QUANTITATIVE APPROACHES TO RISK SCREENING ROADS FOR CLIMATE CHANGE RISKS

Giles Dickenson-Jones (corresponding author).
Consultant
12/174 Raglan Street Mosman,
Sydney, NSW 2088 Australia.
Tel: +61439472603
Fax: +612 9247 2455
E-mail: Giles.Dickenson.Jones@gmail.com

Daisuke Mizusawa
Infrastructure Specialist
The Asian Development Bank
6 ADB Avenue,
Mandaluyong City 1550,
Metro Manila, Philippines
Tel: +632 632 4444
Fax: +632 636 2446
Email: dmizusawa@adb.org

Chen Chen
Transport Specialist
The Asian Development Bank
6 ADB Avenue,
Mandaluyong City 1550,
Metro Manila, Philippines
Tel: +632 632 4444
Fax: +632 636 2446
Email: cchen@adb.org

Submission date: Monday, February 13, 2012

Word Count = 6188 (text) + 250*4 (Tables) + 250* 1 (Figure) 7,438 <7,500

ABSTRACT

This research addresses the need for a more comprehensive approach to identifying roads at risk from climate change. Although subjective assessments can be useful, their inability to be conclusively tested makes it difficult to compare and rank their results across projects. In recognition of this, this paper develops techniques to provide simple, objective and transparent methodologies for identifying the point at which climate change is relevant for a road project's design. Factors identified as being the most likely to impact roads are sea-level rise, deterioration from changes in average temperate and rainfall and changes in peak and average rainfall which result in inundation. Where potential risk factors are identified, a more detailed assessment of the risks is recommended.

Keywords: CLIMATE CHANGE, ROADS, RISK SCREENING, CLIMATE RISKS,

INTRODUCTION

The quality of a road is generally assessed according to its 'roughness', which is a measure of the severity and frequency of surface imperfections on a road's surface. A rougher road can limit driving speeds and increases wear and tear on vehicles. A range of individual surface imperfections may contribute to overall roughness such as potholes, surface cracks and rutting. Typically roughness is measured by the 'International Roughness Index' (IRI) which provides a standardized measure of road surface imperfections over a given distance. A road with more surface imperfections will be 'rougher' and have a higher IRI (1).

For a road to successfully retain its structural integrity and a desired level of roughness, it is essential that each component of the structure performs effectively under local environmental conditions. Environmental factors potentially relevant to the longevity of road infrastructure are those which are likely to impact its usefulness, or serviceability, with reference to its original design intentions. Key factors identified in the literature include precipitation, temperature, wind speeds, sea-level rise and extreme events (2).

Higher temperatures often increase the local moisture content of the air resulting in the softening of asphalt. This can expedite deterioration through increasing the road's sensitivity to a given traffic loading (2; 3). Additionally, higher and more variable temperatures can damage road infrastructure through the expansion and contraction of joints, coatings and sealants as well as through the more regular occurrence of freeze/thaw cycles. Additionally higher temperatures may result in the degradation of the strength of permafrost on which the structural capacity of a road may depend (3; 4).

Similarly, unanticipated changes in rainfall can have significant impacts on the maintenance costs and efficacy of roads. Specifically, rainfall can increase the moisture content of the underlying soil (or subgrade) significantly lowering its load-bearing capacity and risking faster deterioration or potential structural failure (5-7).

In the future, rising sea-levels may strongly affect road infrastructure in low-lying coastal areas. Coastal road networks may be exposed to greater levels of moisture, higher salinity and storm surges (7). Roads that are inundated as a consequence of rising sea-levels are also likely to either deteriorate more rapidly or be severely damaged.

In addition, floods, droughts and cyclones have the potential to disrupt and permanently damage road networks, a scenario which is all the more severe when considering the vital role of transportation networks in natural disaster evacuations and aid mobilization (8).

Although it is clear that roads are highly dependent on their environmental context, current design standards already perform satisfactorily under a range of weather variations. Accordingly this research focuses on identifying when a changing climate is likely to be beyond the typical resilience of a road. Because understanding this requires the consideration of the probability and impact of a specific component of climate change, risks are taken to be a combination of:

- The likelihood that a climate change related event occurs (flood, extreme temperature, sea-level change);
- The probability of transport network damage or failure as a result of this event (chance of delays, increase in roughness, complete failure); and
- The economic and social impact of the event (repair and replacement costs, disruption costs, loss of time, mortality etc.) (Adapted from: 2).

Regmi made an early attempt to assess the effects on roads from a changing climate through surveying transport professionals in Asia. The survey focused on the concerns of transport professionals with reference to climate change and current design standards. Respondents indicated that there was widespread concern as to the impact climate change may have on road infrastructure. Furthermore there was some concern as to the level to which current design standards may not be sufficiently durable to adapt to changes in future climates (6).

This concern is also shared by a number of researchers with Gardiner conducting an assessment of the risk climate change poses to transport infrastructure in New Zealand (2). The research involved an extensive review of the literature and sought input from a range of transport practitioners. Importantly, the survey asked participants to identify the *likelihood* and *consequence* of the effect of climate change on transport infrastructure which allowed for a qualitative estimate of individual risks. A summary of the survey results for roads is provided in Table 1.

TABLE 1: Key Climate Change Risks to Road Infrastructure

Climate Variable	Likelihood	Consequence	Risk
Coastal flooding	Likely	Severe to catastrophic	High
Flooding	Very likely to almost certain	Severe to catastrophic	High
Rainfall	Very likely to almost certain	Major to Severe	High
Inland erosion and instability	Likely to almost certain	Major to catastrophic	High
Coastal erosion	Likely	Severe	High

Although valuable for the identification of risk, qualitative assessments rely almost exclusively on the experience and opinions of participants. This may be a particular concern if respondents are biased ill-informed, or asymmetric in their treatment of risk. In addition, the inability to derive statistically testable point-estimates from qualitative surveys means that often the absolute and relative risks are difficult or impossible to objectively analyze.

In a Canadian study, Tighe, Smith, Mills et al. noting the increased focus on incorporating climate change into the design of infrastructure, provided a quantitative investigation of the impact of climate change on low-volume roads in Southern Canada. The study found that whilst deterioration would increase as a consequence of climate change, its impact was expected to be modest relative to the impact of traffic and the region's baseline climate (9).

Similarly a quantitative assessment of the potential impact of climate change on the Australian transportation network was conducted by Austroads. The study suggested that rising sea-levels, water tables and levels of salinity could all potentially impact road infrastructure. Areas where rainfall was expected to increase would face higher maintenance costs as a consequence of faster deterioration (7).

Harvey, Chong and Roesler adopted an empirical approach in considering the impact of climate change for road infrastructure in different regions in California. Their research identified significant differences in pavement deterioration depending on the regional differences in climate. In addition to finding differences in deterioration as a result of rainfall and temperature it also revealed that a ten degrees Celsius difference (41 degrees Celsius to 49 degrees Celsius) could significantly accelerate pavement failure (10).

The impact of increased exposure to moisture was empirically tested by Berjarano et al (11). The research monitored the performance of flexible pavements with and without permeable base layers to determine the impact of approximately 51.3millimeters (mm) rainfall per week on pavement performance. The research found clear signs of early failure in non-permeable pavements with an approximate decrease in pavement life of eighty per cent.

Based on previous studies it appears likely that the factors that have the greatest impact for road infrastructure are those which alter the longevity of the structure such as temperature or moisture exposure, or those impacts which erode the load-bearing capacity of the subbase.

Although there appears to be a significant level of confidence as to what components of climate change will likely have an impact, the likelihood of discrete events such as increases in sea-level, temperature and rainfall occurring vary significantly. Consequently, the probability of a particular event occurring needs to be considered when assessing the magnitude of the risks from climate change to roads. A summary of forecast confidences or the expected likelihood of particular characteristics of climate change occurring is provided in Table 2.

TABLE 2: Forecast Confidence

	Climate Variable
High Confidence	Mean temperature. Sea-level rise.
Moderate Confidence	Extreme temperature. Mean precipitation.
Low Confidence	Storm frequency/severity. Extreme local precipitation.

(Adapted from: 12)

Taking the level of forecast confidence as a reasonable indication of the likely probability of an individual component of climate change occurring in conjunction with its magnitude (as outlined in Table 1) suggests the following as being the chief risks to road infrastructure from climate change:

1. **Sea-level rise:** high forecast confidence, severe to catastrophic consequences.
2. **Rainfall**: moderate forecast confidence, severe consequences.
3. **Temperature:** high forecast confidence, low to moderate impact.

Accordingly, this research develops techniques to identify the risks which are considered a credible threat to roads. These are taken to include changes in temperature, peak and average precipitation and rising sea-levels.

METHODOLOGY

The relevance of climate change to an individual road project is expected to be dependent on a range of factors specific to the implementing agency, the structure itself and expected changes in climate over the road's lifetime. As such, the extent that climate change poses a significant risk will vary on a project by project basis. In recognition of this, the methods demonstrated in the following sections are designed to be parsimonious and easily customized by individual institutions and practitioners in accordance with their risk preferences.

The impact of sea-level is expected to predominantly depend on the proximity of a project site to the coast, its altitude relative to the local sea-level during a high-tide or storm-surge event and the projected rise in sea-level during the project's life. Because these are chiefly issues relating to the geographical properties of the project site, this research develops a technique based on Geographic Information System (GIS) mapping to assess the altitude of the project with reference to sea-level projections to determine its exposure to risk from rising sea-levels.

Estimating the consequence of temperature and rainfall on the rate of deterioration is performed in this research using a simplified component of the Highway Development and Management Model (HDM-4). HDM-4 itself is a widely used software package designed to assist in the planning of transport networks. A particular property of the model which is useful for the study is its framework for forecasting the deterioration profiles of a road network under a given set of environmental conditions (7).

To determine the risk that changes in average rainfall pose to a road a methodology was developed based on typical drainage design standards and records of precipitation events in Asia (13).

Whereas, for extreme rainfall events, commonly applied drainage formulas are used in conjunction with accepted drainage standards. This information has then been used to determine the level of unanticipated rainfall that would change the standard of drainage for a road and therefore potentially expedite its deterioration.

Sea-Level Rise Risk Screening

To assess the current proximity of a project site to sea-level, data sourced from the Shuttle Radar Topography Mission (SRTM) is used. SRTM has been chosen as it provides a low-cost, easily accessible resource with broad geographical coverage (14). It also remains the most accurate and comprehensive digital topographic database available (15).

The estimated elevation for a section of a project as indicated by SRTM will be denoted as $\hat{z}$. Although it is expected the data will be correct on average, at any given point it is probable $\hat{z} \neq z$. However, the true altitude of a project is likely to lay within the SRTM's ±16 meters error bounds or (14):

$$z \cong \hat{z} \pm 16 \quad (1)$$

Given that, the true altitude of points identified by SRTM data may be lower than that indicated. Estimating at what level the lowest true altitude is likely to lie, requires that the bound of error is accounted for. Letting δ signify the margin of error, the likely lowest true altitude becomes:

$$\hat{z}_{lower\ bound=}\hat{z} - \delta \quad (2)$$

Letting 'S' represent the level of subsidence over the road's lifetime, the altitude that a given point of the road is expected to be in the future becomes '$\hat{A}'$ such that:

$$\hat{A} = \hat{z}_{lower\ bound} - S \tag{3}$$

Sea-level rise scenarios can then be selected alongside relevant tidal variations to approximate the potential sea-level at a given point in the future: $\hat{R}$. Denoting the forecasted sea-level rise as $\hat{\alpha}$ and the upper level of tide as $\hat{\sigma}$ gives:

$$\hat{R} = \hat{\alpha} + \hat{\sigma} \tag{4}$$

When the point at which the sea is expected to rise to is the same level as the point being assessed $\hat{R} = \hat{A}$. Therefore when $\hat{R} \geq \hat{A}$ the location can be deemed to be 'at risk' and potentially will be impacted by rising sea-levels. Assessing this for an entire project becomes a matter of assessing the number and magnitude of times where $\hat{R} \geq \hat{A}$ or where during the road's life it may potentially meet the sea given a high-tide event.

Applying these principles under the assumption of:

- A road project's lifetime being twenty years.
- Relatively high subsidence approximating twenty centimeters per decade (based on (based on: 16; 17).
- A seven meter tidal variation based on 'king tide' events in Australia (18).
- A vertical error range of sixteen meters at the ninety per cent level of confidence (14).
- A rise in sea-level at the site of 1.4 meters (19).

Under such a scenario, coastal road segments the altitude of which are identified as being equal or less than 25 meters above sea-level may face heightened risk of inundation from sea-level rise during their lifetime. It would consequently be recommended that a more detailed analysis of this risk is conducted for such sites.

Rainfall and Temperature Related Deterioration Risk Screening

The Highway Development and Management model (HDM-4) was developed to assist transport officials make informed decisions about highway management from the proposal to implementation stage. The model forecasts the deterioration and maintenance requirements of road infrastructure over its lifetime (fifteen to forty years). Factors taken into account include traffic loading, drainage and environmental weathering (20).

Individual factors contributing to HDM-4's estimation of a road's roughness such as rutting, cracking and potholing are presented as individual components of the model. Annual changes in roughness are assumed to be determined by structural deformation, rutting, cracking, potholing and environmental effects (21). These are explained in more detail below.

The structural component of HDM-4 estimates the annual changes in IRI as a result of annual traffic loads, time since maintenance was last performed and the environment. The overall change in structural integrity of the road is expected to be negatively associated with traffic loads, the time since the road was last maintained and the road's exposure to heat and rainfall.

Rutting occurs when pavement materials are distorted due to traffic loads and environmental effects. The impact of a given distortion on a road's roughness will depend both on the depth of the rutting and its uniformity. Specifically, variations in the depth of ruts are expected to cause increased roughness (22).

Cracks and potholes may emerge during a road's life impacting a road's roughness. The impact of potholes on a roads IRI depends on the number of potholes, the ability of users to avoid them and the number that will be repaired in a given year (22).

Impacts on the IRI not related to traffic or pavement strength are defined as 'environmental effects' and are primarily a result of temperature, moisture and movements of the structural base of the road (22).

Broadly, HDM-4 assumes that the change in roughness for a given year is equal to the sum of the contributions of cracking, rutting, potholing, structural impacts and environmental effects or:

$$\Delta RI = \Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_p + \Delta RI_e \quad (5)$$

Where:

ΔRI: The total change in the roughness index (meters per km).
ΔRI_s: Change in roughness from impacts on the structure.
ΔRI_c Change in roughness from cracking.
ΔRI_r; Change in roughness from rutting.
ΔRI_p: Change in roughness from potholing.
ΔRI_eChange in roughness from environmental effects.

To examine the impact of the environment on a road's deterioration over time, the relationship is simplified to include only components which are impacted by the environment. In the HDM-4 model this is primarily addressed through incorporating an environmental variable 'm' into the deterioration relationship. Isolating components of the roughness relationship where the environmental variable has influence and denoting the total change in roughness as a result of climate as 'ΔRI_{cc}' the relationship becomes:

$$\Delta RI_{cc} = \Delta RI_s + \Delta RI_e \quad (6)$$

Or the deterioration of a road from the environment is the sum of the change in roughness from structural impacts on the road and the change in roughness from environmental effects.

Expanding:

$$\Delta RI_{cc} = \frac{K_{gs} 134^{K_{gm} \cdot m \cdot AGE3}}{(1 + SNPK_b)^5} \cdot YE4 + K_{gm} \cdot m \cdot RI_a \quad (7)$$

Where:

$SNPK_b = \max[(SNP_a - dSNPK), 1.5]$

$dSNPK = K_{snpk} 0.0000758[\min(63, ACX_a) HSNEW + \max(\min(ACX_a - PACX, 40), 0)\, HSOLD]$

m: Environmental coefficient

K_{gs}: Calibration factor for the structural component of roughness
K_{gm}: Calibration factor for the environmental coefficient.
K_{snpk}: $Calibration\ factor\ for$ SNPK.
$AGE3$: $Years\ since\ last\ overlay$.
$SNPK_b$: Adjusted structural number due to cracking at the end of the analysis year.
SNP: Adjusted structural number at the start of the analysis year.
$dSNPK$: The reduction in the structural adjustment number due to cracking.
$HSOLD$: Total thickness of previous underlying surface layers in mm.
$HSNEW$: Thickness of most recent surfacing in mm.
ACX: Area of indexed cracking at start of analysis year in per cent.
$PACX$: Area of previous indexed cracking in old surfacing, in per cent.
$YE4$: Annual number of equivalent standard axels (ESALs), in millions per lane.
RI_a: Roughness at the start of the analysis year.

To generalize the relationship, the calibration factors, which are typically used to customize the model for local experiences, are set equal to one and it is assumed the structural adjustment number is constant. The change in roughness for a given year then becomes:

$$\Delta RI = \frac{134^{m \cdot AGE3}}{(1 + SNPK)^5} \cdot YE4 + m \cdot RI_a \quad (8)$$

The relationship suggests that deterioration will be faster where:

1. The road is poorly built (indicated by a low value of $SNPK$);
2. The road's initial condition is poor as indicated by a higher RI_a;
3. The road is infrequently maintained, indicated by a high value for $AGE3$;
4. Traffic loads are heavier signified by a relatively high traffic loads (YE4); and
5. The environmental influence or value of 'm' is high.

The values of 'm' used in the HDM-4 model have been developed collaboratively to best reflect the experience of how roads deteriorate in different climates (23). Although it is accepted that the precise rates of deterioration caused by temperature and rainfall will be largely unique, m is expected to be a reasonable guide. Broadly it is hypothesized that any deterioration will be the highest in cool regions with high rainfall and lowest in warm regions with low rainfall this is illustrated in more detail in Table 3.

TABLE 3: HDM-4 Environmental Factor 'm'

	Temperature Classification (degrees Celsius)				
Moisture Classification (annual rainfall)	**Tropical (20-35 °C)**	**Sub-Tropical hot (-5-45°C)**	**Sub-Tropical cool (-10-30°C)**	**Temperate cool (-25-25°C)**	**Temperate freeze -40-20°C)**
Arid (<300mm)	0.5%	1.0%	1.5%	2.0%	3.0%
Semi-arid (300-800mm)	1.0%	1.5%	2.0%	3.0%	4.0%
Sub-humid (800-1600mm)	2.0%	2.5%	3.0%	4.0%	5.0%
Humid (1500-3000mm)	2.5%	3.0%	4.0%	5.0%	6.0%
Per-humid (>2400mm)	3.0%	4.0%	5.0%	-	-

Maintenance is assumed to be conducted by a local authority which would trigger a maintenance event only after the road reaches a condition that the authority is unable to tolerate, termed the ‘roughness threshold’. The authority would then return the road to a desired condition, accounting for current state of the road and the deterioration expected during the year of repair.

Let:

$$q_t = \Delta RI^e{}_{t+1} + RI_{t-1} - RI^d \quad (9)$$

Where:
q_t: The magnitude of maintenance or repair.
$\Delta RI^e{}_{t+1}$: The expected deterioration in the next year.
RI_{t-1}: Condition of the road in the previous year.
RI^d: The desired level of roughness for the road.

Maintenance will be scheduled when: $RI_{t-1} > RI^T$

Where:
RI^T: The ‘roughness threshold’.

Although this research does not apply maintenance in order to exaggerate the impacts of climate on a road’s deterioration, it is assumed expectations are formed by the authority based on past observations of a road’s deterioration. The relevant authority’s expectations can then projected into the future based on a trend term and past observations of deterioration using ordinary least squares (OLS) regression (see: 24).

Because any manifestation of climate change on a road’s rate of deterioration is likely to be subtle, it will be up to the assessor of the road to determine when any climate change impact is significant, relying on specificities of the project. For this research it is assumed that it is of concern where at some point the changes are ‘tangible’ such that a user would be able to discern the difference between a road with and without climate change.

To this end a change of 0.29 IRI has been chosen as the level of change required for climate change to be of material concern. This has been based on the lowest difference in IRI required for a tangible change in a road’s quality standard (25).

As predicted changes in average rainfall and temperature may be too subtle to alter a road’s environmental classification in HDM-4, OLS regression is used to provide an estimate of the marginal impact of rainfall and temperature on the value of ‘m’. Midpoints of temperature and rainfall are used to represent data points which determine the magnitude of ‘m’. After trialing multiple functional forms the following identity explained 97 per cent of the variations in the value of ‘m’.

$$\hat{m} = 1.66 - 0.08T + 0.003R - 6.53^{E-07}R^2 \quad (10)$$

t-statistic: (11.3) (-18.6) (13.1) (-10.4)

Where:
$\hat{m}$: The estimated value of HDM-4’s environmental variable (%).
T: Average temperature, measured in degrees Celsius (°C).
i) R: Average annual rainfall measured in mm.

The functional form states that the magnitude of the environmental variable 'm' depends on the level of temperature in degrees Celsius and the level and squared level of annual rainfall in mm per hour. Based on the first derivative it is expected that for every 1 degree Celsius increase in temperature the value of m will decrease by 0.076, whilst any increase in rainfall will result in an increase in m by 0.003 + 1.31^{e-06}R per mm of annual rainfall.

Simulating the impacts of climate change through the model then becomes a matter of applying the specification in equation 8 (above) over the life of a project. The resulting deterioration profile can then be compared with and without a change in climate, determining the level of change required in the value of m for there to be a 0.29 change in the IRI between scenarios. In order that the environment has the maximum impact on a road's deterioration it is assumed:

- The road is located in an area classified as arid for rainfall and temperate-freeze for temperature with an initial 'm' of 1.66%;
- Initial temperature of zero degrees Celsius with no change throughout road's life and an initial level of rainfall of nil;
- The structural adjustment number is 2.06 and the initial roughness is 3.4 consistent with a poorly built road (26);
- The road's life is twenty years;
- No maintenance is performed during the road's lifetime;
- Traffic of one ESAL growing at three per cent per annum;
- Average rainfall increases occur in the second year of the road's life;

With an initial value of m of 1.66% rainfall would need to increase by approximately 85 mm over the road's life for climate change to tangibly impact the road project.

For road projects facing similar conditions to the scenario, where rainfall is expected to increase by approximately 85 mm or more a detailed consideration of climate change's impact on the project's viability is recommended.

Average Rainfall Risk Screening

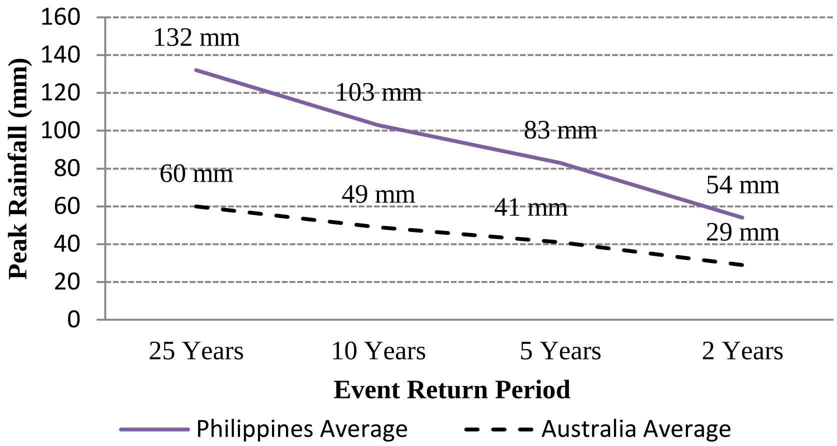
Whether a road experiences prolonged exposure to moisture is strongly influenced by the capacity of drainage systems to cope with local precipitation levels. Inundation from insufficient drainage may result in faster deterioration or a temporary or even permanent loss in its serviceability.

The uncertain nature of anticipating future drainage needs requires that the engineer makes some assessment about the extent to which the project would be able to withstand an extreme rainfall event. Because it is potentially costly to protect against all rainfall scenarios, a trade-off is necessary. The approach is therefore to select an acceptable chance of the design specifications being insufficient for a peak rainfall event and to design the drainage system to be able to operate effectively under these conditions (27).

Typically, shorter peak rainfall events are more intense and place the greatest pressures on a road's drainage system. Road engineers will therefore commonly design drainage to perform adequately for a one-hour peak rainfall event (27). A properly designed and maintained drain will consequently have some additional capacity to cope with increases in average rainfall to the extent that the peak rainfall event the drain has been designed for exceeds typical or average rainfall in the region.

Although it is uncertain at any time when a given extreme rainfall event may occur the probability of one occurring at a specified magnitude is higher over a longer time period than a shorter one. As such, peak rainfall events are defined by ‘return periods’ with the level of a maximum peak rainfall event increasing as the time interval increases. As an example this concept is illustrated in Figure 1 for peak rainfall in Australia and the Philippines.

FIGURE 1: One hour peak-rainfall event



(Adapted from: 28)

A consequence of the different rainfall patterns is that road drainage tends to have different capacities to accommodate increases in regularly occurring or ‘average’ rainfall events depending on local rainfall variations. Specifically, in areas where the difference between peak and regular rainfall events is less, road drainage is *on average* less likely to have as much excess capacity as would drainage systems in regions with more variable precipitation patterns.

Given this, Bogor, Indonesia is selected, having the least rainfall variability and highest average rainfall from a recent sample of precipitation patterns for Asia. Rainfall statistics for the region are then used to provide a conservative estimate of potential surplus drainage capacity, as illustrated in Table 4.

TABLE 4: Hypothetical Drainage Capacity

Drainage system's design return period	**25 Year**	**10 Year**	**5 Year**	**2 Year**
Peak rainfall (mm)	109	106	90	80
Additional capacity (mm)	29	26	11	-
Increase required to reach peak rainfall.	37%	33%	13%	0%

(Adapted from: 28)

The above analysis implies that for a drainage system built to accommodate peak rainfall for a five year return period, average rainfall would need to increase by 11 mm or 13 per cent to reach the system's capacity.

Although this is not necessarily true in all circumstances, it is suggested that it represents a conservative estimate that on average would tend to over identify projects at risk given that:

1. A five year return period is half the standard recommended for the drainage systems of low-volume roads (13);
2. A two year peak rainfall event has been used to represent average rainfall which is expected to be proportionally higher than what would be typically experienced as average rainfall; and
3. The level of rainfall variability chosen from the research sample was the minimum and therefore would tend to underestimate the typical capacity of a drainage system.

Consequently, climate change is expected to on average be a significant concern for road infrastructure in Asia when average rainfall is projected to increase by more than 13 per cent. In regions where rainfall is projected to increase beyond this, it is suggested a more detailed assessment of the impact of climate change on the road should be conducted.

Peak Rainfall Risk Screening

Road engineers typically design drainage to perform adequately for a given peak rainfall event rather than average rainfall. Consequently any increase in the intensity of rainfall above that considered during design will be in excess of the drain's capacity and likely result in water remaining on the pavement surface for longer periods than is desirable (27). Longer drainage times may also result in faster deterioration and a potential loss of serviceability for a given road.

The approach taken here, therefore, is to determine what level increase in peak rainfall is necessary to cause a movement in drainage standards. In the first instance, this is a matter of determining how much water will accrue and need to be disposed of for a given increase in rainfall. A typical method of doing this is the 'Modified Rational Method' (MRM). What level of exposure to water is significant then needs to be determined. For the purposes of this research the American Association of State Highway and Transportation Official's (AASHTO) drainage standards are used (22).

The MRM estimates the volume of rainfall Q_Y as a positive function of the size of the catchment area a, the intensity of the rainfall $I_{T_C}^{Y}$ and the proportion of rain that will be transferred from the surface as runoff C_Y.

Formally:

$$Q_Y = \frac{C_Y \cdot I_{T_c}^{Y} \cdot a}{360} \tag{11}$$

Where:
Q_Y : Volume of runoff in m^3 per second
C_Y : Runoff coefficient for rainfall event.
$I_{T_C}^{Y}$: Average rainfall intensity for a storm of T_C hours and a return period of Y years in mm/hr.

a : Area exposed to rainfall (hectare).
(Adapted from: 29).

Because not all rainfall will be delivered as runoff, the method includes a runoff coefficient 'C_Y' to alter the proportion of rainfall that will be delivered to the drainage system. A higher runoff coefficient implies that a greater volume of water would be transferred from the catchment area as runoff, while a lower coefficient would indicate that an area is more permeable and therefore will deliver less rainfall as runoff. For sealed pavements the coefficient can be expected to be 0.8 to 0.95 for asphalt and 0.7 to 0.95 for concrete. Unsealed roads can be considered to have rates closer to zero (13).

Once the quantity of runoff is known, the speed at which it will be drained can be approximated through an adapted form of Manning's formula, commonly used for calculating water velocity for a given channel. The formula estimates the cubic meters of water which will flow per second (Q_Y) for a given channel area (A) and slope (S), whilst the hydraulic radius is designed to proxy the flow efficiency of the channel.

The hydraulic radius is equal to the water area divided by the area that water is in contact with (the 'wetted area' 'P'). The lower the wetted area is relative to the cross sectional area of the channel, the greater the flow efficiency or 'hydraulic radius'.

$$Q_Y = \frac{R^{2/3} \cdot S_0^{0.5} \cdot A}{n} \tag{12}$$

Where:
Q_Y: Volume of water flow in m^3 per second.
R: $\frac{A}{P}$
P: The channel's wetted perimeter.
S_0: Channel slope.
n: Manning's roughness value.
A: The cross-sectional area in m^2.
(Adapted from: 29).

When drainage is sufficient to accommodate a given rainfall event the Manning's and MRM equation should be equal:

$$\frac{C_Y \cdot I_{T_c}^{Y} \cdot a}{360} = \frac{R^{2/3} \cdot S_0^{0.5} \cdot A}{n} \tag{13}$$

Solving for $I_{T_c}^{Y}$:

$$I_{T_c}^{Y} = \frac{360 \cdot A \cdot S^{0.5} R^{2/3}}{n \cdot C_Y \cdot a} \tag{14}$$

Many factors in the relationship may vary during a given rainfall event such as the drainage area, slope and the permeability of the soil. For this treatment it is assumed that during the rainfall event, the properties of the drainage system will remain constant. Accordingly, assumptions have been chosen that illustrate how a drain is likely to operate under a worst-case scenario during the rainfall event.

For the present scenario minimum drainage dimensions recommended by the United Nations Food and Agriculture Organization (FAO) (13) are use. In addition:

1. There will be a low level of permeability with a runoff coefficient of 0.95.

2. A Manning's roughness coefficient of 0.5 is to simulate a poorly maintained drainage system with vegetal covering (30).
3. A minimum standard 'triangular ditch drain' 0.3 meters deep and 0.9 meters wide (13).
4. A slope of 0.001.
5. A catchment area of one hectare.

Under such a scenario it is expected that the drainage system would be able to accommodate approximately eight cubic meters of runoff per hour or 0.8 mm of rainfall for a catchment area of one hectare. Under AASHTO standards the shortest time water can remain on the pavement for there to be a change in drainage standards is twenty-two hours. This would require that the level of unanticipated peak rainfall increase by 18 mm. When compared against a maximum peak rainfall event for Asia this would amount to at least a seven per cent increase in peak rainfall (28).

Accordingly, road projects in areas where peak rainfall is expected to increase by seven per cent or more are likely to be at risk from climate change and a more detailed assessment should be conducted.

CONCLUSIONS

This research developed quantitative techniques useful for identifying road projects that may be at risk as a consequence of climate change. A review of relevant literature revealed the largest risks to roads are likely to manifest themselves through changes in sea-level, rainfall and temperature.

This paper used an elevation profiling technique using publically available altitude data to assess risks from sea-level. A component of the HDM-4 model was used to estimate the marginal impact of temperature and rainfall on a road's deterioration. Whereas the risk from changes in peak and average rainfall were assessed using a combination of typical drainage design principles and rainfall data for Asia.

The risk to a road from sea-level rise was expected to be higher where it is likely to be inundated or impacted by coastal erosion during its life. The chance of this occurring was assumed to be a function of the road's altitude, the local tide variations, subsidence and local rises in sea-level. Given the chosen assumptions it was suggested that all projects equal or less than 25 meters above sea-level should be considered against the risk of sea-level rise.

Importantly, over half of the altitude threshold estimated for screening projects for sea-level rise risk was a consequence of the margin of error associated with the SRTM data. Whilst the SRTM data was chosen on the basis of its low cost and broad coverage it is expected more accurate data will become freely available in the future. Accordingly the technique is likely to greatly improve with improvements in the detail and availability of geographical data.

Passive changes in the rate of deterioration from changes in rainfall and temperature were assessed using a simplified version of the HDM-4 model. In the model the rate of deterioration is a function of the initial condition of the road, the structural strength of the road, the regularity of maintenance, the level of traffic and the average level of rainfall and temperature. Increases in temperature were hypothesized to decrease the rate of deterioration whilst rainfall was hypothesized to increase it. Under a scenario of an unmaintained road it was found that for climate change to have a tangible impact on the road annual average rainfall would need to increase by 85 mm or more.

Although the deterioration modelling in this research has been based on relationships defined by HDM-4, this paper's technique is designed to be significantly simpler and require fewer assumptions than the full software package. As such, conclusions drawn from the methodology need to be carefully considered to ensure the underlying assumptions are appropriate for the particular analysis. Accounting for this, pessimistic assumptions were selected in order to avoid underestimating the impact of the environment on the road's deterioration profile throughout its life.

Increases in average rainfall were expected to pose the biggest risks where historical differences between the intensity of peak and average rainfall events were low. It is suggested that average rainfall would pose a risk where it increased to or greater than the level of peak rainfall. Rainfall statistics suggested that an increase in average rainfall of at least 13 per cent would be necessary to overcome a road's drainage system built to withstand a one-hour peak rainfall event with a five year return period.

An increase in peak rainfall unanticipated by a road's designers is expected to result in some level of inundation. To determine the length of time a road would need to be inundated for it to pose a risk, the AASHTO drainage guidelines were used alongside engineering equations to estimate runoff volumes and the capacity constraints of a given water channel. It was found that for a change in drainage standards to occur, an increase in peak precipitation of at least 18 mm was necessary. For Asia this would require an increase in peak precipitation of at least seven per cent.

The tools developed in this research have the distinct advantage of being inexpensive and simple to apply in a range of circumstances. Although this research estimated a series of critical thresholds for when climate change presents a risk for road projects, its chief intent is to demonstrate the application of quantitative tools for the purposes of screening roads for climate change risk at the project inception stage, as actual critical values are likely to be unique to regions and organizations.

The uncertainties associated with anticipating the structural needs of a road in the face of climate change provide a strong justification for making climate change assessments mandatory on an organizational basis. However, there exists a clear opportunity cost to investing time and expertise to formally assess the risk of climate change to a road where there is no need. Conversely, not exploring the implications for new roads may be potentially costly if climate change threatens its viability.

Although this research is agnostic as to what the optimal level of consideration is, it is argued that the techniques developed herein provide an alternative framework for exploring these concepts. Such techniques will also likely become more relevant and applicable as humanity's ability to understand and forecast climate change improves.

ACKNOWLEDGEMENTS

Parts of this research were supported by the Asian Development Bank's internship program in 2011.

The views expressed in this article are those of the author (authors) and do not necessarily reflect the views and policies of the Asian Development Bank (ADB) or its Board of Governors or the governments they represent. ADB does not guarantee the accuracy of the data included in this publication and accepts no responsibility for any consequence of their use.

REFERENCES

1. Sayers, M.W., 1998. The Little Book of Profiling: Basic Information About Measuring and Interpreting Road Profiles. University of Michigan, Ann Arbor, Transportation Research Institute, Michigan.
2. Gardiner, L., Firestone, D., Waibl, G., Mistal, N., Van Reenan, K., Hynes, D., Byfield, J., Oldfield, S., Allan, S., Kouvelis, B., 2009. Climate Change Effects on the Land Transport Network Volume One: Literature Review and Gap Analysis.
3. Taylor, M.a.P., Philp, M., 2010. Adapting to Climate Change–Implications for Transport Infrastructure, Transport Systems and Travel Behaviour. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice* 19(4), 66.
4. Mills, B., Andrey, J., 2002. Climate Change and Transportation: Potential Interactions and Impacts. *Proceedings from The Potential Impacts of Climate Change on Transportation, October*.
5. Mannering, F.L., Washburn, S.S., Kilareski, W.P., 2009. *Principles of Highway Engineering and Traffic Analysis*, 4ED ed. John Wiley & Sons, Inc., New Jersey.
6. Regmi, M.B., 2009. Assessment of Impacts of Climate Change on Road Transport, In: H., S. (Ed.). Department of International Development Engineering
Tokyo Institute of Technology, Ookayama, Tokyo.
7. Austroads, 2004. Impact of Climate Change on Road Infrastructure, *AP-R243/04*. Austroads, Sydney, NSW.
8. Manton, M., Della Marta, P., Haylock, M., Hennessy, K., Nicholls, N., Chambers, L., Collins, D., Daw, G., Finet, A., Gunawan, D., 2001. Trends in Extreme Daily Rainfall and Temperature in Southeast Asia and the South Pacific: 1961–1998. *International Journal of Climatology* 21(3), 269-284.
9. Tighe, S.L., Smith, J., Mills, B., Andrey, J., 2008. Evaluating Climate Change Impact on Low-Volume Roads in Southern Canada. *Transportation Research Record: Journal of the Transportation Research Board* 2053(-1), 9-16.
10. Harvey, J., Chong, A., Roesler, J., 2000. Climate Regions for Mechanistic-Empirical Pavement Design in California and Expected Effects on Performance. *CAL/APT Program, Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley*.
11. Bejarano, M.O., Harvey, J.T., Ali, A., Russo, M., Mahama, D., Hung, D., Preedonant, P., 2004. Performance of Drained and Undrained Flexible Pavement Structures under Wet Conditions, Accelerated Test Data Test Section 544—Undrained. Citeseer.
12. Andrey, J., Mills, B., 2003. Climate Change and the Canadian Transportation System: Vulnerabilities and Adaptations. *Weather and Transportation in Canada*, 235-279.
13. Fao, 1998. *Watershed Management Field Manual: Road Design and Construction in Sensitive Watersheds*. Food and Agriculture Organization of the United Nations, Rome.
14. Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., 2007. The Shuttle Radar Topography Mission. *REVIEWS OF GEOPHYSICS-RICHMOND VIRGINIA THEN WASHINGTON-* 45(2).
15. Gusmao, D.D., 2011. Sea-Level Rise Projections for Solomon Islands Second Road Improvement Project (Sirip 2) - North Malaita, In: Hemming, J., Gilham, R., Camp, J., Hartley, A., Morgan, N., Hemming, D. (Eds.). Met Office - Hadley Centre.

16. Nicholls, R.J., Hoozemans, F.M.J., Marchand, M., 1999. Increasing Flood Risk and Wetland Losses Due to Global Sea-Level Rise: Regional and Global Analyses. *Global Environmental Change* 9, S69-S87.
17. Aobpaet, A., Cuenca, M.C., Hooper, A., Trisirisatayawong, I., 2009. Land Subsidence Evaluation Using Insar Time Series Analysis in Bangkok Metropolitan Area.
18. Deccw, 2009. A Snapshot of Future Sea Levels: Photographing the King Tide. New South Wales Department of Environment, Climate Change and Water Sydney, Australia. .
19. Rahmstorf, S., 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. *Science* 315(5810), 368.
20. Kerali, H.G.R., 2000. *Hdm-4 Highway Development & Management: Volume One, Overview of Hdm-4*. The World Road Association (PIARC).
21. Kosasih, D., Robinson, R., Snell, J., Ia Review of Some Recent Geometric Road Standards and Their Application to Developingcountries.
22. Kerali, H.G.R., 2001. *Hdm-4 Highway Development & Management: Volume Six, Modelling Road Deterioration and Works Effects in Hdm-4*. The World Road Association (PIARC).
23. Harral, C.G., Faiz, A., Bank, W., 1988. *Road Deterioration in Developing Countries: Causes and Remedies*. World Bank.
24. Brooks, C., 2008. *Introductory Econometrics for Finance*. Cambridge Univ Pr.
25. Hunt, P.D., Bunker, J.M., 2003. Study of Site-Specific Roughness Progression for a Bitumen-Sealed Unbound Granular Pavement Network. *Transportation Research Record: Journal of the Transportation Research Board* 1819(-1), 273-281.
26. Tsunokawa, K., Ul-Islam, R., 2003. Optimal Pavement Design and Maintenance Strategy for Developing Countries: An Analysis Using Hdm-4. *International Journal of Pavement Engineering* 4(4), 193-208.
27. Finn, G., Buckley, D., Kelly, K., Mcdaid, J., Laoghaire, D., Mullaney, D., Power, J., 2004. Guidelines for Road Drainage. Department of the Environment, Heritage and Local Government, Ireland.
28. Sherman, T.B.K., 2008. 5.4. 1 Traditional Methods to Establish Idf Curves for Precipitation. *Asian Pacific FRIEND*, 37.
29. Alderson, A., Group, A., 2006. The Collection and Discharge of Stormwater from the Road Infrastructure. *RESEARCH REPORT-AUSTRALIAN ROAD RESEARCH BOARD ARR* 368.
30. Chow, V.T., 1959. Open-Channel Hydraulics. *New York/Tokyo; McGraw-Hill, 1959, 680 p.*