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Optimal Pavement Management: Resilient roads in support of emergency response of Cyclone Affected Coastal Areas

Abstract

Roads in poor road condition disrupt emergency operations in disaster-prone areas during emergency periods. Prolonged inundation of pavements from storm surge accelerates deterioration of pavements and increases maintenance cost. The objective of this study is to propose an optimized decision support system for pavement maintenance and rehabilitation (M&R) operations guided by geo-physical risk and community vulnerabilities. A case study of regional highways, arterial and collector roads at the district of Barguna, in Bangladesh is selected given the frequency of cyclones and storm surges in this area. A geo-physical risk and vulnerability (*GEOPHRIV*) index was estimated for each road's segment by integrating the geo-physical risk; community, structure and infrastructure vulnerabilities; and damage indices. Linear programming was applied to optimize M&R strategies to ensure good pavement condition for all roads at a minimum M&R budget. Lifecycle optimization of M&R operations estimated that USD 2.49 million is the minimum annual budget that ensures having good average road's condition in the study area. Most of the annual M&R budget will be invested for overlay and resealing treatments on the roads at high and medium *GEOPHRIV* areas. This study helps transportation authorities to identify deteriorated pavement sections, maintain the pavement periodically to prevent or minimize damage before storm surge, and allocate resources for M&R operations.

Keywords:

Pavement deterioration; maintenance; Geo-physical risk; vulnerability; cyclone; optimization.

1 Introduction

Road infrastructure supports the accessibility of emergency resources, evacuation of vulnerable people, and reconstruction and recovery of communities in a disaster-affected area (Faturechi and Miller-Hooks, 2015). Natural disasters have an adverse impact on vulnerable population potentially turning a large portion of road network inaccessible. The inaccessibility of roads in disaster-prone areas makes the evacuation of people and logistic support challenging. Evacuation activities reduce the exposure of vulnerable people to natural hazards and logistics support ensures the lifeline to the survivors in disaster-affected areas (Yi and Kumar, 2007). Both of these operations require the active operation of major roads connecting the affected areas to major supply centers, shelters and hospitals.

The coastal areas of *Bangladesh* are vulnerable to cyclones and storm surge. These areas were devastated by severe cyclones and suffered the losses of human lives, livestock and economic production. The 1970 Great Bhola Cyclone caused massive destruction of coastal areas of Bangladesh: 500,000 human lives and billions of dollars in property damage. Another deadliest cyclone, 2B, killed at least 138,000 people, left 10 million people homeless and caused two billions dollars of property damage in the coastal areas of Bangladesh on April 1991. The district of *Barguna* is perhaps the hardest hit by cyclones and storm surges among all the coastal areas of Bangladesh. Since 1887, this district was hit by approximately 35 cyclones and storms. The 2007 cyclone SIDR, that caused up to 9.5 meters height of storm surge, killed 1,335 people, annihilated an area of 1119.89 sq. km. (61.15 percent of the district's total area), destroyed 60 to 70 percent of the crops, and fully and partially damaged 95,412 houses (36.89 percent of total houses) in the Barguna district (Tamima, 2009).

Roads in poor condition and flooded roads in *Barguna* disrupted the evacuation, rescue and relief operations before and after the cyclones and storm surges (Figure 1). Flooded and deteriorated major roads of *Barguna* aggravated the emergency circumstances and increased human and economic losses. In addition, the prolonged flooding of pavements produced the entrance of moisture in the pavement's structure accelerating rutting and cracking. Increased damage in pavements from flooding results in rapid deterioration of pavements, reduction in pavement live, and increased maintenance cost (Mallick et al., 2014). Ironically, pavement maintenance and rehabilitation's (M&R) budget was significantly reduced in Bangladesh during 2012-2017. The Roads and Highways Department (2012) estimated the reduction of total M&R costs for national, regional and district level roads as 96.17 percent, 92.7 percent and 89.06 percent during the period 2012-2017, respectively. The decreasing M&R budget, poor pavement condition, and rapid deterioration of pavements from flooding require a pavement management system (PMS) to optimize the M&R budget for the road network of Barguna. A well-structured PMS will help identify deteriorated pavement sections and maintain the pavement systematically to prevent or minimize the damage before flooding, supporting the availability of critical response routes for emergency attention and evacuation of traffic, and to allocate resources for post-disaster M&R operations.

[Figure 1]

This study estimates the geo-physical risk and vulnerability ($GEOPHRIV$) index of each road segment at the district of Barguna by integrating geophysical risk, social and physical vulnerabilities of the communities, and damages from the previous natural disasters. The optimization of pavement's M&R operations for road network of Barguna is achieved by minimizing the *GEOPHRIV* index in addition to the pavement roughness progression subject to an annual budget constraint.

2 Literature review

This study reviews the literature on natural disaster and road infrastructure and categorizes the studies into two broader themes such as physical damage of road infrastructure and its impact on transport mobility; and social impact and rehabilitation strategy against natural disaster. Chang and Nojima (2001) measured the accessibility and network coverage of urban rail and highway transportation systems in Kobe, Japan, which was devastated by the 1995 Hyogoken-Nanbu earthquake. Chang and Nojima (2001) identified a significant spatial disparity in the recovery of accessibility among sub-areas throughout the restoration process in Japan. Kim et al. (2002) developed an integrated commodity flow model to optimize network flows considering the partial or complete damages of road segments aftermath of natural disasters. Kim et al. (2002) compared the transportation cost with and without disaster scenario. Cho et al. (2000) estimated the transportation and economic cost of a hypothetical magnitude 7.1 earthquake on the Elysian Park blind thrust fault in Los Angeles by combining bridge and other structure performance model, transportation network model, spatial allocation model, and inter-industry model. Sohn (2006) estimated the distance and distance-traffic volume as the two criteria of accessibility to determine the potential impact of flood damage on the state transportation system in Maryland. Sohn (2006) estimated greater accessibility loss at the county level considering the distance-traffic flow criterion. Rowan et al. (2013) evaluated the threshold level of sensitivity of transportation assets to a given level of exposure to changes in climate or natural hazards. Rowan et al. (2013) focused on the key elements of damage functions without characterizing the entire function.

Very few studies evaluate the pavement performance and M&R costs in disaster affected areas. Some studies (Gaspard et al., 2006; Helali et al., 2008; Zhang et al., 2008; Vennapusa et al., 2013) show that transportation agencies have performed some sampling using visual inspections and field tests (particularly non-destructive tests) to determine the impact of natural hazards on pavement performance. Pantha et al. (2010) calculated the maintenance priority index by integrating International Roughness Index (*IRI*) and slope stability condition in Nepal mountains. Mallick et al. (2014) estimated the long-term impact of climate change on pavement performance and maintenance cost for a grid cell located in Massachusetts. Mallick et al. (2014) estimated that the climate change could significantly reduce the structural strength of both subgrade and hot mix asphalt (HMA) layers of a grid cell located in Massachusetts. Mallick et al. (2014) also estimated that the average pavement life would decreased from 16 to 4 years over the span of 100 years and the maintenance cost could increase up to 160 percent. However, Mallick et al. (2014) considered the asphalt mix overlay as the only maintenance activity and didn't calculate the effect of increased maintenance costs. Mallick et al. (2015) evaluated the contribution of pavement materials, climate and construction quality on the pavement's vulnerability to flooding. Mallick et al. (2015) recommended the need for increasing the strength of pavements that lie in flood prone areas, using aging resistant asphalt binders, greater thickness, lower permeability and lower air voids in the HMA layer. Mallick et al. (2015) applied aging-related equations that have limited ability to evaluate pavement's long term performance.

No study develops a PMS to minimize pavement deterioration and increase resiliency through M&R for the pavements in the disaster prone areas. This study optimizes pavement M&R operations by minimizing the geophysical risk of disaster, physical and social vulnerabilities, and pavement roughness progression for a long term exercise subject to annual budget constraints.

3 Methodology

This study has been executed in three main steps: first the estimation of geo-physical risk and vulnerability (*GEOPHRIV*) index of each road segments, second the estimation of pavement performance applying the *IRI* and third the optimization of long term budget allocation and scheduling of interventions (Figure 2).

[Figure 2]

3.1 Geophysical risk and vulnerability (*GEOPHRIV*) index of roads

Geophysical risk of a hazard is defined by the probability of occurrence and extent of resulting consequences aftermath of the hazard. The 'Multipurpose Cyclone Shelter Program (MCSP)' and 'National Survey on Current Status on Shelters and Developing and Operational CYSMIS' defined the geophysical risk zones of cyclones and tropical storms in coastal areas of Bangladesh (Figure 3). MCSP demarcate the risk zones based on the level of inundation under the surge water (Tamima and Amin, 2009). Tamima (2009) collected data on inundation level at each rural community of *Barguna* after the cyclone SIDR and identified that the height of storm surge was within a range of 0.91 to 9.15 meters (Figure 3). The most devastated rural communities were *Kakchira, Kalmegha, Patharghata, Baliatali, Naltona* and *Pancha Koralia* (Figure 3). This study categorizes the geo-physical risk zones as very high, high, medium and low by combining the results of MCSP and Tamima (2009).

[Figure 3]

The vulnerability index of any community in the district of Barguna susceptible to cyclone and storm surge was determined using the Equation 1.

$$\text{Vulnerability index} = (D)^{(COMV + STRINFV)} \qquad (1)$$

Where: *D*, *COMV* and *STRINFV* are damage, social, and structure-infrastructure vulnerability indices, respectively. A principal component analysis (PCA) was applied to estimate the values of *D*, *COMV* and *STRINFV* indices. The value of each index was calculated by multiplying the standardized value of the corresponding attributes (Figure 2), the proportion of variance explained by each attribute and the proportion of variance explained by each factor (under which that particular attribute is loaded) (Amin and Tamima, 2015). The standardized value of each attribute was used in order to remove the effect of different units of measurement and to warrant cross comparisons.

The power function on Equation 1 is continuous and differentiable at all points of its domain, except at the point $D = 0$ when $0 < (COMV + INFRAV) < 1$. Different degrees of *COMV* and *STRINFV* indices can extend the severity of damages. The integer of vulnerability index was defined by the Cavalieri's quadrature formula (Equation 2) to include all points of the domain on Equation 1.

$$\text{Vulnerability index} = \int_0^{D_n} [(D)^{(COMV + STRINFV)}]dD = \frac{D_n^{(COMV + INFRAV)}}{(COMV + INFRAV) + 1} \quad D = 0,.....D_n \quad (2)$$

The $GEOPHRIV$ index of each community was calculated integrating geophysical risk and vulnerability index (Equation 3). The values of $GEOPHRIV$ were defined within a 0 to 10 scale in order to obtain values analogous to those for the International Roughness Index (*IRI*).

$$GEOPHRIV = \frac{R! \quad D_n^{(COMV + INFRAV)}}{(R-1)!(COMV + INFRAV) + 1} \qquad 0 \geq GEOPHRIV \geq 10 \qquad (3)$$

Where *R* defines geophysical risk zones that were categorized as 1, 2, 3 and 4 representing low, medium, high and very high geophysical risk zones, respectively. The *GEOPHRIV* value of each road link was estimated by summing up the *GEOPHRIV* values of all rural communities within a 3 km buffer zone of the corresponding road link. Tamima (2009) observed that local people used to travel on average 3-km to reach shelter after a cyclone warning.

3.2 Pavement performance modeling

Road pavements in Bangladesh are built with an unbound aggregate base underneath a hot mixed asphalt (HMA) layer. Moisture in either the HMA layer and/or the granular base layer may damage the pavements subject to flooding (Little and Jones, 2003). This study applied the basic design equation of the 1993 American Association of State Highway and Transportation

Officials (AASHTO) guide to estimate the present serviceability index (*PSI*) of flexible pavements in coastal regions at a time *t* (Equation 4).

$$PSI_t = PSI_{t-1} - 2.7 \times 10^{a} \quad (4)$$

$$a = \left[0.40 + \frac{1094}{(SN+1)^{5.19}}\right] \left[\log_{10}(ESALs_t) - (Z_R \times S_0) - 9.36\log_{10}(SN+1) - 2.32\log_{10}(M_R) + 8.27\right]$$

Where PSI_{t-1} is the *PSI* at time (*t*-1), $ESALs_t$ is the 80 KN equivalent single axle load at time *t*, Z_R is the standard normal deviate that considers the design uncertainties, S_0 is the combined standard error of traffic prediction and performance prediction, *SN* is the structural number or structural strength of the pavement, and M_R is the subgrade resilient modulus (AASHTO, 1993). The *SN* was calculated from the thickness of layers and their corresponding layer coefficients and drainage coefficients (AASHTO, 1993). Drainage coefficients of different layers of pavement are determined based on the time of standing water and saturated condition. After the storm surge, water stagnation prolonged more than one month causing the very poor drainage quality in the study area that is defined by the drainage coefficients within the range of 0.75-0.40 (AASHTO, 1993). This study considered the reliability level and corresponding Z_R value as 95 percent and -1.645 for the roads of Barguna district, respectively (AASHTO, 1993). The value range of S_0 for flexible pavements was considered as 0.40 to 0.50 (AASHTO, 1993). The M_R was calculated based on the California Bearing Ratio (*CBR*) method. Heukelom and Klomp (1962) related M_R and *CBR* using Equation 5. Alam and Zakaria (2002) collected the samples from Katchpur area along Dhaka-Chittagong highway and from Aminbazar area along Dhaka-Aricha highway and kept in water for 4, 7, 30 and 45 days. Alam and Zakaria (2002) estimated that the average *CBR* values with medium compaction efforts were 2.7, 2.5, 2.2 and 1.9 keeping the samples in water for 4, 7, 30 and 45 days, respectively.

$$M_R = 1500 \times CBR \quad (5)$$

The ESALs for different categories of vehicles on the roads of *Barguna* for the period *t* were calculated applying Equation 6 as proposed by the Bangladesh Road Materials and Standard Study (BRMSS) report (Roads and Highways Department, 1996). Where *r* represents the traffic growth rate, $AADT_i$ represents annual average daily traffic of *i* vehicle type, and EF_i is equivalent load factor of *i* vehicle type.

$$ESALs_t = \sum_i^n 365 \times AADT_i \times EF_i \times \frac{\left(1+\frac{r}{100}\right)^t - 1}{\frac{r}{100}} \quad (6)$$

This study converted the *PSI* to *IRI* for each road segment following the Equation 7 since the transportation authorities in Bangladesh assess the performance of flexible pavements in terms of roughness progression. Sayers et al. (1986) developed Equation 7 during the International Road Roughness Experiment conducted in Brazil in 1982, and it was validated by several studies (Paterson et al., 1992; Haas et al., 1994; Prozzi, 2001).

$$IRI = 5.5 \ln \frac{5.0}{PSI} \quad (7)$$

IRI values were categorized as excellent ($0 \leq IRI \leq 2$), good ($2 \leq IRI \leq 4$), fair ($4 \leq IRI \leq 6$) and poor ($6 \leq IRI \leq 10$). The Local Government Engineering Department (LGED) defines the life of a pavement as 10 years for rural roads in Bangladesh. Tamima (2009) estimated that the probabilities of returning severe (wind speed 89-118 km/hr), very severe (wind speed 119-221 km/hr), and super cyclones (wind speed 222 km/hr and above) at 10 years intervals were 0.187, 0.187 and 0.1339, respectively. This study considers a pavement design life and period of returns of 10 and 30 years, respectively. The operational window of pavement M&R operations is presented in Table 1. Roads will require the reconstruction with earth-filling every 10 years because of the washed away effect by storm surges every 10-years.

[Table 1]

3.3 Lifecycle optimization of road maintenance

Lifecycle optimization to achieve and sustain acceptable pavement condition ($\overline{IRI} \leq 4$) at a minimum cost is used to find required levels of annual M&R budget (Equation 8 and 9). The minimization of roughness progression (IRI) and *GEOPHRIV* values under such a budget is then used to find optimal strategic results for pavement management (Equation 10 and 11). This formulation relied on a decision tree containing all possible paths of pavement condition across time, after hypothetically receiving available treatments (Amin and Amador, 2014). This tree is based upon a transfer function used to estimate condition (IRI_{ti}) as a convex combination based on the decision variable and the improvement or deterioration of the specific link on time t (Equation 12).

The optimization programming has two objective functions. The first objective function is to minimize the maintenance costs (Equation 8) maintaining the road condition (IRI) at a threshold level (good condition, IRI≤ 4) (Equation 9). ~~The objective function is to minimize cost (Z) (Equation 8) subject to a target level of pavement condition of IRI of 4 or less (Equation 9).~~ The alternative formulation is to maximize pavement condition of the road network $[\sum_{t=1}^{T}\sum_{i=1}^{a}(L_i IRI_{ti})]$, which for IRI results in the aim to minimize its value, in addition to minimize the levels of GEOPHRIV index (Equation10). This annual maintenance costs derived from Equation 8 should not exceed the annual budget of Local Government Engineering Department in Bangladesh that is explained in Equation 11. The second objective function (Equation 10) is to minimize the pavement roughness (IRI) and geo-physical risk (GeoPHRIV) with the maintenance operations that are optimized by Equations 8 and 9. ~~This alternative formulation uses annual budget as a constraint (Equation 11)~~

$$MINIMIZE \quad Z=\sum_{t=1}^{T}\sum_{i=1}^{a}\sum_{j=1}^{o} C_{tj} X_{tij} L_i \tag{8}$$

$$\text{Subject to}: \sum_{t=1}^{T}\sum_{i=1}^{a} L_i IRI_{ti} \geq \left(\overline{IRI}\right)\sum_{i=1}^{a} L_i \tag{9}$$

$$\text{MINIMIZE} \quad \sum_{t=1}^{T}\sum_{i=1}^{a}(W_{1t} * L_i IRI_{t,i} + W_{2t} * GEOPHRIV_{it}) \tag{10}$$

$$\text{Subject to}: \quad Z=\sum_{t=1}^{T}\sum_{i=1}^{a}\sum_{j=1}^{k} C_{t,j} x_{t,i,j} L_i \leq \mathrm{B_t} \tag{11}$$

$0 \leq IRI_{t,i} \leq 10$ and $0 \leq GEOPHRIV_{,it} \leq 10$

$$\sum_{j \in J_{t,i}} x_{t,i,j} \leq 1 \text{ for all times } t \text{ and for each road } i$$

$$IRI_{tij} = X_{tij} \, (IRI_{(t\text{-}1)ij} + E_{ij}) + (1\text{-}X_{tij}) \, (IRI_{(t\text{-}1)ij} + D_{it}) \quad (12)$$

Where X_{tij} is a binary decision variable equal to 1 if treatment j is applied on road segment i at year t, zero otherwise; IRI_{ti} is condition Index for road segment i at year t; IRI_{tij} *is* condition Index of road segment i at year t after receiving treatment j as shown on the dynamic transfer function (Equation 12); $IRI_{(t\text{-}1)ij}$ is condition Index of road segment i at year (t-1) before receiving treatment j; C_{tj} is cost ($) of treatment j at year t; L_i is length of road (km) for road segment i; E_{ij} is improvement (+) on road segment i from treatment j, D_{it} is deterioration (-) on road segment i at time t, B_t is budget at year t, $GEOPHRIV_{,it}$ is the *GEOPHRIV* value for road i at time t, and W_1 and W_2 are the weights of the *IRI* and *GEOPHRIV* indices, respectively. These weights follow a dominance analysis in order to remove inferior combinations (Amador and Afghari 2012).

4 Results and discussion

4.1 Geo-physical risk and vulnerability analysis

A PCA was applied to estimate the *D*, *COMV* and *STRINFV* indices. The first step of performing PCA was to assess the data suitability. The pattern of relationships among variables was identified from the correlation matrix, determinant of correlation, total variance (before and after rotation) and the component matrix (before and after rotation). The 'Eigenvalues' associated with linear components (factor) before extraction, after extraction and after rotation were evaluated. The 'Eigenvalues' represented the variance explained by the linear component. If the total variance of each test is unity, the 'Eigenvalues' of the first factors have the theoretical maximum equal to the number of tests (Kinnear & Gray, 2009). The first factors have the greatest sums and thus account for the greatest part of the total variance. Table 2 illustrates that the first seven factors, six factors and first factor explain 80.46 percent, 78.12 percent and 82.05 percent variance of *D*, *STRINFV* and *COMV* indices and have eigenvalues greater than 1, respectively. This study considers the proportion of variances explained by each factor and variables from the rotated sum of squared loading. The rotated sum of squared loading, representing the effects of optimising the factor structure, was examined to equalise the relative importance of the most significant factors (Table 2).

[Table 2]

The communality of each variable, the total proportion of variance accounted for the extracted factors, was calculated by the squared multiple correlations among the test and the factors emerging from the PCA. The relationship between the variables and extracted factors were identified by the rotation component matrix of PCA (Table 3). The rotations were performed by the Varimax with Kaiser Normalization process and the convergence of rotation was obtained after 7 iterations.

[Table 3]

The values of *D*, *COMV* and *STRINFV* indices for each rural community were calculated by multiplying the standardized value of the corresponding attributes, the proportion of variance explained by each attribute and the proportion of variance explained by each factor. The value of *GEOPHRIV* index for each rural community was estimated following Equation 3. The *GEOPHRIV* value of each road link was estimated by summing up the *GEOPHRIV* value of all rural communities within the 3 km buffer zone of the corresponding road link. Figure 4 and 5 show the values of *GEOPHRIV* index for road links and rural communities in the year 2001 and 2011, respectively.

[Figure 4]

[Figure 5]

4.2 Optimization of pavement M&R operations

The prioritization of maintenance operations for each link of the rural road network was determined by minimizing the weighted values of *IRI* and *GEOPHRIV* for each link within the annual budget constraint. It is very difficult to define the annual road maintenance budget of LGED for each district. During the financial year of 2016-2017, the Roads and Highways Department and LGED have M&R budgets of USD 14.38 million and USD 17.56 million, respectively. Assuming the equal distribution of this fund among sixty-four districts in Bangladesh, the anticipated annual M&R budget for each district is USD 500,000. However, the lifecycle optimization reveals that the condition of the whole road network in *Barguna* will deteriorate (IRI increase) by 10 percent with such current M&R budget (Figure 7). Since the objective of life-cycle optimization of M&R operations is to maintain the pavements in good condition ($IRI \leq 4$), the minimum annual M&R budget was estimated using Equation 8 and 9 (Figure 6). Required annual M&R budget was estimated at USD 1.51 million in order to improve the condition of the whole road network to good levels after 20th year of optimal allocation of M&R works (Figure 7), however the level of condition decayed after that. The minimization of

IRI and *GEOPHRIV* under different percentile distributions of proposed M&R budgets was then calculated to find the optimal strategic results for pavement management applying Equations 10 and 11 (Figure 6 and 7). It was found that USD 2,487,849 is the minimum annual budget that ensures having good network-average roads condition for 30 years (Figure 7 and 8). However, roads in poor condition will appear by year 25, explained by the short design life of reconstructed roads in Bangladesh, the only way to counteract these phenomena is by extending the design life, but this in turn requires a policy change that escapes this research.

[Figure 6]

[Figure 7]

[Figure 8]

A significant portion of the predicted annual M&R budget will be allocated to regional highways. Regional highways will require on an average 43 percent of the annual M&R budget, while arterial and collector roads will require 33 percent and 24 percent of the annual M&R budget to maintain in good condition during the estimation period, respectively (Figure 9). The allocated annual M&R budget for different types of roads will maintain annually an average of 42 km, 33 km and 24 km of regional highways, arterial and collector roads, respectively (Figure 10). During the first 10 years of the estimation period, the annual M&R budget will maintain a range of 106-187 km length of the road network in Barguna district that was reduced to 42-65 km during the last 10 years (Figure 10). The length of the treated road will be significantly reduced at the tail of the estimation period because a major portion of M&R budget will be allocated for the overlay, major rehabilitation and reconstruction activities (Figure 11). Most of the annual M&R budget (a range of 60 to 100 percent of the annual M&R budget during the estimation period) will be allocated for maintaining the roads with the high and medium *GEOPHRIV* values. This reveals that the roads located at the high and medium geo-physical risk and vulnerability regions are given priority in the proposed PMS.

[Figure 9]

[Figure 10]

[Figure 11]

The majority of the M&R budget will be invested for overlay followed by resealing, this is again explained by the low cost effectiveness of current reconstruction strategy under limited design life of 10 years. For example, 66 percent, 53 percent and 44 percent annual M&R budget allocated for regional highways, arterial and collector roads will be invested for overlay, respectively (Figures 12-14). The regional highways located at the high, medium and low *GEOPHRIV* zones will obtain 42 percent, 39 percent and 19 percent of overlay treatment budget, respectively (Figure 12). The arterial roads located at the high, medium and low *GEOPHRIV* zones will obtain 41 percent, 35 percent and 24 percent of overlay treatment budget, respectively (Figure 13). Half of the overlay treatment cost for collector roads will be allocated for roads at medium *GEOPHRIV* zone (Figure 14). The resealing treatment will require 21 percent, 14 percent and 7 percent of the annual M&R budget allocated for regional highways, arterial and collector roads, respectively (Figures 12-14).

[Figure 12]

[Figure 13]

[Figure 14]

It is worthwhile mentioning that the herein proposed model improves over the conventional PMS by minimizing the pavement deterioration and optimizing the M&R budget for the pavements in the disaster prone areas. Firstly, it incorporates the geo-physical risk of disaster, and physical and social vulnerabilities of the communities susceptible to disaster. Secondly, this proposed model develops the pavement performance curves that are subjected to prolonged inundation after the storm surge. Thirdly, this model optimizes the annual M&R budget including the geo-physical risk, community vulnerabilities and pavement deterioration. Traditional methods use visual evaluation and field tests at the disaster affected areas to evaluate the condition of the pavements. These tests are usually performed at a very limited sample of road segments in the disaster affected areas. Roads are maintained based on the results of tests. However, these roads become inaccessible before, during and after the disaster because of continuing deterioration. Roads at the disaster-prone areas require to be accessible especially during the emergency period for evacuating the vulnerable people and supplying the logistic supports to the survivors in the disaster-affected areas. Both of these operations require the active operation of major roads connecting the affected areas to major supply centers, shelters and hospitals. This model helps the transportation authorities to identify deteriorated pavement sections, maintain the pavement systematically to prevent or minimize damage before flooding, route choice for emergency or evacuation traffic, and allocate resources for post-disaster M&R operations.

5 Conclusions

Cyclone and storm surge has an adverse impact on the pavement condition of road network in the disaster-prone areas that disrupts the evacuation, rescue and relief operations during the emergency period. The deteriorated and submerged roads aggravate the emergency circumstances and increased the human and economic losses. In addition, the prolonged inundation of pavements from storm surge causes the entrance of moisture in pavements that accelerates rapid deterioration and increases maintenance cost. This study estimates the geo-physical risk and vulnerability (*GEOPHRIV*) index of each road segment of Barguna district integrating geo-physical risk, social and physical vulnerabilities of the communities, and damages from the previous natural disaster. The optimization of pavement M&R operations for road network of Barguna district is achieved by minimizing the *GEOPHRIV* index and pavement roughness progression within the annual budget constraint. The regional highways, arterial and collector roads of Barguna district, a coastal area of Bangladesh, is considered as a case study. Barguna district is the hardest hit of cyclones and storm surges among the coastal areas of Bangladesh. Since 1887, this district was hit by approximately 35 cyclones and storms.

This study has been executed in three main steps: first the estimation of geo-physical risk and vulnerability (*GEOPHRIV*) index of each road segments by integrating the geo-physical risk and damage, community, and structure and infrastructure vulnerability indices, second the estimation of pavement performance applying the *IRI* and third the optimization of long term budget allocation and scheduling of interventions. The principal component analysis (PCA) of multivariate analysis techniques was applied to estimate the value of each index multiplying the standardized value of variables, the proportion of variance explained by each variable and the proportion of variance explained by each factor. The 1993 AASHTO guide was applied to estimate the deterioration of flexible pavements. Linear programming was applied to develop

M&R strategies ensuring the good pavement condition of roads at a minimum maintenance budget.

Lifecycle optimization of M&R operations estimated that USD 2,487,849 is the minimum annual budget that ensures having good average roads condition in Barguna district for 30 years. Most of the annual M&R budget (a range of 60 to 100 percent of the annual M&R budget during the estimation period) will be allocated for maintaining the roads with the high and medium *GEOPHRIV* values. This reveals that the roads located at the high and medium geo-physical risk and vulnerability regions are given priority in the proposed PMS. The majority of the M&R budget will be invested for overlay followed by resealing. The regional highways located at the high, medium and low *GEOPHRIV* zones will obtain 42 percent, 39 percent and 19 percent of overlay treatment budget, respectively. The arterial roads located at the high, medium and low *GEOPHRIV* zones will obtain 41 percent, 35 percent and 24 percent of overlay treatment budget, respectively. Half of the overlay treatment cost for collector roads will be allocated for roads at medium *GEOPHRIV* zone. Low Cost effectiveness of reconstruction given limited design life of new pavements call for a change in policy to increase the design life of reconstructed pavements.

The developed model of M&R operations has three-fold improvement on the conventional methods of PMS. Firstly, it incorporates the geo-physical risk of disaster, and physical and social vulnerabilities of the communities susceptible to disaster. Secondly, this proposed model develops the pavement performance curves that are subjected to prolonged inundation after the storm surge. Thirdly, this model optimizes the annual M&R budget including the geo-physical risk, community vulnerabilities and pavement deterioration. This model helps the transportation authorities to identify deteriorated pavement sections, maintain the pavement systematically to prevent or minimize damage before flooding, route choice for emergency or evacuation traffic, and allocate resources for post-disaster M&R operations.

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Figure 1: Storm surges breaks up the pavements of road network in Barguna district, Bangladesh

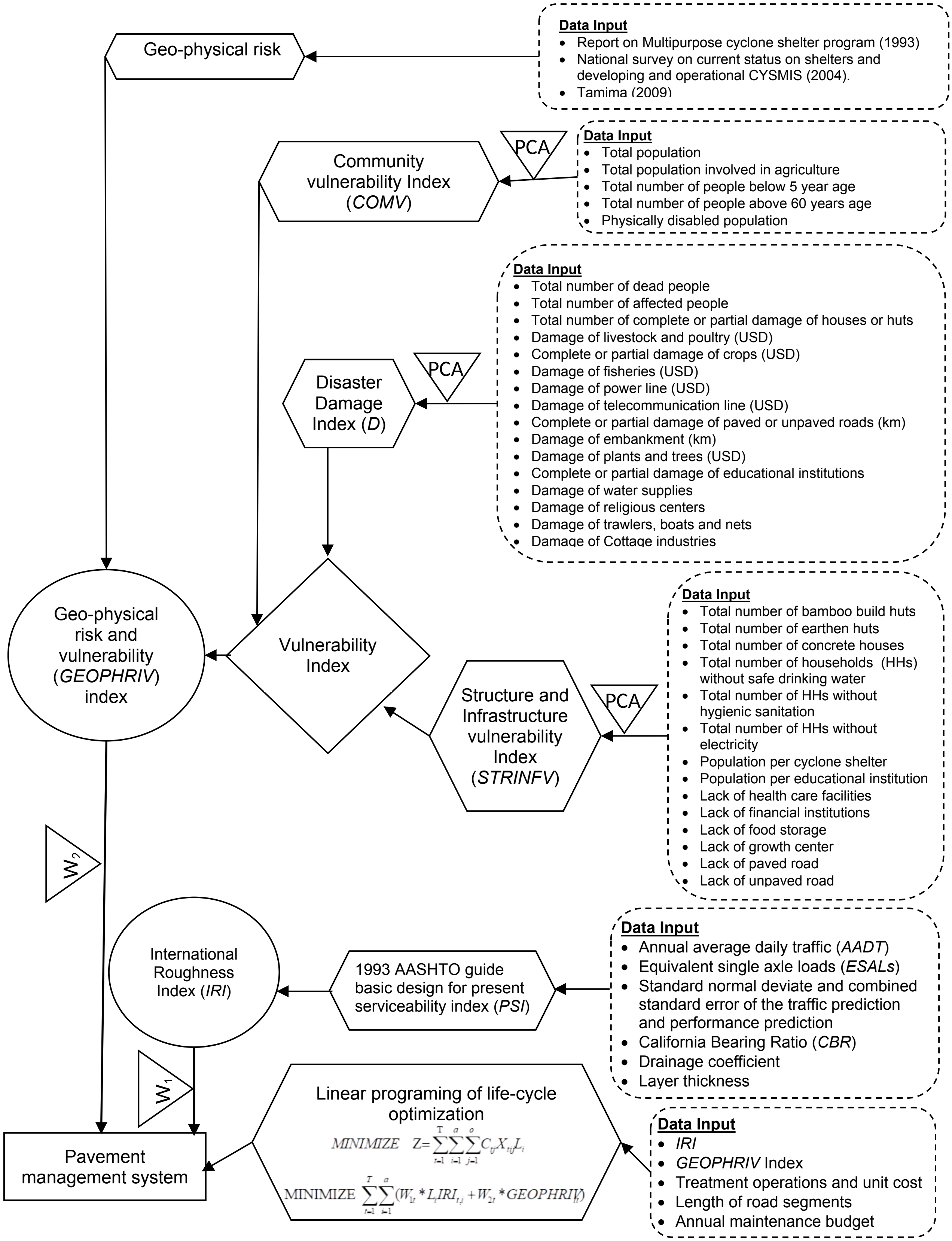

Figure 2: Flow diagram of methodology

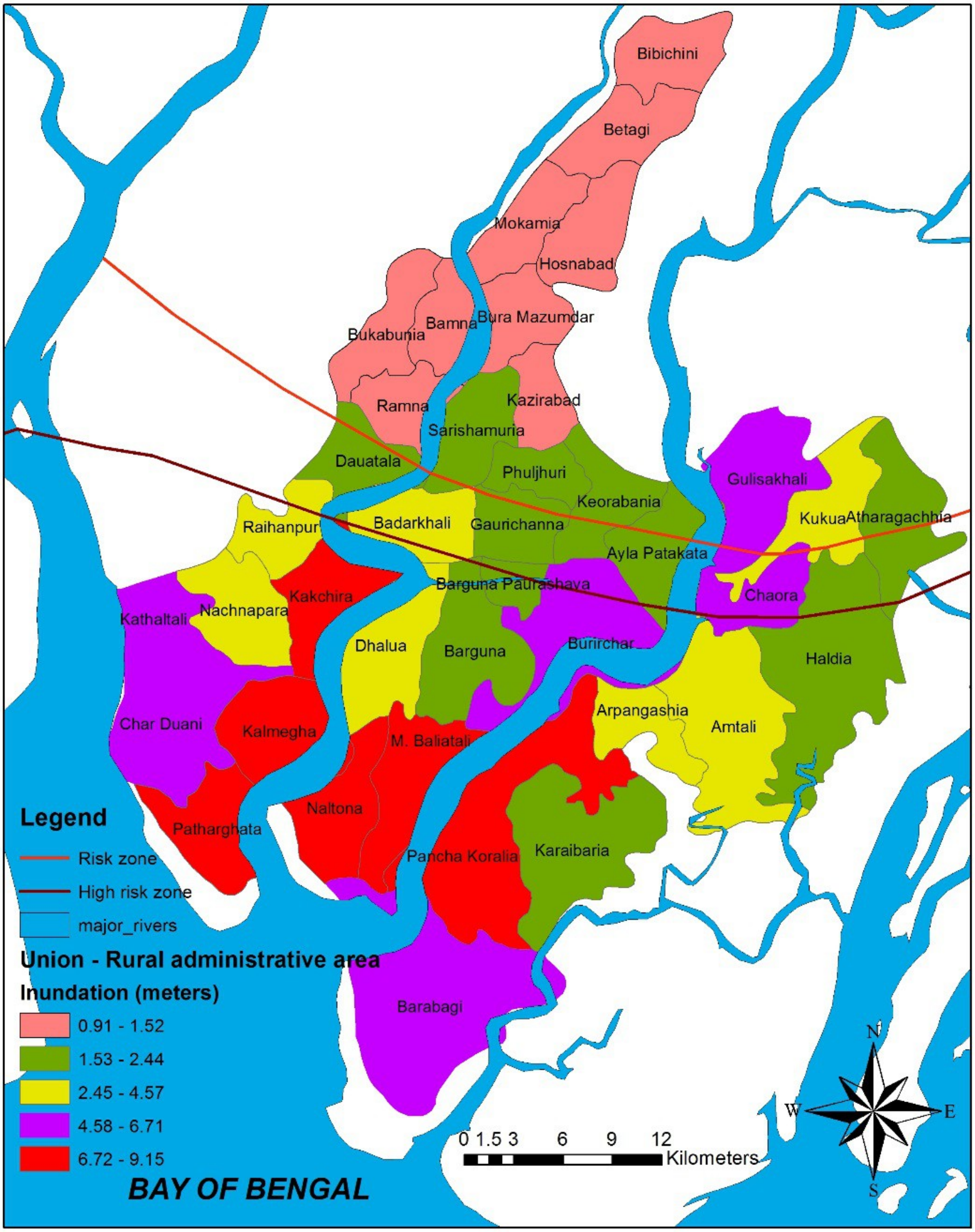

Figure 3: Inundation and risk levels of rural communities at Barguna's district

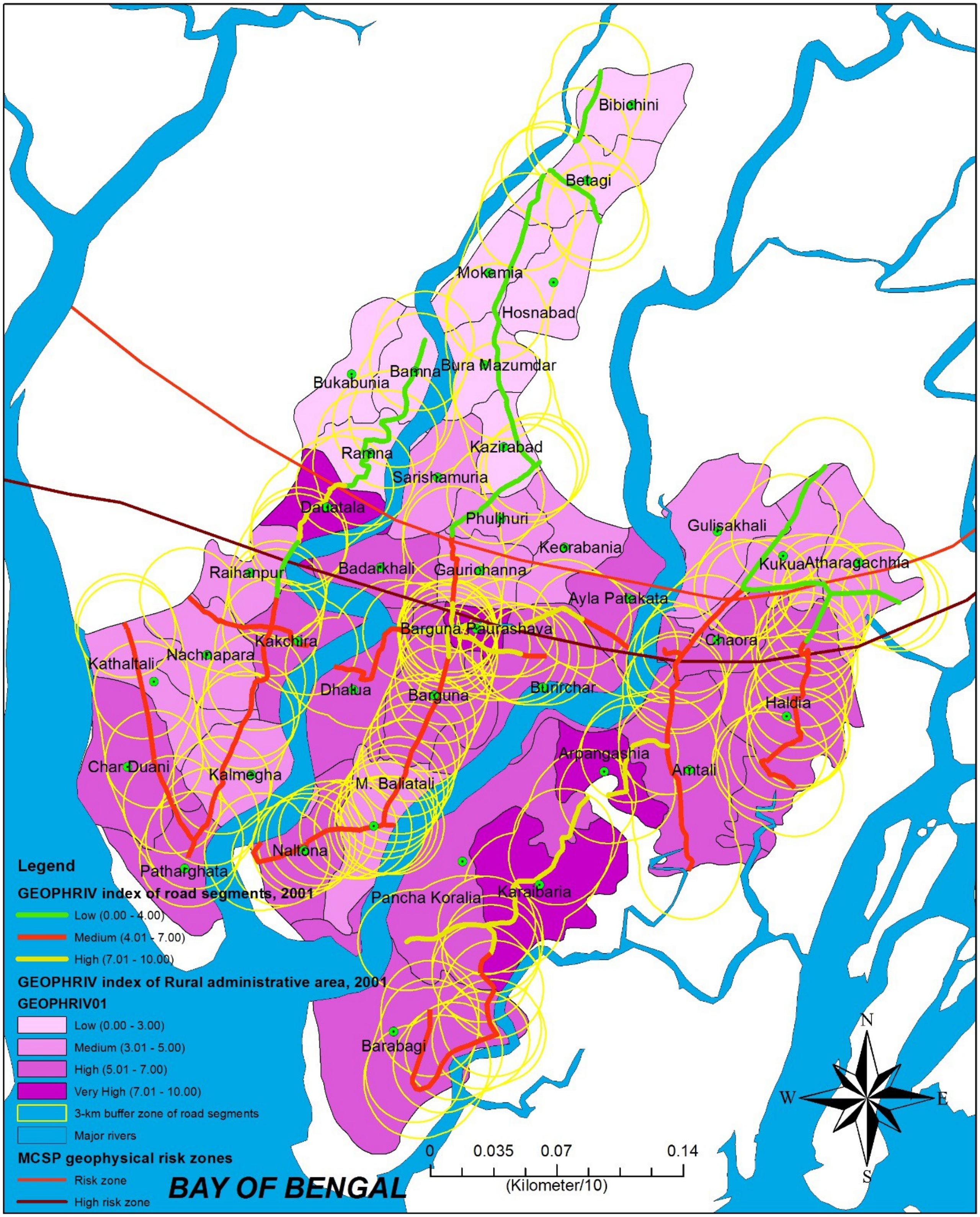

Figure 4: *GEOPHRIV* index map of road network in Barguna district in the year 2001

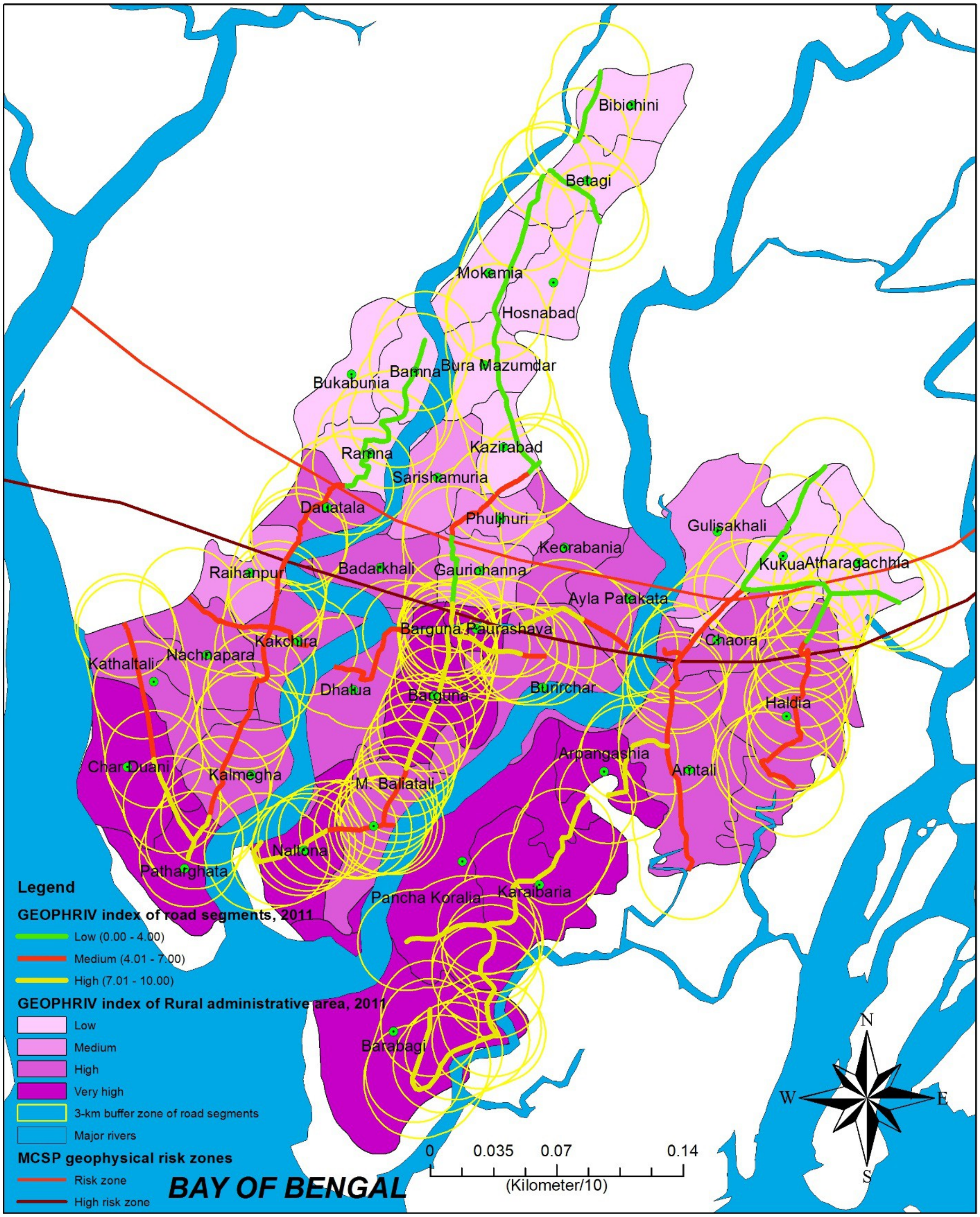

Figure 5: *GEOPHRIV* index map of road network in Barguna district in the year 2011

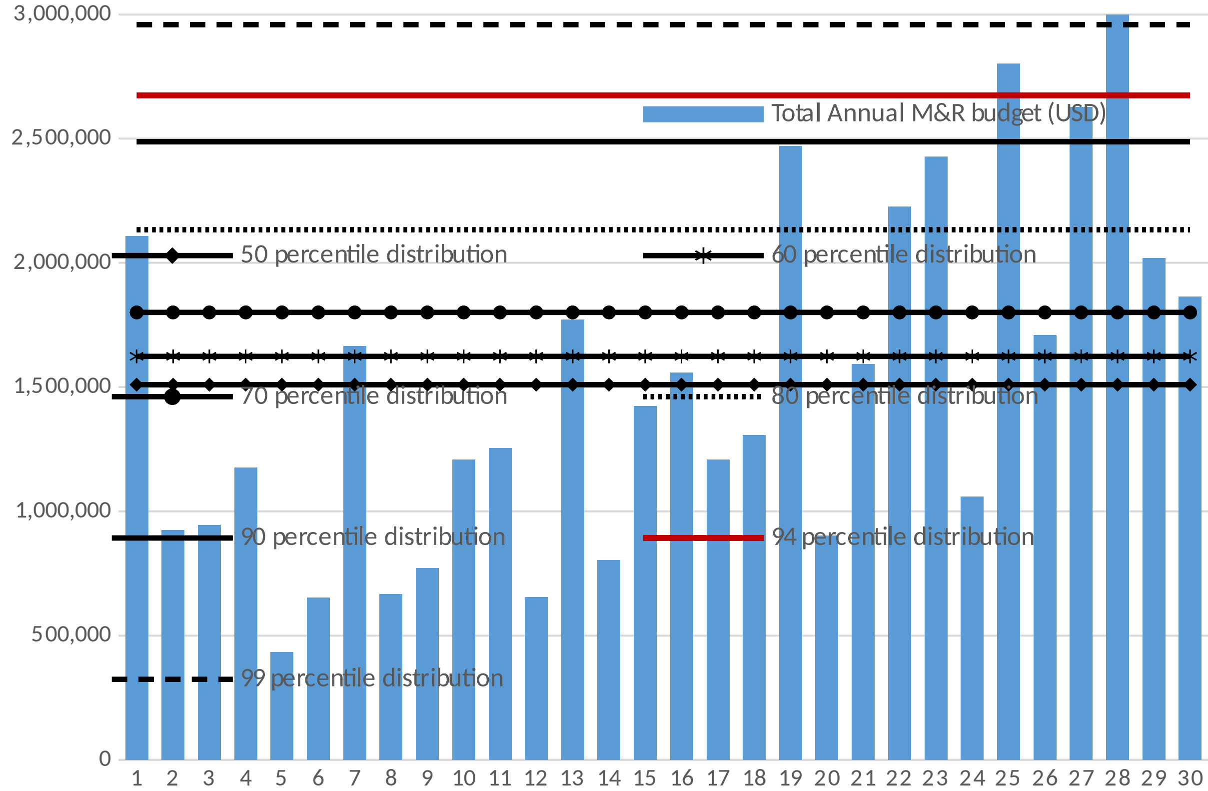

Figure 6: Minimum annual M&R budget requires to maintain the road network in good condition

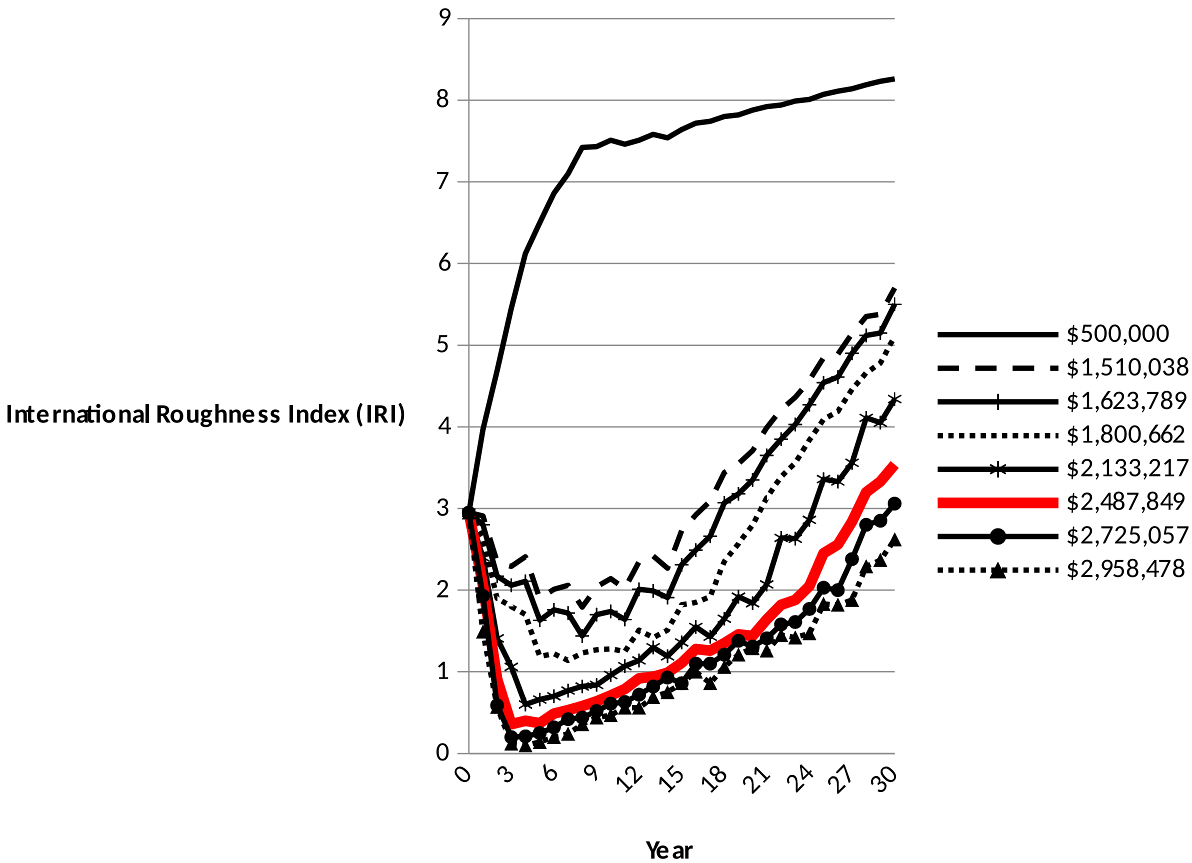

Figure 7: International Roughness Index (*IRI*) for different annual M&R budgets

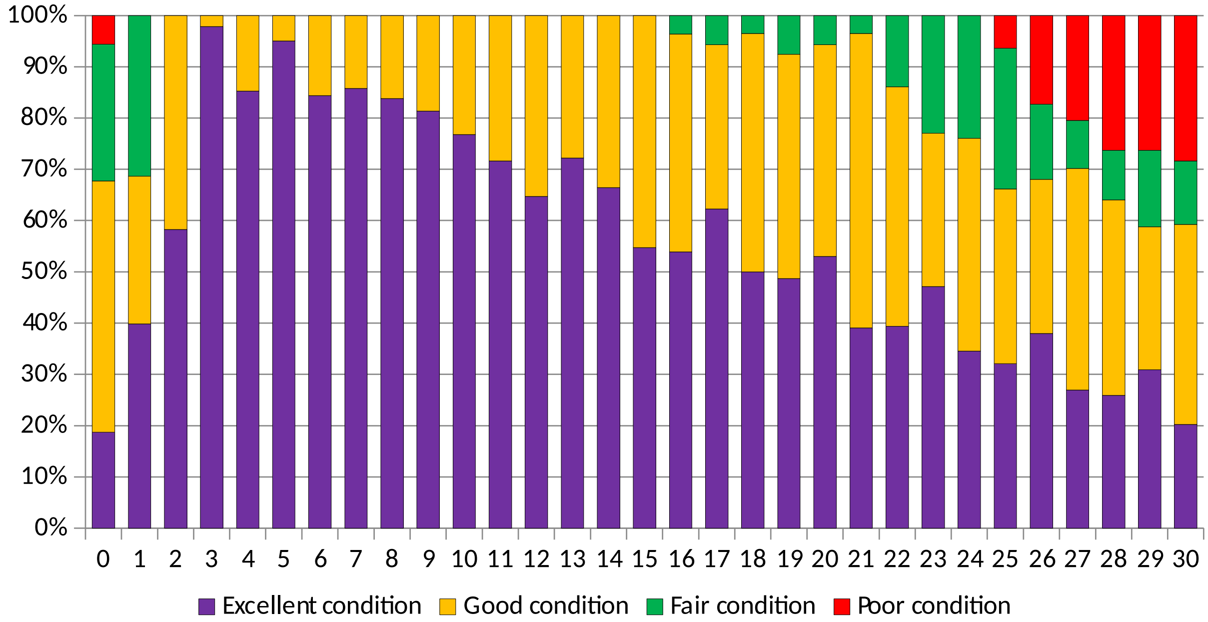

Figure 8: Condition of road network in Barguna district with the proposed USD 2.49 million annual M&R budget

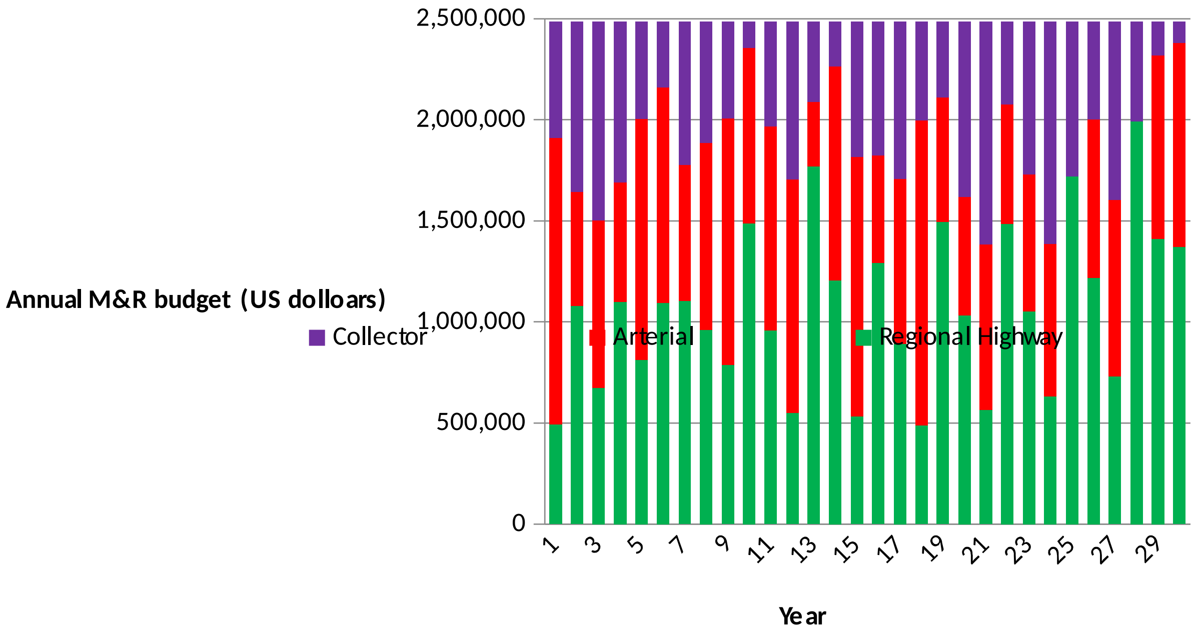

Figure 9: Distribution of annual M&R budget among different road hierarchies

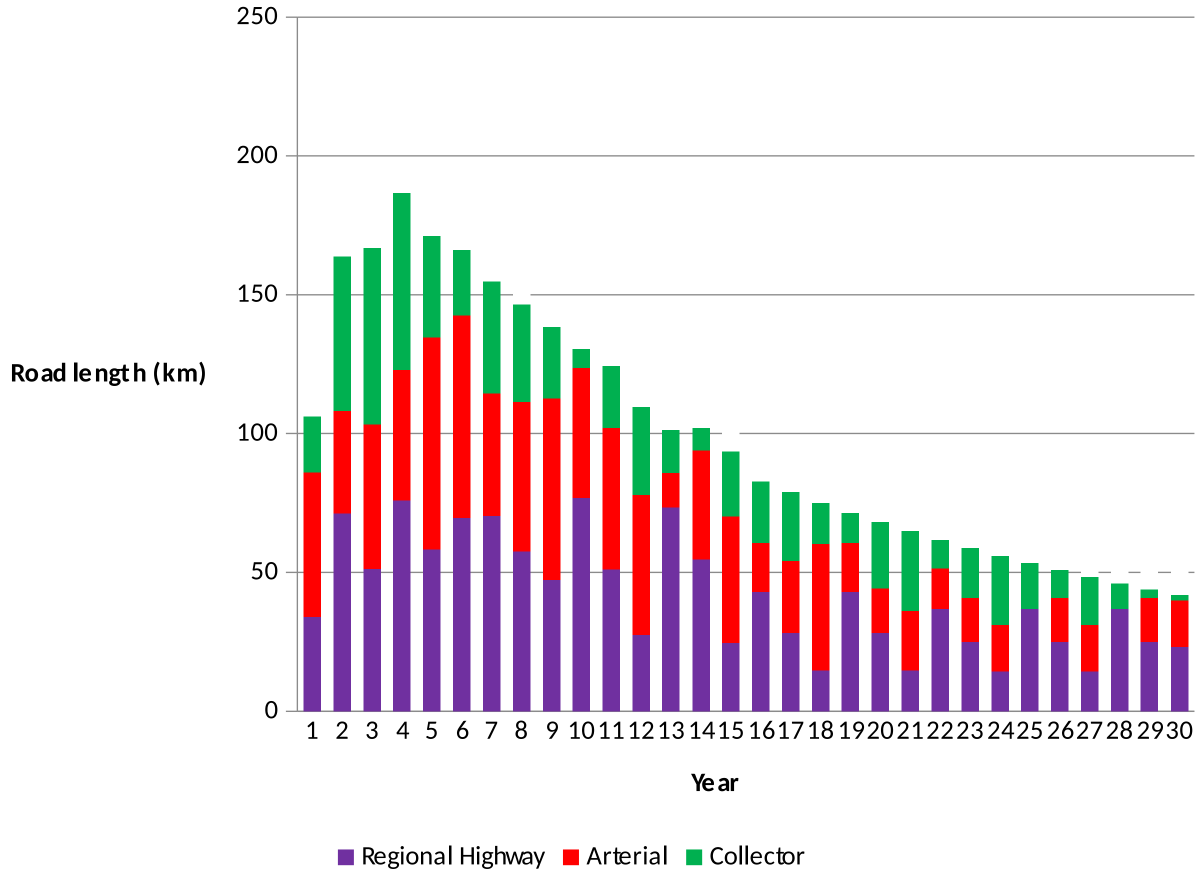

Figure 10: Total length (km) of different road hierarchies treated annually with the proposed M&R budget

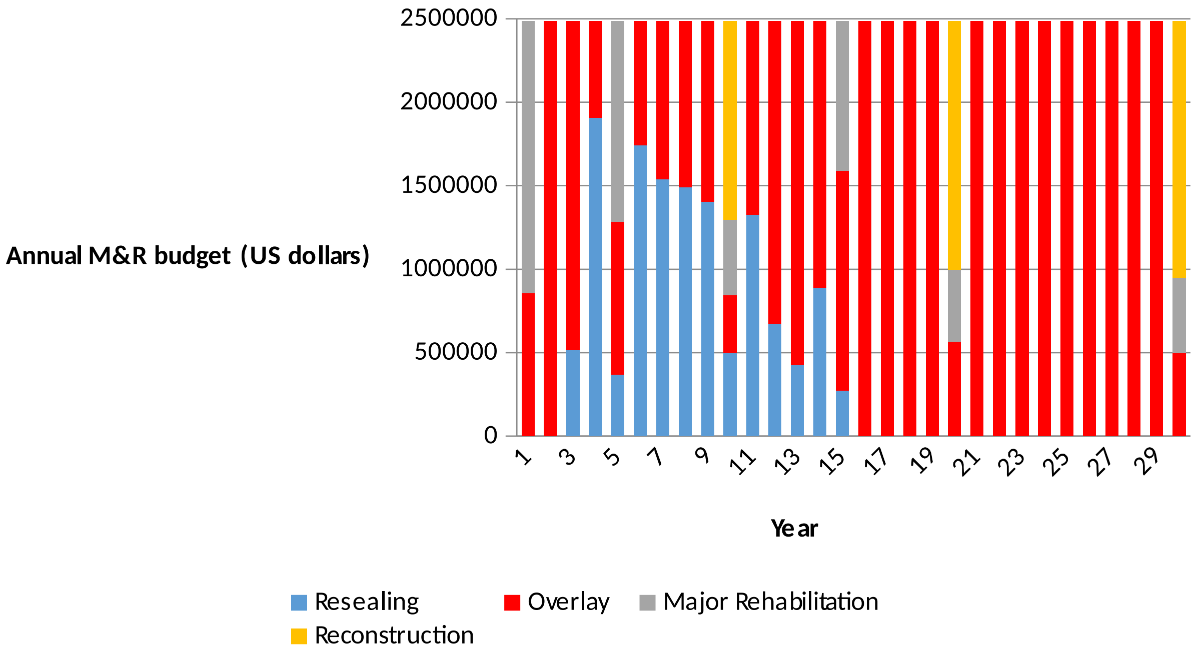

Figure 11: Distribution of annual M&R budget among different treatment operations

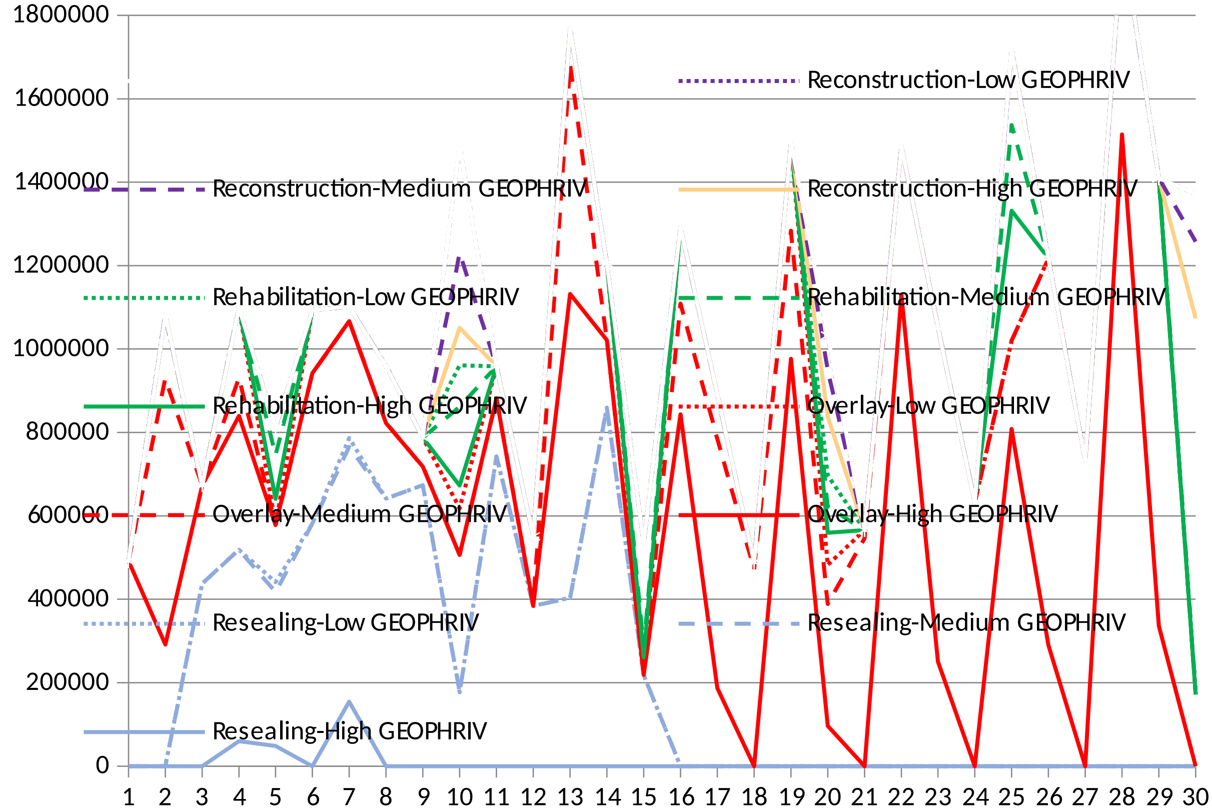

Figure 12: Distribution of annual M&R budget for different treatment operations on regional highway

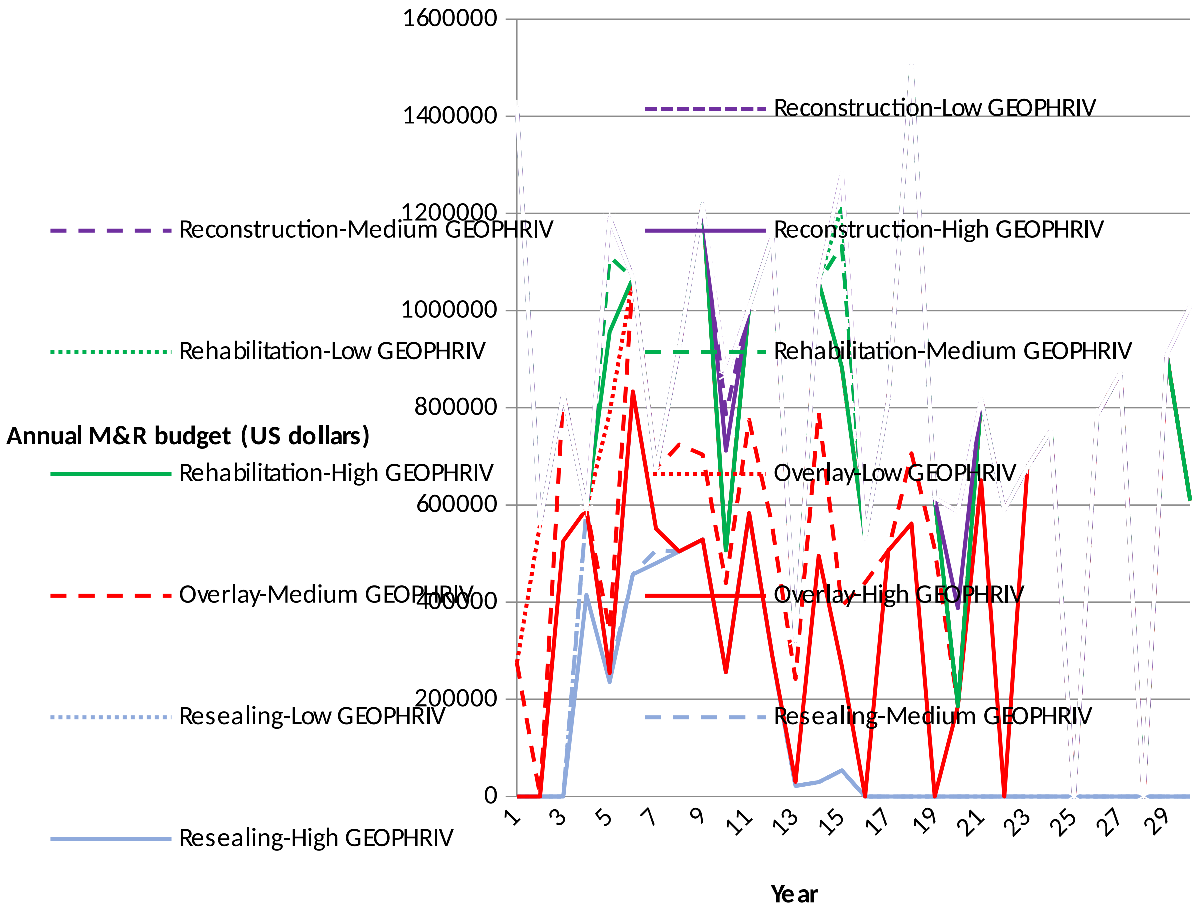

Figure 13: Distribution of annual M&R budget for different treatment operations on arterial roads

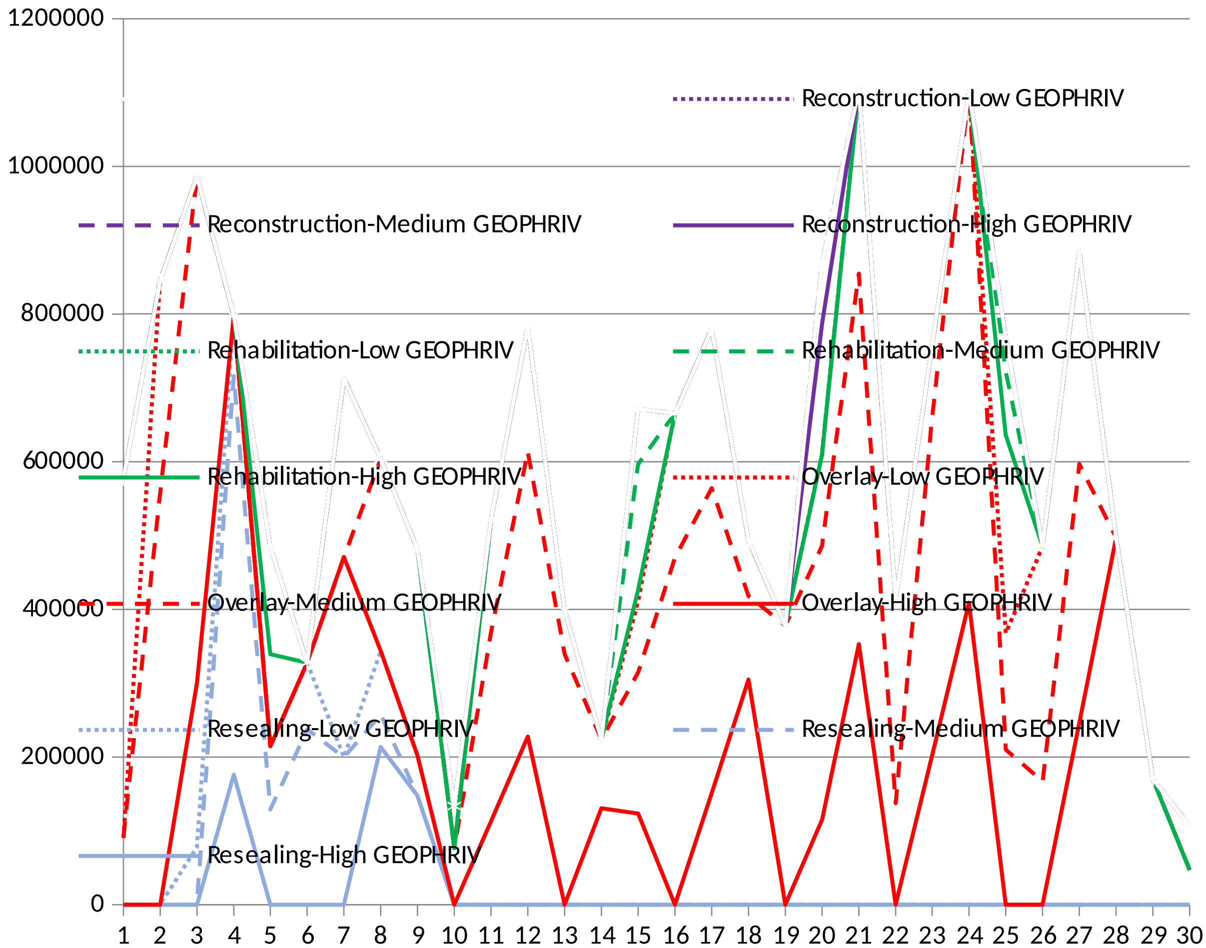

Figure 14: Distribution of annual M&R budget for different treatment operations on collector roads

Table 1: Treatment and operational windows used in network-level trade-off analysis

Treatment operations	Road hierarchy	GEOPHRIV zones	Operational window	Cost (USD) per km
Resealing (7mm/12mm seal coat, single/double bitumen surface treatment	Regional Highway	High	1≤ IRI < 2, Age ≤ 2	10853
		Medium	1≤ IRI < 2, Age ≤ 2	
		Low	1≤ IRI < 2, Age ≤ 2	
	Arterial	High	1≤ IRI < 2, Age ≤ 2	
		Medium	1≤ IRI < 2, Age ≤ 2	
		Low	1≤ IRI < 2, Age ≤ 3	
	Collector	High	1≤ IRI < 2, Age ≤ 3	
		Medium	1≤ IRI < 2, Age ≤ 4	
		Low	1≤ IRI < 2, Age ≤ 5	
Overlay (spot improvement with bituminous carpeting, 25mm/40mm dense or normal graded bituminous carpeting)	Regional Highway	High	2≤ IRI < 4, 2≥ Age ≤ 4	14454
		Medium	2≤ IRI < 4, 2≥ Age ≤ 3	
		Low	2≤ IRI < 4, 2≥ Age ≤ 4	
	Arterial	High	2≤ IRI < 4, 2≥ Age ≤ 3	
		Medium	2≤ IRI < 4, 2≥ Age ≤ 5	
		Low	2≤ IRI < 4, 3≥ Age ≤ 7	
	Collector	High	2≤ IRI < 4, 3≥ Age ≤ 4	
		Medium	2≤ IRI < 4, 4≥ Age ≤ 6	
		Low	2≤ IRI < 4, 5≥ Age ≤ 8	
Major Rehabilitation (additional thickness in the base course layer, plus 25mm/40mm bituminous carpeting followed by seal coat)	Regional Highway	High	4≤ IRI <6, 4≥ Age ≤ 5	34704
		Medium	4≤ IRI <6, 3≥ Age ≤ 5	
		Low	4≤ IRI <6, 4≥ Age ≤ 8	
	Arterial	High	4≤ IRI <6, 3≥ Age ≤ 4	
		Medium	4≤ IRI <6, 5≥ Age ≤ 7	
		Low	4≤ IRI <6, 7≥ Age ≤ 9	
	Collector	High	4≤ IRI <6, 4≥ Age ≤ 6	
		Medium	4≤ IRI <6, 6≥ Age ≤ 8	
		Low	4≤ IRI <6, 8≥ Age ≤ 9	
Reconstruction and earth filling (one meter height of earth filling is recommended to avoid submerging the roads	Regional Highway	High	IRI >= 6, Age ≥ 5	82234
		Medium	IRI >= 6, Age ≥ 5	
		Low	IRI >= 6, Age ≥ 8	
	Arterial	High	IRI >= 6, Age ≥ 4	
		Medium	IRI >= 6, Age ≥ 7	
		Low	IRI >= 6, Age ≥ 9	
	Collector	High	IRI >= 6, Age ≥ 6	
		Medium	IRI >= 6, Age ≥ 8	
		Low	IRI >= 6, Age ≥ 9	

from storm surge i.e. soil, sand and coarse aggregate layers are 76 cm, 12 cm and 22 cm, respectively)				

Table 2: Percentage of variance explained by factors

Factors	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	D	*COMV*	*STRINFV*	*D*	*COMV*	*STRINFV*	*D*	*COMV*	*STRINFV*
1	24.430	82.047	19.102	22.702	82.047	19.102	14.398	82.047	15.717
2	17.305		17.164	14.024		17.164	13.743		14.685
3	15.347		14.282	14.243		14.282	12.613		14.155
4	7.297		12.095	8.359		12.095	11.755		13.947
5	6.496		8.717	6.535		8.717	11.349		11.675
6	5.904		6.758	5.846		6.758	6.556		7.939
7	3.683			3.984			5.280		

Table 3: Extracted variables from the factor matrices

Factors	Indices	
1st factor	*D*	Total causalities, completely damaged houses, total damage of livestock, total damage of electricity lines, total damage of religious structures, partially and completely damaged earthen roads, partially damaged educational institutions, total damage of shallow tube wells, and total damage of cottage industries.
	COMV	Total population, annual average family income, total population below 5 years age, total population above 60 years age, and disabled population.
	STRINFV	Total number of tents for homeless people, and total number of people without hygienic sanitation.
2nd factor	*D*	Partially damaged paved roads, partially and completely damaged embankments, and total damage of fishing boats.
	STRINFV	Total number of houses, total number of structured houses, total number of people without electricity supply, total number of people per educational institution, total number of people per growth center, and total number of people per financial institution.
3rd factor	*D*	Completely damaged crops, total damage of fisheries, completely damaged paved roads, total damage of forests, and total damage of ponds.
	STRINFV	Total number of huts, total number of semi-structured houses, and total number of people without safe drinking water.
4th factor	*D*	Affected area, total affected population, partially damaged houses, total damage of poultry, and total damage of deep tube wells.
	STRINFV	Total number of people per healthcare facility,
5th	*D*	Total damage of telecommunication lines, and total damage of industries.
	STRINF	Total number people allocated for each cyclone shelter, and total number

factor	*V*	of people per food storage.
6th factor	*D*	Completely damaged educational institutions.
	STRINFV	Total number people per kilometer of paved roads.
7th factor	*D*	Partially damaged crops.