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International Water Resources Association (IWRA)

Investigation of Heavy Rainfall Induced Runoff Analysis at Small Catchment Scale by Using Distributed Runoff Models

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WORLD WATER CONGRESS
Water for All
Harmony between Humans and Nature

第18届
世界水资源大会
水与万物：
人与自然和谐共生

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1. Background

• Globally, about 2 billion people are at risk of flooding, nearly 600 million of whom live in poverty. According to the report released by the United Nations Office for Disaster Reduction (UNDRR), during the past two decades (2000-2019), a total of 3,254 flood events have been reported worldwide, accounting for 44 % of all disasters. A total of 1.65 billion people were affected by floods, and about 100,000 people were killed.

1. Background

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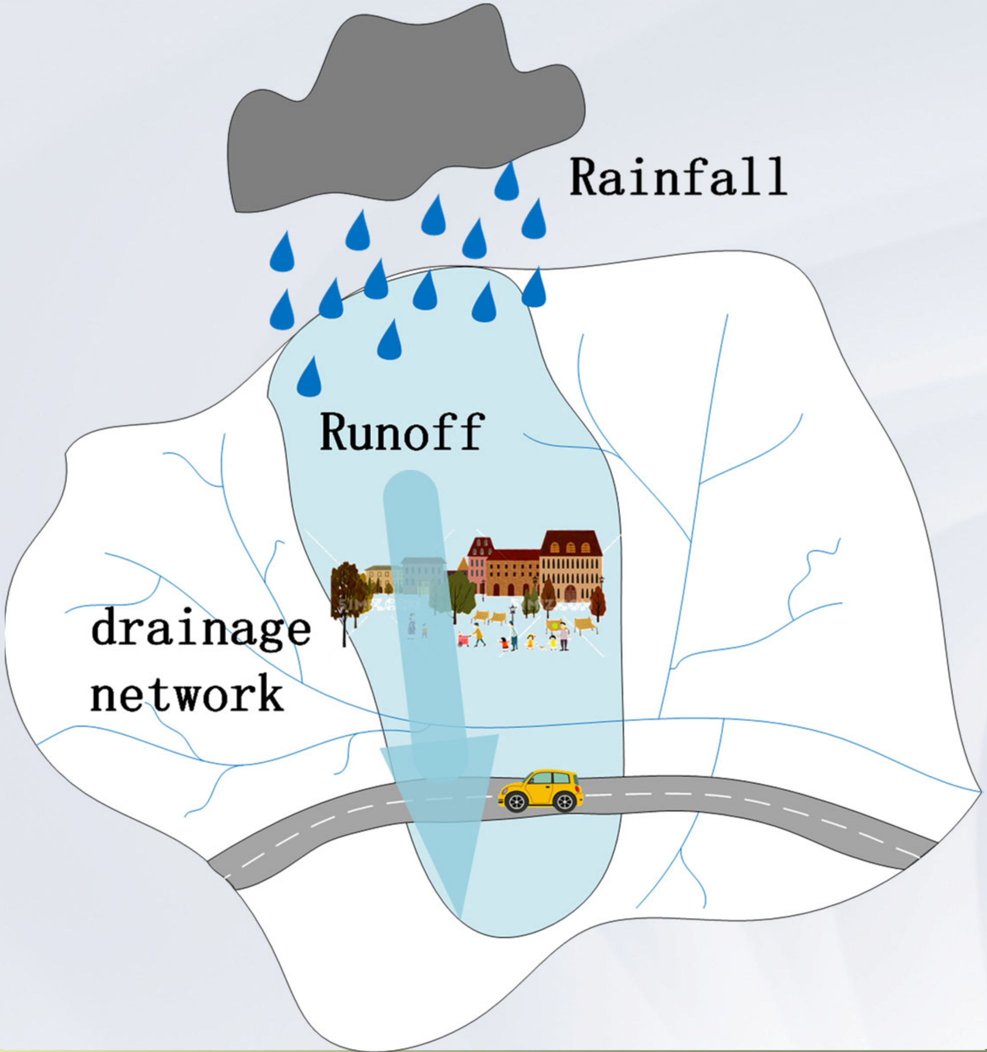
- In recent years, geological disasters such as mountain flood, urban flood, and debris flows caused by heavy rainfall have occurred frequently around the world. The runoff process plays a vital role in the generation of these disasters and the simulation of distributed runoff depth is an important means to evaluate geological hazards.
- Therefore, many scholars are committed to solving a key problem:

How to quickly simulate rainfall-runoff processes in mountainous or urban areas?



2. Existing hydrodynamic methods

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Although the equations of motion of shallow water equation can be solved as-is, the timesteps need to be small, and the equations cannot be used for predications on the time scales of actual liquid flow problems.

Shallow water equations:

Equation of continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = R - I$$

Equations of motion:

$$\frac{\partial (uh)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -hg\frac{\partial H}{\partial x} - hgS_{fx} + D_x$$

$$\frac{\partial (vh)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2)}{\partial y} = -hg\frac{\partial H}{\partial y} - hgS_{fy} + D_y$$

Zhu, Y.L., Ishikawa, T., Subramanian, S. S., et al., 2020. Simultaneous analysis of slope instabilities on a small catchment-scale using coupled surface and subsurface flows. Engineering Geology, 275, 105750.

Equations of motion: → Diffusion wave approximation (Zhu et al., 2020):

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = G_x + F_x + D_x \Rightarrow 0 = G_x + F_x$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hu^2)}{\partial y} = G_y + F_y + D_y \Rightarrow 0 = G_y + F_y$$

Ignore some insignificant terms to improve computing efficiency!

> 99%

Contributions of each term in the equations of motions for surface water flows.

Slope angle (°)	Inertia term (%)	Velocity term (%)	Driving force term (%)	Friction Term (%)	Advection Term (%)
	$\frac{\partial u}{\partial t}, \frac{\partial v}{\partial t}$	$\frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y}, \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y}$	G_x, G_y	F_x, F_y	D_x, D_y
<1°	<0.001	<0.001	50.038	49.961	<0.001
5°	<0.001	0.005	49.584	50.410	<0.001
10°	<0.001	0.011	49.595	50.393	<0.001
15°	0.003	0.015	49.535	50.446	0.001
30°	0.024	0.219	52.537	47.200	0.020
45°	0.051	0.850	44.260	54.730	0.109
60°	0.159	0.327	50.808	48.679	0.027

2. Existing hydrodynamic methods

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Integrated watershed model of runoff and seepage:

The governing equation of the integrated watershed model of runoff and seepage is as follows ((more details are discussed by Mori et al. (2015)).

$$-\nabla M_p - Q = \frac{\partial(\phi S_p)}{\partial t}\ ,\ p = (\text{water}, \text{air})$$

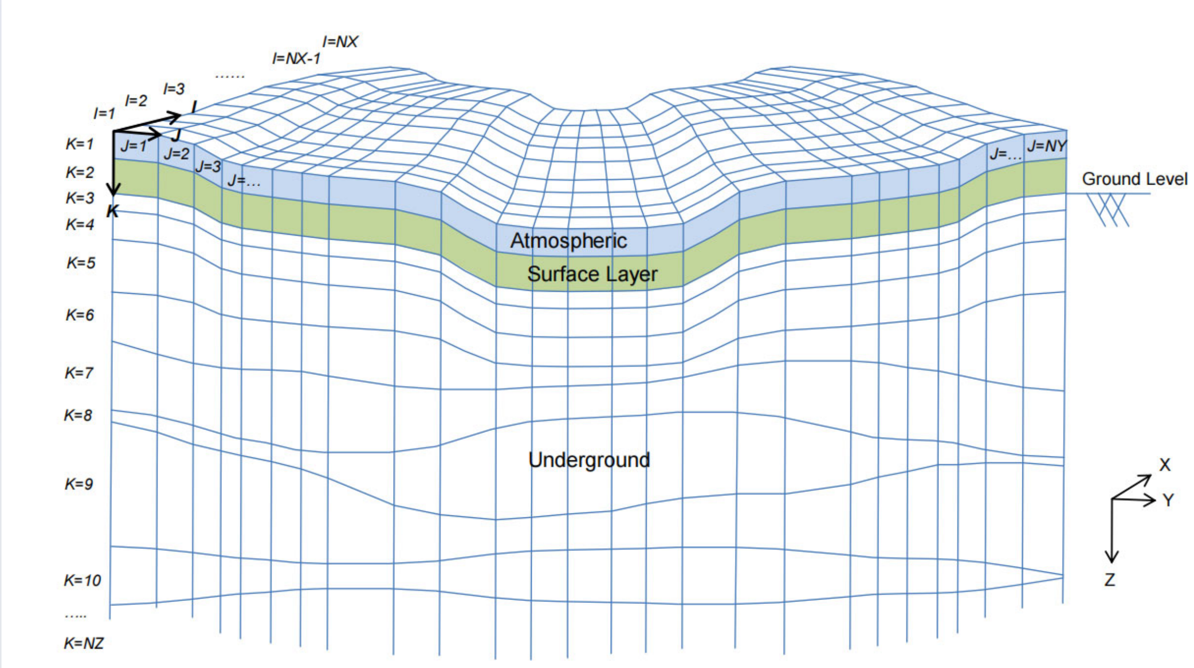
Runoff:

$$M_w = -\frac{h^{2/3}}{n_m\sqrt{|S|}}\nabla(h+z)$$

$$M_a = -\frac{k_s\, k_{r,a}}{\rho_a g}\cdot\nabla(\Psi_a)$$

Seepage:

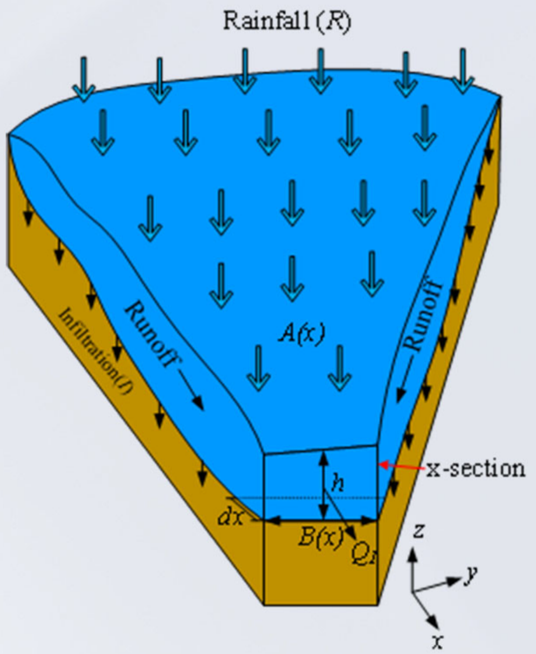
$$M_p = -\frac{k_s\, k_{r,p}}{\rho_p g}\cdot\nabla(\Psi_p)$$

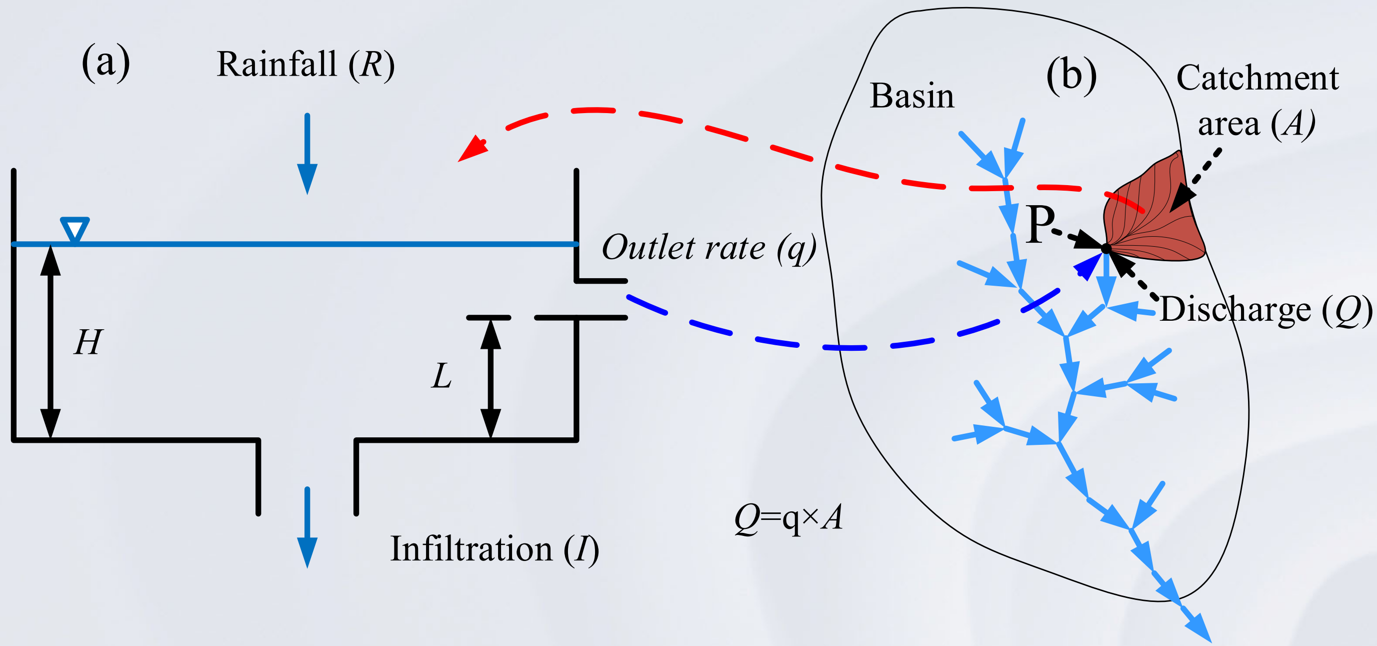


Mori, K., Tada, K., Tawara, Y., et al., 2015. Integrated watershed modeling for simulation of spatiotemporal redistribution of post-fallout radionuclides: application in radiocesium fate and transport processes derived from the Fukushima accidents. Environmental Modelling & Software, 72, 126-146.

3. Distributed Runoff Model (DRM)

Distributed Runoff Model (DRM)----A fully integrated hydrological-hydrodynamic model:





Establish a mathematical association

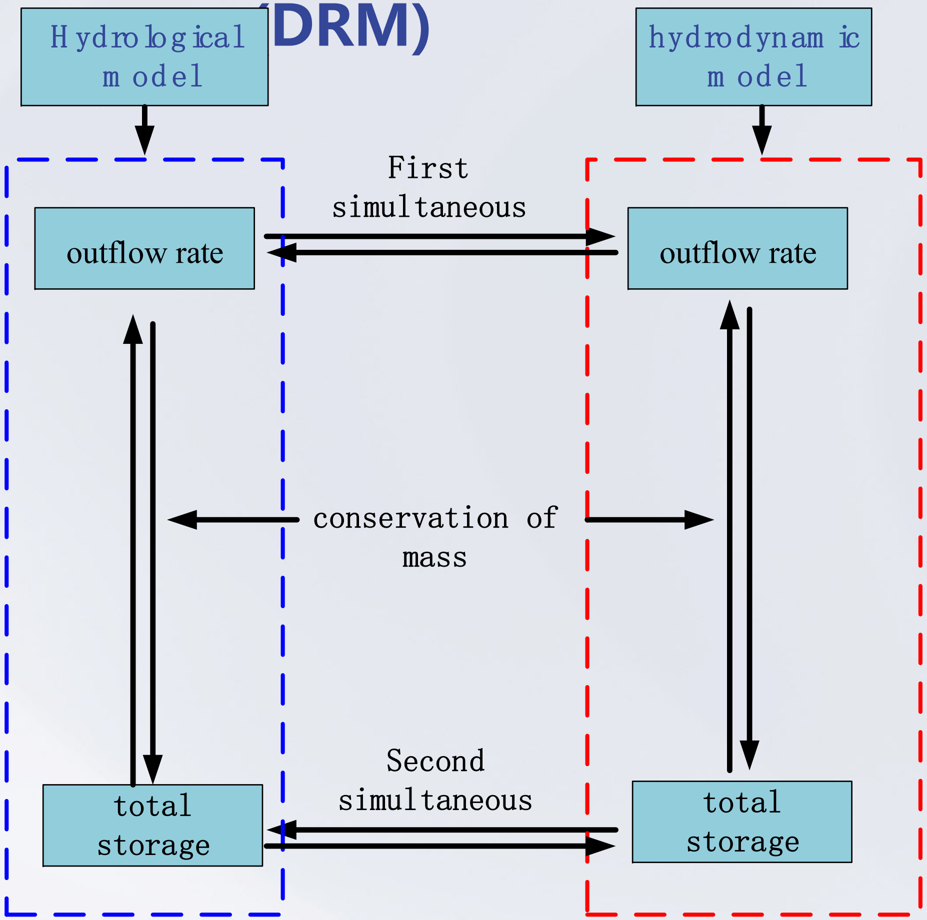
$$\left.\begin{aligned} \frac{\partial h}{\partial t} + \frac{\partial (Q_1)}{\partial l} &= R - I \\ Q_1 &= a h^m \\ a &= \frac{\sqrt{S}}{n_m} \end{aligned}\right]$$

Hydrodynamic model ⟷ **Hydrological model**

$$\left[\begin{aligned} \frac{dH}{dt} &= R - I - q \\ Q &= q \times A \end{aligned}\right.$$

3. Distributed Runoff Model (DRM)

Distributed Runoff Model (DRM)



Establish a mathematical association

$$\left.\begin{aligned} \frac{\partial h}{\partial t} + \frac{\partial (Q_1)}{\partial l} &= R - I \\ Q_1 &= a h^m \\ a &= \frac{\sqrt{S}}{n_m} \end{aligned}\right\} \Longleftrightarrow \left\{\begin{aligned} \frac{dH}{dt} &= R - I - q \\ Q &= q \times A \end{aligned}\right.$$

fully integrated hydrological-hydrodynamic model (Zhu et al., 2022)

$$\Longrightarrow \left\{\begin{aligned} \frac{dH_x}{dt} &= R - I - q_x \\ H_x &= \left(\frac{n_m}{\sqrt{S}}\right)^{0.6} {q_x}^{0.6} b A(x)^c \\ h(x) &= \left(\frac{n_m}{\sqrt{S}}\right)^{0.6} (k q_x)^{0.6} \left(\frac{A(x)}{B(x)}\right)^{0.6} \\ V(x) &= \frac{\sqrt{S_p}}{n_m} h(x)^{\frac{2}{3}} \end{aligned}\right.$$

Zhu, Y.L., Zhang, Y.F., Yang, J., Nguyen, B. T., & Wang, Y.* (2022). A novel method for calculating distributed water depth and flow velocity of stormwater runoff during the heavy rainfall events. Journal of Hydrology, 612, 128064.

4. Effectiveness of DRM

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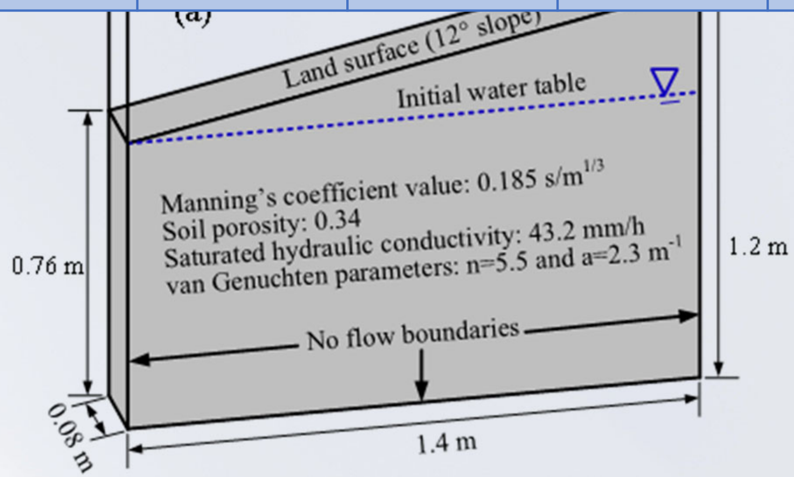
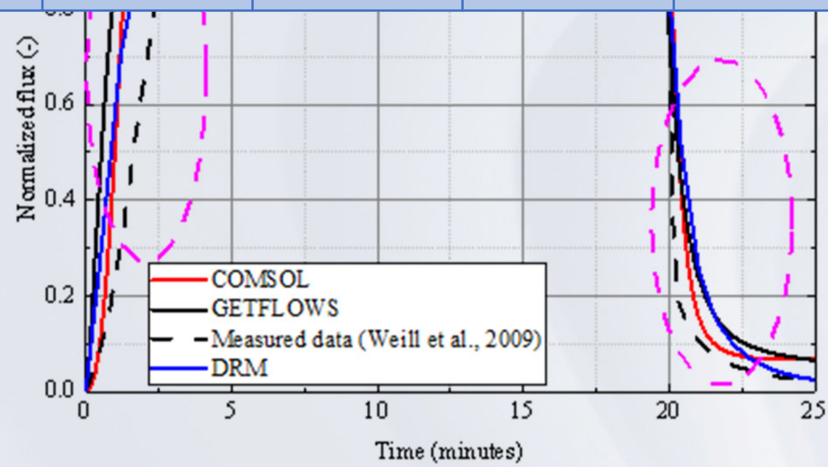
Validation of DRM by Abdul and Gillham sy

Parameters	n_m ($s/m^{1/3}$)	S (1)	b	c	k	L (mm)	A(x) (km^2)	B(x) (m)	f (1/h)
Value	0.185	0.105	3	0.21	1	0	0.112×10^{-6}	0.08	0



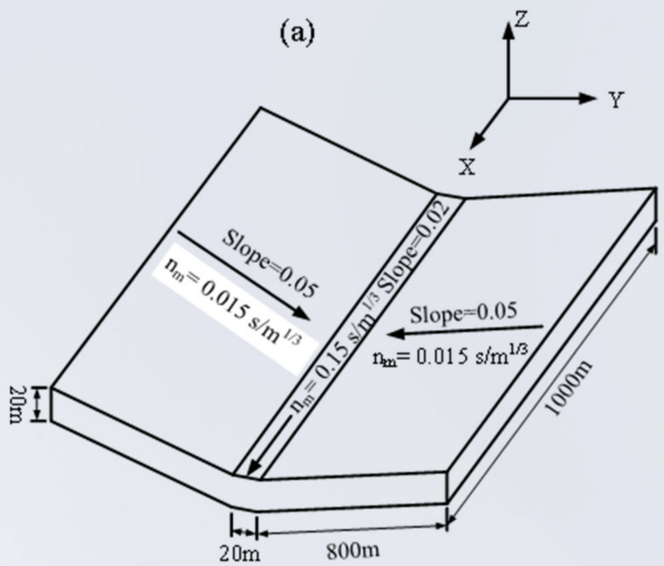


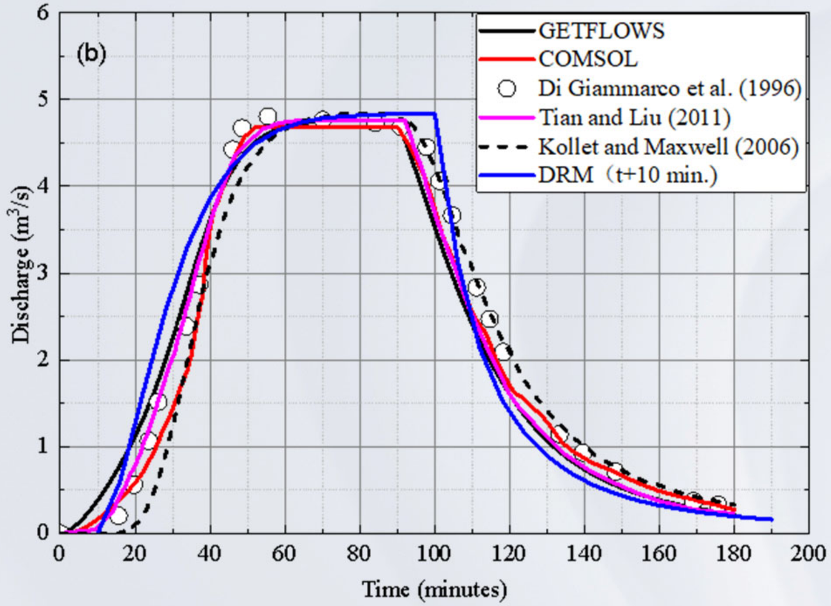
Accordingly, by using the Abdul and Gillham system, the effectiveness of DRM on the scale of the test chamber (the catchment area is 0.112×10^{-6} km^2) has been well verified.

4. Effectiveness of DRM

Validation of DRM by V-catchment system

Parameters	n_m (s/m$^{1/3}$)	S (1)	b	c	k	L (mm)	$A(x)$ (km^2)	$B(x)$ (m)	f (1/h)
Value	0.015	0.05	4	0.21	1	0	1.62	20	0





Accordingly, by using the Abdul and Gillham system, the effectiveness of DRM on the scale of the test chamber (the catchment area is 0.112×10^{-6} km^2) has been well verified.

4. Effectiveness of DRM

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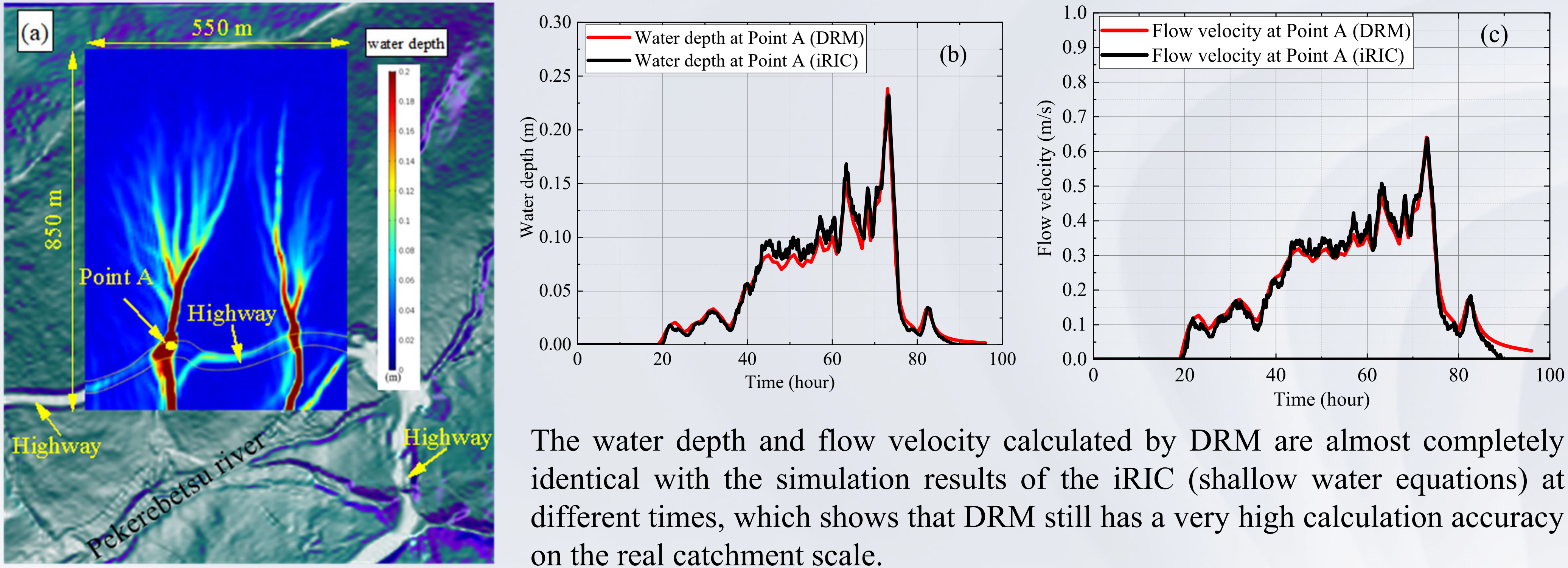
Validation of DRM in a real catchment

Parameters	n_m (s/m$^{1/3}$)	S (1)	S_p (1)	b	c	k	L (mm)	$A(x)$ (km^2)	$B(x)$ (m)
Value	0.3	0.25	0.1	4	0.21	1	0	0.1356	20



The water depth and flow velocity calculated by DRM are almost completely identical with the simulation results of the iRIC (shallow water equations) at different times, which shows that DRM still has a very high calculation accuracy on the real catchment scale.

4. Effectiveness of DRM

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The improvement of calculation efficiency

Model	Catchment area	Simulation time	Calculation time of shallow water equations	Calculation time of DRM	**The improvement of calculation efficiency**
Test Model	1×10^{-3}	1 hour	14 s	4 s	**71.4%**
		1 day	1 min. 33 s	27 s	**71.0%**
		3 day	6 min. 12 s	84 s	**77.4%**
Catchment Model	0.1356	3 hour	14 min 57 s	One Point：4 s	**99.5%**
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The calculation efficiency of DRM has increased by 78.6%, 87.1%, and 89.0% respectively, so the calculation efficiency has increased by 70% ~ 90%.

5. Conclusions

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- A fully integrated hydrological-hydrodynamic model-DRM is proposed to calculate the distributed water depth and flow velocity of heavy rainfall-induced stormwater runoff under time-dependent rainfall by fully coupling the conceptual hydrological model and hydrodynamic model.
- The effectiveness and practicality of DRM on different catchment scales (i.e., 0.112×10^{-6} km^2, 1×10^{-3} km^2, and 1.62 km^2) have been verified by comparing with the test results and three other methods, i.e., shallow water equations, integrated watershed model, and iterative cross-coupled model of runoff and seepage.
- Results indicate that the DRM proposed in this study greatly improves the calculation efficiency and reduces the calculation difficulty of the distributed water depth and flow velocity of the heavy rainfall-induced stormwater runoff while meeting the accuracy requirements.

Thank you very much for your kind attention and comments