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on Natural Disaster Reduction - Flood
Taiwan, R.O.C.

Technology for Runoff Analysis

– in Gauged and Ungauged Watersheds

Kwan Tun LEE

Director of Geographic Information Center
Professor of the River and Harbor Engineering
National Taiwan Ocean University
Keelung, Taiwan, R.O.C.

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Objective of Watershed Runoff Analysis

Engineering design work

1. To provide design discharge information for engineers to perform the design work at target positions.
2. Target positions may locate at anywhere in the watershed.
3. Working time is usually not strictly limited.

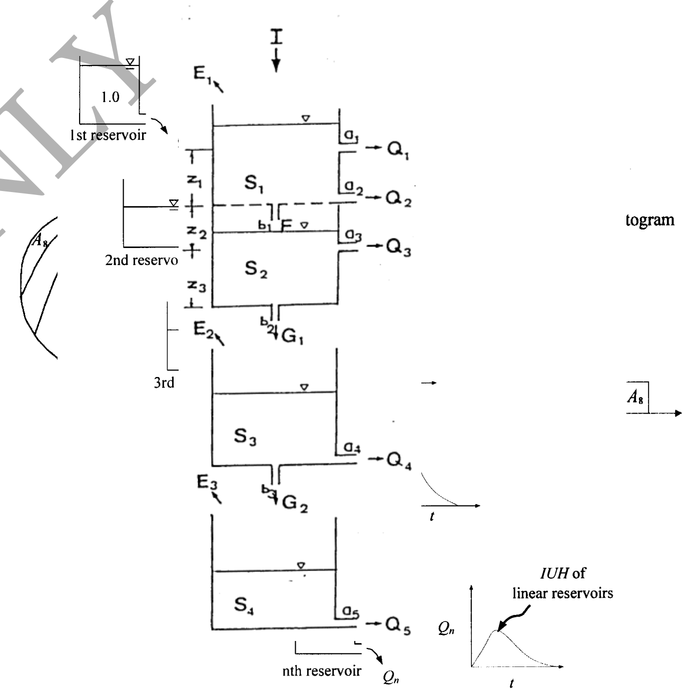
Real-time flood forecasting

1. To provide incoming discharge for authorities to disseminate flooding information and to perform flood disaster control.
2. Target positions may locate at anywhere in the watershed.
3. Working time is usually strictly limited.

Conventional Watershed Runoff Modeling

Linear system model / black-box model /conceptual model

unit hydrograph (UH; Sherman, 1932)
instantaneous unit hydrograph (IUH)
time-area method (Clark, 1945)
linear reservoir method (Nash, 1957)
tank model (Sugawara, 1974)
……

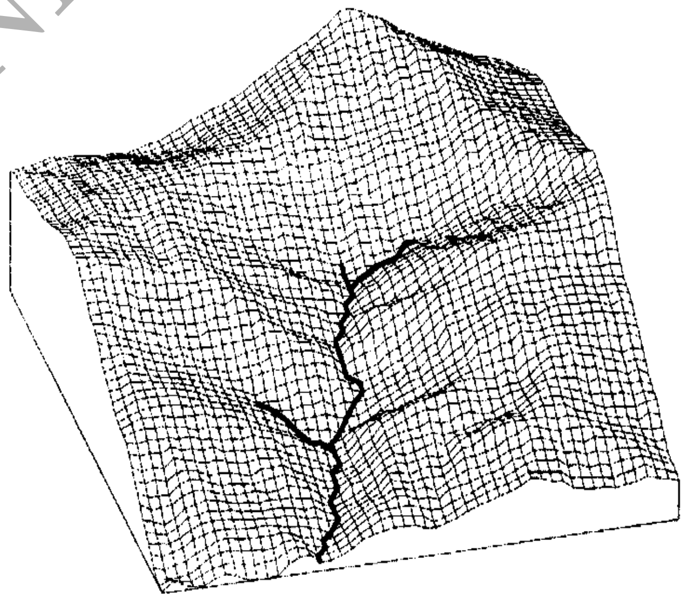


- Model input requirement
  watershed rainfall & flow records
  for model parameters calibration

- Practical application problems
  The models can not be applied to ungauged watersheds, and simulation is poor for watersheds with highly nonlinear & time-variant characteristics.

Contemporary Watershed Runoff Modeling

Grid-based numerical models
kinematic-wave watershed model
diffusion-wave watershed model
dynamic-wave watershed model



- Model inputs requirement
  digital topography data
  land cover data
  channel cross section data
  rainfall records

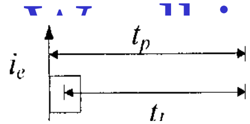
- Practical application problems
  Lots of computing time is required for runoff simulation. Consequently, the gird-based model is basically impossible to be applied for real-time flood forecasting.

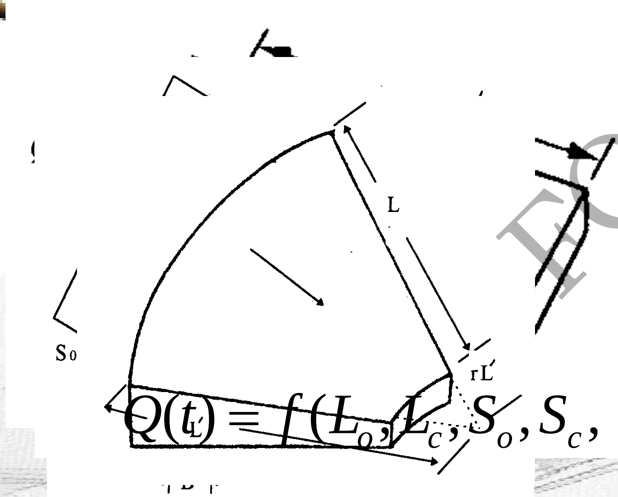
All Purposes Watershed Runoff Modeling

- The model should be derived based on watershed geomorphologic characteristics. So, it can be applied to any location with/without flow record data.
- It should be a nonlinear & time-variant model to account for the hydrodynamic phenomena of the watershed.
- The model should be performed in an efficient way to conduct the real-time flood forecasting work.

Previous Geomorphology-Based Modeling

- SCS (1957): synthetic hydrograph method
- Henderson and Wooding (1964): overland-plane model
- Wooding (1965): V-shaped overland-plane model
- verging overland-plane model
- Valdes (1979):





$$T_L = 0.6T_c$$

$$T_b = 2.67T_p$$

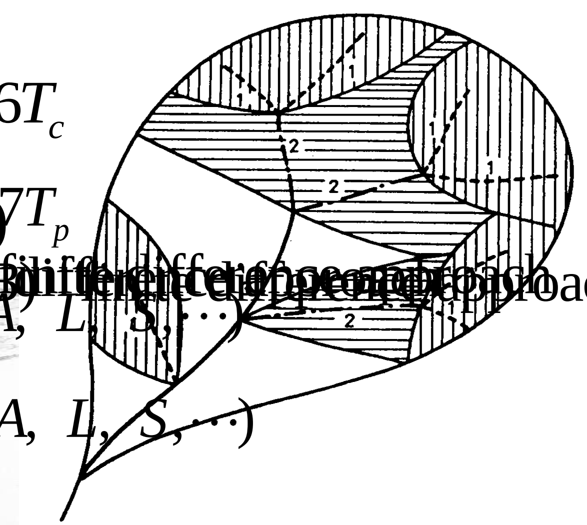
rograph (GIUH)

$Q(t) = f(L_o, L_c, S_o, S_c)$ finite difference approach

$$T_c = f(A,\ L,\ S, \cdots)$$

$$Q_p = f(A,\ L,\ S, \cdots)$$

$$Q(t) = f(L_o, L_c, S_o, S_c,\ network\ structure)$$



Geomorphologic Instantaneous Unit Hydrograph (GIUH)

- unit rainfall → N independent raindrops

- the probability for a raindrop adopting a specified path

$$P(w) = P_{OA_i} \cdot P_{x_{oi}x_i} \cdots P_{x_i x_j} \cdots P_{x_k x_\Omega}$$

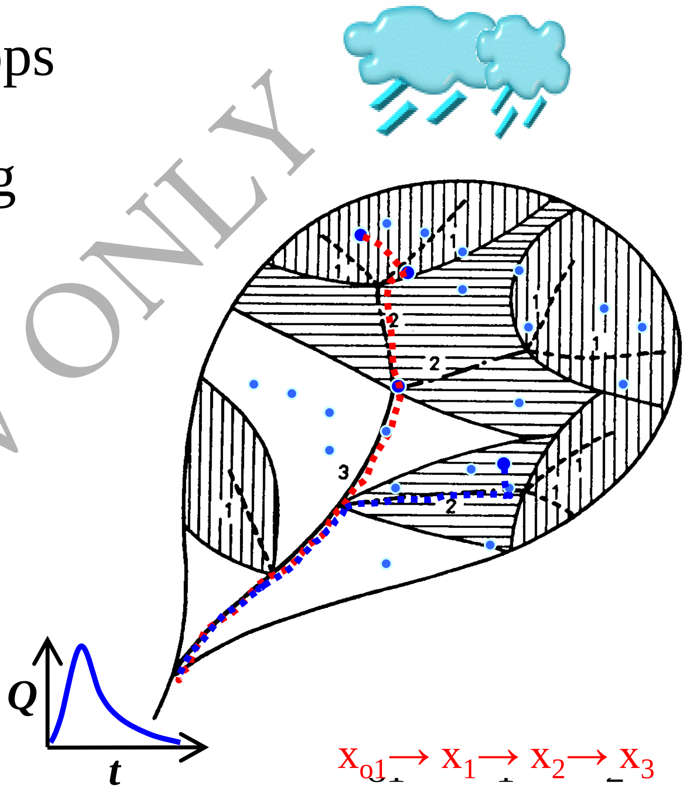
- total runoff travel time along the path

$$T_w = T_{x_{oi}} + T_{x_i} + T_{x_j} + \cdots + T_{x_\Omega}$$

- watershed geomorphologic IUH (Rodriguez-Iturbe & Valdes, 1979)

$$u(t) = \sum_{w \in W} \left[f_{x_{oi}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_w \cdot P(w)$$

where $f(t)$ is the runoff travel time distribution



$x_{o1} \rightarrow x_1 \rightarrow x_2 \rightarrow x_3$

$x_{o1} \rightarrow x_1 \rightarrow x_3$

$x_{o2} \rightarrow x_2 \rightarrow x_3$

$x_{o3} \rightarrow x_3$

Kinematic-Wave Overland Travel Time

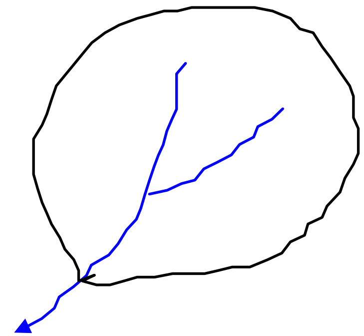
- travel time for *i*th-order overland-flow

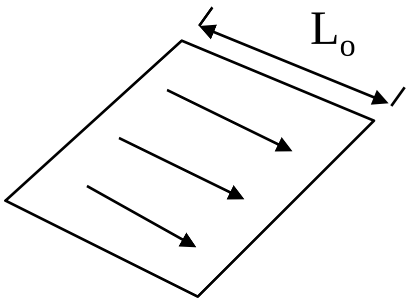
$$\frac{\partial q_{o_i}}{\partial x} + \frac{\partial y_{o_i}}{\partial t} = i_e$$

$$\frac{\partial h_i}{\partial t} + \frac{\partial q_i}{\partial x} = q_o$$

$$\Rightarrow \quad T_{x_{oi}} = \left(\frac{n_o \overline{L}_{o_i}}{\overline{S}_{o_i}^{1/2} \, i_e^{m-1}} \right)^{\frac{1}{m}}$$

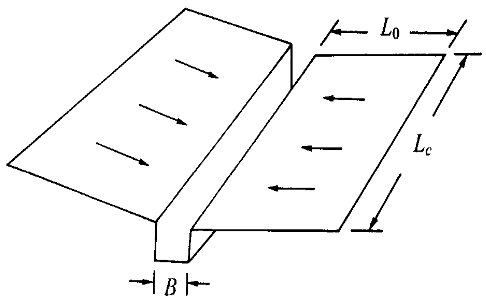
Henderson & Wooding (1964)





K-W Channel Travel Time – Single V-Shaped Model

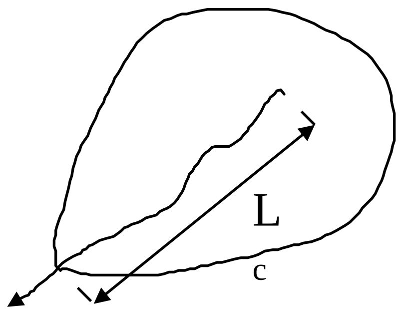
$$\begin{cases} \dfrac{\partial h_c}{\partial t} + \dfrac{\partial q_c}{\partial x} = \dfrac{2 i_e L_o}{B} \\ q_c = \alpha_c h_c^{m} \quad ; \ \alpha_c = \dfrac{\sqrt{S_c}}{n_c} \end{cases}$$



define $$\frac{dx}{dt} = \alpha_c m h_c^{m-1}$$

$$\Rightarrow \frac{Dh_c}{Dt} = \frac{2 i_e L_o}{B} \qquad \Rightarrow h_o = \frac{2 i_e L_o}{B} t$$

$$\Rightarrow \int_0^{L_c} dx = \int_0^{T_{cc}} \alpha_c m h_c^{m-1} dt = \alpha_c m \int_0^{T_{cc}} \left(\frac{2 i_e L_o}{B} t \right)^{m-1} dt$$



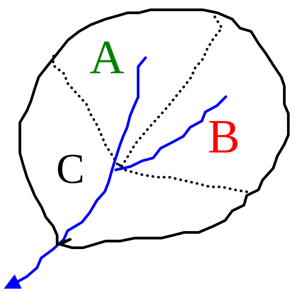
$$\therefore \ T_{cc} = \frac{B}{2 i_e L_o} \left(\frac{2 i_e n_c L_o L_c}{\sqrt{S}\, B} \right)^{\frac{1}{m}}$$

Wooding (1965)

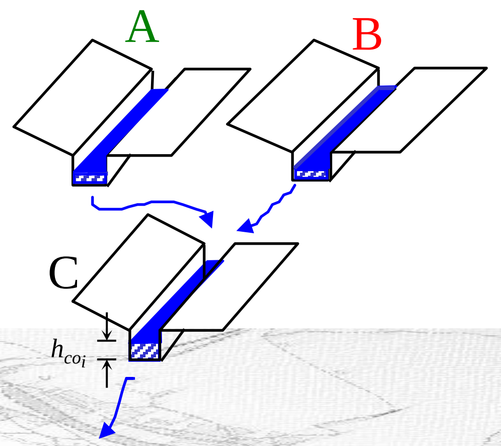
K-W Channel Travel Time (Network V-Shaped Model)

- travel time for *i*th-order channel-flow (Lee and Yen, 1997)

$$T_{x_i} = \frac{B_i}{2 i_e \bar{L}_{o_i}} \left[\left(h_{co_i}^m + \frac{2 i_e n_c \bar{L}_{o_i} \bar{L}_{c_i}}{\sqrt{\bar{S}_{c_i}}\, B_i} \right)^{\frac{1}{m}} - h_{co_i} \right]$$



the inflow depth of the *i*th-order channel due to water transported from upstream reaches (Lee and Yen, 1997)



$$h_{co_i} = \left[\frac{i_e n_c \left(N_i \bar{A}_i - AP_{OA_i} \right)}{N_i B_i \bar{S}_{c_i}^{1/2}} \right]^{\frac{1}{m}}$$

$a_{oi}, b_i, \cdots, b_\Omega$

Kinematic-Wave-Based GIUH Model (KW-GIUH)

If the runoff travel time distribution can be assumed to follow an exponential distribution, then the IUH can be expressed analytically as

$$u(t) = \sum_{w \in W} \left[a_{o_i} \exp(-\frac{t}{T_{x_{o_i}}}) + b_i \exp(-\frac{t}{T_{x_i}}) + \cdots + b_\Omega \exp(-\frac{t}{T_{x_\Omega}}) \right]_w \cdot P(w)$$

where $a_{oi}, b_i, \cdots, b_\Omega$ can be determined by comparing coefficients in partial fractions after applying the Laplace transformation.

$$T_{x_{oi}} = \left(\frac{n_o \bar{L}_{o_i}}{\bar{S}_{o_i}^{1/2} i_e^{m-1}} \right)^{\frac{1}{m}}$$

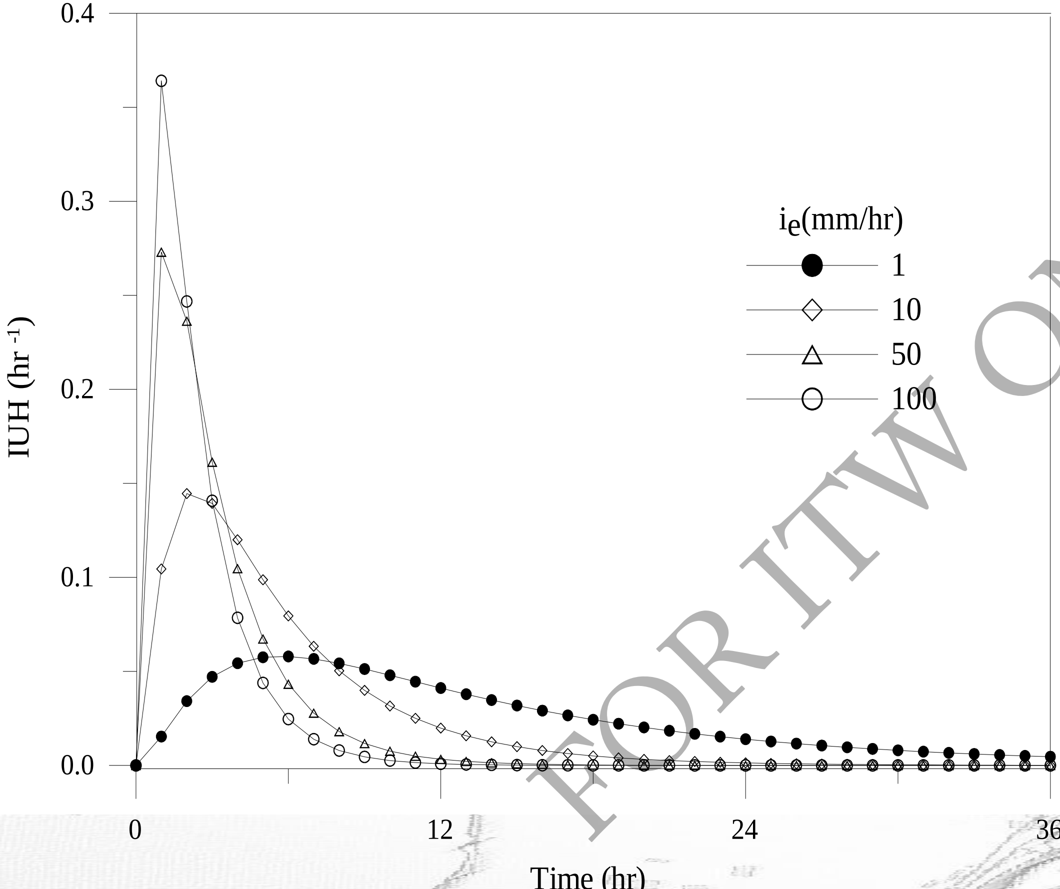
$$h_{co_i} = \left[\frac{i_e n_c \left(N_i \bar{A}_i - AP_{OA_i} \right)}{N_i B_i \bar{S}_{c_i}^{1/2}} \right]^{\frac{1}{m}}$$

$$T_{x_i} = \frac{B_i}{2 i_e \bar{L}_{o_i}} \left[\left(h_{co_i}^m + \frac{2 i_e n_c \bar{L}_{o_i} \bar{L}_{c_i}}{\bar{S}_{c_i}^{1/2} B_i} \right)^{\frac{1}{m}} - h_c \right.$$

<u>nonlinear & time-variant model</u>

Kinematic-wave-based geomorphologic IUH (Lee and Yen, 1997)

Time varying & Nonlinearity of the KW-GIUH



Flow travel time estimation

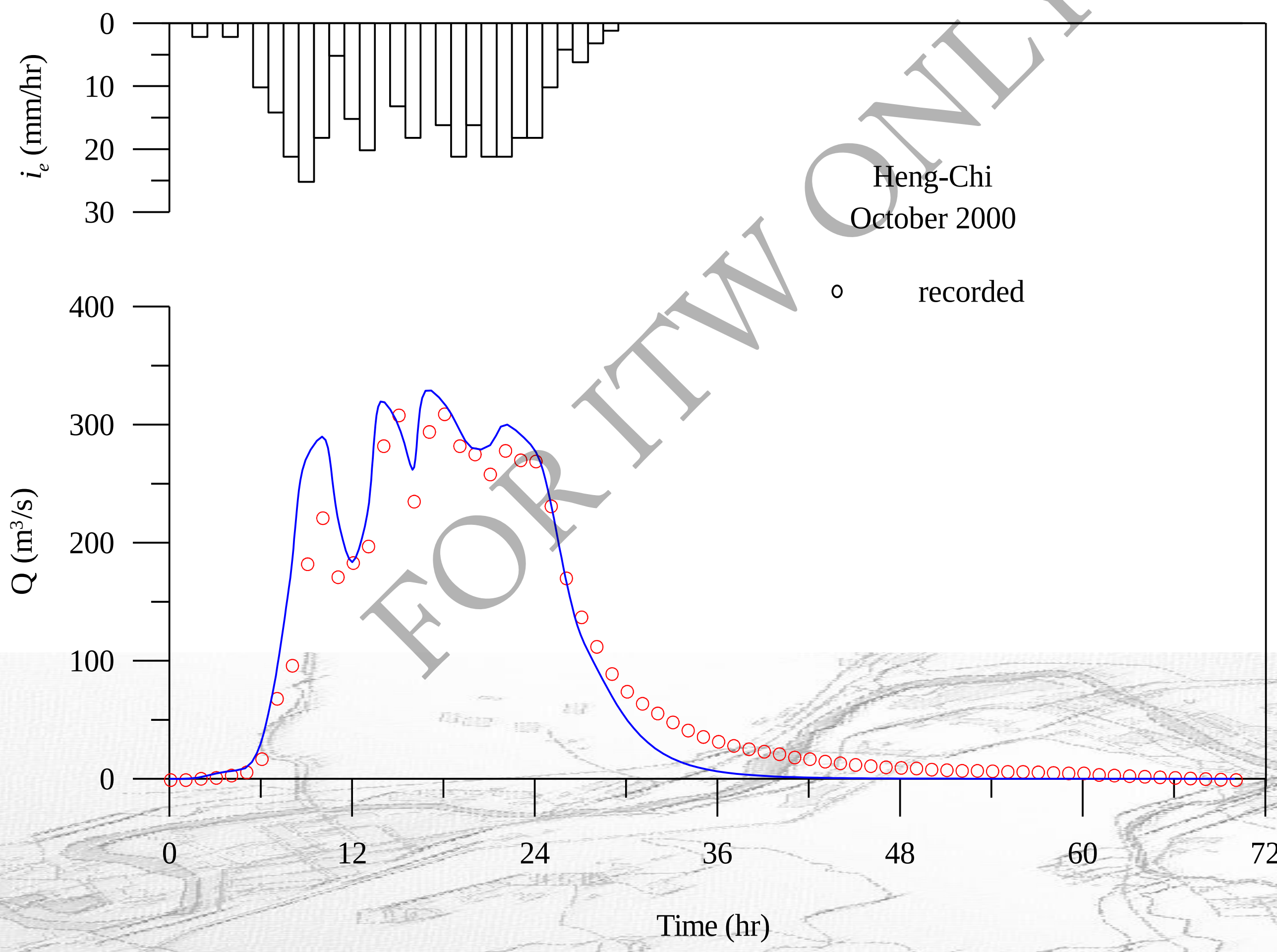
$$T_{x_{oi}} = \left(\frac{n_o \bar{L}_{o_i}}{\bar{S}_{o_i}^{1/2} i_e^{m-1}} \right)^{\frac{1}{m}}$$

$$T_{x_i} = \frac{B_i}{2 i_e \bar{L}_{o_i}} \left[\left(h_{co_i}^m + \frac{2 i_e n_c \bar{L}_{o_i} \bar{L}_{c_i}}{\bar{S}_{c_i}^{1/2} B_i} \right)^{\frac{1}{m}} - h_{co_i} \right]$$

- the IUH is a function of the rainfall intensity
- a set of IUHs instead of only one IUH for a specified watershed

Runoff simulation in Heng-Chi watershed

Storm event in Oct. 2000 (n_o = 0.8, n_c= 0.05)



Channel Roughness Coefficient (Chow, 1959)

Material	n
Metals	
Steel	0.012
Cast iron	0.013
Corrugated metal	0.025
Nonmetals	
Lucite	0.009
Glass	0.010
Cement	0.011
Concrete	0.013
Wood	0.012
Clay	0.013
Brickwork	0.013
Gunite	0.019
Masonary	0.025
Rock cuts	0.035
Natural streams	
Clean and straight	0.030
Bottom: gravel, cobbles and boulders	0.040
Bottom: cobbles with large boulders	0.050

*Compiled from Chow (1959).

reasonable range
0.012 – 0.05

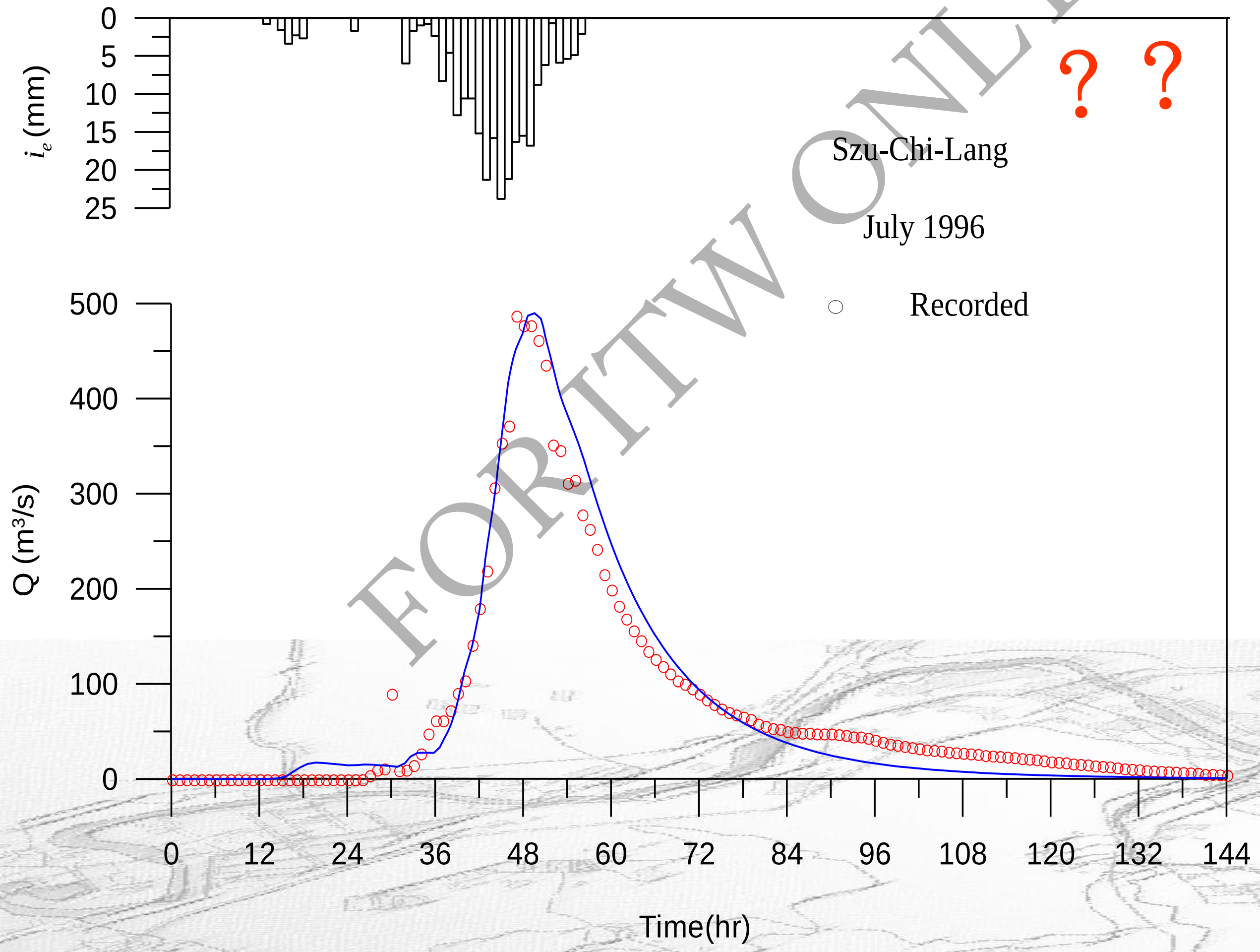
Overland Roughness Coefficient (SCS, 1986)

Surface Description	*n*
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤20%	0.06
Residue cover >20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods:	
Light underbrush	0.40
Dense underbrush	0.80

reasonable range
0.011 – 0.8

Runoff Simulation in Szu-Chi-Lan Watershed

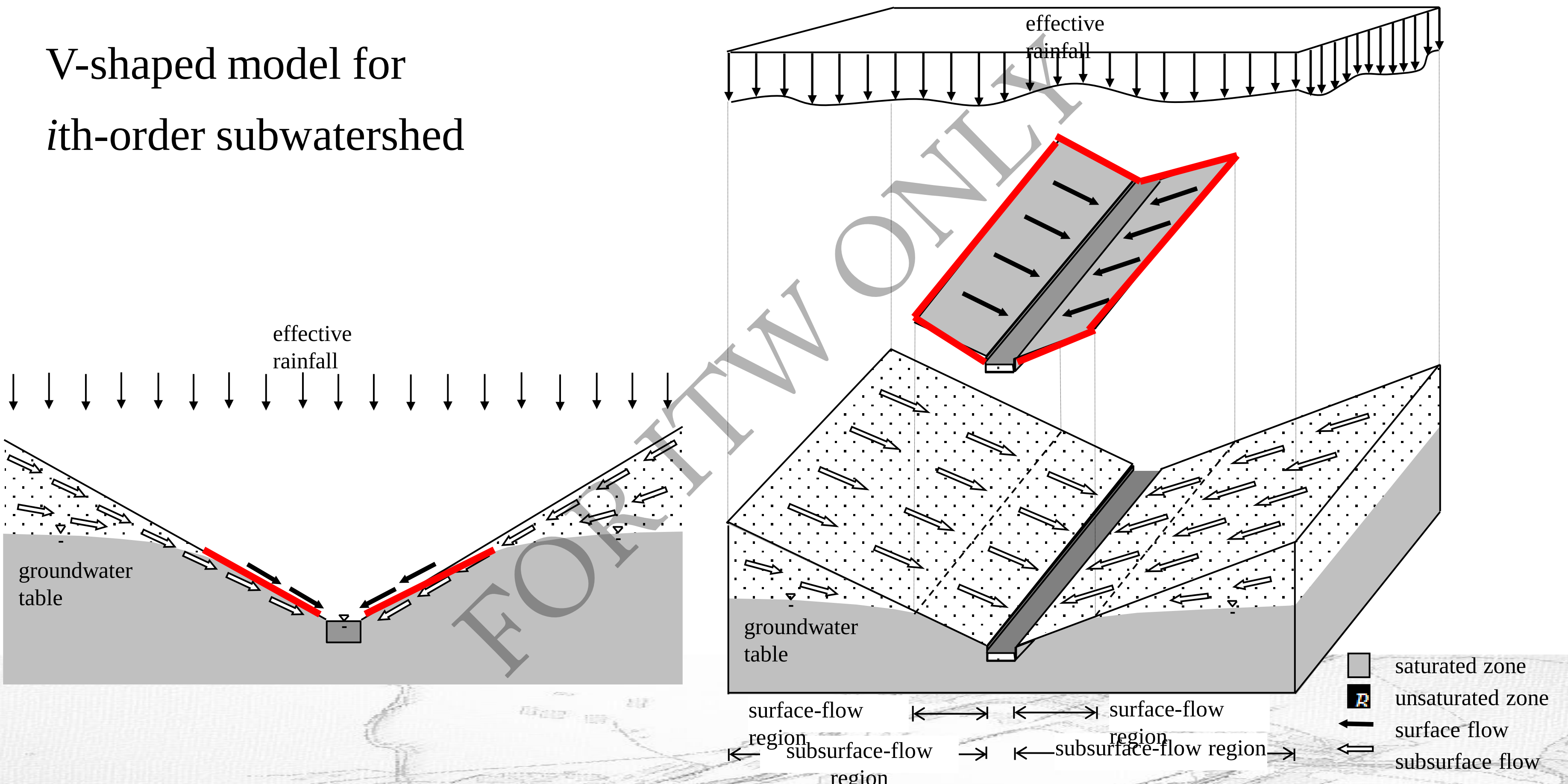
Storm event in July 1996 (n_o = 16.7, n_c= 0.05)



V-Shaped Watershed Considering Subsurface Flow

V-shaped model for

*i*th-order subwatershed



Field investigation showed that the surface flow occurs only on the partial contributing area (PCA) during a storm.

KW-GIUH Model Considering Subsurface Flow

- Flow path probability

  surface flow $P(w_s) = R_{PCA_i} \cdot P_{OA_i} \cdot P_{x_{o_i} x_i} \cdot P_{x_i x_j} \cdots P_{x_k x_\Omega}$

  subsurface flow $P(w_{sub}) = (1 - R_{PCA_i}) \cdot P_{OA_i} \cdot P_{x_{sub_i} x_i} \cdot P_{x_i x_j} \cdots P_{x_k x_\Omega}$

- Runoff travel time

  surface flow $T_{w_s} = T_{x_{o_i}} + T_{x_i} + T_{x_j} + \cdots + T_{x_\Omega}$

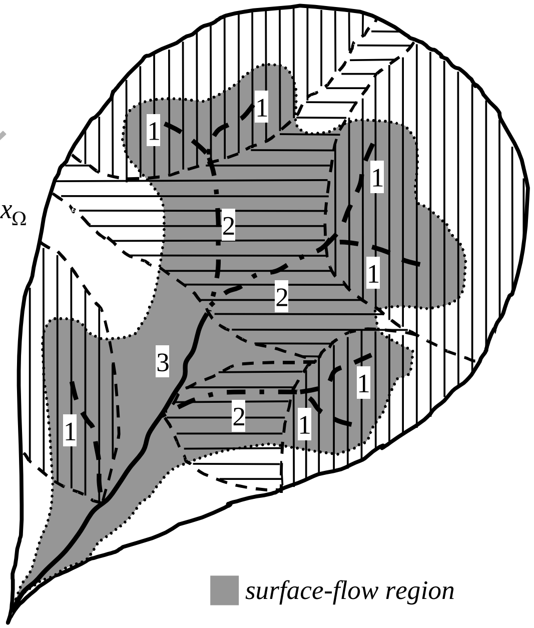
  subsurface flow $T_{w_{sub}} = T_{x_{sub_i}} + T_{x_i} + T_{x_j} + \cdots + T_{x_\Omega}$

- Surface & Subsurface IUH

$$u_s(t) = \sum_{w_s \in W_s} \left[f_{x_{o_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_s} \cdot P(w_s)$$

$$u_{sub}(t) = \sum_{w_{sub} \in W_{ubs}} \left[f_{x_{sub_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_{sub}} \cdot P(w_{sub})$$

$$u(t) = u_s(t) + u_{sub}(t)$$



surface flow paths	*subsurface flow paths*
$x_{o1} \to x_1 \to x_2 \to x_3$	$x_{sub1} \to x_1 \to x_2 \to x_3$
$x_{o1} \to x_1 \to x_3$	$x_{sub1} \to x_1 \to x_3$
$x_{o2} \to x_2 \to x_3$	$x_{sub2} \to x_2 \to x_3$
$x_{o3} \to x_3$	$x_{sub3} \to x_3$

Subsurface-flow kinematic-wave based geomorphologic IUH (Lee and Chang, 2005)

Runoff Travel Times Estimation

- Overland-flow travel time

$$T_{x_{o_i}} = \left(\frac{n_o \bar{L}_{o_i}}{\bar{S}_{o_i}^{1/2} \, i_e^{\,m\text{-}1}} \right)^{\frac{1}{m}}$$

- Subsurface-flow travel time

$$T_{x_{sub_i}} = \frac{\eta \bar{L}_{sub_i}}{K_0 \bar{S}_{sub_i}}$$

- Channel-flow travel time

$$T_{x_i} = \frac{B_i}{2 i_e \bar{L}_{sub_i}} \left[\left(h_{co_i}^m + \frac{2 i_e n_c \bar{L}_{sub_i} \bar{L}_{c_i}}{B_i \bar{S}_{c_i}^{1/2}} \right)^{1/m} - h_{co_i} \right]$$

$$u_s(t) = \sum_{w_s \in W_s} \left[f_{x_{o_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_s} \cdot P(w_s)$$

$$u_{sub}(t) = \sum_{w_{sub} \in W_{ubs}} \left[f_{x_{sub_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_{sub}} \cdot P(w_{sub})$$

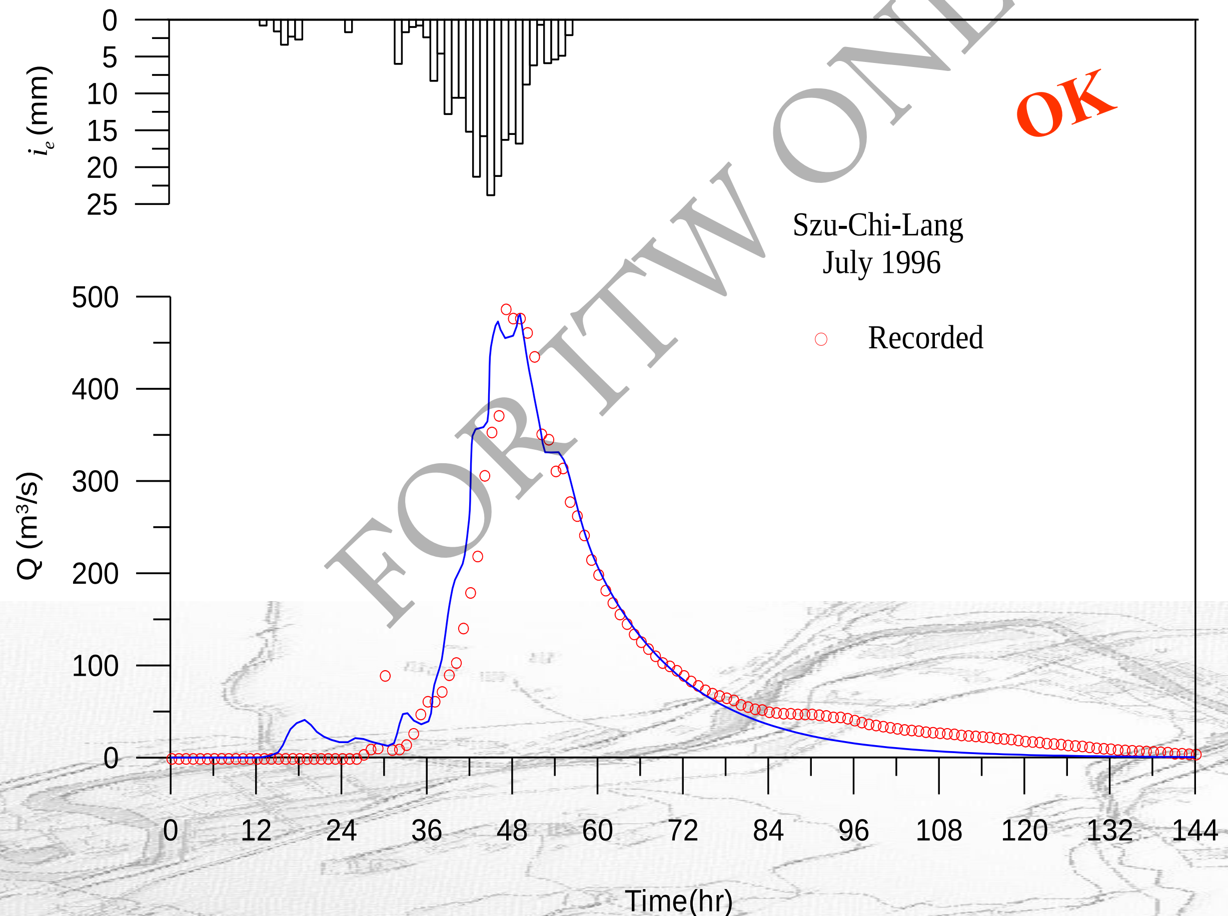
$$u(t) = u_s(t) + u_{sub}(t)$$

Surface- & subsurface-flow KW-GIUH

Runoff Simulation in Szu-Chi-Lan Watershed

Storm event in July 1996

(n_o = 0.6, n_c= 0.05, K_0= 0.011 m/s, η = 0.5, R_{PCA}= 0.21)



Spatial Distribution of Partial Contributing Area

T_{th}= 7.77 (R_{PCA}=0.2)

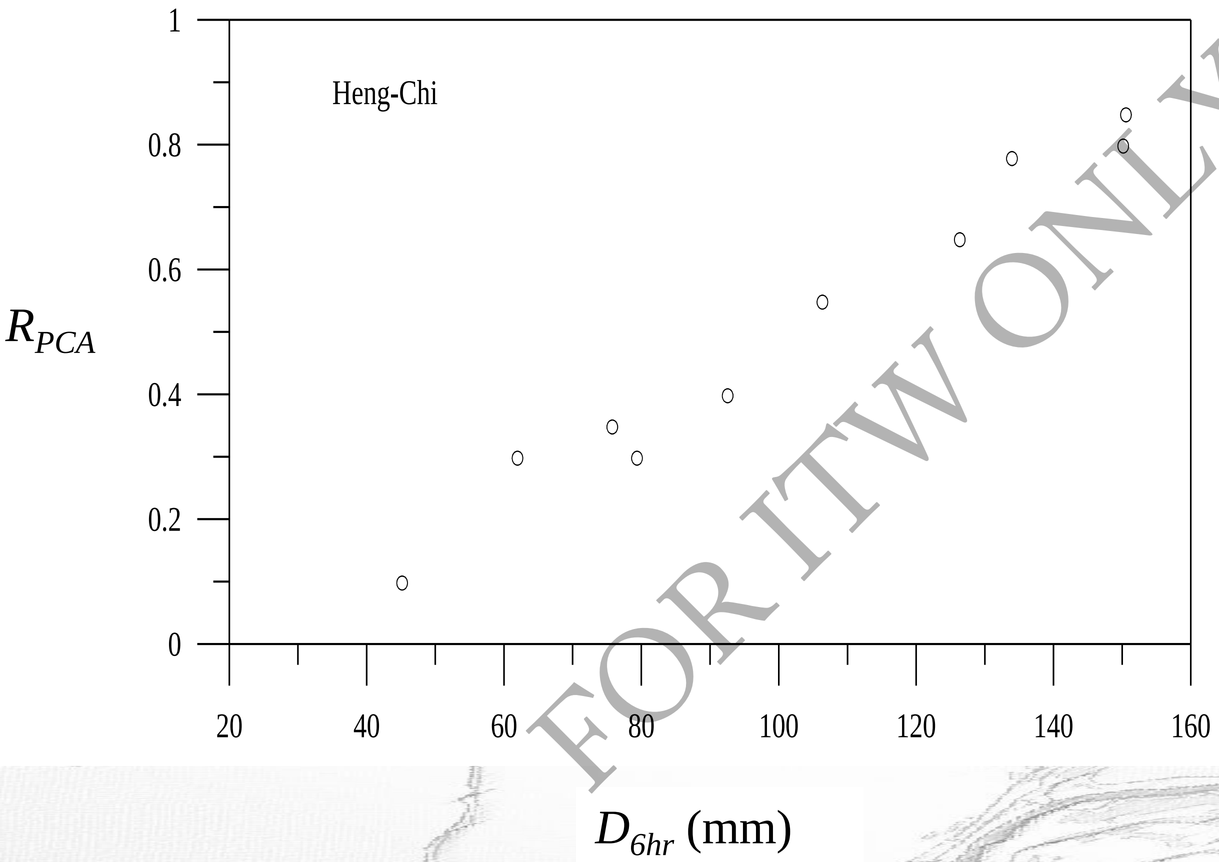
T_{th}= 5.90 (R_{PCA}=0.6)

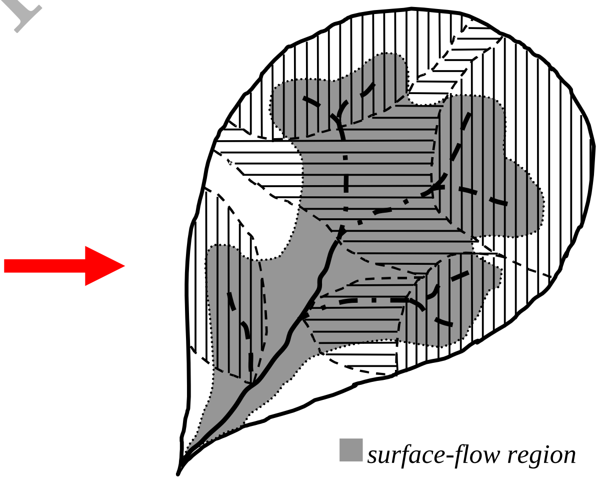
$$T_{th} = \ln\left(\frac{a}{\tan\beta}\right) \rightarrow R_{PCA}$$

Topographic index threshold

Ratio of partial contributing area

R_{PCA} and Rainfall Depth for Specified Duration

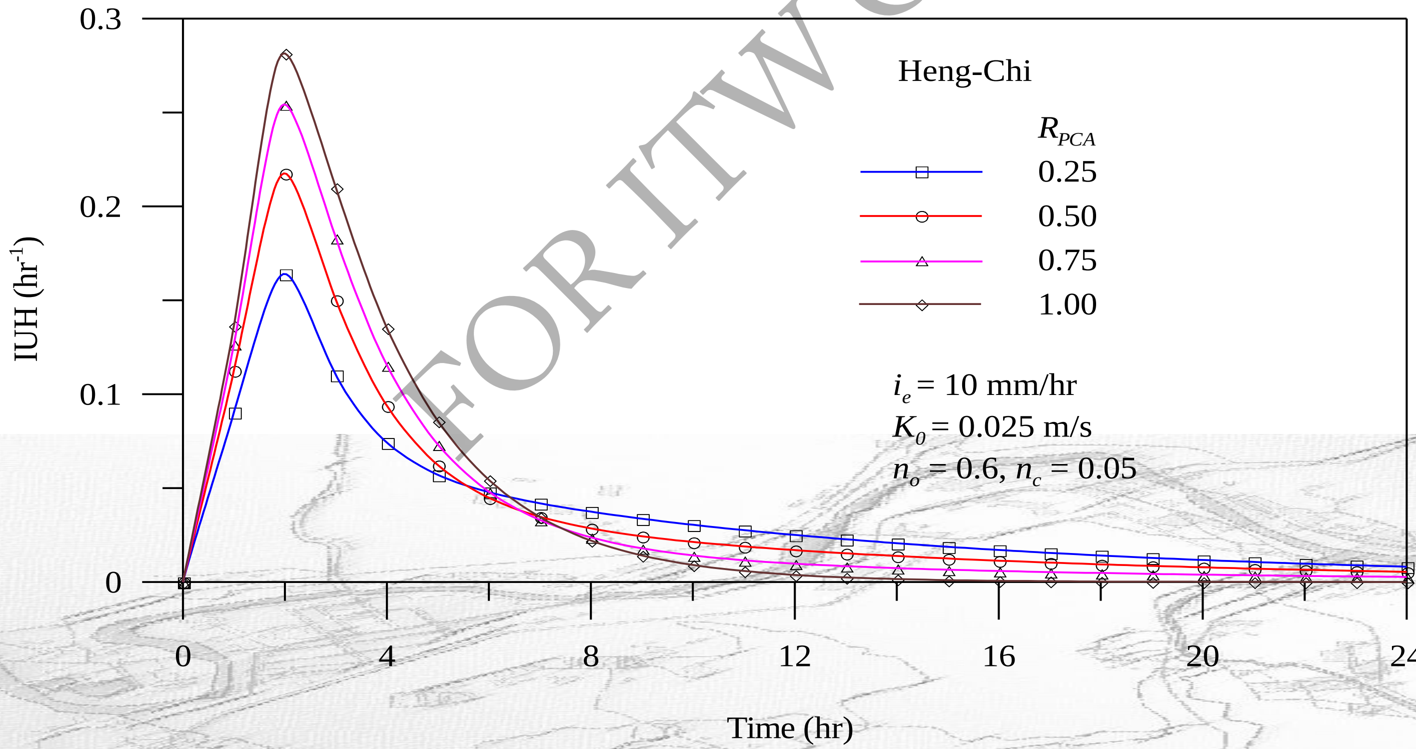




Relationship between max. 6-hr total rainfall depth D_{6hr} and the PCA ratio R_{PCA} in Heng-Chi watershed

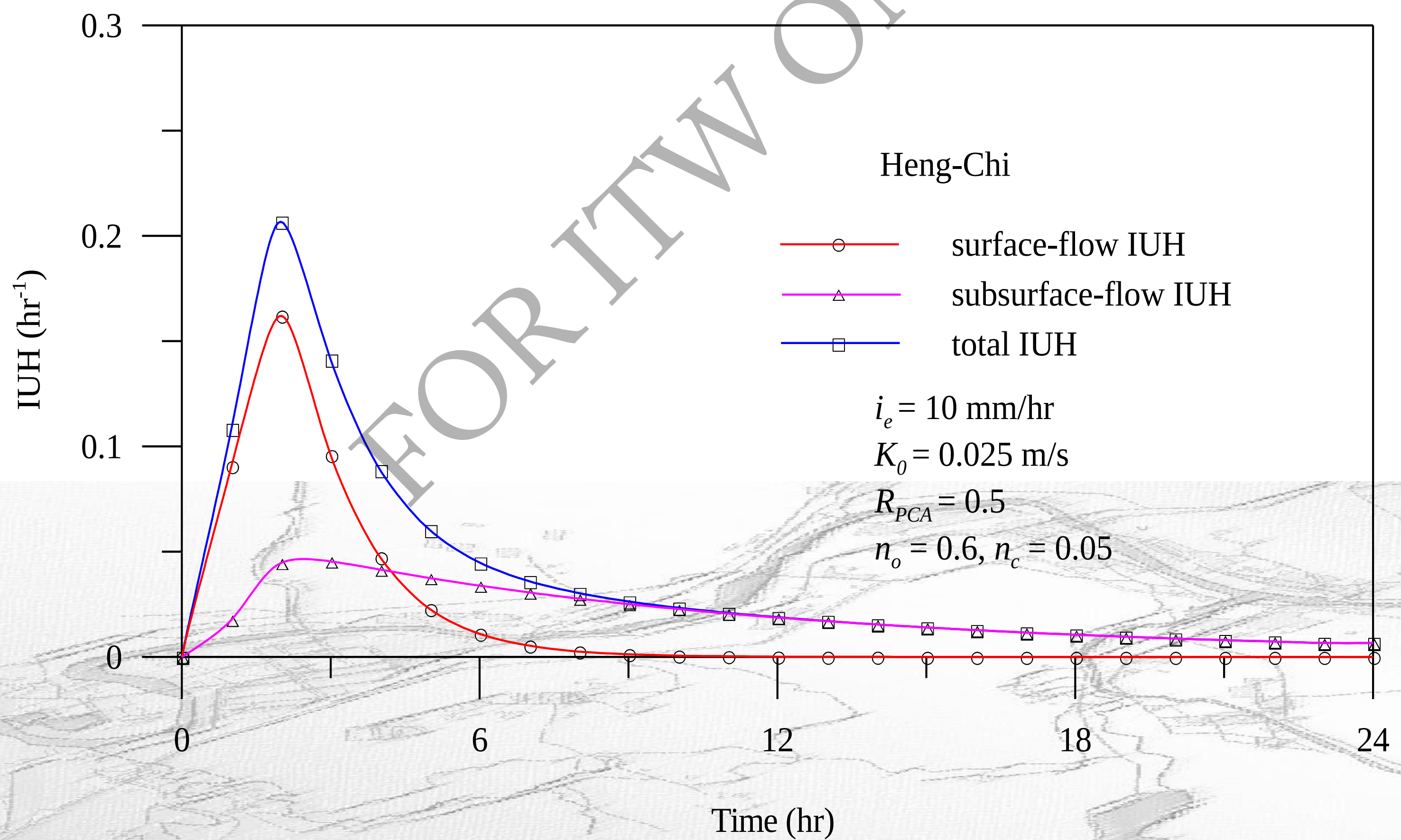
Influence of R_{PCA} on IUH

- A higher R_{PCA} value results in a sharp hydrograph because the surface-flow mechanism dominates the rainfall-runoff process.
- A lower R_{PCA} value results in a mild hydrograph because the subsurface-flow mechanism is dominant.



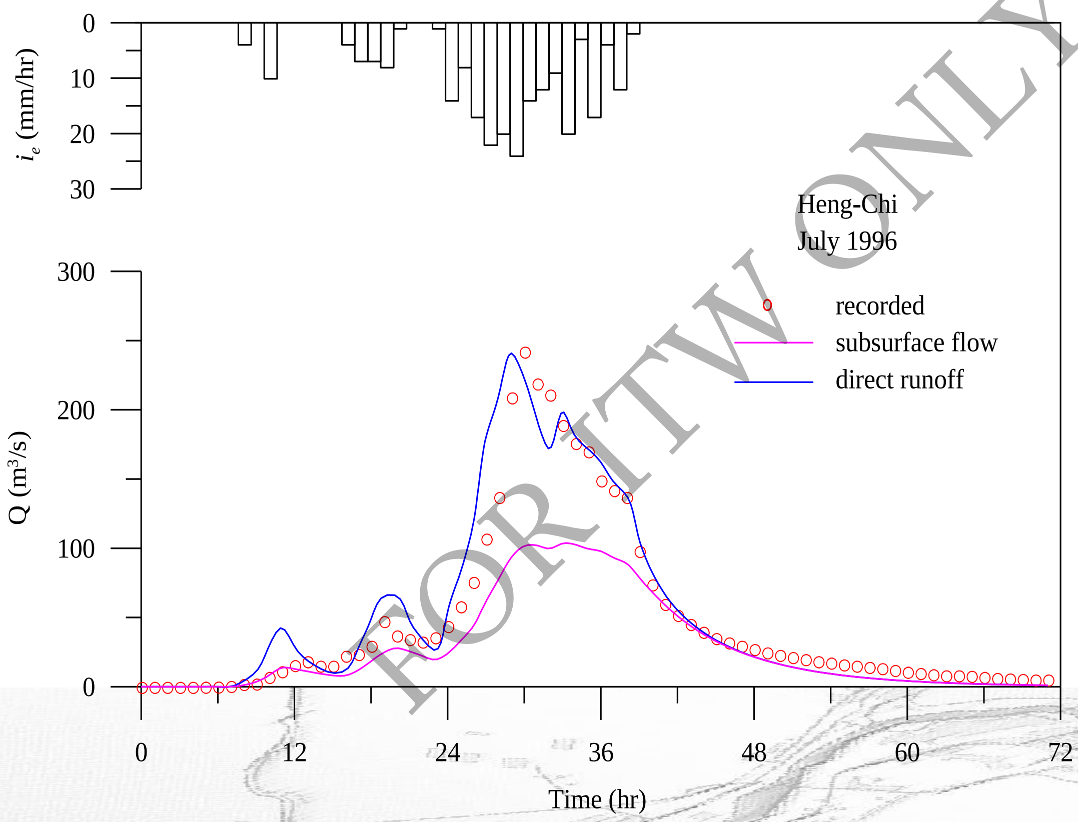
Comparison of Surface- and Subsurface-Flow IUHs

- The rising limb of the IUH is dominated by surface-flow mechanism, and the recession limb is dominated by subsurface-flow mechanism.
- The duration of the subsurface flow IUH is longer than that of the surface-flow IUH.



Runoff Simulation in Heng-Chi Watershed

- Rainstorm in July 1996

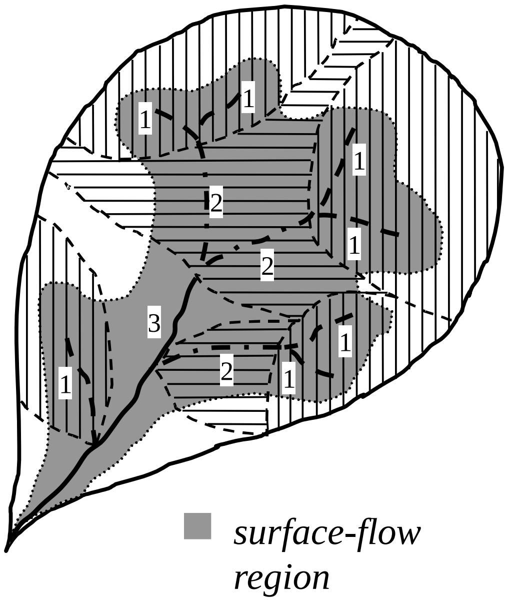


Chang, C.-H., Lee, K. T. (2008). Analysis of geomorphologic and hydrological characteristics in watershed saturated areas using topographic-index threshold and geomorphology -based runoff model, *Hydrological Processes*, 22, 802-812.

Input of KW-GIUH Model

- **Watershed geomorphologic factors**

$\bar{L}_{oi}$	ith-order overland-flow length
$\bar{S}_{oi}$	ith-order overland-flow slope
$\bar{L}_{ci}$	ith-order channel-flow length
$\bar{S}_{ci}$	ith-order channel-flow slope
$\bar{A}_{i}$	ith-order subwatershed contributing area
B_{Ω}	channel width at the watershed outlet
n_o	roughness coefficient for overland flow
n_c	roughness coefficient for channel flow
K_o	hydraulic conductivity



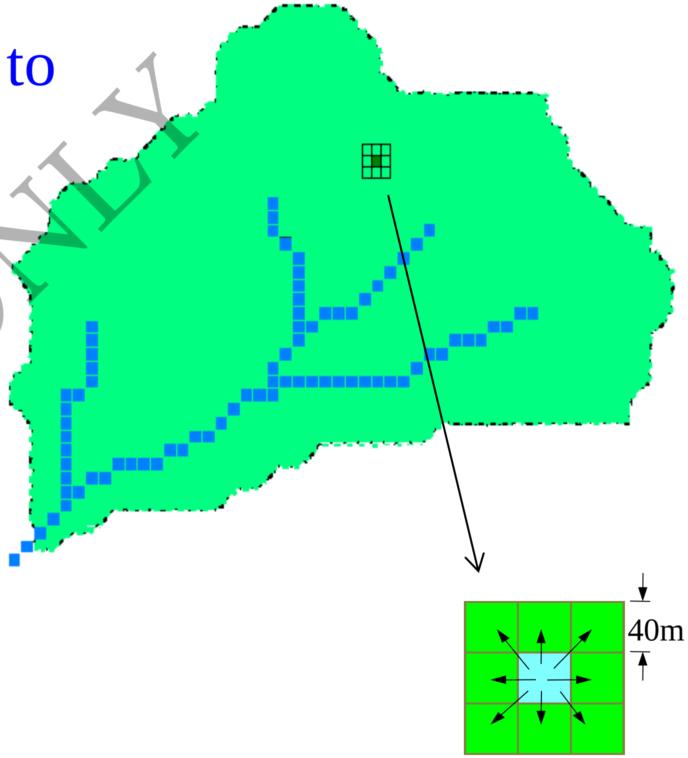
- **Watershed hydrological characteristics**

i_e	rainfall intensity
R_{PCA}	ratio of the surface-flow region to the total area of watershed

Digital Elevation Model (DEM)

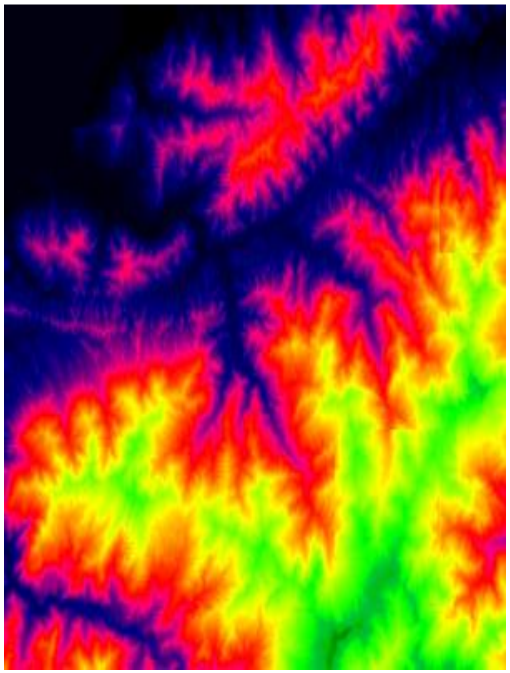
Flow direction is determined according to the elevation in the eight adjacent cells

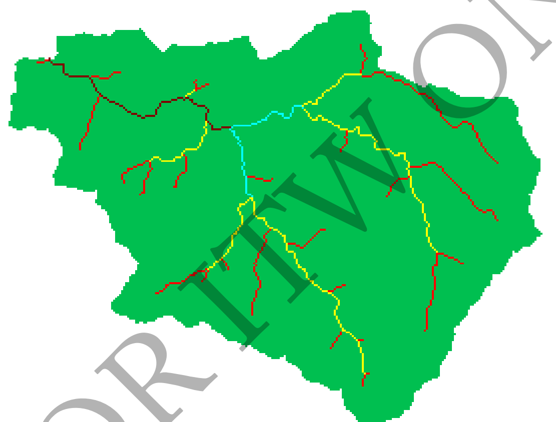
- Flow direction determination
- Depressionless
- Flow accumulation value calculation
- Channel network extraction
- Subwatershed delineation
- Geomorphologic factors calculation



digital elevation dataset

Geomorphologic Factors Calculation—DEM



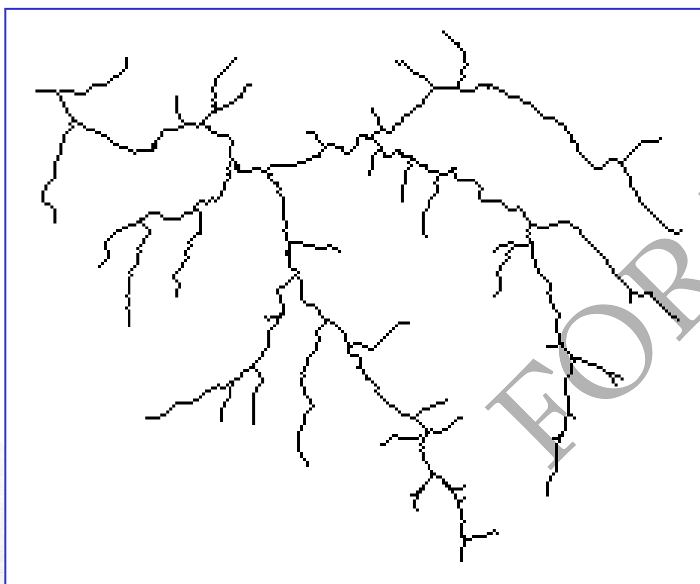


A	watershed area
H	mean elevation
$\bar{S}$	mean slope
L	mainstream length
S	mainstream slope
Ω	stream order
A_i	ith-order subwatershed area
S_{ci}	*i*th-order channel slope
S_{oi}	ith-order overland slope
L_{ci}	*i*th-order channel slope

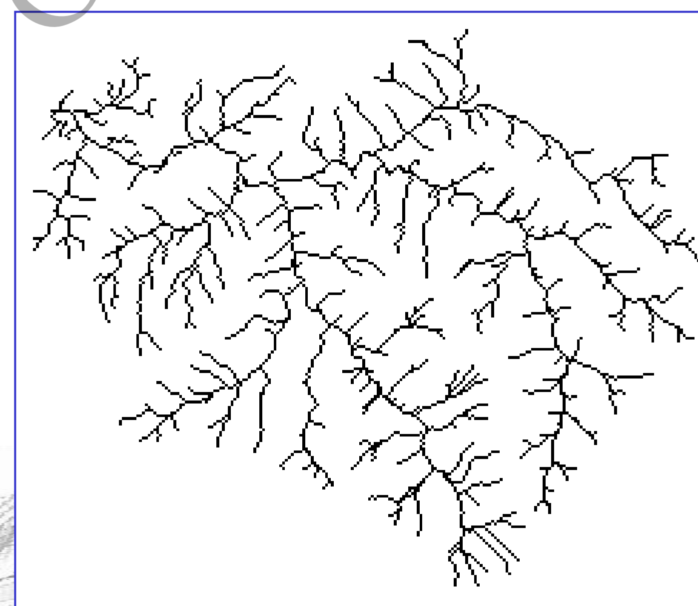
digital elevation dataset → watershed boundary and stream network → watershed geomorphologic factors

Channel Network Resolution

Resolutions of the channel network can be determined by using different threshold areas A_{th} to extract the network from the digital elevation dataset for different objectives of design work.



A_{th}=185 cells (0.296km^2)
for mainstream flood control work

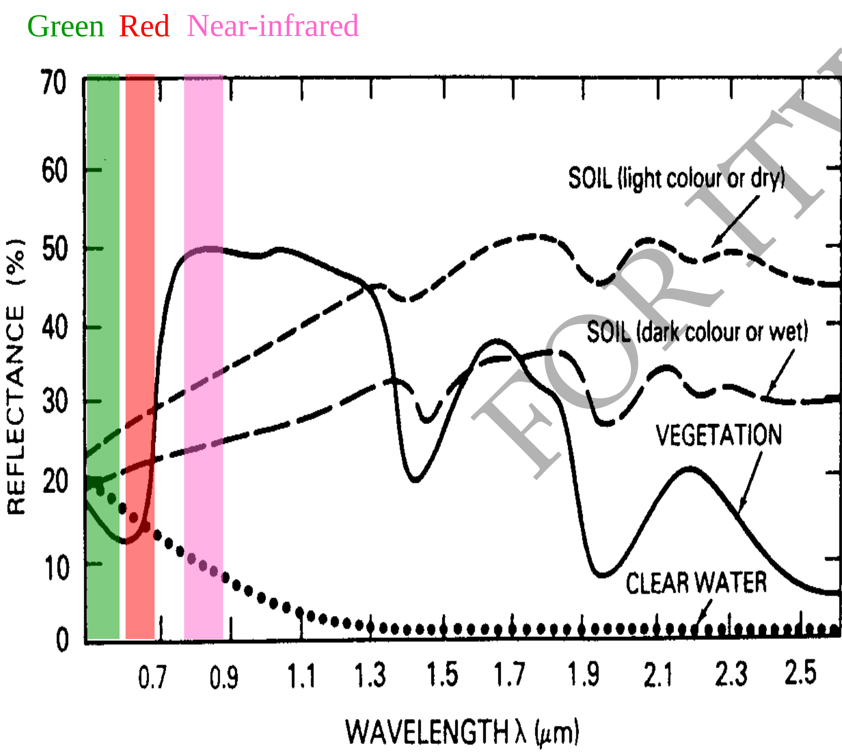


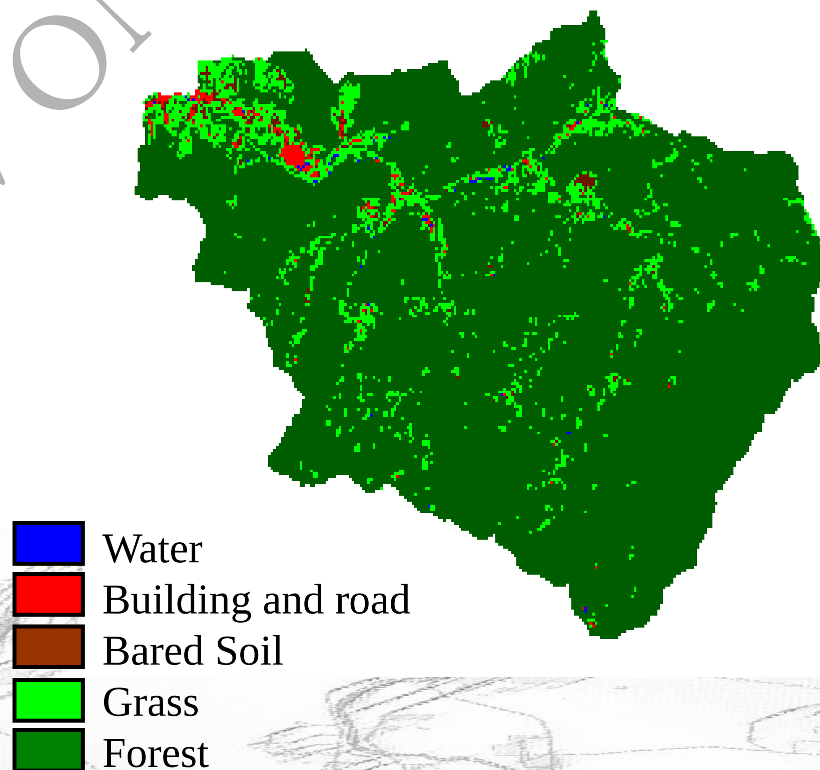
A_{th}=30 cells (0.048km^2)
for soil conservation engineering

Overland Roughness Determination – SPOT Image

- Applying remote sensing images to classify the land cover distribution of a watershed for overland roughness coefficients determination.

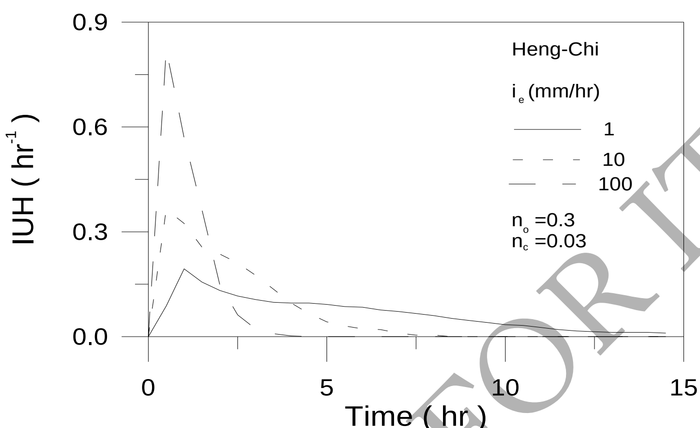
SPOT satellite

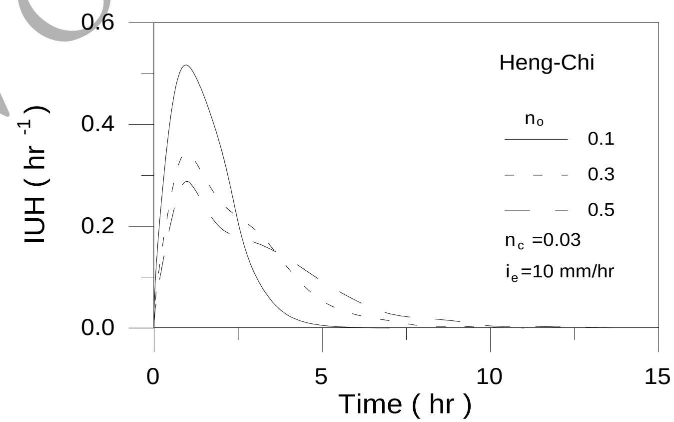


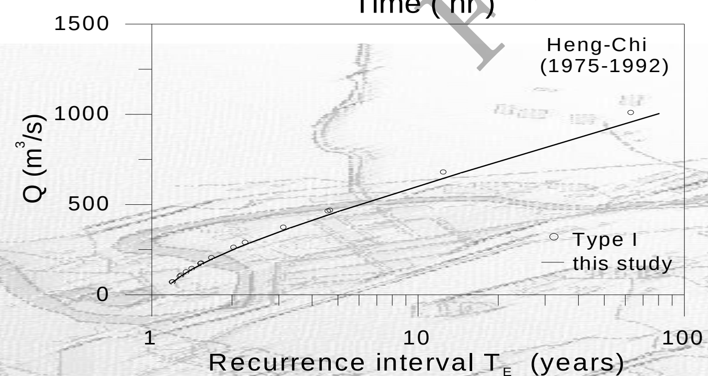


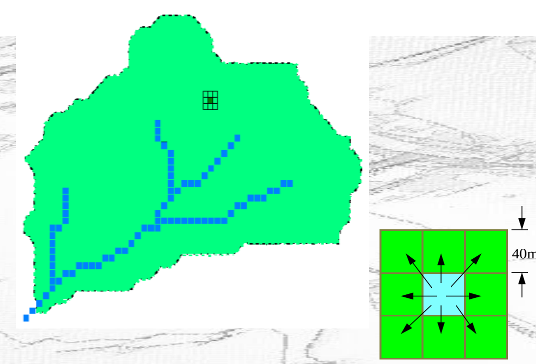
Merits of the KW-GIUH Model

- Influence of rainfall intensity can be considered
- Influence of environmental changes can be simulated
- Flow frequency analysis in ungauged areas can be performed
- Geomorphologic factors can be obtained by using a DEM









Flow Frequency Analysis in Ungauged Watersheds

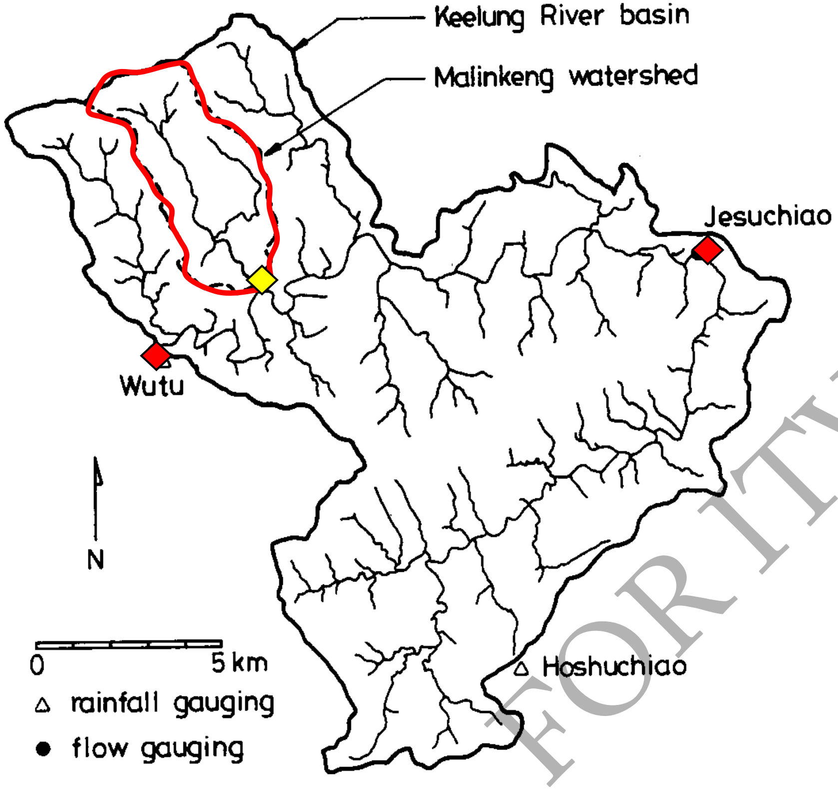


Figure 2. Location Map of the Malinkeng Watershed.

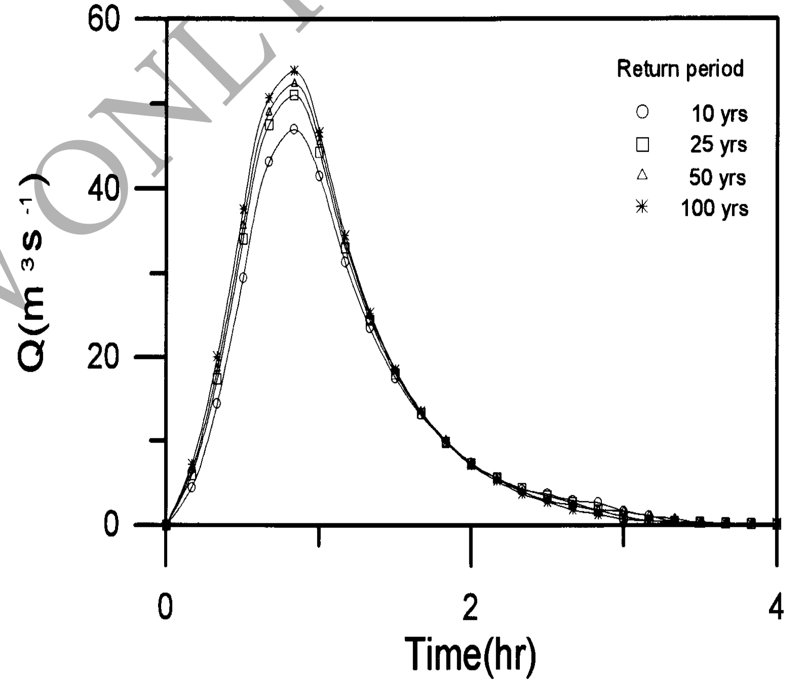


Figure 5. Design Hydrographs of the Malinkeng Watershed for Different Return Periods.

Lee, K. T. (1998). "Generating design hydrographs by DEM assisted geomorphic runoff simulation: a case study," *J. Am. Water Resour. Assoc.*, 34(2), 375-384.

Flow Attenuation in Ungauged Reservoir Watershed

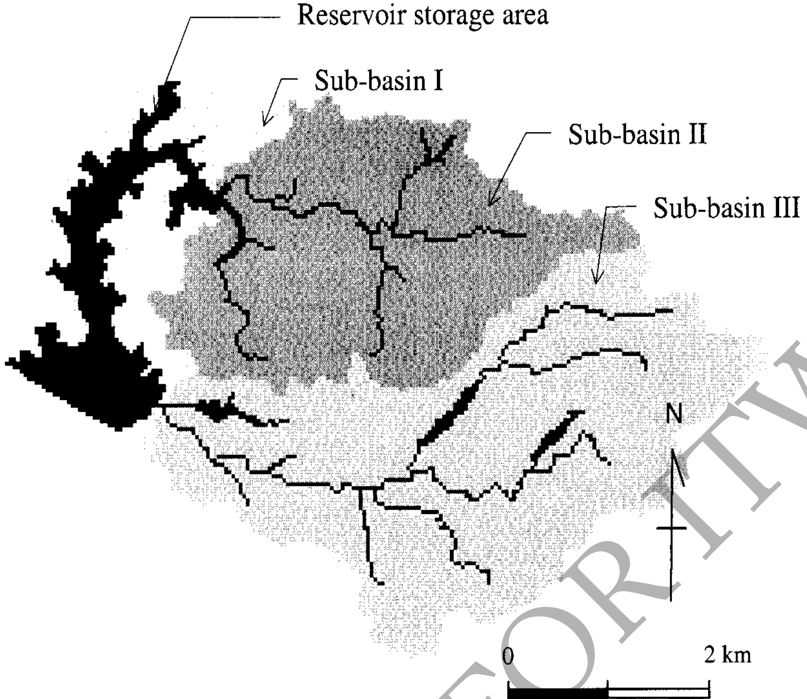


Fig. 2 Map of the Akung-Tien basin.

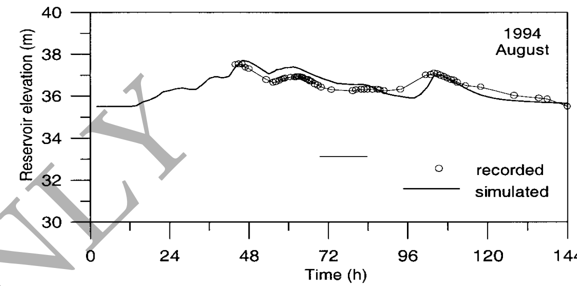


Fig. 4 Recorded and simulated water stage for August 1994 event.

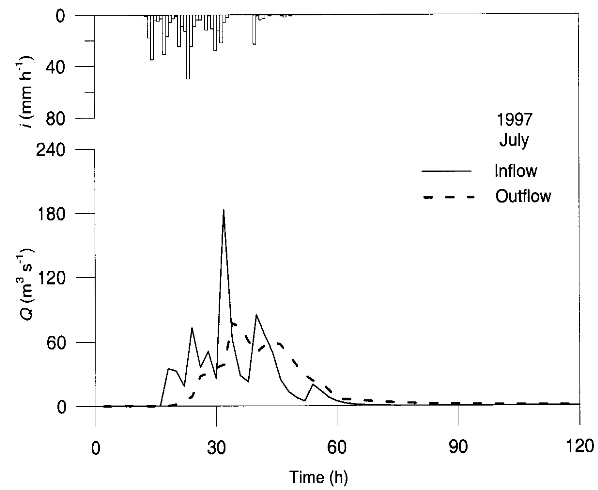
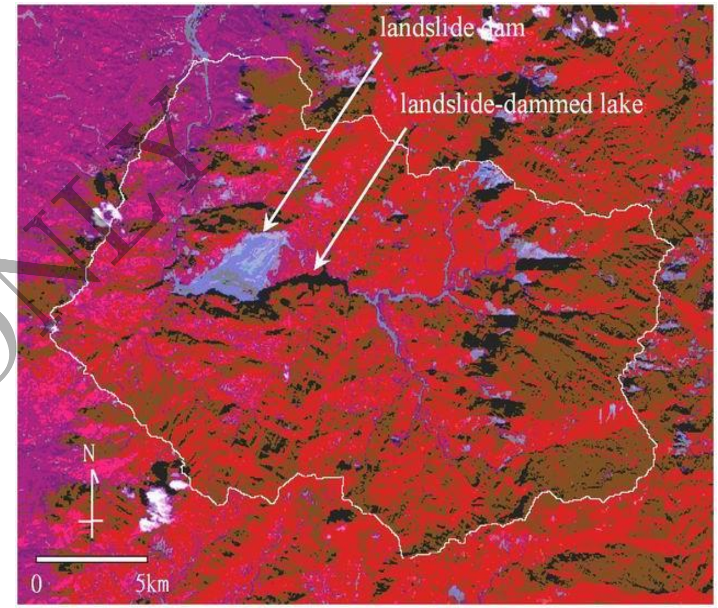


Fig. 6 Simulated inflow and outflow hydrographs for the July 1997 event.

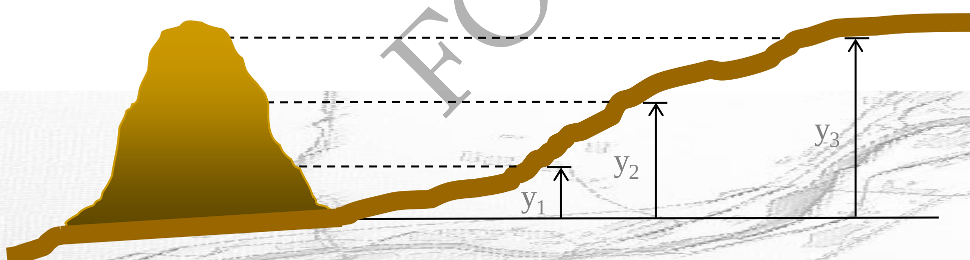
Lee, K. T., Chang, C.-H., Yang, M.-S., and Yu, W.-S. (2001). "Reservoir attenuation of floods from ungauged basins," *Hydrological Sciences Journal*, 46(3), 349-362.

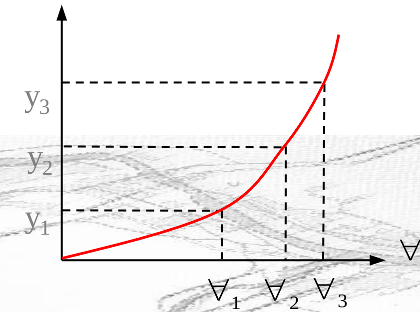
Flow Analysis in Landslide-Dammed-Lake Watershed

- Watershed geomorphologic factors and characteristic curve of the landslide-dammed lake are calculated using DEM
- Land cover condition is obtained from remote sensing image analysis
- Flow analyses are performed by using KW-GIUH model and TOPMODEL



Extensive landslide in 1999 earthquake

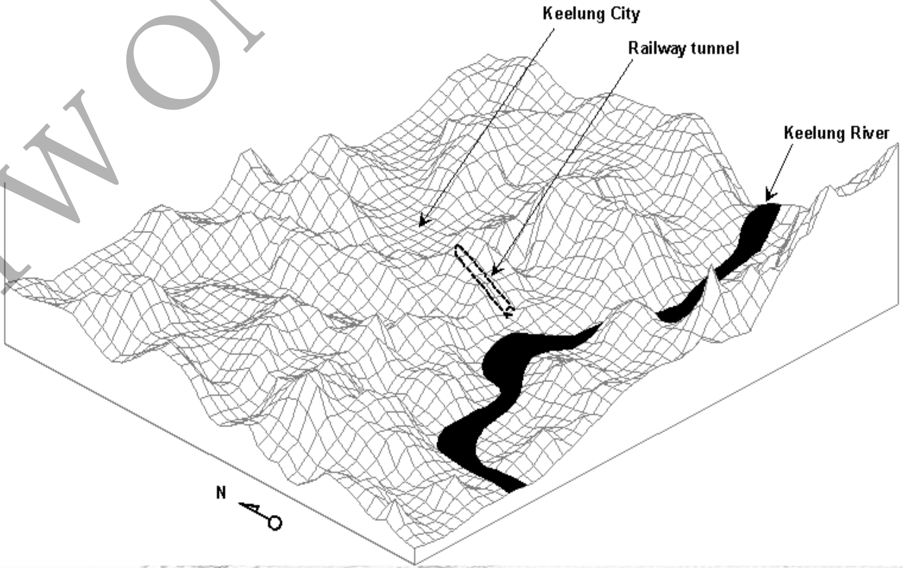




Lee, K. T., Lin, Y.-T. (2006). "Flow analysis of dammed-up-lake watersheds: a case study," *Journal of the American Water Resources Association*, 42(6), 1615-1628.

KW-GIUH & HEC-RAS for Overbank-Flow Simulation

- Using KW-GIUH model to estimate runoff hydrographs from subwatersheds and lateral flow areas
- Using HEC-RAS model to simulate flood wave transport in open channel

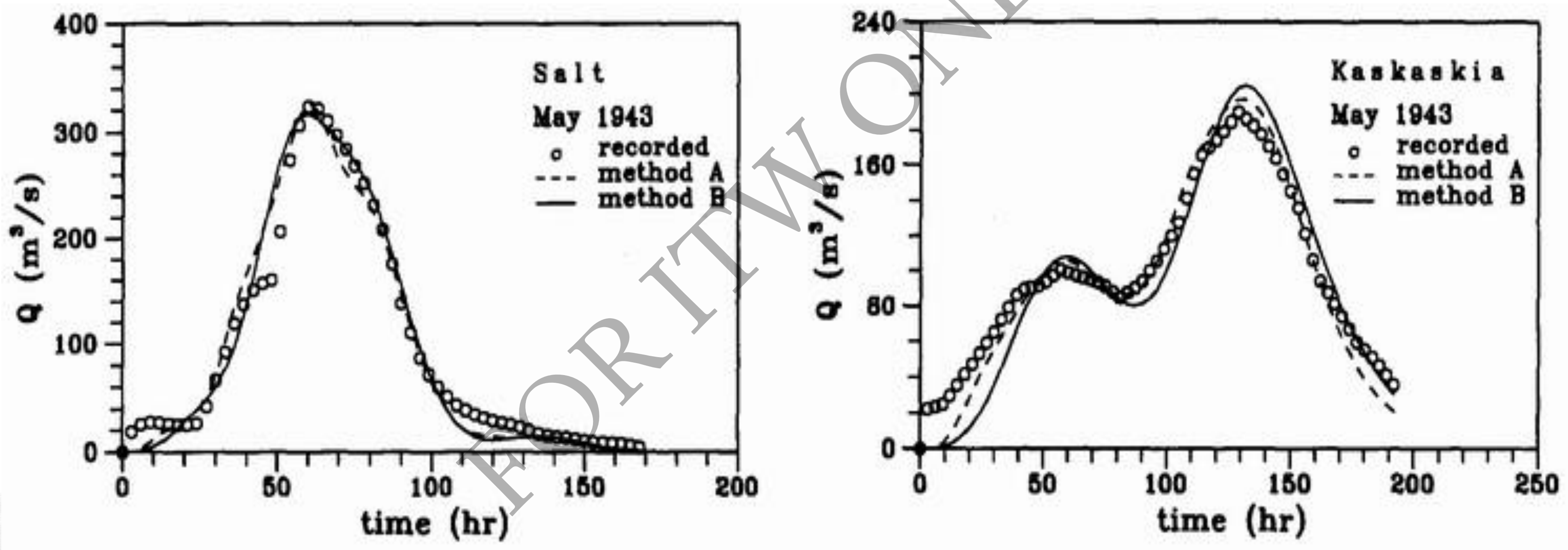


Containers blocked at the railway bridge in 2001 Typhoon Nari

Lee, K. T., Ho, Y.-H., Chyan, Y.-J. (2006). “Bridge blockage and overbank flow simulations using HEC-RAS in the Keelung River during the 2001 Nari typhoon.” *J. Hydraulic Engineering*, ASCE, 132(3), 319-323.

Runoff Analysis in United States of America

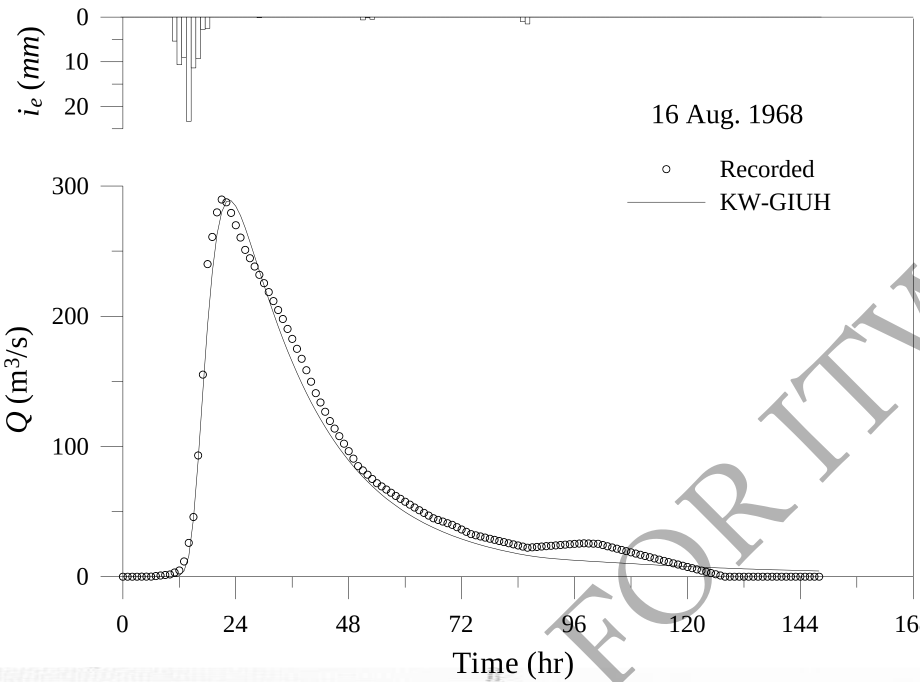
Illinois, U.S.A.
Salt watershed (Area=876 km^2)
Kaskaskia watershed (Area=2692 km^2)

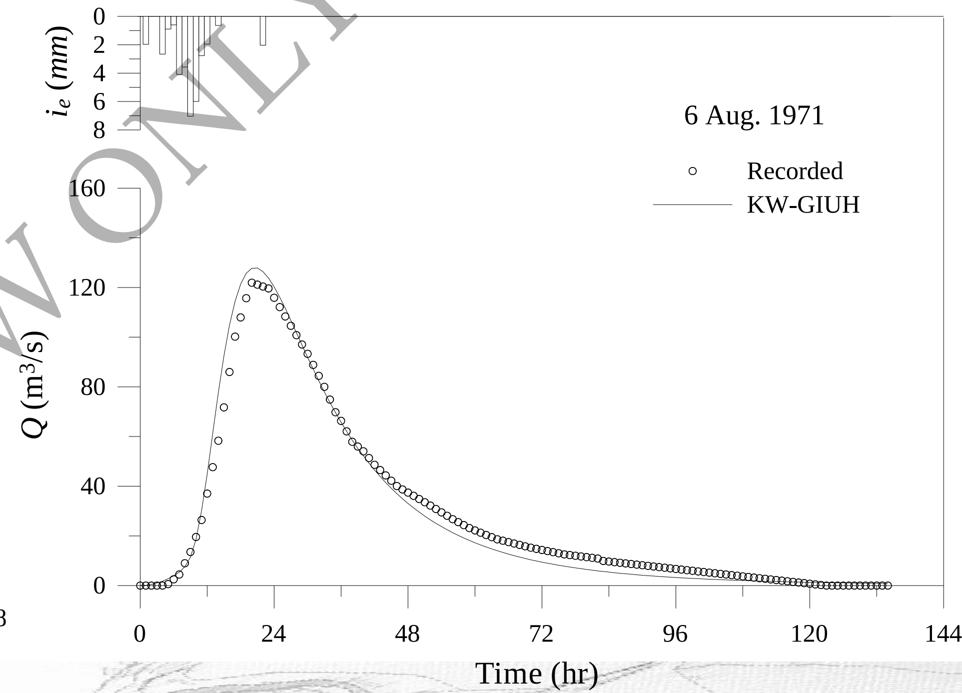


Yen, B. C. and Lee, K. T. (1997). “Unit hydrograph derivation for ungauged watersheds by stream order laws,” *J. Hydrologic Engrg.*, ASCE, 2(1), 1-9.

Runoff Analysis in Russia

Sadovy watershed, Komarovka River Basin, Russian (Area=395 km^2)





Lee, K. T., Chen, N.-C., Gartsman, B. I. (2009). Impact of stream network structure on the transition break of peak flows, *Journal of Hydrology*, 367, 283-292.

Runoff Analysis in Palestine

Faria catchment, Palestine (Area=334 km²)

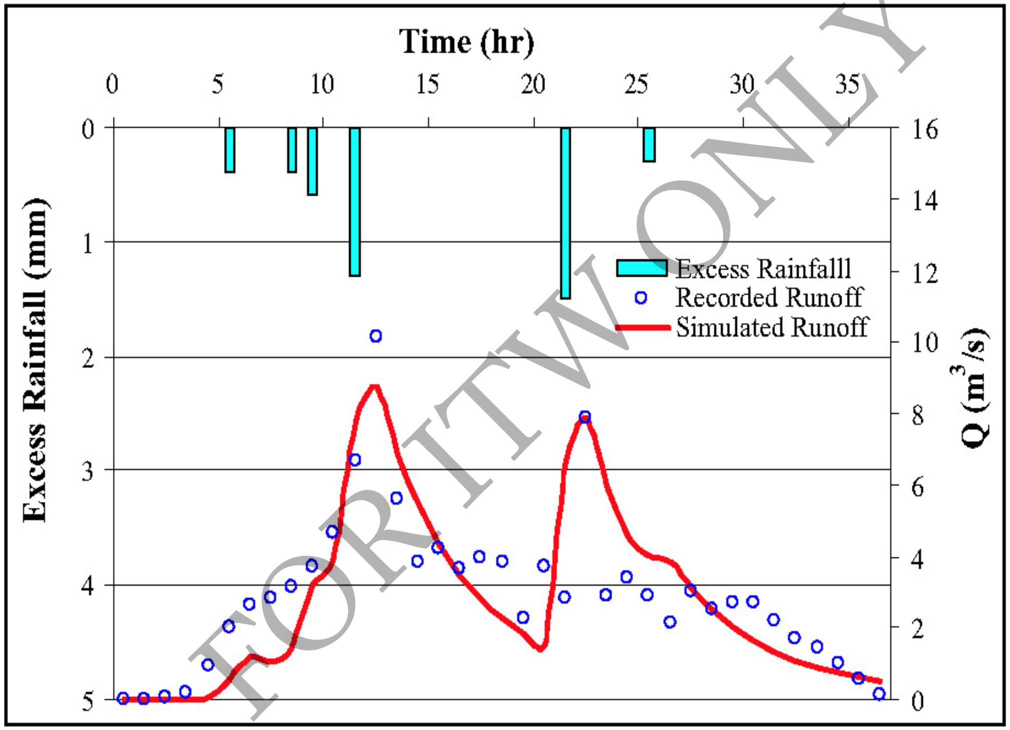
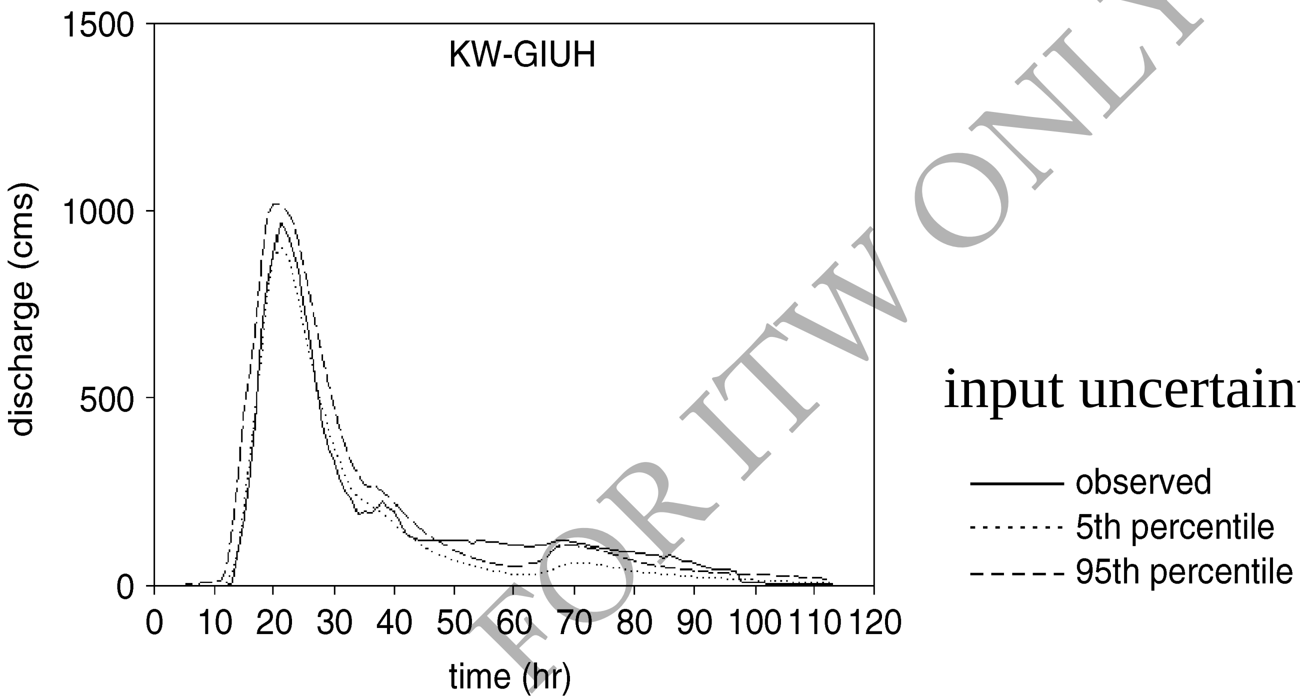


Figure 10. Recorded and estimated direct runoff hydrograph for Al-Badan Sub-catchment, event of 5/2/2005

Shadeed et al. (2007). "GIS-based KW-GIUH hydrological model of semiarid catchments: the case of Faria catchment, Palestine. *Arabian Journal for Science and Engineering.*

Runoff Analysis in Japan

Yasu River basin, Japan (Area=387 km^2)

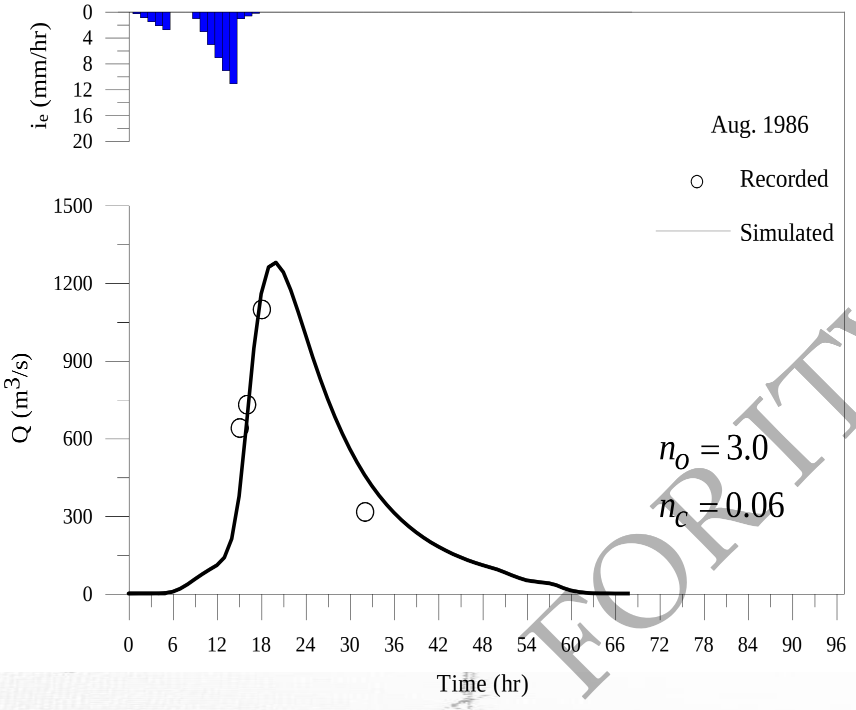


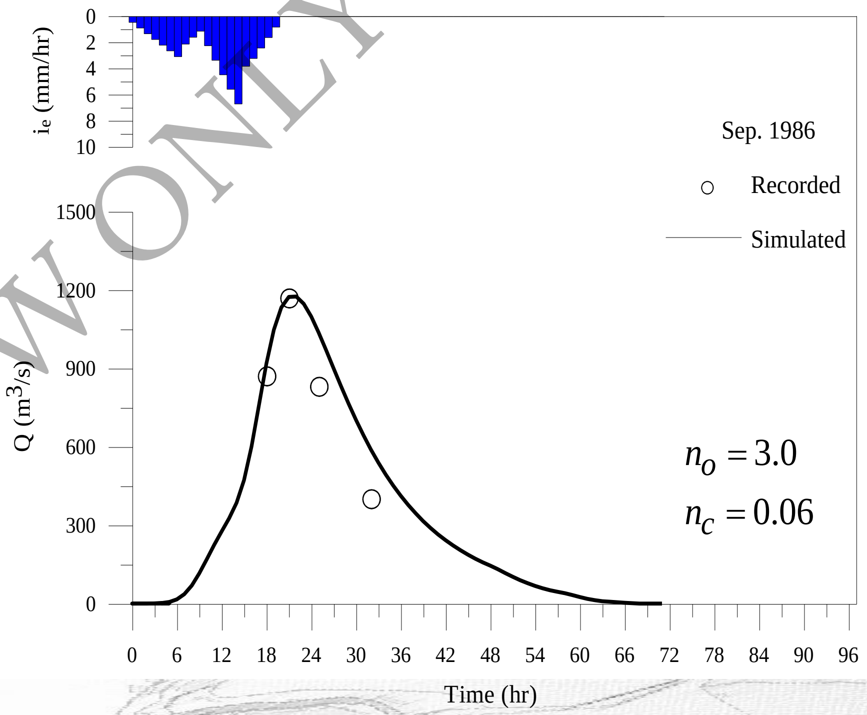
input uncertainty = 1 mm/hr

Chiang et al. (2007). Hydrological model performance comparison through uncertainty recognition and quantification, *Hydrological Processes*, 21(9), 1179-1195.

Runoff Analysis in Mainland China

Yi-Jin River watershed, Sichuan, China (Area=1700 km²)

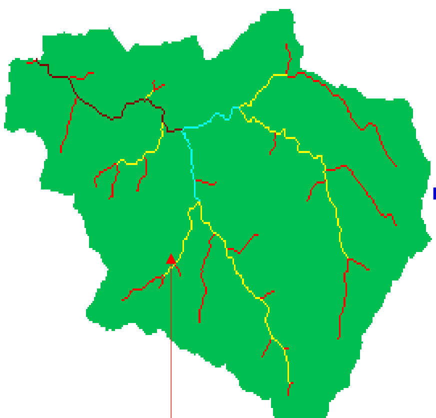




Cao, S.-Y., Lee, K. T., Ho, J.-Y., Huang, E., Liu, X., Liu, X., Zhang, W. (2008). "Runoff Simulating for Ungauged Mountainous Watersheds in Sichuan, China." ***International Symposium of IAHS-PUB and the 2nd International Symposium of China-PUB*****, Chengdu, China.**

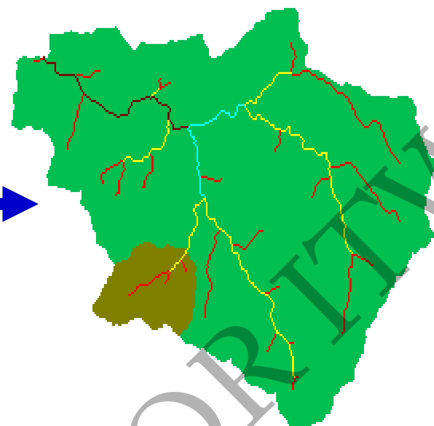
Convenient Operation Platform

User clicks on screen to specify a subwatershed outlet



X=292680
Y=2755120

Two degrees transverse Mercator coordinated system (TM2)



Subwatershed boundary delineation

Watershed area
Mean elevation
Stream network
Stream order
Overland slope
Overland length
Channel slope
Channel length

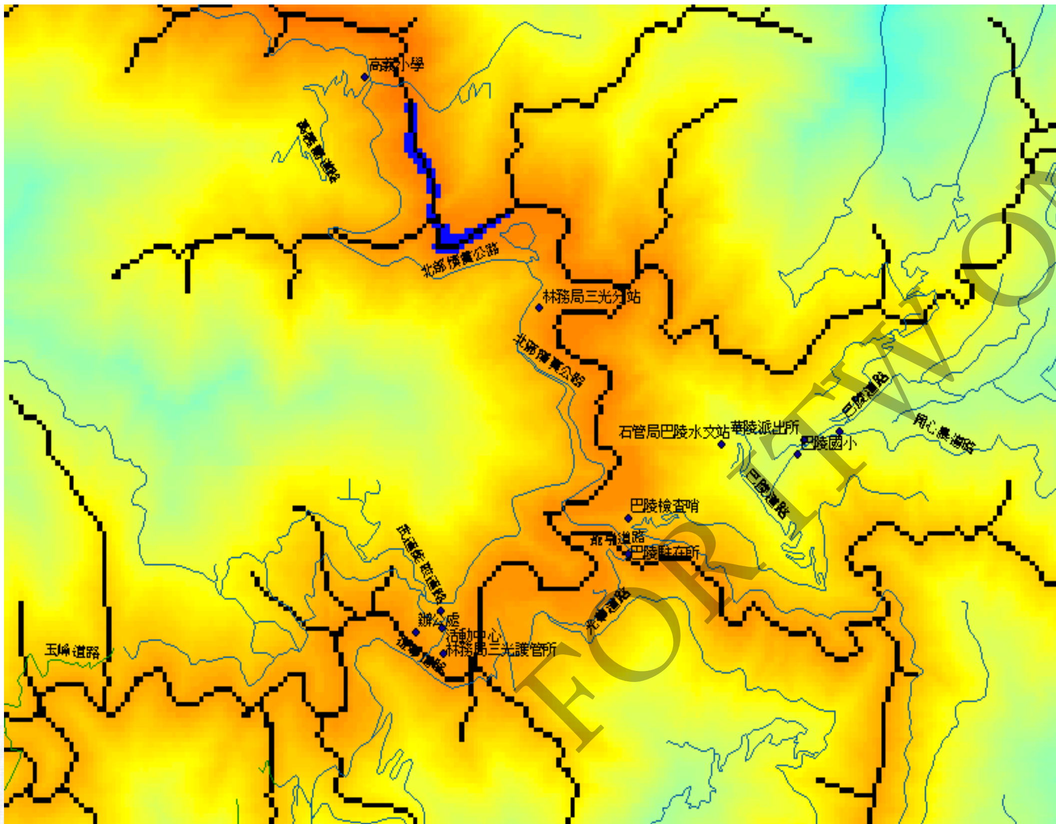
Geomorphologic factors calculation

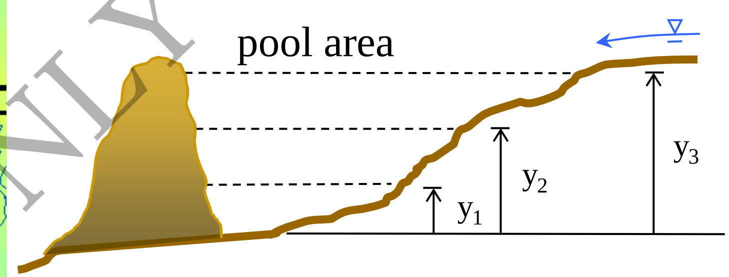
Time of concentration

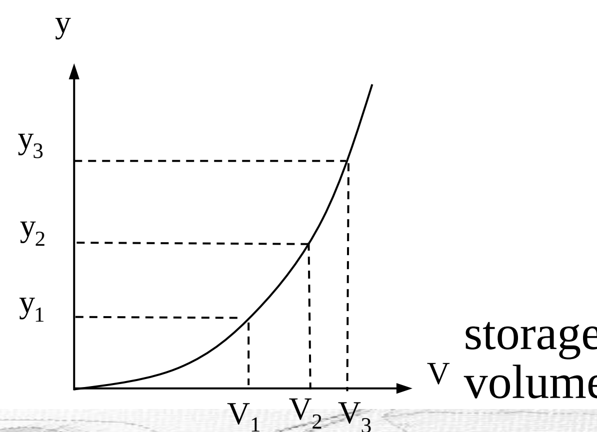
Spatial rainfall
Design discharge

Hydrological analysis

Reservoir Elevation-Area Function Extraction



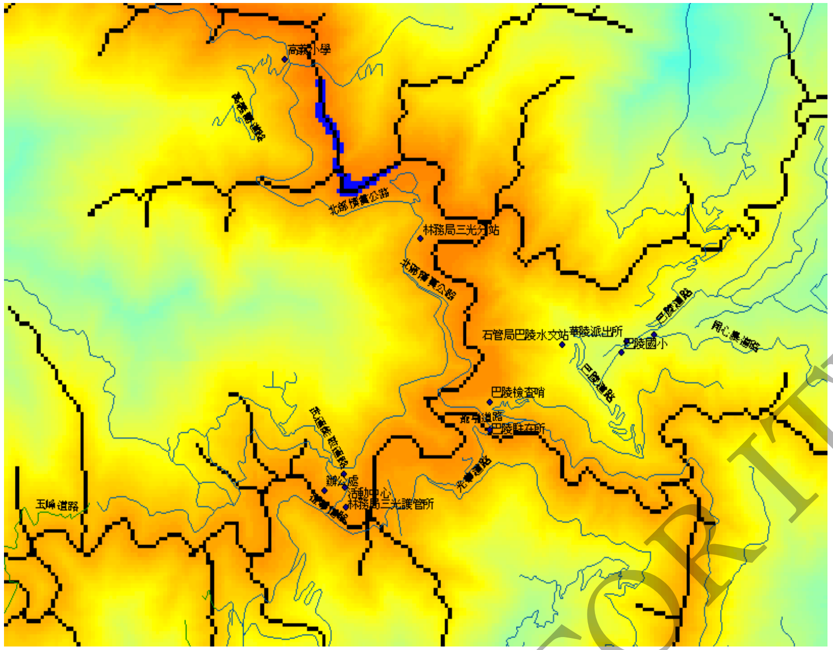


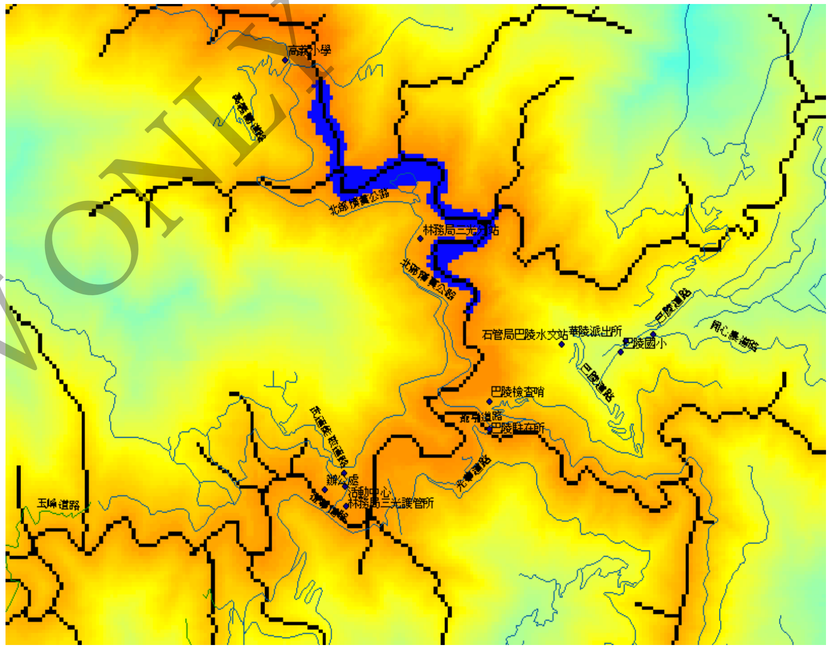


$$V(y) = \int A(y)dy$$

To specify a new dam site in the watershed

Reservoir Elevation-Area Function Extraction





Dam-top elevation: 457 m

Pool area: 190,400 m^2

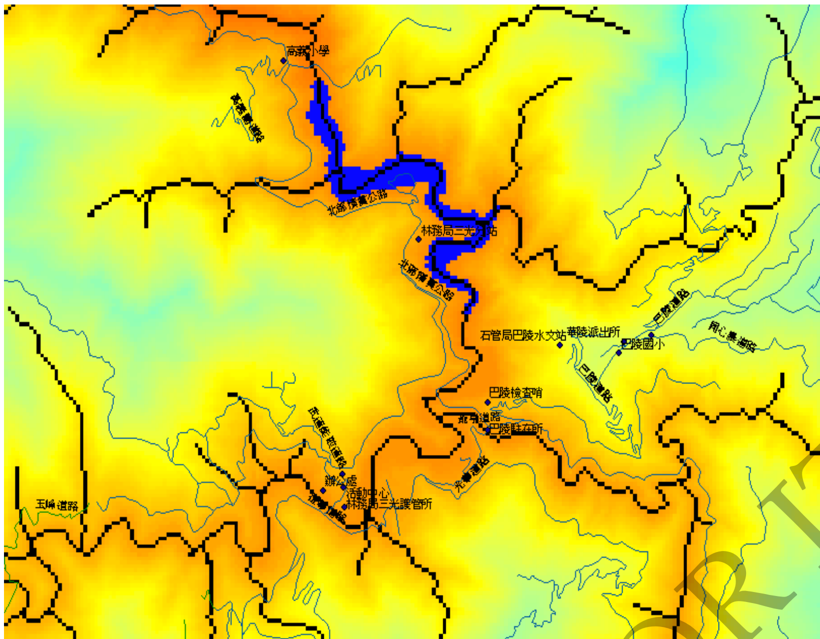
Storage volume: 1,483,200 m^3

Dam-top elevation: 497 m

Pool area: 969,600 m^2

Storage volume: 21,945,600 m^3

Dam Site/Height Information System



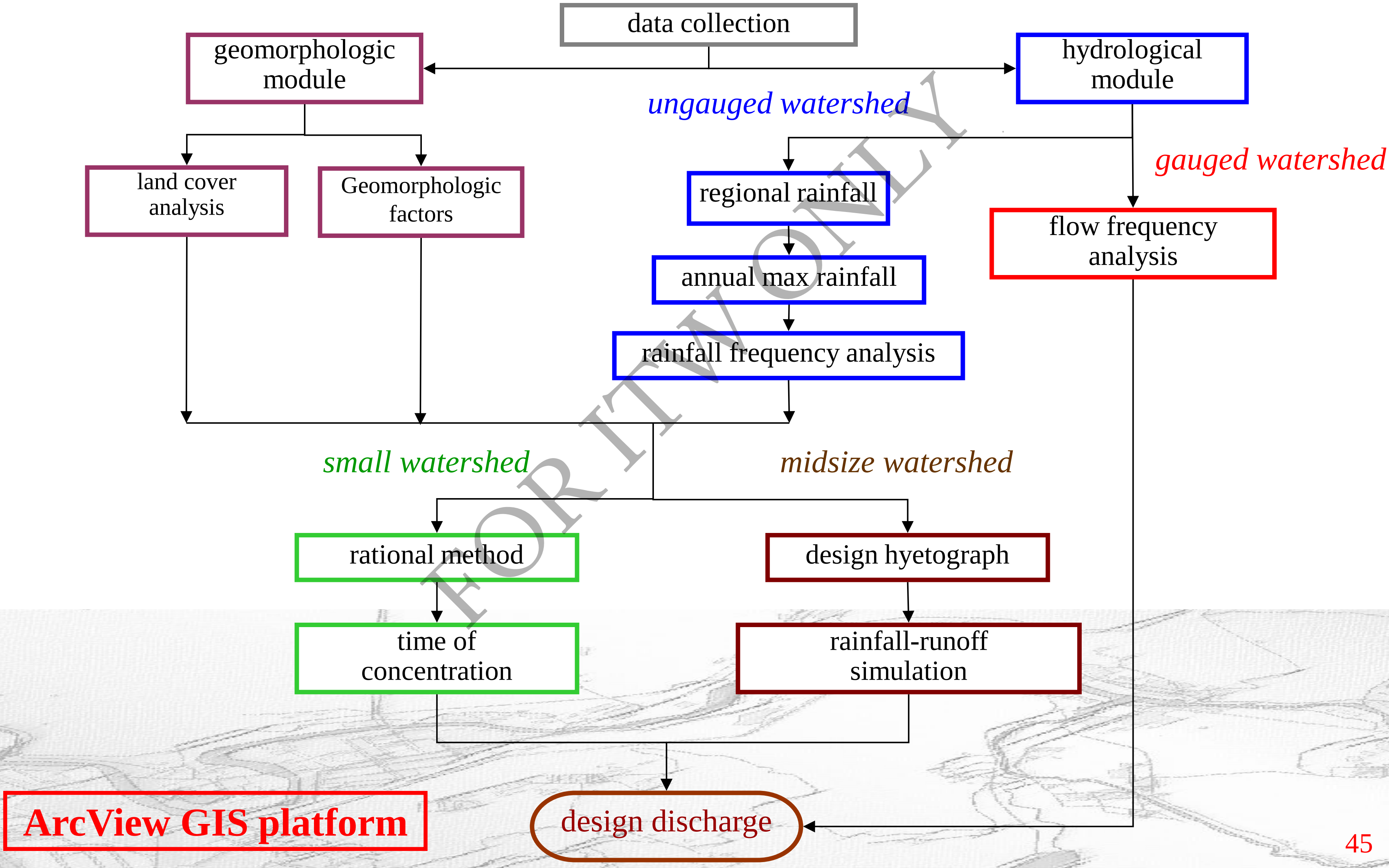
Dam-top elevation: 497 m

Pool area: 969,600 m^2

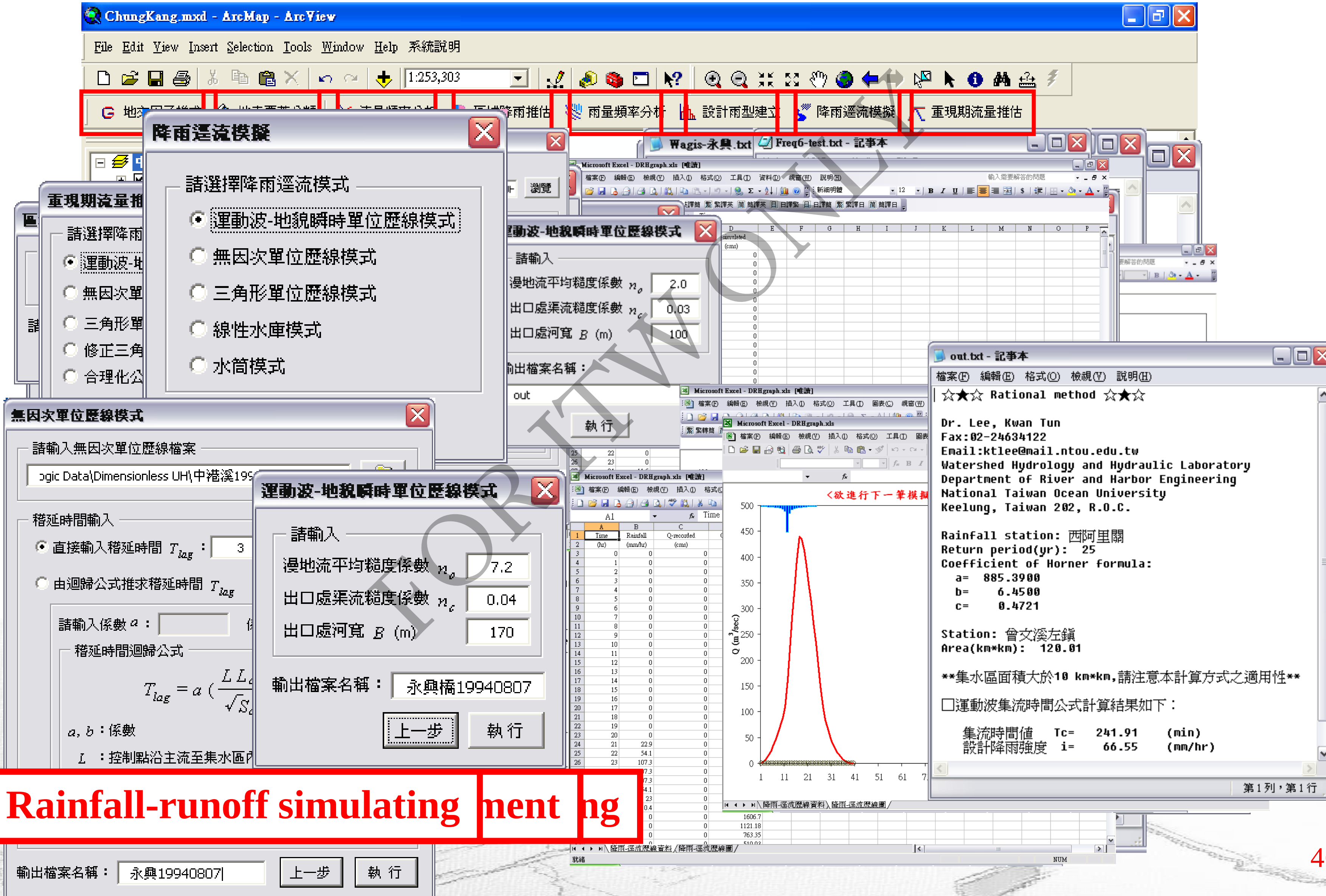
Storage volume: 21,945,600 m^3

Dam-top Elevation (m)	Dam Height (m)	Pool Area (km^2)	Storage Volume (10^6 m^3)	Note
447	10	0.08	0.36	
457	20	0.19	1.48	
467	30	0.34	3.98	
477	40	0.48	7.90	
487	50	0.71	13.58	S.-K. road inundated
497	60	0.97	21.95	S.-K. road inundated

Integrated System for Watershed Management

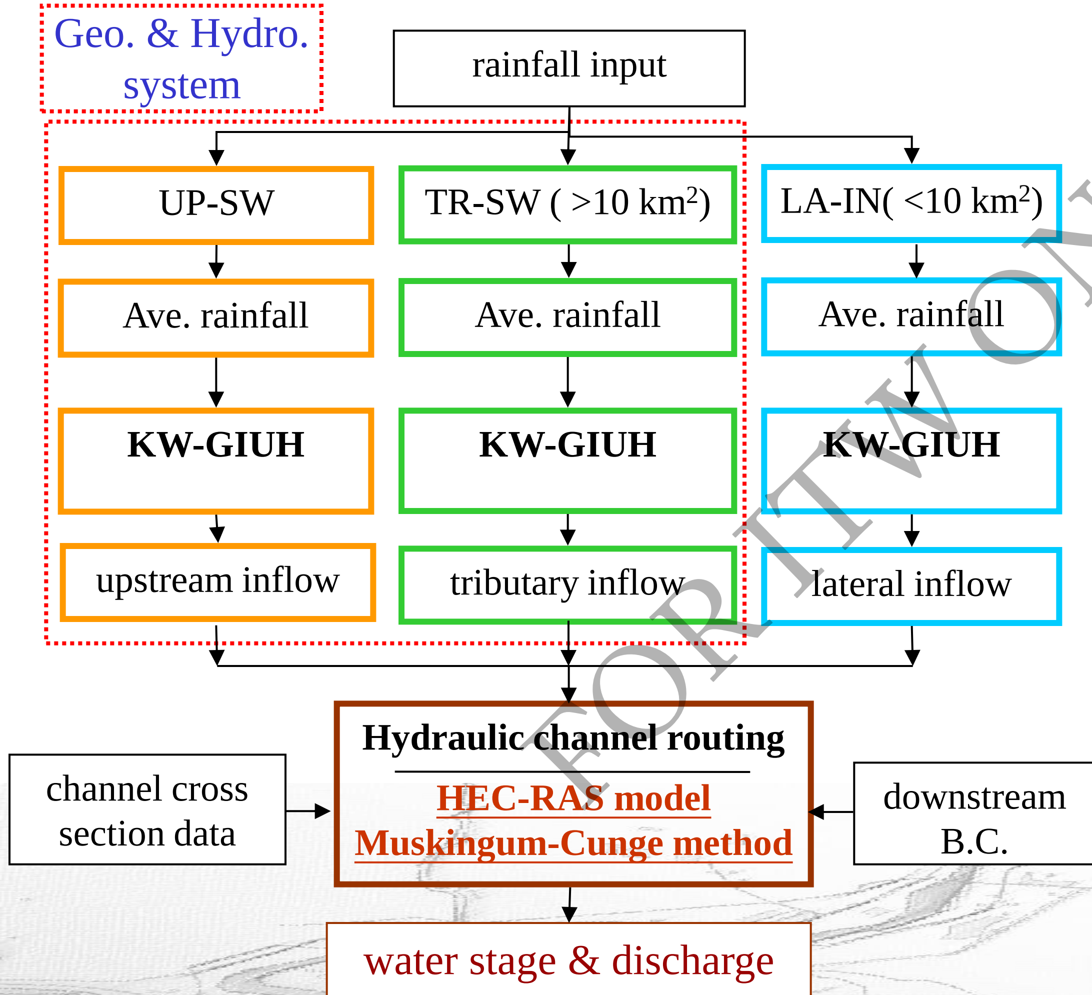


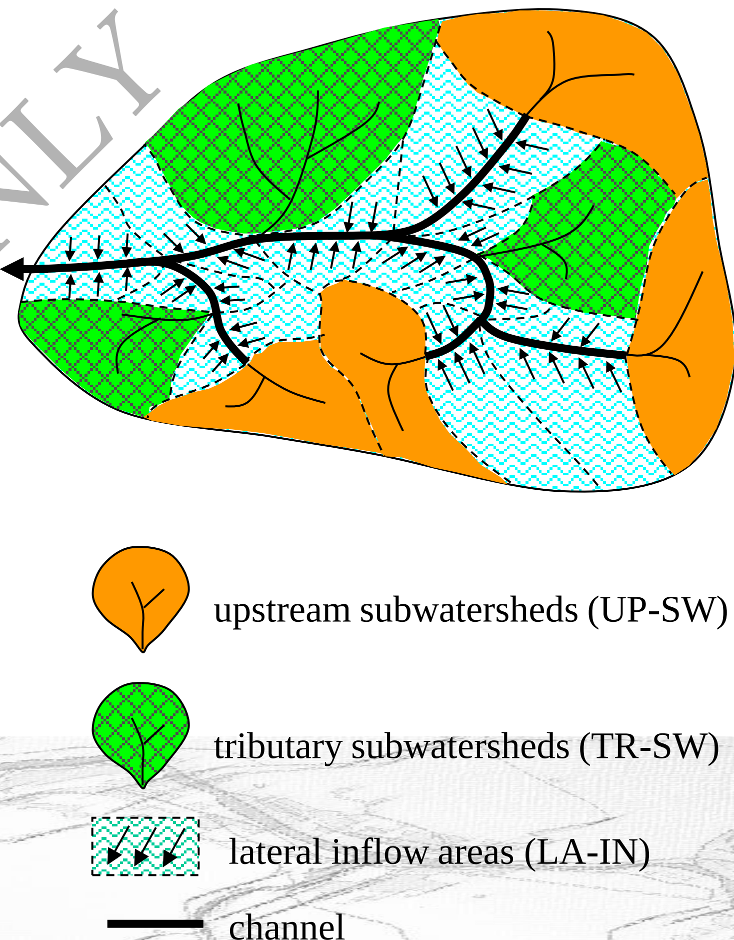
Integrated Geo. & Hydro. Information System (1st stage)



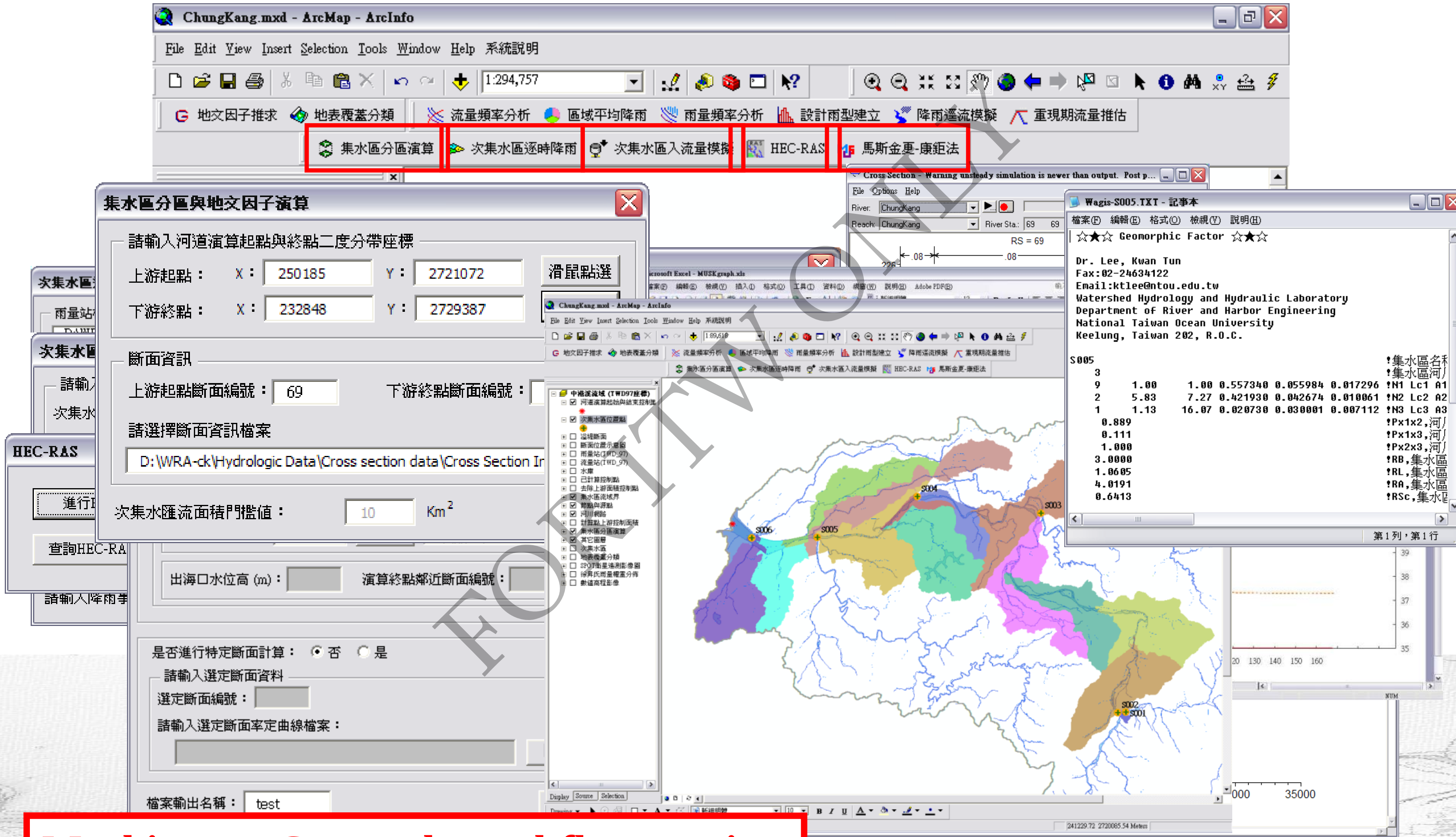
Rainfall-runoff simulating ment ng

Integrated Channel-Flow-Routing System (2^{nd} stage)



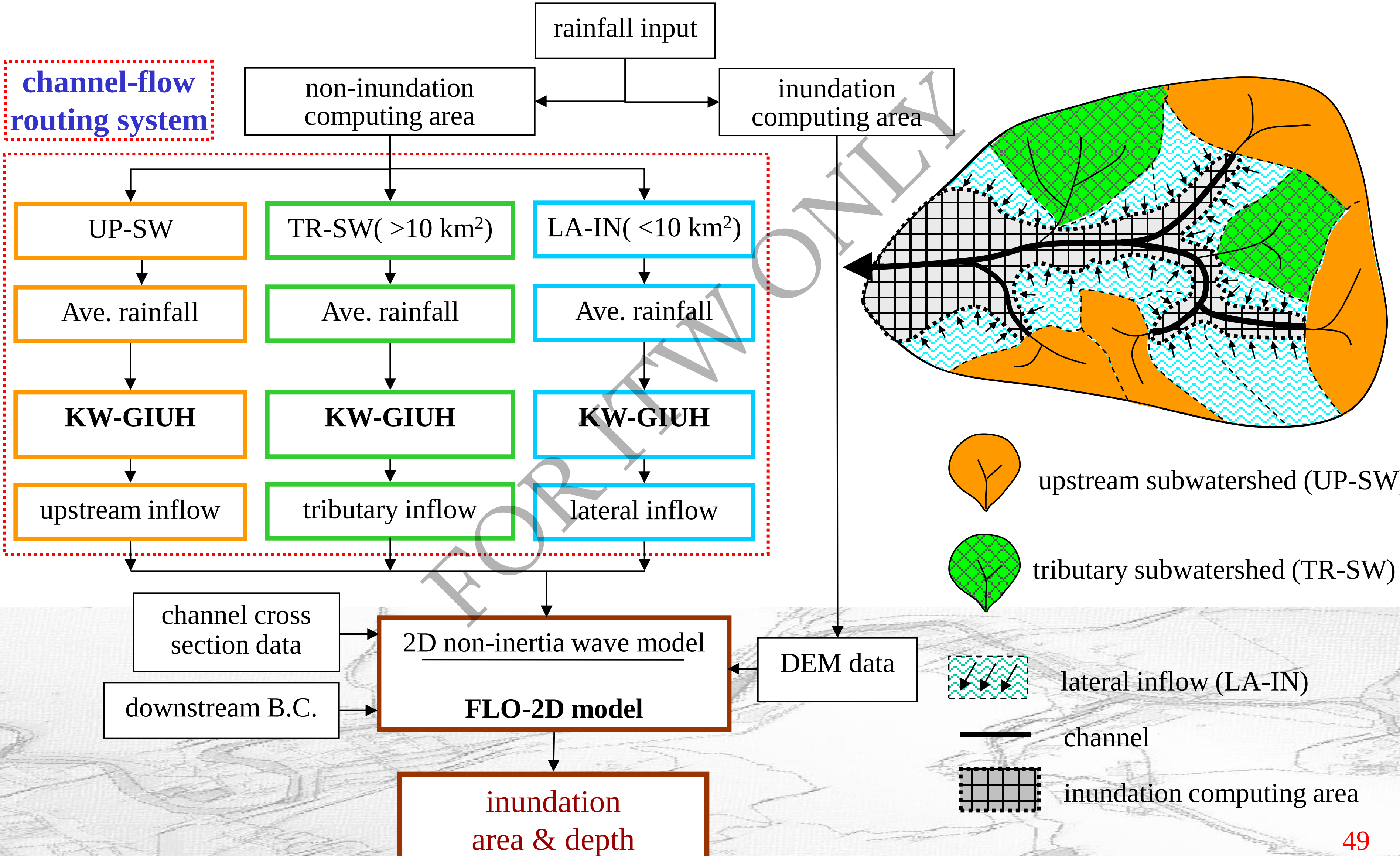


Integrated Channel-Flow-Routing System (2nd stage)



Muskingum-Cunge channel-flow routing

Integrated Inundation-Simulation System (3rd stage)



Windows-Based Integrated Analysis System

Geo. & Hydro. Analy.

- flow frequency analysis
- Geomorphologic factors
- land cover analysis
- Regional rainfall
- Rainfall frequency analysis
- Design hyetograph
- rainfall-runoff simulation
- design discharge

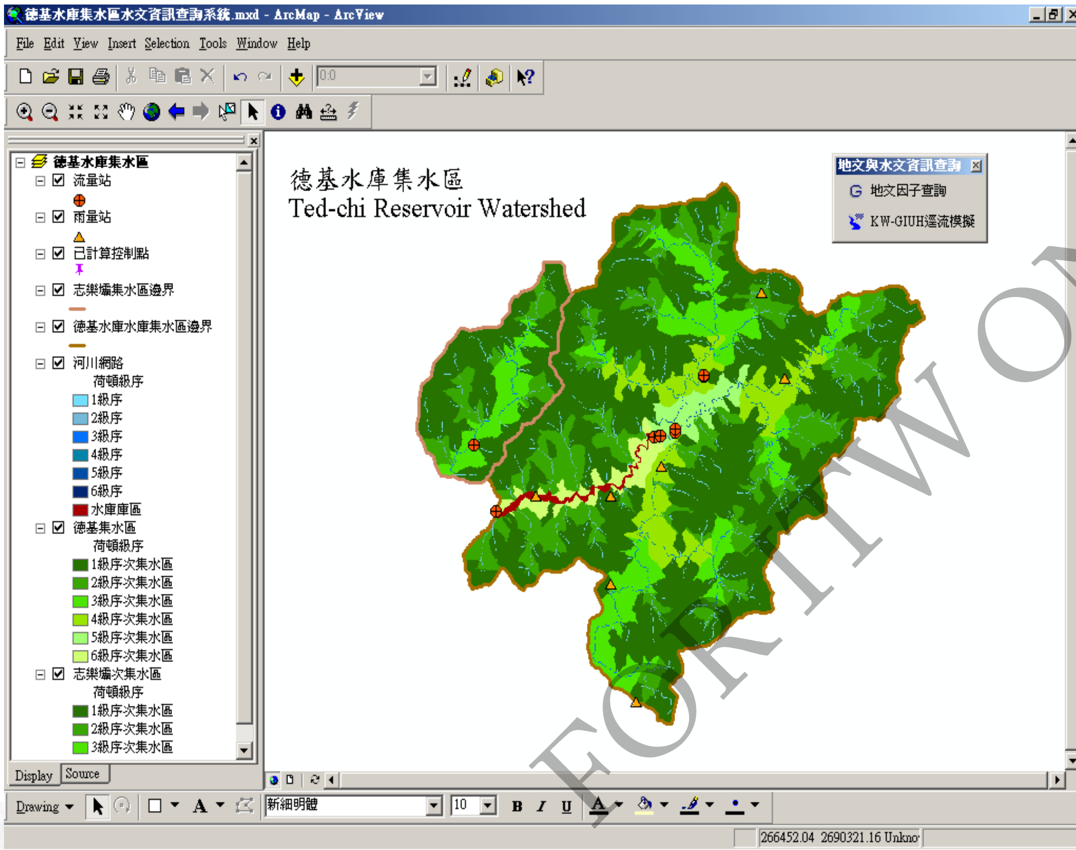
Channel Routing Sys.

- Subwatershed boundary delineating
- Subwatershed rainfall calculating
- Subwatershed inflow calculating
- HEC-RAS
- Muskingum-Cunge

Inundation Simu.

- Subwatershed rainfall calculating
- Subwatershed inflow calculating
- non-inertia wave model
- FLO-2D

Window-Based Information System



- Integrated on a user-friendly graphical interface ArcView system
- Using Avenue / VB language to link with Fortran computational programs
- The system can be further extended to other purpose of applications

Information systems have been developed for 26 major river basins in Taiwan for the <u>Taiwan Water Resource Agency</u> from 2001-2008.

Conclusions

- The KW-GIUH model can be applied to gauged and ungauged watersheds for runoff simulation in good agreement with records only based on watershed geomorphologic information.
- Instead of using grid-based routing models, the IUH concept operating provides an efficient way for rainfall-runoff simulation, and the runoff nonlinearity can be considered in the KW-GIUH modeling.
- The integrated windows-based platform can provide both geomorphologic and hydrological information for engineers to perform the design work or real-time forecasting at any desired point within the study watershed.

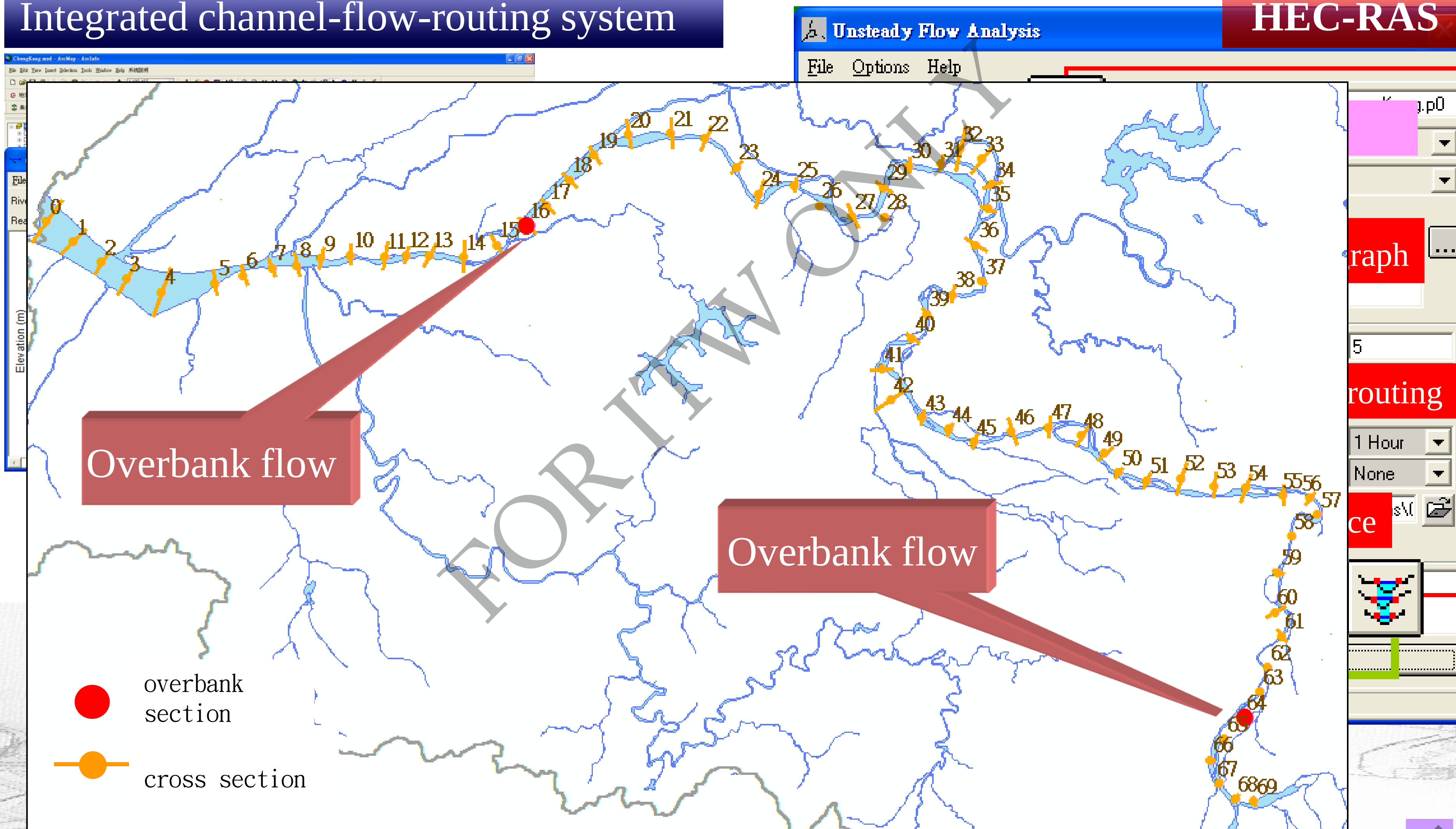
Thank You

Prof. Kwan Tun LEE
Watershed Hydrology and Hydraulic Lab.
Department of River & Harbor Engrg.
National Taiwan Ocean University
Keelung, Taiwan, R.O.C.
E-mail: ktlee@ntou.edu.tw

HEC-RAS Module

Integrated channel-flow-routing system

HEC-RAS



Muskingum-Cunge Module

Muskingum-Cunge method

$$Q_{i+1}^{j+1} = C_0 Q_i^{j+1} + C_1 Q_i^j + C_2 Q_{i+1}^j + C_s q_l$$

$$C_0 = \frac{-KX + 0.5\Delta t}{K(1-X) + 0.5\Delta t}$$

$$C_1 = \frac{KX + 0.5\Delta t}{K(1-X) + 0.5\Delta t}$$

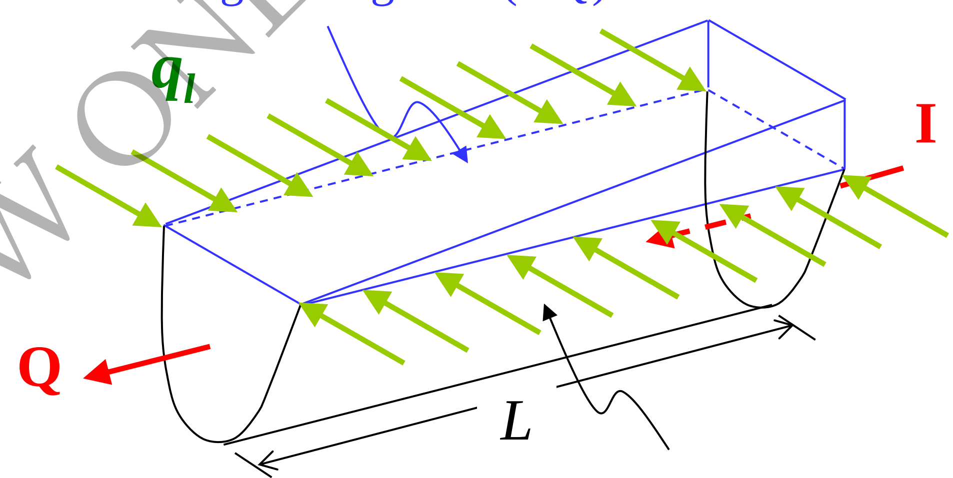
$$C_2 = \frac{K(1-X) - 0.5\Delta t}{K(1-X) + 0.5\Delta t}$$

$$C_s = \frac{\Delta x \Delta t}{K\left(1-X\right) + 0.5\Delta t}$$

Cunge (1969)

$$K = \frac{L}{c_k} \qquad X = \frac{1}{2}\left(1 - \frac{q}{c_k L S_0}\right)$$

Storage function S=KQ+KX(I−Q)



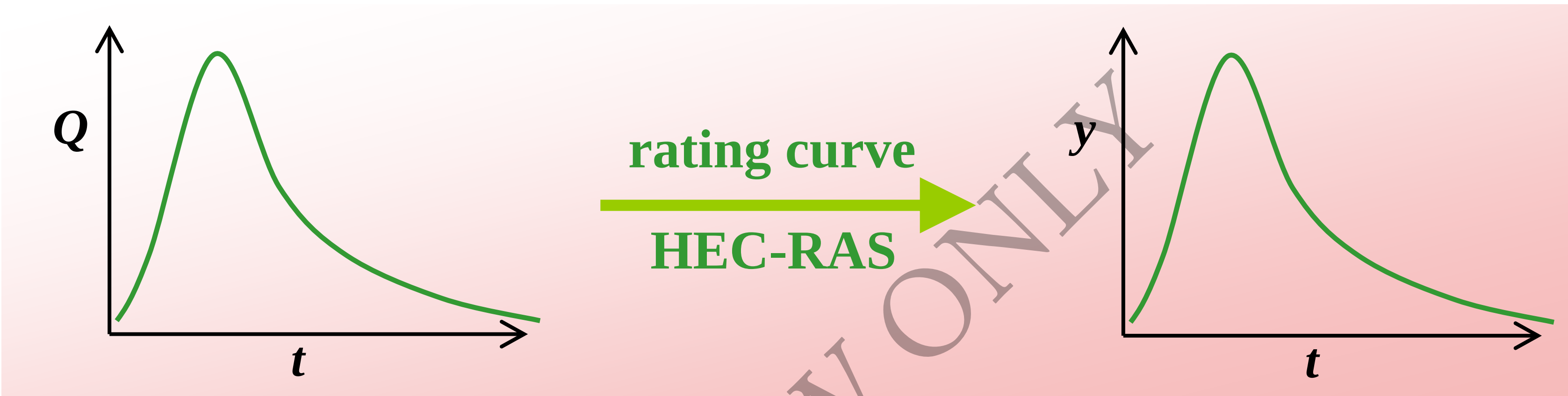
K : storage constant

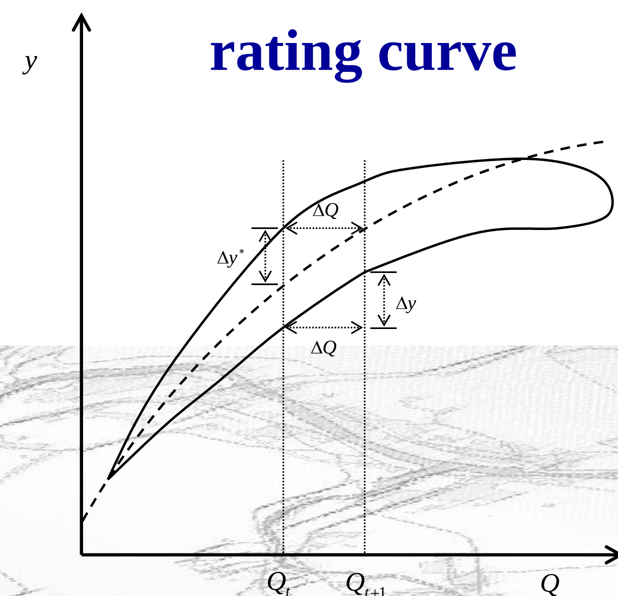
X : weighting factor

L=channel length; c_k =K.W. celerity;

q=discharge; S_0=channel slope

Muskingum-Cunge Module





Considering hysteresis effect

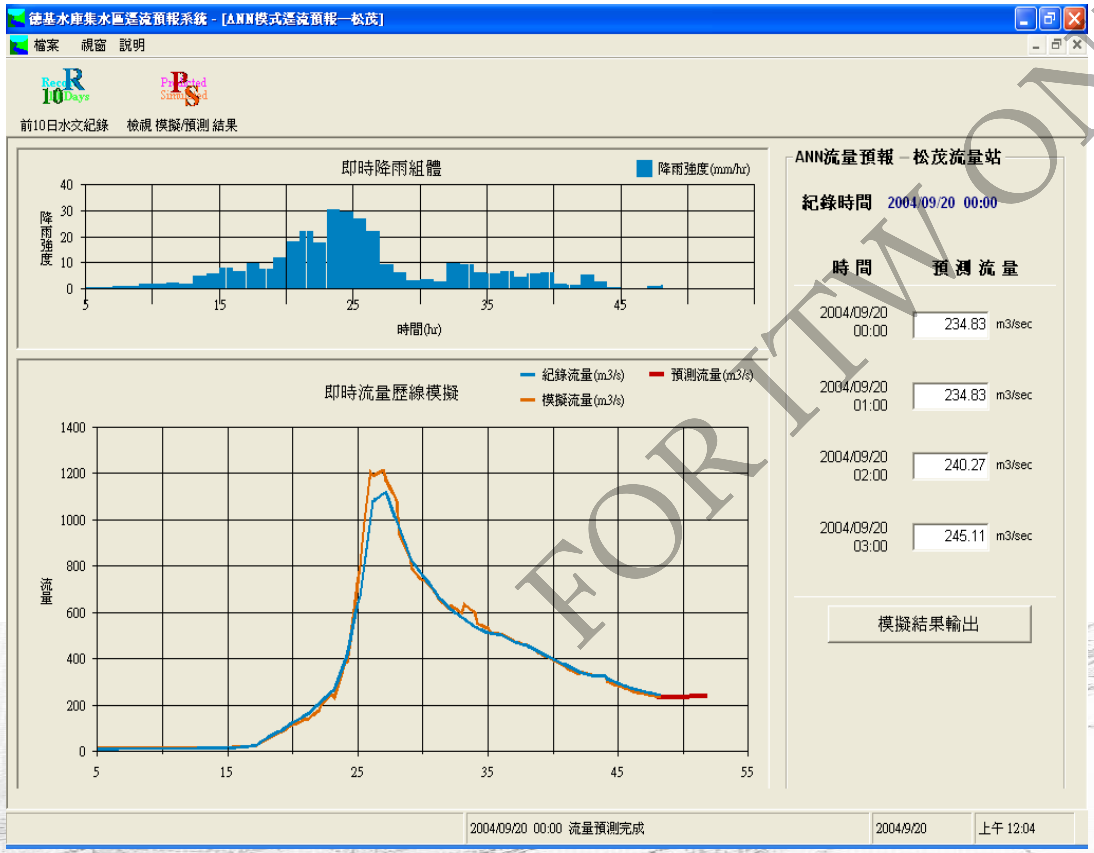
Jones (1915)

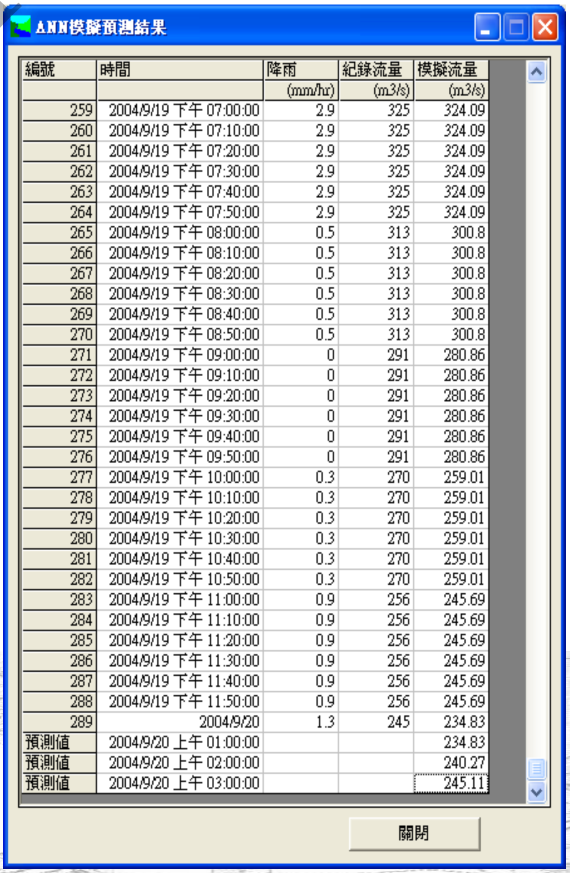
$$Q = Q_o\left(1+\frac{1}{cS_o}\frac{\partial y}{\partial t}\right)^{1/2}$$

Q_o= normal discharge; S_o=channel slope
C=celerity; y= depth

研究方法—視窗化即時流量預報系統

利用Visual Basic 6.0建立逕流預報系統操作介面，可顯示即時雨量與流量回傳資訊，並可預測下數時刻之流量。





編號	時間	降雨 (mm/hr)	紀錄流量 (m3/s)	模擬流量 (m3/s)
259	2004/9/19 下午 07:00:00	2.9	325	324.09
260	2004/9/19 下午 07:10:00	2.9	325	324.09
261	2004/9/19 下午 07:20:00	2.9	325	324.09
262	2004/9/19 下午 07:30:00	2.9	325	324.09
263	2004/9/19 下午 07:40:00	2.9	325	324.09
264	2004/9/19 下午 07:50:00	2.9	325	324.09
265	2004/9/19 下午 08:00:00	0.5	313	300.8
266	2004/9/19 下午 08:10:00	0.5	313	300.8
267	2004/9/19 下午 08:20:00	0.5	313	300.8
268	2004/9/19 下午 08:30:00	0.5	313	300.8
269	2004/9/19 下午 08:40:00	0.5	313	300.8
270	2004/9/19 下午 08:50:00	0.5	313	300.8
271	2004/9/19 下午 09:00:00	0	291	280.86
272	2004/9/19 下午 09:10:00	0	291	280.86
273	2004/9/19 下午 09:20:00	0	291	280.86
274	2004/9/19 下午 09:30:00	0	291	280.86
275	2004/9/19 下午 09:40:00	0	291	280.86
276	2004/9/19 下午 09:50:00	0	291	280.86
277	2004/9/19 下午 10:00:00	0.3	270	259.01
278	2004/9/19 下午 10:10:00	0.3	270	259.01
279	2004/9/19 下午 10:20:00	0.3	270	259.01
280	2004/9/19 下午 10:30:00	0.3	270	259.01
281	2004/9/19 下午 10:40:00	0.3	270	259.01
282	2004/9/19 下午 10:50:00	0.3	270	259.01
283	2004/9/19 下午 11:00:00	0.9	256	245.69
284	2004/9/19 下午 11:10:00	0.9	256	245.69
285	2004/9/19 下午 11:20:00	0.9	256	245.69
286	2004/9/19 下午 11:30:00	0.9	256	245.69
287	2004/9/19 下午 11:40:00	0.9	256	245.69
288	2004/9/19 下午 11:50:00	0.9	256	245.69
289	2004/9/20	1.3	245	234.83
預測值	2004/9/20 上午 01:00:00			234.83
預測值	2004/9/20 上午 02:00:00			240.27
預測值	2004/9/20 上午 03:00:00			245.11

Value of Partial-Contributing-Area Ratio R_{PCA} ?

- Flow path probability

surface flow $$P(w_s) = R_{PCA_i} \cdot P_{OA_i} \cdot P_{x_{o_i} x_i} \cdot P_{x_i x_j} \cdots P_{x_k x_\Omega}$$

subsurface flow $$P(w_{sub}) = \left(1 - R_{PCA_i}\right) \cdot P_{OA_i} \cdot P_{x_{sub_i} x_i} P_{x_i x_j} \cdots P_{x_k x_\Omega}$$

- Runoff travel time

surface flow $$T_{w_s} = T_{x_{o_i}} + T_{x_i} + T_{x_j} + \cdots + T_{x_\Omega}$$

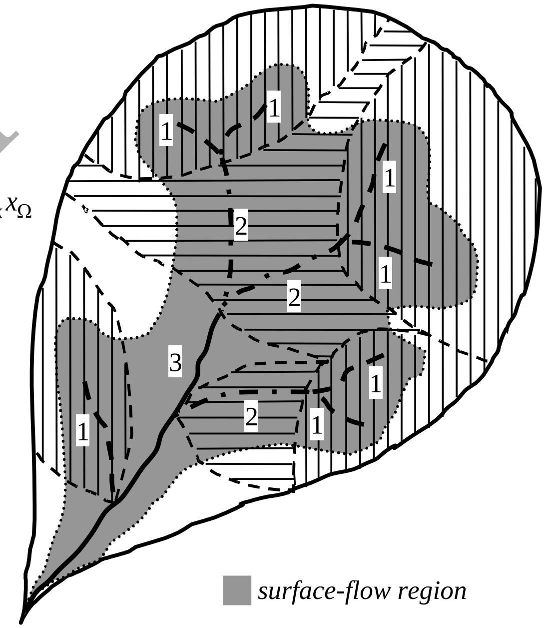
subsurface flow $$T_{w_{sub}} = T_{x_{sub_i}} + T_{x_i} + T_{x_j} + \cdots + T_{x_\Omega}$$

- Surface & Subsurface IUH

$$u_s(t) = \sum_{w_s \in W_s} \left[f_{x_{o_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_s} \cdot P(w_s)$$

$$u_{sub}(t) = \sum_{w_{sub} \in W_{ubs}} \left[f_{x_{sub_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{w_{sub}} \cdot P(w_{sub})$$

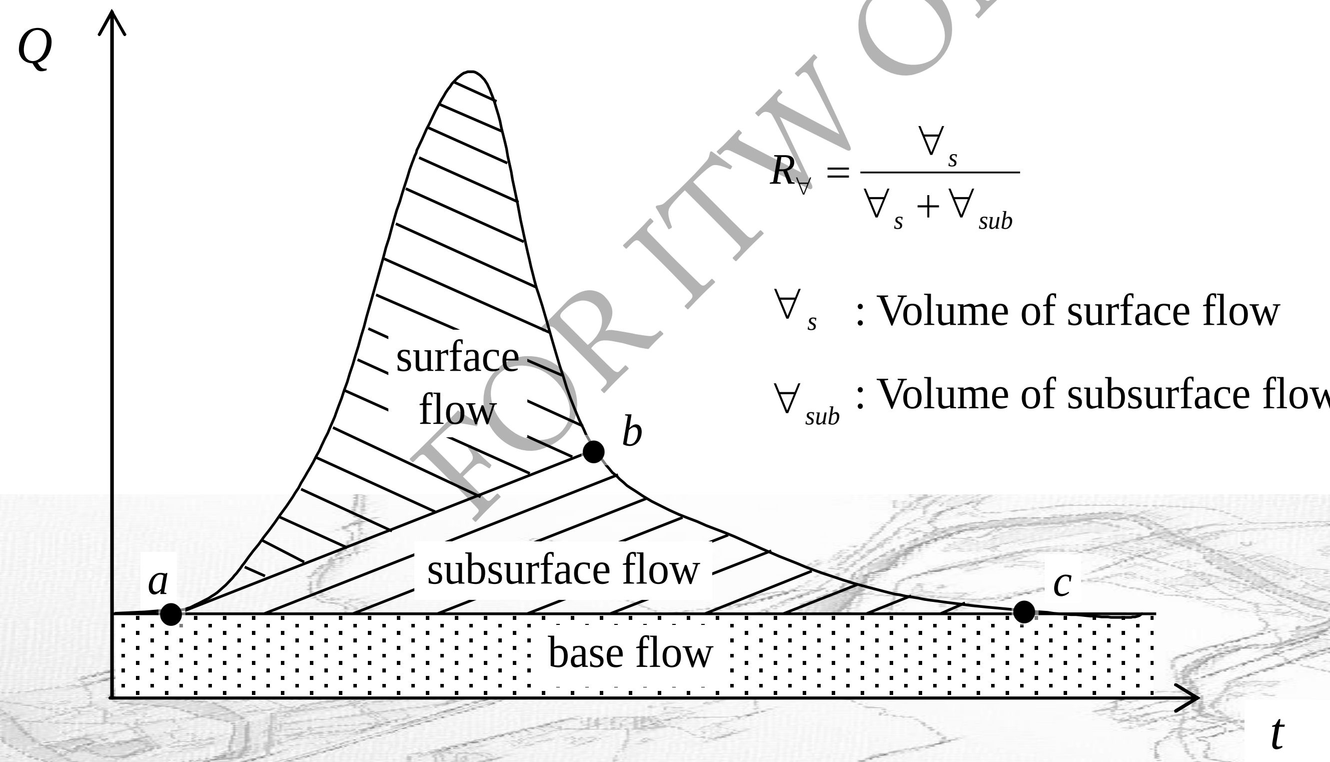
$$u(t) = u_s(t) + u_{sub}(t)$$



surface flow paths	*subsurface flow paths*
$x_{o1} \to x_1 \to x_2 \to x_3$	$x_{sub1} \to x_1 \to x_2 \to x_3$
$x_{o1} \to x_1 \to x_3$	$x_{sub1} \to x_1 \to x_3$
$x_{o2} \to x_2 \to x_3$	$x_{sub2} \to x_2 \to x_3$
$x_{o3} \to x_3$	$x_{sub3} \to x_3$

R_{PCA} and Flow Hydrograph Analysis

- Assume the partial-contributing-area ratio is equal to the ratio of surface-flow volume to the direct-runoff volume, that is $R_{PCA} = R_{\forall}$. So, the R_{PCA} for each storm can be estimated using flow record.

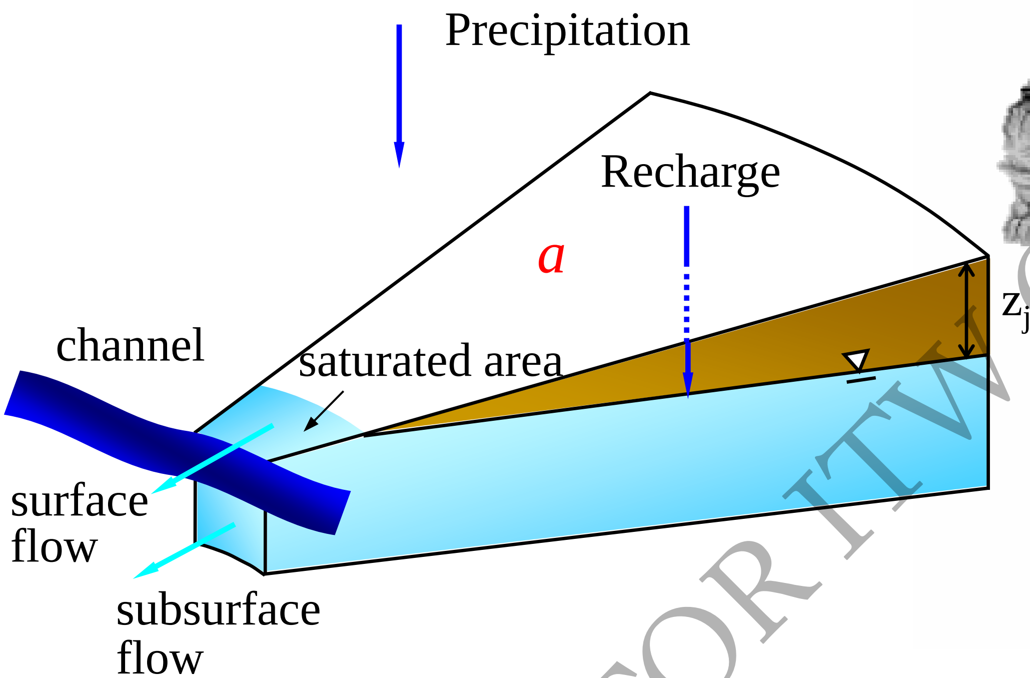


$$R_{\forall} = \frac{\forall_s}{\forall_s + \forall_{sub}}$$

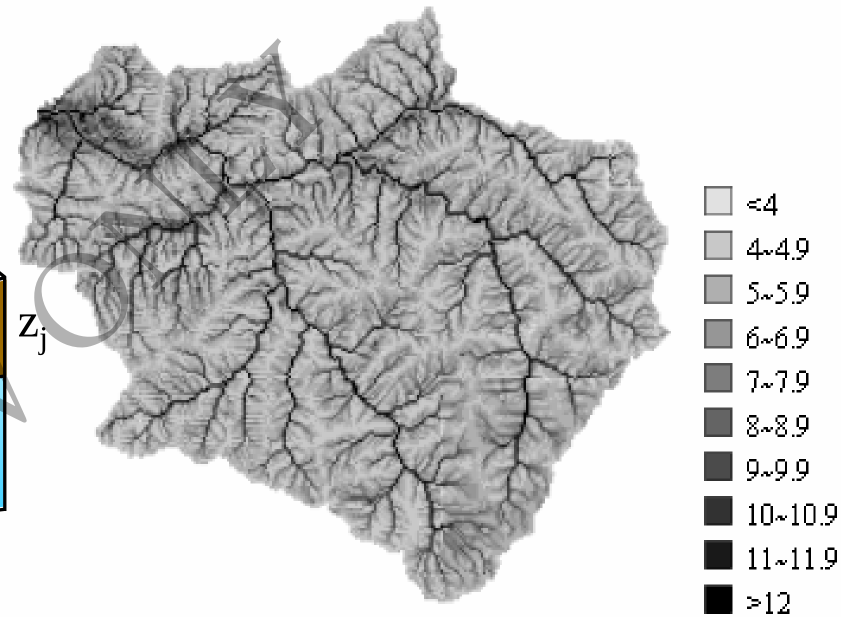
$\forall_s$: Volume of surface flow

$\forall_{sub}$: Volume of subsurface flow

Spatial Distribution of Topographic Index



$$T = \ln\left(\frac{a}{\tan\beta}\right)$$



$$T = \ln\left(\frac{a}{\tan\beta}\right)$$

Topographic index (Kirkby, 1975)

Horton-Ratio-Based KW-GIUH model

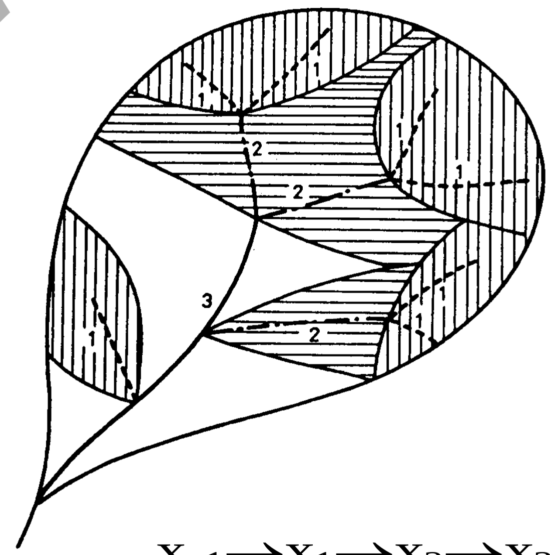
Horton-Strahler law (1945/1957)

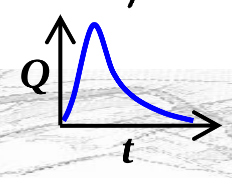
bifurcation ratio $R_B = \dfrac{N_{i-1}}{N_i}$, $R_B = 3\sim5$

length ratio $R_L = \dfrac{\bar{L}_{c_i}}{\bar{L}_{c_{i-1}}}$, $R_L = 1.5\sim3.5$

slope ratio $R_S = \dfrac{\bar{S}_{c_i}}{\bar{S}_{c_{i-1}}}$, $R_S \approx 0.5$

area ratio $R_A = \dfrac{\bar{A}_i}{\bar{A}_{i-1}}$, $R_A = 3\sim6$





$x_{o1} \rightarrow x_1 \rightarrow x_2 \rightarrow x_3$

$x_{o1} \rightarrow x_1 \rightarrow x_3$

$x_{o2} \rightarrow x_2 \rightarrow x_3$

$x_{o3} \rightarrow x_3$

Empirical results indicated that Horton-Strahler ratios are limited to small ranges in a large area.

Horton-Ratio-Based KW-GIUH model

- travel time for *i* th-order overland

$$T_{x_{oi}} = \left(\frac{n_o A P_{OA_i} \sum_{l=1}^{\Omega} R_L^{l-\Omega}}{2a^{1/2} S_{c_\Omega}^{b/2} L\, i_e^{m-1} R_B^{\Omega-i} R_L^{i-\Omega} R_S^{b(i-\Omega)/2}} \right)^{\frac{1}{m}}$$

- travel time for *i* th-order channel

$$T_{x_i} = \frac{B_\Omega L R_L^{i-\Omega} R_B^{\Omega-i} \sum_{l=1}^{i} R_L^{l-\Omega}}{i_e A P_{OA_i} \left(\sum_{l=1}^{\Omega} R_L^{l-\Omega} \right)^2} \left[\left(h_{co_i}^m + \frac{i_e A P_{OA_i} n_c \sum_{l=1}^{\Omega} R_L^{l-\Omega}}{B_\Omega S_{c_\Omega}^{1/2} R_S^{(i-\Omega)/2} R_B^{\Omega-i} \sum_{l=1}^{i} R_L^{l-\Omega}} \right)^{\frac{1}{m}} - h_{co_i} \right]$$

bifurcation ratio $R_B = \frac{N_{i-1}}{N_i}$

length ratio $R_L = \frac{\bar{L}_{c_i}}{\bar{L}_{c_{i-1}}}$

slope ratio $R_S = \frac{\bar{S}_{c_i}}{\bar{S}_{c_{i-1}}}$

area ratio $R_A = \frac{\bar{A}_i}{\bar{A}_{i-1}}$

- the geomorphologic IUH

$$u(t) = \sum_{w \in W} \left[a_{o_i} \exp\left(-\frac{t}{T_{x_{o_i}}}\right) + b_i \exp\left(-\frac{t}{T_{x_i}}\right) + \cdots + b_\Omega \exp\left(-\frac{t}{T_{x_\Omega}}\right) \right]_w \cdot P(w)$$

Horton kinematic-wave based geomorphologic IUH (Yen and Lee, 1997)