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A Graph Theory Approach for Spatial Data-Based Surface Water Flow Modeling

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Abstract

A comprehensive comprehension of the flow of water from high to low locations is a prerequisite for effective management of water resources. Since there are still many obstacles to overcome in order to solve flow issues and provide more realistic modeling, such as the migration of water flow from high to low places, surface water flow modeling has proven to be an intriguing area of research. This study suggests a novel method for modeling surface water flow using the Single Flow Direction (SFD) or D8 algorithm, which blends graph theory with geographical data. This study's primary goal is to give a thorough explanation of how water moves from higher to lower elevations. Because each pixel that the water flow traverses will be connected by a line, creating a clearly defined water flow path, test results demonstrate that the graph theory approach is useful for producing more comprehensive flow output. This strategy has the advantage of encouraging the future development of more advanced modeling tools and useful applications. It also significantly advances our understanding of hydrology and facilitates the management of water resources more effectively. As a result, the study's findings could significantly advance water flow modeling and simulation due to their capacity to generate accurate water flow modeling. It is anticipated that this research will be expanded by including flow divergence in the surface water flow modeling issue.

Keywords: *Water Flow Modeling, D8 Algorithm, Graph, Spatial Data*

Abstrak

Pemahaman yang baik mengenai aliran air dari lokasi tinggi ke lokasi rendah merupakan prasyarat untuk pengelolaan sumber daya air yang efektif. Karena masih banyak kendala yang harus diatasi untuk menyelesaikan masalah aliran dan memberikan pemodelan yang lebih realistis, seperti adanya perpindahan aliran air dari tempat yang tinggi ke tempat yang rendah, sehingga pemodelan aliran air permukaan menjadi bidang penelitian yang menarik. Penelitian ini menyarankan metode baru untuk memodelkan aliran air permukaan dengan menggunakan algoritma Single Flow Direction (SFD) atau D8, yang memadukan teori graf dengan data geografis. Tujuan utama dari penelitian ini adalah untuk *memberikan penjelasan menyeluruh tentang bagaimana air bergerak dari tempat yang lebih tinggi ke tempat yang lebih rendah. Karena setiap piksel yang dilalui aliran air akan dihubungkan dengan sebuah garis, menciptakan jalur aliran air yang jelas, hasil uji coba menunjukkan bahwa pendekatan teori graf berguna untuk menghasilkan keluaran aliran yang lebih komprehensif. Strategi ini memiliki keuntungan untuk mendorong pengembangan alat pemodelan yang lebih canggih di masa depan dan aplikasi yang berguna. Strategi ini juga secara signifikan memajukan pemahaman kita tentang hidrologi dan memfasilitasi pengelolaan sumber daya air secara lebih efektif. Sebagai hasilnya, temuan penelitian ini dapat secara signifikan mendorong pengembangan pemodelan dan simulasi aliran air karena kemampuannya untuk menghasilkan pemodelan aliran air yang akurat. Diharapkan penelitian ini akan diperluas dengan memasukkan divergensi aliran dalam masalah pemodelan aliran air permukaan.*

Kata Kunci: *Pemodelan Aliran Air, Algoritma D8, Graf, Data Spasial*

1. INTRODUCTION

Observing the direction of surface water flow is a common practice nowadays, with numerous scholars extensively researching the issue to offer comprehensive and accurate findings. In the study conducted in this paper, we found many methods that have been introduced and have advantages and disadvantages. The D8 algorithm is commonly employed in water flow modelling, particularly for addressing single- or multiple-flow direction issues [1].

A thorough understanding of surface water flow is essential to water resources management. This includes water movement through rivers, sewers, and the various processes involved in real-life water movement. Surface water flow modeling is a critical element of water resources management, land use planning, flood risk mitigation, and understanding the impacts of climate change [2] [3]. Understanding surface water flow patterns is critical to efficient water resource management, flood mitigation, environmental conservation, and sustainable regional development planning.

Spatial data can be used to model surface water flow, which is the primary source of information for water flow methods such as the D8 (eight directions) algorithm [4], which will be used in this research. Spatial data is geographic information that describes objects on Earth with geographic references [5] [6]. This spatial data is usually based on maps that contain interpretations and projections of all phenomena on Earth, including natural and artificial phenomena [7] [8]. Initially, all data and information on maps represented objects on the Earth's surface. Modeling the water flow on the ground surface is challenging for academics and practitioners because they try to get results close to the actual situation.

One of the problems in surface water flow modeling is the presence of poorly defined flows [9] because the visualization of direction is usually only in the form of arrows and colors, so if there are different flow directions and branching in one area, it will result in poorly defined flows. To overcome this challenge, an approach that combines graph theory with spatial data has emerged as an innovative tool for application-based surface water flow modeling. Using graph theory, we can represent the water flow network as a graph, where the vertices and edges reflect geographical elements such as rivers, river confluences, and water distribution. This approach allows for a more in-depth analysis of flow patterns, identification of primary water sources, and modeling of water flow dynamics under various conditions. Therefore, this research aims to investigate and apply the graph theory approach in spatial data-based surface water flow modeling in the hope of providing a better understanding of water resources management, environmental management, and adaptation to climate change.

2. RESEARCH METHOD

2.1 Modeling

Modeling simplifies or represents a complex system into a more straightforward form or mathematical model. The main goal of modeling is to understand, analyze, predict, or simulate the system's behavior without facing the full complexity of the original system [10] [11]. Modeling can be applied in various fields of science, including natural sciences, social sciences, engineering, economics, and many more.

2.2 Surface Water Flow

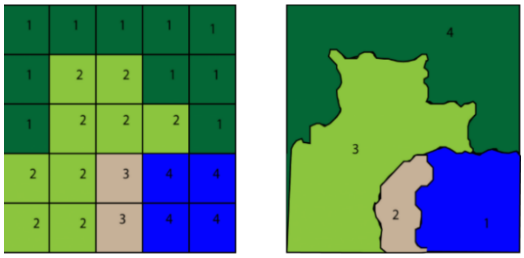
Surface water flow is an essential component of the hydrological cycle, which occurs when rainfall or water from other sources flows over the land surface carrying soil particles with it. This phenomenon significantly impacts the environmental context and human daily life [12]. One crucial aspect of understanding surface water flow is the ability to predict flow direction. This ability has a significant impact on various aspects of people's lives.

First, modeling that can predict the direction of surface water flow is a precious source of information for society. This information can be used to identify areas vulnerable to flooding or other problems related to surface water flow. With this information, communities can take appropriate preventive steps, such as building drainage channels or efficient flood control systems. In addition, a good understanding of the direction of water flow can also be used in sustainable urban development planning, ensuring that urban structures and infrastructure are built to consider surface water flows properly.

2.3 Spatial Data

Spatial data is information geographically related to objects on the Earth's surface [13]. Information in spatial data is generally presented through maps, which depict representations and projections of various phenomena found on Earth, including natural and artificial phenomena. Initially, all data and information on the map represented objects on the Earth's surface [14] [15].

Over time, technological developments have made maps not only represent objects on the Earth's surface but also objects above the surface (in the air) and below the Earth's surface [16]. Spatial data has two types, namely vector type and raster type. The vector data model displays, places, and stores spatial data using points, lines, curves, or polygons and their associated attributes. At the same time, the raster data model is used to display and store spatial data using a matrix structure or pixels that form a grid. The choice between these two spatial data models depends on the objectives and needs to be achieved.



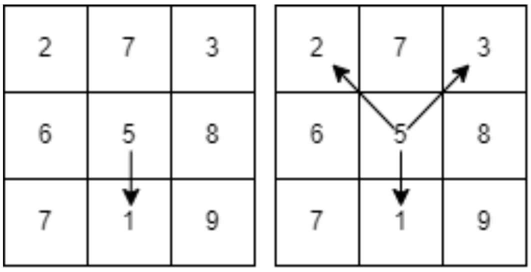
Picture 1. The difference between raster (left) and vector (right) data
[Source: www.gispedia.com]

The spatial resolution or size of pixels on the earth's surface strongly influences the accuracy of spatial data models. Raster data models have spatial entities stored in several functional layers representing maps [7]. In a raster data model, matrices can be organized based on local coordinates: columns (x) and rows (y). In addition, in the pixel coordinate system of a computer monitor, the origin of the raster coordinate system is located in the upper left corner. Therefore, x values increase downwards, and y values increase to the right. This local coordinate system can also be changed so that the coordinate origin is in the lower left corner, with x values increasing upwards and y values increasing as they move to the right. In the vector data model, the coordinates used are two-dimensional cartesian coordinates (x, y) [7]. This research will focus on surface water flow modeling using the representation of elevation data obtained in spatial data from the National Digital Elevation (DEMNAS).

Digital Elevation Model (DEM) is a digital data created based on elevation data of a land surface presented in a square grid. The value of each grid is a representation of each pixel on the grid [17]. DEM is used for various purposes, one of which is for making river networks as found in mapping applications, including ArcGIS, QGIS, and other mapping software.

2.4 Surface Water Flow

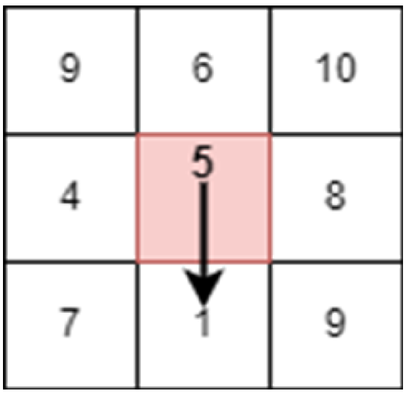
Water flow direction algorithms can be classified into two primary groups based on water flow. There are two flow direction methods: single flow direction (SFD) and multiple flow direction (MFD) [4], [12]. Moreover, Picture 2 depicts the distinction between SFD and MFD.



Picture 2. SFD Concept (left) and MFD Concept (right)
[Source: Private]

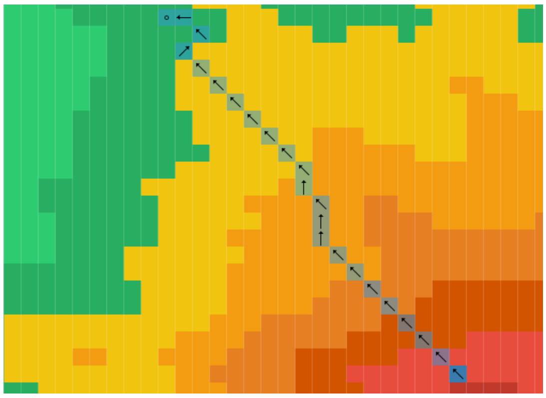
Figure 2 is a visualization of the working concept of the SFD (Single Flow Direction) and MFD (Multiple Flow Direction) methods. In the SFD method, the value of the origin pixel is compared with all neighboring pixels and the smallest one is selected as the flow direction to be used next. The MFD method also compares the origin pixel value with all neighboring pixels. However, in this case, all pixel values smaller than the origin pixel value are considered flow directions [18]. This allows more than one flow to be formed in the MFD method. In this research, the author focuses on applying the SFD method.

The D8 algorithm is an implementation of the SFD principle. It involves 8 neighbors or comparison pixels in a 3x3 window [12]. The angle between one direction and another is about 45 degrees, which means the flow is limited to 8 specific flow directions. You can see a conceptual overview of the D8 algorithm in Figure 3.



Picture 3. Concept of the D8 algorithm
[Source: Private]

By applying the workings of the D8 algorithm, visualization results are obtained as in the following image.



Picture 4. D8 visualization results without using graphs
[Source: Private]

Figure 4 is the result of flow visualization using the D8 algorithm concept without using graphs, wherein the image shows that the flow is produced only in the form of arrows depicting the flow's direction, indicating that the pixel or area is being traversed by water. However, this can still be improved by using graphs to connect flow directions so that a network is formed that is connected.

2.5 Graph Implementation of the D8 Algorithm

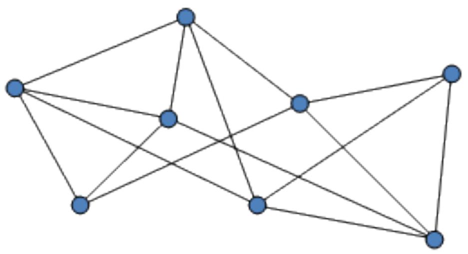
Graph theory is the examination of graphs, which are mathematical constructs utilized to represent the connections between items in pairs. In this context, graphs are composed of vertices (also known as nodes or vertices) interconnected by edges (also referred to as links or edges). There are two generally used types of graphs: undirected graphs, where the edges join two vertices symmetrically, and directed graphs, where the edges connect two vertices asymmetrically [19]. Graphs are a fundamental focus of investigation in the field of discrete mathematics.

In a limited but very general sense of the term, a graph is an ordered pair *G = (V, E)* consisting of:

1) *V, a set of vertices (also called vertices or vertices);*
2) *E, a set of edges (also called links or lines);*
3) *Φ: E → {{x, y} | x, y Ɛ V and x ≠ y}, event functions that map each edge to an*

unordered pair of vertices (i.e., an edge is associated with two different vertices).

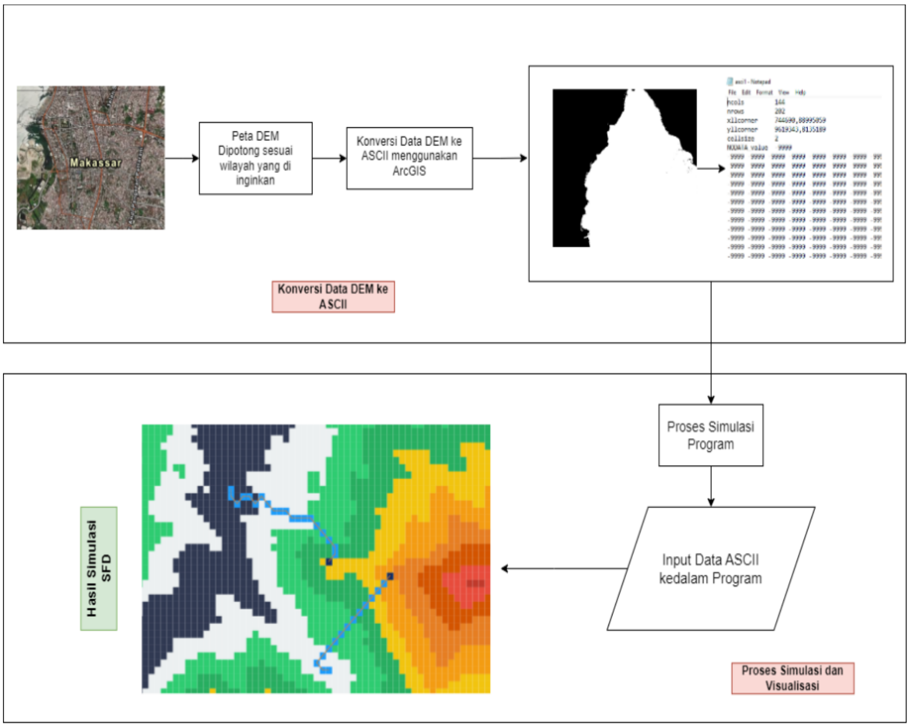
This type of object can be called an undirected multigraph to avoid ambiguity.



Picture 5. Example of graph implementation
[Source: Private]

3. RESULT AND CONCLUSION

This research was tested on digital elevation model (DEM) maps where the data was taken from DEMNAS (Digital Elevation Model Nasional) which can be accessed via https://tanahair.indonesia.go.id [18] by taking several digital maps which will be used as samples in testing using an application that we created by applying the D8 algorithm for finding flow directions and graph concepts. The DEMNAS data used is raster data which is then converted into ASCII (numeric) data. To solve the problem in this paper, the solution system workflow scheme is described as follows.



Picture 6. System workflow
[Source: Private]

Figure 6 is the system workflow to solve the water flow direction problem. The image explains how the system you want to create works, starting from the stages of data collection, data cropping, and data conversion to the simulation process and flow visualization.

3.1 Graph Implementation in SFD

The data utilized in this instance is a digital map that was first in raster format and subsequently transformed into ASCII numbers. This data has three-dimensional coordinate points (x, y, and z) where x and y represent positional coordinates. On the other hand, z represents the vertical measurement of the ground surface for each picture map, indicated by a coordinate point (x, y), which also includes a corresponding height value (z).

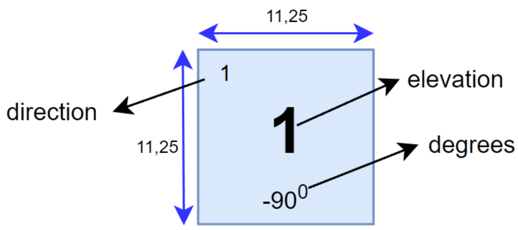
The flow direction algorithm ascertains the orientation of water movement from the initial point to the subsequent location, adhering to the principle of water descending from a higher to a lower elevation. The single flow direction technique will be integrated with a graph that simulates the water flow for each iteration. This procedure is illustrated in the accompanying graphic, demonstrating how the flow search process operates.

	Step 0								Step 3								Step n						
elevasi	20	10	9	14	11	20	20		20	10	9	14	11	20	20		20	10	9	14	11	20	20
	14	20	16	8	20	9	9		14	20	16	8	20	9	9		14	20	16	8	20	9	9
	13	14	10	7	14	13	13		13	14	10	7	14	13	13		13	14	10	7	14	13	13
	11	16	12	20	6	12	12		11	16	12	20	6	12	12		11	16	12	20	6	12	12
	18	10	19	18	5	13	13		18	10	19	18	5	13	13		18	10	19	18	5	13	13
	10	12	16	11	4	15	15		10	12	16	11	4	15	15		10	12	16	11	4	15	15
	16	19	20	2	13	20	20		16	19	20	2	13	20	20		16	19	20	2	13	20	20
	(a)								(b)								(c)						
status	-1	1	-1	-1	-1	-1	-1		-1	1	1	-1	-1	-1	-1		-1	1	1	-1	-1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	1	-1	-1	-1		-1	-1	-1	1	-1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	1	-1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	1	-1	-1
	-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1	-1	-1		-1	-1	-1	1	-1	-1	-1
	(a.1)								(b.1)								(c.1)						

Picture 7. The process updates the values at each iteration
[Source: Private]

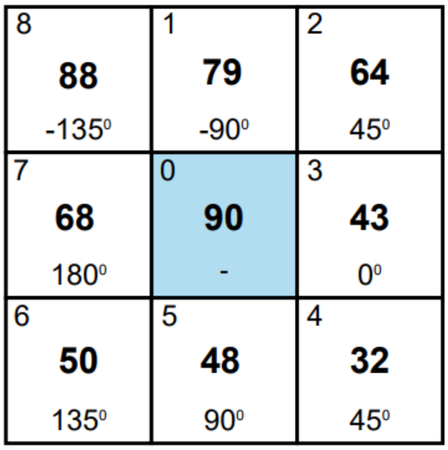
In Figure 7 above is the value update process, where the initial value is set to value = -1 (as in Figure 7 (a.1)) for all pixels; this is done to provide a marker that the pixel has never been visited so it does not have flow direction. In picture 7 above, you can see dark blue and light blue colors. The dark blue hue signifies the initial pixel chosen. In contrast, the light blue hue signifies the pixels traversed during the search for flow direction, specifically in the context of surface water flow. Figure 7 illustrates the initiation of water movement from a pixel with a height of 10, which serves as the pixel origin. It will continually search for the flow direction for the origin pixel point by comparing the values of neighboring pixels in the review space. Each pixel selected to be streamed must meet the requirements; namely, the origin pixel must be more significant (>) than the review pixel. The status must be equal = -1; however, if there are two or more review pixel values that are less than (<) the origin pixel, then it will be selected the smallest pixel value in the review space reviewed by each algorithm. However, if two or more viewing pixel values have the same height value (=) as the other viewing pixels, then the flow determination is determined by taking the first direction in the search.

For the case in Figure 3.2, it can be seen that the pixel with a value of 10 will flow to the smallest pixel value, namely 9, and then flow to the pixel with a value of 8. This will be done until it reaches the lowest pixel value, namely 2 in red, known as a sink. (pixels that have no direction of flow). The thing that needs to be paid attention to with each movement is that for each movement, the pixel data will be updated from a value of -1 to a value of 1 to distinguish between pixels that have been traversed and that have not been traversed. The type of data used in this research is raster data or a pixel grid, which represents topographic images of the earth's surface. The pixel size obtained for each area is 11.25 m2.



Picture 8. Pixel size in DEMNAS data
[Source: Private]

The D8 algorithm is a computational method with eight distinct flow directions within it designated review region. This algorithm identifies the minimum value among the pixel values of the surrounding area [20]. If a pixel value or height is lower than the original pixel, it is chosen as the pathway via which the water will flow [21]. The working scheme of the D8 algorithm can be seen in the following image.



Picture 9. D8 algorithm flow scheme
[Source: Private]

The resolution to the issue of water flow direction with graphs is primarily expressed as a permutation of a sequence of pixel indices corresponding to preset nodes. To build a symmetric problem, we generate n nodes referred to as origin pixels (X_{op}). For each direction, there exists a single arc linking every pair of nodes (pixels), also known as review pixels ($X_{neighbor}$). The example X_{op} is defined as {0}, where the direction decision variable is determined by the number of viewing pixels, namely $X_{neighbor}$ (1, 2, ..., n), and is based on the smallest value of the viewing pixel ($X_{neighbor}$). The formula [7] demonstrates the application of mathematics.

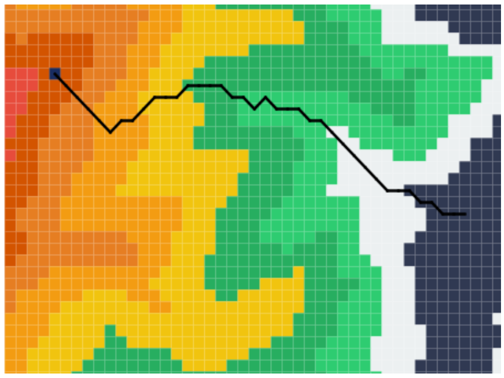
$$array = [m] \ x \ [n]$$
$$flowdirection = (X_{op} \rightarrow X_{neighbor}, V_{pixels})$$
$$V_{pixels} = \{V1, V2, V3, \ldots, Vn\}, E_{conn} \subseteq \{(V_i, V_j) \mid i \neq j\}$$
$$C: V_{pixels} \ x \ V_{pixels} \rightarrow R, C = (C_{ij})n \ x \ n$$

In this situation, variable C is referred to as the cost matrix. Meanwhile, C_{ij} denotes the expense incurred when travelling from city i to city j. This expedition aims to locate the minimum pixel value in the DEM data. Alternatively, it is expressed in the following manner:

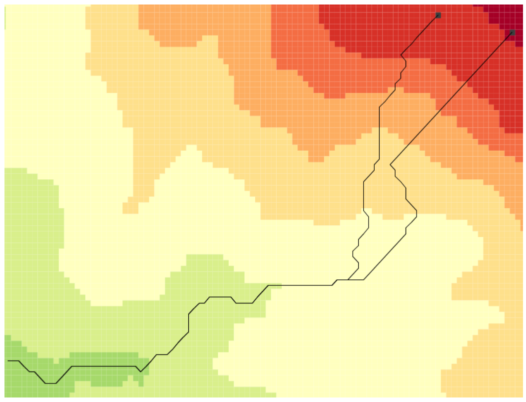
$$Flowdirection = X_{op} < X_{neighbor} \quad (2)$$

2.5 Results of program implementation

This study also utilized surface water flow by constructing a water flow direction algorithm. The testing of this application was conducted using a dataset acquired from DEMNAS. Figures 10 and 11 display the results of the application testing.



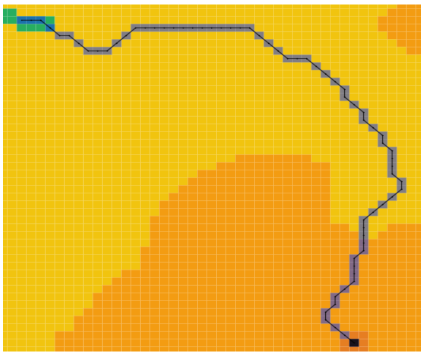
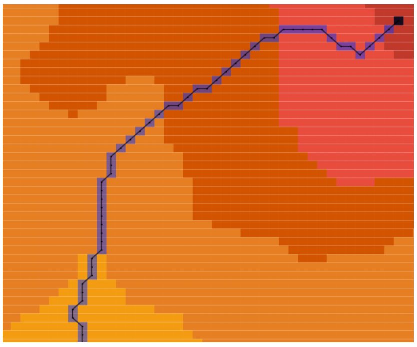
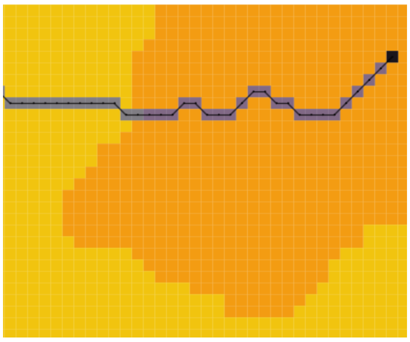
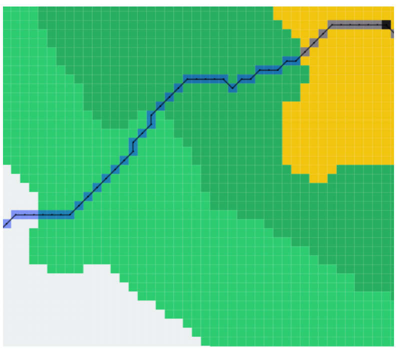
Picture 10. Flow visualization results of the D8 algorithm
[Source: Private]

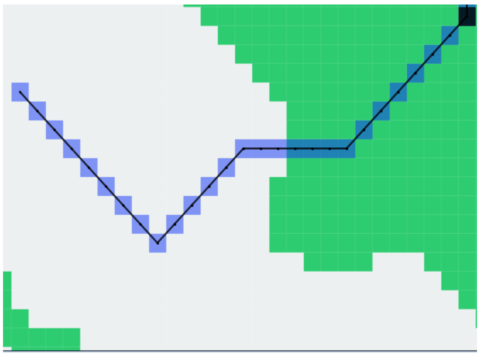
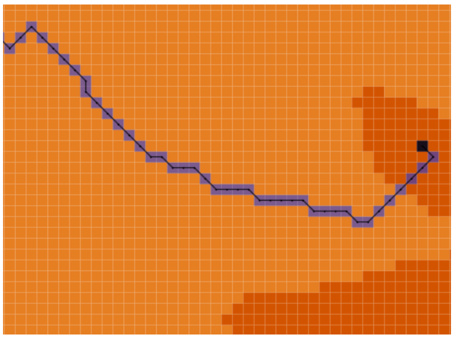
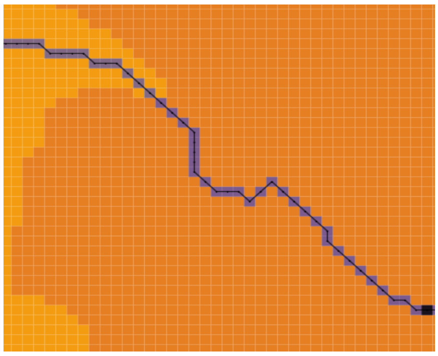
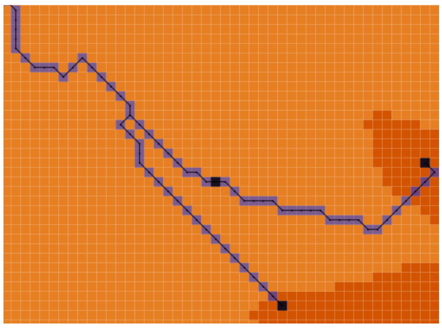


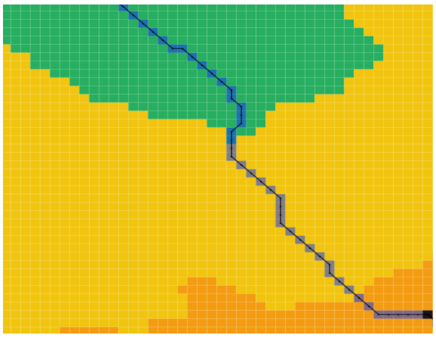
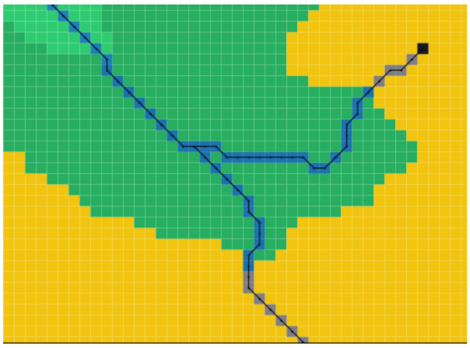
Picture 11. Flow visualization results of the D8 algorithm with two flows
[Source: Private]

The test results obtained using the application developed in this study gave satisfactory results. The D8 method determines the flow direction for movement from the first pixel to the next pixel with a lower value. The test shows that the graph theory approach can provide a more detailed flow output. This success is due to the relationship between each pixel that the water passes through via lines, forming a clear flow path. The test results in two different areas, specifically mountains (Figure 10) and hillsides (Figure 11), are depicted in Figures 10 and 11 respectively. In addition, tests were also conducted by taking 20 sample areas by comparing the actual flow output with the flow generated from the graph implementation in the visualization of surface water flow modeling which can be seen in Table 1 below.

Table 1: Akurasi Aliran
[Source: private]

No	Comparison of actual flow results (blue color) and graph implementation (black line)	Validation
1		Valid
2		Valid
3		Valid
4		Valid

5		Valid
6		Valid
7		Valid
8		Valid

9		Valid
10		Valid

The test results in Table 1 demonstrate that the graph theory method can produce an output for flow movement that is precisely the same as the actual flow. On the other hand, the graph implementation yields more precise results for the pixels that the water passes through. This achievement is because a clear flow path is formed by the relationships formed between each pixel, such that the water flows through connected lines. This method produces a visual representation that is more detailed and makes it possible to identify water movement accurately from pixel to pixel. Thus, graph theory's capacity to create well-structured flow routes significantly increases knowledge of surface water flow patterns and dynamics.

4. CONCLUSION

The test findings obtained in this study provided excellent results. The program utilizes the D8 algorithm and graph theory to simulate the movement and spread of water on a three-dimensional surface where x and y are pixel points, and z is the elevation represented by color. The D8 method determines the flow direction for movement from the first pixel to the next pixel with a lower value. Test results in two different geographical areas, specifically mountains (Figure 10) and hillsides (Figure 11), are represented by Figures 10 and 11, respectively.

Based on the results of the experiment (Table 1), which compares the direction of the flow generated by the graph with the actual flow, a more thorough surface water flow modeling output has been produced by integrating graph theory and geographic data through the concept of Single Flow Direction (SFD). The success of applying graphs to surface water flow visualization allows the flow route to be well-defined along the line connections between the pixels traversed by the water flow. More thorough modeling significantly improves our understanding of water flow patterns and dynamics within a given geographic area. In addition, the possibility of creating more sophisticated modeling tools and practical applications provides hope for advancing hydrological methodologies by adding several parameters that affect water flow. The results of this study can serve as a basis for improving hydrological modeling and simulation in the future.

STATEMENT OF APPRECIATION

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