Lecture Notes
in Geoinformation and Cartography

LNG&C

Alias Abdul-Rahman *Editor*

Advances in 3D Geoinformation

Springer

Alias Abdul-Rahman
Editor

Advances in 3D Geoinformation

Springer

Editor
Alias Abdul-Rahman
Department of Geoinformation
Universiti Teknologi Malaysia
Johor Bahru
Malaysia

ISSN 1863-2246 ISSN 1863-2351 (electronic)
Lecture Notes in Geoinformation and Cartography
ISBN 978-3-319-25689-4 ISBN 978-3-319-25691-7 (eBook)
DOI 10.1007/978-3-319-25691-7

Library of Congress Control Number: 2016952002

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

The Hierarchical Three-Dimensional (3D) Dynamic Water Infiltration on Multi-layers of Soil According to Voronoi Sequence Nodes Based on the Three-Dimensional Triangular Irregular Network (3D TIN)

Siti Nurbaidzuri Reli, Izham Mohamad Yusoff, Habibah Lateh and Uznir Ujang

Abstract Understanding soil water infiltration movement has been birthed from extensive interest and concern in the last few decades. The arrangement of particles (i.e. structures and sizes) and the interaction between both the soil and soil water have a profound effect on the soil water infiltration. The challenging task in the soil fluid modelling is the indeterminate spatial extent that has no specific boundaries and the fact that it is difficult to sense. Plenty of investigations and studies have been conducted to measure the water movement. However, less focus has been given on the movement of the dynamic soil water infiltration. This paper will focus on modelling the three-dimensional (3D) soil water infiltrations that flow downward due to the gravitational factor and gradient pressure. The 3D hierarchical soil water infiltration model proposes the integration of techniques which includes the Tree-map to isolate the depth of the soil that acts as a route of the soil water flow from the surface of the terrain to the subsurface flow. Moreover, the 3D Gosper curve is used to represent the soil water flow pattern that is based on the law of gravity and Horton equation, which control the flow of the soil water in the model. The curves that consist of a series of nodes adopt the Three-Dimensional Triangular Irregular Network (3D TIN) which creates a network of flow direction that allows the water to pass through the nodes according to a predetermined sequence. The study area has an average of 8.5 mm total rain and −5 m water level. The soil is divided into a few layers to represent the flow of the soil water according to the sequence of nodes. The soil depth (40, 80, 120, 160 and 200 cm) isolation in the

S.N. Reli (✉) · I.M. Yusoff · H. Lateh
School of Distance Education, Universiti Sains Malaysia (USM),
11700 Minden, Pulau-Pinang, Malaysia
e-mail: baidzuri88@gmail.com

U. Ujang
Department of Geoinformatics, Faculty of Geoinformation Science & Engineering,
Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, Malaysia

A. Abdul-Rahman (ed.), *Advances in 3D Geoinformation*,
Lecture Notes in Geoinformation and Cartography,
DOI 10.1007/978-3-319-25691-7_25

form of Voronoi-shaped polygon nodes allows the soil water to flow down where the depth is chosen based on the soil wetting range of the subsurface soil.

Keywords Soil water · Infiltration · Three-Dimensional (3D) · Fluid modelling

1 Introduction

The study on the streamflow has been gaining much attention nowadays as the knowledge is essential in studies related to hydrology, geology, environment and hazard management. The research on streamflow includes the studies that focus on the flow of the stream, stream flow direction, stream management and also the process that generates stream. The process that generates stream can be divided into the Infiltration Excess Overland Flow (IEOF), Saturation Excess Overland Flow (SEOF), Shallow Subsurface Flow (SSF), Direct Precipitation onto Stream Surface (DPOSS), percolation, evapotranspiration and ground water (GW). Infiltration happens in most of the processes of stream generation and it is important in hydrological studies where the process involves several mathematical equations and formulas.

Among the earliest studies on water movement is by Barnes and Allison (1988) who traced the water movement in the saturated zones using stable isotopes of hydrogen and oxygen. In 1941, Hursh and Brater came out with the studies on the role of the subsurface storm flow where they showed the stream hydrograph response to storm rainfall that was composed of two main components namely the channel precipitation and subsurface stormflow (Hursh and Brater 1941). The study on streamflow was continued by Hoover and Hursh (1943) and they showed that the soil depth, topography, and hydrologic characteristics were associated with different elevations that were influenced by peak discharge. Dunne and Black (1970) on the other hand, pointed out that the most important transition between the flow systems seems to be at the soil surface, when water is released from the extreme damping effect of the subsurface flow. There are several methods used to detect the movement of water such as by using stable-isotope and chloride tracers (Newman et al. 1997), hydrogen and oxygen isotopes, chloride, and chlorine-36 (Liu et al. 1995) and gravimetric sampling (Nielsen 1964).

The use of the three-dimension (3D) in hydrology has received increasing attention in the present studies but only for the visualization purpose. However, it is very difficult to see the focus of study that uses the temporal data to create a 3D model used to represent the soil water infiltration process that happens underneath the soil. The previous studies on the soil water movement and 3D model are mostly carried out separately. Thus, this study will propose for the advancement using both the graft and mathematical representation models of the soil water infiltration that used the 3D model to show the dynamic movement of the soil water through a static pattern of sequence that represents spaces in soil. The nature of the soil water which is in the liquid state, has resulted in the decision on using the 3D dynamic fluid flow model according to the voronoi sequence grid nodes hierarchically based on the multi-layers of the soil. The soil water that flows within the soil particles requires further research, particularly on the suitability of these data models to cater for the acquired 3D soil water movement. This research is not only focusing on the visualization but it also translates and converts the temporal data of rainfall and dynamic data of soil water flow into the 3D model. The natural process of the soil water flow requires the 3D model because the soil water not only moves downward but also horizontally in any direction which depends on the soil water potential. Static objects can be represented and analyzed in 2 Dimension (2D). However, the dynamic nature of the soil water is not suitable to be represented in 2D because the soil water flow constantly needs the depth information (z). In addition, the geometric representation of soil which involves volume of water requires 3D representation. The method used in this study is explained in Sect. 3.

The reviews on the role of the GIS in soil water infiltration studies, the advancement of 2D into 3D soil water movement and the practical relationship between the intended 3D modelling and the dynamic water infiltration that show the contribution of the 3D GIS to the studies related to soil water movement are discussed in Sect. 2. Meanwhile, the methodology part (Sect. 3) will discuss and explain the relevance of the chosen methods for the development of the 3D model. The tree-map is used to provide a hierarchy to the depth of the soil and tree algorithm shows how the isolation is done. The 3D Gosper curve is chosen to represent the soil water flow pattern that best suits the direction of the soil water, and the infiltration and volume of soil water depend on the Horton equation.

2 Literature Review

This section describes the related issues and information on the role of the GIS in soil water infiltration studies which show the needs to execute the 3D modelling for soil water infiltration movement with the help of the advancement of 2D, into 3D.

2.1 The Role of GIS in Soil Water Infiltration Studies

Soil-related studies using GIS technologies are mostly dedicated to water balanced (Alemaw and Chaoka 2003; Ju et al. 2010; Pimenta 2000; Portoghese et al. 2005), real time flood prediction (Al-Sabhan et al. 2003), characterized maximum infiltration rate (Brito et al. 2006) and distributed rainfall-runoff model (Zollweg et al. 1996; Jain et al. 2004). One of the examples of the GIS and soil water studies is done by Tan et al. (2008) that implements a 3S-based hydro-geological model for conducting a study regarding an effective assessment of a regional rainfall-induced landslide in order to investigate shallow landslide in the watershed. In this research, the 3S refers to the Geographic Information System (GIS), the Global Positioning

System (GPS) and the Remote Sensing (RS) framework that is essential in establishing physical, mechanical, geological and hydraulic properties. The TRIGRS model helps in analysing the response of transient pore-pressure during a rainfall event that also estimates the result for landslide susceptibility while the Kringing interpolation method is used to analyse the rainfall intensity distribution. The 3S-based hydrological model provides an effective assessment of the regional rainfall-induced landslide where every system offers great contributions to the studies.

With the advent of the increasing GIS technique and computing power, a robust innovative physical-based hydrologic modelling has become important in contemporary hydrology to evaluate the impact of human intervention or possible climatic change on basin hydrology and water resources, but most of the designs have been found to be less suitable for real time applications and are usually not well integrated with spatial datasets for example the GIS (Alemaw and Chaoka 2003; Al-Sabhan et al. 2003).

Although the awareness on the importance of GIS technologies is rising but the studies that concentrate on soil water infiltration are less emphasized, even though it is very important in the hydrological process. Infiltration is an important soil feature that controls the runoff, leaching and crop water availability. Besides, soil water infiltration also becomes one of the triggering factors to hazards like soil erosion, flood and landslide. As soil water infiltration contributes to surface terrain changes, it is relevant to adapt to the use of the GIS in soil water studies. Attention towards this research has been scarce, even in the scope of knowledge that the soil water infiltration leads to many hazards such as flood and landslide.

Aspects of the real world objects can be described and represented in a computer by the data model comprising of a set of constructions or rules. The geographic space representation should be first identified in order to visualize natural phenomena. The GIS can best represent either geographic objects or surfaces as data through mathematical construction. The evolution of the data model proves the advance and proliferation in computer technology and the competitive nature of the GIS. Vector, raster and TIN data models are examples of data models with different types of the geographical representation used in the GIS. Simple spatial features are represented as a collection of point, line and polygon in the vector data model. The vector data model can be processed, accessed and interpreted by the computer by organizing geometric objects and their spatial relationships into digital data files. However, in the raster data model, geography is represented as cell matrixes which store numeric values where this model is a better option to represent continuous phenomena that use a regular grid in order to cover the space. The TIN data model on the other hand, represents geography as a set of contiguous non-overlapping triangles.

Since the soil water infiltrations occur underneath the soil and the flow direction is unpredictable, the dynamic flow requires a better representation and analysis which is in the form of 3D models. Apart from the use of the GIS techniques, the indeterminate spatial extend of soil water infiltration necessitates the 3D to show its dynamic movement based on the precipitation data. The advancement of 2D into 3D soil water movement is to be discussed next.

2.2 The Advancement of 2D into 3D Soil Water Movement

According to MacEachren and Kraak (1997), the concept of visualization is a key issue in the changing nature and using of maps in science as a consequence of the growing need of geo-referenced data and rapidly evolving technologies that can provide this information in more innovative ways. This technology evolution also important and give huge contribution in the field of hydrology. As stated by Fuhrmann (2000) the spread of modern information and communication technologies within the last three decades has led to an increased collection, availability and use of spatial and temporal digital hydrological data. Therefore the key issue for both public authorities and scientists is the needs and essential for visualization and regionalization of hydrological data and particularly temporal and spatial aspect of hydrological modelling.

This section reviews some of the studies that involve 3D in hydrological related studies. In 2002, Drogue et al. applying GIS by using ArcView as a 3D visualization tools and Hydrological Recursive Model (HRM), a conceptual rainfall-runoff model that represent downstream variation of daily streamflow where 3D spatio-temporal cartography of mean annual high raw and specific discharges are illustrated. Spatial analyst in ArcView was used to determined hydromorphometric data, land cover data and geological data for every catchment. The obtained regional parameter set in this study was used for model transposition and production of realistic streamflow mapping in combination with the 3D module of ArcView.

The linear spatialization and 3D mapping of the hydrograph is an important issues in hydrological analysis because it allow visualization and a temporal survey of streamflow in any point of the drainage network and is helpful from a pedagogical point of view for river management, as well as for the identification of runoff generating areas and critical influences in a drainage basin (Drogue et al. 2002). As the demand from GIS applications in the 3D environment increases, the basic form (e.g. single z-value for an x and y location) of data representation are no longer adequate (Raper and Kelk 1991). Stream and other flowing soft geo-object can be simulated in 3D by using various technique such as the combination of GIS flow element (FE) and GIS soft voxel (SV) which were applied in simulating soil erosion and overland flow (Shen et al. 2006) and using 3D Volumetric Soft Geo-object (VSG) data model to visualize areas and overland flow volume generated from IEOF process dynamically, driven by Green-Ampt infiltration equation (Izham et al. 2010). Spatial data representations may be describe as surface-based (grid, shape model, boundary representation (b-rep and facet model) and volume-based (3D array, octree, constructive solid geometry (CSG) and 3D TIN) (Li 1994) where surface based of an object was represented by surface primitive while volume-based describe as object's interior that describe by solid information.

2.3 Practical Relationship Between Intended 3D Modelling and Dynamic Water Infiltration

The research on soil water usually involves mathematical model, graph representation or 2D soil moisture profile. As the study involve soil water infiltration focus more on 2D model, this study shows the importance and relevance of the advancement into 3D model that able to show the movement of fluid according to appropriate pattern as a result of gravity forces. The previous studies of integrated hydrology and 3D GIS includes 3D model for stream water, flood, over land flow and IEOF. This research attempt to emphasize the 3D modelling of liquid movement under the soil surface that use soil water and subsurface flow as the representation of the liquid movement in the model. Apart from showing the dynamic movement of soil water and subsurface flow, this model create a geometric representation of soil that consist of pores that provides the path for the water flow.

Since soil water infiltrates dynamically with uncertain direction, and the movement is influence by volume of precipitation and soil characteristics, the best way to show the dynamic movement of soil water is through 3D modelling. Besides, the movement of water into the soil is difficult to describe with text or represent solely by equation. However, the equation can be used to control the movement of liquid that represent the soil water in the 3D model. This study shows the relationships between mathematical equation (Horton), soil water infiltration and soil water direction movement (tree-map and 3D Gosper curve) that used to create the 3D model which applied 3D TIN for representing the sequence of soil water flow direction. Precipitations, rate of infiltration, rate of water accumulate in soil and volumes of water that become subsurface flow are the dynamic data that modeled in form of fluid flow in the model. The triggering factor of this model is precipitation. The soil water infiltration does not stop although the precipitation stops, but always moving with the times due to the present of gravity force that continue to move the water. Thus, the used of 3D model in this research can shows the movement of soil water that receive less attention in most hydrological model.

3 Methodology

This section explains the relevance of the method chosen based on previous related studies that highlight the ways to divide layers in the soil. Appropriate algorithm, curve and equation used for the 3D soil water infiltration modelling are also included.

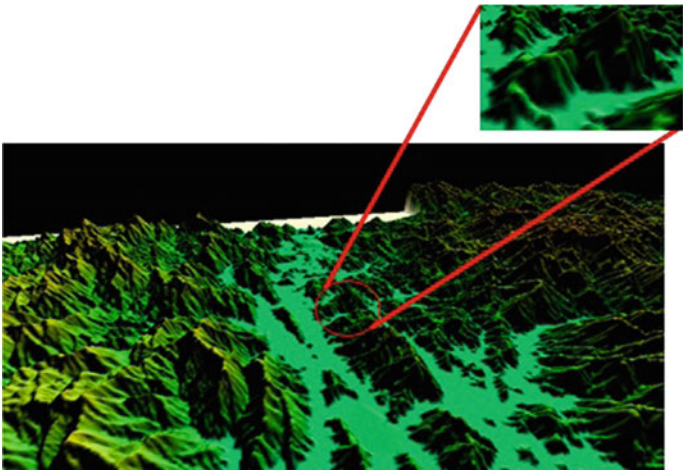

Fig. 1 Study area of East West Gerik-Jeli highway

3.1 Determination of Soil Water Infiltration Using Digital Terrain Model (DTM)

According to Brito et al. (2006), the area with sandy soil types, vegetated land used and the non-existent slope has high infiltration while the area with the steep slope of greater than 25 %, clay soil, and an impervious land use shows poor infiltration. The location of the study area is at N 05, 33.113 E 101, 21.253 at km 70.52, East West Gerik-Jeli Highway, the cut-slope sides of the highway heading to Kelantan, Malaysia (Fig. 1). The surface terrain is computed by the ASCII format data to 2.5 Dimension of surface representation from Global Mapper 14. The study area consists of clay soil and is covered by grass and trees and has −5 m water level and 8.5 mm total rain. The soil water infiltration determination is based on the soil types, soil surface (DTM), slope percentage and temporal precipitation.

3.2 Isolation Layer of Indeterminate Spatial Extend of Soil Water Movement Using 3D Gosper Curve

The distribution of water in soil is one of the indeterminate spatial extends which is difficult to sense and which has no specific boundary. Other examples of the indeterminate spatial extend are smoke, soil type and temperature. However, this paper will discuss on the soil water movement that proves to be important in the streamflow generating process and hazard management. A Gosper curve that originally generates shapes to facilitate visualization and navigation of hierarchy (Auber et al. 2013) is converted into a 3D Gosper curve that is able to show the sequence of the water flow infiltration that moves into the soil with the voronoi-shaped polygon nodes sequence. The algorithm created is able to isolate areas according to the depth of the corresponding nodes that represent the wetting area of soil after precipitation. In other words, this paper focuses on the isolation of soil layer in the form of 3D vertically where the soil water moves downward through the soil particles due to gravity force. The tree-map used and the linear arrangement of leave are modified according to the appropriateness of the model. The soil water distribution pattern, flow arrangement and the explanation the output are discussed in Sect. 4. Since the soil water involves a dynamic movement of fluid underneath the soil surface, the water flow in the model that is influenced by the temporal data of precipitation is stored and managed using a dynamic data structure which allows the growth of data.

3.3 Tree-Map and Algorithm Used to Isolate the Soil Layer

Humans tend to give different responses to the descriptions delivered through different methods. The ability to identify the spatial configuration of element in the form of picture has been tested and approved. Besides, humans also have the ability to notice the relationship between those elements easily. Visual ability enables people to get the content of the picture faster than those represented in the form of text (Kamada and Kawai 1991).

Hierarchical information usually presented by a method called the Tree-Maps, is expected to be able to produce similar visualization techniques achieved in other areas (Johnson and Shneiderman 1991) where the hierarchical information represented in the form of a rectangular 2D is displayed in a space-filling manner. The Tree-Map allows interactive control that can display both content and structural information. Every point of the Tree-map corresponds to a node in the hierarchy. The sibling nodes will never overlap due to the node's bounding box that completely encloses the bounding boxes belonging to its children. The methods of the Tree-maps include the slice and dice, Squarified treemap, Strip layout, Quantum treemap, Mixed treemap, Voronoi treemaps and Rectangle Hillbert treemap (Auber et al. 2013).

Large hierarchies contribute to the problem of navigation and visualization. The algorithm designed preserves the region containment based on the hierarchy. GosperMap creates boundaries as contour lines that mark the region with a similar altitude that has the same level of hierarchy. The method that is usually used to visualize hierarchies is the tree representations that slice information displaying a different hierarchy by using a single image, and the solution is based on the 2D space-filling curves (SFC).

Every curve has its own advantages and disadvantages. Researchers need to consider the needs of their research in order to select the most appropriate curve. The study by Asano et al. (1997) combines several recursive and general SFCs namely the Recursive SFC (RSFC) that improve the number of seek operations.

The SFC revolves around the ways on mapping multi-dimensional space in 1 Dimensional (1D) space where it functions as the route that passes through every cell available in a cell element to ensure that every cell is visited once (Mokbel, 2003). There are many kinds of SFC available that suggest different ways of mapping to the 1D space such as the z-order, Hillbert's curve, Gray code and Snake code (Asano et al. 1997). The shape of the curve is shown in Fig. 2.

A non-standard database system considers the importance of the query performance and the use of SFC for a multidimensional data structure is to map multi-dimensional points to one dimension which produces two points in the data structure. Nevertheless, the research by Uznir et al. (2013) presents an opponent data technique of the 3D Hilbert curve used to represent the 3D City Model. These new techniques that extend Hillbert SFC into a higher dimension prove on the improvement in the data retrieval time.

This study has proposed the use of the Tree-map for dividing soils into several stages of depth in order to represent the flow of the soil water infiltration. The

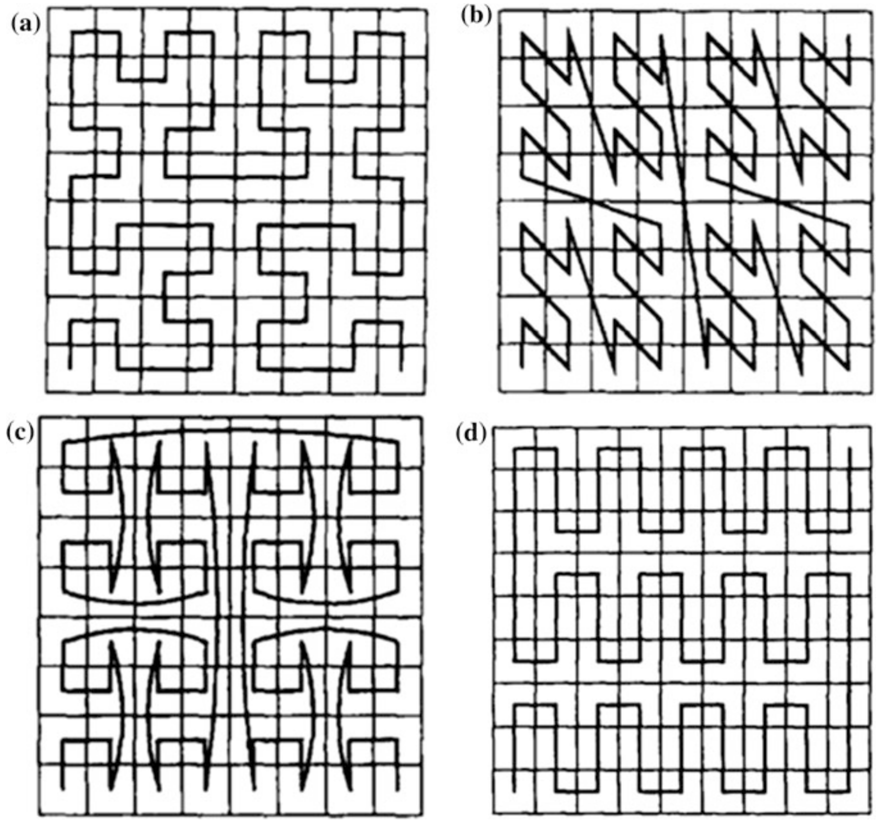

Fig. 2 Categories of space-filling curve. **a** Hillbert's curve. **b** z-curve. **c** Grey code curve. **d** Snake curve. Image from (Asano et al. 1997)

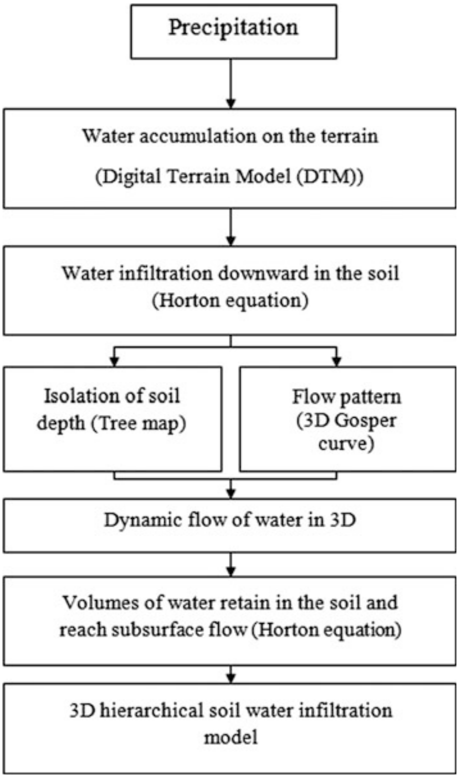

Fig. 3 The flow of methodology

Tree-map as explained previously is able to isolate information with boundaries. Tree-map capabilities in doing this isolation give an inspiration to the application of these techniques for the 3D soil depth segregation. The 3D Hillbert SFC curve by Uznir et al. (2013) proves that the curve can be upgraded into 3D. However, these studies proposed that the use of the Gosper curve can meet the requirement of the studies instead of using the Hillbert curve where the Gosper curve represents the hierarchical depth of the soil in the form of 3D. The results of using the Tree-map, Gospers curve, Horton equation and Tulips are described in Sect. 4. The overview of the methodology is summarized in the chart below (Fig. 3).

4 Result and Analysis

The Tree-map is used to represent every depth of the soil from the surface of the terrain to the subsurface flow suitable with its capabilities to divide the plane, from the top of the tree to the bottom. The overview of the algorithm is shown in Fig. 4a. The green node represents the parent, other colours represent the child and the blue numbered nodes are the linear arrangement on the leaves.

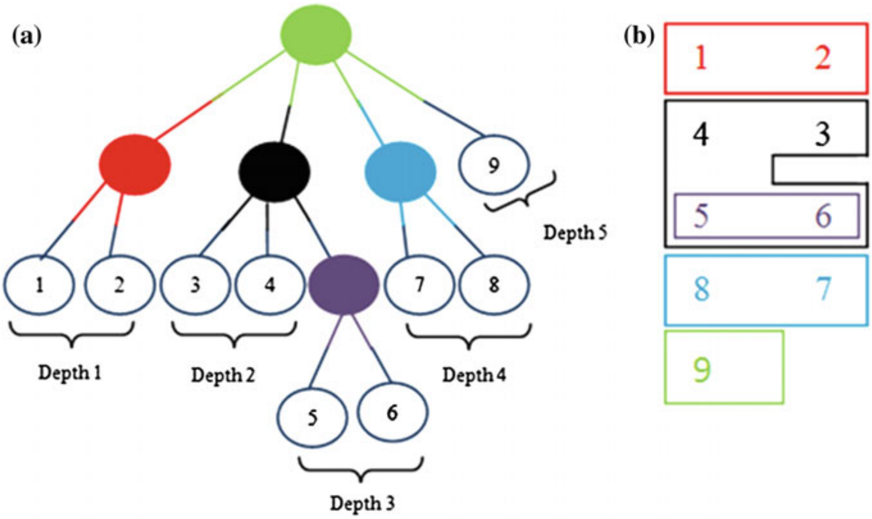

Fig. 4 **a** The overview of the algorithm with soil depth isolation in tree-map. **b** Leaves arrangement

The depth of the soil created from the Tree-map is represented by numbers that belong to every parent and child as shown in Fig. 4a. The isolation of the soil depth is represented well in the Tree-map. The arrangement of leave is represented in Fig. 4b where the pattern is applied from the Gosper curve. The colour of the number and boxes represents the colour of the nodes before. There is open source software that can be used to show the interesting visualization representation of Tree-map, namely Tulip.

Tulip is capable of visualizing a framework of information for analyzing and visualizing relational data that support the design of the interactive information visualization. The model as mentioned before, is divided into five layers with the respective depths of 40, 80, 120, 160 and 200 cm where the depth of the water flow is ascertained by the volume of precipitation. The isolation of depth is in the form of Voronoi-shaped polygon nodes that allow the soil water to flow down where the depth is chosen based on the soil wetting range of the subsurface soil. For clayish soil, Dingman (2002) stated that at steady water input rate, with 0.50 Φ porosity the water infiltrated to 10 cm at 8.3 h and 33 cm after 83 h where the infiltration increased with time. Thus, the wetting range from 0 cm to 200 cm is suitable for modelling soil water infiltration for the subsurface flow since the soil water starts to fulfill the soil composition, which started at the depth of 125 cm onwards (Juma 1999). The precipitation that falls on dry soil will wet the layer of the soil from the present water content to the lower layers. In order to visualize the prototype of the depth information of the soil water flow, Tulip is used to show some of the interactive graphic visualizations of the soil water according to a predetermined depth (Fig. 5).

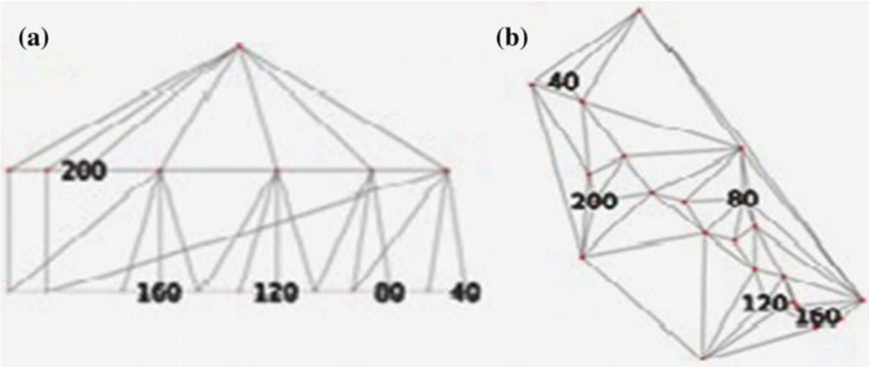

Fig. 5 Interactive information visualization by Tulips. **a** Hierarchy tree. **b** Delaunay triangle

As mentioned before, the Gosper Curve (Fig. 6a) is chosen to represent the pattern of the soil water flow. As mentioned by Asano et al. (1997), this curve divides the plane into hexagons where the obtuse angles lead to smoother boundaries and the curve has the locality of property, with $c = \sqrt{6.34}$. However, the linear arrangement that represents the pattern of the soil water flow (Fig. 6b) has changed slightly according to the Tree-map created before where the curve does not make any repetition upward to comply with the soil water that moves downward due to gravity. In addition, the curve is not represented in a planar form but vertically down to meet the requirement of the 3D modelling.

Figure 7a shows the position of nodes along the Gosper curve, where the image includes the soil surface, soil water flow direction, subsurface flow and depth which are represented by each node. Based on the arrangement of nodes, the flow pattern can be seen in Fig. 7b. Water from the precipitation that reaches node 1 is infiltrated into the soil and then flows to the next nodes, depending on the rate of precipitation. Low precipitation rate may result in the absorption of water not reaching 200 m and accumulating as subsurface flow in consequence of which there is water remaining

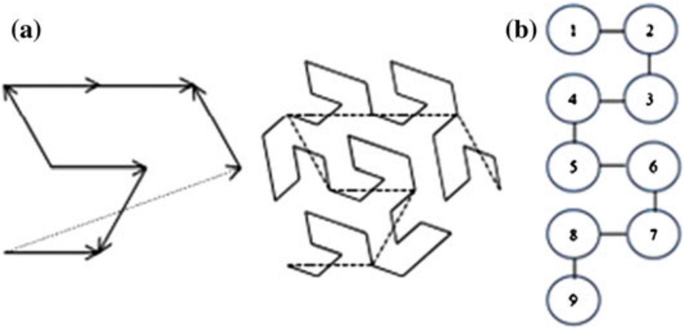

Fig. 6 **a** Gosper curve. **b** Linear arrangement of the leaves

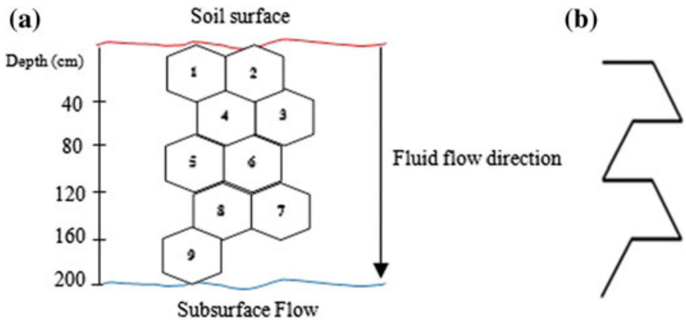

Fig. 7 **a** Position of nodes along Gosper's curve. **b** Soil water pattern

in the soil before succumbing to the downward trend. The rate of precipitation will not be the same with the volume of water that reaches the subsurface flow due to the soil characteristics that retain some of the water that flows through it. The number of nodes that are occupied by soil water is determined by calculating the soil wetting depth. In order to calculate the depth of wetting, it is necessary to calculate the storage capacity on a mass as well as on a volume basis (Juma 1999) shown as follows.

Storage capacity on a gravimetric basis (Θ_m)

$$= \text{Field capacity} - \text{present water content}$$

Storage capacity on volumetric basis (Θ)

$$= \Theta_m \times (\text{Bulk density of soil} / \text{density of water})$$

Depth of wetting

$$= \text{Volume of rain} / \text{volume of water stored per cm of soil}$$

Each and every Voronoi-shaped node illustrated in Fig. 8 is known as mask ($3 \times 3 \times 3$). The water infiltrated in the nodes does not enter and flow through the empty nodes but it flows through a series of TIN which produces the 3D TIN. However, this study uses the 3D TIN application in Voronoi polygon instead of using square.

The principle of the 3D Triangular Irregular Network (3D TIN) is adopted in order to create the 3D flow sequence of soil water in each 3D Gosper node. The mask measuring $3 \times 3 \times 3$ is numbered and it has 16 voxel elements (Fig. 9). The mask is divided into 4 sections of triangle, where each triangle is divided into three non-overlapping tetrahedra. Thus, every 3D Gosper node consists of 12 tetrahedra (Fig. 9a–d) that represent the flow sequence and the path of the soil water movement. As mentioned previously, there are 9 nodes in the 3D Gosper curve and the number of the tetrahedra for this model is 109. This non-overlapping tetrahedra

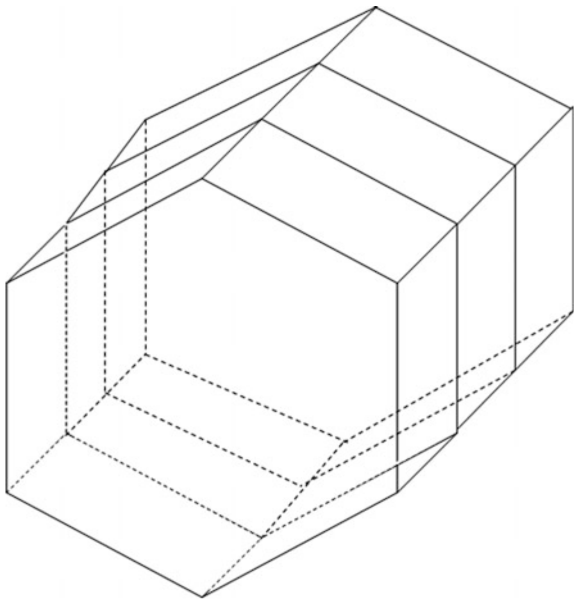

Fig. 8 A mask for each Voronoi-shape polygon nodes

form a 3D TIN that creates a network of flow directions that allows the water to pass through the nodes according to a predetermined sequence. This 3D TIN structure is designed for subsurface soil water flow.

In contrast of the use of the Gosper curve that lays out the hierarchical data and which is visualized in the 2D map, this study adopts the use of the Gosper curve to isolate layers of soil horizontally that forms a 3D pattern of dynamic soil water flow. In this model, the subsurface soil is represented by nodes that are arranged in sequence, from number 1 to 9. The nodes which are in a Voronoi-shaped polygon use the Voronoi tessellation to create a convex polygon (Auber et al. 2013). For the modelling part, the Voronoi-shaped polygon is used to retain water underneath nodes 1, 3, 5 and 7 from flowing down to the subsurface flow as a representation of water retained in the soil. The water starts its infiltration process when it reaches every first node of the 3D Gosper's curve and the water flow according to the sequential number of the nodes. The remaining water that stops moving is collected to calculate the overall volume of the subsurface flow. The rate of the infiltration of water in the porous media of soil is calculated using the Horton equation (Horton 1933):

$$f_t = f_c + (f_0 - f_c)e^{-kt}$$

Where:

- f_t infiltration rate at time t
- f_0 initial infiltration rate or maximum infiltration rate
- f_c constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate
- k decay constant specific to the soil

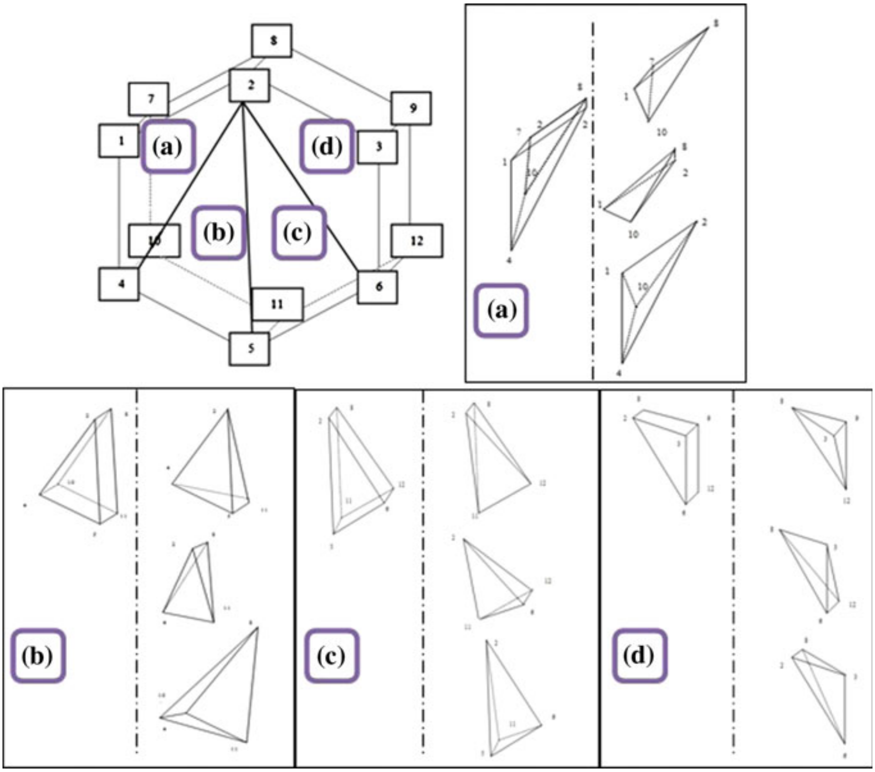

Fig. 9 Mask numbering and predefined topology. **a**, **b**, **c**, and **d** From 4 divisions, the polygon created by 12 non-overlapping TENs

The advantage of using Horton is that it can also be used to calculate the volume of infiltration (F) after a certain amount of time (t):

$$F_t = f_c t + \frac{(f_0 - f_c)}{k}(1 - e^{-kt})$$

The infiltration rate and infiltration volume are both essential in determining the flow of water in the nodes of the soil water flow. The time it takes for the water to flow in each node, the volume of water remaining in the nodes, the volume of water that reaches the sub-surface flow layer, the amount of accumulation of the sub-surface flow in the 3D model depends on these equations. The use of the Tree-map for hierarchical soil depth determination, the Gosper curve that represents soil water flow pattern which is based on the water flow in accordance with the law of gravity and the use of Horton equation that influence the water flow, showed suitable integration to develop a model of 3D soil water infiltrations.

5 Concluding Remarks

This study aims to enliven the 3D research that has been burgeoning and the focus of the study is on the 3D modelling of soil water infiltration in porous media of soil. Environmental-related studies have started to show an improvement on the use of the GIS for the analyzing part. As we know, the process that happens naturally requires appropriate modelling methods as some of the processes sometimes lead to hazards that are life-threatening, damaging property and disrupting ecosystems. A proper and accurate modelling is needed and the most appropriate model that can handle the dynamic and temporal data is the 3D GIS geospatial modelling. The integration of the 3D GIS with a mathematical method can produce a better model for environmental studies. The tree-map is used to show the hierarchical depth of the soil modified from its original use that groups together similar information from a high number of data. Besides, by adopting the idea of the Gosper curve, the 3D pattern of the soil water movement was introduced to represent the flow route of the soil water infiltration. The application of 3D TIN in Voronoi-shaped Gosper nodes explains the route and sequence direction of the soil water flow in the model. The non-overlapping tetrahedral that forms a 3D TIN helps in representing the flow in multilayered soils. TIN that is used to connect three neighbouring (2D TINs) adopted a similar principle for the 3D TIN where in this study, the 3D TIN has been constructed to provide a sequence of soil water flow in the Voronoi-shaped polygon of 3D Gosper curve. 3D TIN served to give the coordinate for each node of the tetrahedral that represents the location of infiltration occurred. This model is beneficial for those who need to know the soil water content, soil water distribution, soil water movement and subsurface water that are required in their research. The 3D GIS is needed to facilitate the dynamic flow of water that does not simply flow linearly down the soil but also towards an unpredictable direction. The information of the water content at certain depth of the soil can also be predicted using this model that often changes over time. The spatial data model is needed to define the content and structure of the data that can be used to carry out the task and operations for the purpose of identifying soil water infiltration.

Acknowledgments The authors would like to thank UTM Research University Grant, Vote J.130000.2427.02G77 and MOHE-JICA Grant No. 203/PJJAUH/6711279 for supporting this work.

References

Alemaw, B. F., & Chaoka, T. R. (2003). A continental scale water balance model: A GIS-approach for Southern Africa. *Physics and Chemistry of the Earth*, *28*(20–27), 957–966. http://doi.org/10.1016/j.pce.2003.08.040.

Al-Sabhan, W., Mulligan, M., & Blackburn, G. a. (2003). A real-time hydrological model for flood prediction using GIS and the WWW. *Computers, Environment and Urban Systems, 27*(1), 9–32. doi:10.1016/S0198-9715(01)00010-2.

Asano, T., Ranjanb, D., Roosc-, T., Welzld, E., & Widmayer, P. (1997). Space-filling curves and their use in the design of geometric data structures, *3975*(96).

Auber, D., Huet, C., Lambert, A., Renoust, B., Sallaberry, A., & Saulnier, A. (2013). GosperMap: using a gosper curve for laying out hierarchical data. IEEE Transactions on Visualization and Computer Graphics, *19*(11), 1820–1832. http://doi.org/10.1109/TVCG.2013.91.

Barnes, C. J., & Allison, G. B. (1988). Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology*, *100*(1–3), 143–176. http://doi.org/10.1016/0022-1694(88)90184-9

Brito, M. G., Costa, C. N., Almeida, J. a., Vendas, D., & Verdial, P. H. (2006). Characterization of maximum infiltration areas using GIS tools. *Engineering Geology, 85*(1-2), 14–18. doi:10.1016/j.enggeo.2005.09.022.

Dingman, S. L. (2002). Water in soils: Infiltration and redistribution. In *Physical hydrology* (pp. 222–242).

Drogue, G., Humbert, J., Deraisme, J., Mahr, N., & Freslon, N. (2002). A statistical-topographic model using an omnidirectional parameterization of the relief for mapping orographic rainfall. *International Journal of Climatology*, *22*(5), 599–613. http://doi.org/10.1002/joc.671

Dunne, T., & Black, R. D. (1970). Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research, 6*(5), 1296–1311. http://doi.org/10.1029/WR006i005p01296

Fuhrmann, S. (2000). Designing a visualization system for hydrological data. *Computers and Geosciences, 26*(1), 11–19. http://doi.org/10.1016/S0098-3004(99)00040-0

Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. *Transactions of the American Geophysical Union*, 445–460. http://doi.org/10.1029/TR014i001p00446

Hursh, C., & Brater, E. (1941). Separating storm-hydrographs from small drainage-areas into surface-and subsurface-flow. *Papers, Hydrology*, 863–871. Retrieved from http://cwt33.ecology.uga.edu/publications/806.pdf

Hoover, M. D., & Hursh, C. R. (1943). Influence of topography and soil-depth on runoff from forest land. *Transactions of 1943 of the American Geophysical Union, 1*. http://doi.org/10.1017/CBO9781107415324.004

Izham, M. Y., Uznir, U., & Rahman, A. A. (2010). Developments in 3D geo-information sciences. Applied sciences, vol. 219.

Jain, M. K., Kothyari, U. C., & Ranga Raju, K. G. (2004). A GIS based distributed rainfall-runoff model. *Journal of Hydrology, 299*(1-2), 107–135. doi:10.1016/j.jhydrol.2004.04.024.

Johnson, B., & Shneiderman, B. (1991). Tree-maps: a space-filling approach to the visualization of hierarchical information structures. In *Proceeding Visualization'91*. http://doi.org/10.1109/VISUAL.1991.175815.

Ju, W., Gao, P., Wang, J., Zhou, Y., & Zhang, X. (2010). Combining an ecological model with remote sensing and GIS techniques to monitor soil water content of croplands with a monsoon climate. *Agricultural Water Management, 97*(8), 1221–1231. doi:10.1016/j.agwat.2009.12.007.

Juma, N. G. (1999). Introduction to soil science and soil resources. *The Pedosphere and Its Dynamics: A System Approach to Soil Science*, 1.

Kamada, T., & Kawai, S. (1991). A general framework for visualizing abstract objects and relations. *ACM Transactions on Graphics, 10*(1), 1–39. doi:10.1145/99902.99903.

Liu, B., Phillips, F., Hoines, S., Campbell, A. R., & Sharma, P. (1995). Water movement in desert soil traced by hydrogen and oxygen isotopes, chloride, and chlorine-36, southern Arizona. *Journal of Hydrology, 168*(1-4), 91–110. doi:10.1016/0022-1694(94)02646-S.

MacEachren & Kraak (1997). The map reader: Theories of mapping practice and cartographic representation. *Computers & Geosciences, 23*(4), 335–343. doi:10.1016/S0098-3004(97)00018-6

Mokbel, M. F., Aref, W. G., & Kamel, I. (2003). Analysis of multi-dimensional space-filling curves. *GeoInformatica, 7*(3), 179–209. doi:10.1023/A:1025196714293.

Newman, B. D., Campbell, A. R., & Wilcox, B. P. (1997). Tracer-based studies of soil water movement in semi-arid forests of New Mexico, *196*, 251–270.

Nielsen, D. R. (1964). Water movement through panoche clay loam soil. *Journal of Agricultural Science, 35*(17), 491–503.

Pimenta, M. T. (2000). Water balances using GIS. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 25*(7-8), 695–698. doi:10.1016/S1464-1909(00)00087-3.

Portoghese, I., Uricchio, V., & Vurro, M. (2005). A GIS tool for hydrogeological water balance evaluation on a regional scale in semi-arid environments. *Computers and Geosciences, 31*(1), 15–27. doi:10.1016/j.cageo.2004.09.001.

Raper J. F. & Kelk, B. (1991). Three-dimensional GIS. In D. J. Maguire, M. F. Goodchild & D. V. Thind (Eds.), Geographic information systems: Principles and applications (Vol. 1, pp. 299–316). Longman: London.

Shen, D. Y., Takara, K., Tachikawa, Y., & Liu, Y. L. (2006). 3D simulation of soft geo-objects. *International Journal of Geographical Information Science, 20*(3), 261–271. http://doi.org/10.1080/13658810500287149

Tan, C. H., Ku, C. Y., Chi, S. Y., Chen, Y. H., Fei, L. Y., Lee, J. F., et al. (2008). Assessment of regional rainfall-induced landslides using 3S-based hydro-geological model. In *Landslides and engineered slopes: From the past to the future* (Vols. 1, 2). Chinese Inst Soil Mech & Geotech Engn; Chinese Nat. http://doi.org/10.1201/9780203885284-c225

Uznir, U., Anton, F., Suhaibah, A., Rahman, A. A., & Mioc, D. (2013). Improving 3D spatial queries search: Newfangled technique of space filling curves in 3D city modeling. *ISPRS Annals Photogrammetry, Remote Sensing and Spatial Information Sciences, II*, 319–327.

Zollweg, J. A., Gburek, W. J., & Steenhuis, T. S. (1996). SMoRMod—A GIS-integrated rainfall-runoff model. *Transactions of the Asae*, *39*(4), 1299–1307.