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ABSTRACT:

The development of roads nowadays often has negative impacts. Roads cause floods and water logging along the way, whereas the more concentrated run-off from drains and culverts cause erosion and sedimentation. These negative impacts are often related with the practice in road engineering to evacuate water away from the roads as soon as possible rather than making use of the water for beneficial purposes.

This negative character however can be turned around and roads can be used as instruments for water harvesting. This can generate substantial positive impact especially as water is getting scarcer. With the investment in roads in many countries exceeding that of any other programmes, there is a large opportunity to improve the productive environment and increase the climate resilience of the population in the vicinity of the road.

In Tigray, the northernmost region of Ethiopia, steep slopes have been cultivated for many centuries and are subject to serious soil erosion. This problem can be exacerbated by improperly planned road development, posing a serious threat to the livelihoods of people who survive by subsistence agriculture on areas adjacent to the road. This article presents an assessment of the effects of the concentrated run-off from roads on the surrounding environment. It also explores the status and opportunities for water harvesting from roads in the Freweign-Hawzien-Abreha Weatsbeha-Wukro route in Tigray, Northern Ethiopia.

Water harvesting from roads: climate resilience in Tigray, Ethiopia

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1. Introduction

With 7-10 Billion USD invested annually in roads in Sub Saharan Africa alone and 70,000 kilometer of new road constructed a year, roads have a major impact on water management and on the environment immediately surrounding them (Kubbinga 2010).

In Sahel roads sometimes inadvertently cause sand dune movement – they open up deserts and create wind tunnels when positioned in the dominant wind direction. In the Mekong Delta in Vietnam and Cambodia roads affect flooding patterns but also fish movement. Roads serve as dikes in coastal zones as in Bangladesh, yet there is a sometimes compromised balance between transport convenience and flood protection safety standards.

In pastoral lowlands in South Sudan roads determine flooding patterns and hence moisture availability and with this timing to regenerate the grazing area through bushfires. Then, the proliferation of feeder roads in recent years has connected many previously remote areas, but the dust they create is a health issue and affects crop productivity too. In summary roads not only have a major impact on the transport of people, goods and services, but they equally have a major impact on the environment immediately surrounding them – the movement of water, sediment, wild-life and others. Roads have a particular important impact on water run-off, because the facto roads either serve as water embankment or a drain. Roads are one of the major elements in a landscape and their development and maintenance should preferably be managed that way.

The development of roads nowadays often has negative impacts. Roads cause floods and water logging along the way, whereas the more concentrated run-off from drains and culverts cause erosion and sedimentation. These negative impacts are often related with the practice in road engineering to evacuate water away from the roads as soon as possible rather than making use of the water for beneficial purposes.

This negative character however can be turned around and roads can be used as instruments for water harvesting. This can generate substantial positive impact especially as water is getting scarcer. With the investment in roads in many countries exceeding that of any other programmes, there is a large opportunity to improve the productive environment and increase the climate resilience of the population in the vicinity of the road.

In addition, road water harvesting can also contribute to road longevity. In many cases In Ethiopia for instance problematic drainage is the most common factor in construction delays and water is the cause of 35% of the road damage. Yet proper drainage on unpaved feeder roads is not only the essence of preventing damage but also creates the opportunities to divert water to adjacent farm land or storage reservoirs. Another example is that culverts and river crossings often trigger the development of gullies because they concentrate run-off. Given time these gullies will undermine the road itself too. Here again the foe can be turned into a friend by utilizing the water that exits from the culverts.

Road development changes the surface and sub-surface hydrology; roads massively change run-off patterns and can collect water from their own surfaces and this is a phenomena that should be put into beneficial use (García-Landarte et al. 2014). This paper discusses the program of road water harvesting in Tigray, Ethiopia where the negative is being changed into a positive. The paper discusses first the situation as it existed with much distributed damage (section 2) and then presents some highlights of the road water harvesting campaign that was started in 2014. The paper concludes with a plea that roads can contribute importantly to climate resilience not by making the road itself climate proof but by contributing to better resource management in the surrounding landscape whilst at the same time safeguarding the integrity and sustainability of the roads.

2. The negative impact from road development

This section discusses research on road impact undertaken along the route Freweign-Hawzien-Abreha Weatsbeha-Wukro in Tigray, Northern Ethiopia in 2013-2015. This road section of 64 kilometer length crosses three woredas (districts): Saesie Tsaeda Emba (woreda center is Freweign town), Hawzien woreda (woreda center is Hawzien town), and (c) Klite Awlaelo woreda (woreda center is Wukro town) (Figure 1). The surveyed routes include both feeder roads and asphalt: Freweign-Megab route is asphalt, and Megab-Abreha Weatsbeha-Wukro route is all weather gravel road.

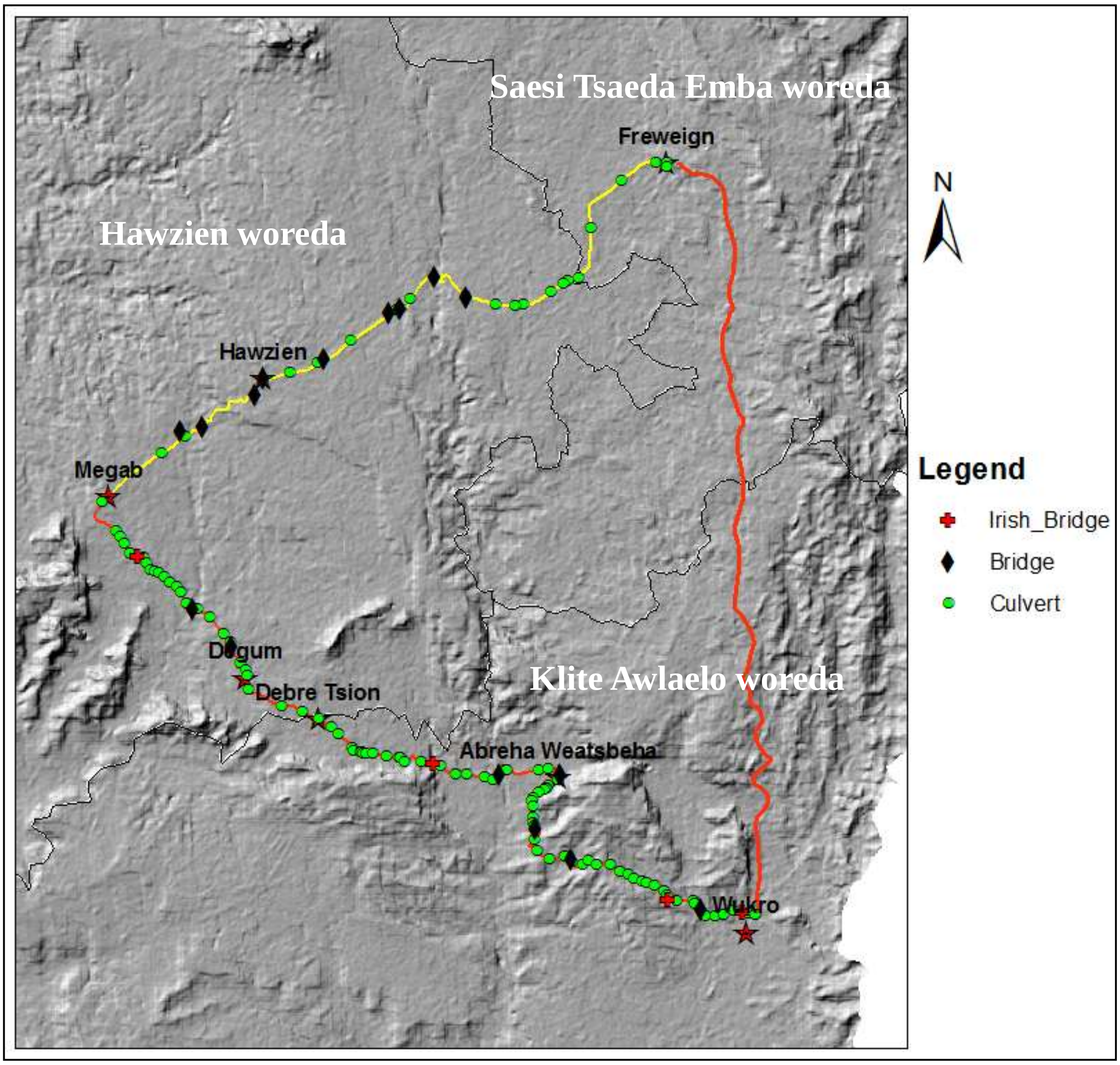

Figure 1. Location map of the Freweign-Hawzien-Abreha Weatsbeha route, Tigray, Northern Ethiopia.

According to the Ethiopian CSA (2007), an estimated total population of 236,486 (51.7% female, 48.3% male) live in the three aforementioned woredas. About 76.4% of the total population live in rural areas. Communities in the study area have been food insecure for a number of reasons including land degradation, water insecurity due to short rainy season coupled with high rainfall variability between seasons, small land size that rarely exceeds 0.5 ha per family and absence of irrigation practices.

The landscape of the study area presents a wide range of landforms. The slope gradients range from flat plains to over 40%. The geohydrology of Tigray region in general and the study route in particular is highly variable. Silty sand soils are the most dominant type along the route. Results of inverse auger hole test revealed that the permeability of these soils ranges from $2.5*10^{-2}$ cm/sec to $3.4*10^{-3}$cm/sec. Most of the unconsolidated sediments along the route are categorized as good aquifers for shallow groundwater development. This has led to extensive shallow groundwater development in the plains of the study area. Groundwater is the main source of water for domestic use in the area. Moreover, shallow groundwater is increasingly used for small-scale irrigation in the area (Woldearegay and van Steenbergen, 2014). Out of the total 1800 hectares of potential irrigable land, 550 ha was irrigated in the year 2013 using shallow groundwater mainly. In the year 2014, the irrigated land has increased to 610 ha using shallow groundwater systems. The maximum land size that a single farmer was able to irrigate in the year 2013 (using shallow groundwater and other sources) in the area was 30% of the cultivable land. The limiting factor for irrigation expansion in the area is shortage of water.

As mentioned, 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 water logging and flooding; and sites where efforts have been made to implement different soil and water conservation measures along a 5 kilometer radius from the main route. The survey was carried out in the period of July to September 2013.

The survey result revealed that a number of problems have been created due to water from roads which include: (a) erosion (downstream areas and road sides), (b) siltation/sedimentation of downstream, upstream, and side drainage areas, (c) water logging and damage on dwelling houses and on water harvesting systems (groundwater wells and ponds). In the 64 kilometre of roads there were 159 problems spots - close to 3 per kilometer. By and large these damage undermined the climate resilience of the road side communities.

Effects gully erosion: From a total of 118 culverts found along the road, gully erosion was recorded at downstream of 68 culvert locations. Gullies have a severe effect on agricultural activities; they reduce the water tables, affecting the availability of soil moisture and hence agricultural production. Once deepened, gullies decrease the accessibility of the land and can cause damage to all infrastructure (Frankl et al. 2012), including the road bodies that caused the gullying in the first place. The size of the surveyed gullies were found to be variable: 1 to 4.5 m deep, and 1.5 to 5m wide. The length ranged from 10m to over 500m. In 35 locations, road side erosion was recorded. Expansion of gullies and creation of new ones is common in the study area. In all the erosion affected sites, gullies have terminated after reaching the bedrock. Soil samples were collected from the field and analyzed in the laboratory to evaluate the in-situ moisture distribution across a gully site. Results of the analysis (Table 1) showed that the in-situ moisture content of the soil increased with increase in distance from the gully. Close to the gully the moisture content was no more than 8% but at 10m away from the gully the moisture content reached up to 45%. A reduction of soil moisture results in loss of productivity and increase expenditure in fertilizers to maintain yields as natural nitrogen fixation is closely linked to soil moisture (Morgan, 2005). Crops close to the gully have shown early maturation due to less moisture content in the soil, which has a direct effect on the yield.

Table 1: Moisture distribution across a gully (LS= Left Side; RS= Right Side) in Freweign area, Tigray, Northern Ethiopia. Note that the depth of sampling was 0.5m and the soil type in the site is silty sand type. Samples were collected one day after a 50mm rainfall in the area.

Sample Code	***Distance from gully (m)***	***Moisture content (%)***	***Soil type***
LS01	1	5	Silty sand
LS02	5	18	Silty sand
LS03	10	38	Silty sand
RS01	1	8	Silty sand
RS02	5	26	Silty sand
RS03	10	45	Silty sand

Effects on siltation/sedimentation: Sedimentation problems were recorded at 15 culvert out of 118 locations and at 5 road sides. The sediments have affected the road drainage systems and water harvesting structures like ponds and shallow groundwater wells. As a result, farmlands have been affected due to flooding and excessive accumulation of sediments on the farmland has forced farmers to plough and saw up to 3 times. In some cases, however, the accumulation of sediments has become an opportunity for sand mining; providing an extra source of income for some households. This could even be optimized by systematic reversal of the slopes of side drains.

Effects on waterlogging: at 37 locations along the road alignment water logging was recorded/documented. Waterlogged areas include farm lands, grazing lands, and water harvesting schemes (like shallow groundwater wells). The causes for waterlogging observed during the field survey were due to one or a combination of the following: (a) inlet level of the culvert being higher than the upstream ground level, (b) outlet level of the culvert being lower than the downstream ground level, (c) reduction in pipe diameter due to siltation/sedimentation problems, and (d) absence of drainage systems and/or improper locations of drainage systems.

Effects on flooding: In 34 locations, water from culverts and road side drains had caused flooding of farmlands, ponds, and shallow hand-dug wells. The flooding caused damage to dwelling houses, silting-up of ponds and shallow groundwater wells. In one event in 2013 46 houses were destroyed. In the most flood prone land the uncontrolled flooding of farm land forced farmers to replant their land up to two or three times

3. The positive impact of road water harvesting

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 the mass mobilization campaign of June-July 2014 when farmers provide labor days for watershed improvement. The main technologies and approaches implemented were: (a) use of pits/ponds to collect road side drainage, (b) channeling water from culverts and road side drainage into series of deep trenches, (c) use of borrow pits (for surface water storage and groundwater recharge), (d) channeling water from culverts and road sides to farm lands, (e) shallow groundwater development upstream of Irish bridges and fords and (f) reuse of borrow pits for water storage and groundwater recharge.

Use of ponds/pits to harvest water from roads: Since 2010, ponds have been constructed to collect water from any source including road-side 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 channeled 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.

Channeling water from bridges, culverts and road sides into series of deep trenches: In 7 locations along the route, water from culverts and road side drainages was channeled into deep trenches (Figure 2a). Deep trenches are often used to control runoff and enhance groundwater recharge processes. 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 (Figure 2b).

Figure 2a. 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.

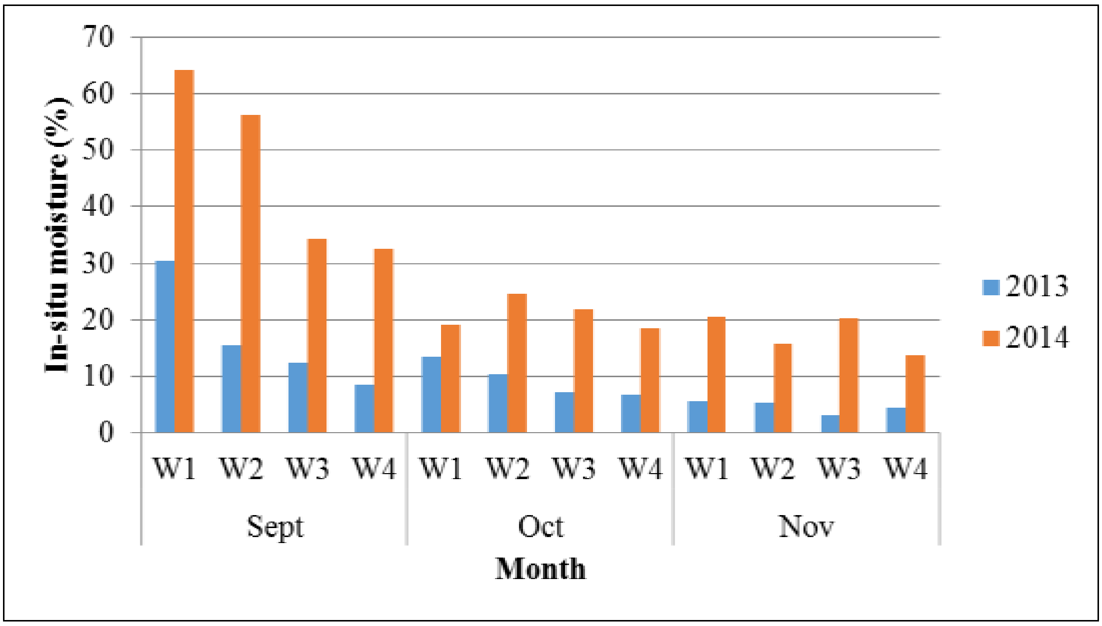

Figure 2b. In-situ moisture distribution in soils (before and after the construction of deep trenches at downstream of culverts in Megab area, Tigray, Ethiopia. Construction of the deep trench was done on June 2014. Monitoring was done for the period September-November for both years (2013 and 2014). (W1= Week one; W2=Week two; W3=Week three and W4=Week four).

Channeling water from culverts and road sides into farm lands: Diverting runoff (from road sides and culverts) into farm lands (Figure 3a) is one of the technologies implemented in Tigray. The purpose is to enhance availability of water for crop production. In-situ soil moisture measurement results (Figure 3a) 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%).

Figure 3a. Diverting roadside runoff into farm lands as part of moisture conservation in Kiken area (along Mekelle-Wukro road), Tigray, Ethiopia.

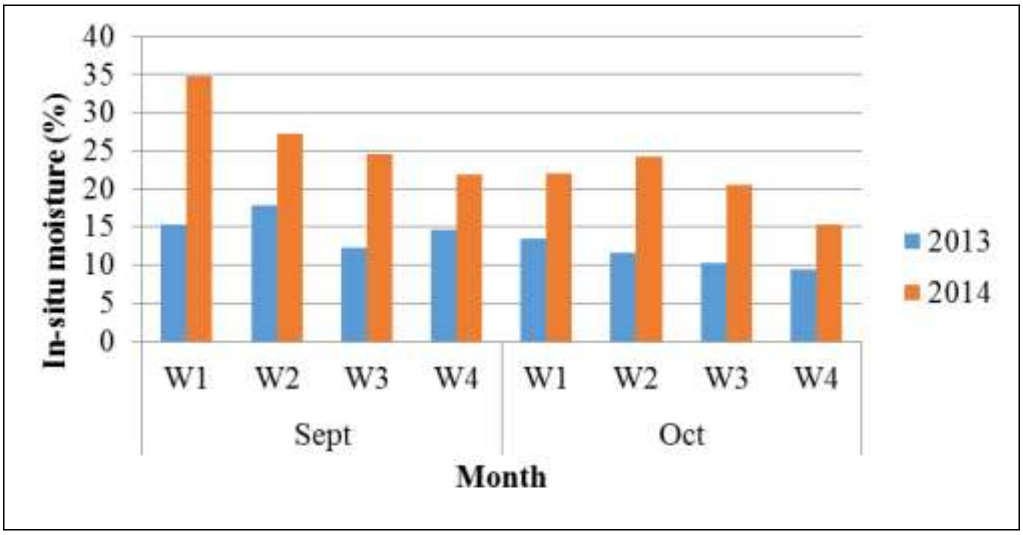

Figure 3b. In-situ moisture distribution in soils (before and after the construction of structures that divert runoff from culverts into farm lands along the Mekelle-Wukro road (Kihen), Tigray, Ethiopia. Construction of the diversion structures was done on May-June 2014. Monitoring was done for the period September-October for both years (2013 and 2014). (W1= Week one; W2=Week two; W3=Week three and W4=Week four).

Channeling water from bridges, culverts, and road sides 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 road sides and for the purpose of enhancing groundwater recharge check-dams are constructed in many parts of Tigray (e.g. Figure 4a). Results of the groundwater level measurement shows that due to the construction of the check-dam, the shallow well which used to have no yield in the dry season has become very productive even in the dry season (Figure 4b).

Figure 4a. Channelling water from a culvert into a check-dam is enhancing groundwater in Selekleka area, Tigray, Ethiopia.

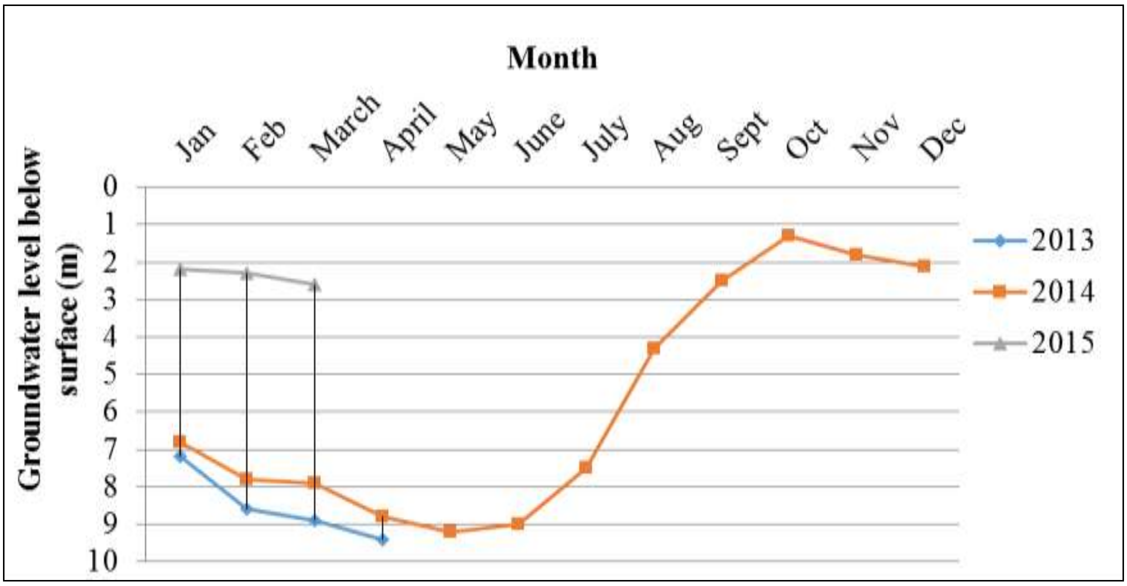

Figure 4b. Groundwater fluctuation in Selekleka area, Tigray, Ethiopia (at downstream of a check-dam which was constructed in the period January-May, 2014). The check-dam is designed to store water from a box culvert. New groundwater is created at downstream of the box culvert and the construction of the check-dam has enhanced groundwater level in the area.

Shallow groundwater development upstream of Irish bridges: Along the Freweign-Hawzien-Abreha Weatsbeha-Wukro route, 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: close to Freweign catchment run-off 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 run-off through a 3 kilometer long canal to the river, but this would require considerable land acquisition. A more cost effective solution was used when a 250 meter long canal was excavated to the borrow pit which was converted 5000 cubic meter storage and recharge pond.

4. Conclusions: redefining climate resilience from roads

The potential for water harvesting from roads and in particular roaded catchments in Tigray and in many parts of Africa is high. Road development is one of the major public investments and significantly alters the hydrology. If not managed properly, water from roads causes problems to the surrounding areas and to the roads themselves. Through the proper integration of road development with water harvesting, the negative effects of water from roads could be turned into positive. In Ethiopia and in many part of Africa there is shortage of water during dry seasons and water harvesting remains one of the most important considerations for enhancing agricultural productivity. For example, the 64 kilometer road that was investigated passes almost through the water divide in Tigray: about 1.34Million Cubic meter of surface water could be harvested without major investment. At the same time water-related road maintenance costs can be reduced, which now stand at 35%, a figure that may be higher if road water-related land-slides are included.

In the 2014 campaign described in section 3 adjustments were made that made use of the road as it was and saw a large number of water harvesting structures implemented. There is a need to go one level up and to consider modified road design that optimize both transport functions as well as the beneficial use that roads can have on water management. In many areas – but it semi-arid mountain or flood plain this is essential. There a number of recommendation so as to integrate road development with water harvesting:

- When planning road development in a certain catchment it is important to look at options on how water from a road (drains, culverts, bridges, fords, road surface) could be harvested for economic benefit of the local communities. This concerns both paved and unpaved roads. In paved road the beneficial use of water from cross drainage structures is a main opportunity. In unpaved roads the development of water bars and led out drains can be combined with water harvesting and create the incentive for maintaining these essential drainage structures

- The location, alignment and size of drainage systems (culverts, road side drainages, etc) and in some cases the entire alignment of the road should be designed with the objective of harvesting water from roads either to be collected into surface water reservoirs or used for groundwater recharge. This requires an understanding and evaluation of the surface as well as subsurface geohydrology of the area.
- There is large scope to optimize the designs of road bodies: in cross drainage, in road subsurface, in fords, in systematic capture of road-side springs. Borrow pits development (for the extraction of construction material) for instance is one of the major activities in road construction. It is advisable that the location and size of the borrow pit to be developed is identified during/or even before the final design of the road is made. Based on this the locations of culverts and even the road alignment could be designed in such a way that water from roads (road side drainages, culverts, bridges) is channeled into borrow pits and they are shaped accordingly. Using borrow pits for surface water storage as well as groundwater recharge is one of the best options in road design and construction.
- Water harvesting from roads could be implemented effectively if road development in a certain catchment is considered as part of the watershed/catchment development plan. Through such approach, the possible negative effects of water from roads and options for mitigating such problems through water harvesting and natural resources management could be implemented.
- Water harvesting from roads involves multi-stakeholders. For water harvesting from roads to be implemented effectively there should be strong linkages and cooperation among the sectors through a more powerful body but with clear tasks and responsibilities for each stakeholder. In the program in Tigray it become clear that the cooperation and linkages among the stakeholders at field level is essential. There is a need to include road side communities in the design and implementation of the road and water programs and also to regulate access to the new water resources generated for male and female community members.

There has been recent attention to make roads more climate resilient. In some work design standards have been proposed to be adjusted to make road bodies and drainage system better able to deal with higher temperatures and steeper floods. This has however often led to road designs that are far more costly – making it difficult to expand the coverage of the road network, which is essential for many developing areas.

We believe that the above – to make the roads themselves more climate resilient - is a partly misguided approach. It makes more sense to develop roads so as to optimize their hydrological potential for water harvesting and others. This will very positively contribute to water security in view of climate change and improve the resilience of those living close to the roads. It will turn the negative impact on climate resilience of road-side communities into a positive and contribute to productive growth. At the same time rather than increasing costs, it will importantly reduce the cost of road maintenance

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