Roshani, Atena, Mirfenderesk, Hamid, Rajapakse, Jay, & Gallage, Chaminda
(2015)
Groundwater table response to sea level rise and its impact on pavement structure. In
Barnes, Paul H. (Ed.)
9th Annual International Conference of the International Institute for Infrastructure Renewal and Reconstruction (8-10 July 2013)., Queensland University of Technology, Brisbane, Australia, pp. 531-538.

Groundwater Table response to Sea Level Rise and its Impact on Pavement Structure

Roshani, Atena [1] ; Mirfenderesk, Hamid [2] ; Rajapakse, Jay [1] ; and Gallage, Chaminda[1]

1Earth Environment & Biological Science, Queensland University of Technology
2Waterway and flood management, Gold Coast City Council
E-mail: atena.roshani@student.qut.edu.au
E-mail: HMIRFENDERESK@goldcoast.qld.gov.au
E-mail: jay.rajapakse@qut.edu.au
E-mail: chaminda.gallage@qut.edu.au

It has been predicted that sea level will rise about 0.8 m by 2100. Consequently, seawater can intrude into the coastal aquifers and change the level of groundwater table. A raise in groundwater table due to seawater intrusion threats the coastal infrastructure such as road pavements. The mechanical properties of subgrade materials will change due to elevated rise of groundwater table, leading to pavement weakening and decreasing the subgrade strength and stiffness.

This paper presents an assessment of the vulnerability of subgrade in coastal areas to change in groundwater table due to sea-level rise. A simple bathtub approach is applied for estimating the groundwater level changes according to sea-level rise. Then the effect of groundwater level changes on the soil water content (SWC) of a single column of fine-sand soil is simulated using MIKE SHE. The impact of an increase in moisture content on subgrade strength/stiffness is assessed for a number of scenarios.

Key Words: *Seawater intrusion, bathtub approach, groundwater, Subgrade performance, resilient modulus*

1. INTRODUCTION

It has been predicted that the sea-level will rise about 0.8 m by 2100[1-4)]. A literature review shows that seawater intrusion due to sea-level rise influences the balance of the coastal aquifers by both changing the saltwater-freshwater interface and changing the level of groundwater table[5-10)].

A change in groundwater table and salinity due to sea-level rise is expected to have substantial impacts on coastal infrastructure. A literature review shows that there is a knowledge gap in quantifying these impacts, despite the important role of this assessment on government's management plans[11)]. Many of these assets, such as foundation of buildings, roads, underground stormwater and sewer system are vulnerable to change in water table. An increase in the elevation of underground water table can result in saturation of road and building foundations in low-lying areas, compromising their structural integrity. Also intrusion of saltwater into the coastal groundwater basins, due to sea-level rise, can cause erosion of unprotected sections of stormwater and sewer network[3)]. For instance, a recent study by Mirfenderesk et al [12)] has estimated that 50cm, 80cm and 110cm sea-level rise can result in an additional 9%, 13% and 16% (correspondingly) exposure of stormwater network to saltwater.

As the water table rises, the dissolved salt and elevated humidity appear closer to the surface. The moisture can affect the pavement subgrade strength and reduce the average life of road up to four times[13-15)]. IPWEA [16)] has shown that life span of a road pavement is significantly reduced if groundwater level rises to within 2 meters of the surface. Most studies on the effect of water logging and salinity on road assets show that the problem will escalate in the next 20 years. For instance McRobert & Foley 17) estimated that 230 km of the total 740 km main roads of Western Australia was affected in 1999 and has predicted that this length will increase to double in the next 10 to 20 years. Therefore, a new approach in assessing the life-cycle of for low lying coastal roads appears to be necessary.

A literature review shows that there is a gap of knowledge on the impact of sea-level rise on groundwater table variations. Most studies in this field have had a focus on salinity intrusion. The existing knowledge on groundwater table variations has a focus on precipitation and evapotranspiration and is less focused on seawater intrusion.

This paper provides an insight into the groundwater variations due to seawater intrusion through a simple bathtub approach. The paper also presents an assessment of the impact of groundwater level rise on unsaturated zone water content. The assessments are carried out for a single column of fine-sand soil. Road infrastructure vulnerability due to increased soil water content is assessed through assessing the subgrade resilient modulus changes.

2. SEA-LEVEL RISE – EFFECTS ON GROUNDWATER LEVEL

Even a small change in the sea-level can lead to crucial changes in hydrologic cycle and coastal areas3, 4). The latest estimation of rate of rise of sea-level due to climate change (between 1993 and 2003) is about 3mm/yr. This is two times greater than the rate of rise in early 19th century1-4, 18-20). Current rate of increase in green house gas emission fits well with the predictions associated with the IPCC's A1F1 scenario that results in 0.8m increase in mean sea level rise by 2100.

Increasing sea-levels will cause groundwater levels in coastal areas to rise in order to adjust to the new conditions8, 10). The research on the interaction between seawater and coastal aquifers has had a focus mainly on seawater intrusion and consequent salinity contamination of coastal aquifers. Ranjan et al 7) studied salinity intrusion in coastal aquifers using *Hadley Centre climate model (HadCM3*) under high and low emission scenarios *(SRESA2 and B2)*. Webb & Howard 21) applied a two-dimensional model set-up by *SEAWAT*. Masterson & Garabedian 6) and Werner et al 22) simulated the effects of sea-level rise on the depth and position of the fresh water/salt water interface. Masterson & Garabedian 6) used a density-dependent, three-dimensional numerical groundwater flow model, while Werner et al 22) devised simple indicators presenting the occurrence propensity of seawater intrusion *(SWI)* in both confined and unconfined aquifers. CSIRO 18) assessed sea-level rise impacts on coastal regions with a focus on frequency of extreme events such as flooding.

The physical response and quantitative bounds of groundwater table due to seawater intrusion have not been explicitly articulated in previous studies. Most studies implied the mathematical representation of sharp interface of saltwater and fresh water. Just recently some researchers have addressed the effects of seawater intrusion on depth of water table. In a study by Werner & Simmons 10), the groundwater table changes were detected using two conceptual models, a flux-controlled system and a head-controlled system. This study provides an assessment of physical effects of seawater intrusion in coastal unconfined aquifers under two scenarios, i.e. without any change in recharge and with an increase in recharge of the aquifer. Bjerklie et al 5) simulated current and future groundwater level using *MODFLOW* software platform for a 0.91 meter sea level rise scenario in New Haven. He also test a scenario based on 12% increase in groundwater recharge. Rotzoll & Fletcher 8) studied the vulnerability of low-lying coastal areas to groundwater inundation due to groundwater table rise based on three different scenarios in urban Honolulu, Hawaii. According to all these studies, seawater intrusion not only can change the saltwater toe, but it also causes the groundwater table to rise. Figure 1 illustrates a conceptual diagram of an unconfined aquifer under sea-level rise conditions.

In this study the saltwater toe is not the case and a simple bathtub approach is applied to predict the groundwater level changes due to sea-level rise in the future.

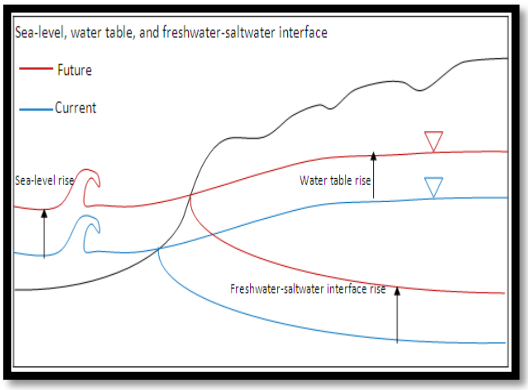

Figure 1.Conceptual illustration of a coastal unconfined aquifer under sea-level rise condition considering the freshwater-saltwater interface. Adopted from Rotzoll & Fletcher [8]

Table 1.Groundwater level prediction based on bathtub approach (sea-level rise predictions are base on Bicknell[1])

Year	**2030**	**2070**	**2100**
Sea-level rise (m)	0.1	0.4	0.8
Groundwater level rise (m)	0.1	0.4	0.8

3. BATHTUB APPROACH

Models used in water resources management can be classified into two categories: (1) Conceptual, and (2) physical-based models. Bathtub approach is considered as a simplified conceptual model, suitable for first pass assessment and feasibility studies. The hydrologic cycle components in a bathtub model are simulated section by section. It means that each component is considered as a compartment that its volume should be filled before running over into the next compartment[23].

In this study a simple bathtub approach is applied (as an alternative to physically based modeling) for assessing the impact of sea-level rise on change to groundwater table. Bathtub approach can be considered as a suitable alternative to numerical modeling for first pass assessment of climate change impacts. It eliminates the need for the development of expensive numerical models, saving time and resources[23].

Based on the bathtub approach if the sea-level rises by 0.8 m, the groundwater level in coastal aquifers will experience 0.8 m rise. Figure 1 illustrates a schematic of groundwater level change as a consequence of sea-level rise (the interface between fresh and salt water is not the subject). Table 1 shows the prediction of groundwater table rise due to sea-level rise for future (based on A1F1scenario) using a simple bathtub approach.

4. ROAD DAMAGE DUE TO HUMIDITY

It is well established that environmental changes, e.g. change in temperature and humidity, affect the pavement performance significantly. Change in temperature and humidity can affect all layers of a pavement, i.e. base, sub-base, and subgrade. However, the most negative effect of humidity is on the subgrade performance. The principal aim of a road design is to protect materials below the wearing course from water penetration. Many studies have identified excess moisture in subgrade as the principal cause of pavement failure[11, 24].

The function of subgrade is very important in pavement performance. Like a foundation, it bears all the loads on the road and transfers them to the soil. The local materials generated from excavations associated with road construction are usually used as subgrade (sometimes after some improvements through mixing with coarse-grained soils)[25]. The high subgrade moisture content leads to pavement weakening and decreases the subgrade strength and stiffness. Reduction in subgrade bearing capacity results in longitudinal rutting in the wheel paths and associated cracking, and ultimately pavement failure[26, 27]. The wetter a subgrade is, the thicker, stronger, and more expansive pavement should be designed.

There are different tests for evaluating mechanical properties of subgrades including: R-V test, triaxial coefficient c and φ, Elastic modulus (E), modulus of subgrade reaction (K-value), California Bearing Ratio (CBR), and resilient modulus (M_R). Based on AASHTO Guide for Design of Pavement structures the resilient modulus is the primary parameters for evaluating subgrade properties[28]. Another factor is CBR

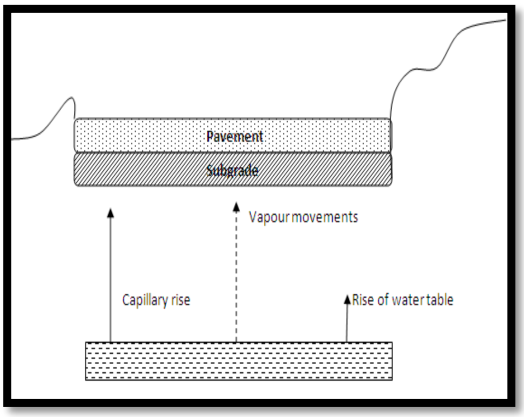

Figure 2.Source and movement of water in subgrade from saturated zone (due to depth of water table). Adopted from Houghton et al [11], and Vorobieff[24]

which is more popular due to its less complexity in calculation. CBR reflects the soil type, its density and moisture content. Higher CBR and resilient modulus means higher bearing capacity of subgrade and therefore the need for a thinner and less expensive wearing surface.

As the mechanical properties of subgrade materials are highly dependent on their moisture content, predicting future variation of soil moisture content of a subgrade is important. There are many ways that water can reach the pavement structure. The infiltrated precipitation through cracks in the pavement, shoulders, and side ditches are considered as atmospheric sources. The other sources originate from saturated zone and depend on the depth of groundwater (see Figure 2)[24, 29, 30].

Studies addressing how the unexpected moisture in subgrade affects the pavement performance have mostly focused on change in precipitation and temperature. Groundwater table as a free-water surface can act as a source of capillary water. The range of water movement due to capillary potential mostly depends on the soil texture and structure. Both free-water surface and capillary water can be transformed to water vapor due to change in temperature and pressure conditions. A water table rise increases capillary rise, increasing the subgrade *soil water content (SWC)*, *Equilibrium moisture content (EMC*) and *Field moisture content (FMC*)[11]. The effects of high groundwater level on pavement strength have been generally studied in the context of seasonal imbalance between recharge (precipitation) and discharge (evapotranspiration or abstraction); and to a lesser degree climate change induced change in temperature and precipitation. Daoulas et al[31] assessed the significant impacts of inadequate drainage of surface and subsurface water on pavement performance. Li, Mills, & McNeil [32]applied the Mechanistic-Empirical Pavement Design Guide (MEPDG) software to analyze the deterioration of pavement performance under climate change. The factors considered in this study were temperature and precipitation. Heydinger [33] presented the seasonal variation of daily air temperature, and variation of temperature and moisture in subgrade base on a case study in Delaware country. The LLTPP program was used in this study as the software platform, determining the climatic effects on pavement performance. Erlingsson[34], Main Roads Department Western Australia[35], McInnes[36], and McRobert & Foley[17] quantified the adverse impact of moisture and salt content of road base on pavement performance in the context of change in aquifer recharge and discharge and salinity.

Groundwater level as a source of subgrade moisture can affect the water content of subgrade due to capillary rise, reducing both CBR and M_R[11]. The depth at which the capillary rise can affect the subgrade soil water content depends on soil texture and structure. Al-Samahiji, Houston, & Houston [37]estimated the wet soil above groundwater table is at the degree of saturation about 60 percent due to capillary rise. Different studies have investigated the effect of groundwater level on subgrade strength due to change in SWC for different soil types. Generally the subgrade moisture content will be influence by the water table, if its depth from the surface is less than 7 m for heavy clay (plasticity index(Pl) >40%), 6m for clay, 3m for sandy clay or silt (with plasticity index <20%), and 1m for sand (non plastic soil)[38]. Houghton et al [11] estimated the effect of groundwater depth on CBR of five different soil types. The soils with CBR< 5 were considered as vulnerable subgrade. Based on this study, the silty clay soil with Pl=30 is vulnerable, if the water level rises to less than 2m of the surface, and this depth for sandy clay soils with Pl=20 is 0.5m from surface. The recommendations on the depth of free-water surface from a pavement surface vary substantially. Zhang [29)] reported a range between 3.7m in Saskatchewan to 1.5m in Michigan.

In this study the soil water content correspondent to the relative depth of groundwater is estimated for a fine-sand soil.

5. ESTIMATING SOIL WATER CONTENT (SWC) IN UNSATURATED ZONE USING MIKE SHE

Detecting the effects of soil moisture content on pavement performance needs an assessment of soil water content (SWC) in different depth of unsaturated zone. In this study, water content of unsaturated zone at different depths is estimated for a range of groundwater levels associated with the current and future climates. The groundwater level for three planning horizons, i.e. 2030, 2070, and 2100 are estimated, using the bathtub approach. The SWC is then calculated based on simulation of a single column of unsaturated zone, using MIKE SHE software platform.

MIKE SHE covers the major hydrological processes. Depending on the study goals, available field data and modeler's choice, MIKE SHE can undertake simulations with different levels of spatial distribution and complexity. This software can be considered as the first generation of spatial distributed and physically based hydrologic model which solves he partial differential equations describing mass flow and momentum transfer [39, 40)]

Unsaturated flow, as one of the significant hydrologic processes, can be modeled in MIKE SHE. This zone is usually heterogeneous and extends from ground surface to the groundwater table. The soil moisture content is characterized and fluctuated by change in rainfall, evapotranspiration and level of groundwater. As vertical flow plays the major role in infiltration and capillary rise in this zone, the unsaturated flow is calculated only vertically in MIKE SHE[40)].

Since the SWC in unsaturated zone is a function of rainfall, evapotranspiration, extraction, and groundwater level, if the groundwater level rises due to seawater intrusion, the SWC will increase due to capillary rise. As the most coastal aquifers are sandy, a fine-sand soil was selected as a representative sample of coastal subgrade. The soil class is specified as A-3 and SP, based on AASHTO soil classification system and Unified classification system, correspondingly. The soil was compacted at the optimum moisture content (OMC) of 12% with maximum dry density (MDD) of 1.69 g/cc. A single column of this fine-sand soil was simulated using MIKE SHE. The depth of groundwater should be specified as the boundary. Generally the long-term groundwater level in coastal area is shallow. Considering the shallow water table in coastal aquifers and according to the available guidelines on the depth of groundwater in which the sandy subgrades are vulnerable (less than 1m), we adopted two different groundwater levels, 3m, and 2 m as the long-term groundwater level. Then the predicted changes in groundwater level based on bathtub approach were applied to the model. The changes in soil water content in different depth of this single column are illustrated in Figure 3 and Figure 4.

The figures show that there is not any significant change in soil water content between present day and 2030 for both conditions. The soil water content does not change significantly down to the depth of 1.25 m from surface when the long-term groundwater level is 3m. In the case of a groundwater depth of 2m, the depth of no-change in soil water content reduces to 0.35m.

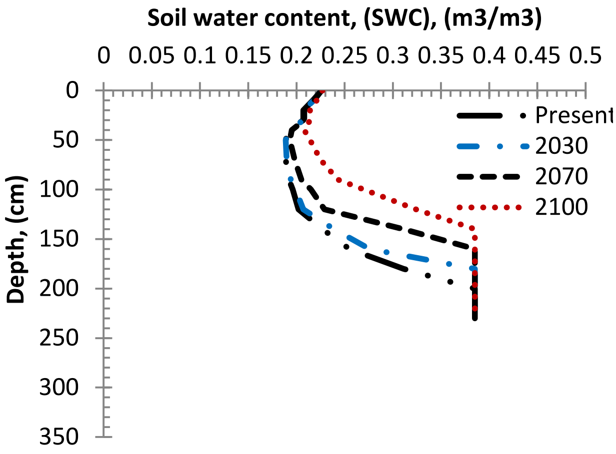

Figure 3.Soil water content in a fine-sand profile based on the bathtub approach predictions of groundwater level in the future and the long-term level of 2m

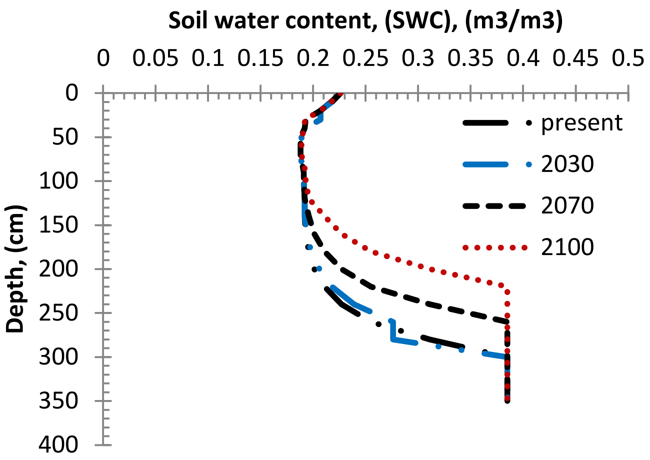

Figure 4.Soil water content in a fine-sand profile based on the bathtub approach predictions of groundwater level in the future and the long-term level of 3m

6. SOIL WATER CONTENT – EFFECT ON RESILIENT MODULUS

Although CBR and k-value are more popular properties among pavement designers (due to ease of their calculation in comparison with resilient modulus), the resilient modulus is a more robust indicator the subgrade strength/stiffness. Resilient modulus is a measure of the elastic response of a soil (e.g., how well a soil is able to return to its original shape and size after being stressed) under repeated loading. It is defined as the deviator dynamic stress (due to the moving vehicular traffic) divided by the resilient axial (recoverable) strain29). The resilient modulus value will change with loading and change in environmental factors. The factors determining the resilient modulus are: soil type, soil properties, dry unit weight, water content, test procedures, and size effect29). The moisture content can be considered as a main factor influencing the resilient modulus value.

Zhang 29)presented the results of different studies evaluating the effect of moisture content on resilient modulus of different subgrades. The relationship between degree of saturation and change in resilient modulus is highly dependent on soil type. Zhang29) expressed that the resilient modulus of coarse-grain soils are not significantly changed by the amount and manner of saturation (about 20% reduction) whereas this reduction is significant for fine-grain soils (50% to 75% reduction), depending on the degree of saturation and saturating method. Based on this study, an increase in the soil moisture content results in resilient modulus reduction in base materials and underlying subgrade soils and consequently reducing pavement life span.

There are different models predicting the resilient modulus of various soil types according to the moisture content. NCHRP41)summarized models that analytically predict the resilient modulus values due to change in moisture content. In all these models the resilient modulus of current situation is determined according to the resilient modulus at the optimum moisture content (R_{eopt}). . A brief summary of these models are:

- *Li & Selig model*: this model is used for fine-grained subgrade soils and the resilient modulus is predicted relative to the maximum dry density and R_{eopt}
- *Drumm et al. Model:* this model is for fine-grained subgrade soils and it is based on the linear relationship of degree of saturation and resilient modulus
- *Jinet al. Model:* this model is for granular subgrades and considers the moisture content, dry density, state of stress and temperature in estimating the resilient modulus
- *Jones and Witczak model:* this is a simple model with two variables related to moisture content and degree of saturation for fine-grained soils
- *Santha's model:* this model is fro Coarse-grained and Fine-grained soils
- *CRREL model:* this model is for Frozen Coarse-grained/ Fine-grained subgrade soils

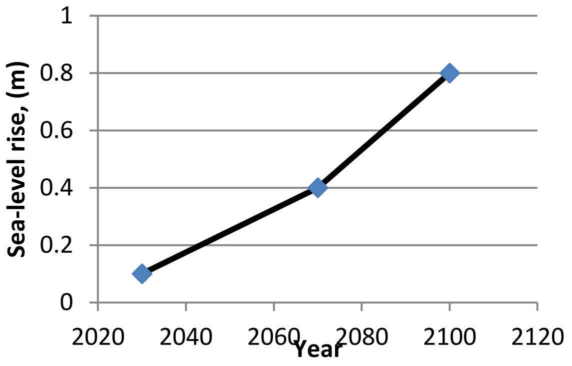

Figure 5.Sea-level rise projection through 21st century based on Bicknell1) study

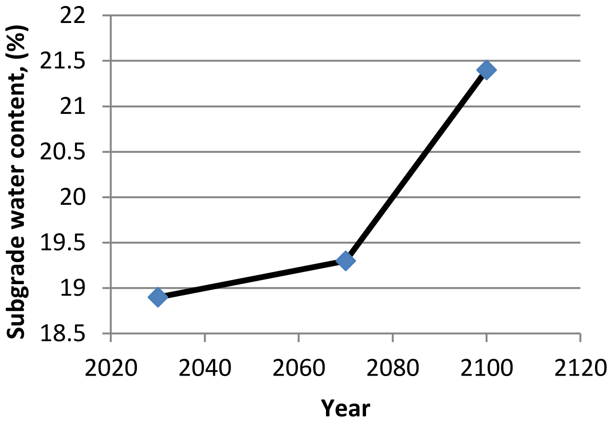

Figure 6.Subgrade Water Content projection through 21st century when the current groundwater depth is 2m

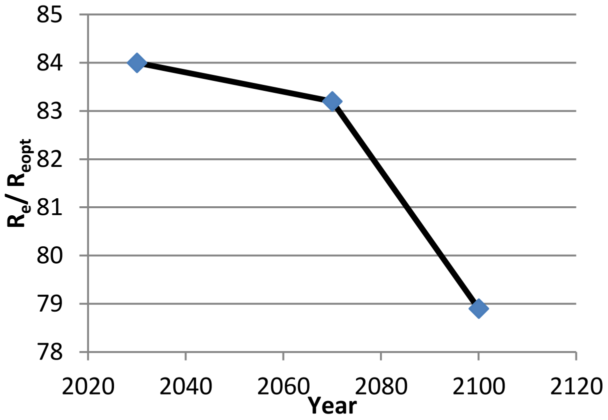

Figure 7.Resilient modulus of subgrade relative to resilient modulus at the optimum moisture content base on the subgrade water content projection through 21st century

In most of these models, degree of saturation, gravimetric or volumetric moisture content, and suction are used to evaluate the effects of moisture on resilient modulus. The R_e/ R_{eopt} or log (R_e/ R_{eopt}) versus moisture content or degree of saturation are presented for most of models. Also the linear relationship between “soil water content minus optimum moisture content” (w-w_{opt}) versus log (R_e/ R_{eopt}) for different soil classes based on AASHTO classification system is presented in the study by NCHRP41) .

In this study, the subgrade water content for the current and 2030, 2070, and 2100 climates (based on the bathtub approach prediction of groundwater level in the future) are estimated using MIKE SHE simulation results. Both conditions of current long-term groundwater depth of 2m and 3m are considered in the simulations. Considering the optimum moisture content of soil (w_{opt} = 12%), the difference between existing water content and optimum moisture content is calculated for all mentioned situations. Then the R_e/ R_{eopt} is specified through the presented relationship in NCHRP41) for A-3 soils.

According to the results, when the long-term groundwater is 3m, there will be no change in resilient modulus in the future in comparison with the current values. But for the groundwater depth of 2m, the resilient modulus of subgrade in 2100 will reduce about 5.1% in comparison with the current value. Figure 5, Figure 6 and Figure 7 present the sea-level rise projection, subgrade water content predictions, and reduction in resilient modulus when the current groundwater depth is 2m.

7. CONCLUSION AND RECOMMENDATION

This study investigated the subgrade resilient modulus reduction for a fine-sand soil (AASHTO class A-3) due to groundwater table rise projections for three future planning horizons. According to the results of this study, if the current long-term groundwater level is more than 3m deep, the groundwater level rise due to seawater intrusion will not have significant effect on the subgrade resilient. This result comes from the fact that the capillary fringe of coarse-grained soils is small and therefore this type of soils are less sensitive to the moisture content. Therefore, this soil type can be considered as a good material for subgrade in high groundwater situation. When groundwater is shallow (depth of less than 2m) , the groundwater variations due to seawater intrusion can cause up to 5.1% reduction in resilient modulus compared with the current climate.

It is clear that the groundwater table rise due to sea-level rise can reduce the resilient modulus of subgrade. However, the magnitude of the impact for different soil types is still unknown. Further research in this field is warranted. Such research program needs to address a number of issues such as, the impact of sea level rise on the long-term groundwater table, how any change in soil water content can affect the subgrade made of different soil type in different regions and various road types.

8. REFERENCE

1. Bicknell, C.: Sea Level Change in Western Australia. Application to Coastal Planning. 2010.
2. Church, J.A. and White, N.J.: A 20th century acceleration in global sea-level rise, *Geophysical Research Letters*. Vol. 33(L01602), 2006.
3. Department of Climate Change. Climate change risk to Australia's coast, first pass national assessment, Retrieved from Australian Government web site: http://www.climatechange.gov.au/publications/coastline/climate-change-risks-to-australias-coasts.aspx. 2009.
4. IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, et al., Editors, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA,. pp. 996. 2007.
5. Bjerklie, D.M., et al.: Preliminary investigation of the effects of sea-level rise on groundwater levels in New Haven, Connecticut, *in U.S Geological Survey Open-File Report 2012–1025*U.S Geological Survey. pp. 46. 2012.
6. Masterson, J.P. and Garabedian, S.P.: Effects of Sea-Level Rise on Ground Water Flow in a Coastal Aquifer, *Ground water*. Vol. 45(2): pp. 209–217, 2007.
7. Ranjan, P., Kazama, S., and Sawamoto, M.: Effects of climate change on coastal fresh groundwater resources, *Global Environmental Change*. Vol. 16: pp. 388-399, 2006.
8. Rotzoll, K. and Fletcher, C.H.: Assessment of groundwater inundation as a consequence of sea-level rise, *Nature Climate Change*. Vol., 2012.
9. Werner, A.D.: A review of seawater intrusion and its management in Australia, *Hydrogeology Journal* Vol. 18: pp. 281-285, 2010.
10. Werner, A.D. and Simmons, C.T.: Impact of Sea-Level Rise on Sea Water Intrusion in Coastal Aquifers, *Ground Water*. Vol. 47(2): pp. 197-204, 2009.
11. Houghton, N., McRobert, J., and Styles, E.: Salinity and rising water tables-risks for road assets Austroads: Sydney. 2004.
12. Mirfenderesk, H., et al.: Coastal Infrastructures Vulnerability Assessment-Trade-Off between Cost-Time Saving and Accuracy, *in Queensland Coastal Conference*: Cairns, Australia. . 2010.
13. Austroads. Pavement design: a guide to the structural design of road pavements, Austroads: Sydney. 1992.
14. Murray–Darling Basin Ministerila Council. The Salinity Audit of the Murray Darling Basin. A 100-year perspective, MDBMC: Canberra. 1999.
15. O'Flaherty, K.: *Road and salinity*Sydney, Australia: Department of Infrastructure, Planning and Natural Resources 2003. 2003.
16. IPWEA. Local government salinity management handbook- A resource guide for the public works professional, Institute of Public Works Engineering Australia: Sydney NSW. 2001.
17. McRobert, J. and Foley, G.: The impacts of waterlogging and salinity on road assets: a Western Australian case study *in special report number 57*ARRB Transport research: Victoria. 1999.
18. CSIRO. Sea level rise. *Understanding the past - improving projections for future* 2009; Available from:

http://www.cmar.csiro.au/sealevel/. [Acces on 7 Jan. 2013].

19. Douglas, B.C.: Global sea rise: a redetermination *Surveys in Geophysics*. Vol. 18: pp. 279–292, 1997.
20. Church, J.A. and White, N.J.: Sea-Level Rise from the Late 19th to the Early 21st Century, *Surv Geophys*. Vol. 32: pp. 585–602, 2011.
21. Webb, M.D. and Howard, K.W.: Modelling the Transient Response of Saline Intrusion to Rising Sea-Levels, *Ground Water*. Vol. 49(4): pp. 560–569, 2011.
22. Werner, A.D., et al.: Vulnerability Indicators of Sea Water Intrusion, *Ground Water*. Vol. 50(1): pp. 48–58, 2012.
23. White, L.W., et al.: Estimation of optimal parameters for a surface hydrology model, *Advances in Water Resources* Vol. 26: pp. 337-348, 2003.
24. Vorobieff, G.: Techniques to use on roads affected by salinity, *in Urban Salt 2005*: Sydney. 2005.
25. Rahardjo, H., et al.: Soil–water characteristic curves of gap-graded soils, *Engineering Geology*. Vol. 125: pp. 102-107, 2012.
26. Nowamooz, H., et al.: Unsaturated resilient behavior of a natural compacted sand, *Computers and Geotechnics*. Vol. 38(4): pp. 491-503, 2011.
27. Salem, H.M.: Effect of Seasonal Moisture Variation on Subgrade Resilient Modulus, *in Paper 4*U.S. Department of Transportation, Federal Highway Administration,: Washington, DC. 2005.
28. AASHTO: *Guide for Design of Pavement Structures*. Washington, DC: American Association of State Highway and Transportation Officials. 1993.
29. Zhang, C.: The effect of high groundwater level on pavement subgrade performance *in Department of Civil and Environmental Engineering*Florida State University. 2004.
30. Huang, Y.H.: *Pavement analysis and design*. 1993.
31. Daoulas, J., et al.: Forensic investigation and remediation of pavement performance affected by groundwater seepage case history in Virginia, *Transport Research Record: Journal of the Transportation Research Board*. Vol. 2212(1): pp. 65-73, 2011.
32. Li, Q., Mills, L., and McNeil, v.: *The implications of climate change on pavement performance and design*: University of Delaware University, Transportation Center (UD-UTC). 2011.
33. Heydinger, A.G.: Evaluation of Seasonal Effects on Subgrade Soils, TRB Paper 03-03801, *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1821: pp. 47-55, 2002.
34. Erlingsson, S.: Water impact on the structural behavior of a pavement structure. in *8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, BCR2A'09, June 29, 2009 - July 2, 2009*. Champaign, IL, United states: CRC Press. 2009.
35. Main Roads Western Australia. Interim guide to prediction of pavement moisture for strength assessment of granular base-course and subbase materials *in Engineering road note No 5*Government of Western Australia,: Western Australia. 2003.
36. McInnes, D.: Rising water table levels — some consequences for road infrastructure. in *1st National Salinity Engineering Conference*. Perth, Western Australia. 2004.
37. Al-Samahiji, D., Houston, S.L., and Houston, W.N.: Degree and extent of wetting due to capillary rise in soils, *Transportation Research Record: Journal of the Transportation Research Board*. Vol. 1709(1): pp. 114-120, 2000.
38. Arampamoorthy, H. and Patrick, J.: Design moisture condition guidelines for pavement design and material assessment, NZ Transport Agency research: New Zealand. pp. 38. 2010.
39. DHI. MIKE SHE user manual volume 1: user guide, Danish Hydraulic Institute, Editor: Hørsholm, Denmark. . 2011.
40. DHI. MIKE SHE user manual volume 2: reference guide, Danish Hydraulic Institute, Editor: Hørsholm, Denmark. . 2011.
41. NCHRP. Guide for mechanistic-empirical design of new and rehabilitated pavement structures, NCHRP: Washington DC. 2000.