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Optimizing CO_2 Truck Transport Routes from Sources to Storage in Northeastern Thailand

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Abstract

The rise in CO_2 emissions has closely paralleled the country's economic growth, with the energy sector serving as the primary contributor. In northeastern Thailand, power generation, particularly from biogas-based plants, contributes significantly to these emissions. To effectively mitigate CO_2 emissions, this study focuses on capturing and transporting CO_2 from emission sources to the storage site of the Nam Phong power plant for the implementation of carbon capture and storage (CCS) technologies in a depleted gas field, the assessment of logistics is required. This study determines optimal truck transportation routes for 23 CO_2 emission point sources in northeastern Thailand, providing comprehensive details such as starting and ending points, working hours, pickup quantities, total distance traveled, and cost per trip. The analysis identifies an optimal solution utilizing seven vehicles to efficiently collect CO_2 emissions from all designated locations, with daily CO_2 emissions at approximately 20 tones and annual emissions at around 5,565 tones. Key challenges in CO_2 transportation include natural hazards like flooding, geological obstacles, technical issues related to maintaining cold temperatures and safety protocols, and regulatory hurdles such as obtaining permits and ensuring compliance with environmental regulations.

Keywords: CCS, CO_2 transportation, Route optimization, Nam Phong Power Plant, Northeastern Thailand

1. Introduction

Climate change and global warming present significant global challenges, primarily driven by human activities such as the burning of fossil fuels and deforestation. These activities release greenhouse gases (GHGs) that trap heat in the Earth's atmosphere, intensifying the greenhouse effect. Carbon capture and storage, or CCS, is one approach that could play an important role in reducing carbon dioxide (CO_2) emissions into the atmosphere, essential for combating the steady rise in global temperatures, with 2024 expected to be one of the hottest years on record. Most GHG emissions originate from fossil fuel combustion in automobiles, industries, and electricity generation. This increase in GHG emissions has led to various impacts, including shifts in the timing of seasonal events, changes in agricultural productivity, and alterations in nutrition levels. The ongoing rise in temperatures and the resulting climatic changes underscore the urgent need for concerted global efforts to reduce greenhouse gas emissions and mitigate the adverse effects of climate change. (Chaichaloempreecha et al., 2019)

In Thailand, CO_2 emissions and emission rates have been increasing in step with economic growth. As a developing country, Thailand is one of the fastest-growing energy-intensive economies in Southeast Asia, continuously requiring energy to drive its economy. The energy sector stands as the primary source of these emissions, with power generation playing a significant role. Coal-fired and gas-based power plants are the main contributors to CO_2 emissions (Energy Policy and Planning Office (EPPO), 2023. These plants are predominantly located in the onshore Khorat Plateau of northeastern Thailand, a region well-known for its substantial natural gas reservoirs, particularly within the Permian carbonate rocks.

In context, CCS emerge as a beacon of hope in Thailand's quest for sustainable development. By capturing CO_2 emissions at their source and securely storing them underground in a depleted petroleum reservoir, CCS offers a pathway to mitigate the nation's carbon footprint while sustaining economic growth. Yet, for CCS to become a reality, meticulous planning is imperative. This includes careful consideration of transport and storage logistics, with thorough cost estimates accounting for the region's unique geological features.

This study aims to determine the optimal transportation routes for CO_2 from its sources to storage sites in Northeastern Thailand. Key aspects of this study include identifying crucial locations along the routes, assessing geomorphological features that may influence transportation, and evaluating potential obstacles that could impact the movement of CO_2.

2. Nam Phong power plant and gas field

Presently, the Nam Phong Power Plant is the largest in the Khorat Plateau, northeastern Thailand, operated by the Electricity Generating Authority of Thailand (EGAT). It is the only power plant in the region that uses natural gas as fuel for electricity generation (Figure 1). The gas field is located around 60 km north of the Nam Phong Power Plant. In 1981, a 1.5 trillion ft^3 natural gas reserve was discovered in the Permian carbonate rocks at a depth of approximately 3,000 meters. Initial production averaged 40 million ft^3 per day (Electricity Generating Authority of Thailand, 2024). In the next few years, this reservoir is expected to become a gas-depleted reservoir, making it the target storage site for this study (Chenrai et al., 2022; Jitmahantakul et al., 2023).

The scope of this study covers transportation routes using the location of the Nam Phong Power Plant as both the starting and ending point for trucks traveling to the CO_2 emission point sources. Transportation of the collected CO_2 from the Nam Phong Power Plant to the depleted gas field is not the focus of this study.

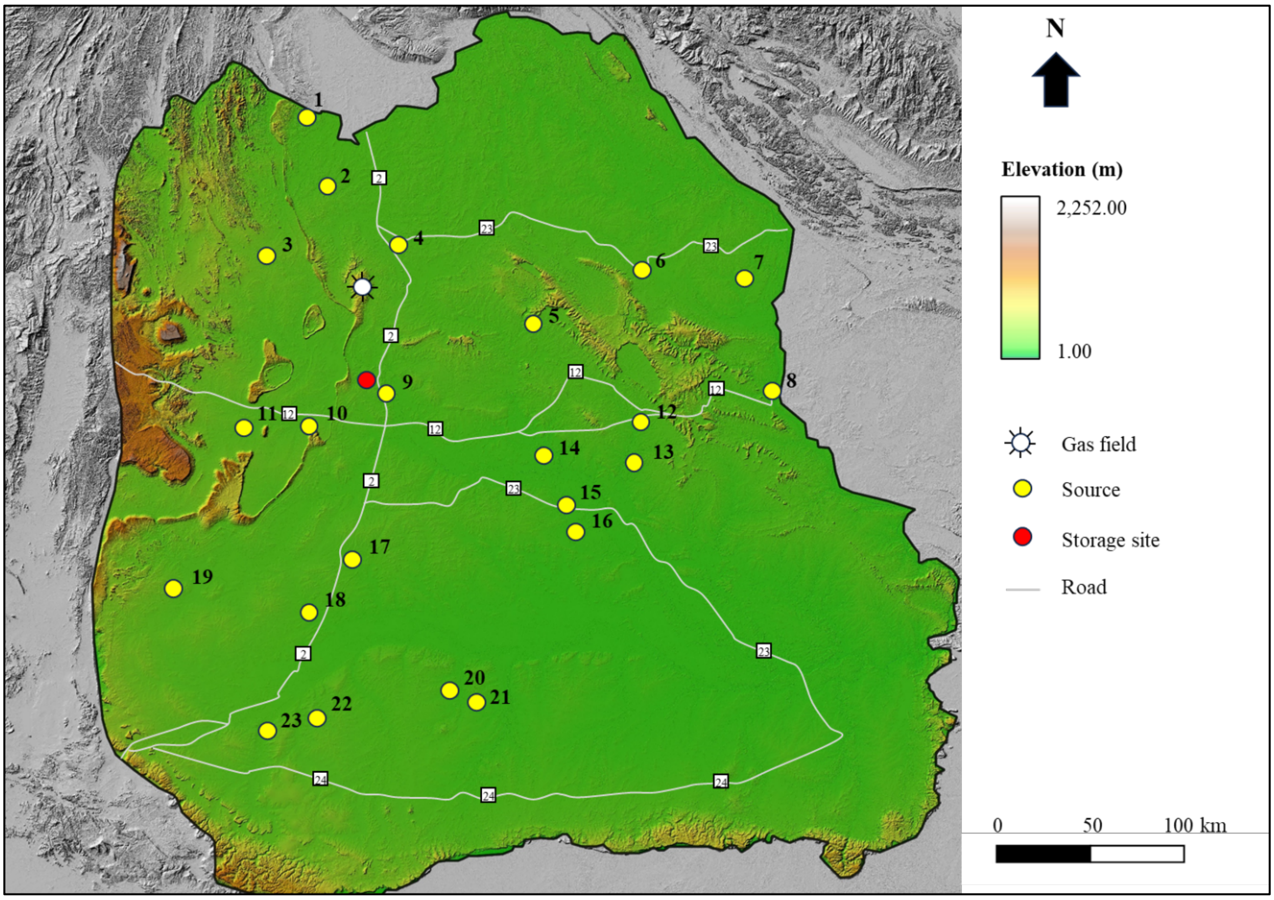

Figure 1. Elevation map of the Khorat Plateau, northeastern Thailand, showing location of Nam Phong power plant (ground storage site) gas field (underground storage site) and CO_2 emission point sources used in this study (CO_2 emission data from Choomkong et al., 2017).

3. CO_2 emission sources

CO_2 emission in Khorat Plateau is mainly from biomass power plants with an emission range from 0.0033-0.0107 M ton per year. These were selected based on the criterion that they can be reached within a one-day trip without exceeding an 8-hour driving time limit. (Table 1) shows a list of 23 source locations used in this study.

Table 1. CO_2 emission sources, estimated CO_2 emission, source and locations, and principal highway distance from source to Nam Phong power plant (NPPP).

No.	Point sources	CO_2 emission (Mton)	Latitude	Longitude	Principal highway distance to NPPP (km)
1	ES01	0.0107	17.936	102.449	119.96
2	ES02	0.0107	17.603	102.555	86.54
3	ES03	0.0107	17.269	102.258	64.34
4	ES04	0.0107	17.320	102.896	54.21
5	ES05	0.0107	16.928	103.542	82.03
6	ES06	0.0073	17.181	104.063	143.57
7	ES07	0.0073	17.128	104.576	181.74
8	ES08	0.0107	16.595	104.703	158.29
9	ES09	0.0107	16.622	102.815	9.14

Table 1. (continued)

No.	Point sources	CO_2 emission (Mton)	Latitude	Longitude	Principal highway distance to NPPP (km)
10	ES10	0.0107	16.470	102.442	48.02
11	ES11	0.0107	16.473	102.132	74.41
12	ES12	0.0107	16.467	104.046	105.35
13	ES13	0.0107	16.267	104.012	105.46
14	ES14	0.0107	16.312	103.571	75.32
15	ES15	0.0073	16.079	103.674	90.85
16	ES16	0.0033	15.957	103.700	100.80
17	ES17	0.0107	15.849	102.633	66.27
18	ES18	0.0107	15.605	102.429	96.82
19	ES19	0.0107	15.724	101.773	130.11
20	ES20	0.0107	15.227	103.088	129.97
21	ES21	0.0107	15.172	103.211	145.64
22	ES22	0.0107	15.108	102.465	125.59
23	ES23	0.0107	15.049	102.227	130.76

*CO_2 emissions from biomass sources were estimated from the production of power generation and suitable emission factors following Choomkong et al., (2017).

4. Geomorphology of NE Thailand

The Khorat Plateau is a broad, elevated region with an average elevation of about 200 meters above sea level. The landscape is predominantly flat to gently undulating, interspersed with some hills and low mountains. The plateau features numerous floodplains and river terraces formed over time by the fluvial processes associated with major rivers such as the Mun and Chi rivers. Due to its generally flat to gently undulating topography, this region can impede efficient drainage of water during heavy rains.

Considering the existing infrastructure in the Khorat Plateau and the need for flexibility in handling multiple sources, trucking transportation emerges as the most suitable approach. The region benefits from an extensive network of principal highways and secondary roads, which supports efficient transportation logistics. Trucks can be used to collect CO_2 and are highly flexible for multiple pickup points and deliveries. Trucking also allows for easy scaling of operations based on the amount of CO_2 to be transported. However, urban and flood areas might experience traffic congestion, which can delay transportation.

5. Methodology

To determine the optimal transportation routes for CO_2 from source to storage site, it is essential to first evaluate the biomass power plants located in the Khorat Plateau and quantify their CO_2 emissions. This study employs several open-source software tools—VROOM developed by VERSO, Valhalla developed by the core engineers at Mapbox, and VRP Spreadsheet Solver developed by Güneş Erdoğan, Professor of Operational Research and Director of Studies for the MSc Business Analytics Programme at the University of Bath—to estimate CO_2 emissions and identify the most efficient routes. Each of these tools has its unique features and limitations, which are crucial to consider when planning transportation logistics. By analyzing the pros and cons of these software options (Table 2), we aim to provide a comprehensive understanding of their effectiveness in optimizing CO_2 transport. This evaluation will help in selecting the best tool for ensuring cost-effective and environmentally friendly CO_2 transportation routes.

Based on the review of the pros and cons of the software options, VRP Spreadsheet Solver stands out as the best tool for simulating the optimal transportation route. Its interface is an Excel sheet equipped with built-in simulation functions, making it user-friendly. To use it, simply input the specified parameters. The software allows for the definition of detailed parameters such as vehicle type, vehicle speed, cost, pickup amount, and working time limits, and it simulates the map using data from Bing Maps. The three main parameters to be defined are as follows.

5.1 Trucking

Emphasizing the importance of certain factors, particularly the number of sources, storage sites, and the selection of travel mode and route type, is crucial. This study concentrates specifically on truck transportation and real-time traffic route type, with one storage site and 23 sources. Thus, it's essential to define the average speed of the vehicle as 80 km/hr., in compliance with truck regulations.

5.2 Location, pickup amount, and service time

For the location parameters, input all sources and sinks, along with the latitude and longitude of each location. Regarding the pickup amount and service time, these can be calculated using the following formula:

$$\textit{Pickup amount (volume)} = \frac{Mass\ (kg)}{Density\ (kg/m3)} \ldots\ldots (1)$$

*Density of liquid CO_2 (2MPa, -20°C) = 1,100 kg/m³ (Ramadhan et al., 2023)

$$\textit{Service time} = \frac{Volume\ (liters)}{Pumping\ rate\ (liters/mins)} \ldots\ldots\ldots (2)$$

Table 2. Software comparison

Software	Advantages	Disadvantages
VROOM	Simulate the transportation route map Estimate time duration Estimate total distance	Cannot change the vehicle parameter such as speed Required specific format to import data (JSON)
Valhalla	Simulate the transportation route map Estimate time duration Estimate total distance Can define vehicle parameter such as vehicle type, speed	Cannot input no more 20 locations
VRP_Spreadsheet _solver	Simulate the transportation route map Estimate time duration Estimate total distance Can define vehicle parameter such	Effective for 1 day transportation Required various parameter

as vehicle
type, speed,
delivery
amount, costs

5.3 Truck Capacity

This stage is crucial as it involves defining all parameters, beginning with selecting the vehicle type and specifying its capacity. For this study, a 10-wheeled truck with a capacity of 18,000 liters will be employed. Subsequently, costs, working time, driving time limits, and distance limits will be established in compliance with regulations. Furthermore, it is essential to experimentally determine the optimal number of vehicles needed to achieve the most cost-effective results while ensuring that all designated pickups can be completed within the allotted working time, driving time, and specified distance limits. This entails running tests to ascertain the minimum number of vehicles required to minimize expenses and successfully fulfill the predetermined pickup requirements.

6. Result and discussion

6.1 Optimal transportation route and cost estimation

The result of VRP_Spreasheet_Solver can visualize the transportation routes map. (Figure 2) and indicate the optimal starting location, departure and arrival times, working hours, and the pickup quantities required at each location. Additionally, they can provide a summary of the total distance traveled and an estimated cost per trip.

For the optimal transportation route, seven vehicles must be utilized to determine the best route. This configuration ensures the most cost-efficient solution while accommodating the pickup of CO_2 emissions from all locations. However, it is important to note that this analysis is conducted under conditions without involving hubs and seasonal factors. It simulates based on real-time traffic, excluding geomorphology influences from the outcomes. Additionally, pickup amounts for these routes will be estimated, with pickups rounded to either one or two rounds to first store excess CO_2 emissions in certain power plants due to truck capacity constraints. The seven transportation routes are shown in (Table 3), and the costs are shown in (Table 4).

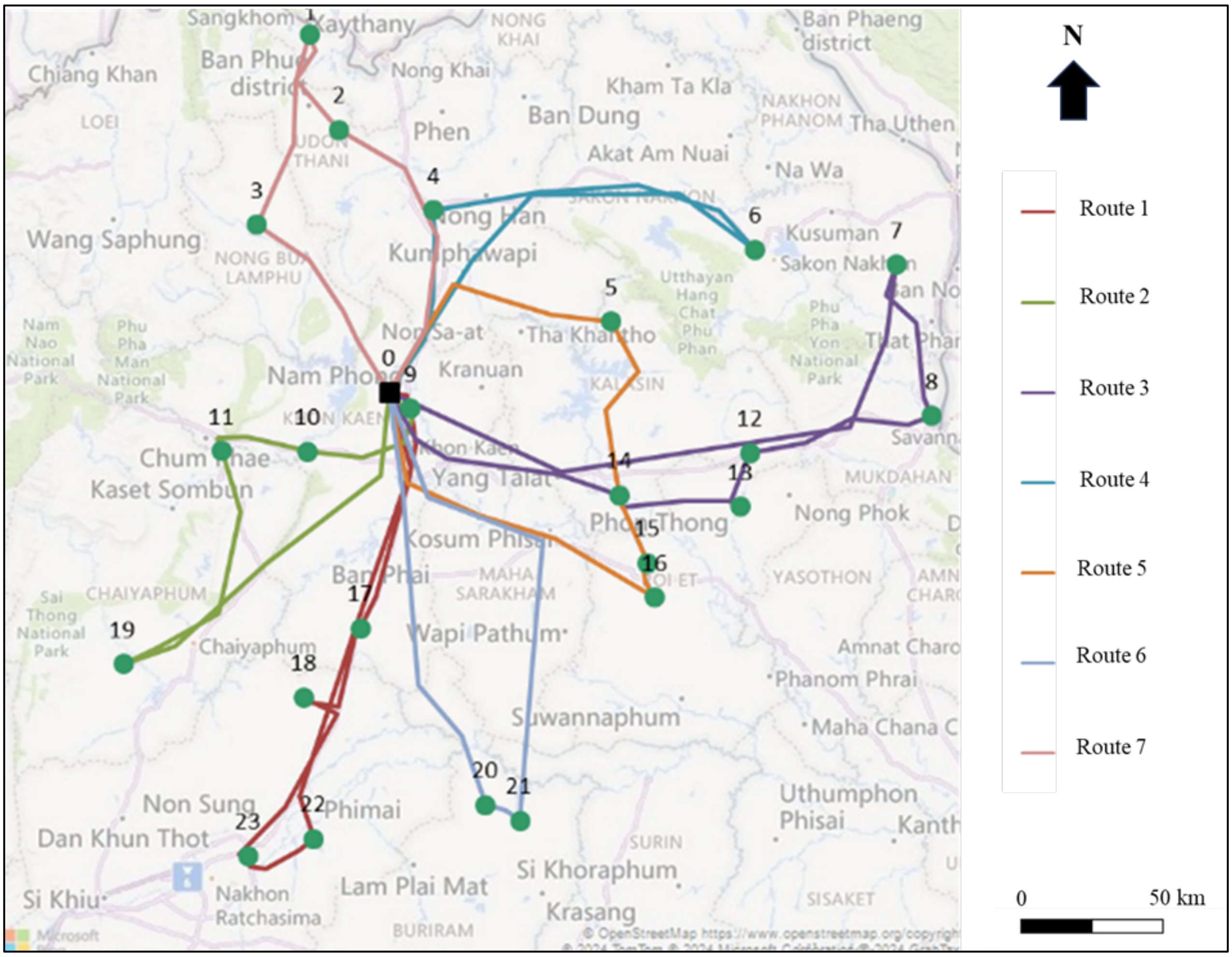

Figure 2. The optimal transportation routes map

6.2 CO_2 Emission Estimation

In calculating the carbon dioxide emissions of 7 routes, the values are as shown in Table 5. These values are calculated based on the travel distance and the load weight by using EcoTranITworld. Additionally, they include the carbon dioxide emissions from certain power plants where the vehicles must store the emissions for 1-2 rounds first.

From the calculations, it was found that the vehicles emit a total of 20.6895 tones of CO_2 in one day of transportation. If operating throughout the year (269 working days), the total CO_2 emissions would be approximately 5,565 tonnes per year.

Table 3. The summary table of seven optimal transportation routes

Route	Location	Arrival Time	Departure Time	Working Time	Load (liters)
1	Nam Phong Power plant	-	8.00 AM	0 hr.	0
	ES09	8.13 AM	8.38 AM	38 mins	160
	ES17	10.10 AM	10.35 AM	2.35 hrs.	320
	ES18	11.23 AM	11.48 AM	3.48 hrs.	480
	ES23	1.15 PM	1.40 PM	5.40 hrs.	640
	ES22	2.24 PM	2.49 PM	6.49 hrs.	800
	Nam Phong Power plant	5.52 PM	-	9.52 hrs.	0
2	Nam Phong Power plant	-	8.00 AM	0 hr.	0
	ES10	9.00 AM	9.35 AM	1.35 hrs.	160
	ES11	10.14 AM	10.39 AM	2.39 hrs.	320
	ES19	12.36 PM	12.51 PM	4.51 hrs.	11,472
	Nam Phong Power plant	3.44 PM	-	7.44 hrs.	0
3	Nam Phong Power plant	-	8.00 AM	0 hr.	0
	ES14	9.44 AM	10.09 AM	2.09 hrs.	160
	ES13	11.00 AM	11.25 AM	3.25 hrs.	320
	ES12	11.54 AM	12.19 PM	4.19 hrs.	480
	ES08	1.34 PM	1.59 PM	5.59 hrs.	640
	ES07	3.19 PM	3.34 PM	7.34 hrs.	11,792
	Nam Phong Power plant	7.21 PM	-	11.21 hrs.	0
4	Nam Phong Power plant	-	8.00 AM	0 hr.	0
	ES04	9.27 AM	9.52 AM	1.52 hrs.	160
	ES06	12.14 PM	12.29 PM	4.29 hrs.	11,312
	Nam Phong Power plant	3.46 PM	-	7.46 hrs.	0
5	Nam Phong Power plant	-	8.00 AM	0 hr.	0
	ES16	10.32 AM	10.47 AM	2.47 hrs.	11,152
	ES15	11.11 AM	11.31 AM	3.31 hrs.	17,822
	ES05	1.28 PM	1.53 PM	5.53 hrs.	17,982
	Nam Phong Power plant	3.48 PM	-	7.48 hrs.	0
6	Nam Phong Power plan	-	8.00 AM	0 hr.	0
	ES20	11.18 AM	11.43 AM	3.43 hrs.	160
	ES21	12.12 PM	12.37 PM	4.37 hrs.	320
	Nam Phong Power Plant	3.59 PM	-	7.59 hrs.	0
7	Nam Phong Power Plant	-	8.00 AM	0 hr.	0
	ES02	10.09 AM	10.34 AM	2.34 hrs.	160
	ES01	11.28 AM	11.53 AM	3.53 hrs.	320
	ES03	1.37 PM	2.02 PM	6.02 hrs.	480
	Nam Phong Power Plant	3.48 PM	-	7.48 hrs.	0

Table 4. The total distances and costs summary of seven optimal transportation routes

Route	Total distances (km)	Costs for storage first	Costs for remaining	Total cost (baht)
1	312.27	51,781.72	6,436.81	58,218.53
2	208.41	22,734.18	6,341.24	29,075.42
3	425.52	35,214.60	6,776.57	41,991.17
4	288.40	11,325.26	6,365.19	17,690.45
5	273.66	17,264.73	6,320.99	23,585.72
6	285.92	23,653.66	6,357.75	30,011.41
7	246.66	34,625.04	6,239.98	40,865.02
				241,437.72

Table 5. The CO_2 emission amount of each route

Route	CO_2 emission amount (Tonnes)
1	3.9860
2	1.6250
3	5.9120
4	1.0450
5	1.7440
6	3.1671
7	3.2104
	20.6895

6.3 Obstruction for transportation

Transporting CO_2 from its source (biomass power plants) to storage sites involves various challenges and potential obstructions. These can be broadly categorized into key hazards, technical obstructions, and regulatory obstructions.

6.3.1 Flood

Various hazards can impede the process and pose significant risks. Understanding and mitigating these hazards is crucial for safe and efficient operations. The primary hazards include flooding and geological features. In flood-prone areas, especially near rivers, should be avoided during peak seasons. On the Khorat Plateau, overlaying the flood risk map with traffic routes (Figure 3) revealed that routes 1, 5, 6, and 7 require caution during the rainy season. Alternative routes should be sought to avoid flooded areas. In addition, in terms of geological features, in the Khorat Plateau, the geomorphology features numerous basins and mountains, which may result in impacts on certain routes.

6.3.2 Technical obstructions

When CO_2 is transported by trucks, it is usually liquid, which needs very cold temperatures. Special equipment and regular maintenance are necessary to keep the CO_2 in this liquid state while it is being moved. In addition, ensuring CO_2 is transported safely in trucks means following strict safety rules to stop leaks and deal with emergencies properly. This involves using strong tank designs, having systems that release pressure if needed, and checking the equipment regularly.

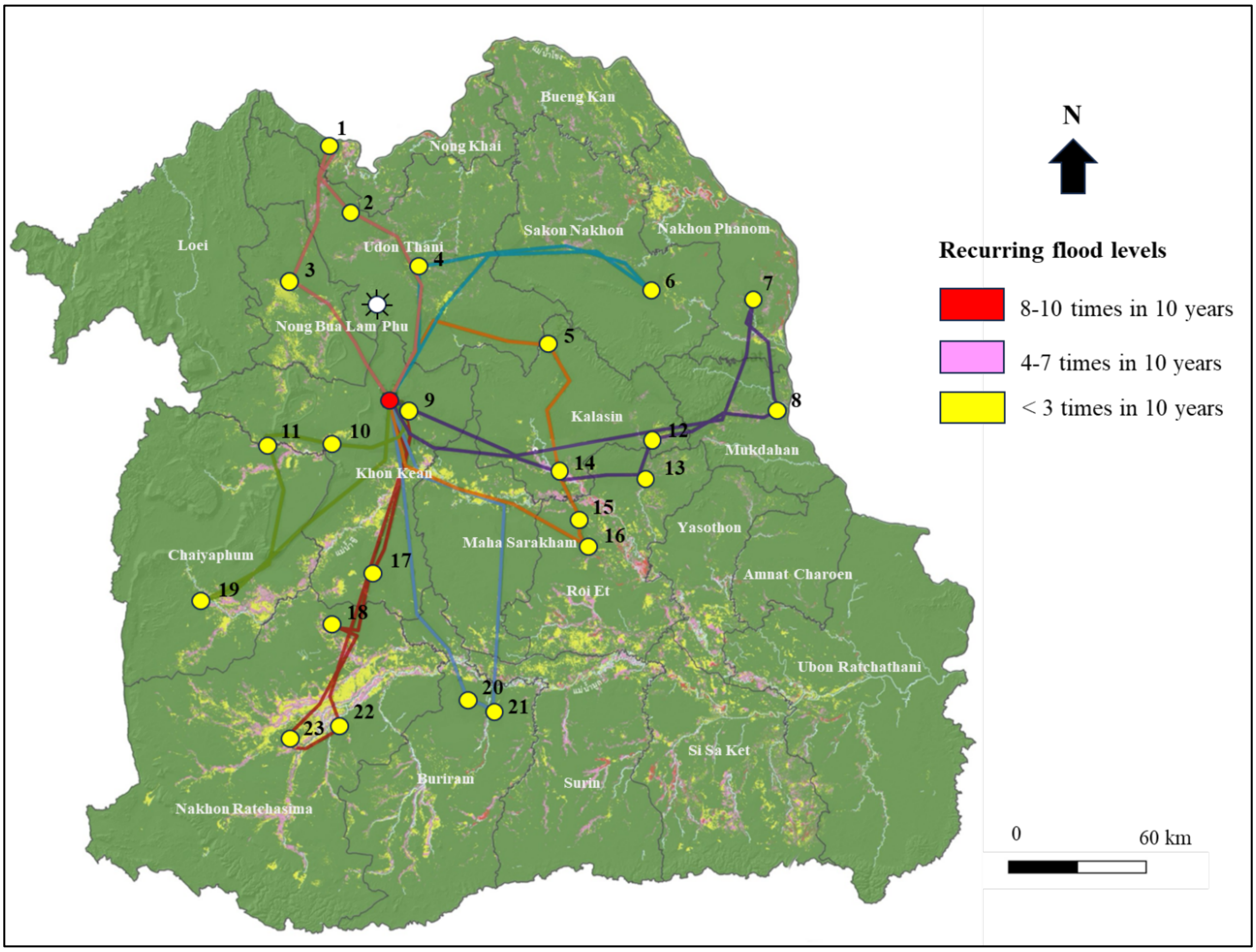

Figure 3. Flood risk map overlay with transportation routes in Northeastern Thailand (Land Development Department, 2020)

6.3.3 Regulatory obstructions

Navigating regulatory hurdles poses a significant challenge in the truck transportation of CO_2. Obtaining permits for transporting hazardous materials like CO_2 requires compliance with stringent regulations at local, national, and potentially international levels. These regulations encompass vehicle standards, driver qualifications, and safety protocols, including time limits for working and driving. With stipulations like working hours capped at 8 hours, with the possibility of overtime and driving time limited to less than 8 hours. Furthermore, ensuring compliance with environmental regulations and liability frameworks adds complexity to the regulatory landscape. Overcoming these challenges requires careful planning and close collaboration with regulatory authorities to ensure legal compliance and operational integrity throughout the transportation process.

7. Conclusions

The VRP_Spreadsheet_Solver tool enables the visualization of transportation routes and provides detailed information about optimal routes, including starting and ending points, working hours, and pick-up quantities. It also estimates the total distance traveled and the cost per trip. For the optimal route, seven vehicles are utilized to ensure the most cost-efficient solution while accommodating the pickup of CO_2 emissions from all designated locations. However, this analysis does not account for hubs or seasonal factors and assumes that pickup amounts will be rounded to either one or two rounds to store excess CO_2 emissions in certain power plants due to truck capacity constraints.

The tool also estimates CO_2 emissions based on travel distance and load weight using EcoTranITworld. The total CO_2 emissions for one day of transportation are approximately 20 tonnes, and if operating throughout the year, the total CO2 emissions would be around 5,565 tonnes per year. Additionally, the tool highlights various challenges and potential obstructions in transporting CO_2 from its source to storage sites, including key hazards such as flooding and geological features, technical obstructions like maintaining cold temperatures and ensuring safety protocols, and regulatory obstructions like obtaining permits and complying with environmental regulations.

Given this simulation of transportation routes, it is crucial to conduct thorough site assessments and evaluate cost-effectiveness before proceeding with actual implementation. This step ensures that the project aligns with its goals and is economically viable while considering environmental impacts, operational efficiency, and regulatory requirements.

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