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Investigation of Failures in Wadi-Crossing Pipe Culverts, Sennar State, Sudan

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***Abstract*—**Crossing culverts are essential element of rural roads. The paper aims to investigate failures of recently constructed wadi-crossing pipe culverts in Sennar state and provide necessary remedial measures. The investigation is conducted to provide an extensive diagnosis study in order to find out the main structural and hydrological weaknesses of the culverts. Literature of steel pipe culverts related to construction practices and common types of culvert failures and their appropriate mitigation measures were reviewed. A detailed field survey was conducted to detect failures and defects appeared on the existing culverts. The results revealed that seepage of water through the embankment and foundation of the culverts leads to excessive erosion and scouring causing sever failures and damages. The design mistakes and poor construction were detected as the main causes of culverts failures. For sustainability of the culverts, various remedial measures are recommended to be considered in urgent rehabilitation of the existing crossings.

***Keywords*—**Culvert, erosion, failure, sustainability.

I. Introduction

RURAL, low-volume, and farm-to-market access roads are significant parts of any transportation system. They are necessary to serve the public in rural areas, to improve the flow of goods and services, to help promote development, public health and education [1]. When these roads pass over rivers and wadis, they need crossing structures such as culverts and bridges. The communities' activities depend on functioning road networks and safe crossings. Unfortunately, because of their improper design and poor construction, many crossings in rural areas are more likely to sustain damage from water runoff and large storms [2]. When culverts fail, the road is also frequently damaged and in extreme cases, the road can wash out and be closed for many days. This critical situation can isolate the inhabitants of the surroundings villages and prevent emergency services from reaching people in need of help. Road closures also cause travel delays, lost income for local businesses on these routes, and lost income for those who can't access their places of work. Yet crossings can be properly designed to avoid these problems [1]. Improved wadi-crossings deliver social and economic benefits and are a key element of adapting crossings culverts to climate change. In fact, their construction cost is a burden to poor countries [2].

Recently, many rural areas in Sudan are facing very serious drainage problems during the rainy season (June to September). As a result, vehicles flow is completely ceased for a long period due to inaccessible roads. This situation has adverse impacts on transportation and social activities. IFAD has financed a project for constructing market access crossings in Sennar state to facilitate the people movements a cross khors and wadis [3]. The design engineer of the project has used large diameter flexible pipe culverts (corrugated steel pipes) to replace small bridges and have realized significant savings to the project. However, there is a perception that in some situations, these· flexible pipe culverts have not performed adequately. Shortly after construction and the last raining season, the crossings culverts suffered from water erosion and damages [3]. Therefore, the purpose of this research is to study the prevailing situation of the crossings in order to identify the causes of failures and to suggest technical measures for urgent rehabilitation.

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II. Literature Review

A. General

Culverts are commonly used as cross-drains for ditch relief and to pass water under natural drainage and stream crossings. Culverts are made of concrete or metal (corrugated steel or aluminum), and plastic pipe is occasionally used, as well as wood and masonry. The type of materials used depends on cost and availability of these materials. Generally, concrete and metal pipes are more durable compared to plastic pipes. The culverts are commonly used in different shapes, namely round pipes; arch pipes; structural arch; and box, depending on the site, the required span and the permissible height of backfill soil [1]. Culverts need to be properly sized and installed, and protected from erosion and scour. The key factors in culvert selection are that the culvert has adequate flow capacity, fits the site, and that the installation is cost-effective, [4].

B. Culvert Installation

Culvert installation for drainage crossings is quite important process for sustainability of the culvert, [1]. Important installation details include install culverts at natural stream grade, using quality, well compacted bedding and backfill material; and using inlet, outlet, and stream bank protection measures, [5]. Culvert installation at natural stream levels and protection of backfill materials are shown in Fig. 1. Bedding and backfill material for culverts is commonly specified as “select granular material”. However, any soil of low moisture, mud, roots, expansive clay, and boulders can be used. Bedding material beneath the pipe should not have rocks larger than 3.8 cm. Clay soil can be used if it is carefully compacted at a uniform, near optimum moisture content, [4].

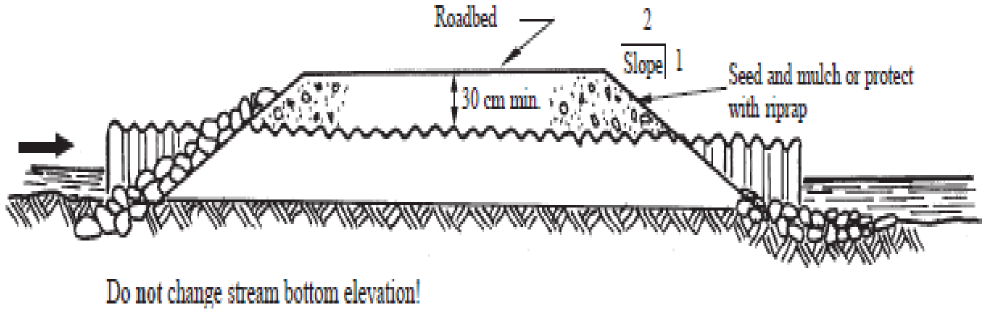

Fig. 1 Install culvert at natural stream grade [1]

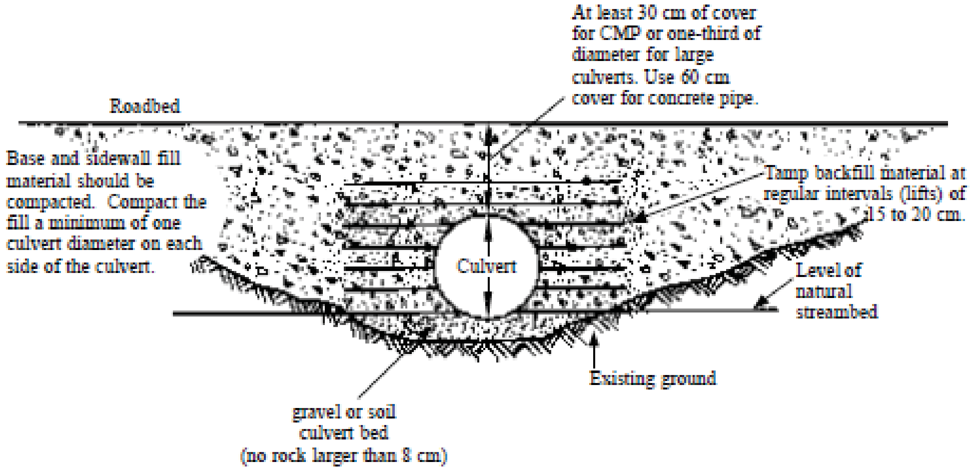

Fig. 2 Culvert backfill and compaction [4]

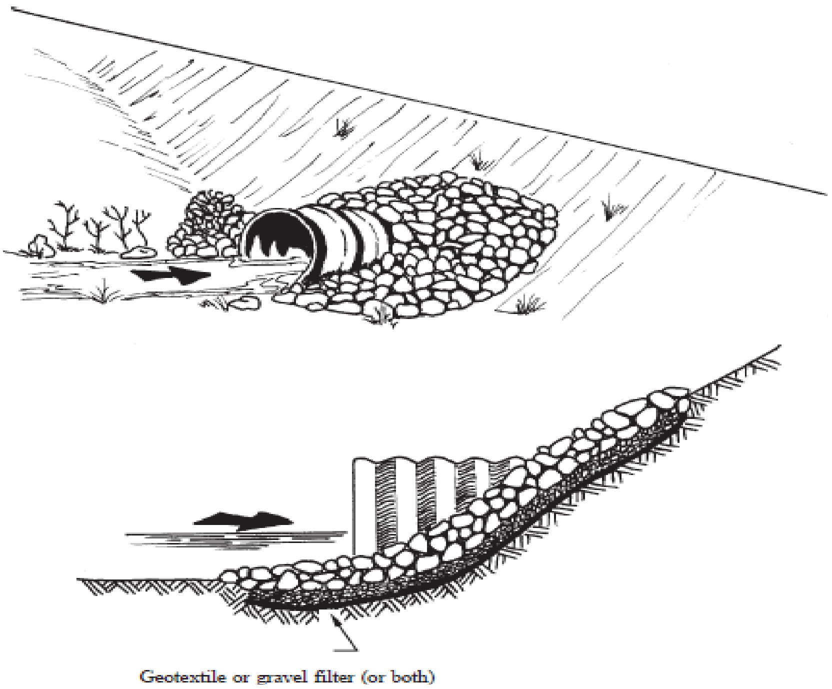

Fig. 3 Normal metal culvert installation using riprap around inlet and outlets of culverts [6]

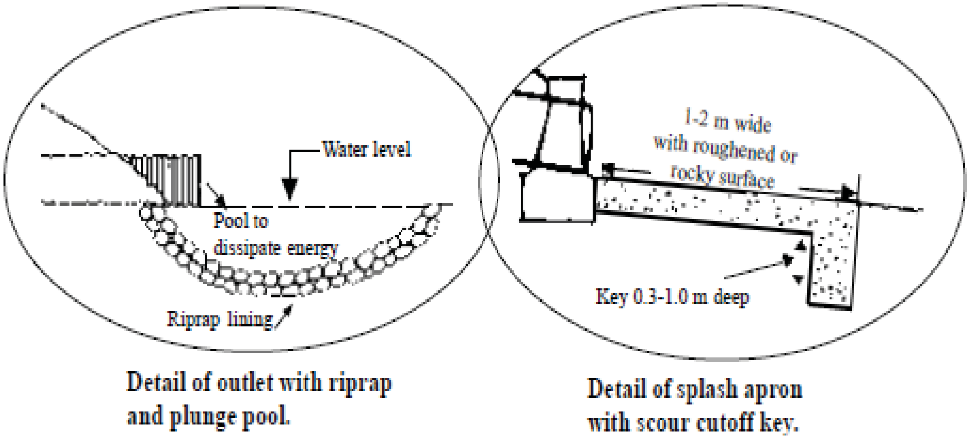

Fig. 4 Culvert installation with outlet protection details using splash apron or riprap lined plunge [4]

To prevent pipe crushing by heavy trucks, backfill of 30 cm minimum thickness must be used to cover the corrugated steel pipe culverts. It is essential to use well-graded fill materials and avoid using fine sand and silt soils because of their susceptibility to piping. The fill materials must be well compacted in layers as shown in Fig. 2. [4].

To prevent water erosion and improve culvert efficiency at the inlet and outlet of culverts, riprap, flared metal end sections, masonry or concrete are required for protection of headwalls [5]. As shown in Fig. 3, graded gravels (or rocks) and a geotextile filter are used for slope protection under riprap [6], [7].

To protect the apron at culvert outlet, a plunge pool, riprap or a splash apron with a rock surface and cutoff key are recommended to be used (see Fig. 4) [4].

C. Culvert Failures

Failure or damage of a culvert is resulting from water erosion of embankments due to insufficient culvert capacity and/or inefficient end sections. The inadequate capacity may be a result of inappropriate hydrologic analysis of flood peaks and volumes, and/or application of inappropriate culvert design criteria. Careful determination of the cause for the damage is necessary, as different causes require different mitigation, [8]. The culverts failure may occur due to deformation of the pipes, backfill failures, and damages of culvert inlets, outlets, head and wing walls and/or foundation failure.

The manner in which a culvert fails by deformation has been described clearly by [9]. The deformation failure description is given below and is illustrated on Fig. 5. A flexible culvert will deform under the vertical backfill load, with vertical diameter decreasing and the horizontal diameter increasing. The outward movement of the sides of the culvert against the backfill develops the passive resistance of the backfill soil which acts horizontally against the culvert. The horizontal passive backfill resistance keeps the actual deformation of the culvert considerably below the amount of culvert would deform if located by the backfill, but without lateral support.

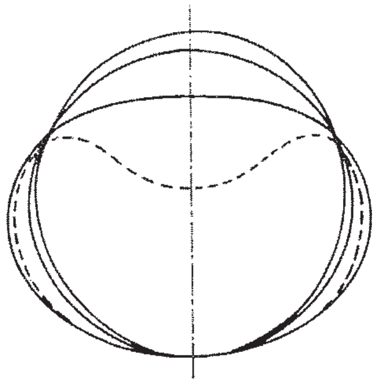

Fig. 5 Stages during deformation of a flexible culvert [9]

TABLE I
COMMON TYPES OF CULVERT FAILURES AND THEIR APPROPRIATE MITIGATION MEASURES [8]

Failure	Mitigation Measures
Embankment erosion at inlets and/or outlet, or around the outside of the culvert.	– Shape culvert entrance – Construct a cutoff wall – Install appropriate culvert end sections – Construct an energy dissipater – Extend culvert inlet or outlet – Place riprap along eroded slope
Road surface and shoulder erosion caused by water flowing over the top of the roadway	– Increase roadway elevation – Construct shoulder protection - increase capacity of culvert by adding more drainage structure
Overtopping and/or erosion of head walls due to insufficient culvert capacity and/or inefficient inlets and outlets.	– Replace with larger pipe culvert – Increase efficiency of entrance and/or outlet design – Change culvert alignment – Add multiple pipe culverts – Replace with a bridge – Install a high water overflow crossing
Plugging of the culvert with debris and/or silt.	– Install an entrance debris barrier – Install a sediment catch basin – Install a relief culvert – Install a perforated standpipe
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FEMA [8] has provided hazard mitigation programs that help communities to reduce or eliminate future disaster damage in roads and culverts. Some common types of failures in culverts and various mitigation measures provided are presented in Table I.

When culverts fail, there are safety impacts as roads become unsafe to travel and communities become separated from the emergency services they require. Due to culvert failures, the closures of road for repair may prevent people to access their jobs, other social activities, and emergency services. In Tropical Storm Irene event, due to failure of bridge and road thirteen Vermont towns near the Green Mountain National Forest were separated from main roads [10].

People who use roads impacted by culvert failures are likely to experience travel delays and may need to travel longer distances due to closures and detours, resulting in lost productivity. Road closures can lead to lost days of work for businesses located on the road or employees residing on roads that are closed, resulting in lost income. Perrin and Jhaveri [11] on their study of culvert failures in USA found that the user delays cost as a major portion in emergency maintenance costs is 4 to 140 times greater than routine and planned maintenance costs. It can be challenging to estimate these costs, particularly on smaller roads where data about traffic volume and types of vehicles on the road are unavailable.

The major costs of culverts problems can be avoided by upgrading wadi crossings are the expenditures for the repair of roads and other infrastructure that are damaged as a result of inadequately sized culverts. Undersized crossings are more likely to fail when there are extreme flows of water in the wadi, and they may be clogged by debris during major floods. Thus, serious failure of the road at the site leads to downstream flooding. A study of culvert washed out during Tropical Storm Irene was conducted at a site in Vermont and the results revealed that the cost of road repair alone was $1.1 million [10].

Like social benefits, most of the economic benefits of improved road-stream crossings result from avoided flooding. While flood damage costs potentially avoided by upgraded culvert crossings, it is very difficult to properly quantify theses damages. A recent study found that estimating the full range of economic costs from natural disasters is both conceptually and practically difficult. Data on disaster impacts are insufficient, not systematic and most data sets are underestimates of all losses [12].

III. Case Study

The objective of this investigation is to provide an extensive diagnosis to find out the structural and hydrological weaknesses of the failed culverts. The investigation based on an extensive visual inspection and the design and construction data of the culverts. The diagnosis had to emphasize the embankment, inlets and outlets and foundation structural conditions. The study was concentrated on wadi-crossings culverts in Sennar state.

The methodology adopted in this investigation is based on two sequential phases, Phase I is office work and Phase II is field survey. Phase I covered all the office work required for the study. The office work involves in data collection and design review from the available documents. Phase II composed of site inspection and analysis.

A. Project Description

IFAD has financed a project for constructing market access crossings (wadis crossings) to facilitate the people movements a cross khors and wadis in Sennar state. The project title is Supporting Small–Scale Traditional Rain-fed Producers in Sennar State (SUSTAIN) which aims to reduce poverty, increase food security and incomes of about twenty thousand rural households in the project area. Its main objective is to increase productivity for marketing and cash crops for the people in Sennar state.

There are twenty nine crossing were constructed at different locations, twenty three crossings in Aldindir and nine crossings in Almazmoum. The pipes used in this project are manufactured from corrugated sheets of galvanized steel. These pipes are available in a variety of lengths and diameters. They are assembled from rounded segments by bolting them together on site. Shortly after construction, the crossings culverts suffered from water erosion and damages occurred in the embankment, wing walls, inlets and outlets. Thus, it is essential to investigate the failures occurred in the culverts.

B. Records Review

A detailed records review was conducted with the great help of IFAD staff, Sinja office in Sennar state to obtain some information about the design and contract documents of the project. The documents contain information data about the project history, pipe culvert design, construction materials properties and specifications, laboratory tests results, construction and contract records, and other relevant information such as soil or geological records, and weather or rainfall data. These collected data are very important for both the field survey task and the evaluation process of the crossings. The documents available for reviewing include: inception report; investigation and design report; technical Specification; design sheets; bill of quantities; as built drawings; and Laboratory tests results.

C. Field Survey

The author with a technical team had conducted a visual inspection for some crossings in Aldindir and Almazmoum to detect any defects and failures in the crossing embankment and culvert structure. While this survey covered 29 crossings, the results were surprising in that the percentage of the pipes that failed were higher than expected. In small pipes of 90 cm diameter, 10 percent or less of the surveyed culverts had failed, but in the larger diameter pipes (120, 160, 180 and 240 cm) the percentages of failures were significantly higher. The general observations and comments on most of the surveyed culverts are briefly described in paragraphs below.

It was clearly observed that the side edges of the top embankments and the head walls of the culvert are much suffered from serious failures due to excessive water erosion.

Severe cracks and potholes were clearly seen on top embankment especially at the edges nearby the pipes inlets and outlets. Also the head walls of the pipes showed severed failures and collapse of the gabion mesh used to protect the embankment around the pipes as shown in Fig. 6. The gabion mesh was placed between the pipes only without any link between them. The gabion mesh was fall down when the embankment failure occurred due to water erosion.

Fig. 6 Severe cracks and potholes on embankment edges due to water erosion

Fig. 7 Collapse and failure of wing walls embankment due to water scouring

It was observed also partial breaching and weakening of the wing wall embankments at inlets and outlets of culverts which may result in complete collapse. This embankment weakening was happening mainly due to scouring effect of the incoming wadi which flows adjacent to the embankment section parallel to the crossing axis. This scouring has caused the embankment slope to get steeper and has increased the wadi depth which has increased the embankment height that can lead to failure. During the rainy season, this steeper section was falling into the wadi where it got saturated and washed downstream. In some crossings, the embankment has changed its original section, dimension and shape throughout the entire length of the crossing where the top embankment is narrowed and the side edges with severe cracks and potholes and the slopes at inlets are flattened in some sections and steeped at others (see Fig. 7).

In addition to breaching and weakening of the embankment, the other concern observed in the crossings is sediment deposition and vegetation in the apron area of outlets. The sediment deposition has reduced the storage capacity of the pipes by significant volume. This is mainly due to huge sediment load from the catchment area which leads to reduction in pipes capacity (see Fig. 8).

Fig. 8 Sediment deposition and vegetation in the apron area

In most crossings, it was observed that the wing walls of the inlets and outlets which are protected by gabion mesh showed better performance than the head walls as shown in Fig. 9. While in very few crossings, the mesh of the gabion missed or opened and some of the stones were thrown away from the walls. This problem may adversely affect the stability of embankment slope.

Fig. 9 The gabion mesh used for lining of wing walls

It is clearly observed from Fig. 10 that the subbase layer laid on the embankment is becoming very thin (i.e. thickness less than 20 cm) to support the traffic loading and partially accumulated at the sides. As a result, the underneath embankment of clayey soil suffered from severe cracking and potholes occurred at edges above the pipes inlets and outlets.

Fig. 10 Sever cracks and potholes on Subbase and embankment layers

It was noticed that the Fresh crossing in west Aldindir was properly design and constructed. The pipes are protected with a head wall build of brickworks and the side wing walls are lined with stone pitching as shown in Fig. 11. It is clearly observed that the crossing is in a good condition particularly in the inlets and outlets of the pipes.

Fig. 11 Head and wing walls of the Fresh crossing are in good condition

IV. Results and Discussion

To a chief the objective of this investigation, the documents reviewing and the site inspection were analyzed to diagnosis and find out the probable causes of the failures and defects appeared on the crossings structures. Water is the main contributor to the wear and damage of embankments. The runoff water on the embankment and through the foundation of the pipe culverts may lead to excessive scouring and erosion causing sever failures. The following are prevailing situations that resulted in failures.

A. Water Erosion

Water seeping through the earth embankment may have many adverse effects:

1) Runoff and Seeping water generated erosive force which dislodged particles from the soil structure and then by washing away soil particles caused scouring and erosion.
2) Internal erosion of the soil mass finally progressed from the top embankment to form potholes and serious cracks.
3) The internal pressure in the soil water was able to reduce that part of the soil strength that was developed by internal friction thereby, leading to weakening of the soil mass and even failure by shear.
4) Water flow through the pipes with low speed deposited soils (silting) which obstructed the passage of water.

B. Improper Design

The most probable cause of culverts failures may be due to improper design. The gabion mesh used as wall protection for the pipes have no link with each other. As embankment failure occurred by water erosion, the gabion meshes were completely fall down due to shear forces. Thus leading to collapsing and wash away with water at inlets and outlets sides. The design of the culverts is inadequate for the following reasons.

1) The culverts inlets and outlets used in this project are the projecting inlets where the pipes extend from the fill with a significant pipe distance uncovered by the fill. The force available to resist uplift pressures which expose by expansive clay in this uncovered length consists only of the weight of the pipe and water within the pipe. This condition creates the most severe situation possible for uplift failure.
2) Headwalls around the culvert inlet and outlet serves to protect the embankment on top of the culvert pipes. Together with the wing walls, the head walls also act as collectors, directing the water to the pipes. The gabion mesh used for headwalls protection has proved instable and impractical technique because when erosion occurred in embankments of the headwalls it was collapsed. While the gabion mesh used for wing walls lining showed better condition because of the relatively large surface area with reasonable slope. The gabion mesh used for head walls protection for the pipes have no link with each other. As embankment failure occurred by water erosion, the gabion meshes were completely fall down due to shear forces, thus, leading to collapsing and wash away with water at inlets and outlets sides.
3) The embankment used above the pipes has thickness about 60 cm for large pipe diameter 2.4 m. This thickness is too small to resist traffic loads as previously explained in the literature.

C. Poor Construction

The embankment close to the wing walls of culverts got saturated due to excessive seepage. It was eroded, producing small slumps/slides presenting relatively steep faces which once again became saturated by seepage from the inlets and slumped again, forming slightly higher and unstable faces. This raveling process kept on going until the remaining portion of the embankment became too thin to withstand the water pressure, thus leading to the collapse of embankment and wing-walls.

Improper compaction of the approach sections, before and after the culvert was observed. Thus, it continued to settle due to traffic moving on the road. The culvert pipe is a rigid structure so the section above the culvert pipe was subjected to less settlement compared with the adjoining sections. As a result, the traffic caused more consolidation of the road embankment before and after the culvert, and the road embankment section directly above the culvert much suffered from improper compaction which causes bumps in the road surface.

D. Poor Quality Control

The quality control for construction process and materials is very essential. In this project, the contractor was requested to submit any quality control documents performed during the construction of the crossings. Unfortunately, he submitted only few tests results of embankment. The field density for compaction of the embankment layers is not available. The quality control during construction was limited and very poor. As a result, the quality of construction is very poor and many defects and damages occurred.

V. CONCLUSIONS

This research work has been undertaken to investigate the failures of the constructed wadi-crossings culverts and provide corrective measures. Some of the important conclusions drawn from this study are summarized as follows:

- Significant failures and damages were observed in embankments, head walls and aprons of the culverts. However, the sever failure occurred in the head walls of inlets and outlets of the culverts as the result of water erosion and scouring.
- The deterioration of the embankment is more serious and occurred more rapidly. This may lead to higher maintenance demands and in the worst cases result in serious damage which may obstruct the passage of traffic.
- Damage and wear to the crossing culverts can be reduced if the runoff water is properly controlled and regular maintenance is provided to repair minor damages.
- It was pointed out that the main causes of culverts failures are design mistakes, poor construction and inadequate water control. Therefore, culverts need to be properly designed and installed, and protected from erosion and scour by applying effective drainage measures.
- For sustainability of the crossing culverts, regular maintenance is needed. Government authorities should consider providing a specific budget on an annual basis for both maintenance and improvement works. Also a program for cleaning out the pipes is essential. Inlets and outlets of culverts need to be cleaned and maintained regularly.

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