Estimating Pavement's Flood Resilience

Misbah U. Khan, CPEng.[1]; Mahmoud Mesbah, Ph.D.[2]; Luis Ferreira, Ph.D.[3]; and David J. Williams, Ph.D.[4]

Abstract: Although several studies observed pavement responses after flooding, no detailed quantification has been done to date. This paper has estimated different pavements' performances with flooding to identify flood-resilient roads. This was shown through (1) new roughness and rutting-based road deterioration (RD) models, (2) the relationship between changes in roughness [International Roughness Index (IRI)] versus time and modulus of resilience (Mr) loss at granular and subgrade layers versus time, and (3) flood consequence results. The comparative analysis on different pavement performances shows that a rigid and strong pavement built to a high standard is the most flood-resilient, which may be adopted as a preflood strategy. Results obtained using two proposed new gradients of IRI (incremental change in IRI, ΔIRI) in Year 1 over probability of flooding ($\Delta\text{IRI}/Pr$) and ΔIRI in Year 1 over loss in Mr ($\Delta\text{IRI}/MrL$) as well as flood consequences provided similar results. Road authorities should consider changing their roads to flood-resilient pavements in the future. It is recommended to investigate after flood roads' structural conditions and performances to validate the new ratio values of $\Delta\text{IRI}/Pr$ and $\Delta\text{IRI}/MrL$. **DOI:** 10.1061/JPEODX.0000007.

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Introduction

Pavement performance shows deterioration of roads with time in its service life, which is dependent on traffic loading, material properties (pavement type, structure, strength, and subgrade strength), climate and environment, drainage, initial road condition, and maintenance activities (Hunt and Bunker 2001). It is generally expressed by roughness versus time. Roughness is related to pavement structural and functional conditions, traffic loading, and environmental factors, and it has a direct relationship with vehicle operating costs, accidents, and driver comfort (Gopinath et al. 1994; Odoki and Kerali 2000; Prozzi 2001). Therefore, it is the most representative index for evaluating a pavement performance. AASHTO also uses roughness for pavement design.

A pavement shows an abrupt change in road condition, e.g., roughness and rutting, after a disaster such as flooding. As a result, higher pavement deterioration is observed, for example, significant roughness [denoted by International Roughness Index (IRI)] increase is found due to flooding. Studies reveal that the incremental change in IRI (ΔIRI) due to a flood depends on loss in pavement modulus of resilience (Mr) and the probability of flooding.

Several studies have identified that the Mrs of granular and subgrade layers are reduced due to moisture intrusion (Brown and Dawson 1987; Drumm et al. 1997; Yuan and Nazarian 2003). Both Monismith (1992) and Huang (1993) found an increase in pavement deflection due to a lower Mr, and consequently a reduced pavement life. There are no studies that can address pavement performance with flooding.

Recently, Khan et al. (2014a, 2017c) and Khan (2017) developed project and network levels roughness and rutting-based road deterioration (RD) models at different probabilities of flooding. Additionally, Khan (2017) and Khan et al. (2017a) determined pavement responses during flooding using the Mr loss values in granular and subgrade layers. Using the roughness prediction model of AASHTO (2008) (based on AASHTO's pavement design guide of 2008) and the Highway Development and Management Model (HDM-4) (Odoki and Kerali 2000), they observed poor pavement performance after a flood when Mr was reduced. The impact of pavement performance due to different probabilities of flooding was shown in Khan et al. (2014a). Both these studies (Khan et al. 2014a; Khan 2017) provided IRI versus time and rutting versus time because of a flood. An after-flood effect on pavement roughness was estimated while assessing flood risk for the road network (Khan 2017; Khan et al. 2017b), which gives ΔIRI due to a flood.

The current paper has aimed to measure pavement performances with flooding in order to obtain strong pavements that can better sustain flooding in their lifecycle, which was determined using the pavement performances with flooding scenarios, that is, (1) performance at different probabilities of flooding, (2) performance at different Mr loss values in Year 1, and (3) change in IRI due to a flood. The newly derived RD models are valid for a short period up to 2–3 years (Khan 2017; Khan et al. 2017c). The RD models with flooding, ΔIRI in Year 1 divided by the percent of probability of flooding ($\Delta\text{IRI}/Pr$) and ΔIRI in Year 1 divided by the percent of Mr loss at subgrade and granular layers ($\Delta\text{IRI}/MrL$) for different road groups and flood consequence results provide valuable information in this regard.

The current paper has proposed two new gradients: (1) $\Delta\text{IRI}/Pr$, and (2) $\Delta\text{IRI}/MrL$ using the IRI versus percent probability of flooding and IRI versus percent Mr loss relationships, respectively. The consequence of a flood for a road group using ΔIRI also gives useful information. The gradient of rutting (ΔRutting) versus the percent probability of flooding provides similar relationships; hence, the ΔRutting in Year 1 over probability of

[1]Ph.D. Candidate, School of Civil Engineering, Univ. of Queensland, Brisbane, QLD 4072, Australia; Senior Asset Systems Engineer, Central Coast Council, 2 Hely St., Wyong, NSW 2259, Australia (corresponding author). E-mail: misbah_70@yahoo.com

[2]Senior Lecturer, School of Civil Engineering, Univ. of Queensland, Brisbane, QLD 4072, Australia. E-mail: mahmoud.mesbah@uq.edu.au

[3]Professor, School of Civil Engineering, Univ. of Queensland, Brisbane, QLD 4072, Australia. E-mail: l.ferreira@uq.edu.au

[4]Professor, School of Civil Engineering, Univ. of Queensland, Brisbane, QLD 4072, Australia. E-mail: d.williams@uq.edu.au

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flooding is not discussed in this paper. All these help to obtain a flood-resilient pavement, which helps enhance flood resilience of existing weak pavements.

The earlier work derived new roughness and rutting-based RD models at different probabilities of flooding for network-level and site-specific roads. This paper has shown the practical implications of these models, i.e., quantifying different categories of pavements' performances after a flood. It proposes $\Delta\text{IRI}/Pr$ and $\Delta\text{IRI}/MrL$ for determining pavement flood resilience. Therefore, it is an extension of the previous study. These two indicators give sound results on pavement performances after flooding and subsequently on flood-resilient pavements. Therefore, it addresses a critical issue in the infrastructure management.

The RD models are validated with actual data using the January 2011 flooding in Queensland. Four flood-affected roads in the Logan, Australia, area were used for verification. Moreover, a t-test was used. The AASHTO (2008) and HDM-4 roughness models also revealed a close match to the network-level and site-specific RD models (Khan 2017).

As a case study, the paper uses the 34,000-km road database of the Transport and Main Roads Authority, Queensland (TMR-QLD), which has the last 10–12 years of records including after-flood roughness and rutting data. Queensland experienced devastating flooding in 2011. The scope of this research covers flood-damaged pavements that were saturated but for which the embankment and structure have remained intact (not completely damaged or washed away), that are at moderate risk of further flooding and need preventive maintenance and rehabilitation with or without partial reconstruction. These roads need appropriate attention before and after a flood.

The initial part of this paper includes a literature review and shows the approach used. The results and detailed conclusions are shown subsequently.

Literature Review

The section is divided into three components: effect of a flood, recent studies with flooding, and RD model with a flood.

Effect of a Flood on Pavement

Studies on pavement responses due to flooding are limited. Helali et al. (2008) studied performance of 544 km of roads due to the effect of Hurricanes Katrina and Rita in the United States in 2005. Roads were submerged for weeks and heavy traffic loading was moving over these flooded roads. It was found that 90 to 190 mm of asphalt concrete (AC) as rehabilitation was required for the flooded road to enhance its pavement structural strength. They also found that the flooded sections deteriorated more than the controlled sections with 2.5–6.5 times higher deflection values. Similarly, a case study assessed the flood impact due to Hurricane Katrina and then Hurricane Rita, mainly in New Orleans (Zhang et al. 2008). In total, 3,220 km of roads were flooded for 5 weeks. The study considered 383 km of flooded and nonflooded roads as its sample. The initial investigation results revealed that the losses of average pavement strength [Structural Number (SN)] and subgrade modulus due to flooding were 18 and 25%, respectively. The AC pavement experienced 20% subgrade Mr loss and 46% increase in deflection, whereas concrete pavements had only 1% subgrade Mr loss and 9% increase in deflection. The study found that flooded pavements have lower Mr at granular and subgrade layers, and hence higher deflection and lower strength (Zhang et al. 2008).

Yuan and Nazarian (2003) noticed that a flooded road would experience on average approximately 15 times more damage compared with a well-drained section. Gaspard et al. (2006) assessed after-flood data for Hurricane Katrina, and found the following:

- Thinner asphalt pavements became weaker than a thicker one;
- Very little damage was detected for the rigid as well as composite pavements;
- Flooding duration beyond 7 days did not have any further damaging effect on the pavements;
- Both pavement structural data (SN, deflection, and Mr) and functional data (IRI, rutting, and cracking) were necessary for after-flood structural evaluation; and
- The composite pavements needed 25 mm of AC as rehabilitation because they perform better during the flooding period, whereas the thin pavement needed a minimum 75 mm of AC.

The January 2011 flood in Queensland affected 70% of the state and 60% of its population. The indicative loss to the economy has been estimated at AUD$13–30 billion [1–2.3% of gross domestic product (GDP)] (PWC 2011). The total damage to the public infrastructure across the state was AUD$5–6 billion. In addition, Cyclone Yasi added another AUD$800 million loss to the road and transport network (PWC 2011). A recent assessment revealed that approximately 28% of major roads (9,170 km) were severely damaged during these events and 300 roads along with nine major highways were closed (TMR 2012). The TMR-QLD could not manage to complete its largest program (AUD$4.2 billion) to reconstruct 6,709 km of roads even after 2–3 years (TMR 2012). The program was not based on any after-flood pavement performance assessment. Therefore, an after-flooding pavement structural analysis would be useful for future planning purposes.

In the reviewed studies, Mr values of the pavement layers (granular and subgrade) were reduced significantly due to high moisture content during flooding. As a result, deflection increased and SN reduced. However, all the preceding studies collected after-flood data and assessed pavement responses with deflection and structural strength. The studies could not capture pavement performances with flooding.

Recent Studies with Flooding

Sultana et al. (2014) considered the same Queensland flooding being used in this paper. They tried to develop a deterministic model of SN versus time for low-volume sealed roads using deflection data. The study used road groups based on traffic volume only. Sultana et al. (2016) used one specific road in Brisbane, Australia, to develop the RD model. Pavement performance resembled uncertainty; therefore, a probabilistic model is more justified. These studies did not derive network-level models. No simulation has been done to get RD models for different probabilities of flooding. In addition, appropriate network-level and site-specific roughness and rutting models were not derived, which helped in selecting postflood treatments.

Hurricanes Katrina and Rita were also used to assess pavement performance by Chen and Zhang (2014). The study used before and after flood roughness data for 2 years. A slightly higher roughness was found for the flooded roads. This study used road grouping based on pavement types. Although the real data were assessed, no RD models with flooding were generated. In addition, it did not assess different types of pavement performances with flooding.

Another new study (Shamsabadi et al. 2014) derived a simple regression model of IRI versus time using noncontinuous road data, which is valid for local conditions. The independent variables used were flooding depth, duration, loading and initial IRI, which are not always easy to collect. This model may be used for one type of road group only. In addition, a simulation-based probabilistic RD model with different probabilities of flooding was not addressed.

New RD Models That Include a Flood

As mentioned previously, RD models with flooding are needed for better asset preservation. All the preceding studies did not develop a realistic RD model that could predict road deterioration at different probabilities of flooding. None of the derived models are probabilistic. Therefore, Khan et al. (2014a, 2017c) recently derived pavement performances and RD models with flooding. They developed IRI and rutting versus time relationships at different probabilities of flooding for up to 2–3 years and IRI versus different Mr loss due to flooding in Year 1. The new RD models with flooding have recently been verified with actual field data of some roads in Logan, Australia, and were found to be consistent (Khan et al. 2017c; Khan 2017). The models were derived using nonhomogeneous transition probability matrix (TPM) and Monte Carlo simulation. Khan et al. used the percentage transition method to generate nonhomogeneous TPM from the observed roughness and rutting versus time data. Details can be seen in Khan et al. (2014a, 2017c). Khan et al. (2017a) used AASHTO (2008) and HDM-4 (two well-known and useful models) for deterioration prediction using IRI after a flood.

Khan et al. (2014a) used the whole road database of TMR-QLD to derive RD models with flooding. They also developed preflood and postflood road maintenance strategies, which can be seen in Khan (2017) and Khan et al. (2016, 2015). The analysis used 27 representative road groups for the network considering three types of pavement (flexible, rigid, and composite), three types of loading (low, moderate, and high), and three types of pavement strength (poor, fair, and strong). The traffic loading ranges were set low for <1 million equivalent single-axle loading (MESAL), moderate for 1–10 MESAL, and high for >10 MESAL. Pavement strength was determined using a score derived from pavement age, seal age, and pavement thickness [score $= (1/\text{pavement age}) \times (1/\text{seal age}) \times \text{pavement thickness}$]; where <1 was termed as poor, 1–5 as fair, and >5 as strong. It shows that the higher the total pavement thickness (covering surface and granular layers), the higher is the score. Considering two hypothetical roads, the newer pavement has a higher strength score, if seal age and pavement thickness are the same. Details are given in Khan et al. (2014a).

The enhanced integrated climatic model (EICM) of AASHTO (2008) was used to determine Mr loss at granular and subgrade layers due to moisture intrusion. These Mr losses have been used as inputs in the AASHTO (2008) and HDM-4 roughness prediction models for deriving pavement performances, i.e., ΔIRI in Year 1. The results were compared for seven flexible pavement road groups at varying Mr loss (Khan et al. 2017a).

Apart from that, Khan (2017) and Khan et al. (2017a) did a flood risk assessment using change in roughness as consequence of a flood. Actual representative roughness distribution data before and after a flood were used for a road group.

A detailed quantification on pavement performances with flooding for all the road groups is necessary, which was not done before. Therefore, this paper has used two new indicators ($\Delta\text{IRI}/Pr$ and $\Delta\text{IRI}/MrL$) to measure different types of pavement performances after flooding. This shows a practical use of the RD models in a pavement management system (PMS). The flood consequences are also used to determine pavement resilience with flooding.

A flood-resilient pavement is expected to perform better after a flood. Generally, a raised pavement, adequate drainage structure, proper subsurface drainage facilities, appropriate materials, and stable embankment slope can ensure better performance of a road with a flood. All these solutions are outside the scope of the research; rather, this paper considers pavements that need appropriate postflood rehabilitation. As a result, pavement strengthening with a thick AC overlay and/or stabilization of granular layers is considered here for transforming one road to a flood-resilient pavement. Strengthening overlay and stabilization are being used in Queensland and elsewhere to increase structural strength of flood damaged roads. Hence, this paper suggests the common practices as a solution. However, optimum solutions have been derived for the preflood and postflood strategy, which is outside the current scope.

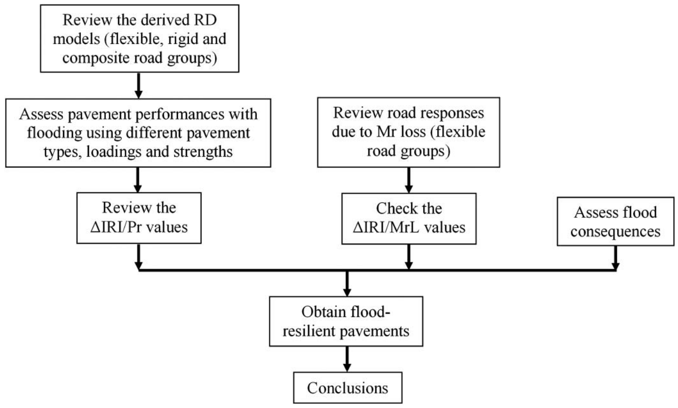

Fig. 1. Approach used in the study

Methodology

The ultimate aim of this paper is to measure pavement performances after a flood and to obtain flood-resilient pavements using the findings from (1) new RD models, (2) $\Delta\text{IRI}/Pr$, (3) $\Delta\text{IRI}/MrL$, and (4) flood consequences results. The roughness and rutting-based RD models were used to assess different types of pavement performances with flooding. In addition, a new gradient of IRI on probability of flooding ($\Delta\text{IRI}/Pr$) was considered to obtain the impact of a flood on a pavement's performance. These results provide valuable information to obtain flood-resilient pavements. Details of the RD model development with flooding are discussed in Khan et al. (2014a, b).

Flooding causes moisture intrusion in a pavement, which reduces the Mr at the granular and subgrade layers, and ultimately pavement strength is reduced. As a result, pavement performances would be poorer. This investigation of using the impact of Mr loss on pavement performances provided another valuable indicator of $\Delta\text{IRI}/MrL$, which helps to visualize pavement performances due to a flood. Details of the impact of Mr loss on pavement performance is shown in Khan et al. (2017a). In addition, the flood consequences obtained from before and after a flood's roughness distribution data for a road group have been used to determine pavement flood resilience.

Fig. 1 shows the approach in deriving pavement performances with flooding and obtaining flood-resilient pavements. All the gradient results are analyzed separately for this purpose.

Major Findings

Road Deterioration Modeling Results

The new IRI and rutting-based RD models have been derived for all the road groups. However, no rutting-based models were derived

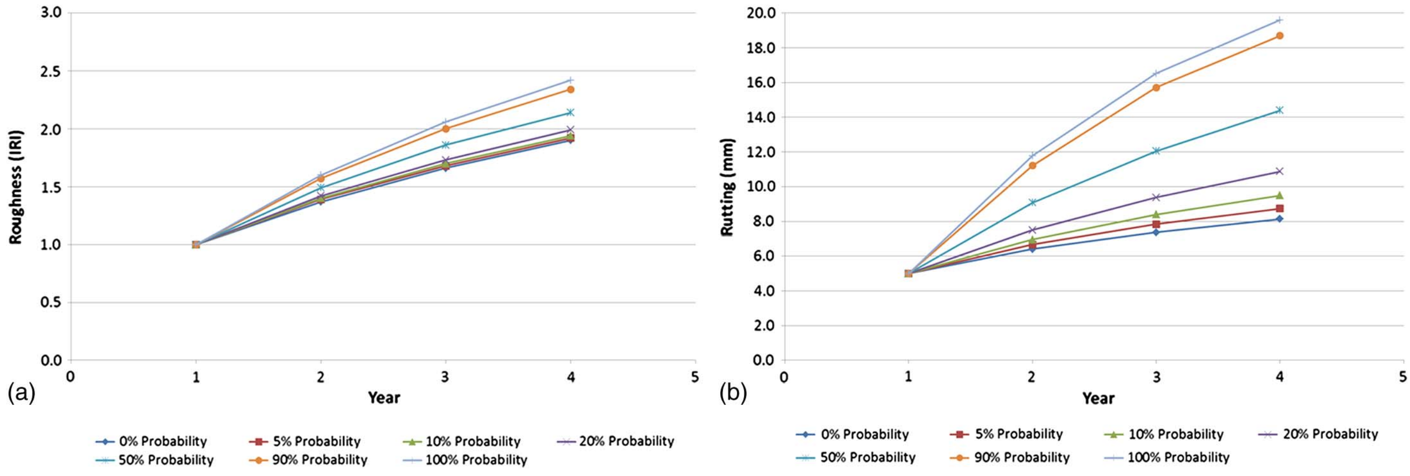

Fig. 2. New (a) IRI-based, (b) rutting-based RD models for F_HT_S

for rigid pavements because they do not link to rutting. The nonhomogeneous TPMs with and without flooding were generated for a road group using 10–12 years of data, which were used in the Monte Carlo simulation for RD modeling. In the simulation, a random probability was generated to select the flood or without flood TPM. Then, another set of random variables were produced to compare with condition states. After 10,000 trials, a RD model was developed for a road group. The simulation process assumes (1) excellent road condition at the start, (2) no rehabilitation in the first few years, and (3) validity of the RD models for up to 2–3 years.

As an example, a specific road group of flexible pavement with high traffic loading and strong strength (F_HT_S) has been chosen here, which has IRI and rutting-based RD models at different probabilities of flooding (Fig. 2). It shows that a pavement performs more poorly at a higher probability of flooding. The rutting-based RD model shows a more dispersed trend in this case. The results show that ΔIRI at 100% probability of flooding in Year 1 is 0.62, while it is 0.35 at no flooding. Therefore, ΔIRI due to a certain flood is 0.27, which is adequate to change a postflood rehabilitation treatment selection for a high traffic loading road group like F_HT_S. In addition, the effect of a flood on pavement performance also relates to maintenance standard. The ΔIRI for F_HT_S is low because this road group has a high maintenance standard. These RD models are important in selecting postflood rehabilitation because they show the actual pavement deterioration trends with a flood. Results on other road groups can be seen in Khan et al. (2014b, 2017c).

As stated previously, these network- and project-level RD models are validated with actual data obtained from four flood-affected roads in Logan, Australia, and close matches were found, which was also supported by a t-test. In addition, the AASHTO (2008) and HDM-4 model results provided similar findings (Khan 2017).

After a critical assessment of the RD models, it was found that the IRI-based RD models are valid for 13 road groups, while the rutting-based RD models are valid for seven road groups. It is observed that some road groups did not have enough data to generate RD models. Moreover, some derived RD models were not appropriate due to (1) inconsistency when compared with other pavement types, loading, and strengths; (2) providing highest ΔIRI/ΔRutting at 0% probability of flooding or at normal condition; and (3) having no change in ΔIRI/ΔRutting at 0% probability of flooding or at normal conditions. In fact, the second and third reasons reveal abnormality in road deterioration. These are due to inconsistent data, which affect the derived normal and flooding TPMs of a road group.

Using the RD models, the current paper has generated $\Delta\text{IRI}/Pr$ values for all the road groups. The lowest gradient value indicates a better pavement performance with flooding. These results give sound flood-resilient pavements, which are discussed in detail in the next sections.

Effect of Different Types of Pavements, Loadings, and Strengths on Performances with Flooding

Generally, a pavement performance with flooding for some initial years (2–3 years) depends on pavement type, traffic loading, pavement strength, and set maintenance standards. Moreover, it has a linkage with flooding probability because the highest probability reveals the poorest performances.

Considering pavement type, a rigid pavement performs better than composite and flexible road groups incorporating flooding. Both composite and flexible road groups show similar performance up to 2–3 years. The stabilized layer of a composite pavement becomes granular after some years, hence composite and flexible pavements behave in the same way. As an example, Fig. 3 shows a comparison of pavement performances with flooding for three different types of road groups, that is, F_HT_S, composite pavement with high traffic loading and strong strength (C_HT_S),

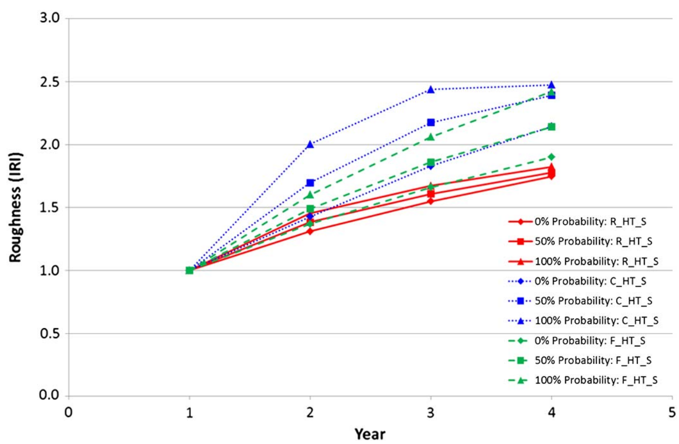

Fig. 3. Comparison of pavement performance with flooding using three types of pavement

and rigid pavement with high traffic loading and strong strength (R_HT_S). Fig. 3 shows that a rigid pavement (R_HT_S) performs the best at any probability of flooding, and flooding effect is not critical for this road group. This is also supported by Gaspard et al. (2006). The current results show that a flexible pavement performs better than a composite one at the initial years after flooding, though Gaspard et al. (2006) observed a better performance for a composite pavement than a flexible one. In future, this may be investigated. As a result, it is settled that a rigid pavement is more flood-resilient.

The high-loading road groups perform better than medium-loading and low-loading roads because generally high-loading roads have higher maintenance standards. However, if their maintenance standards are the same, then the low-loading road groups perform the best. In general, a higher standard indicates a better pavement maintenance practice at a set lower IRI. Fig. 4 reveals an example of pavement performance with flooding for three loading scenarios. Three road groups has been chosen here, that is, F_HT_S, flexible pavement with medium traffic loading and strong strength (F_MT_S), and flexible pavement with low traffic loading and strong strength (F_LT_S). The results show that the low-loading road group with the lowest standard of 4.5 IRI performs the worst with flooding. Both the medium- and high-loading road groups have the same set standards of 4.0 IRI. Hence, the medium-loading road group performs better with flooding during the initial years than the high-loading road groups.

The impact of loading on pavement performance with flooding generally means that a road performs better if it carries a low loading. The simulation analysis considers road condition or TPMs, and it did not analyze the impact of loading during the flooding period. The current results show that the maintenance standard, which relates to loading, influences pavement performance. It is observed that a higher standard road with lower loading can ensure better performance with a flood.

Another key observation is that a strong pavement road group performs the best, while a fair strength pavement performs better than a poor one. Moreover, it is known that a strong pavement road group has a higher standard. Fig. 5 shows an example of pavement performance with flooding for two different strength road groups. The RD modeling outputs did not provide results for the three pavement strength types to compare. In fact, the flexible pavement with high traffic loading and fair strength (F_HT_F) road group did not have a logical RD model because of inconsistent data. Therefore, a comparison has been done among F_HT_S and flexible pavement

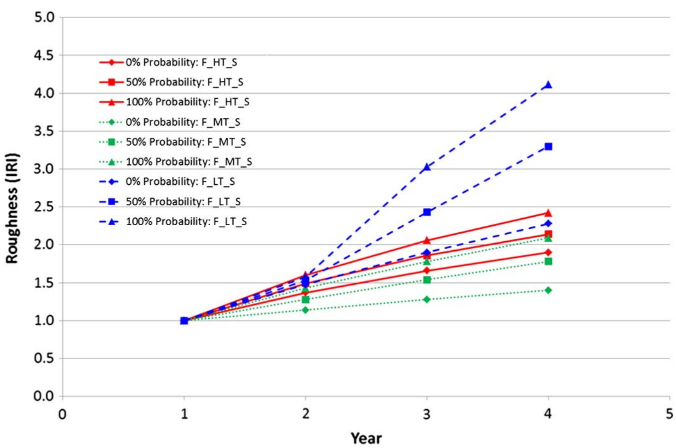

Fig. 4. Comparison of pavement performance with flooding using three types of traffic loading

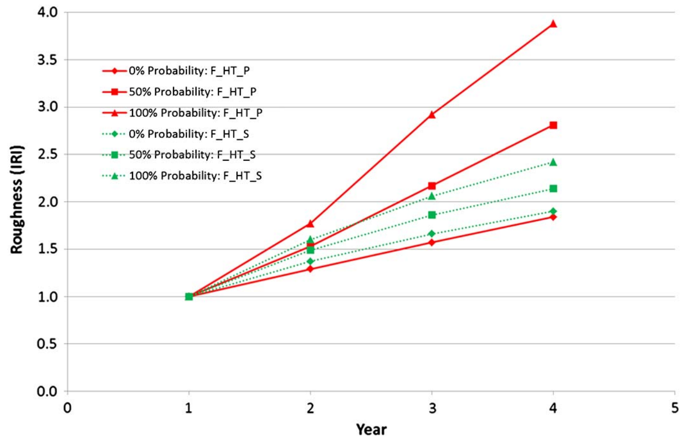

Fig. 5. Comparison of pavement performance with flooding using two types of strength

with high traffic loading and poor strength (F_HT_P). As expected, the strong pavement road group performs much better in its service life with flooding than the poor one, which is supported by Gaspard et al. (2006). This indicates that a strong pavement is more flood-resilient.

In addition, it is noticed that the high-standard road groups perform better than moderate- and in turn low-standard roads. High-standard roads are strong with higher pavement thickness and are maintained efficiently because they carry heavy traffic. The TMR-QLD data reveal that these roads have frequent maintenance performed. As a result, a high-standard road has a lower deterioration rate during flooding.

Roughness jumps were observed from Years 2–3 for F_LT_S (Fig. 4) and F_HT_P (Fig. 5). Simulation results were based on the TPMs derived from the IRI versus time data for the respective road groups, and outcomes are generally acceptable. Therefore, it was difficult to know why a different trend is found for the two cases. However, these do not have any impact on the results to assess pavement performances at different types, loading, and strength.

ΔIRI/Pr Results

The newly proposed indicator, $\Delta\mathrm{IRI}/Pr$, has been used to get a pavement's performance with flooding. In this case, a certain flooding or 100% probability of flooding is considered. The values of $\Delta\mathrm{IRI}/Pr$ of all road groups have been assessed. It indicates that a pavement performance is better if $\Delta\mathrm{IRI}/Pr$ is lower. Table 1 shows pavement resilience with flooding.

Overall, five types of pavements show less than 0.25 IRI increase in 1 year after a flood, and others provide higher increase. Generally, normal deterioration in Australian roads after 1 year is found to be approximately 0.08–0.10 IRI (AustRoads 2015). Therefore, these road groups show sound responses. As an example, F_LT_S, R_HT_S, and R_MT_F have $\Delta\mathrm{IRI}/Pr$ values of 0.10, 0.14, and 0.18, respectively. It shows that a rigid and strong road performs the best. A strong and low-loading road performs well in this case, which is reasonable.

It was not possible to extract results for some road groups because of the absence of consistent data in RD modeling. The following are expected results on a theoretical basis about the performances of these road groups. It may be expected that the flexible pavement with medium or high loading and fair strength roads would have lower $\Delta\mathrm{IRI}/Pr$ values compared with F_HT_P, whereas those values might be higher than the values of F_MT_S and F_HT_S. Similarly, composite pavement with low traffic

Table 1. ΔIRI/Pr Results for Different Road Groups

Road group	ΔIRI/Pr at 100% probability of flooding (Khan 2017)
F_LT_F	1.20
F_LT_P	0.23
F_LT_S	0.10
F_MT_F	N/A
F_MT_P	N/A
F_MT_S	0.29
F_HT_F	N/A
F_HT_P	0.48
F_HT_S	0.23
C_LT_F	0.28
C_LT_P	N/A
C_LT_S	N/A
C_MT_F	1.28
C_MT_P	0.67
C_MT_S	0.91
C_HT_F	N/A
C_HT_P	N/A
C_HT_S	0.57
R_LT_F	0.99
R_LT_P	2.00
R_LT_S	1.70
R_MT_F	0.18
R_MT_P	N/A
R_MT_S	1.64
R_HT_F	0.80
R_HT_P	N/A
R_HT_S	0.14

loading and strong strength (C_LT_S) and composite pavement with high traffic loading and fair strength (C_HT_F) may have lower values. Rigid pavement with high traffic loading and poor strength (R_HT_P) and rigid pavement with medium traffic loading and poor strength (R_MT_P) road groups might have higher ΔIRI/Pr values because they are poor in strength. These results provide an indication on performances of some road groups in the TMR-QLD road database.

ΔIRI/MrL Results

The ΔIRI/MrL values were generated for seven flexible pavement road groups to evaluate their performance with flooding. The lower the ΔIRI/MrL after a flood, the better is the performance. These ΔIRI/MrL values were derived at 60% subgrade and 40% granular layer Mr losses, which were found as extreme moisture intrusion or flooding (Khan et al. 2017a).

Table 2 reveals these results. It shows that F_HT_S has the lowest ΔIRI/MrL value of 0.15 during flooding. Therefore, it performs the best during flooding. Because F_HT_S is a strong road group with a higher maintenance standard and is maintained appropriately because of high loading, it performs the best. Apart from this road group, F_MT_S and F_HT_F also perform well due to their higher standards, and their gradient values are 0.22 and 0.23, respectively. The F_MT_S is a strong road group with a higher standard, and hence it performs the second best.

Table 2 gives an indication on results of the flexible pavement with low traffic loading and strong strength (F_LT_S) and flexible pavement with medium traffic loading and poor strength (F_MT_P) road groups, which are missing now. It seems that a F_LT_S road performs well like F_MT_S and F_HT_S roads. However, a F_MT_P road group may give a ΔIRI/MrL value in the range of 0.35–0.52, which performance might be in between the flexible pavement with high traffic loading and poor strength (F_HT_P) and flexible pavement with low traffic loading and poor strength (F_LT_P) road groups.

Table 2. ΔIRI/MrL Results for Different Road Groups

Road group	ΔIRI/MrL at 60% subgrade Mr loss and approximately 40% granular layer Mr loss (Khan 2017; Khan et al. 2017a)
F_LT_F	0.33
F_LT_P	0.52
F_LT_S	N/A
F_MT_F	0.32
F_MT_P	N/A
F_MT_S	0.22
F_HT_F	0.23
F_HT_P	0.35
F_HT_S	0.15

The analysis did not consider rigid or composite pavements. It appears from the Zhang et al. (2008) study that Mr loss was not an issue with rigid pavements, and therefore it can be reasoned that decrease in Mr will have a minor impact on the IRI for rigid pavement roads.

Flood Consequence Results

Flood consequence results for specific floods are determined using roughness distribution data. These findings show ΔIRI because of a flood (Table 3). Though each road group has flood consequence values, they are not based on the same probability of flooding. Therefore, it is not easy to compare the results. In general, strong and high- or medium-loading road groups perform well, having lower consequences (Table 3). Four flexible pavement road groups have 0.25 or less IRI increase in 1 year after a specific flood. The

Table 3. Flood Consequence Results for Different Road Groups

Road group	Likelihood of a flood (Khan 2017; Khan et al. 2017a)	ΔIRI as flood consequences (Khan 2017; Khan et al. 2017a)
F_LT_F	>10 years	2.03
F_LT_P	>10 years	0.62
F_LT_S	10 years	0.56
F_MT_F	8 years	0.21
F_MT_P	>10 years	0.66
F_MT_S	>5 years	0.22
F_HT_F	2 years	0.25
F_HT_P	9 years	0.38
F_HT_S	3 years	0.24
C_LT_F	>5 years	0.67
C_LT_P	>9 years	1.50
C_LT_S	>10 years	0.43
C_MT_F	8 years	0.86
C_MT_P	9 years	0.68
C_MT_S	>6 years	0.41
C_HT_F	>10 years	1.15
C_HT_P	2 years	0.59
C_HT_S	6 years	0.69
R_LT_F	5 years	1.03
R_LT_P	>10 years	2.50
R_LT_S	>5 years	1.51
R_MT_F	2 years	0.70
R_MT_P	2 years	1.03
R_MT_S	2 years	1.13
R_HT_F	>3 years	1.13
R_HT_P	2 years	0.93
R_HT_S	2 years	0.48

rigid pavements did not show sound results. However, other analyses provide that rigid pavement perform well after a flood.

The likelihood has been estimated from the time gap of two consecutive flood events. However, because 10–12 years of data were used, some road groups did not provide actual likelihood data. As a result, engineering judgment was used for estimating likelihood. For example, no second flood was found in the flexible pavement with low traffic loading and fair strength (F_LT_F) road group; as a result, its likelihood was at least greater than 10 years. A likelihood score based on moderate (1 in 10 years) to unlikely (1 in 50 years) flooding was assumed for this road group. The likelihood ranges are discussed in Khan (2017) and Khan et al. (2017a). Consequence score was calculated by subtracting average IRI after a flood to average IRI before that flood. Detailed results are shown in Khan (2017) and Khan et al. (2017a).

The preceding findings suggest that any road authority may consider flood-resilient pavements as a proactive approach before a flood by ensuring strong and rigid pavements in vulnerable locations. This can be done through providing appropriate rehabilitation with strengthening overlay and/or stabilizing granular layers and replacing with a rigid pavement. Recently, the World Bank (2013) planned to invest in a climate-resilient road project through rehabilitation of 1,000 km of paved and unpaved roads in Mozambique. They mainly concentrated on stabilization of granular layers based on previous experiences only.

Conclusions

Although several studies have observed pavement responses with flooding, no quantification on different pavement performances have been undertaken to obtain a definite answer. Therefore, the current paper has tried to estimate pavement performances with flooding for different pavement types, which helps obtain pavements' flood resilience. The severe thaw-related problems during winter may provide a similar effect to flooding on pavements. The unbound layers get saturated by the excessive amount of moisture that has accumulated during the freeze period; as a result, pavements are damaged. However, this was not in the scope of this study.

This paper has quantified flood resilience of different types of pavements, which helps in pavements' criticality, obtaining flood-resilient pavements, and ultimately improving a PMS incorporating flooding. It has identified flood-resilient pavements so that a flood-damaged road may be upgraded into a flood-resilient one before a flood comes. The outcome ensures better pavement performances and reduces service life maintenance costs with flooding. It is basically assumed that all pavements are designed and constructed to the best standards of pavement guidelines. However, no current guideline mandates a proactive approach in considering a probable flood in a pavement design. In addition to normal design considerations such as loading, flood resistance can be used as a criterion to choose the pavement type and strength during pavement design. Furthermore, no PMS takes a proactive approach in considering a flood. This paper is a step forward to consider this probabilistic approach.

Four methods were used to get the findings using (1) pavement performances at different probabilities of flooding, (2) proposed $\Delta\text{IRI}/Pr$, (3) proposed $\Delta\text{IRI}/MrL$, and (4) flood consequence results. All these reveal valuable information to obtain a flood-resilient pavement.

It was not possible to obtain results for all the road groups due to inconsistent data for some of the groups in RD modeling. The Mr loss analysis was only done for some selected flexible pavement road groups. The flood consequence results are only valid for specific probabilities of flooding. However, these results provide adequate confidence in obtaining flood-resilient pavements.

The RD models were validated with actual after-flood data obtained for four flood-affected roads in Logan, Australia, especially with the Mount Lindesay Highway and Beaudesert-Beenleigh road (Khan et al. 2017c). Comparing the RD models at different pavement types, loading, and strength scenarios give pavement performances after a flood. The $\Delta\text{IRI}/Pr$ or $\Delta\text{IRI}/MrL$ provide pavement performances at change in flooding probability or Mr loss, respectively. Certainly, a lower $\Delta\text{IRI}/Pr$ or $\Delta\text{IRI}/MrL$ indicates a better pavement performance with flooding because it means less road deterioration after a flood. Although all these techniques provide pavement performances with flooding, they are not compared because they are based on different approaches. However, they give sound indication.

The results obtained from different techniques have been shown here. The two proposed indicators, i.e., $\Delta\text{IRI}/Pr$ and $\Delta\text{IRI}/MrL$, along with flood consequence results provide useful findings. It may be concluded that a rigid and strong pavement with a high standard is the most flood-resilient.

Different floods have different likelihoods, and they affect the pavement performance. Khan et al. (2014a) showed that a pavement performs the poorest at the highest probability of flooding. As a result, likelihood was considered for flood risk assessment. However, major emphasis was given to the flooding consequence score to obtain pavements' flood resilience. Location and topography factors were not used in the analysis, which may be considered for future road groupings.

In future, road authorities may consider changing their roads into flood-resilient pavements. A pavement's strength may be enhanced through strengthening overlay and/or layer stabilization. Moreover, a road may be converted into a rigid or composite pavement through granular layers' stabilization. Apart from that use of moisture-resistant materials, excellent drainage and load restrictions during the flooding period would help limit road damage during flooding. A road's structural conditions and performances may be investigated properly after a flood. These results then may be used to validate the values of $\Delta\text{IRI}/Pr$ and $\Delta\text{IRI}/MrL$.

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