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Soil salinization risk assessments under future climate conditions: The case of central Huai Luang River Basin, Northeast, Thailand

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Abstract

Salt-affected soil is one of the main problems decreasing the productivity of agriculture in Northeast Thailand. The Central Huai Luang Basin is the important rice producing area of Udon Thani Province that is affected by saline soil. Regional and local groundwater flow systems are the major mechanisms responsible for spreading saline groundwater, waterlogging and the consequences of saline soils in this basin. Climate change may have an impact on groundwater recharge, on water table depth and the consequences of waterlogging, and on the distribution of soil salinity in this basin. A simulation model, in combination with groundwater models and the Geographical Information System (GISs), could be used to evaluate the risk of salinization. Five data, including soil salinity, soil group, irrigation area, groundwater salinity and waterlogging were used to input criteria data into a soil salinity risk model, which then calibrates the soil salinity simulation using field data. Three future climate conditions of RCPs from the CanESM2 models were downscaled to investigate the impact of future climate conditions on soil salinity risk. The impact of climate change was investigated by using a set of groundwater numerical models, namely HELP3 and SEAWAT, to estimate groundwater recharge and flow, and salt transport of the groundwater simulation, respectively. The results revealed that within the next 30 years (2045) the future average annual temperature and precipitation are projected to increase by 1.79ºC and 7.56% from current figures, respectively. The results showed that the impact of climate change on soil salinity distribution is projected to increase in every climate condition. By 2045 the salinity risk area will increase by about 216.90 km^2, or 23.62% from the current salt-affected area. The projected soil salinity assessment presented here is useful for targeting critical areas that may require special management for preventing or controlling soil salinization.

Keywords: Climate change, Soil salinity, Waterlogging, Groundwater salinity, SEAWAT, HELP3

1. Introduction

Globally, salt-affected areas that were estimated by FAO in 2000 totaled 8.31 million km^2 [1] and extended over all continents.[2] This salinization has a major impact on surface water and groundwater resources, agricultural productivity, and environmental health. Soil salinization is the process of enrichment of soil with soluble salts that results in the formation of salt-affected soil.[3] This process decreases crop yields, the quality of water resources, and in some cases reduces the quality of the crop.[4]

Salt-affected areas in Thailand were about 36,100 km^2. Almost 80% of salt-affected areas were found in the northeast where the source of salt originates from rock salt layers underlying the area derived from ancient buried sea beds.[5] Natural halite in unconsolidated formations of the Maha Sarakam unit was identified as the source of salt in northeast Thailand.[6] The major processes of spreading saline groundwater to subsurface water resulting in saline soils are groundwater flow and evapotranspiration[7]; naturally occurring salt-affected areas exist in several places in NE Thailand.[8] Changes in climatic variables can significantly alter the hydrologic cycle and groundwater recharge which controls the water level and salinity distribution of groundwater, and consequently affects land availability for agriculture.[9] Therefore, climate change can be one of the most sensitive reasons for groundwater salinity and soil salinity distribution in the future. Several earlier studies have developed and applied future climate change models in Thailand for different purposes. [10-16] Most of their results indicated that there would be an increasing trend in average annual rainfall and temperature in the period from 2016-2056.

There are several techniques for recovering salt-affected soils, but they usually have a high economic cost. Thus, prevention of salt accumulation is more advisable than soil desalinization. [4] The prediction of saline soil under climate change in the future can help in deciding the most suitable management for each combination of climate, soil and water. The Central Huai Luang Basin (CHLB) is spatially affected by saline groundwater and saline soil along the Huai Luang Floodplain. It is the most important rice producing area of Udon Thani Province, which claims the socio-economic status as the second biggest province in Northeastern Thailand.[17] Groundwater and soil salinity problems have interrupted activities and have required additional supplies of water in this area, including water for irrigation and agricultural purposes, etc.

The purpose of this study is to assess the soil salinization risk under climate change conditions in the future. This study extends the capabilities of salinity simulation models on a regional scale, using groundwater modeling to simulate groundwater levels and salinity in the future with geographical information system (GIS) operations. With these combined tools it is possible to make predictive maps of soil salinity risk, identify problem areas and determine their extent.

2. The study area

The Central Huai Luang Basin (CHLB) is one of the sub-basin located in the Huai Luang Basin that is part of the transboundary Mekong River basin. It covers an area of approximately 1,529 km^2, represented as a typical feature of Salt-affected areas, it was selected as the study area. It exists with an undulating topography covered with various salinization levels. Data of CHLB was collected from secondary data and field investigations. Relevant information included meteorological and hydrological records, soil type, soil properties, saline soil, land use, existing well data, lithologic logs, water levels and quality of surface water. Field soil, hydrology and hydrogeological investigations were conducted from September 2014 to December 2015.

2.1 Climate

The meteorological records of the station at Udon Thani (Thai Meteorological Department (TMD), 2014) and 11 rainfall stations [18-19] during the years of 1984-2015 indicate an average annual rainfall of 1,268.6 mm with an increasing trend over the recorded time period. The records show that almost 90% of rainfall occurs in the rainy season from May through October. The average daily temperature was 27.0^{o}C and also has a slightly increasing trend. January is the coolest month, with a daily temperature of about 22.4^{o}C, and April is the hottest month, at approximately 29.8^{o}C. The average evaporation from the Class A Pan measurement was 1,683 mm/year.[18]

2.2 land use

The land is largely occupied by agricultural areas, whereas the main products are rice, sugarcane and cassava. Paddy fields are located along the Huai Luang River floodplain and eastern parts on about 40% of the land [20] about 26% of the paddy field area is irrigated. There is only one crop of rice that grows each year, from May to November, in the rain-fed paddy fields, while that land is barren during the dry season. Whereas in irrigated areas, rice crops can be grown twice per year. The northwestern and southwestern parts support sugarcane and cassava on around 23% of the land. Forested areas, urban areas and water bodies cover 16 % of the watershed (Figure 1 (a)).

2.3 Soil Groups and Soil Salinity

Soil groups were characterized based on their properties, parent material, and affect to plants.[21] Soil groups 18, 35 and 49 are the main soil groups of CHLB, covering an area of about 78.7% of the land (Figure 1 (b)). Soil group 18 is composed of deep clay with poor to very poor drainage but fair to good paddy fields, inherent fertility is commonly low to medium, and it covers an area of about 32.5% of the land, notably, some parts of this soil group were found with salt crust on the soil surface. Soil group 35, with about 29.1% of land surface area, is a deep soil with sandy loam soil, it is fairly drained to well drained and makes fair to good crop land, but its inherent fertility is usually low. Soil group 49 was found to occupy about 17.2% of land with shallow soil of laterite and clay, it's well drained, but inherent fertility is commonly very low making it not suitable for agricultural activities.

Soil properties and salinity tests of the 32 locations distributed among the main soil groups were conducted for characterizing soil texture and electrical conductivity (ECe) in November, 2014. Ten soil locations were selected for collections in order to analyze ECe, SAR (sodium adsorption ratio), soil water content, soil texture and soil hydraulic properties (saturated water content, dry bulk density and saturated hydraulic conductivity). Soil samples at each site were collected at four different depths of 30, 60, 100 and 200 cm below the ground surface. Moreover, installation of in-situ equipment was undertaken for monitoring soil water content of the four main representative soil groups. Subsequently, monitoring of soil water content and soil salinity was conducted every 3 months.

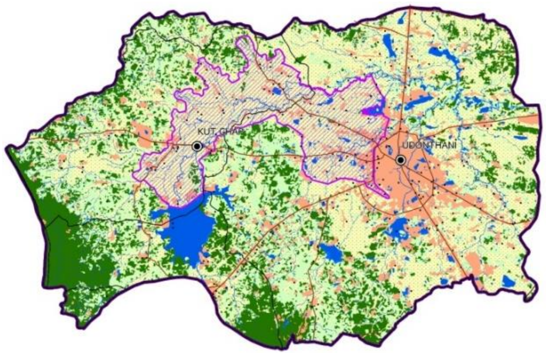
The Land Development Department has been implementing the assessment and monitoring of salinization using image analysis of remote sensing data (Landsat). This data is then verified by ground truth data and laboratory investigations, carried out by ground based surveys using electromagnetic induction (EM34 and EM38) [22]

Soil salinity was classified into five categories based on salt crust occurring on the ground surface [23], as shown in Figure 1 (c), the soils that were affected by salt totaled about 35%. Moderately to very severely salt-affected soils were located in the lowlands of the central and eastern parts of the study area. Slightly and non-Salt-affected soils were found at highland and upland areas in the western and southern parts of the study area. Based on the saturation extract (ECe) of soil that was collected and analyzed in September 2014, severely and very severely salt-affected soils had an ECe at the soil surface of about 13.2-79.1 dS/m, while moderately and slightly saline soil had ECe of about 1.2-15.1 dS/m. This ECe of salt-affected soil, as measured in CHLB, showed the same range as salt-affected soils in Northeast Thailand as reported by [24], and soil salinity classes based on relative ECe values, salt crust and crops in Thailand that have been previously classified [6, 25-26] as shown in Table 1

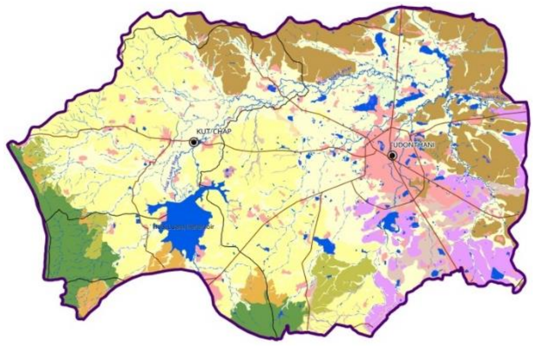
In the slightly and moderately salt-affected areas, farmers can grow rice, but the plant growth is non-uniform and affected by the invasion of salt tolerant weeds.[25] Salinity impacts on rice physiology include diminished weak leaf strength at the transplanting stage, reduced clump biomass, diminished rice seed size and decreased crop production.[28] The rice productivity of susceptible cultivars can decrease by more than 50% in moderately saline soil, and 10-50% in slightly saline soil.[29] A similar observation was reported by Clermont-Dauphin et al., who performed field experiments on the effects of soil salinity on rice yields in northeast Thailand.[30]

Table 1 Approximate soil salinity classes by Salinity tolerance ratings for soils [6, 25-26]

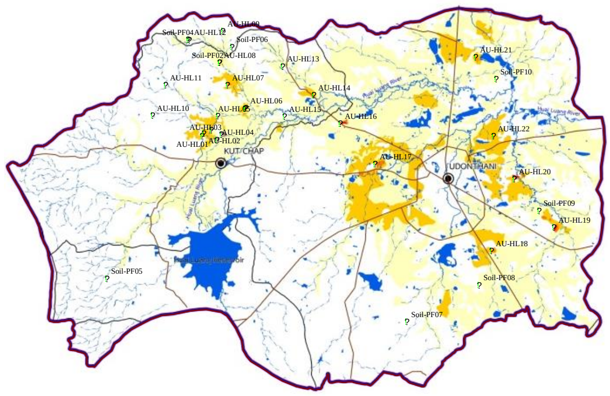
Degree of Soil Salinity	Area Covered by Salt Crust	Ece (dS/m)	Salt Tolerant Crops
Non saline	salt –free areas	< 2	No effects
Slightly saline	< 1%	2 – 4	Salinity effects usually minimal
Moderately saline	1-10%	4 – 8	Yield of salt sensitive plants restricted
Severely saline	>10-50%	8-15	Only salt tolerant plants yield satisfactorily
Very severely saline	>50%	>15	Few salt tolerant plants yield satisfactorily



(a) Land use (LDD, 2013 and irrigation area [19]



(b) Soil group [23, 27]



(c) soil salinity [23]

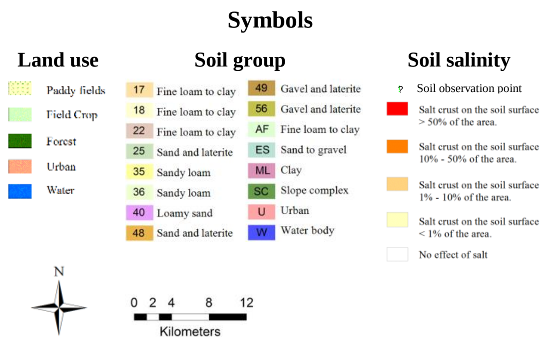


Figure 1 Maps of land use, soil group, and soil salinity in CHLB

2.4 Hydrology and Hydrogeology

Hydrological investigations of 31 river cross sections, water level measurements and surface water quality samplings were conducted. Huai Luang Reservoir and the Huai Luang River are major water sources for water supply and irrigation. The Huai Luang River flows from west to east, while Huai Luang dam is located in the southwestern part of the study area. Total volume of the flow throughout CHLB is around 262.4 MCM/year (Mm^3/year). During the dry season, water quality of the Huai Luang River and its tributaries are mildly brackish with electrical conductivities greater than 1,500 µS/cm and Total Dissolved Solids (TDS) greater than 1,000 mg/l. It becomes fresh to slightly brackish in the rainy season, while water quality in Huai Luang Reservoir that is used for irrigation in irrigated areas was found to be fresh the whole year. Hydrogeological mapping from 33 wells of piezometer and pumping test wells for drilling and construction were carried out during the period of September 2014 to February 2015. The groundwater level and salinity of 189 wells were measured in every season. CHLB is underlain by sand, clay and gravel of Alluvium (Al) and Terrace (Te) Deposit units, which are located along the flood plain of the Huai Luang River. The siltstone and sandstone aquifer of the Upper Phu Thok (Upt) unit lies underneath the Al unit, with a thickness of 30 m, and shale and mudstone deposits with a thickness of 50 to 200 m in the Lower Phu Thok (Lpt) unit are underlain by rock salt (RS) layers at the Maha Sarakham (MS) unit. The Khok Kruat (Kk) unit is found at the toe of the mountain, consisting of siltstone and sandstone with a thickness of 430 to 700 m. [31-33] Selected groundwater samples were collected from 30 wells in February 2015 for analyzing concentrations of major ions. Water level measurements from the year 2014-2015 show that the local and regional groundwater flow pattern is replicated according to topographic elevation and flows from the western and southern areas to the central regions along the Huai Luang River. Throughout the basin, TDS of groundwater varies from less than 1,000 (fresh) to greater than 10,000 mg/l (saline). The high TDS or salinity varies with depth and was found in the lowlands at the central part of the study area along the Huai Luang River or discharge area. The groundwater type at the discharge area was classified based on Deutsch (1997) and is of Na-Cl type.[34]

3. Methodology

To assess the risk areas of soil salinization, the data criteria was divided into two types: 1) thematic maps that analyze existing data and field investigations (soil salinity, soil group and irrigation area), and 2) groundwater modeling (groundwater salinity and waterlogging). In this study, an assessment method based on multi-criteria evaluation techniques using a combination of geographical information systems (GIS) with fuzzy logic and a weighting method, were employed. The observed soil salinity data were used to calibrate the criteria for weighting along with a score rating, by comparing it with the primary soil salinity risk map of the period from 2006-2015. Then the calibrated weighting criteria and score rating were used to examine the projected impact of climate change on saline soil risk area. Future climate of the GCMs under the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) was considered for the next 30 years (2045) under 3 scenarios.[35] The framework of this technical evaluation procedure is shown as a flowchart in Figure 2

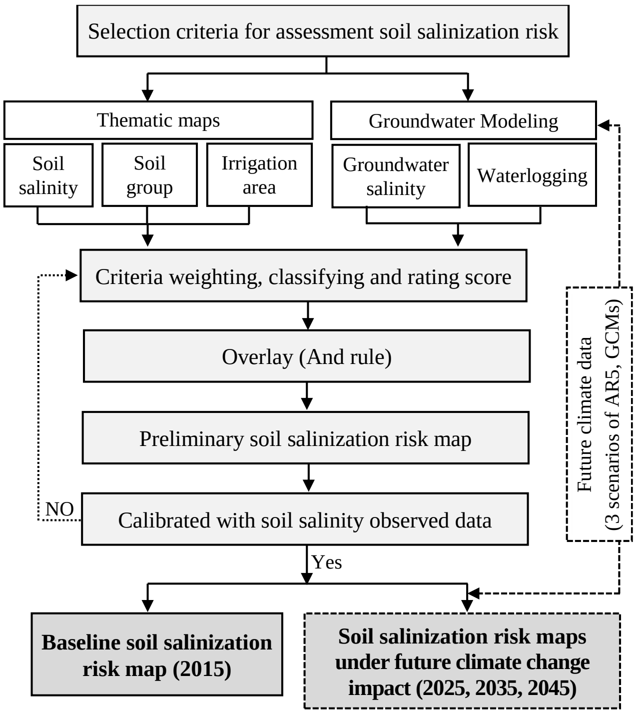


Figure 2 Flowchart diagram of the soil salinization risk area assessment approach

3.1 Groundwater Modeling

Groundwater salinity and waterlogging were selected as the criteria for assessing the risk of soil salinity. These criteria are considered to be criteria that obviously vary with time and climate conditions. Therefore, groundwater modeling was used for projecting groundwater salinity and waterlogging for climate changes that alter hydrologic and salinization processes. Numerical modeling is a robust and useful approach for assessing past and future groundwater resources [36-38] specifically, temperature, and precipitation changes to groundwater recharge.[39] Saline groundwater and waterlogging were evaluated by using the variable density groundwater model, SEAWAT version 4 [40] The physically based Hydrologic Evaluation of Landfill Performance version 3 (HELP3) computer program [41] was used to estimate groundwater recharge rates and input into the SEAWAT model to simulate groundwater flow and salt transport in CHLB. The HELP3 model has been used to estimate the impact of climate change on varying spatial groundwater recharge rates [9, 42-45]

During the period from 2006-2015, the models of HELP3 and SEAWAT were calibrated and validated with observed groundwater levels and salinity levels. Simulations of groundwater flow and salt transport were conducted under future climate variables from GCMs. The GCMs were retrieved from the Coupled Model Intercomparison Project Phase 5 (CMIP5) data portal for 3 scenarios with CanESM2. Downscaled CanESM2 climate scenarios were used to investigate the impact of groundwater on the CHLB for the next 30 years. Future temperature and precipitation from the climate model were used as the input data in the HELP3 model to estimate the net recharge for 2016 to 2045. Then the projected groundwater recharge for each scenario was used as the recharge input for the SEAWAT model in order to simulate groundwater levels, flow patterns, and salinity distributions. For a detailed description of groundwater flow and salt transport in CHLB.[46] The impact of climate change on groundwater resources affects recharge rates, patterns, and timing; decreases/increases in groundwater levels; and the deterioration of groundwater quality. [9, 36, 38, 42] Patterns of groundwater salinity and water table elevations in the uppermost layer from SEAWAT were used to assess the degree of soil salinization and distribution. The projected impact of future climate change waterlogging and salinity distribution in the watershed was determined by means of the projected areas of water table depth and groundwater salinity at the current time, and over the coming years in 2025, 2035 and 2045.

3.2 Future Climate Scenarios

To examine projected saline groundwater and waterlogging under climate change in the near future, future climate of the GCMs from the IPCC Fifth Assessment Report (AR5) was considered. The GCMs from AR5 were explored in order to represent the future climate of the CHLB for the latest Assessment Report. Several GCMs have been widely used in Thailand, such as CNRM-CM5, MIROC-ESM, FGOAL-s2, MPI-ESM-LR, CESM1-BGC, CCSM4, CanESM2, HadGEM2-CC, and GFDL.[16] The CanESM2 was selected to be representative of the future climate of CHLB, as it is due to results from the statistically analyzed records of temperature and precipitation data for the CHLB and from the GCMS during the baseline period (2006-2015). Visual comparisons and statistical (SD, Mean, Median and R^2) measurements indicate that the CanESM2 has shown the best correlation when compared to the others. Therefore, it was found that CanESM2 was reasonably reliable in representing the future climate of the CHLB. The second generation Canadian Earth System Model (CanESM2) consists of a physical atmosphere-ocean model coupled with a terrestrial carbon model and an ocean carbon model.[47] GCM's precipitation amounts and temperatures were downloaded and correction using the PRECIS (Providing Regional Climates for Impacts Studies) model. Adopted to downscale the climate data by using Gamma-Gamma transformation with an optimizing parameter method. The characteristics of the gamma cumulative density function (CDF) were used to remove any biases from the RCM precipitation data and to provide information with higher resolution (10 km) for future climate projections.[16]

The CanESM2 downscaled climate scenarios, which were used to investigate the impact of groundwater on the CHLB, were the Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5. The RCPs were named according to the radiative forcing target level for 2100. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents. The three selected RCPs were considered to be representative of the literature, and included one mitigation scenario leading to a very low forcing level (RCP2.6), some medium stabilization scenarios (RCP4.5) and one very high baseline emission scenario (RCP8.5) [48]

3.3 Soil Salinity Risk Assessment Model

A large number of studies have been carried out using difference remote sensing methods and the Geographic Information System (GIS) to determine salinity risk on a regional scale.[4] GIS is a very helpful tool to store, manipulate and quantitatively evaluate soil degradation and salinity risk.[49] It is appropriate for revealing land that has been affected by salinity at various levels, and also makes it possible to make predictive maps of salinity risk, identify problem areas and determine their extent. Several authors have modeled risk of salinization on a regional scale using GIS [4, 49, 50-64] with the main objective of identifying areas that have a high risk of salt accumulation. The common criteria for assessing soil salinity risk has been to use soil characteristics and groundwater information such as soil typology, soil texture, soil drainage, chemical properties of soil and irrigation water, irrigation situation, climate, soil hydraulic properties and land use in combination with models.[65] In this study five criteria for the causes of soil salinity were used as the input data of the model for assessing soil salinity risk in the baseline time period and into the future using a GIS spatial tool. The five criteria include: soil salinity, soil group, irrigation area, groundwater salinity and waterlogging, which were prepared from existing maps, data sets and numerical modeling.

Fuzzy logic was selected to identify the degree of risk relative to the vulnerability of various criteria. This is strong logic for the standardization of information layers in order to resolve any uncertainty due to ambiguity and imprecision in the decision making.[66] Subjective criteria are commonly presented linguistically in the fuzzy membership set with linguistic terms such as low, moderate, and high risk. The linguistic terms can be represented by membership functions valued in the actual unit interval from 0 to 1, which translates the imprecision and vagueness of human opinion regarding the main problem.[67] The application of these methods has shown to be useful in mapping salinity risk.[68-69] The maps of criteria were revised based on their relative degree of importance, classified to input cell values and replaced with new output cell values based on their fuzzy membership functions. The description of the criteria and their fuzzy functions, based on the literature review, field evidence and detailed field work, are as follows:

(i) Soil salinity; the status of soil salinity was considered by using existing salt crust on the ground surface according to LDD (2006), it is one of the salt sources that can spread to other areas and indicate the effected degree to crops. For assessing the risk of soil salinity, existing salt crust was classified into 4 groups based on the effect to tolerant plants, including salt–free areas, salt crusting < 1%, 1-10% and >10%. The group of salt crusting >10-50% and salt crusting >50% were merged, due to their both not being suitable for glowing crops or rice.[23]

(ii) Soil group; soil group was considered to be an indicator of the capillary fringe that brings saline groundwater upward to the root zone or soil surface. [69-70] The height of the capillary fringe is given by the soil texture. The capillary height is based on Food and Agriculture Organization guidelines, which states that sands and loams will be between 0.2 and 0.5 m, and clays 0.8 m. This means that clay soils have more risk of bringing salinity groundwater up to the soil surface than sands and loams.[71] The soil texture map is based on the soil group and soil series [27]

(iii) Irrigation area; irrigation water in CHLB is completely supplied by the Huai Luang Reservoir, which stores runoff water in the rainy season with low salinity (EC is about 100-250 µS/cm), so irrigation water quality in irrigated areas is not a cause of increasing salinity in the soil. In contrast, irrigation areas indicated a sufficiency of water for controlling the salinity impact on rice production, which will dilute the salt solute and check soil salinity [29]

(iv) Groundwater salinity; groundwater salinity is the primary source of salt that can exhibit upward movement and become saline soil. Based on the salinity of irrigation water, or any water salinity that has a high potential to become saline soil [71-73] Problematic salinity is defined as being greater than 1,000 mg/l. Groundwater salinity is characterized in terms of total dissolved solids (TDS), which is the same with the groundwater salinity output from the groundwater model. In Thailand, a correlation of EC and TDS can be considered by using the following equation TDS (mg/l) = EC (µS/cm) x 0.64 [74] Groundwater salinity data in the baseline period (2006-2015) and projected groundwater salinity in future climates for 2025, 2035 and 2045 were evaluated and exported from the groundwater model in the top layer.

(v) Waterlogging; waterlogging damages plant growth and is the pioneer of land salinization in many areas, it can obstruct a plant's growth and adversely affect crop yield.[75] Some research defines waterlogging as Critical Depth, the maximum depth of saline groundwater that causes salinization of the soil in the root zone under the influence of capillary rise and evapotranspiration.[9, 74, 76-79] Waterlogging area refers to an area where the water table fluctuates within the root zone depth when the pores within the soil almost fill with water. In northeast Thailand waterlogging was determined by means of a soil column study. The study was conducted under a project to devise a hydrological model for the management of salt contamination in the Kong-Chi-Mun project area. Results indicated that the critical depth of saline soils and waterlogging in this region is approximately 4 m [74] Waterlogging data in the baseline period (2006-2015) and projected groundwater salinity for the future climate in 2025, 2035 and 2045 were evaluated and exported from the groundwater model and the same with groundwater salinity.

After the criteria for risk assessment were classified based on their relative degree of importance to soil salinization and given fuzzy membership functions (rating score), each criterion had the same important degree. On the other hand, the salinization in CHLB was controlled by the criterion that some features were more critical than others, therefore, weighting of the criteria was determined. A paired comparison method is a common approach used for evaluation weighing of a criterion.[80] The criterion weighing of salinization was determined as a basic ordering from highest importance to least importance. In this study, the source of salinity being soil and groundwater salinity were assigned to have the highest importance, or first order, waterlogging was in the second order, then came the irrigation area and soil group. The criterion, weighting, classifying and rating score that was used in the risk assessment for soil salinization is shown in Table 2

Table 2 Criteria for soil salinity risk map development

Criteria (a)	Weight (b)	Class (c)	Rating score (d)	Total (e=b×d)
Soil salinity	10	Non salt crust	0.3	3.0
		salt crust < 1%	0.5	5.0
		salt crust 1-10%	0.8	8.0
		salt crust >10%	1.0	10.0
Soil group	5	Sand and loam	0.5	2.5
		Clay	1.0	5.0
Irrigation area	7	Irrigation area	0.5	3.5
		Non irrigation area	1.0	7.0
groundwater salinity (TDS)	10	<1,000 mg/l	0.3	3.0
		1,000-5,000 mg/l	0.8	8.0
		>5,000	1.0	10.0
Waterlogging (Depth to water table)	9	>4 m	0.5	4.5
		2-4 m	0.8	7.2
		<2 m	1.0	9.0

Different thematic maps of each criterion were prepared from the sets of Fuzzy logic and weighting of criteria. These criteria were integrated into the Arcview v.3.2 GIS tool by Weighted Index Overlay Analysis (WIOA) in order to perform a mapping risk of soil salinity for the baseline period and into the future under climate change conditions. The areas of soil salinity risk were assigned a classification and categorized by the total WIOA score, or risk score defined as the total score (column e in Table 2) of all criterion. The risk score in each polygon incorporates the effect of all five criterions for classifying the four severity classes (Table 3). This facilitated the production of a map that shows the different degrees of risk of soil salinization. The classes of risk in the soil salinity map are classified based on the degree of soil salinity in each class (Table 1**),** which is defined by the area covered by salt crust, ECe and salt tolerant crops.

Table 3 Classes of Severity in the Soil Salinization Risk Maps

Risk classes	Risk score	Degree of soil salinity	ECe(dS/m)
No risk	16.5-21	Non saline	< 2
Slight risk	>21-26	Slightly saline	2 – 4
Moderate risk	>26-31	Moderately saline	4 – 8
Severe risk	>31	Severely saline	>8-15

To evaluate the reliability of the overall soil salinity risk map, soil salinity at 32 locations across the CHLB were used to calibrate the risk assessment methodology. ECe of the soil samples at the ground surface were compared with the ECe range of degree of soil salinity. Weighting and the rating score, as well as risk score classing, were calibrated until the degree of soil salinity fit with the ECe of the soil samples.

4. Results and discussion

4.1 Baseline Soil Salinization Risk Area

The soil salinization risk area situation for the baseline period (2006-2015) was evaluated under the conditions of the criterion data, especially the groundwater situation.

4.1.1 Baseline groundwater situation

The groundwater condition of the CHLB in the baseline period (2006 to 2015) was simulated by using SEAWAT and HELP3 numerical models. A simulation of groundwater flow and salinity was calibrated with the hydraulic heads and salinity of the 89 wells distributed in the CHLB, and measured from September, 2014 to December, 2015. The model was validated with 33 observation wells, which had been monitored during the years from 2010 to 2012. While groundwater recharge, as simulated by HELP3, was calibrated together with the SEAWAT in order to estimate the spatially distributed, long-term average recharge rates in the CHLB, the simulation of the HELP3 model for the baseline period indicated that the recharge rates had varied from 0% to 15.25% of rainfall throughout the CHLB. High recharge rates were found in upland to highland areas with forest and field crop land use, which is located in the southern and western part of CHLB. The average annual recharge was around 98.36 MCM, and almost 90% of that recharge had taken place during the wet season (May to October). In order to simulate groundwater flow and salinity distribution in the baseline period, the simulated recharge was used as input in the SEAWAT model.

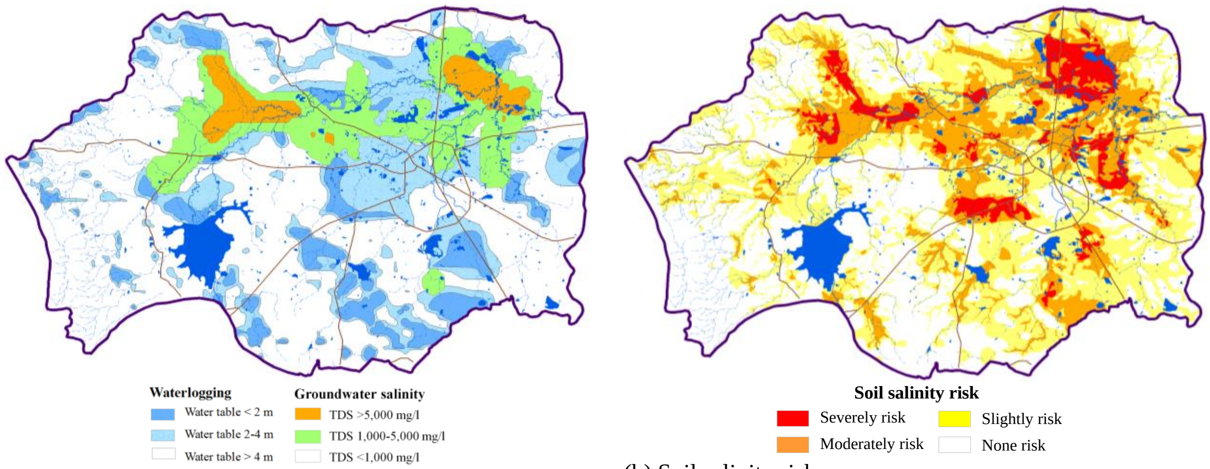
The groundwater model was calibrated by making visual comparisons of groundwater levels and salinity in terms of TDS between the observed versus the simulated models of both groundwater level and TDS. The model's performance was evaluated by statistical measurements, and indicated that statistical measurements of Root Mean Square error (RMSE) were 2.28 m and 529.39 mg/l for groundwater level and salinity, respectively. Major groundwater flow directions were replicated for the topographic terrain. The comparison of simulated and observed hydraulic heads and TDS is satisfactory and reasonable. The water balance in the baseline period showed that average annual inflow to the aquifers from groundwater recharge and river leakage had been about 104.44 MCM, while the average annual outflow from the aquifers through well abstraction, river leakage, and outflow from the basin as GHB had been only 22.11 MCM. It was found that the inflow to the aquifers was greater than the water outflow from the aquifers by about 82.33 MCM/year. Therefore, groundwater levels tended to increase every year in the baseline period, which made for an increase of waterlogging areas, as well as groundwater salinity rising upward closer to the soil surface and finally becoming salinity soil.

Waterlogging and groundwater salinity in the baseline period were analyzed from the top layer of the groundwater model, which represents the groundwater level and salinity that affects top soil salinity. Salinity of the groundwater was classified into 3 ranges based on TDS value classes for assessing soil salinity risk: less than 1,000 mg/l, 1,000-5,000 mg/l, and more than 5,000 mg/l. The waterlogging area was analyzed according to water table depth and classified into 3 classes for evaluating soil salinity risk: shallower than 2 m, 2-4 m, and deeper than 4 m. Saline groundwater (TDS > 1,000 mg/l) and waterlogging area (water table <4 m) covers an area of 205.80 km^2 or 13.8%, and 566.98 km^2 or 37.08% of the CHLB, respectively. Both areas can be found in the flood plain of the Huai Luang River and in the surrounding areas (Figure 3 (a)).

4.1.2 Baseline soil salinization risk situation

Two criteria from the groundwater model and another three from the thematic maps were analyzed under the conditions of fuzzy logic and the weighting method to assess soil salinization risk in the baseline period. The salinity of 32 soil samples, which were observed in November 2014, was considered in order to calibrate risk assessment conditions. The data of the 32 soil samples were distributed in all degrees of soil salinity. The results from the soil salinity risk assessment predicted very well the observed data from the soils. Soils with ECe >8 dS/m were classified as severely saline, those >4 dS/m were moderately saline, those >2 dS/m were slightly saline, and those <2 dS/m were non-saline (Figure 4). Only those cases where the soil ECe was close to a threshold (4 or 2 dS/m) were not well predicted. The observed soil salinity and precipitation soil salinity risk during the baseline period (2006-2015) were statistically analyzed by coefficients of determination (R^2), it showed that the best correlation was R^2 of 0.81. Therefore, the calibration of the presented technique was adequate to make a screening analysis of the salinity risk in the study area.

The soil salinization risk map in the baseline period was analyzed under five criterions using GIS operations and classified into 4 risk classes: no risk, slight risk, moderate risk and severe risk. Soil salinity risk (severe, moderate and slight risk) covered an area of 981.13 km^2, or 60.19% of the CHLB. Severe and moderate risk areas were mostly located in the flood plain of the Huai Luang River, which had high groundwater salinity and severely saline soil, as well as in the lowlands that have clay soil (Figure 3 (b)).



(a) Waterlogging and groundwater salinity (b) Soil salinity risk map

Figure 3 Waterlogging and saline groundwater areas (a) and soil salinity risk map (b) under baseline conditions

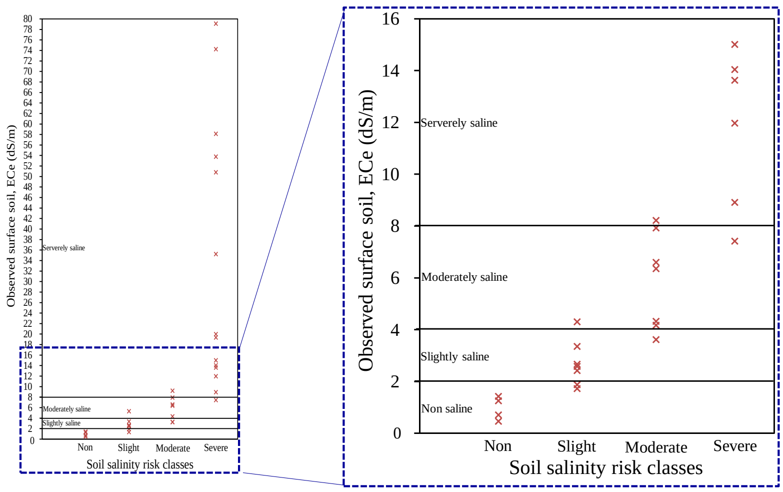
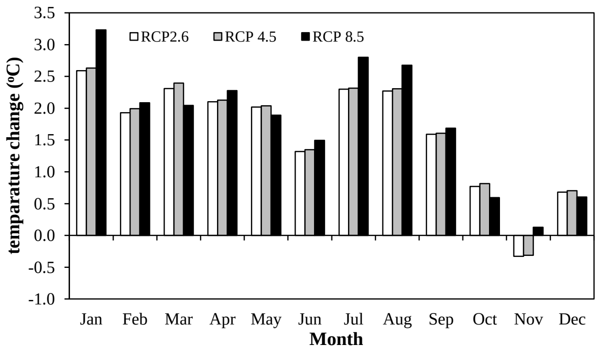


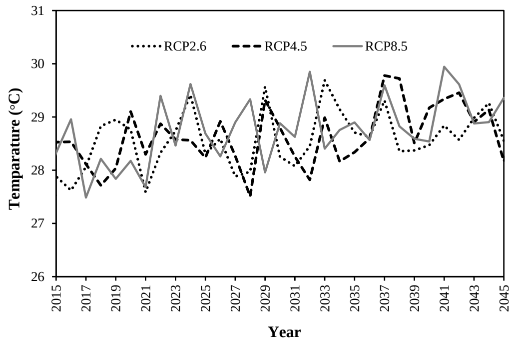
Figure 4 Comparison of observed soil salinity (ECe) at surface with soil salinity risk

4.2 Future Climate Conditions

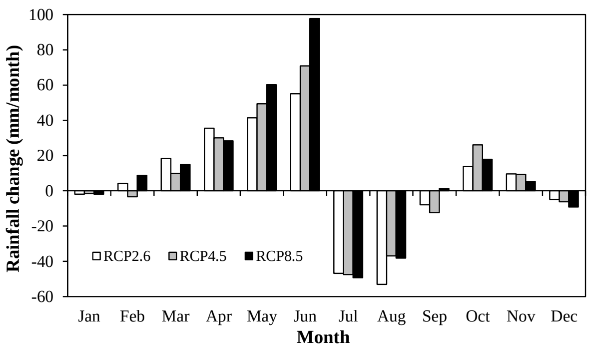
The projected average annual temperatures from CanESM2 climate models for the years from 2016 to 2045 and their decade periods compared to the baseline period (2006-2015) indicate that the average annual temperatures of the models are higher than the baseline period for all scenarios and almost every month (Figure 5 (a)). Furthermore, a significant trend, showing gradual increases year by year, was discovered (Figure 5 (b)). Compared to the 3 scenarios, the annual temperatures were not found to have a significant difference, but it's noteworthy that monthly temperatures of the RCP2.6 and the RCP4.5 are very close, while monthly temperatures of the RCP8.5 had some gap with the others (Figure 5 (a)). By the year 2045 the average annual temperatures are projected to increase by 1.6ºC, 1.7ºC, and 2.07ºC under the RCP2.6, the RCP4.5, and the RCP8.5 scenarios, respectively, compared to year 2015. Figure 5 (a) shows that for all scenarios the average monthly temperatures will increase for every month.



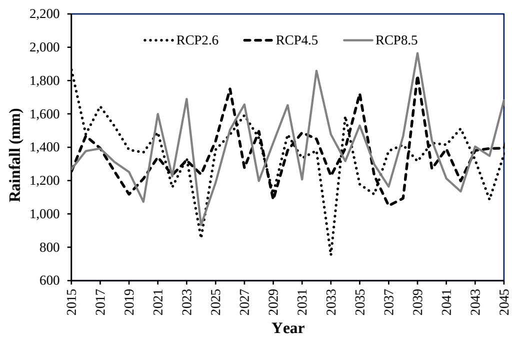
(a) Monthly temperature change



(b) Annual temperature



(c) Monthly rainfall change



(d) Annual rainfall

Figure 5 Changes in average monthly temperature and rainfall (a and c) against baseline under 3 climate scenarios and annual temperature and rainfall (b and d) under 3 climate scenarios

Projected annual rainfall is higher than the baseline period for all scenarios. The RCP 8.5 scenario projected the highest annual rainfall for almost every decade. The annual rainfall for all scenarios showed a gradually increasing trend from the 2016-2025 to the 2026-2035 decades, and then a slight decrease in the last period (2036-2045) of this projection (Figure 5 (d)). Compared to baseline, average annual rainfall was projected to increase by 5.85%, 6.94% and 11.26% under the RCP2.6, the RCP4.5 and the RCP8.5 scenarios, respectively.

Rainfall regime in the CHLB has a distinct wet season (May to October) and dry season (November to April). Rainfall changes during the wet seasons are more distinct compared to the dry seasons. The average monthly rainfall in the climate model shows that rainfall in the wet season is expected to increase significantly in May and June, whereas, under all the scenarios, it is projected to decrease slightly during the months of July and August (Fig 5 (c)). The distribution of rainfall that occurs in the wet season consists of about 85% of average annual rainfall, which is a decrease from the baseline period that states about 90%.

4.3 Impact of Climate Change on Soil Salinization Risk

The soil salinization risk situation for the baseline period (2006-2015) was evaluated under the condition of criterion data, especially the groundwater situation. Results of the future impact of climate change on groundwater and soil salinization risk areas in the period of 2016-2045 were evaluated as the followings.

4.3.1 Impact of climate change on groundwater

The projected climate data was used to estimate future groundwater recharge using the calibrated HELP3 model. The result shows that annual groundwater recharge is projected to increase from the baseline period for all scenarios of future climate. Groundwater recharge in the CHLB is projected to increase by about 14.97%, 15.21%, and 18.90%, compared to the baselines, under the RCP2.6, RCP 4.5, and RCP 8.5 scenarios, respectively. The volume and pattern of rainfall in future climates will dictate the amounts of groundwater recharge. This increasing groundwater recharge responds to groundwater flow, storage and salinity, which were all simulated by the calibrated SEAWAT model. The results show that the projected water inflow to the aquifers in all scenarios is more than the water outflow from the aquifers, and varies from 99.81 to 118.11 MCM/year, also, groundwater levels tend to increase annually for all scenarios. The simulated groundwater storage in the CHLB was expected to increase from baseline by about 28.04%, 28.76 %, and 32.06% under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. The future groundwater recharge is the most significant aspect that controls aquifer storage in the CHLB and corresponds well to the projected groundwater storage.

The simulation of groundwater model results indicates that areas of saline groundwater will gradually increase at almost the same rate until the year of 2045 in every scenario. The projected groundwater salinity area under the RCP 8.5 scenario indicated the highest increase compared to the baseline period. The spatial aspects of the saline groundwater distribution show that areas of high salinity (TDS>5,000 mg/l) will invade the low salinity areas (TDS about 1,000-5,000 mg/l), while the low salinity areas will expand into non-salinity areas. By 2045 the saline groundwater area (TDS>1,000 mg/l), as projected under the RCP2.6, RCP4.5, and RCP8.5 scenarios, will cover an area of 327.10 km^2 (22.28% of CHLB), 329.82 km^2 (22.47% of CHLB), and 334.37 km^2 (22.78% of CHLB), respectively, Table 4. Saline groundwater areas will expand from the flood plain of the Huai Luang River to the discharge areas. Future waterlogging areas show a similar trend with saline groundwater, they will gradually increase in every scenario. The waterlogging area tends to extend from the discharge to the recharge areas in some areas (Table 4). By 2045 the waterlogging (water table < 4m) area, as projected under the RCP2.6, RCP4.5, and RCP8.5 scenarios, will cover an area of 865.86 km^2 (56.63% of CHLB), 938.14 km^2 (61.36% of CHLB), and 985.02 km^2 (64.42% of CHLB), respectively. Increases in groundwater storage lead to the rising of groundwater levels which then causes an expansion of waterlogging areas. The projected areas of waterlogging and saline groundwater, which will affect soil salinity, are expected to increase.

Table 4 Projected groundwater salinity distribution and waterlogging areas

Year	Groundwater salinity distribution area (km^2)				Waterlogging area (km^2)			
	Baseline (2006-2015)	Climate model			Baseline (2006-2015)	Climate model		
		RCP2.6	RCP4.5	RCP8.5		RCP2.6	RCP4.5	RCP8.5
2016-2025	205.8	253.45	313.50	320.39	566.98	678.41	717.14	728.78
2026-2035	205.8	282.98	322.10	325.64	566.98	721.44	841.89	855.69
2036-2045	205.8	327.10	329.82	334.37	566.98	865.86	938.14	985.02

4.3.2 Impact of climate change soil salinization risk

Soil salinity risk maps for the three climate scenarios were produced for evaluating the impact of climate change in the near future. The results indicate that soil salinity risk areas will gradually increase at almost the same rate throughout 2045 in every climate scenario. All soil salinity risk levels show an increasing trend, with the highest increase being under RCP8.5. By 2045 the soil salinity risk area is projected to cover an area of 1085.91 km^2 (71.19% of CHLB), 1145.01 km2 (75.06% of CHLB), and 1174.18 km2 (76.97% of CHLB) under the RCP 2.6, RCP4.5 and RCP8.5, respectively. Based on the soil salinity risk area in the baseline period, projected increases are about 18.27%, 24.71% and 27.89% under the RCP 2.6, RCP4.5 and RCP8.5, respectively (Figure 6). Spatial aspects of the soil salinity distribution show that most of the severe and moderate risk areas are spread out in lowland areas in the flood plain of the Huai Luang River, whereas the slight risk areas have invaded into the lowland area of tributaries of the Huai Luang River and some uplands, which results in expanded waterlogging area.

The projected soil salinity risk shows that the projected impact of future climate change on soil salinity risk is anticipated to significantly increase in every scenario. The result also shows a strong relation between rainfall and soil salinity expansion, especially evident in the RCP 8.5 scenario, which shows the highest expansion based on the highest projected rainfall and recharge rates, with the consequence of, waterlogging, saline groundwater and finally, saline soil.

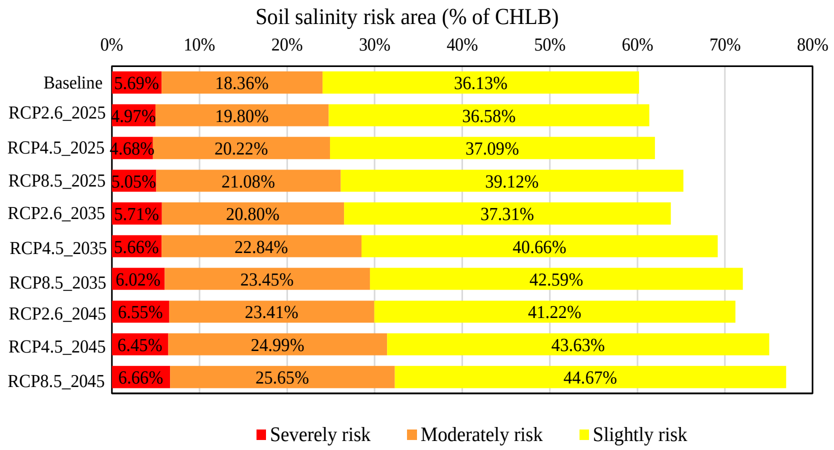


Figure 6 Percentage of soil salinity risk distribution under RCP's climate model

5. Conclusions

The soil salinity risk model developed here using a groundwater model and the GIS system is a useful and reliable tool for assessing soil salinization processes in the CHLB. Over the next 30 years (to 2045) under the three RCP climate conditions, the average annual temperature in the CHLB is projected to increase by 1.79°C and average rainfall is expected to increase by 7.56%. The increase of temperature and rainfall is the main cause of groundwater salinity and waterlogging expansion. The projected impact of climate change on soil salinity has been examined. The projected soil salinity risk areas were found to increase in every risk level for all three climate scenarios. By 2045 the salinity risk area will increase by about 216.90 km^2, or 23.62% of baseline. The highest expansion areas were observed under the RCP 8.5 scenario due to the higher projected precipitation rates and, as a consequence, higher projected recharge and shallower water table.

The effects of soil salinization may consequently exacerbate the future livelihoods of people living in CHLB, in addition to the high uncertainty of future climate projections and extreme event. Adaptation options are recommended to be applied in order to find suitable adaptation options for planning and living in a salinity environment and minimizing the impact of climate conditions and the extension of salt-affected areas in the near future.

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