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ITN-2 River Basin Hydrology Model, a Distributed Conceptual Model For Predicting Flood Without Using Calibration

Model Hidrologi DAS ITN-2, Sebuah Konsep Model Distribusi Untuk Memprediksi Banjir Tanpa Menggunakan Kalibrasi

Kustamar [1], Silvester Sari Sai [2], Erni Yulianti [3], Sunik [4]
[1] Water Resources Engineering, Civil Engineering & Planning Faculty, ITN Malang, email: kustamar@yahoo.co.id
[2] Geodesy Engineering, Civil Engineering & Planning Faculty, ITN Malang, email: detuyesil@yahoo.com
[3] Water Resources Engineering, Civil Engineering & Planning Faculty, ITN Malang, email: ernibuyung@yahoo.com
[4] Civil Engineering, Universitas Widyakarya Malang, email: ssunik@yahoo.com

ABSTRACT

The change process induced by rain in one area which eventually converts such area to a river basin is relatively complicated due to a number of physical factors present in the interrelated river basins. Hence, a proper hydrology model is required in order to be able to predict flood debits. Insufficient data on rain and hourly debits in the process of setting a Regional and Space Planning demands the invention of a hydrology model that can be utilized to predict flood debits with high accuracy without conducting any calibration process. In order to meet such a need, the Hydrology Model of ITN-2 River Basin, as an improvement of the former Hydrology Model of ITN-1 River Basin, has been developed. Test results have indicated that Hydrology Model of ITN-2 River Basin is adequately sensitive to the condition change in land utilization and can be used to predict debits without any calibration process.
Keywords: Hydrology Model of River Basin, Flood Analysis without Calibration

ABSTRAK

Proses perubahan yang disebabkan oleh hujan di satu daerah yang akhirnya mengubah wilayah tersebut menjadi sebuah Daerah Aliran Sungai (DAS) yang relatif rumit, karena sejumlah faktor fisik hadir saling terkait di daerah aliran sungai tersebut. Oleh karena itu, model hidrologi yang tepat diperlukan agar dapat memprediksi debit banjir. Karena data hujan dan debit per jam tidak memadai dalam proses menetapkan Perencanaan Wilayah & Ruang, menuntut penemuan model hidrologi yang dapat digunakan untuk memprediksi debit banjir dengan akurasi yang tinggi tanpa melakukan proses kalibrasi. Untuk memenuhi kebutuhan seperti itu, telah dikembangkan Model Hidrologi DAS ITN-2, sebagai perbaikan dari Model Hidrologi DAS ITN-1. Hasil tes telah menunjukkan bahwa Hidrologi Model DAS ITN-2 adalah cukup sensitif terhadap perubahan kondisi dalam pemanfaatan lahan dan dapat digunakan untuk memprediksi debit tanpa proses kalibrasi.
Kata-kata Kunci: Model hidrologi DAS, analisis banjir tanpa kalibrasi

INTRODUCTION

Anticipation towards disaster caused by flood in Indonesia has been very low as reflected in each process of setting a Regional & Space Planning. Identification of flood-threatened areas has been conducted, generally, by using statistical models based upon the occurrence of disasters. The accuracy of such method becomes questionable when factors such as environmental damage and the effects of change in land utilization planning that have taken place are not taken into account (Kustamar dan Sari Sai, 2008).

The change process carried by rain in one area which then converts such area to a river basin is relatively complicated due to a number of interrelated factors. According to Kustamar *at.all* (2009), the primary factors include rain intensity and duration, drainage system density, topography, soil density and texture, and condition of land utilization. These factors produce results such as, among others, interception, evapotranspiration, infiltration, speed of surface water runoff, and speed of ground water flow. Due to the complexity of the process, a model is required in order to be able to analyze it.

The type of such model should be the distributed one. Various hydrology models have been developed, either of distributed or lumped type (Singh and Woolhiser, 2002). According to Evangelos Rozos (Rozos, et al., 2004), the abilities of such models vary, ranging from calculating surface water flow debit, ground water flow, and river debit hydrograph to estimating surface erosion. The core model of all models is the River Basin hydrology model that performs the computation of river debits due to rain. One of the distributed types of River Basin hydrology models is ITN-1 River Basin Hydrology Model.

ITN-1 River Basin Hydrology Model was developed in order to analyze flood debit in a river basin where a couple of rain data and hourly debits, along with adequate spatial information were present. Increasing the accuracy of flood debit prediction caused by change in land use was conducted by providing 2 (two) numerical calibration facilities. Based upon the pair of rain data and hourly debits, calibration was performed by simulating calibration coefficients until the correct peak value and debit hydrograph slope rate were obtained (Rozos, at al., 2004).

In setting Space & Regional Planning, the availability of spatial data to predict flood debit can be said relatively sufficient, while the pair of data on rain and hourly debit, on the other hand, are scarce. Hence a hydrology model that can be used to predict flood debit with high accuracy, without conducting any calibration process, is required. To meet such a need, ITN-1 River Basin Hydrology Model was then expanded to produce ITN-2 River Basin Hydrology Model.

The improvement found in ITN-2 River Basin Hydrology Model is the model's increased sensitivity towards the change in land type and land use condition, supported by the strategy in the computation process. The model's increased sensitivity towards land use condition is performed by accommodating its effect on infiltration capacity. This effect is formulated in a correction coefficient (Cc), i.e., the comparison of the magnitude of infiltration capacity measured in one location with the infiltration capacity obtained from soil type information.

Improvement has been made in the analysis process as well, i.e., the separation of spatial analysis process and numerical computation found in the former model is replaced by performing them simultaneously in the current model. In the former ITN-1 River Basin Hydrology Model, the spatial analysis was conducted by means of ArcView GIS, while the numerical analysis was performed by using Fortran. In ITN-2 River Basin Hydrology Model, on the other hand, the spatial and numerical analysis is conducted by means of Model Builder found in ArcGIS. This is expected to provide ease in its execution.

Lesti River Basin, which is under the administration of Malang Regency, East Java (Figure 1) was selected in regard of its facilities for the model capacity test while its field data was used for problem prototype.
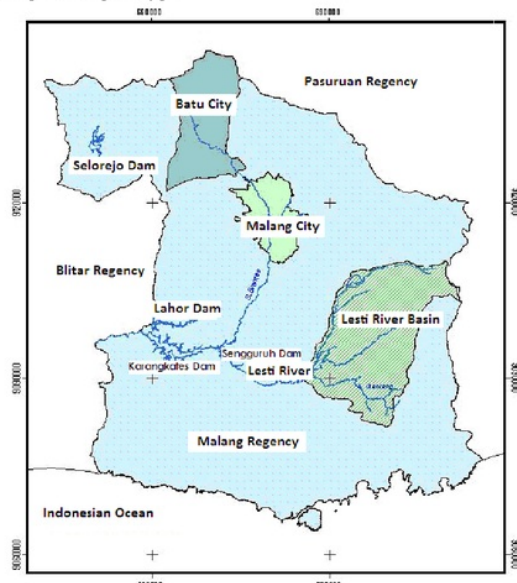

Figure 1. Location of Lesti River Basin

THEORETICAL BASIS

River Basin Hydrology Model

The term "River Basin hydrology" is defined as the branch of hydrology dealing with the integration of hydrology process in one river basin in relation with the basin's responsiveness. Its hydrological process and spatial diversities are indicated by climate, topography, geology, land, vegetation and land use.

The development of River Basin hydrology models has been very rapid, in terms of quantity, concepts, problem approaches, and data analysis methods as well. This is related with the development of data computation system and data acquisition technique. Based upon documented data for the purpose of viewing the handling of spatial data variabilities, River Basin hydrology models can be grouped into 3 (three), namely distributed, quasi-distributed and lumped.

The lumped-type model perceives a River Basin as a unity, and therefore disregards spatial variation in terms of process, input, boundary condition, or hydrological magnitude. On the other hand, the distributed type is suitable for handling spatial variables either in terms of a river basin's physical aspects or its hydrological factors by performing equation solution for each data group or grid. The distributed type is suitable for handling a river basin's complex conditions, therefore it requires a great number of input data, as opposed to the lumped one. In order to reduce the amount of input data required, another type called the Quasi-Distributed model was then developed.

A summary of the description of each distributed-type of River Basin hydrology models can be found in Table 1. From the summary of each River Basin hydrology model in Table 1 it can be concluded that the majority of the models is comprised of a combination of surface water runoff model and ground water flow, and includes parameters such as interception, evapotranspiration, infiltration, surface and ground water flow. This matches the objective of modeling that is predicting river debits and/or surface erosion in one river basin as a result of rainfall.

River Basin Hydrology Model Application

A river basin hydrology mathematical model is designed to respond to Penman's question at one level of detail depending on the existing problem and is used in a broad spectrum dwelling between river basin management and design. These models are used in planning, design and design projects to maintain water and land resources as well as preserve their quality. In land reviews, models are used for a variety of purpose such as planning and designing land conservation practice, irrigation water management, marsh-land reclamation, and sub-surface water management. In a broader scope, models can be used for protection-against-flood project, dam rehabilitation, flood control management, water quality evaluation, and water availability forecast.

Table 1. Summary of Description of Distributed-type River Basin Hydrology Model

Model Identity	Concept Component & Approach	Capability
TOPOG_IRM	1. Transpiration, infiltration and surface runoff 2. Vegetation carbon balance, by plant- growth simulation	Prediction of dynamic interaction between land, vegetation and atmosphere in River Basin
FRHYMAP	Hydrology Model & Hydraulics: 1. Surface runoff (2-D), 2. Ground water addition, potential hourly Evapotranspiration, by Penman-Montrith.	Prediction of effect of land use change on flood debits and ground water
SHAL_Z	1. Rain, Evapotranspiration, 2. Surface catchment area, infiltration, 3. 2-D Surface Runoff, Perkolasi.	Hourly hydrograph analysis, and maximum water surface

PRMS	1. Interception, Evapotranspiration, surface & sub-surface water flow by non-linear routing , River Basin is divided into HRU 2. GIS for: displaying spatial data being processed as well as result of simulation	Continuous daily debit prediction
MIKE-SHE	1. SHE: Interception, Unsaturated Surface Water by Richard equation, 3-D Ground water flow, 2-D Surface runoff, difussion, 2. MIKE-11, flow in channel by 1-D routing.	Water flow process simulation in River Basin
InHM	1. Surface runoff by 2-D wave difussion, 2. Flow through saturated porous medium by 3-D Richard model ,	Computing surface and sub-surface flow , and sediment transportation as well
IGSM2	1. Ground water horizontal flow analysis by finite element, 2. Inter-layer approached by vertical water flow	Ground water surface elevation simulation in various aquiver layers
MODFLOW	1. Surface runoff with 1-D non-permanent flow 2. Ground water flow, difference up to 3-D 3. Database System by GIS	Continuous River Debit prediction
Model Hidrologi DAS ITN-1	1. Surface runoff with 1-D non-permanent flow 2. Accommodating effects of: Interception and infiltration. 3. Infiltration capacity information based on soil type map	Continuous River Debit prediction

Source: Kustamar and Yulianti, E. (2009)

A river basin model is used to understand the dynamic interaction between climate and "*land-surface hydrologi*". According to Sokrut (2001) utilized a distributed-type hydro-logy model, a combination of surface runoff and sub-surface models as a means to manage river basins. Readers are referred to Yeo, et al. (2004). Optimizing Patterns of Land Use to Reduce Peak Runoff Flow and Nonpoint Source Pollution combined hydrology and land use models to optimize land use planning for the purpose of reducing peak surface runoff debit. The optimized land use planning obtained was able to achieve a debit peak decrease caused by rain with a repeatable period of 1, 2, 5 and 10 years with a magnitude of 15% up to 20% from the previous conditions. In short, a river basin model has become an important means for water resource planning, development and management.

During 1980-1990 hydrology models were related to chemistry, geology, environmental biology, meteorology and climate science. This relation was based on two considerations. First, an improved understanding in spatial variabilities of hydrology processes and the role of scaling. Secondly, the digital revolution made the use of GIS, remote sensing technology and database system management possible. In the future, river-basin hydrology mathematical models will become the means for water resources planning, development, design, operation and management. This anticipates the future where the integration of river-basin hydrology models into environment and ecology management will be cultivated extensively (Haji and Legowo, 2001).

Most of the current river-basin hydrology models are comprehensive, distributed in type and based upon physical conditions. They possess accurate capabilities to imitate river-basin hydrology and can be applied to a broad scope of water resource problems (Singh and Woolhiser, 2002). Supported by the rapidly developed information technology, models's quality can be escalated by the use of tools for spatial analysis, such as in the form of Geographical Information System (GIS).

River Basin Hydrology Model Component

Vertically-bound Water Motion

Referring to the model's purpose of acquiring a surface runoff debit, the factors which contribute to the debit's magnitude should be taken into account. Those factors are interception, infiltration, and land surface roughness (Kustamar, 2008).

Interception

Interception is a portion of hydrology component that shows the magnitude of rain warer trapped in land cover and then re-evaporated. The size of interception coefficient (%) is determined by land type and use condition. Consequently, modeling that has the objective of analyzing the effects of land use on river water flow should be taken into account.

Following the vegetation's growth, the effects of vegetation's condition on interception (It) are as follows:
1. Lesser amount of water escapes (Al) due to denser branches.
2. Increase in trunk flow (Ab) even though in small amount.
3. Increase in receiving capacity of canopy's surface and fallen leaves' zones.

Evapotranspiration

Evapotranspiration will take place with the presence of 2 (two) primary conditions, namely the energy factor causing the evatranspration and the evapotranspirable-water. Such factors are sun's radiation, wind, relative humidity and temperature.

The value obtained from empirical formula signifies the size of potential evapotranspiration. The size of actual evapotranspiration, on the other hand, is very much dependent on the availability of water content that can be evaporated.

In relation with interception, the types of plantation can be classified into 2 (two), i.e., heterogeneous and homogeneous. The interception value if each type is shown in Table 2 and Table 3.

Table 2. Interception Value in Heterogeneous Plantation in Konto Atas River Basin

Parameter	% of Monitored Rain
Evaporation from canopy	0.30
Interception during rainfall	17.6
Interception after rain	8.8

Table 3. Interception Value in Plantation with Homogeneous Vegetation

Plant Species	Int. (%)
Acacia aneura	13.0
Acacia harpophylla	15.2
Aegle maramelos	13.1
Agropyron koeleria	22.3
Bouteloua Curtipendula	18.1
Crosotebush	12.2
Digitaria deceumbens	15.5

Eucalyptus	8.3
Eucalyptus camadldulensis	14.3
Eucalyptus Regnans	23.3
Eucalyptus Rossii	10.6
Eucalyptus Obliqua	15.0
Hilaria belangeri	10.8
Mixed conifer and hardwood	22.0
Montance rain forest	18.2
Oats	20.5
Pinus radiata	26.5
Pinus rigida	19.1
Pinus wallichina	21.0
Rain forest	8.9
Rain forest	27,0
Soya beans	32,0
Tarbush	6.1
Neopanax arboreum scrub	27.0
Cypress	26.0
Bamboo	20.0

Source: Yeo, et al. (2004), Kustamar, et al. (2009).

Infiltration

Water reaches land surface will partly seep (infiltration) downward to become sub-surface water while the rest will rema-

Farmland	Good Vegetation Condition	0.004
Bushes	Natural	0.037
Forest / Trees	Good Condition	0.600
Water Surface	Inundating Water	0.037
Wet Land other than Forest	Good Vegetation Condition	0.130

in on the surface. Actual infiltration depends on the infiltration capacity and the portion of rain water that possesses the potential to get seeped.

Vegetation factors can affect the magnitude of infiltration capacity because the activities in the plants' root system may increase soil aggregate solidity and macro porous space. This way, it can be said indirectly that land use affects infiltration capacity. The infiltration avarage value is shown in Table 4.

Table 4. Infiltration Average in Monte Carlo

Group	Number of Testing Points	Infiltration Average (inch/hour)
Sandy Soil Not Compacted	36	13
Compacted sandy soil	39	1,4
Dry clay not compacted	18	9,8
Other soil types	60	0,2

Source: Pitt, et al. (2001).

Horizontally-bound Water Motion

In River Basin Hydrology modelling of distributed type, water flow on land surfaces is approached by water flow through open channels. For the purpose of analysis, a river basin is divided into independent cell forms. Debit in each cell is computed by 1 dimensional flow concept by using Manning equation as follows (Pitt *et.al* ,2001).

$$V = \frac{1}{n}\left(\frac{A}{P}\right)^{\frac{2}{3}} S^{\frac{1}{2}} \tag{1}$$

$$Q = A * V \tag{2}$$

$$A = L * h \tag{3}$$

$$P = L + h \tag{4}$$

With: n, L, h, S as Manning roughness coefficient (Table 4), cell size, surface runoff water elevation, and topographical slopeness in cell respectively. Cummulative inter cell

Table 5. Manning Roughness Coefficient

Land Use		Manning Roughness
Type	Condition	
Settlement	72% water-resistant	0.075
Open Land	Arid	0.050

Source: Yeo, et al. (2004).

RESEARCH METHOD

Operational Framework

Research proses phases in expanding ITN-1 River Basin Hydrology Model into ITN-2 river Basin Hydrology Model is described briefly in Table 6.

Table 6. Research Process Stages

	Group	Sub Group		Proses Stage
A	Evaluation on ITN-1 River Basin Hydrology Model	Dependence on Rain and Hourly debit data	1	Inventing strategy to abort calibration process while maintaining results with high accuracy
		Spatial data Preparation Stage	2	Merging spatial and numerical analysis processes
B	Model develop-ment	Model component with vertically-bound water motion	3	Equipped with Infiltration Capacity Correction Coefficient Parameter (Kk)
		Numerical analysis model component	4	Aided by *model builder* found in Arc GIS
C	Model Testing	Calibration Process	5	Kk value simulation in relation with the role of numerical calibration

debit is computed with regard to surface water flow di- rection. Water flow direction model is setup based upon land surface slopeness, therefore forming a sequence of synthetical rivers.

Model Development Strategy

The strategy used in developing ITN-1 River Basin Hydro- logy Model into ITN-2 River Basin Hydrology Model is as fo- llows:

1. Evaluating the shortcomings found in ITN-1 River Basin Hy- drology Model in relation with: a) dependency on rain data and hourly debits, and b) user's ease in preparing spatial data format.
2. Identifying the physical parameters of a River Basin that have a great impact on surface runoff debit yet have not been accommodated in ITN-1 River Basin Hydrology Model.
3. Constructing a model component to minimalize the need for numerical calibration.
4. Identifying a user's difficulties in preparing river-basin spa- tial data.
5. Constructing a model component which is able to analyze spatial data without having to convert them first to ASCII format.
6. Replacing a number of components with the component models already developed in order to obtain a compact unified model.
7. Testing the model's reliability.

RESEARCH RESULTS

Model Component Vertically-bound Water Motion

The model component of vertically-bound water motion is developed based upon rain water motion (measured rain) that turns into land surface water. The process of such water motion is clarified as follows: a) rain water falls upon trees' branches will be partly absorbed by them and re-evaporates during the interception process. The amount of the intercepted water depends on the amount of rain and the type of land use.

Water which escapes trees' branches and falls to the land surface (net rain) will in turn get infiltrated while the rest will remain on the land surface. The amount of water remaining on the land surface is affected by the infiltration capacity whose magnitude is determined by soil infiltration capacity (Cinf) and its density effect. This description is illustrated in Figure 2. The amount of water left on the land surface is determined by infiltration capacity whose magnitude is affected by soil infiltration capacity (Cinf) and the effect of its solidity. This description is clarified in Figure 2.
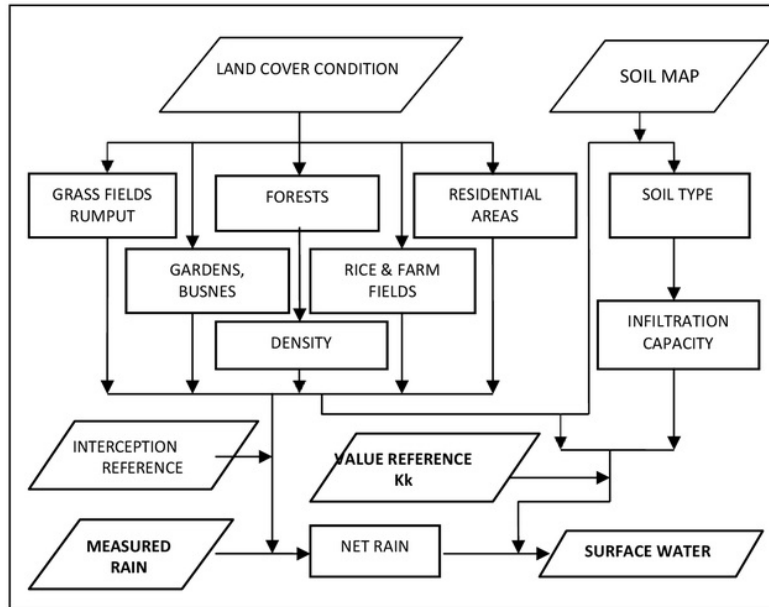

Figure 2: Model Component of Vertically-bound Water Motion

Spatial and Numerical Data Analysis

Model Builder is ArcGIS's Toolset that is used to develop, edit and compose models. By using Model Builder, spatial analysis based on vector or raster data can be performed in a more structured and simpler way. In this research the analysis model used to compute debit value of each cell is constructed from a number of mathematical processes based upon raster data.

Raster spatial data used, i.e., slopeness data obtained from DEM (digital evaluation model) Shutlle Radar Topography Mission (SRTM), data on land use and rainfall rate. Land use raster spatial data and rainfall rate data are obtained from vector or feature towards raster with a grid value of 100 cells. The rasterization process of the vector data is conducted based upon attribute data possessed by each vector data. The attribute and vector spatial data used are rainfall rate, manning coefficient, correction coefficient, interception coefficient, and flowing coefficient. The description on spatial data type and attribute data used to develop raster spatial data is shown in Table 7.

In the next step, the raster data produced is used in the raster spatial analysis phase, i.e., computing net rain analysis, surface run-off analysis, wet cross-sectional area analysis, flow speed analysis, and cell debit analysis. The raster spatial analysis is conducted by using *map algebra expression* tools in *Model Buil-*

der. Description on the required raster spatial data type to perform the analysis along with the mathematical equations used can be seen in Table 8.

Table 7. Vector Spatial Data Type Used for Raster Data's Spatial Data

Raster Spatial Data	Attribute Data	Raster Spatial Data Output	Cell Size
Rainfall Rate	Rainfall Rate	Rainfall Rate Raster	100
Land Use	Correction Coefficient	Correction Coefficient Raster	100
	Draining Coefficient	Draining Coefficient Raster	100
	Interception Coefficient	Interception Coefficient Raster	100
	.Manning Coefficient	Manning Coefficient Raster	100

Table 8. Vector Spatial Analysis Type for Computing Each Cell Debit

Raster Spatial Data	Analysis Type	Output Data	Mathematical Model of Mathematical Operation
-Interception Coefficient -Rainfall Rate	Union	Net Rain	Interception Coefficient * Rain Raster
-Net Rain -Flowing Coefficient -Correction Coefficient -Slopeness	Union	Surface Runoff	Net Rain / (Flowing Coefficient * Correction Coefficient)
-Surface Flow	Union	Wet Cross-Sectional Area	(100 * Surface Runoff)
-Wet Cross section area -Surface Flow -Manning Coefficient -Slopeness	Union	Flow Speed	(1/Manning) * POW((100 * Surface Runoff) / (100 + (2 * Surface Runoff)),0.67) * POW(slope2,0.5)
-Flow Speed	Union	Each Cell's Debit	Flow Speed * Wet Cross=Sectional Area

The whole process to compute each cell's debit is performed by using *ModelBuilder* as shown in Figure 3.
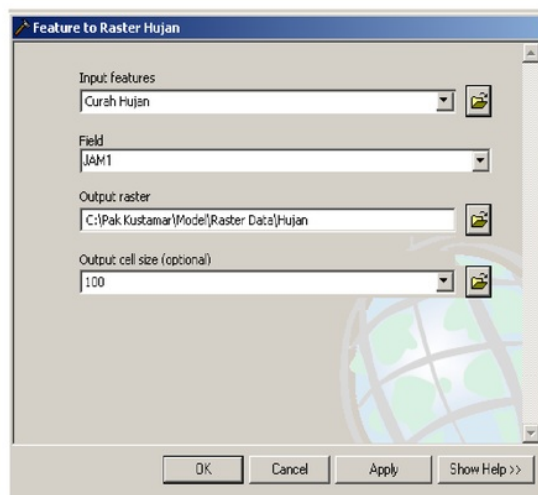

Figure 3. *Model Builder's* Facilities

Model Builder used for computing each cell's debit can be used for computing the debit value of each cell for figuring out each cell's debit value for an hourly time unit by converting rainfall data source in the rasterization process of rainfall rate data such as shown in Figure 5.

Model Description

Merging the above two model components into ITN-1 River Basin Hydrology Model produces a model with the following description:
1) A model of conceptual-distributed type.
2) Accommodating the effects of land use during the change process induced by rain that converts an area into a river by using Interception, Infiltration and *Manning* roughness (n) parameters, .
3) A Surface Runoff model with one-dimensional flow concept (1D),
4) A model equipped with facilities to input **Kk** value which is meant to rectify infiltration capacity data which is based upon soil type map along with land use information.
5) Spatial, hydrology and hydraulics analysis conducted by using *ArcGIS.*

6) Can be used to compute hourly surface runoff debits without going through calibration process.

Model Testing

Model testing is meant for discovering a model's capabilities in simulating and analyzing real world condition, in this case, surface runoff debit hydrograph and low water flow parameters are used as measurement. A model is considered capable to simulate and analyze real conditions if the results of a model's computation possess high equivalents to data yielded from measurement results.
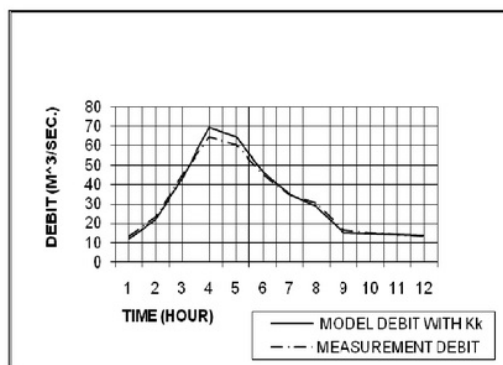

Figure 4. Surface Runoff Debit

A measure of equivalence is demonstrated by a model's capability in imitating graph trends resulting from measurement (debit hydrograph) in the calibration or verification process. In order to find out that equivalence, trend testing is conducted in the form of graph displays by comparing measurement results to the model's results. Two (or more) graphs are considered possessing equivalent trends when they visually display equivalent shapes.

Used in the model testing were the physical data of Lesti River Basin, brief-duration rain data from a number of automatic rain stations, debit processed from the recorded water surface elevation. Computation results produced by ITN-2 River Basin Hydrology Model (ITN-1 River Basin Hydrology Model equipped with the application of KK value) showed a quite significant change.

The effect of applying kk in analyzing surface runoff debit is shown in Figure 4. From the analysis it was discovered that there was a decrease in the Peak Height Coefficient value from 1.08 (in ITN-1 River Basin Hydrology Model) to 1.02. This made

the role of numerical calibration lesser since the model accommodated a greater number of strongly influential parameters. This condition signifies that in the absence of a measurement result of debit data in a river basin, while its other physical data are sufficiently accurate, the required calibration process can be left out.

The perfection of Kk value in various researches which analyze the effect of land use and cultivation is predicted to further decrease this value to be closer to a value of 1. This will result in the increased accuracy of a model as well as ensure the discard of aby calibration process
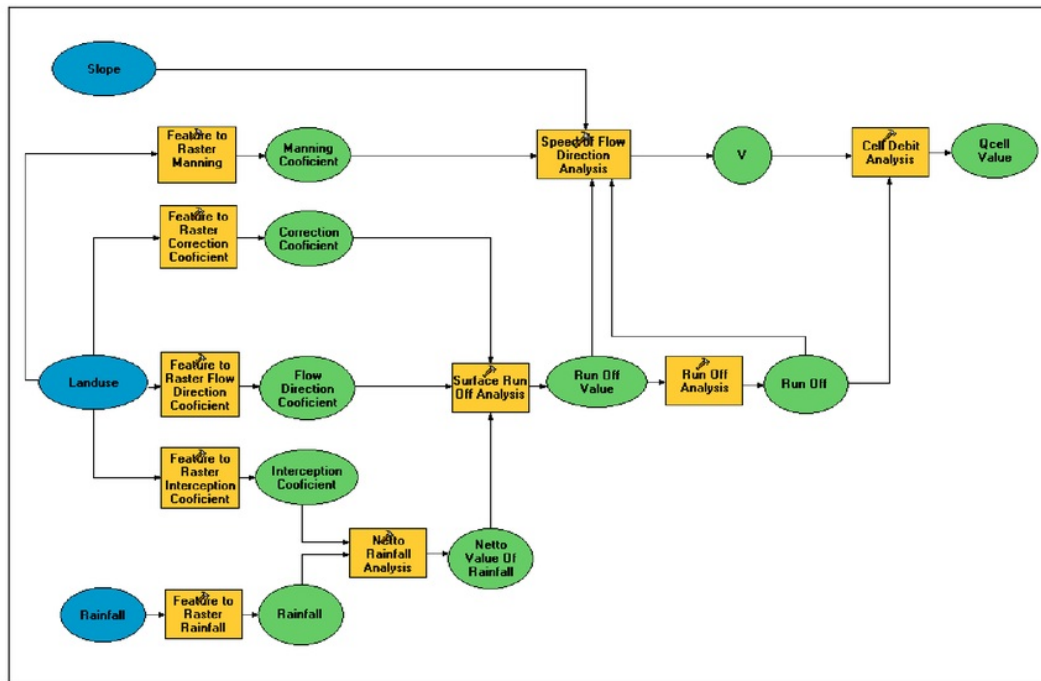

Figure 4. Each Cell's Debit Computation Sequence by Using *Model Builder*

CONCLUSION AND SUGGESTION

Conclusion

Based upon the result of the research above, it can be concluded that:
1. ITN-2 River Basin Hydrology Model is a River Basin hydrology model of conceptual-distributed type, as a result of improving ITN-1 River Basin Hydrology Model.
2. The model's perfection was achieved by introducing Kk parameter which represents the effet of land condition on infiltration capacity, as well as using *model builder* facilities found in ArcView for analyzing flood debit.
3. By accommodating the effect of land use in analyzing infiltration capacity, the role of numerical calibration parameter becomes very small. Hence ITN-2 River Basin Hydrology Model can be used to analyze flood debit without the need of calibration process.

Suggestion

To increase the accuracy of debit analysis results, Kk values should be enriched by researches in order to accommodate land condition in relation with its cultivation.

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