Roads: Instruments for Rainwater Harvesting, Food Security and Climate Resilience in Arid and Semi-arid Areas

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Abstract With an investment of 7–10 billion USD in sub-Saharan Africa, the development of roads is a major factor in the change of landscapes and the drainage patterns. Thus, roads often act as conveyance systems, but the impact is often negative, leading to erosion, waterlogging and flooding. These impacts come down hardest on the more vulnerable and least resilient, such as poor female-headed households. Yet these negative effects can be turned around and roads can be made into instruments for rainwater harvesting, food security and climate resilience. In this regard, there is a variety of techniques that can be used—ranging from simple interventions in the area surrounding the roads to modified designs of road bodies. What drives the transformation of roads is a change in governance too—better coordination between road builders and water resource and agricultural departments and closer interaction with roadside communities. This chapter provides evidence from Yemen and Tigray region in Ethiopia, where road water harvesting has systematically been introduced in all districts since 2014. The chapter describes the process of promoting road water harvesting, the techniques used, the potential of road water harvesting to increase resilience and the hydrological and socio-economic effects.

Keywords Road water harvesting · Erosion · Ethiopia · Yemen

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W. Leal Filho and J. de Trincheria Gomez (eds.), *Rainwater-Smart Agriculture in Arid and Semi-Arid Areas*, https://doi.org/10.1007/978-3-319-66239-8_7

1 Introduction

Roads have a major impact on the landscapes immediately surrounding them—determining the movement of water, sediment, dust and others (Forman et al. 2003). Roads have an important impact on runoff because they often act as either an embankment or a conveyance system, bringing major changes to the natural hydrology (Forman et al. 2003). These changes often have negative impacts: roads cause local floods and waterlogging along the way, whereas the more concentrated discharge from drains and culverts causes erosion and sedimentation (Garcia-Landarte et al. 2014; Demenge et al. 2015). This undermines the resilience of roadside communities, who lose crops or property or suffer health effects from road dust (Greening 2011).

However, this negative aspect can be reversed if roads are systematically used as instruments for rainwater harvesting (Nissen-Petersen 2006). Thus, road harvesting can generate substantial positive impacts: more secure water supply, better soil moisture, reduced erosion and respite from harmful damage (Demenge et al. 2015). In addition, rainwater harvesting leads to better returns to land and labour, and a higher ability of people, households and communities to deal with and prosper regardless of shocks and stresses (Dile et al. 2013). With the investment in roads in many countries exceeding that of any other programme, this is a large opportunity to improve the productive environment and increase the resilience of the population in the vicinity of the road.

This chapter describes the process of promoting road water harvesting to increase resilience. It first describes the techniques and approaches to road water harvesting (Sect. 2). It then zooms in on the experience of Tigray region in Ethiopia (Sect. 3) where the collection of water from roads has been introduced as a systematic feature in the water conservation and moisture management campaigns since 2014. Section 4 describes the link between road water harvesting and resilience, providing examples from Tigray. The chapter concludes with a suggestion on how to systematically build-up resilience by connecting road development and water resources management in sub-Saharan Africa.

2 Methodology

2.1 Study Area

The region of Tigray in Northern Ethiopia and large areas in Yemen are subject to rainfall variability, land degradation and undernutrition. Thus, rainfall is unpredictable and unreliable with a higher concentration between June and August when about 70% of the total runoff is obtained in Tigray (Abebe et al. 2012). However, not all is negative. The Northern Ethiopia highlands in Tigray are greener than at any time in the last 145 years (Nyssen et al. 2014). Since 1980s, soil and water conservation (SWC) and water harvesting techniques have been widely implemented to tackle land degradation and foster development by reducing surface runoff and enhancing infiltration, sediment deposition and vegetation growth (Nyssen et al. 2014). There are a large range of options to collect water with roads and join the SWC efforts in the region such as diverting water from culverts, using the springs that are opened up with road construction or reusing excavation pits as storage reservoirs.

One such area was the upgraded route Freweign-Hawzien-Abreha Weatsbeha-Wukro in Tigray, Northern Ethiopia. This road section of 64-km-length crosses three woredas (districts): Saesie Tsaeda Emba (woreda center is Freweign town), Hawzien woreda (woreda center is Hawzien town) and Klite Awlaelo woreda (woreda center is Wukro town) (Fig. 1). The surveyed routes include both feeder roads and asphalt.

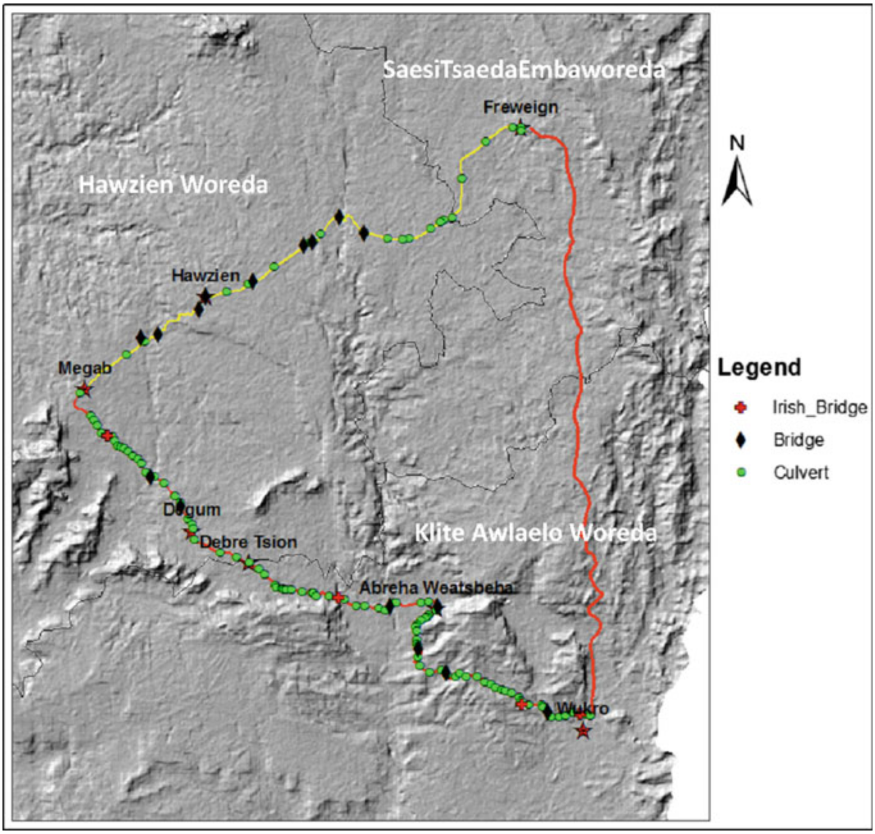

Fig. 1 Location map of the study area in Tigray, Northern Ethiopia (Wukro-Megab is a gravel road planned to be upgraded into asphalt; Megab-Freweign is recently upgraded into asphalt; Wukro-Freweign is an asphalt road which is part of the main highway in Northern Ethiopia)

2.2 Methods

If water from roads is not handled properly, the result is erosion, flooding, and siltation/sedimentation due to the disturbance of natural drainage systems. Such was the case along the Freweign-Hawzien-AbrehaWeatsbeha-Wukro road section as well. A detailed assessment was done of: locations of culverts, Irish bridges and bridges; areas affected by gully erosion; sites affected by waterlogging and flooding; and sites where efforts have been made to implement different soil and water conservation measures along a 5-km-radius from the main route. The survey was carried out in the period of July to September 2013.

Moreover, a socio-economic study was conducted in Saesi Tsaeda Emba district of Northern Ethiopia along the newly constructed Freweign-Hawzen highway. Data were collected from document reviews and randomly selected respondents representing all social groups of the community (such as women, men and wealth groups better off, middle class poor) along the road and water harvesting structures. Both participatory and structured surveys were used to collect data. The participatory rural appraisal (PRA) tools included: participatory mapping, transect walks, wealth ranking matrix, gender matrix, seasonal calendars and interviews with leaders and officials at the *tabia, woreda* and regional level. Participants of the PRA included men and women, representatives of different wealth groups, members of households that practice irrigated and rainfed agriculture and individuals particularly affected by the road. Overall, data were collected from 129 household semi-structured survey and 15 interactive discussions. Finally, data were analysed using descriptive statistics, triangulation and content analytical tools.

3 Results

3.1 Collecting Water from Roads and Road Catchments

Tropical drylands are exposed to significant rainfall variability which leads to recurrent periods of water deficiency and make them particularly vulnerable to droughts, floods and other extreme events (Falkenmark and Rockstrom 2008). At the same time, drylands cover 42% of the world's population on 40% of the world's land area and host two billion people (United Nations 2011). Moreover, poverty and undernutrition are to great extent concentrated in tropical drylands, which are also suffering from water and land degradation. Thus, resilience against droughts and dry spells is fundamental for water and food security in these areas (Falkenmark and Rockstrom 2008).

Farming systems in sub-Saharan Africa drylands consume less than 10% of the seasonal rainfall available, whereas the remaining rainfall constitutes massive water losses (Falkenmark and Rockstrom 2008). At the same time, millions of cubic metres are being drained through the road surface and drainage systems every rainy season. There is an estimated 5.55 million km of roads in sub-Saharan Africa (Kubbinga 2012). Of this, 2.36 million km are in drylands, respectively, in rangelands (1.57 million km) and in cultivated areas (0.80 million km) (Kubbinga 2012). If these water losses could be put to productive use, sustainable productivity levels of farming systems could be multiplied by four (Falkenmark and Rockstrom 2008).

Road water harvesting potential depends on several landscape characteristics. Table 1 presents drainage characteristics, erosion susceptibility and road water harvesting potential for different landscapes.

Rainwater harvesting has repeatedly been suggested as a prime option for a sustainable water management strategy to increase agricultural production (Rosegrant et al. 2002; Reij et al. 2009). Water harvesting systems result in higher farm productivity (Dile et al. 2013) increasing farm productivity by 78% on average (Bouma et al. 2016). Unlocking the potential of roads and road-related infrastructure in order to harvest the massive amount of water being currently lost will help to

Table 1 Roads versus landscape

	Drainage characteristics	Erosion susceptibility	Water harvesting potential
Lowland and plateau	Higher difficulty to drain but depends on soil characteristics. Road embankment can interfere with subsurface and surface flows, especially when no clearly developed drainage pattern	Waterlogging and undermining of road pavements can be a problem. Side drains and embankment stability depends on design standards	Borrow pits, rolling dips, tanks, cross drainage to infiltration areas, hand-dug wells, manually drilled shallow boreholes and flood water spreading. Borrow pits can serve as dug out ponds with natural seepage
Mountain-valley	Easier to drain at toeslopes and moderate vertical profile slope. However, ridge top and valley bottom are harder to drain	Depending on roughness of surface, soil characteristics and slope. Deep, portable soils and steep slopes are prone to trigger erosion issues	Several rainwater harvesting techniques can be applied: spring capture, recharge of borrow pits, retention ponds, water cisterns and tanks, side drains/culverts leading sheet water flows to nearby fields and terraces, canals from culverts to fields, spillways from road surface to farms

Source Garcia-Landarte et al. 2014

improve the livelihoods of rural dwellers now suffering from water scarcity, degradation and malnutrition.

There is a large range of options to collect water with roads (Table 2), most of them falling within two main approaches: “adapting to the road” and “adjusting the road”. The first approach involves utilizing directly or indirectly the runoff and water flows generated by roads. The latter relates to optimizing road design for water harvesting and erosion control. Making roads climate and waterproof are often costly and less roads can be built. Instead, road development should be optimized to lead to food security and climate resilience.

3.2 *Adapting to the Road: Using Runoff and Water Flows Generated by Roads*

There are several interventions that can be implemented to nearby already constructed roads and appurtenant infrastructure. A technique that can be easily implemented is spreading water directly to farmlands from road surfaces by using stone bunds or digging shallow canals. Alternatively, water can also be diverted to

Table 2 Overview of road water harvesting techniques and their benefits

Approach	Techniques	Benefits
Adapting to the road	Spreading water from road surface and culverts	Groundwater recharge Soil moisture increase Erosion/flooding control
	Harvesting water from culverts, side drains and depressions (borrow pits, small reservoirs, infiltration ponds, infiltration trenches and swales)	Groundwater recharge Water storage Soil moisture increase Erosion/flooding control Pollution control by naturally filtering
	Gully plugging	Soil moisture increase Erosion control Groundwater recharge
	Spring capture	Reliable source of clean water (unless naturally polluted)
Adjusting the road	Fords combined with sand dams	Groundwater recharge Water storage Flood control
	Carefully planning road alignment and culvert location	Groundwater recharge Water storage Erosion/flooding control
	Permeable road foundations	Groundwater recharge Pollution control by filtering

structures for surface storage or groundwater recharge. Below is a brief explanation of what can be done with runoff and water flows generated by roads.

3.2.1 Spreading Water from Road Surface and Culverts into Farmland

During rain events, road surfaces generate a large amount of runoff. In addition, a vast amount of water coming from the upper catchment passes through culverts and side drains (Fig. 2). This water can be easily utilized by diverting it to nearby farmlands for supplemental irrigation. Roadside farmers in Tigray region have reported to have an increase of up to 50% in yields as compared to farmers far from the road.

3.2.2 Harvesting Water from Culverts, Side Drains and Depressions

Road drainage structures can be used not only for cross drainage but also to feed as the water source for borrow pits and storage ponds or for enhanced recharge areas such as infiltration ponds, swales and infiltrations pits.

(a) Converted borrow pits

Borrow pits are the result of the excavations made to extract materials for road construction. Borrow pits are often left open and located nearby roads, which offer an opportunity for water harvesting. They can be used as storage reservoirs for rainwater for instance connecting them with culverts and other cross-drainage structures through a canal. However, some measures are needed to improve the

Fig. 2 Water spreading from road surface to farmlands in Tigray, Ethiopia. *Photograph* Kifle Woldearegay

design, safety and accessibility. These measures include technical considerations such as improving the geometry to facilitate access and increase capacity, compress the base and sides to reduce permeability and construction of well for water extraction to allow filtration and improve water quality (AFCAP 2011).

(b) Small reservoirs for water storage

Runoff can also be channelled for storage in small reservoirs (Nissen-Petersen 2006). This water can be later utilized by roadside communities for small-scale irrigation purposes and for livestock watering. There are two main types of ponds that can be built, namely embankment ponds and excavated ponds (USDA 1997). Embankment ponds are built by constructing an embankment or dam across a waterway where the land is depressed enough to allow for water storage. Excavated ponds are built by digging a pit or dug out in an almost flat area. Since they require more labour and machinery, excavated ponds are mostly used where only a small supply of water is needed. Dug outs are particularly useful in dry areas where evaporation losses are high and water is scarce, since they can be built to expose a minimum water surface. A combination of both types of ponds can be built in gently to moderately sloping areas where the capacity is achieved both by excavating and by building a dam or embankment.

(c) Infiltration ponds

Infiltration ponds are designed to capture and retain runoff, letting it to infiltrate for groundwater recharge (Desta et al. 2005). They are advantageous in places where runoff might be polluted (such as next to highways) and where shallow wells and hand-pumps are viable. According to Massman and Allen (2003), the first step to design infiltration ponds is to estimate the volume of runoff that must be infiltrated. Secondly, a trial geometry must be defined. The next step is to estimate the infiltration rate by multiplying gradient and hydraulic conductivity and finally conduct post-design evaluations.

(d) Infiltration trenches

Infiltration trenches protect the fields from upcoming runoff and let the water infiltrate in the soil (Desta et al. 2005) (Fig. 3). They increase the soil moisture of the adjacent farmlands, which in turn has a positive impact in yields.

3.2.3 Gully Plugging for Recharge

When road drainage is not managed properly it can lead to the formation of gullies (Nyssen et al. 2002). Gully plugs are used to rehabilitate gullies and retain the sediments that would be otherwise washed away. Gully plugs are structural barriers that obstruct the concentrated runoff inside gullies and ravines (Knoop et al. 2012) (Fig. 4). They are often temporary structures and are built to favour the establishment of a permanent soil cover and to effectively conserve soil and water.

Fig. 3 Infiltration trenches along an asphalt road in Amhara Region, Ethiopia. *Photograph* Marta Agujetas

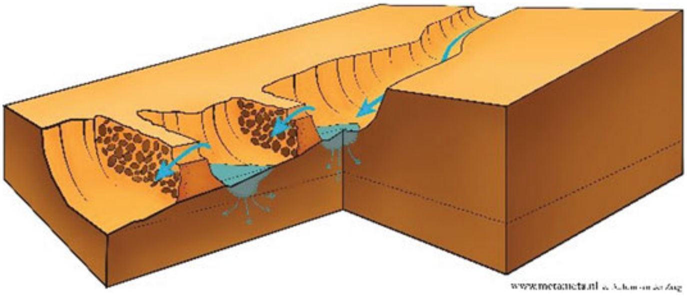

Fig. 4 Gully plug for groundwater recharge. *Source* MetaMeta

Gully plugs can have an enormous beneficial effect on the soil moisture of adjacent lands as well as shallow groundwater tables (Knoop et al. 2012). In fact, in an area where gullies are present, soil moisture will be drained and shallow groundwater will drop to the depth of the drainage line of the gully (Knoop et al. 2012).

3.2.4 Spring Capture

In mountainous areas, the excavation for road building purposes can open springs in mountain aquifers. These newly opened springs can damage cut slopes and erode land (Garcia-Landarte et al. 2014). Capturing newly opened springs in storage reservoirs that are adequately dimensioned and have spillways facilities is a safe way to make available a source of water that otherwise would be lost. When the spring water is not of good quality, it can be diverted to infiltration structures such as ponds or swales.

3.3 Adjusting the Road: Improving Road Design for Multiple Functions

Improved and integrated road designs can increase groundwater recharge and retention while controlling water-related damage (Garcia-Landarte et al. 2014). Optimized designs can particularly improve water storage in the vicinity of the road, in open ponds and cisterns, but also as secure soil moisture and as shallow groundwater.

3.3.1 Fords Combined with Sand Dams

Low-volume rural road river crossings such as fords or non-vented drifts can be used for seasonal rivers to retain and store water in the upstream side while protecting the road embankment (Neal 2012). They can also be used for flood water spreading and riverbed stabilization. When carefully designed and located, fords can also act as sand dams (van Steenbergen and Tuinhof 2010) (Fig. 5). Sand dams that incorporate a ford are a low-cost alternative to culverts and offer a wide array of benefits including groundwater recharge, downstream flow risk reduction and provide reliable water supply in drylands (Neal 2012). However, they can only be built on seasonal rivers with sufficient sandy sediment. The design of spillway should be done in a way that does not cause the river to spread or divert. To prevent the river damaging the road foundation, a concrete apron or gabions extending for 2 m from the base is recommended downstream of the crossing (Neal 2012).

3.3.2 Carefully Planning Road Alignment and Culvert Location

An ideal road follows the existing natural topography. However, this is not often the case as roads end up acting as dams or embankments and changing local water flows (van Steenbergen and Tuinhof 2010). This problem could be reversed by planning road alignment and culvert location in such a way that they maximize water harvesting and recharge (Garcia-Landarte et al. 2014). Road location within the catchment determines water harvesting opportunities from roads. Road alignment and its drainage structures can be purposely designed to feed water storage and recharge facilities such as ponds and borrow pits. They should also be planned in a way that the risk of erosion is minimal and at the same time the potential for

Fig. 5 Road crossing doubling up as a sand dam in Makueni, Kenya. *Photograph* MetaMeta

water harvesting is the highest. For instance, culverts often concentrate runoff in specific spots and often cause gullies and erosion. By studying the hydrology of an area, culverts could be strategically placed to distribute road drainage and prevent erosion.

3.3.3 Permeable Road Foundations

Especially on tarmac roads, the use of permeable substrata would allow percolation or infiltration of runoff through the road surface into the soil. Besides reducing storm water runoff and flooding and replenishing groundwater, it also poses a solution to road-related water quality issues since the water is naturally filtered by the soil underneath. So far, this technology is mostly used in parking lots, sidewalks, low-traffic roads, fire lanes and emergency access roads. However, the potential to harvest storm water is huge due to the expanding road infrastructure in sub-Saharan Africa.

3.4 Case Study in Tigray Region, Ethiopia

Triggered by a research project, the Tigray Bureau of Agriculture and Rural Development introduced in 2014 several road water harvesting technologies in all of its districts as part of the watershed program. Hundreds of road water harvesting structures were built, all indigenous solution to the areas where they were implemented. Monitoring established significant impact in terms of reduced fear of flooding, increased moisture (30–50%), higher shallow groundwater tables (in metres) and higher yields. There is scope to do a lot more—not only in systematically using the water runoff from road catchments but also by even adjusting the design of the roads themselves or consideration of road water harvesting options in design standards. The approaches used to promote road water harvesting in Tigray included: (a) assessment of issues on water and roads along selected routes in Tigray, (b) understanding the perception of the communities on road development versus water-related challenges, (c) designing methods of involving stakeholders to take the lead in the implementation of the interventions, (d) implementing different water harvesting options, and (e) monitoring the effects of the interventions in selected/representative sites where there was prior data (baseline data).

The survey result revealed that several problems have been created due to water from roads including erosion in downstream areas and roadsides and siltation/sedimentation of downstream, upstream and side drainage areas. Waterlogging and damage on dwelling houses and on water harvesting systems (groundwater wells and ponds) were also observed in the study area. In the 64 km of roads, there were 159 problems spots—close to 3 per km.

Until the year 2013/2014, there was no systematic approach for road water harvesting in Tigray, as elsewhere in Ethiopia. There were, however, sporadic practices implemented as part of the soil and water conservation efforts. Since the year 2013/2014, efforts were made to introduce road water harvesting in a more systematic manner. Main practices of water harvesting from roads implemented in the study area thus far were financed by the government (particularly the Tigray Bureau of Agriculture and Rural Development) and implemented during a mass mobilization campaign of June–July 2014 when farmers provided labour days for watershed moisture improvement. The main technologies and approaches implemented are presented below:

- **Use of ponds/pits to harvest water from roads**: Since 2010, ponds have been constructed to collect water from any source including roadside drainages. Along the study route, five ponds have been constructed for surface water storage and groundwater recharge. It is common to have water from a culvert channelled into a properly design pond. The storage of rainwater can provide an extra source of water for irrigation, helping to improve the food security in the area.
- **Channelling water from bridges, culverts and roadsides into series of deep trenches**: In seven locations along the route, water from culverts and roadside drainages was channelled into deep trenches (Fig. 6). Deep trenches are often used to control runoff and enhance groundwater recharge processes (Desta et al. 2005). Measurement of the in situ moisture of the soils around the trenches shows an increase in moisture content of the soil (up to over 100%) as compared to the previous year of the same season (Fig. 7).

Fig. 6 Water from a culvert is channelled into a deep trenches in Megab area, Tigray, Ethiopia. Hand-dug well downstream of these trenches is used for monitoring. *Photograph* MetaMeta

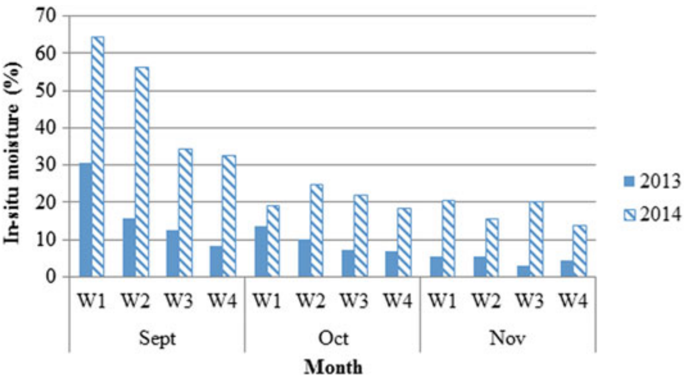

Fig. 7 In situ moisture distribution in soils before and after the construction of deep trenches at downstream of culverts in Megab area, Tigray, Ethiopia. Construction of the deep trench was done on June 2014. Monitoring was done for the period September–November for both years (2013 and 2014). (W1 = Week one; W2 = Week two; W3 = Week three and W4 = Week four)

- **Channelling water from culverts and roadsides into farm lands**: Diverting runoff (from roadsides and culverts) into farmlands (Fig. 8) is one of the technologies implemented in Tigray. The purpose of this structure is to enhance the availability of water for crop production. In situ soil moisture measurement results (Fig. 9) shows that as compared to previous year of the same season, the soil moisture of the soil has improved after the interventions (by up to 100%).

- **Channelling water from bridges, culverts, and roadsides into check dams:** Though check dam construction is a common water harvesting and gully treatment technique in Tigray, linking water from roads with check dams is a new development. With the purpose of storing water from culvert, bridges and roadsides and for the purpose of enhancing groundwater recharge, check dams

Fig. 8 Diverting roadside runoff into farmlands as part of moisture conservation in Kiken area (along Mekelle-Wukro road), Tigray, Ethiopia. *Source* Kifle Woldearegay

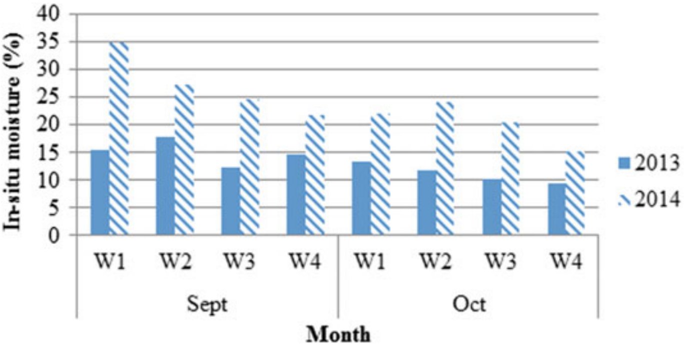

Fig. 9 In situ moisture distribution in soils before and after the construction of structures that divert runoff from culverts into farmlands along the Mekelle-Wukro road (Kiken), Tigray, Ethiopia. Construction of the diversion structures was done on May–June 2014. Monitoring was done for the period September–October for both years (2013 and 2014). (W1 = Week one; W2 = Week two; W3 = Week three and W4 = Week four)

Fig. 10 Channelling water from a culvert into a check dam is enhancing groundwater in Selekleka area, Tigray, Ethiopia. *Photograph* Kifle Woldearegay

are constructed in many parts of Tigray (e.g., Fig. 10). Results of the groundwater level measurement show that due to the construction of the check dam, the shallow well which used to have no yield in the dry season before the intervention has become very productive even in the dry season (Fig. 11).

- **Shallow groundwater development upstream of Irish bridges**: Along the study area, four Irish bridges and fords were identified. These structures can have multiple functions. The first obvious one is to allow road traffic to cross the dry river bed. The fords can, however, also double up as a sand dam, trapping coarse sediment behind them and creating small local aquifers that can store and retain water (Neal 2012).
- **Conversion of borrow pits to water storage and recharge structures**: In some areas, catchment runoff was concentrated in a large cross-drainage structure with three culverts. This new structure created a constant threat and fear of flooding, and in one event, 46 houses were destroyed. To resolve this problem, it was proposed to channel the runoff through a 3-km-long canal to the river, but this would require considerable land acquisition. A more cost-effective solution was used when a 250-m-long canal was excavated to the borrow pit which was converted 5000 m^3 storage and recharge pond. This has resulted in an increase in groundwater level downstream of the pond (Fig. 12) coupled with a reduction of flooding in downstream areas.

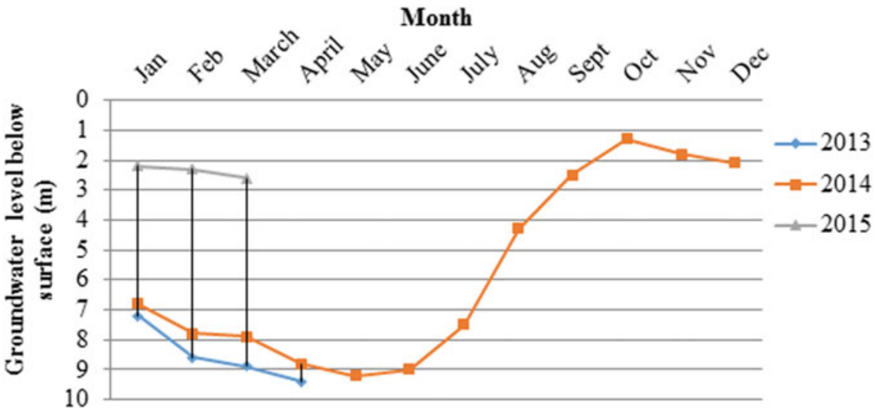

Fig. 11 Groundwater fluctuation in Selekleka area, Tigray, Ethiopia (at downstream of a check dam which was constructed in the period January–May, 2014). The check dam is designed to store water from a box culvert. New groundwater is created at downstream of the box culvert, and the construction of the check dam has enhanced groundwater level in the area

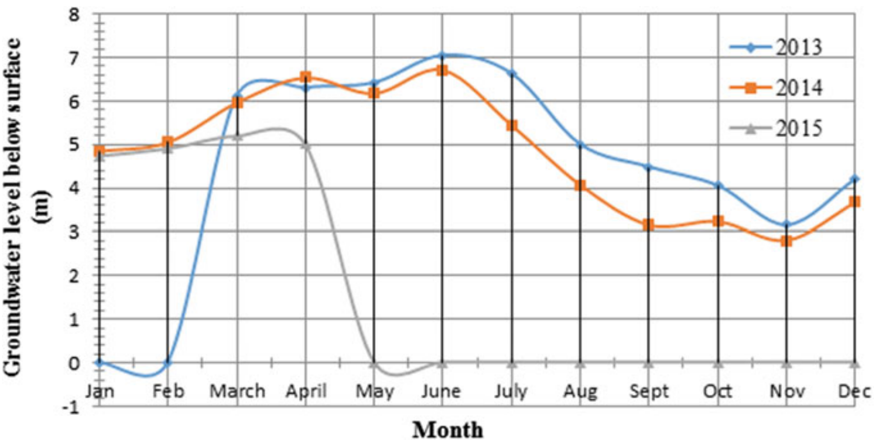

Fig. 12 Groundwater fluctuation in Freweign area, Tigray, Ethiopia. The well is located at downstream of a borrow pit converted into a water storage pond on July 2014. Monitoring was done for the whole period March 2013 to April 2015

3.5 Case Study in Yemen

Yemen has a long and well-established tradition in water harvesting, with a wide variety of technologies showing huge creativity in retaining rain water (Al-wadaey and Bamatraf 2010). Road water harvesting has been successfully introduced in several locations along the national road network and rural feeder roads. In most cases, the technologies have been implemented by farmers themselves.

Other initiatives have been carried out by road engineers and contractors such as the use of borrow pits as recharge ponds or using the road embankment as a dam.

Below there is a description of the road water harvesting practices documented so far:

- **Roofed and open cisterns or tanks collecting water from the side drains**: this technology has been observed along roads in Yemen. Some of the cisterns use sedimentation basin. Figure 13 presents an example of a roofed cistern fed by the side drain. The side drain is partially closed by stones to divert the water to the cistern. The stones are used to block the first runoff after a long dry period as it may be contaminated.
- **Tree planting along roads**: almond, coffee, qat and Ficus trees are being planted to collect road runoff using half-moon stone bunds. They are found in the road embankment, shoulders or in new arable lands near the road to benefit from the diverted flood water from road surface and shoulders.
- **Diverting water directly from culverts to fields**: road water is diverted by using conveyance pipes from the culvert outlet to the farm. Figure 14 shows a conveyance polyethylene pipe with a plastic filter at the pipe intake and a small stone collection basin at the culvert outlet.
- **Diverting road surface water either by using temporary humps or by constructing a catch basin**: temporary humps are built with stones prior rain events to divert road runoff to adjacent farmland or water harvesting structures. Another method is to collect water from roadside drainage using concrete bricks and a bar mesh to trap sediments. The harvested water is then conveyed under the road through a pipe (Fig. 15).

Fig. 13 Roofed roadside cisterns collecting road runoff in Yemen. *Photograph* Mohammed Abdullah Al-Abyadh

Fig. 14 Water from a culvert is gathered in a collection basin and transported through a polyethylene pipe. *Photograph* Mohammed Abdullah Al-Abyadh

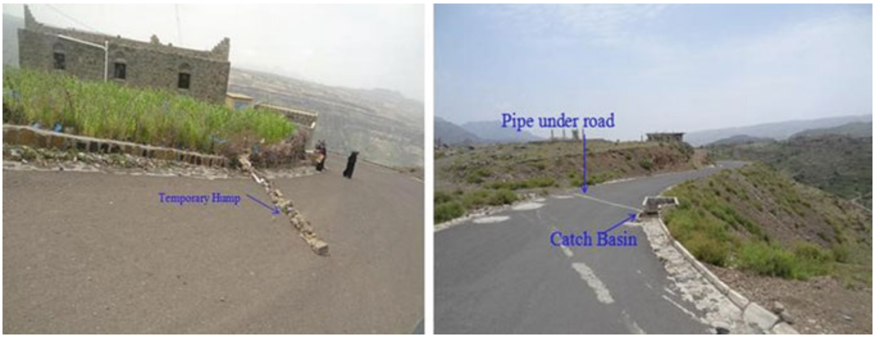

Fig. 15 Temporary hump diverting water from road surface to farmland and catch basin collecting road runoff and transporting it under the road. *Photograph* Mohammed Abdullah Al-Abyadh

4 Discussion

4.1 Enhancing the Resilience of Roadside Communities

A paradigm shift is happening from conventional resource management that aims to reduce variation and increase predictability to resilience thinking or adaptive management as a way of dealing with uncertainty and shocks (Folke 2006). Resilience relates to the capacity to adapt, recover, develop and remain flexible (Falkenmark and Rockstrom 2008). In this section, the authors argue that road water harvesting provides a strategy to build adaptive capacity against shocks and extreme events by providing an extra source of water during dry spells, increasing soil moisture and reducing risk of floods. In addition, water can be stored in ponds, shallow wells and small dams and can be used for livestock or a second cash crop during the dry season. This will provide extra sources of income and therefore increasing farmers' resilience against adversities.

There is a need for a paradigm shift in the design and construction of roads in the following areas:

1. Design roads that have multiple benefits by considering the interest of local communities.
2. Design innovative cost-effective and sustainable infrastructures that are resilient to climate change.
3. Develop national, regional and even global design approaches that consider the multifunctionality and climate resilience of road infrastructures.

Rather than undertaking costly endeavours to protect roads against climate change, new concepts should be developed to integrate roads in the landscape and add to overall resilience. For instance, climate change adaptation costs for road infrastructure in Europe are estimated to be 314–560 million €/year (Nemry and Demirel 2012). There is a need to optimize the multifunctionality of roads to increase resilience. Apart from being used for water harvesting, roads can be also used for sand harvesting, wildlife management and flood control in delta areas (Forman et al. 2003). The main bottlenecks hindering the implementation of this approach are the current practice in road engineering and the lack of coordination between different agencies. Most road engineering guidelines concentrate on how to evacuate water from the road to avoid damage. Harvesting water from roads and their associated infrastructure is not considered as an option in road design. In addition, roads, water and agriculture departments in Ethiopia and elsewhere often work independently and collaborations are rare despite their interdependence. However, to systematically implement road water harvesting, a solid collaboration between government agencies dealing with road development, agriculture and environment needs to be fostered.

Though relatively forgotten and underutilized, capturing water from roadside drains, culverts or along road embankments is in many cases the easiest way to capture runoff. The network of roads is fine-grained and in many areas fast increasing. The ability to better retain water will help farmers to tide over drought periods and increase their capacity to deal with shocks. Results from research in Tigray showed that supplementary irrigation with water from the road increased crop yields by mitigating intra-seasonal dry spells in the month of August, which is the crop maturity period. Moreover, implementing water harvesting systems reduce the risks of crop failure, making farmers more willing to invest in fertilizers and other agricultural inputs (Dile et al. 2013), which will increase even more the crop yields.

4.2 Impacts on Food Security and Poverty Alleviation

Water resilience in agriculture aims at safeguarding water availability under periods of shocks, such as persistent droughts (Falkenmark and Rockstrom 2008). At present, current road building practice reduces resilience of roadside population. Thus, in 100 km of roads there may be 13–25 problem spots—from flooding, waterlogging, erosion or uncontrolled sand deposition. Several studies have found that a reduction in the quality of natural resources often leads to a loss of resilience (Kelly et al. 2015).

This is the case in our study area. Out of 129 respondents, 53.5% of them perceived an increase in water runoff during peak rainy season due to the waterway created along the roads. Thus, many farmers faced flooding, waterlogging and siltation of fields, making land less productive and more difficult to cultivate which in turn resulted in loss of arable land and soil infertility (Table 3).

In the case study site, land holding size was 0.79 ha and crop productivity was 1422.21 kg/ha.

In terms of economic loss, on average about 0.07 ha (11%) of land and 69.23 kg (9%) of yield of crop was lost due to road-induced runoff (Table 4).

Table 3 Impact of road runoff on rainfed farming, living house and runoff intensity

Affected attributes		Frequency	%
Rainfed farm	Flooded	67	51.9
	Silted	67	51.9
	Eroded	39	30.2
Grazing land	Flooded	58	45
	Silted	56	43.4
	Eroded	20	15.5
House	Flooded	32	24.8
Runoff	Increased	69	53.5

Table 4 Impact of road runoff on agriculture

	Minimum	Maximum	Mean	Std. deviation
Farm size	0.25	1.5	0.79	0.28
Farm land loss (ha)	0	0.25	0.07	0.09
Annual yield (kg)	200	5400	1422.20	1002.03
Total yield loss (kg)	0	400	69.26	91.25
Percentage of farm land loss	0	100	10.88	15.70
Percentage of yield loss	0	72.73	8.95	13.05
Monetary loss (ETB)	0	3200	589.76	738.39

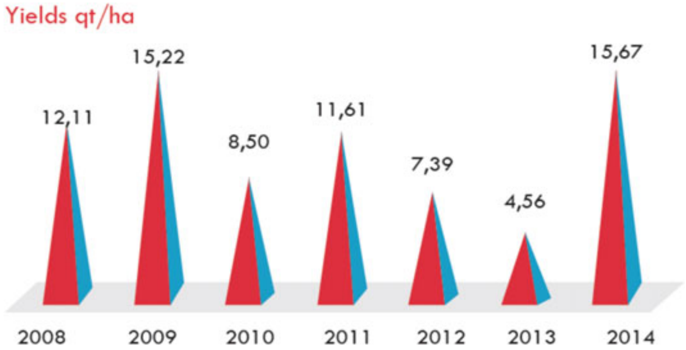

Fig. 16 Yield (in quintal) per hectares in Sinqata before and just after the road construction in 2013

However, road runoff can also have positive impacts if managed wisely. Figure 16 shows that the implementation of road water harvesting structures restored productivity in 2014 even though this was a relatively low-rainfall year.

Figure 16 presents the yield trend of the study area, seven years. From 2008 to 2009, there was slight yield increment due to availability of rainfall while in 2010 there was a decline due to low rainfall. Suddenly, during road construction period (2011–2013), as there was flooding and erosion, crop yield was reduced to 4.56 qt/ha. In response to this decrease on yields, from 2014 the water was diverted to a nearby borrow pit to retain road runoff and increase steady percolation of water. The yields were re-established and the maximum crop yield reached 15.8 qt/ha. There is hence a clear link between making use of roads for water and increased productivity and resilience. Some estimations determine that every 10% increase in yields in Africa leads to a 7% reduction in poverty (Pretty et al. 2011).

5 Conclusions

Road development is not only one of the major investments worldwide but also one of the practices that cause changes in runoff patterns in landscapes. Roads act as conveyance systems or as barriers and can cause water-related problems, if not managed. For road water to be managed and to minimize all the negative effects, there is a need to move towards the development of proper standards and approaches in the design and construction of roads.

The main reason for the link between roads and water not taking place at present is governance. At present, road development is largely single objective. The sole purpose of building roads is that of creating transport corridors. In many countries, there is no cooperation with other stakeholders for instance in agriculture or water resources nor a culture or practice of consulting roadside communities. Though indicated in the design guidelines to take care of environmental concerns, in practice, roads remain among the major causes of environmental problems. The designs and guidelines for road development do not consider the possible beneficial use of water along roads, but are primarily concerned with safeguarding roads from water damage. Among road builders, there is generally little consideration of the impact of roads on the environment immediately surrounding them, though indicated in their design manuals and standards.

To move from 'roads that cause harm' to 'roads for resilience' requires changes in the technology used, appreciation of the different contexts in which roads are developed, the introduction of consultative processes and importantly changes in governance. Governance needs to be multi-stakeholder and recognize the reduction of risk and the distribution of access to benefits. It requires sensitivity of the impact of different road water harvesting options for male and female livelihoods, better linkages to male/female roles in different socio-economic contexts, ensuring female representation in local consultation processes and consideration of special measures to engage and support female-headed households in better road water harvesting and other opportunities created by roads for resilience.

Acknowledgements The support of Netherlands Scientific Council (NWO) under the program 'Feeder road development for inclusive productive employment' in preparing this paper is acknowledged as well as the Global Resilience Partnership Program 'Connecting Roads, Water and Livelihoods for Resilience'. All the collaborating institutions mainly Tigray Bureau of Water Resources, Tigray Bureau of Transport and Road Construction, Tigray Bureau of Agriculture and Rural Development, REST, Amhara Bureau of Agriculture, Oromia Bureau of Water Mines and Energy, Oromia Bureau of Road Transport and Ethiopian Roads Authority are highly acknowledged for their relentless support.

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