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Utilizing digital elevation models and geographic information systems for hydrological analysis and fire prevention in Khuan Kreng peat swamp forest, Southern Thailand

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ABSTRACT

The objectives of this research were to create a topographic model using Mathematica and hydrologic model using ArcGIS for water management aimed at preventing forest fires in the Khuan Kreng peat swamp forest. Pan basin area in Kreng Sub-district, characterized by low mountains, where the Cha-Uat canal intersects the krajood forest, was revealed by the hydrographic model. Kreng Sub-district was traversed by three main streams: Khuan canal, Hua Pluak Chang canal, and Laem canal. Additionally, several tributary canals that interconnect, ultimately converging into the Cha-Uat Phraek Muang canal were identified. During the dry period, the water from these canals flowed into the Cha-Uat Phraek Muang canal. To mitigate the risk of fires, it was essential to install water table measuring devices and underground barrier gates at the drain points. This ensured the return of water from the Cha-Uat Phraek Muang canal to the Khuan Kreng peat swamp forest. Maintaining sufficient water table level was crucial, as the occurrence of fires was more likely when the water table dropped below the soil surface. When the swamp forest was adequately hydrated, wildfires were confined to a narrow area since they could only burn on the forest surface, which was easier to extinguish.

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1. INTRODUCTION

Most of the smoke that engulfed the Southern Thailand region was the result of the burning of peat swamp forests or agricultural peatlands [1]. Forest fires in Thailand were primarily caused by human activities. This was particularly true for the forest fires in 2019. The outbreak of severe forest fires was witnessed from December 2018 to February 2019. This was attributed to the El Niño phenomenon [2]. A significant amount of money had to be allocated by the Thai government to extinguish fires (such as the forest fires in the area of Khuan Kreng peat swamp forest), as demonstrated in Figure 1(a) smoke from the

Khuan Kreng peat swamp forest captured on Jun 29, 2019 [3] and Figure 1(b) smoke from the Khuan Kreng peat swamp forest fire captured on Aug 1, 2019 [4].

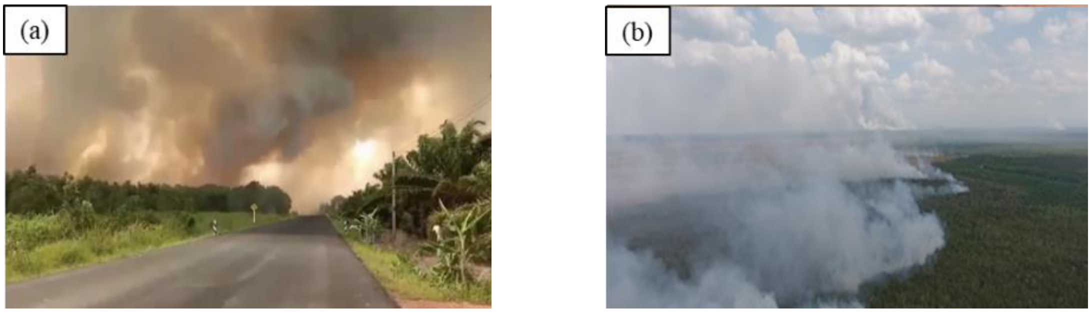

Figure 1. Huge smoke filled the sky (a) smoke from the Khuan Kreng peat swamp forest captured on Jun 29, 2019 [3] and (b) smoke from the Khuan Kreng peat swamp forest fire captured on Aug 1, 2019 [4]

Prolonged months of extreme dry periods in Southeast Asia led to numerous fires in various regions, including Central Kalimantan, South Sumatra, Southern Thailand, and Malaysia. Khuan Kreng peat swamp forest, Thailand's second-largest swamp forest, was situated at the borders of three provinces: Nakhon Si Thammarat, Phatthalung, and Songkhla in Southern Thailand. The formation of the lowland peat swamps in Khuan Kreng was influenced by the topographic conditions of wetlands, where vegetation accumulated and deposited on waterlogged soils at a faster rate than it could decompose. Hydrology played a vital role in the establishment and functioning of peat swamp ecosystems. The hydrological characteristics of a peat swamp depended on factors such as flow direction, topography, natural subsoil, and drainage base [5]. Khuan Kreng peat swamp forest covered an area of 217.76 km^2 in Nakhon Si Thammarat, 93.6 km^2 in Songkhla, and 1.44 km^2 in Phatthalung [6]. Forest fires occurring in the forest reserve typically penetrated the peat layer to depths of approximately 0.2–0.3 meters, similar to the situation in Sirindhorn Swamp forest in Narathiwat Province, Thailand [7], [8]. Fighting wildfires in peat swamp forests was more challenging than land fires due to the need to combat fires horizontally and vertically, considering the heavy smoke and concealed locations. Controlling the water table in early summer within the range of +0.30 to +0.50 meters allowed the water level in the swamp forest to be sustained for 2–3 months, but it could decrease to -0.20 meters during late summer [6].

The surface geography and elevation layers in digital form were represented by the digital elevation model (DEM), a database model. It was used to analyze topography and study hydrological conditions [9]. Data could be organized into structured lists using algorithms implemented in programming languages resembling mathematical notation [10]. DEMs were widely used to illustrate hydrological processes and features such as soil moisture and unstable geographic terrains. Data collection for building DEMs typically involved remote sensing techniques, environmental monitoring, and spatial analysis. The resolution of the DEM closely tied the accuracy of research data [11]. Water flow, including surface water, flow direction, flow accumulation, and water table estimation, was depicted by a hydrographic model, using commonly employed algorithms. One such algorithm was the D8 model [12]. The flow direction could be determined, and reliable results could be provided in the foothill area, which was the natural river basin, but the results were not very accurate in flat land [13]. An explanation for the variation observed in the study area with regard to elevation, considering both two-dimensional (2D) and three-dimensional (3D) dimensions, could be provided by the theory of DEM [14]. Geographic information systems (GIS) and DEMs were implemented and played a substantial role in watershed geomorphological parameterization. High-resolution DEMs were unavailable, requiring digital processing to improve resolution [15]. The use of DEM-based GIS and remote sensors had become popular [16], [17]. Geoprocessing methods typically relied on a raster DEM as the primary data source, with varying resolutions ranging from medium to coarse, which were subsequently used in the watershed for geomorphometric characterization [18].

ArcGIS was employed to compute the D8 flow direction, which determined the flow accumulation from each cell to adjacent cells at lower elevations. While satisfactory results were yielded when this method was applied to the foothill area of the natural basin, limitations were encountered when dealing with flat terrain. However, DEM was still used as the primary data source in hydrography research, where topographic analysis was conducted to identify basins and determine flow direction [19], [20]. All the cells on the network were updated together in parallel. This technique was effectively employed in water management planning to address issues such as flooding and water scarcity. In general, a path was followed by water from higher to lower elevations, flowing through the cells. The flow direction was determined by calculating the flow from one cell to another in the form of a raster, utilizing DEM data. There were eight flow directions. The calculation involved determining the cumulative flow of information from each cell, which subsequently flowed toward the cells at lower inclinations [21]. The water drainage points with a significant cumulative rate could be utilized to determine the water pathway. However, cells in high-altitude areas did not possess a cumulative rate. Mathematica stood out as a highly efficient numerical program, known for its user-friendly interface, making it suitable for both academic and research purposes [22].

A topographic model was created using Mathematica, and a hydrologic model was developed using ArcGIS to aid in water management for the prevention of forest fires in Khuan Kreng peat swamp forest, located in Nakhon Si Thammarat Province, Southern Thailand. DEM data obtained from the Royal Thai Survey Department and the Department of Land were utilized by the researcher. These data provided insights into the real conditions of the area and served as the basis for effective water management strategies. It was important to recognize that any alterations in the hydrology, particularly through the implementation of drainage systems, could have irreversible impacts on the delicate ecosystems present in the peat swamps. Therefore, gaining a comprehensive understanding of the hydrology of these environments was crucial for the sustainable development and management of peat swamp areas.

2. METHOD

2.1. Study area

The study area is located in the Khuan Kreng swamp forest, specifically in the Kreng Sub-district of the Cha-Uat District in Nakhon Si Thammarat Province, Southern Thailand. As depicted in Figure 2, the coordinates of the study area are as follows:

- UTM 582636–609636 N, 884357–911357 E, obtained from the DEM data of the Royal Thai Survey Department.
- UTM 616000–629000E, 870000-895000 N, obtained from the DEM data of the Department of Land Development.

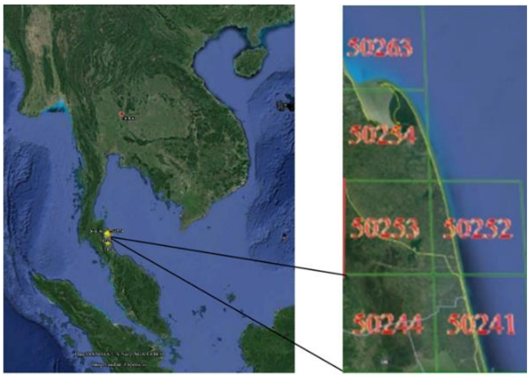

Figure 2. Research area scope in Thailand

2.2. Equipment

The DEM data used in this study were obtained from the Royal Thai Survey Department at a scale of 1:50,000. The data consists of sub-cells with a resolution of 30×30 m^2 based on the universal transverse Mercator (UTM) coordinate system (UTM 582636–609636 N, 884357–911357 E). Specifically, the study focuses on analyzing topographic and hydrographic characteristics within an area of 729 km^2, including Section 50244.

The DEM data used in the study were obtained from the Department of Land Development at a scale of 1:4,000. The data resolution was 5×5 m^2 and is based on the UTM coordinate system. The specific coordinates for this dataset are UTM 616000-629000 E, 870000-895000 N. The study focuses on analyzing the topographic and hydrographic characteristics within an area of 80 km^2. This area consists of 20 sections, as illustrated in Figure 3.

The computer used for the simulation consists of both hardware and software components. The hardware specifications include an Apple MacBook Pro 16 with an Intel Core i9 (8-core) processor, operating at a base frequency of 2.3 GHz and capable of reaching a Turbo Boost speed of 4.8 GHz. It is equipped with DDR4 2400 MHz memory with a total capacity of 16 GB and an SSD PCle storage capacity of 512 GB. Additionally, the installed memory (RAM) is 64.0 GB. Regarding the software, the operating system used for the simulation is Windows XP Professional. The simulation and analysis result program are written in Mathematica 12, ArcGIS 10.6, and Google Earth Pro.

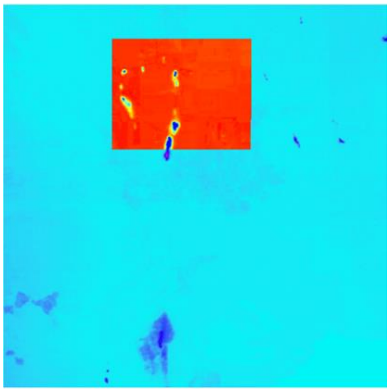

Figure 3. DEMs of the Royal Thai Survey Department are in blue, and the DEMs of the Department of Land Development are in red

2.3. Method

The research process has been detailed in Figure 4. The topography was analyzed using the 2D and 3D topographic models implemented with the Mathematica program [23], [24]. The analysis method of the flow direction model and the flow accumulation model was demonstrated through the utilization of DEM data. The hydrographic model was simulated using the spatial analyst tools available in the ArcGIS software. These tools are a part of the Arc toolbox. Within the hydrology section of the spatial analyst tools, various functions were utilized, including flow direction. The flow direction model employed in this study consisted of eight flow directions based on direction coding [25]. Other functions used in the hydrology analysis included flow accumulation, basin delineation, watershed delineation, and stream order determination.

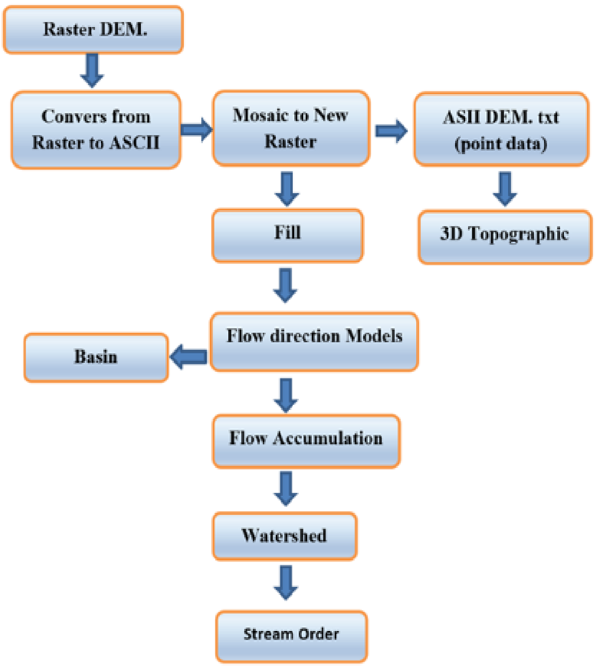

Figure 4. Flowchart depicting the research process

2. RESULTS AND DISCUSSION

In Case Study 1, writing section No. 50244 focused on developing a topographic model program using the DEM data obtained from the Royal Survey Department. The DEM data had a scale ratio of 1:50,000. The topographic model program was implemented using the Mathematica program. In case study 2, this involves writing the 16-section topographic model program with DEM data (ratio 1: 4,000) obtained from the Department of Land Development using Mathematica. Based on the topographic simulation results depicted in Figure 5(a) 2D topographic of section No. 50244 and Figure 5(b) 3D topographic of section No. 50244 and Figure 6(a) 2D topographic image and Figure 6(b) 3D topographic image, it was observed that the majority of Khuan Kreng peat swamp forest comprises a pan basin. This area is approximately 1–2 meters below sea level and is surrounded by seven low hills, namely Khuan Yao, Khuan Pom, Khuan Teen, Khuan Sai, Khuan Rab, and Khuan Ching, with Khuan Kreng being the largest hill. Additionally, three parallel canals, namely Khlong Laem, Khlong Hua Pluak Chang, and Khlong Khuan, can be observed in the area. The elevation of the hills ranges from approximately 30 to 110 meters. Figure 7 illustrates the presence of the krajood forest, while the locations where wildfires occurred between 2010 and 2020 are marked with red points.

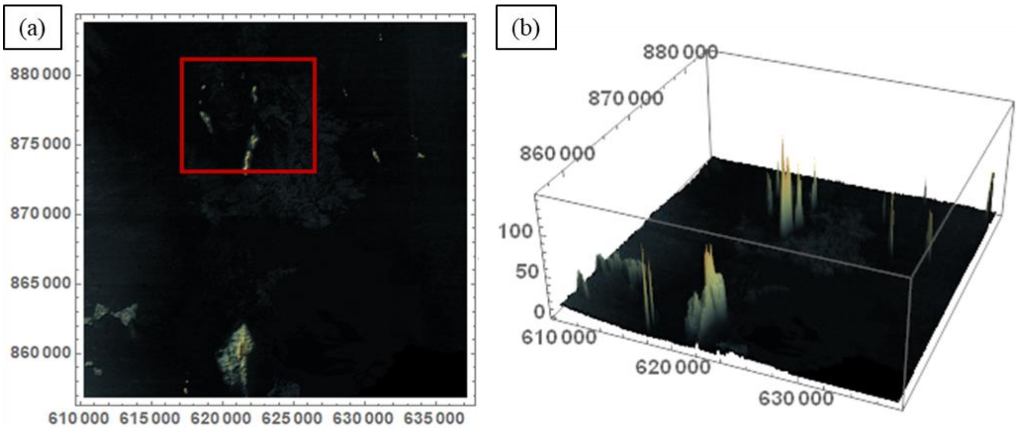

Figure 5. Results of the simulation with Mathematica program, 610000–635000 E and 855000–885000 N. (a) 2D topographic of section No. 50244 and (b) 3D topographic of section No. 50244

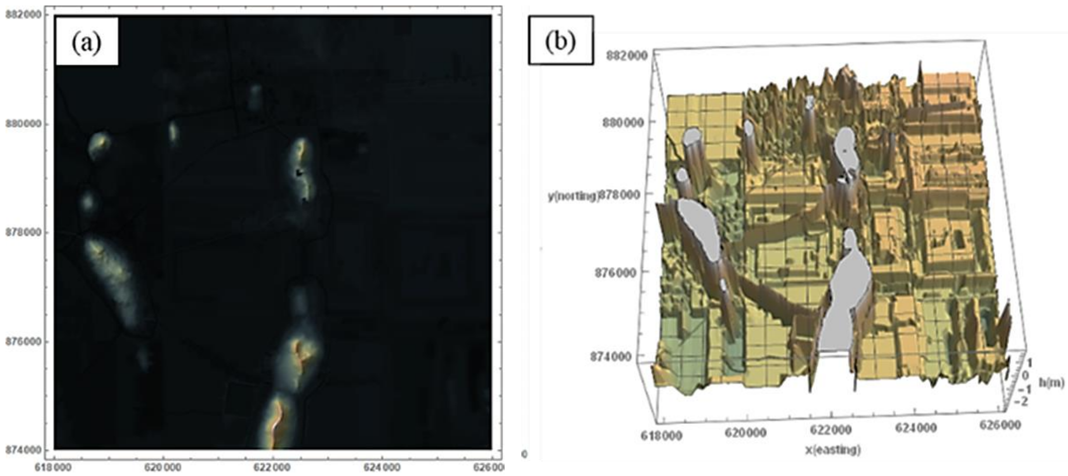

Figure 6. Results of the simulation process run with Mathematica, 618000–626000 E and 874000–882000 N. (a) 2D topographic image and (b) 3D topographic image

During field investigation, it was determined that the krajood forest area is particularly susceptible to fire outbreaks and requires significant fire prevention measures. The Krajood forest consists of three primary plots spanning 4,800, 2,320, and 8,400 acres. These areas serve as the primary source of income for approximately 90% of the Khuan Kreng swamp community, as confirmed by the Village Headman, Mr. Sanan Kongkaew, during an interview. Apart from the impact of drought, the occurrence of forest fires is also attributed to deliberate burning practices aimed at clearing the old krajood trees to cultivate new ones with aesthetically pleasing and slender stems consistent in size. However, maintaining a consistently moist soil surface through adequate water supply would significantly reduce the expansion and severity of forest fires in the area. The analysis of DEM data obtained from the Department of Land Development (classified into 20 levels by attitude) presented in Figure 8 and the Fire outbreak (blue dots) in the study area in Figure 9 provides a clear idea of the predominant area within the Khuan Kreng peat swamp forest, particularly the krajood forest surrounding Khuan Kreng hill. These areas are situated within the gray layer, indicating an elevation range of –1.12 to 0.10 meters, representing flooded or waterlogged conditions.

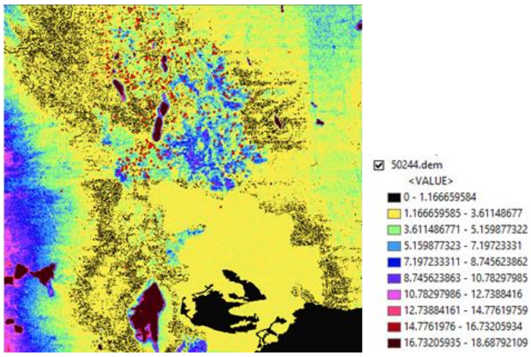

Figure 7. DEM (No.52044) data obtained from the Royal Survey Department
(classified into 20 levels by altitude)

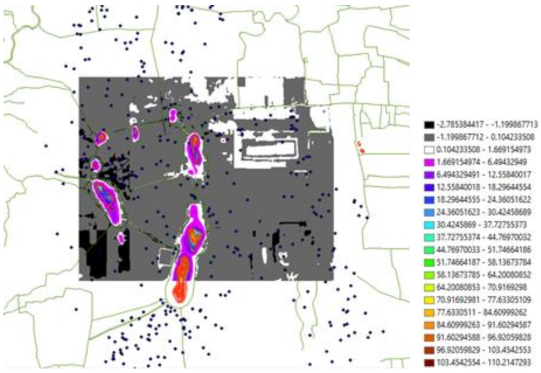

Figure 8. DEM data obtained from the Department of Land Development
(classified into 20 levels by attitude)

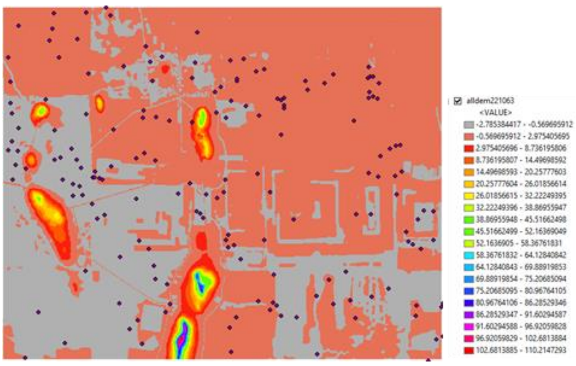

Figure 9. Fire outbreak (blue dots) in the study area (Khuan Kreng peat swamp forest)

In Figure 10, the blue dots represent the specific locations where wildfires broke out between 2010 and 2020. Based on the analysis of flow direction, it can be observed that the flow is divided into two main zones within the study area. Most of the flow is directed toward the southeast, eventually reaching the sea. Another portion of the flow moves toward the northeast, specifically into the Cha-Uat Phraek Muang canal at the top of the area. The water table in a peat swamp is primarily influenced by rainfall, as evaporation and water table outflow remain relatively constant. During the wet season (November–February), rainfall exceeds the combined effect of evaporation and water table runoff, resulting in the water table consistently remaining above the soil surface. These wet conditions are conducive to peat flow accumulation. However, during drier periods that last for weeks, such as in the dry months of the year, the water table in the swamp can drop below the soil surface [26].

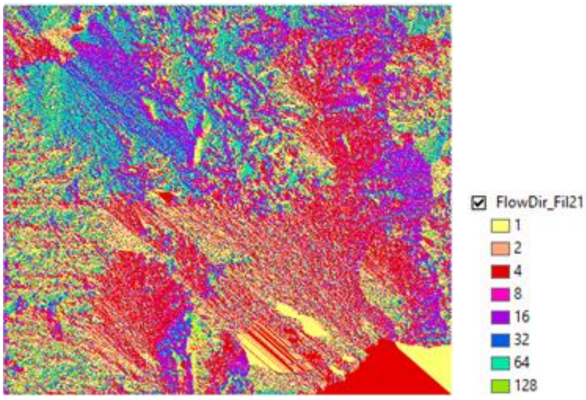

Figure 10. Flow direction model developed using DEM (No. 52044) data obtained from the Royal Survey Department, 610000–635000 E and 855000–885000 N

Figure 11(a) showed the flow accumulation of model based on No.52044 from the Royal Survey Department and Figure 11(b) stream order of the model and Figure 12 depict the flow direction, illustrating the northeast-to-southwest pattern observed from DEM analysis (No 50244). The surface and sub-surface runoff dynamics are closely influenced by the slopes and drainage networks in the watershed, with geomorphology playing a significant role in shaping the catchment area and travel times [27]. The flow direction derived from the DEM (scale: 1:4,000) data obtained from the Department of Land Development in the krajood forest was analyzed. It was observed that the area was excavated to form a square trench, as illustrated in Figure 12. The blue arrow indicates the location of a rectangular grid trench within the krajood forest. Additionally, the canal serves as a transportation route through the swamp, facilitating the villagers' transportation of krajood from the krajood forest situated among the three hills, namely Khuan Yao, Khuan Kreng, and Khuan Ching.

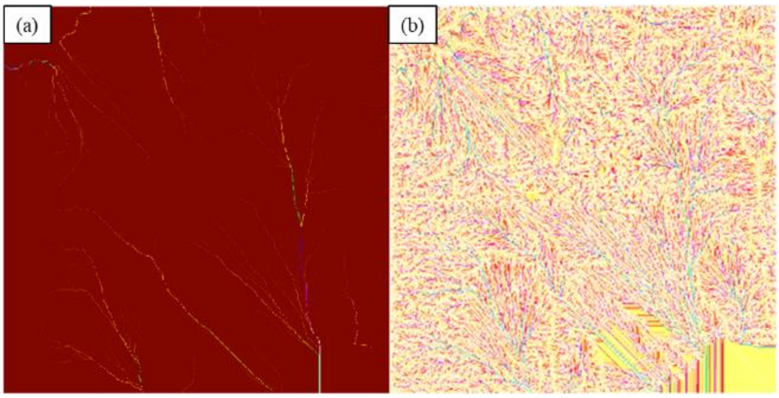

Figure 11. Model based on No.52044 from the Royal Survey Department, 610000–635000 E and 855000–885000 N (a) flow accumulation and (b) stream order

Figure 13(a) shows stream order using DEM data obtained from the Royal Survey Department (No.52044) and Figure 13(b) shows stream order using DEM data obtained from the Department of Land Development. it depicts the flow sequence of currents at DEM 50422 and highlights the location of the mainstream originating from the Nakhon Si Thammarat Mountain Range. These currents traverse various areas, ranging from stream order 1 to 7, including the Khuan Kreng Swamp Forest and its surrounding regions. Figure 14 shows the stream order studied based on the data from the Royal Survey Department No. 52044 (Figure 14(a) Stream order is greater than or equal to 4^{th} and Figure 14(b) stream order is greater than or equal to 5^{th}). Figure 15 illustrates the separation of the mainstream into two directions, stream order is greater than or equal to 4^{th} (Figure 15(a)) and stream order is greater than or equal to 5^{th} (Figure 15(b)).

Firstly, the stream flows from the northeast to the southwest, as depicted at the bottom of the figure, eventually reaching Thale Noi and Songkhla lake. Secondly, the stream flows from the southwest to the northeast, as shown at the top of the figure, and continues its course toward the Pak Phanang canal and the Gulf of Thailand. This division occurs due to the water originating from the Nakhon Si Thammarat Mountain range.

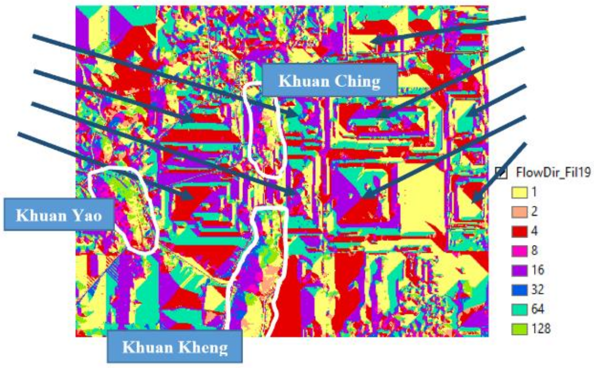

Figure 12. Flow direction model developed using DEM (618000–626000 E and 874000–882000 N)

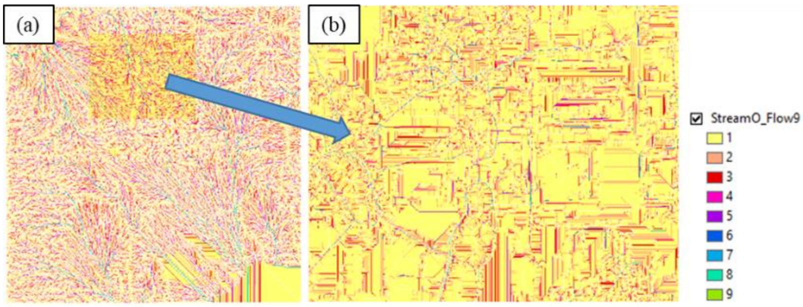

Figure 13. Stream order using DEM data (a) obtained from the Royal Survey Department (No.52044) and (b) obtained from the Department of Land Development

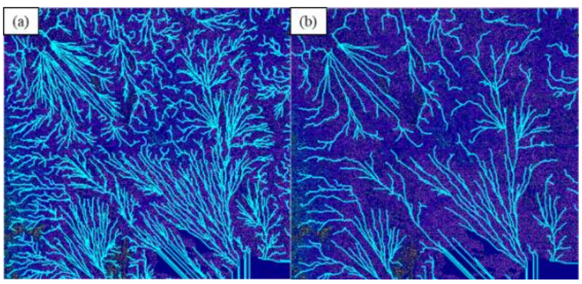

Figure 14. Stream order studied based on the data from the Royal Survey Department No. 52044 (a) Stream order is greater than or equal to 4^{th} and (b) Stream order is greater than or equal to 5^{th}

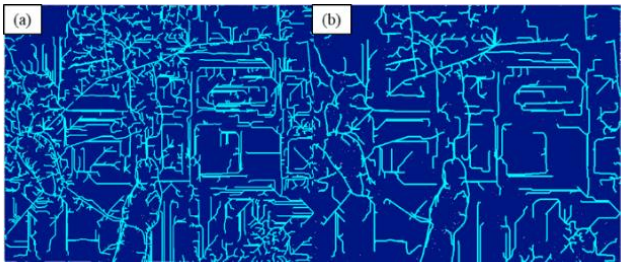

Figure 15. Stream order based on the data obtained from the Department of Land Development, 618000–626000 E and 874000–882000 N. (a) Stream order is greater than or equal to 4^{th} and (b) Stream order is greater than or equal to 5^{th}

The Khuan Kreng peat swamp forest faced a crisis due to drought. The water crisis could be partly attributed to the construction of a canal for drainage. The construction of the canal resulted in the drainage of water from the originally water-rich wetland forest, transforming it into a deprived swamp. Although the drained water could be utilized for agricultural purposes around the forested areas, it led to the degradation of the wetlands, resulting in the deterioration of the forest ecosystem. The water table in the peatlands significantly decreased during the dry season. This increased environmental hazards during the outbreak of the peatland fire, as it was difficult to control the fire outbreak. However, the maintenance of wet conditions in the peatlands can help reduce the occurrence of fires. Therefore, expediting the replenishment of water in the swamp becomes imperative by constructing basins that can store water and serve as a water source for extinguishing forest fires. Field observation studies conducted in various swamps have revealed that the water table levels decrease across the entire swamp by varying levels. In peat swamps, the water table can reach a maximum of 0.58 meters near the periphery of a peat dome, exhibiting differences between the dry and wet seasons [28]. The central region of the swamp shows a slightly smaller seasonal fluctuation of approximately 0.45 meters. Comparatively, the periphery of the swamp, which has steeper slopes, exhibits a deeper water table compared to the flatter central area [29]. Geomorphometry plays a crucial role in understanding the behavior of natural resources within a watershed. Mathematical methods are used, and terrestrial surface data are processed for analysis. Geomorphometry provides insights into the water drainage and flow characteristics of a given area [30], [31]. DEM 50244 represents a watershed area located on the southeastern coast, specifically part 4 of the 22 watersheds found in Thailand [32]. The Pak Phanang River basin, situated in the southern region of Nakhon Si Thammarat Province, falls within this watershed area. The Pak Phanang River basin encompasses an extensive area, including 10 districts of the Nakhon Si Thammarat province, two districts of the Phatthalung province, and one district of the Songkhla province, resulting in a total watershed area of approximately 3,100 km^2 or 775,000 acres [33]. The Nakhon Si Thammarat Mountain Range serves as the source of the Pak Phanang River basin, running parallel to the coastline. The topography within the basin can be classified into three types. The upper part presents a steep slope, followed by wavy terrain in the middle and a gentle slope toward the Pak Phanang River on the eastern side. The main river flows through the central region of the basin, characterized by a pan-like morphology, while a large swamp forest dominates the central watershed area. The krajood forest in the Kreng Sub-district is situated within a small basin between Khuan Kreng, Khuan Yao, and Khuan Ching, located within the Pak Phanang River basin as shown in Figure 16(a), DEM data obtained from the Royal Survey Department (No.52044) and Figure 16(b), DEM data obtained from the Department of Land Development.

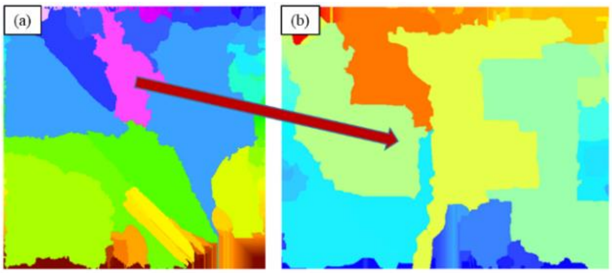

Figure 16. Details of the basin (a) DEM data obtained from the Royal Survey Department (No.52044) and (b) DEM data obtained from the Department of Land Development

When wildfires occur in swamp forests, water shortage is often experienced, exacerbating the situation. The dry peat acts as fuel for the fires, contributing to their intensity and spread. Fires that affect swamp forests possess unique characteristics. They are semi-ground fires that burn in two dimensions, both horizontally and vertically. These peat fires can break out repeatedly, making it challenging to ascertain the full extent of the fire due to the dense smoke. In some cases, fires may not be visible on the surface as they burn unpredictably beneath the ground. Consequently, extinguishing these fires becomes a daunting task. It may take several months and significant financial resources to control and suppress the fires effectively [34]. Several measures can be implemented to maintain the water table at an appropriate level: i) Installation of a water table measuring device within the swamp forest and the retention of water in the peat forest when the peat dries out (when the water table is less than –30 cm) by pumping water back from the main canal surrounding the reserved forest. For instance, the Cha-Uat Phraek Mueang canal can be used to replenish the Khuan Kreng peat swamp forest; ii) Installation of an underground barrier at the water drainage point; iii) Deeper dredging of the internal canals (the small canals in the swamp) to enhance water storage capacity in the swamp forest; and iv) Avoid deepening the main canal around the swamp area, such as the Cha-Uat Phraek Mueang canal. The excessive depth of the Cha-Uat Phraek Mueang canal has led to a decline in water levels within the swamp forest. Furthermore, the increased water volume in the canal has resulted in the expansion of palm plantations surrounding the forests and encroachment on conserved forests for agricultural purposes. A simple cement partition was constructed to contain water and retain the underground water level, intending to reduce fire-prone areas. Measures were taken based on an initial study report and landowner recommendations by *Perbadanan Kemajuan Pertanian Selangor* (PKPS) in Selangor, Malaysia. These measures aimed to protect all canals in the area and raise groundwater levels through the installation of simple water control structures at different sections of the canal. This was accomplished through a partnership between private sector stakeholders and non-governmental organizations, with the objective of mitigating fire threats in peat areas by identifying fire prevention issues and constructing barrier structures to maintain a high-water table. This facilitated the provision of nourishment to the surface during drought conditions, leading to a reduction in the occurrence of wildfires. The fire risk decreased as the water table subsequently increased. The peat soil in that area was consistently moist. Following the flooding of the entire area with the water raised in the water table, the threats of fires were significantly diminished, and the adjacent Forest Reserve was also protected. Consequently, maintaining water levels emerged as the most effective preventive measure against severe peatland fires.

3. CONCLUSION

The Mathematica program was utilized to design the 3D topographical model, resulting in results that accurately represented the realistic and geographic terrain. In the ArcGIS case study, the development of river networks flowing from the highlands to the Khuan Kreng swamp forest pool was demonstrated by the hydrographic models. A stream order was exhibited by the krajood forest, with limited flow accumulation observed in the first and second streams while maintaining continuous flow. Throughout the forest, a square canal was excavated, serving as a designated waterway to facilitate the transportation of krajood out of the krajood forest. The drainage system outside the area could be utilized for agricultural purposes in the forested regions, with the Cha-Uat Phraek Mueang canal traversing the reserve forest. The wetlands of the swamp are effectively safeguarded from degradation by this approach. The subsequent task involved mapping the areas to establish the underground water lines and constructing water gates to facilitate water storage within the swamp.

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