverts increases (so does the road scouring indicator) because discharge gets cross-drained forth and back to the other side of the road. Thus, multiple culverts count the same discharge for water harvesting which can actually only be applied once. The decreased catchment surface area undergoing 'erosion' can be clarified by the same mechanism, a road system with more cross-draining opportunities causes less disturbances and diversion to occur along the road which reduces the total number of cells over the catchment undergoing a net lateral flux of sediment. This decreasing trend for total catchment surface area undergoing erosion does not hold for the culvert positioning scenarios, the scenarios with their culverts located align with natural drainage patterns do not show lower indicator values. No obvious patterns could be found for the remaining indicator values related to the culvert number or positioning technique of a particular road system scenario, which was unexpected. This suggests that culvert positioning does not really affect hydrology and erosion patterns. However, the discovered event reveals that the indicator representing the water harvesting through culverts criterion needs to be updated or formulated differently, before it is able to sufficiently represent its actual objective. Also taking into account that other indicators are based on the total water harvesting through culverts criterion (e.g. total culvert costs). It might be that the formulated indicators can present general differences between alignment options but are actually not able to facilitate a sufficient distinguishing between the different culvert scenarios because of the described event.

The MCA performance ranking revealed that the best performing road system scenario is covered by the road system following the northern road alignment and having a culvert installed based on the modelled patterns of the natural drainage (>25 m^3/hr.). Several remarks can be made about the constructed MCA. The application of the MCA should be evaluated as an attempt in the development of a method for the evaluation of modelling a set of potential road system scenarios, it is believed that it can be sufficient for this purpose. The formulated criteria might not fully address or capture all aspects related to rural road performance, especially the water harvesting potential and cost objective currently seem weak. Both erosion criteria have been divided into two indicators, which

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[3] Erosion was defined in chapter 6 as all cells showing a negative value for net deposition and therefore a lateral flux of sediments.

was done because the model's behaviour was not well known yet. However, both the indicators showing fractional surface area undergoing erosion and the indicator representing gully formation risk at culvert locations need to be reconsidered or removed from the MCA, they did not proof to capture real differences between the scenarios. The MCA is however fully depending on its input data, which are the modelled outcomes for the defined indicators. When the model's performance will be improved, the MCA method can be a sufficient method in the evaluation of a set of formulated road system scenarios. Moreover, the applied criteria weighting system is fully based on the researchers' perspective which is arbitrary, it is not proven by any other stakeholder. Reconsidering the criteria might result in the formulation of different or more aspects related to road performance. An actual application requires a reconsideration of both the formulated criteria and the applied weighting system.

The best performing scenarios were analysed by a rough estimation of their contribution to local food production. The results revealed that integrating water harvesting practises into road design can provide a substantial contribution in annual food demand for the studied region. Especially when one considers that this is additional production after the main rainy season which currently restricts majority of the agriculture which is of a rain fed character (Steenbergen et al, 2014). The increased food production is, except of general investments (seeds and logistics), for free, culvert investments need to be made under all road designs. The estimates show that all scenarios enable at least a doubling of the current cultivated irrigated area and can serve a significant part of the annual barley consumption per capita of 129.9 kilograms. The calculated costs of resulting barley prices are based on the total culvert costs per road system scenario and show a range of approximately 2-7 euro/kg.. The actual market prices for Barley are much lower, retail prices were found to be 750 USD per ton (Tefera, 2015), which equals about 0.70 euro per kilogram. However, the indicator gives an impression of the relative costs of the estimated production between the different road system scenarios. The reference data used for the estimates do cover a region which is larger than the modelled catchment (e.g. population, current irrigated area), the calculated potential is therefore more significant. It is important to note that the applied safety factor (10%) is highly arbitrary and the input data from indicator values questionable as addressed before (total harvested discharge and culvert costs). Also the water harvesting objective does not sufficiently address the overall concept of water harvesting (no quality aspect integrated).

A complete answer to the main research question could not be formulated during this research. The different aspects of road design (covered by the sub-research questions) did not show clear enough patterns or trends between the formulated road system scenarios, which would have allowed for a formulation of concrete guidelines. However, based on the modelling study several important conclusions could be drawn concerning an improved design of rural roads. Road alignment turns out to be of much more importance in road system design performance compared to the culvert positioning technique applied in this research. The road alignment is strongly related to the contributing catchment size, the upstream area of the road determines to a large extent the energy of the runoff along the road system and thereby the balance between potential magnitude of road scouring and harvested runoff volume. This supports the step-wise design approach applied during this research, determining road alignment first after which an optimal culvert scenario can be formulated. The potential of a further integration of water harvesting into future design was revealed by the estimation on increased regional food production, it showed large potential including a cost indication of the cultivated yields. The most important contribution of this research towards improved rural road design is the newly developed method for road design analysis on a catchment scale, the integration of both process based modelling and post-hoc analysis by a MCA has a potential for further investigation and eventual extension when the addressed model shortcomings are solved or compensated. This research followed a phased planning approach for road systems on a catchment scale, a range of different road system scenarios were formulated according to certain agreed preconditions. The range of scenarios were analysed by the means of process-based modelling, which provide much information on hydrology and erosion on both small and larger scales. The set of alternatives is evaluated using a Multi Criteria Analysis in which a range of aspects can be accounted for and balanced towards a final road system design. The application of a MCA enables a post-hoc analysis in which the weighting system can be changed according to the decision maker, the method also facilitates new objectives to be integrated or old ones removed when necessary.

The formulation of actual concrete guidelines was difficult because obvious patterns or trends in road system aspects between different road system scenarios could not be found. This might be caused by two important causes which were identified during the modelling process. The most important aspect turned out to be the insufficient performance of the formulated indicators, the current indicators do not capture the full objectives of improved rural road design as formulated in the method chapter (section 6.5). The indicators representing the process of erosion do not represent actual erosion, but neglect the occurrence of deposition (for reasons mentioned in sections 6.5.3 & 8.1.4). The indicator representing harvested discharge through culverts turned out to be unreliable because of the process of discharge being cross-drained multiple times, even though it was expected to be addressed in the formulation of road system scenarios (section 6.2.3). This indicator forms the base for other indicators, e.g. total culvert costs. The gully formation risk indicator is based on the CTI (Compound Topographic Index) score which did not seem to address gully formation risk sufficiently, mainly caused by the coarse quality of the DEM. The DEM quality is the other major aspect which obstructs the drawing of general conclusions based on model outcomes. The modelling process showed that the estimation of discharge patterns is questionable focussing on a smaller scale of e.g. a single culvert locations. The influence of the initial DEM quality and its sub sequent processing (resampling) is considerable, it results in the representation of rather coarse and unreliable discharge patterns and their alterations under a changing road system design. Several of the mentioned aspects are addressed in formulating recommendations for future work.

8.4 Recommendations

This study revealed several aspects which can contribute to an improved models' performance and evaluation of the road system scenarios, several basic recommendations could be formulated:

- The encountered problems in the representation of transport capacity and resulting estimate of net deposition need to be solved. This would enable the evaluation of the road system on its actual erosion magnitude, instead of the applied indicator in this study. The alterations in total catchment erosion would also enable a comparison with similar studies on catchment sediment yield and transport, thereby give a fair indication of the actual model's performance in representing sediment transport.
- This research showed that the indicators in this research do not sufficiently evaluate the road system performance between different road system scenarios, either because of low quality input data or wrong assumptions made during the formulation of indicators. One can try to reformulate the indicators used in this research, especially the water harvesting potential indicator needs to be reconsidered. Improving the representation of the objectives by improved indicators would enable a better evaluation of a range of different road system designs and the usefulness of the results by the Multi Criteria Analysis.
- The current model needs to be tested for a different catchment. It is recommended to analyse a road system in a much smaller catchment than is covered by this research. The changes in indicator values might be more obvious when a smaller catchment is evaluated. Preferably a smaller catchment is selected, for which a high quality DEM is available. The latter would increase the models' performance in its representation of the small scale processes dealt with in this research (e.g. culvert discharge or diversion of runoff along the road side).

- The final recommendation is the potential application of dynamic modelling in the evaluation of road systems. Dynamic modelling might enable an improved integration of culvert capacity, the integration of road overtopping or waterlogging at culvert locations showing an insufficient capacity. However, no event data could be found during this study. A proxy event could be a good start to test for potentialities. It is important that first model's performance needs to be improved following the aspects previously mentioned.

9 Conclusions

This research developed an adjusted Morgan, Morgan and Finney model in a PCRaster environment, in order to evaluate and potentially improve rural road system performance regarding erosion, costs and the potential of integrating water harvesting into rural road design. The results are based on findings of a catchment study in the Tigray region in Ethiopia, which was analysed through the formulation of a scenario study and developed Multi Criteria Analysis for evaluation purposes. The insights from the modelling study were expected to contribute towards a further formulation of improved rural road design concepts. This chapter describes the main conclusions that can be drawn from this research, it follows the main research question and sub-questions formulated in chapter 3. The main research question was formulated the following:

How can the design of rural road systems be improved regarding costs, erosion and the integration of water harvesting practises? Using the insights from a case study in the Tigray region, Ethiopia?

The most important contribution of this research towards improved rural road design is the newly developed method for road design analysis on a catchment scale, the integration of both process based modelling and post-hoc analysis by a MCA has a potential for further investigation and eventual extension when the addressed model shortcomings are solved or compensated. The developed model can provide much information on hydrology and erosion patterns on both small and larger scales. It enables an integration of a range of aspects with a different character towards a balanced design which includes a certain degree of flexibility by the adjustable criteria weighting system. Furthermore, the aspect of road alignment turns out to be of much more importance in road system design performance compared to the culvert positioning technique applied in this research.
Model improvement should focus on a reformulation of more adequate indicators and a better integration of the erosion objective.

The sub-research questions will be repeated after which they will be shortly answered:

- *How does the current road system affect the local hydrology and erosion pattern?*
- *What is the effect of road alignment on runoff and erosion patterns at the study site?*
- *What is the effect of the number of culverts and their positioning technique on runoff and erosion patterns at the study site?*
- *How can an optimal road system be developed for the selected study site using a Multi Criteria Analysis, regarding costs, erosion and water harvesting potential?*
- *What is the potential for the application of water harvesting practises at the study site under these optimal road system conditions?*

The model enables a general identification of alterations in discharge and erosion patterns, an analysis of the current road system showed processes of diversion of natural flow lines and enhanced concentration of discharge caused by road system presence. The model outcomes showed that the current road system causes an increase in the indicators representing total catchment erosion and fractional eroded catchment surface, when compared to the situation of road absence. Furthermore, the model revealed that current culvert positioning could be improved.

The evaluation of the impact of road alignment on overall road system performance showed clear differences for several indicator values (total harvested water through discharge, total road scouring and total culvert costs) for the road system scenarios following a southern alignment. These patterns were supported by the applied statistics. The effect of road alignment seems to be strongly related to the contributing catchment size. Evaluating the impact of culvert number and culvert positioning technique on road system performance did barely show differences between culvert scenarios, which was unexpected. Culvert positioning might not affect hydrology and erosion patterns, but the analysis also revealed an event which might impede actual patterns. Discharge is being cross-drained forth and back caused by an increased number of cross-draining opportunities for the road system scenarios with a higher number of installed culverts or culvert scenarios being align with natural discharge patterns. This causes the appropriateness of formulated indicators based on individual culvert locations to be questionable.

The MCA performance ranking revealed that the best performing road system scenario is covered by the road system following the northern road alignment and having a culvert installed based on the modelled patterns of the natural drainage (>25 m^3/hr.). The Multi Criteria Analysis was deemed to be an appropriate method for the evaluation of road system performance, even though its outcome showed high sensitivity to the developed weighting system and the formulated indicators.

A rough estimation on the enhanced food production enabled by integrating water harvesting practises into future road design, revealed a considerable extra potential and supports the aim of further improving the constructed model. The estimates the best performing road system scenarios enable at least a doubling of the current cultivated irrigated area and can serve a significant part (approximately 10-20 kg.) of the annual barley consumption per capita of 129.9 kilograms.

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Appendices

Appendix A: GPS coordinates

The enclosed table shows all located culverts and bridges along the surveyed pilot route (Teweldebrihan, 2014).

Table B.2 Records of GPS reading **GPS READING UTM**

Site	No		East	North	Elevation
Sinkata	1		561603	1553360	2396
Sinkata	2	Culvert	561558	1553227	2361
Sinkata	3	Culvert	558885	1551992	2305
Sinkata	4	Culvert	557865	1548990	2273
Sinkata	5	Culvert	557707	1548889	2280
Sinkata	6	Culvert	557253	1548602	2282
Sinkata	7	Culvert	556221	1548110	2276
Sinkata	8	Culvert	555925	1548084	2273
Sinkata	9	Culvert	555187	1548118	2271
Sinkata	10	Bridge	554113	1548383	2272
Sinkata	11	Culvert	554058	1548442	2275
Sinkata	12	Bridge	552911	1549172	2221
Sinkata	13	Culvert	551981	1548309	2239
Sinkata	14	Bridge	551639	1547948	2225
Sinkata	15	Culvert	551625	1547943	2225
Sinkata	16	Culvert	551479	1547892	2226
Sinkata	17	Bridge	551200	1547807	2231
Sinkata	18	Culvert	549766	1546772	2254
Sinkata	19	Bridge	548808	1546091	2261
Sinkata	20	Culvert	548547	1545945	2261
Sinkata	21	Culvert	547495	1545570	2266
Hawzen	22	Culvert	546548	1545371	2250
Hawzen	23	Bridge	546213	1544755	2225
Hawzen	24	Culvert	544269	1543565	2104
Hawzen	25	Bridge	543439	1543440	2095
Hawzen	26	Culvert	543598	1543212	2096
Hawzen	27	Culvert	542717	1542620	2090
Hawzen	28	Culvert	540772	1540990	2096
Hawzen	29	Culvert	540514	1540789	2090
Hawzen	30	Culvert	540256	1540315	2068
Hawzen	31	Culvert	541002	1539714	2050
Hawzen	32	Culvert	541152	1539484	2044
Hawzen	33	Culvert	541294	1539262	2036
Hawzen	34	Culvert	541524	1538903	2032
Hawzen	35	Irish Bridge	541819	1538790	2026
Hawzen	36	Culvert	542059	1538720	2029
Hawzen	37	Culvert	542147	1538522	2029
Hawzen	38	Culvert	542291	1538255	2024
Hawzen	39	Culvert	542429	1538209	2024
Hawzen	40	Culvert	542619	1538193	2025
Hawzen	41	Culvert	542836	1537996	2020

Hawzen	42	Culvert	543037	1537827	2017
Hawzen	43	Culvert	543277	1537628	2017
Hawzen	44	Culvert	543419	1537451	2017
Hawzen	45	Culvert	543659	1537060	2015
Hawzen	46	Bridge	543917	1536851	1993
Hawzen	47	Culvert	544028	1536854	1997
Hawzen	48	Culvert	544503	1536522	2044
Hawzen	49	Culvert	545015	1535886	2072
Hawzen	50	Culvert	545281	1535577	2069
Hawzen	51	BrIdge	545315	1535421	2070
Hawzen	52	Culvert	545632	1534813	2083
Hawzen	53	Culvert	545872	1534541	2095
Hawzen	54	Culvert	545920	1534351	2094
Hawzen	55	Culvert	545847	1534257	2103
Hawzen	56	Culvert	545963	1533827	2114
Hawzen	57	Culvert	547173	1533237	2143
Hawzen	58	Culvert	547993	1533013	2142
Hawzen	59	Culvert	548584	1532732	2134
Hawzen	60	Culvert	549049	1532428	2124
Hawzen	61	Culvert	549324	1532210	2118
Hawzen	62	Culvert	549838	1531656	2116
Hawzen	63	Culvert	549876	1531589	2117
Hawzen	64	Culvert	550126	1531497	2115
Hawzen	65	Culvert	550172	1531494	2113
Hawzen	66	Culvert	550253	1531487	2111
Hawzen	67	Culvert	550358	1531474	2110
Hawzen	68	Culvert	550608	1531487	2105
Hawzen	69	Culvert	551134	1531360	2100
Hawzen	70	Culvert	551598	1531325	2071
Hawzen	71	Culvert	551636	1531305	2069
Hawzen	72	Culvert	551768	1531151	2067
Hawzen	73	Culvert	552395	1531162	2039
Abraha wa Atsbeha	74	Culvert	552842	1531092	1997
Abraha wa Atsbeha	75	Culvert	552843	1531067	1999
Abraha wa Atsbeha	76	Culvert	553104	1531003	1996
Abraha wa Atsbeha	77	Culvert	553715	1530713	1988
Abraha wa Atsbeha	78	Culvert	554088	1530670	1985
Abraha wa Atsbeha	79	Culvert	554772	1530578	1983
Abraha wa Atsbeha	80	Culvert	555104	1530480	1978
Abraha wa Atsbeha	81	Bridge	555325	1530672	1961
Abraha wa Atsbeha	82	Culvert	555486	1530823	1962

Abraha wa Atsbeha	83	Culvert	555601	1530865	1965
Abraha wa Atsbeha	84	Culvert	555924	1530733	1978
Abraha wa Atsbeha	85	Culvert	556323	1530756	1982
Abraha wa Atsbeha	86	Culvert	556779	1530834	1987
Abraha wa Atsbeha	87	Culvert	557158	1530876	1996
Abraha wa Atsbeha	88	Bridge	557619	1530714	2006
Abraha wa Atsbeha	89	Culvert	564857	1525508	2056
Abraha wa Atsbeha	90	Culvert	564641	1525515	2052
Abraha wa Atsbeha	91	Irish Bridge	564406	1525579	2046
Abraha wa Atsbeha	92	Culvert	564055	1525638	2047
Abraha wa Atsbeha	93	Culvert	563678	1525495	2053
Abraha wa Atsbeha	94	Culvert	563392	1525421	2047
Abraha wa Atsbeha	95	Culvert	563015	1525455	2041
Abraha wa Atsbeha	96	Bridge	562876	1525695	2039
Abraha wa Atsbeha	97	Culvert	562620	1525914	2047
Abraha wa Atsbeha	98	Culvert	562534	1525984	2043
Abraha wa Atsbeha	99	Culvert	561947	1525997	2060
Abraha wa Atsbeha	100	Irish Bridge	561618	1526037	2073
Abraha wa Atsbeha	101	Culvert	561575	1526216	2070
Abraha wa Atsbeha	102	Culvert	561467	1526364	2071
Abraha wa Atsbeha	103	Culvert	561120	1526544	2087
Abraha wa Atsbeha	104	Culvert	560788	1526682	2100
Abraha wa Atsbeha	105	Culvert	560672	1526734	2102
Abraha wa Atsbeha	106	Culvert	560350	1526844	2123
Abraha wa Atsbeha	107	Culvert	560138	1526959	2138
Abraha wa	108	Culvert	559803	1527087	2151

Atsbeha					
Abraha wa Atsbeha	109	Culvert	559474	1527347	2182
Abraha wa Atsbeha	110	Culvert	558929	1527331	2178
Abraha wa Atsbeha	111	Culvert	558648	1527479	2149
Abraha wa Atsbeha	112	Culvert	558445	1527341	2124
Abraha wa Atsbeha	113	Culvert	558037	1527437	2060
Abraha wa Atsbeha	114	Bridge	558023	1527543	2058
Abraha wa Atsbeha	115	Culvert	557770	1527627	2066
Abraha wa Atsbeha	116	Culvert	557192	1527569	2063
Abraha wa Atsbeha	117	Culvert	556716	1527836	2075
Abraha wa Atsbeha	118	Culvert	556609	1528254	2042
Abraha wa Atsbeha	119	Bridge	556656	1528688	2005
Abraha wa Atsbeha	120	Culvert	556606	1528805	1998
Abraha wa Atsbeha	121	Culvert	556592	1528869	1996
Abraha wa Atsbeha	122	Culvert	556572	1529087	2001
Abraha wa Atsbeha	123	Culvert	556564	1529496	2000
Abraha wa Atsbeha	124	Culvert	556551	1529725	1990
Abraha wa Atsbeha	125	Culvert	556556	1529803	1989
Abraha wa Atsbeha	126	Culvert	556766	1530013	1999
Abraha wa Atsbeha	127	Culvert	556979	1530101	1998
Abraha wa Atsbeha	128	Culvert	557049	1530153	1999
Abraha wa Atsbeha	129	Culvert	557086	1530186	1997
Abraha wa Atsbeha	130	Culvert	557162	1530268	2000
Abraha wa Atsbeha	131	Culvert	557485	1530486	2012

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Appendix B: Monthly precipitation and temperature data for Hawzen station.

The four tables show monthly precipitation and temperature data for the meteorological station of Hawzen (Baert, 2010).

Hawzen	Average Minimum Temperature (°C)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2002	7.9	7.5	10.9	11.2	12.1	12.3	12.3	11.7	10.1	8.0	8.1	8.6	10.1
2003	6.8	8.8	11.5	11.6	12.8	11.8	12.6	12.9	10.4	8.4	7.8	6.0	10.1
2004	8.1	8.6	9.4	12.5	11.8	12.6	11.4	11.7	9.4	7.5	9.8	10.3	10.3
2005	10.9	12.4	13.9	9.5	9.8	10.0	10.7	9.3	8.2	5.8	5.6	2.9	9.1
2006	6.9	9.0	11.1	12.2	12.9	12.5	12.3	12.5	10.1	9.0	8.4	8.9	10.5
2007	8.4	10.0	10.3	12.5	13.0	12.8	12.5	13.6	9.9	6.9	6.8	3.9	10.1
2008	7.9	6.9	8.2	11.7	12.2	12.3	14.3	12.1	10.4	8.4	7.7	6.4	9.9
2009	7.1	9.1	11.1	11.7	12.6	13.5	11.9	12.6	10.6	10.0	7.8	9.1	10.6
2010	8.7	9.5	11.3	13.6	13.4	13.1	12.6	13.2	11.6	10.5	7.7	6.9	11.0
Average	7.7	8.7	10.8	11.8	12.3	12.3	12.3	12.2	10.1	8.3	7.7	6.6	10.2

Hawzen	Average Maximum Temperature (°C)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2002	26.9	28.3	28.4	28.0	29.4	29.0	26.8	23.6	24.6	26.5	26.5	25.9	27.0
2003	25.7	27.7	28.4	28.8	29.3	27.6	24.0	24.1	25.5	26.4	25.4	25.4	26.5
2004	26.0	26.8	27.8	29.1	29.4	28.2	23.4	23.4	25.6	24.9	25.0	25.4	26.2
2005	25.1	28.4	30.0	29.0	29.0	28.9	23.2	23.4	25.2	26.3	25.9	25.4	26.7
2006	26.7	28.4	28.7	27.3	27.5	28.0	22.9	22.5	25.8	26.6	25.6	25.3	26.3
2007	26.0	28.5	29.5	29.1	30.3	28.6	24.4	24.5	26.1	27.0	26.5	27.0	27.3
2008	27.5	28.5	30.3	29.2	30.3	28.8	27.2	24.8	27.1	27.7	27.0	26.9	28.0
2009	27.5	29.4	30.5	30.9	31.1	31.6	24.3	24.4	26.2	27.2	27.5	26.9	28.1
2010	27.4	29.1	28.9	29.9	30.7	31.4	26.4	24.2	26.2	27.3	27.5	26.7	28.0
Average	26.7	28.3	29.2	29.0	29.7	29.1	24.7	23.9	25.8	26.7	26.3	26.2	27.1

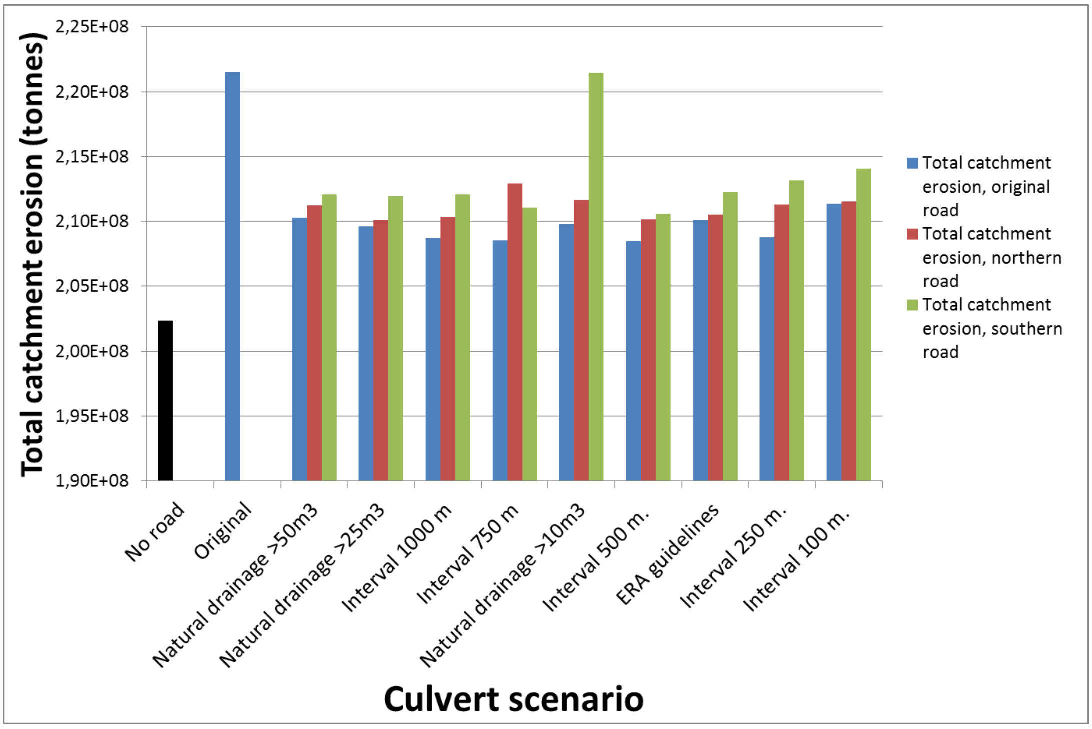
Hawzen	Average Monthly Temperature (°C)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2002	17.4	17.9	19.6	19.6	20.8	20.7	19.5	17.7	17.3	17.2	17.3	17.3	18.5
2003	16.3	18.2	19.9	20.2	21.0	19.7	18.3	18.5	18.0	17.4	16.6	15.7	18.3
2004	17.1	17.7	18.6	20.8	20.6	20.4	17.4	17.5	17.5	16.2	17.4	17.9	18.2
2005	18.0	20.4	21.9	19.2	19.4	19.4	16.9	16.4	16.7	16.1	15.7	14.1	17.9
2006	16.8	18.7	19.9	19.8	20.2	20.2	17.6	17.5	18.0	17.8	17.0	17.1	18.4
2007	17.2	19.3	19.9	20.8	21.7	20.7	18.5	19.1	18.0	17.0	16.7	15.5	18.7
2008	17.7	17.7	19.2	20.5	21.3	20.6	20.7	18.5	18.7	18.1	17.4	16.7	18.9
2009	17.3	19.3	20.8	21.3	21.9	22.6	18.1	18.5	18.4	18.6	17.7	18.0	19.4
2010	18.1	19.3	20.1	21.7	22.1	22.3	19.5	18.7	18.9	18.9	17.6	16.8	19.5
Average	17.2	18.5	20.0	20.4	21.0	20.7	18.5	18.0	17.9	17.5	17.0	16.4	18.6

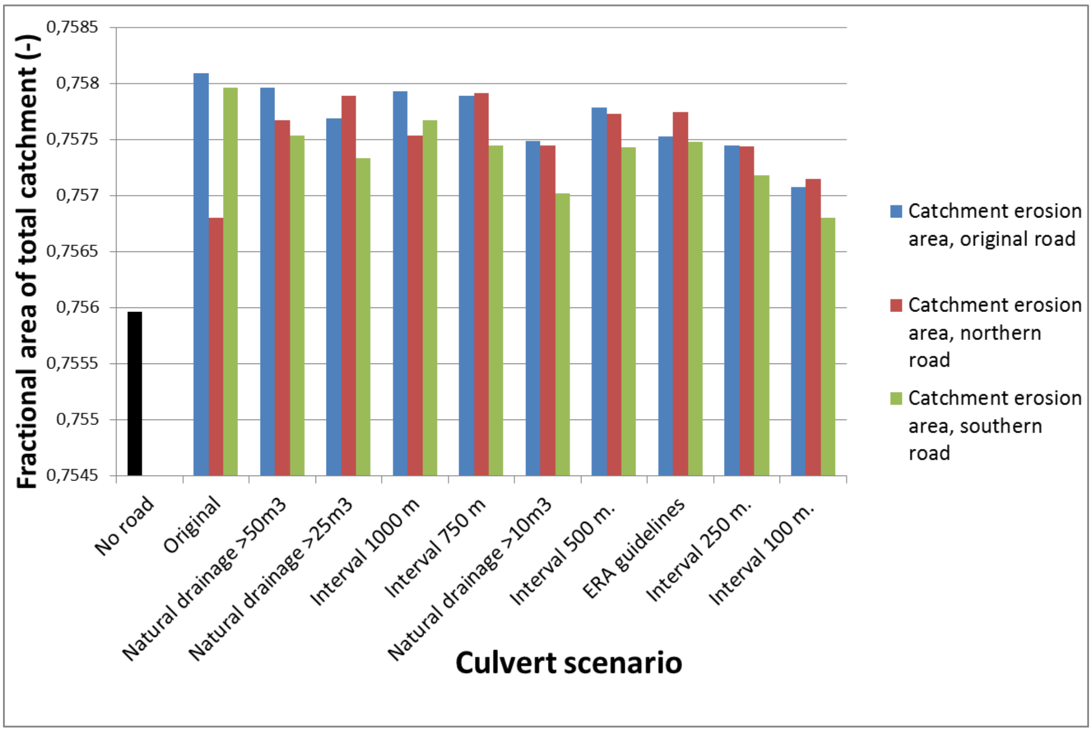
Hawzen	Monthly Rainfall (mm)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2000	0	0	0	24.5	27.9	71.7	243.8	341.1	27.1	25.9	6.5	0	768.5
2001	0	0	71.4	49.8	9	103.7	196.7	337.8	100.2	17.5	0	4.7	890.8
2002	0	17.6	18.2	31.1	27.7	40.2	65.9	188.4	18	0	0	26.2	433.3
2003	0	16.7	8.7	49	0	30.4	168.8	94.3	27.3	0	0	0	395.2
2004	8	0	0	18	3.6	45.4	121.9	161.2	4.3	5.3	0	0	367.7
2005	0	0	10.5	75.7	37.8	26.5	99.2	186.8	9.9	0.5	1.1	0	448.0
2006	0	0	35.4	60.2	75.7	9.9	251.4	246.4	16.2	34.5	16.2	4.6	750.5
2007	0	8.2	9.2	19.4	8.6	75	150.5	149	101	0	2.2	0	523.1
2008	11	0	0	10.2	7.8	40.7	112.1	107.9	34	5.5	11.3	0	340.5
2009	0	5.1	2.7	0	2.5	6.6	208.3	194.6	3.6	15.3	1.6	0	440.3
2010	0	0	7	52.5	5.3	26.9	198.5	224	43.6	0	2	8.2	568.0
Average	2.4	6.0	10.2	35.1	18.8	33.5	153.0	172.5	28.7	6.8	3.8	4.9	474.1

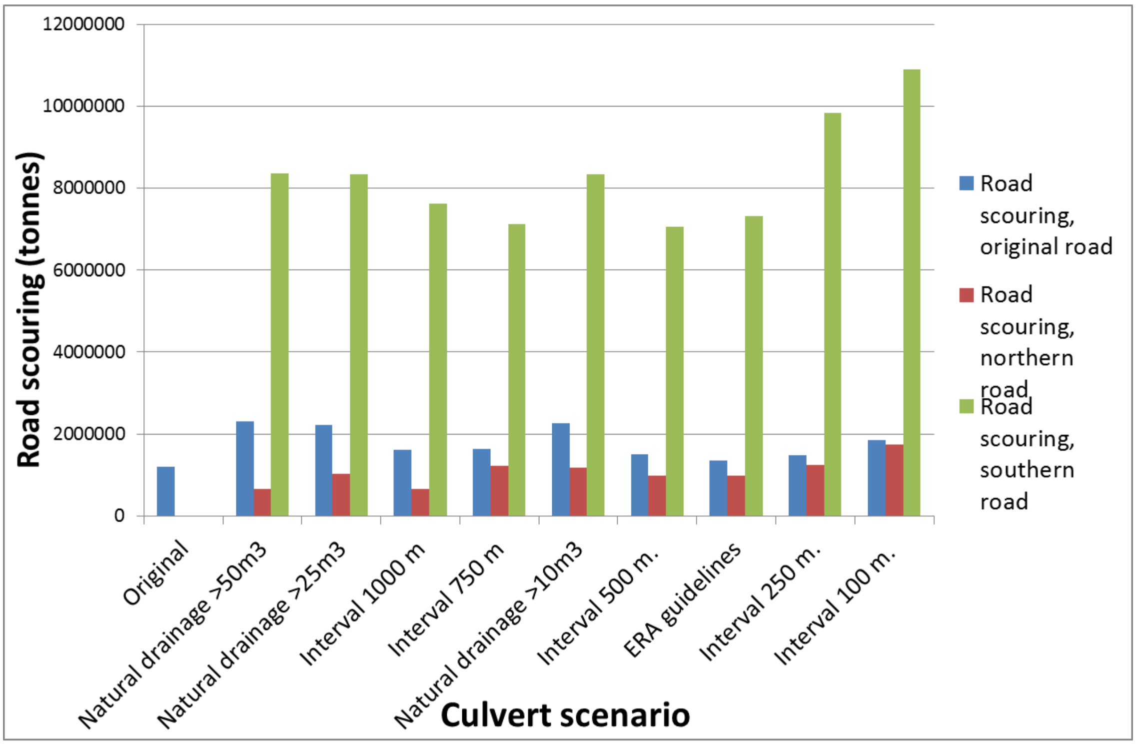
Baert, R. (2011) Hydrogeological Investigation of the Mendae Agricultural Plain and Tsenkanet Reservoir (Tigray, Ethiopia). (Master thesis) Universiteit Gent.

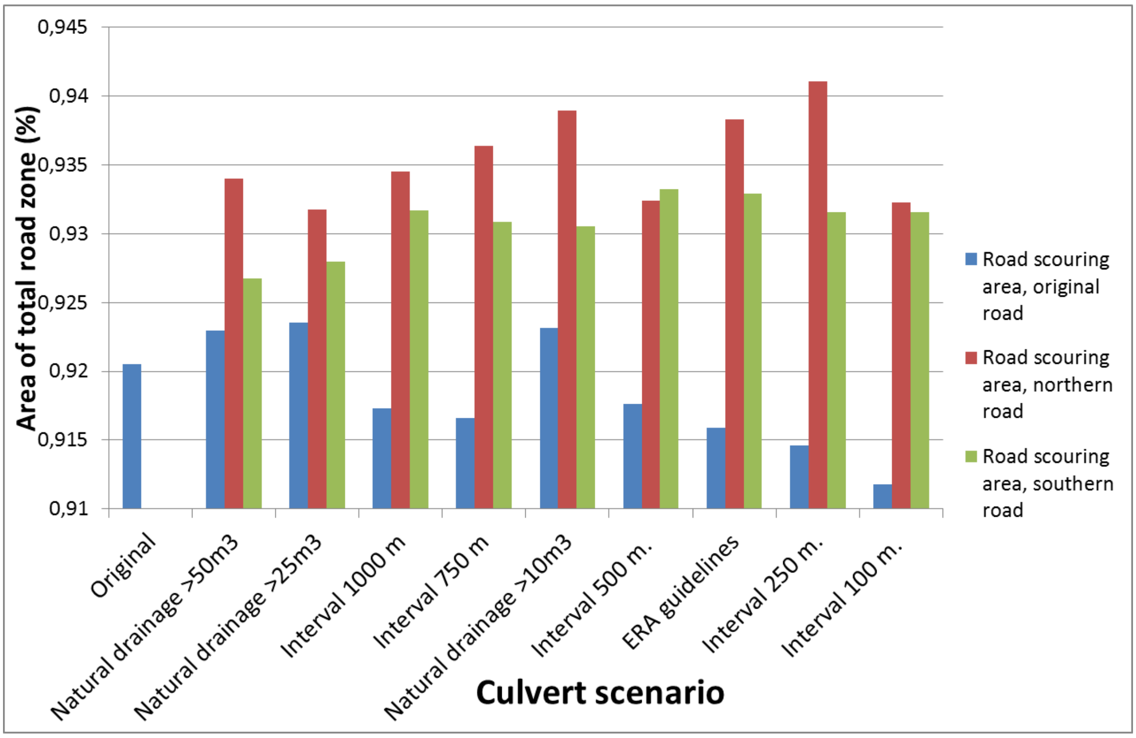
Appendix C: Model outputs for indicators

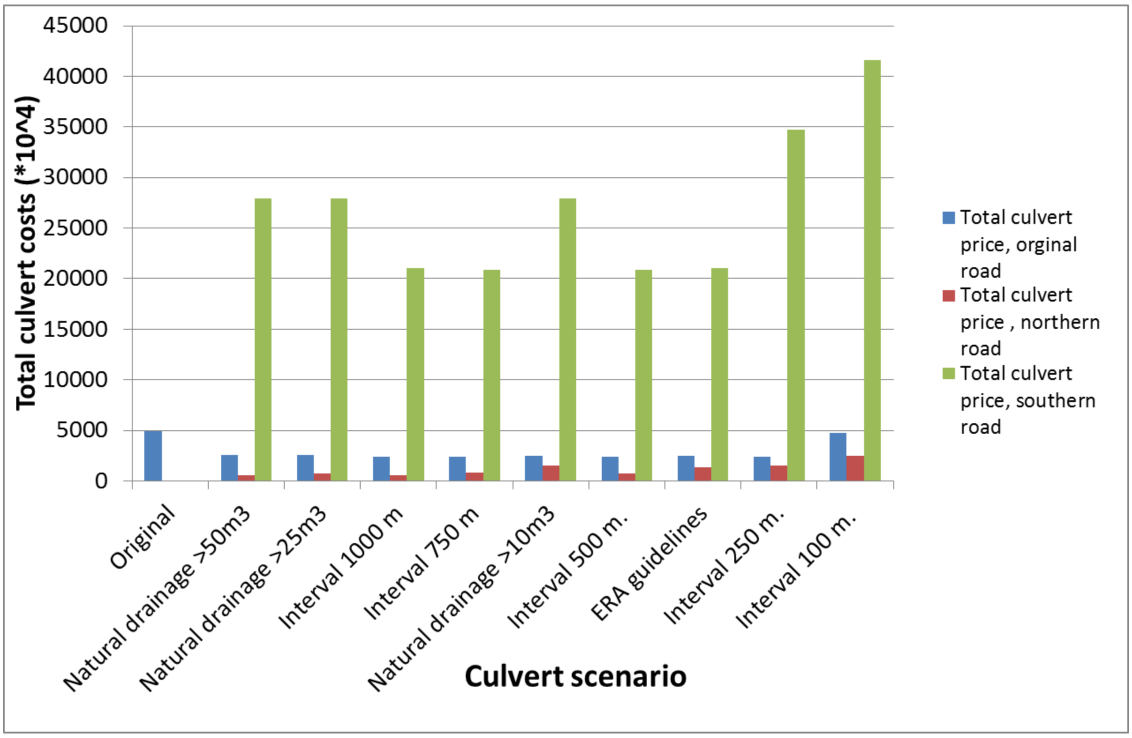
All enclosed figures show the model outcomes of all formulated indicators.



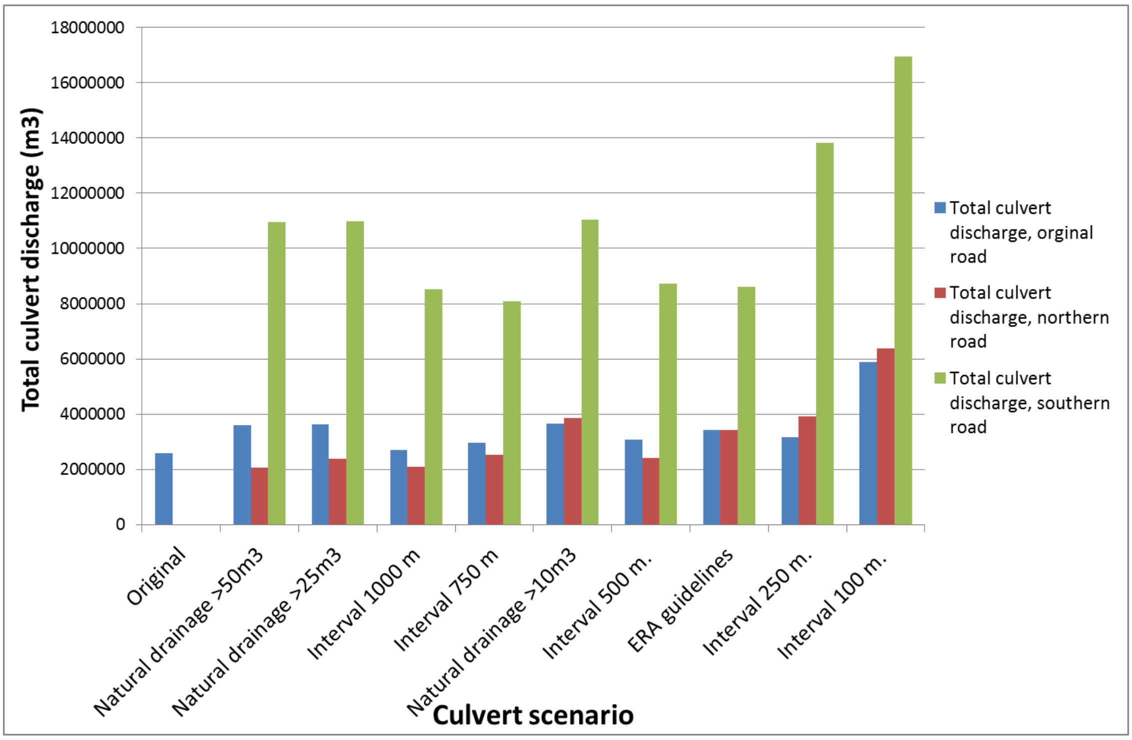



Road scouring (tonnes)
12000000
10000000
8000000
6000000
4000000
2000000
0
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
Road scouring, original road
Road scouring, northern road
Road scouring, southern road

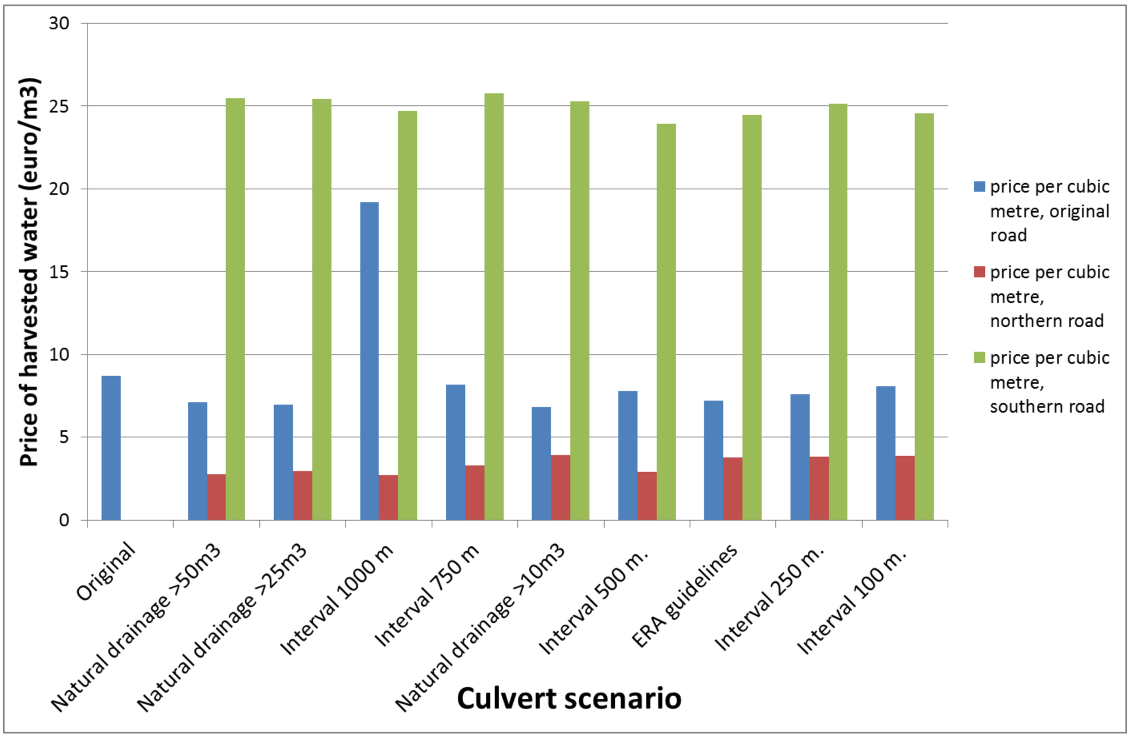

Area of total road zone (%)
0,945
0,94
0,935
0,93
0,925
0,92
0,915
0,91
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
Road scouring area, original road
Road scouring area, northern road
Road scouring area, southern road

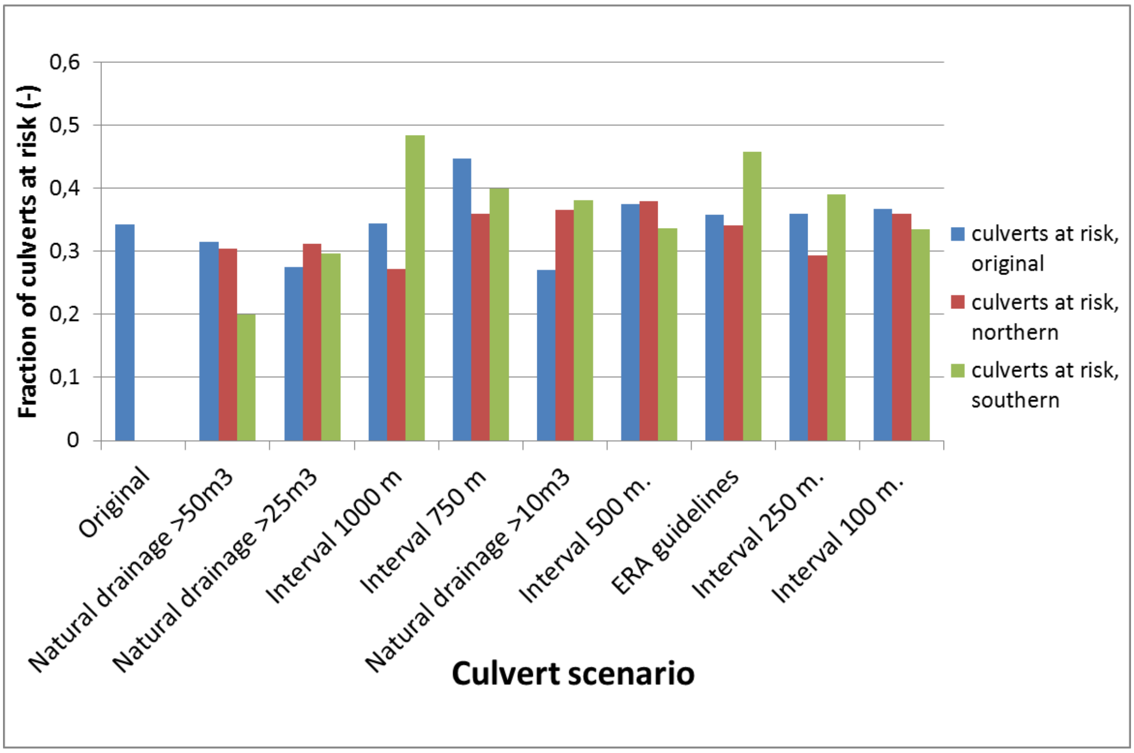


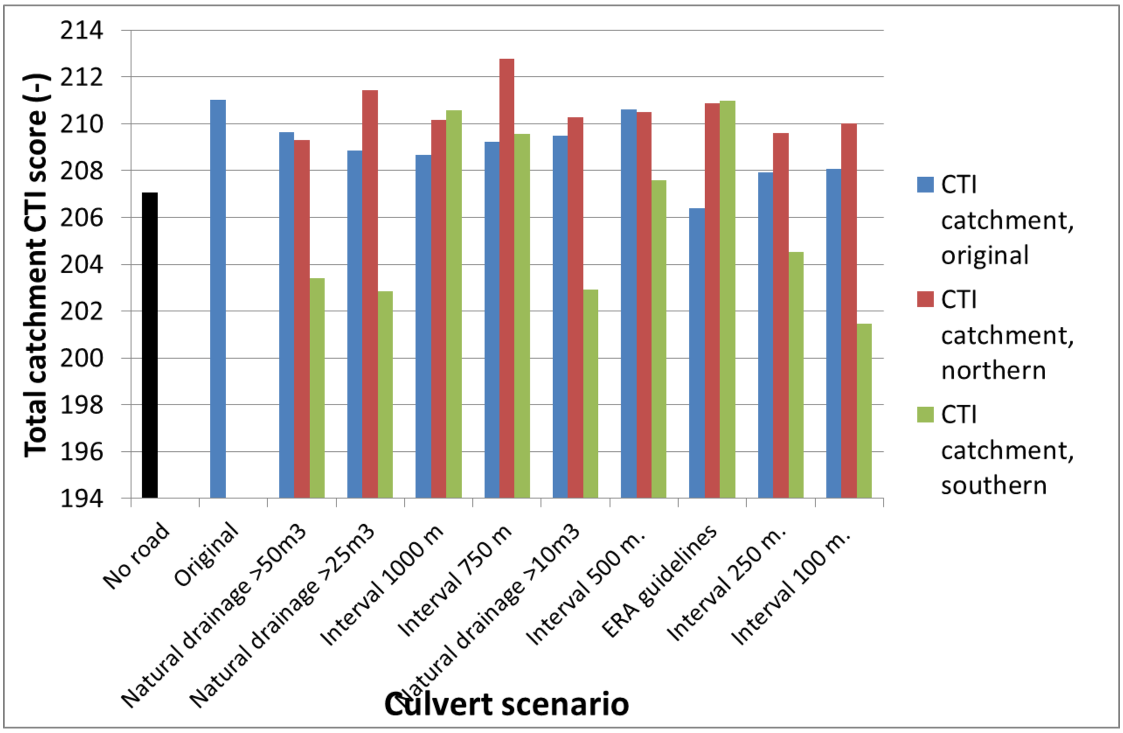
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Total culvert costs (*10^4)
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
Total culvert price, orginal road
Total culvert price , northern road
Total culvert price, southern road



18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
Total culvert discharge (m3)
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
Total culvert discharge, orginal road
Total culvert discharge, northern road
Total culvert discharge, southern road

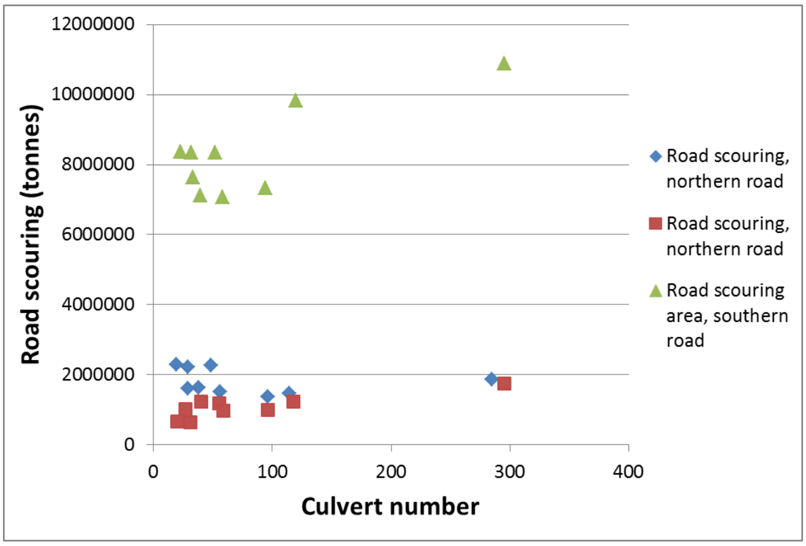

Price of harvested water (euro/m3)
30
25
20
15
10
5
0
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
price per cubic metre, original road
price per cubic metre, northern road
price per cubic metre, southern road

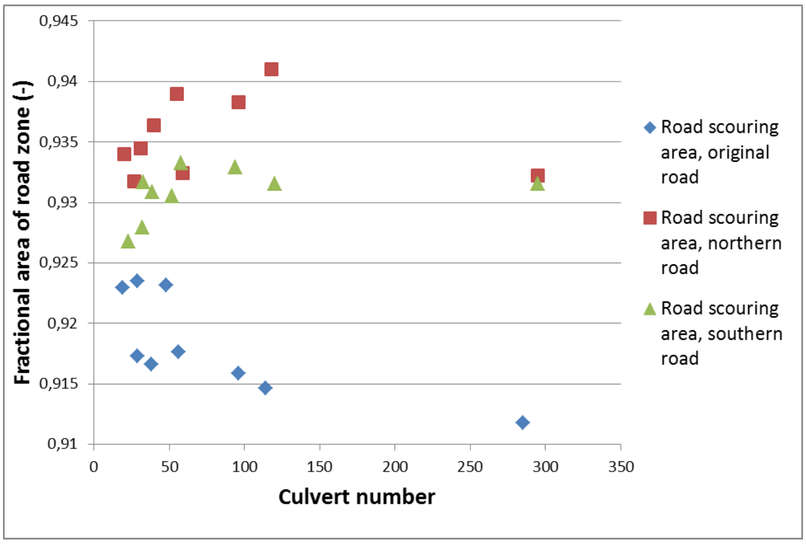

Fraction of culverts at risk (-)
0,6
0,5
0,4
0,3
0,2
0,1
0
Original
Natural drainage >50m3
Natural drainage >25m3
Interval 1000 m
Interval 750 m
Natural drainage >10m3
Interval 500 m.
ERA guidelines
Interval 250 m.
Interval 100 m.
Culvert scenario
culverts at risk, original
culverts at risk, northern
culverts at risk, southern

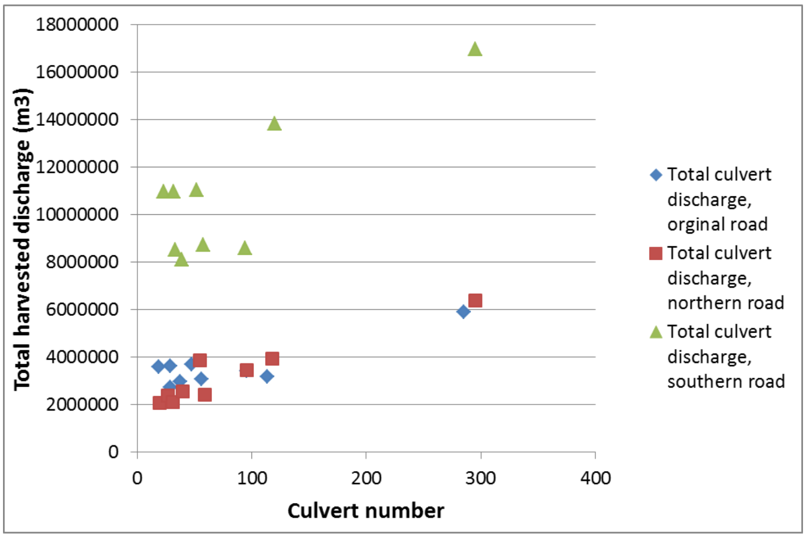


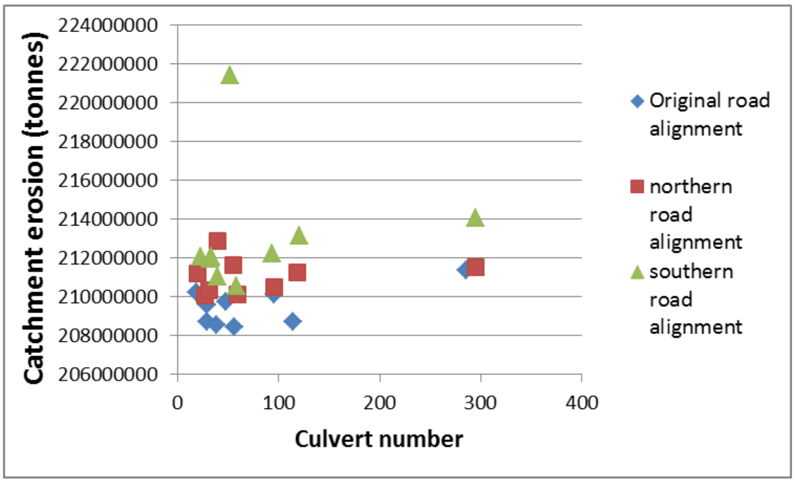
Appendix C: Culvert number and indicator values.

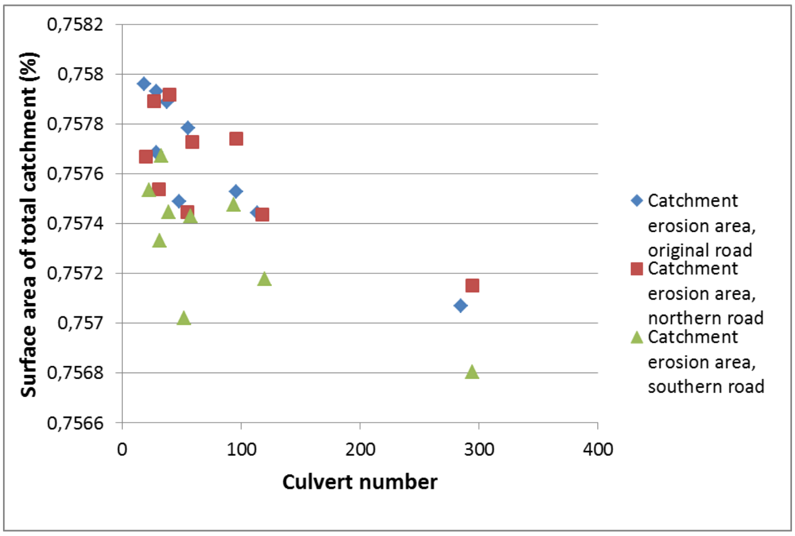
All enclosed figures show the modeled indicator values on the y-axis and the culvert number of the particular road system scenario on the x-axis.

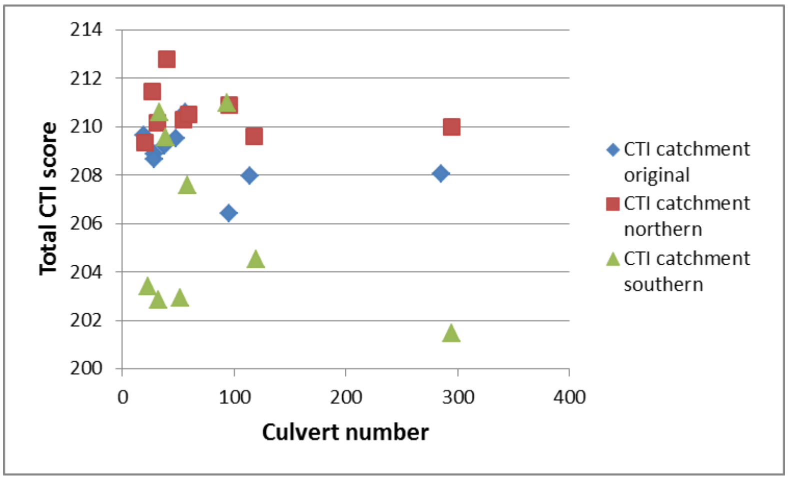


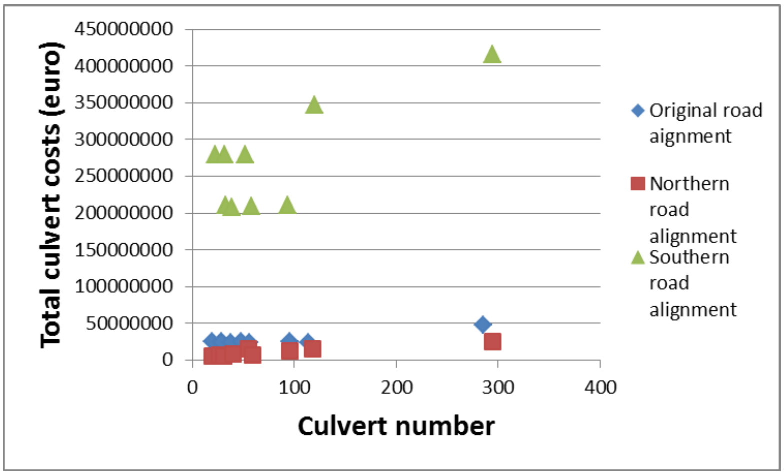

0,945
0,94
0,935
0,93
0,925
0,92
0,915
0,91
Fractional area of road zone (-)
0
50
100
150
200
250
300
350
Culvert number
Road scouring area, original road
Road scouring area, northern road
Road scouring area, southern road

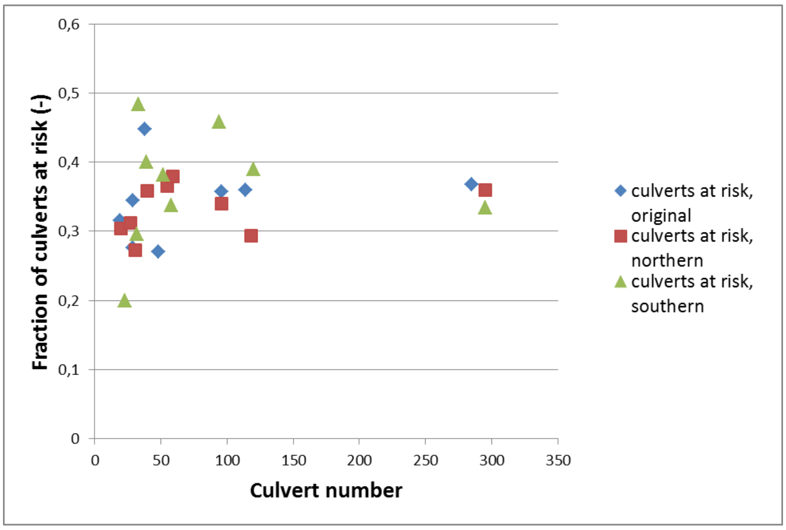

18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
Total harvested discharge (m3)
0
100
200
300
400
Culvert number
Total culvert discharge, orginal road
Total culvert discharge, northern road
Total culvert discharge, southern road

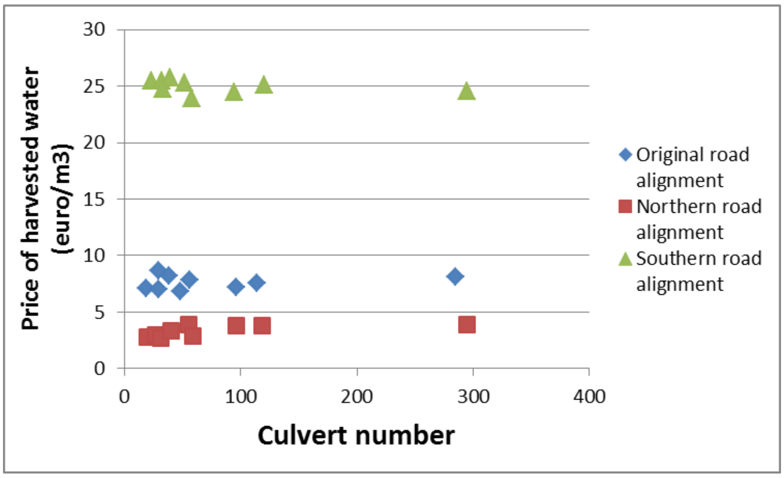

224000000
222000000
220000000
218000000
216000000
214000000
212000000
210000000
208000000
206000000
Catchment erosion (tonnes)
0
100
200
300
400
Culvert number
Original road alignment
northern road alignment
southern road alignment


Surface area of total catchment (%)
0,7582
0,758
0,7578
0,7576
0,7574
0,7572
0,757
0,7568
0,7566
0
100
200
300
400
Culvert number
◆ Catchment erosion area, original road
■ Catchment erosion area, northern road
▲ Catchment erosion area, southern road


Total CTI score
214
212
210
208
206
204
202
200
0
100
200
300
400
Culvert number
◆ CTI catchment original
■ CTI catchment northern
▲ CTI catchment southern


Total culvert costs (euro)
450000000
400000000
350000000
300000000
250000000
200000000
150000000
100000000
50000000
0
0
100
200
300
400
Culvert number
◆ Original road alignment
■ Northern road alignment
▲ Southern road alignment


0,6
0,5
0,4
0,3
0,2
0,1
0
Fraction of culverts at risk (-)
0
50
100
150
200
250
300
350
Culvert number
culverts at risk, original
culverts at risk, northern
culverts at risk, southern


30
25
20
15
10
5
0
Price of harvested water (euro/m3)
0
100
200
300
400
Culvert number
Original road alignment
Northern road alignment
Southern road alignment

Appendix D: Parameter overview for the estimation of food production

The table gives an overview of all used input parameters in the estimation of food production, on a monthly base. The growing season covers the 1st of September till 31st of January and counts a total evapotranspiration of 232,4 mm.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
T (°C)	18	19.2	20.5	21.7	22.1	21.3	19.4	20	19.6	18.6	17.9	17.3	------
ET_0 (mm)	59.9	69.3	79.5	89.1	93.5	86.5	69.3	72.6	71.6	64.4	58.3	55.2	869.2
ET_0 (mm/ day)	±2	±2	±2	±3	±3	±3	±2	±2	±2	±2	±2	±2	
P (mm)	0.5	1.5	9.8	30.6	19.6	53.8	214.4	272	23.1	5.7	0.5	0.9	632.4
Number of rainy days	0	0	1/3	1	2/3	1.8	7	9	2/3	1/6	0	0	Approx. 21 days
Interval between rains	-	-	-	monthly	-	monthly	4 days	3 days	-	-	-	-	
Kc_{ini} fig 29.	0.1	0.1	0.1	0.1	0.1	0.15	0.8	0.9	0.1	0.1	0.1	0.1	
Kc_{ini} fig 30.	0.3	0.3	0.3	0.2	0.2	0.2	1.15	1.15	0.3	0.3	0.3	0.3	
Kc_{ini} final	0.25	0.25	0.25	0.15	0.15	0.20	1.05	1.05	0.25	0.25	0.25	0.25	
Kc_{dev}	0.75	0.75	0.75	0.7	0.7	0.7	1.15	1.15	0.75	0.75	0.75	0.75	
Kc_{mid}	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	
Kc_{end}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
Kc_{avg}	0.25								0.5	0.97	1.2	0.89	
ET_{crop} (mm)	15								35.8	62.5	70	49.1	232.4

Appendix E: Total soil loss for different culvert compositions.

The table shows the estimates of soil loss under a range of different event compositions, which were discussed in section 8.1.2.

Event description	**Total annual runoff (m^3/ha.)**	**Total soil loss per single event (ton/ha)**	**Total soil loss (ton/ha.)**
21 events - 30 mm/hr.	46	214	450200
42 events - 15 mm/hr.	39	278	1170200
63 events - 10 mm/hr.	33	40	249600
126 events - 5 mm/hr.	16	6	74200
630 events - 1 mm/hr.	0,02	0,005	300
17 events - 3 mm/hr. 6 events - 5 mm/hr. 45 events-7.5 mm/hr. 30 events-5.5 mm/hr. Total annual rainfall: 598.5 mm	2094	-	306031

Appendix F: Faults in estimation of the transport capacity

The enclosed figures show an event which could not be clarified or solved during this study. The map for transport capacity shows negative values at several locations on the enclosed image, which results in unrealistically high values for deposition at these locations which can be seen in the second figure.

Figure 50: The figure shows 'TC', which represents the transport capacity per cell given in kg·m^{-3}.

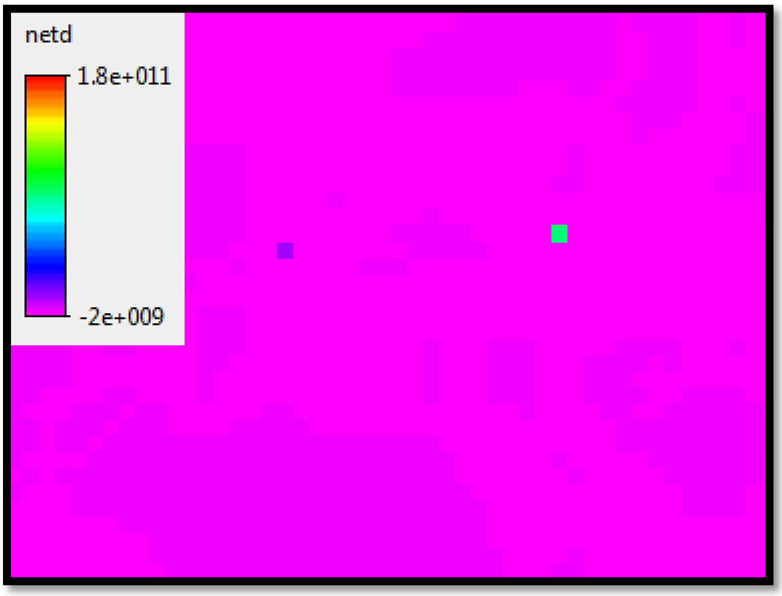


Figure 51: The figure shows 'netd', which represents the net deposition of sediments per cell given in kg.