Coupled effects of microtopography and time-dependant infiltration capacity on rainfall-runoff-infiltration partitioning on a hillslope

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Introduction & motivation

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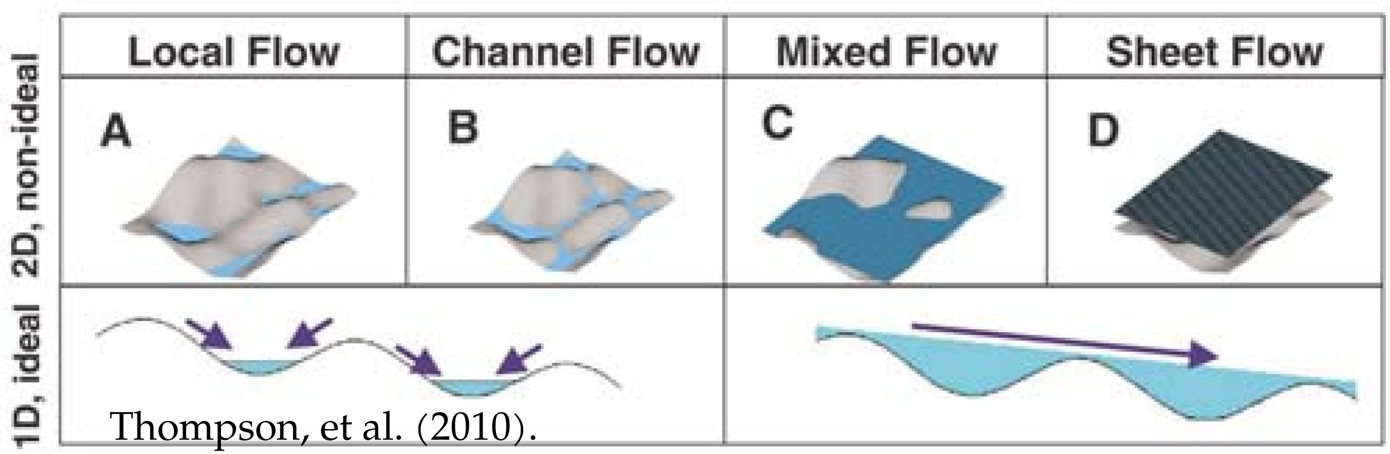
- Runoff generation and hydrodynamics are strongly affected by the macrotopography (slope and shape), microtopography and infiltration properties of a hillslope.
- Microtopography (MT, mm-cm) generates particular flow paths and spill-and-fill processes, which, together with the spatiotemporal dynamics of infiltration result in observable fluxes at larger spatial and temporal scales characteristic of hillslopes and first-order catchments.
- How does this rescaling of fluxes from plot scale dynamics (microtopography + infiltration) into hillslope scales (hydrographs!) occur? Multiscale problem!
- What is the sensitivity of runoff to MT and infiltration in this process?
- Is it possible to link MT and infiltration properties, the small scale hydrodynamic response, hillslope scale hydrographs, and water balances?
- We start by considering the onceptual flow regimes identified by (Thompson et al, 2010), but they studied a 1D idealised hillslope which neglects the complex development of connectivity of 2D flows.



Thompson, et al. (2010).

Approach

- Use a physically-based numerical model to solve rainfall-runoff over a set of surfaces for a single, idealised rain event
- Design a set of surfaces with different slopes and microtopography features, including smooth surfaces without MT
- Examine the effects of different infiltration capacity curves
- Identify features of hydrographs and water depth distributions for each case
- Characterise the change in hydrological partitioning (in terms of infiltration) in the presence of MT relative to smooth surfaces
- Relate the runoff response to MT, infiltration capacity, and identify possible flow regimes

Test surfaces

- Topography is a sloping plane with slope s in the x direction, with a reference elevation z_0
- Microtopography defined as a 2D sine wave with amplitude a and wavelength λ

$$z(x, y) = z_0 + sx + a \sin\left(\frac{2\pi}{\lambda}x\right)\sin\left(\frac{2\pi}{\lambda}y\right)$$

- Range of slopes from 0% to 10%
- Range of amplitudes from 1cm to 10 cm
- Range of wavelengths from 15cm to 200cm
- Reference smooth surfaces with $a = 0$ for all slopes were also generated

Surfaces (examples)

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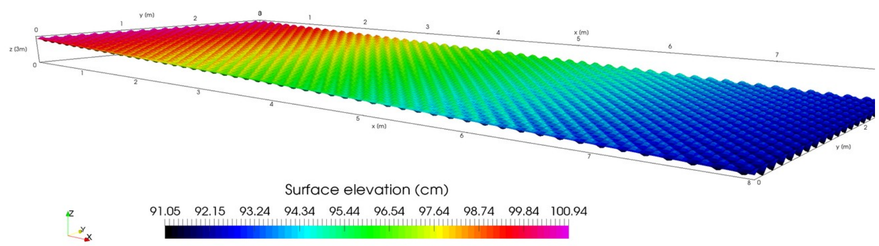
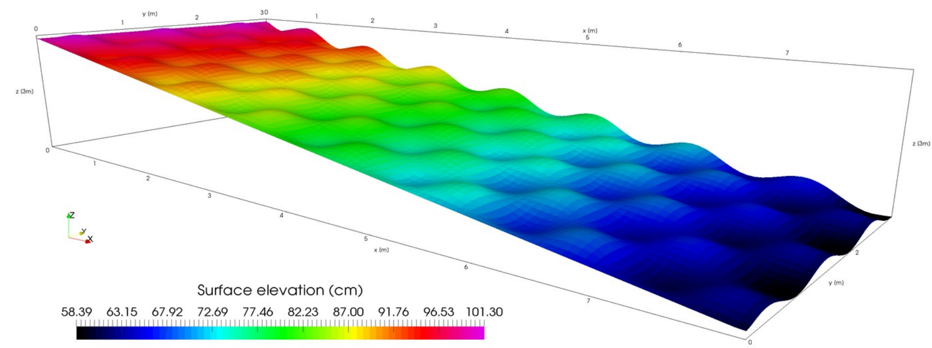
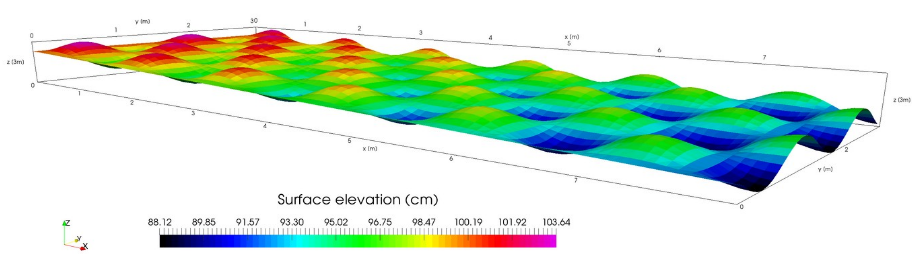
Slope 1%, wavelength 15 cm, amplitude 1cm



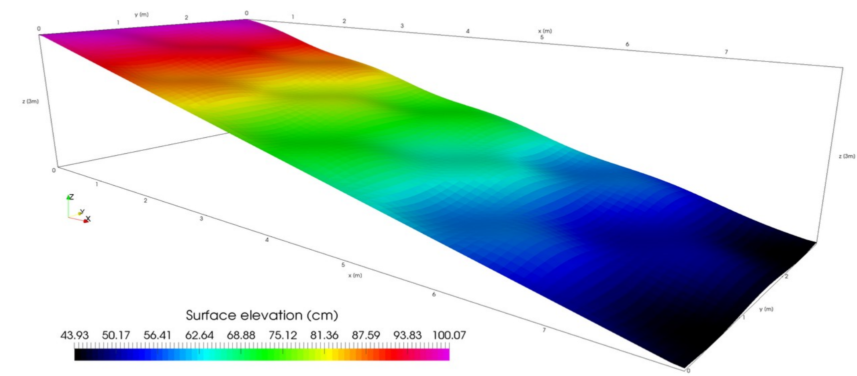
Slope 5%, wavelength 108 cm, amplitude 3 cm



Slope 1%, wavelength 138 cm, amplitude 4 cm



Slope 7%, wavelength 200 cm, amplitude 3cm



Mathematical model

2D zero-inertia (diffusive-wave) approximation to the SWE

$$\frac{\partial h}{\partial t} = \nabla \left(\frac{h^{5/3} \nabla (h+z)}{n||\nabla (h+z)||} \right) = r - i$$

- $h :=$ water depth $[m]$
- $z :=$ soil surface elevation $[m]$
- $r :=$ rain intensity $[m/s]$
- $i :=$ infiltration rate $[m/s]$
- $n :=$ Manning's roughness coefficient $[m^{-1/3}s]$

Solved by a parallelized, explicit, first order Finite Volumes scheme on structured square meshes (Caviedes-Voullième et al., 2020)

Caviedes-Voullième et al. Performance assessment of 2D Zero-Inertia and Shallow Water models for simulating rainfall-runoff processes. Journal of Hydrology. 2020. https://doi.org/10.1016/j.jhydrol.2020.124663

Microtopography indices

Microtopography ratio: $$\tilde{M} = \frac{\lambda}{a}$$

λ ← wavelength

a ← amplitude

Higher $\tilde{M}$ → smoother surface → runoff favoured

Depression Storage ratio: $$\tilde{D} = \frac{DS}{R}$$

DS ← Maximum depression storage

R ← Rainfall volume

$\tilde{D} \approx 1$ Runoff threshold (impervious conditions)

$\tilde{M}$ is not a function of slope (only MT), therefore microscale index

$\tilde{D}$ is a function of slope and MT, therefore multiscale index

Simulation setup

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- Rainfall-runoff simulations for 1440 surface
- Cellsize determined to capture properly sine wave (10 cells per wavelength)
- Closed boundaries except for downslope boundary (outfall)
- Simulation time 8000s.
- Rain duration 1800 s, intensity 7.5 mm/h
- Manning's coefficient 0.055 $m^{-1/3}s$
- Constant infiltration capacity (CIC) of 0.001 mm/s
- Non-constant infiltration capacity (NIC) using Horton's equation (parametrised to obtain the same average rate as CIC)

Infiltration indices

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Infiltration enhancement ratio

$$\tilde{I} = \frac{I_{\mathrm{MT}}}{I_o}$$

Infiltration on surface with MT

Infiltration on smooth surface without MT

Ratio of infiltration enhancement

$$\hat{I} = \frac{\tilde{I}_{\mathrm{NIC}}}{\tilde{I}_{\mathrm{CIC}}}$$

NIC: Non-constant infiltration

CIC: Constant infiltration

Ratio of infiltration

$$\breve{I} = \frac{I_{\mathrm{NIC}}}{I_{\mathrm{CIC}}}$$

Flow regimes and hydrographs

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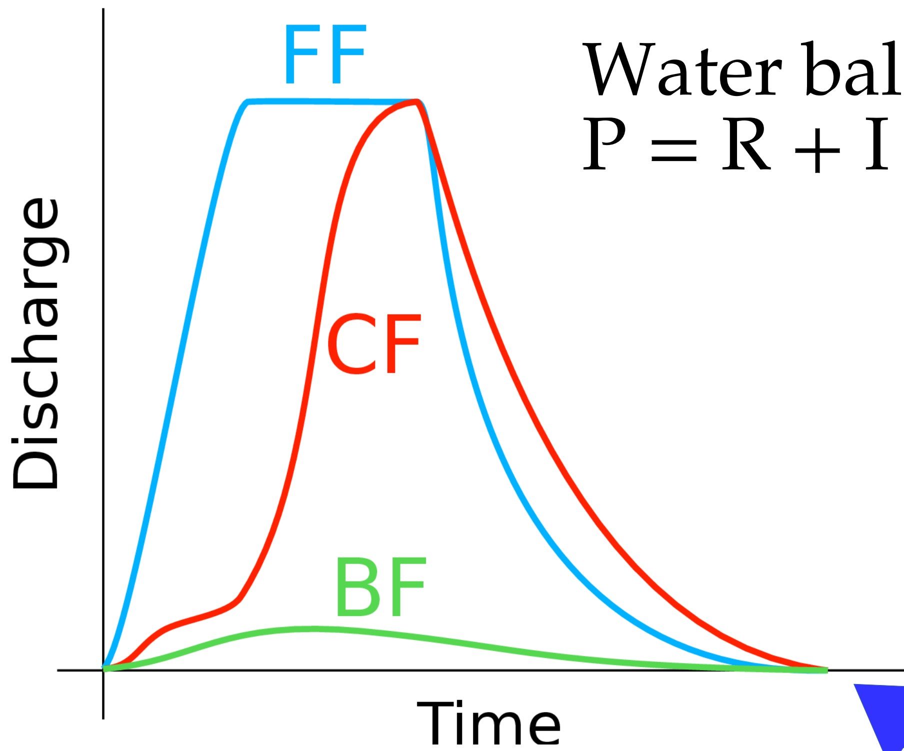
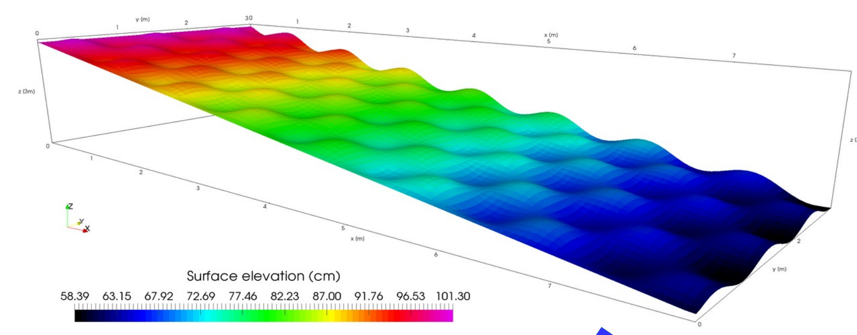
Macroscopic signatures

Water balance
$P = R + I + dS$

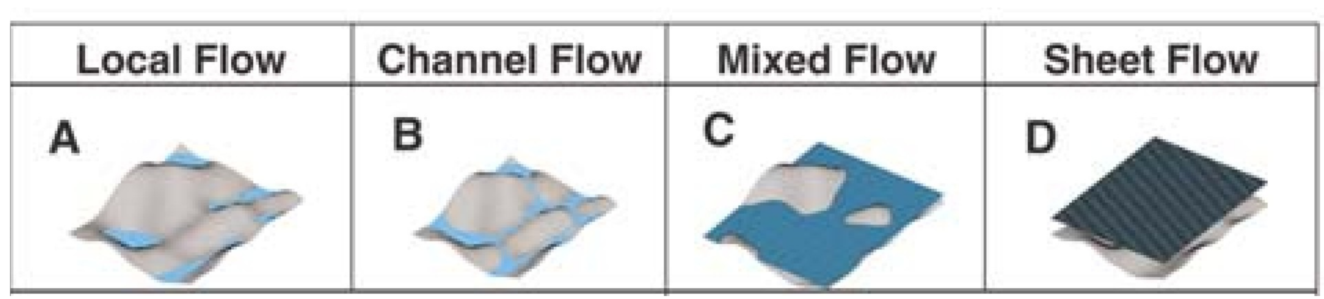


Hydrograph types
Full Flow
Connected Flow
Boundary Flow

MICROTOPOGRAPHY + SLOPE

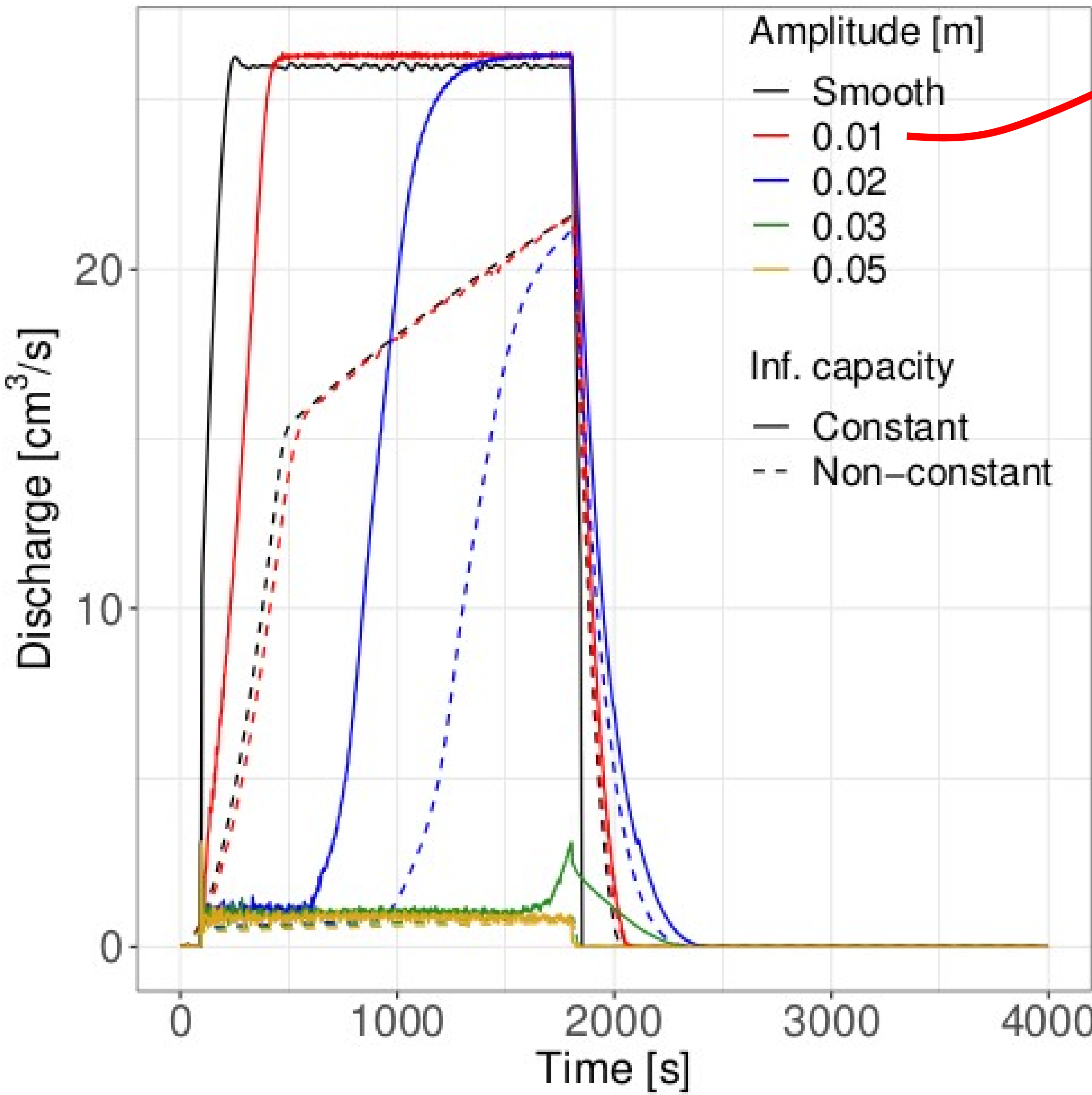


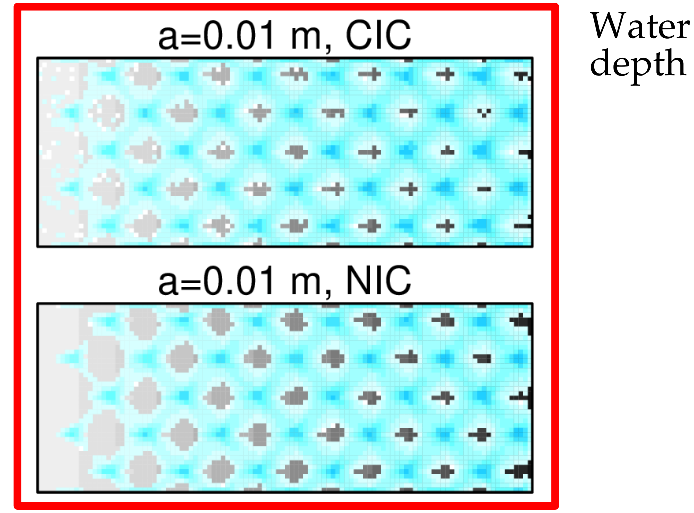
Spatial distributions and flow regimes

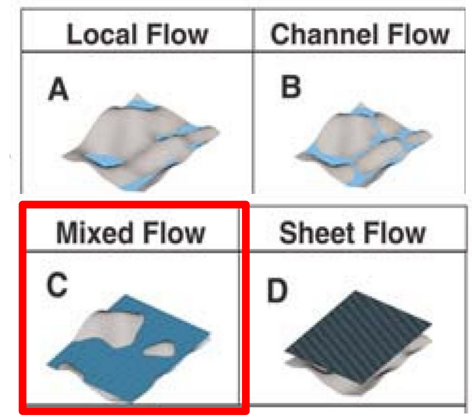


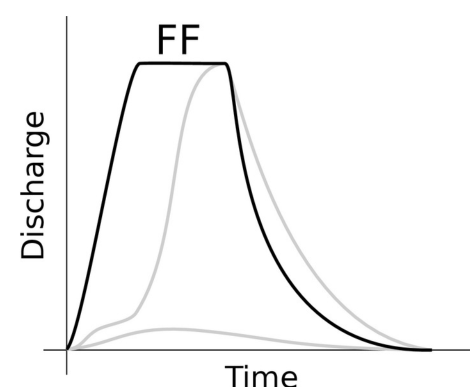
Hydrographs and regimes

$s = 0.05, \lambda = 1.2071\ m$









Hydrographs and regimes

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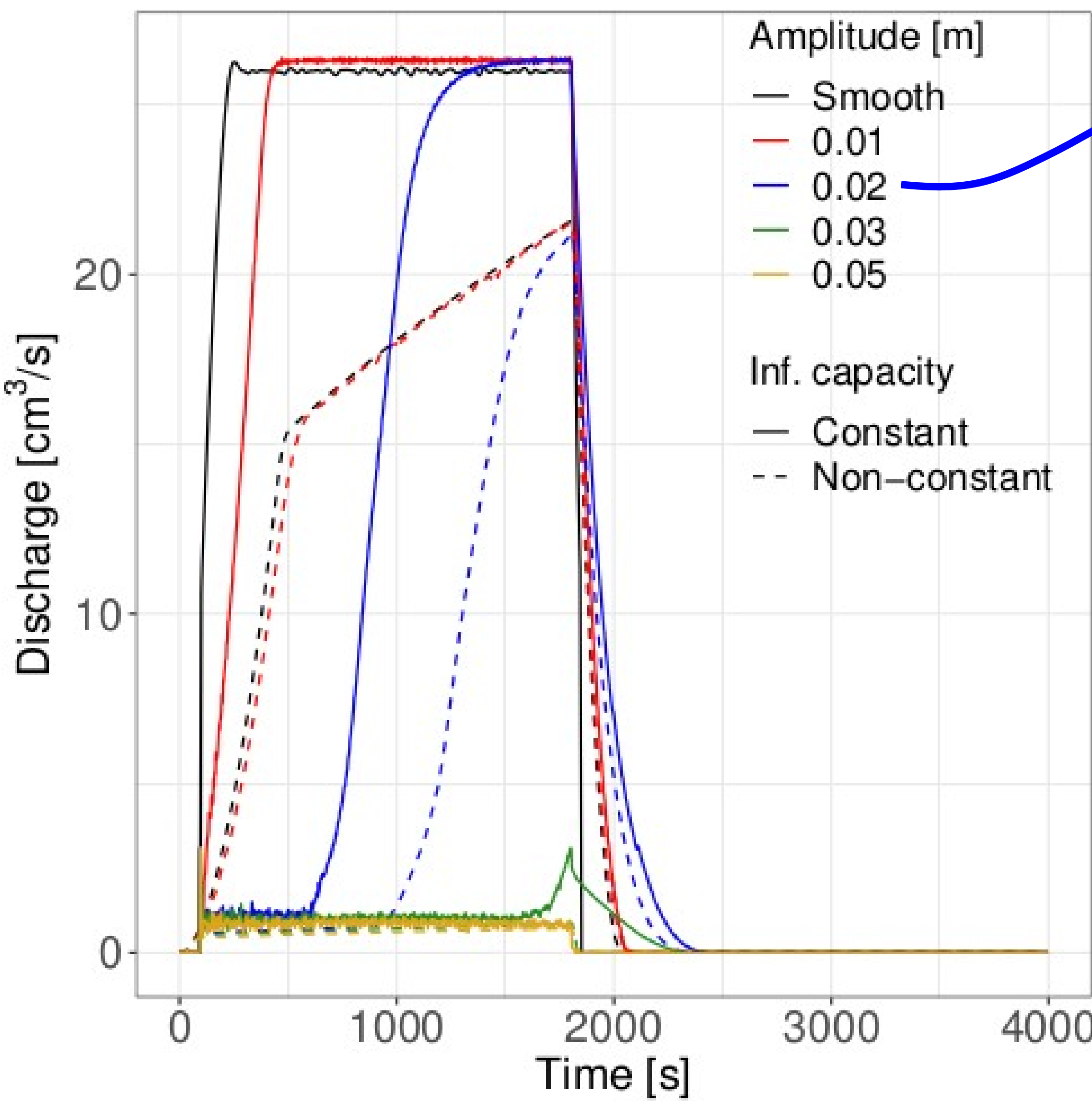
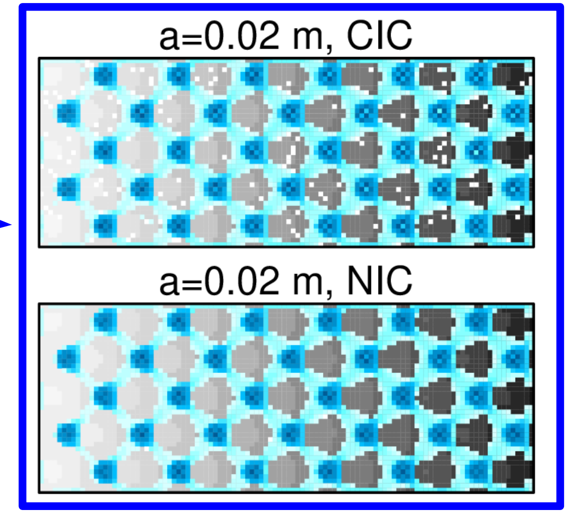
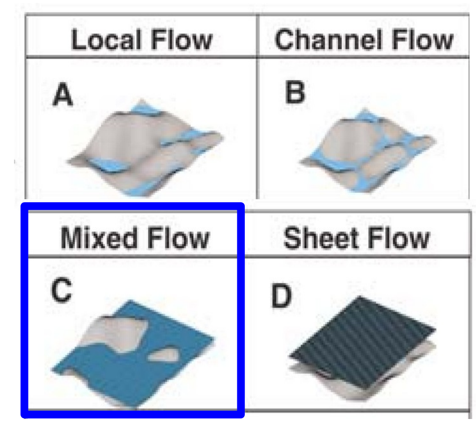
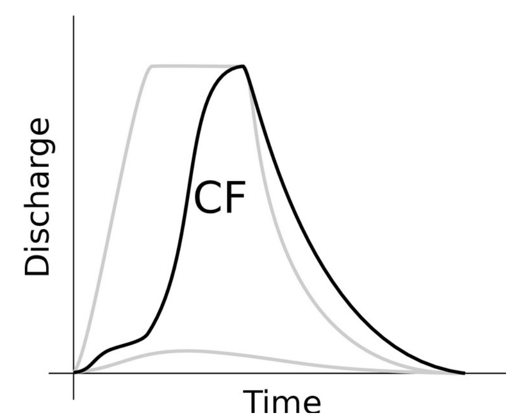




Water depth





Hydrographs and regimes

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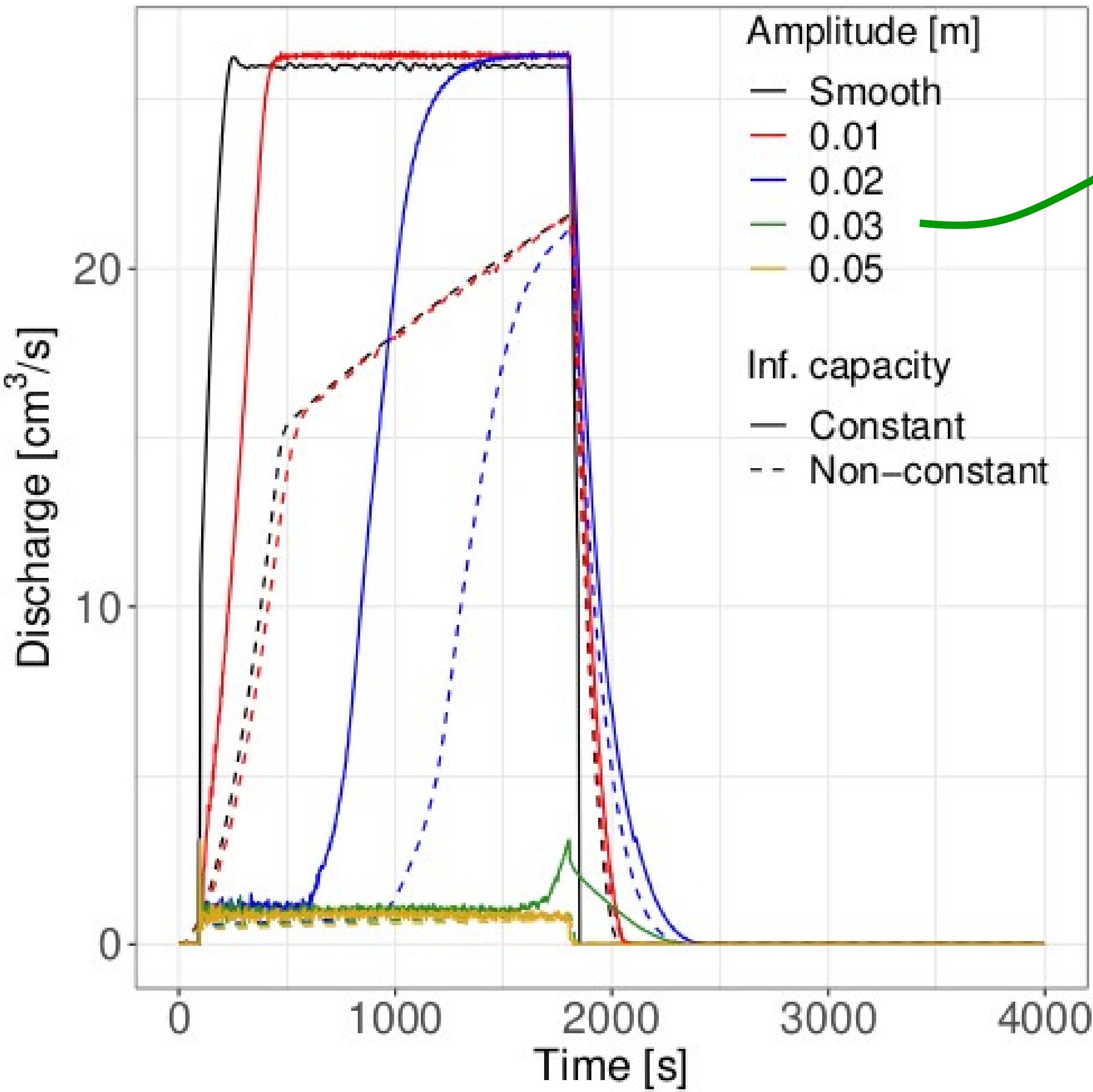
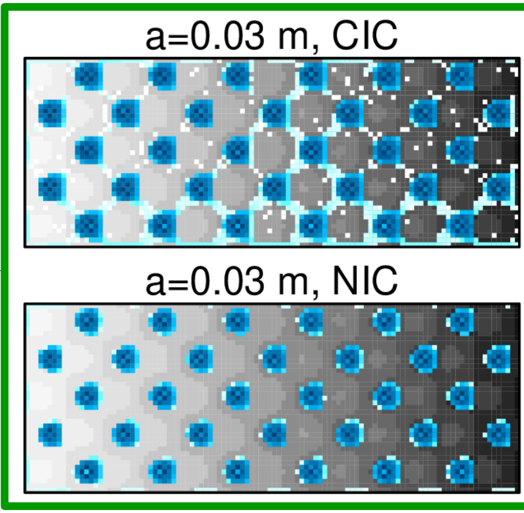
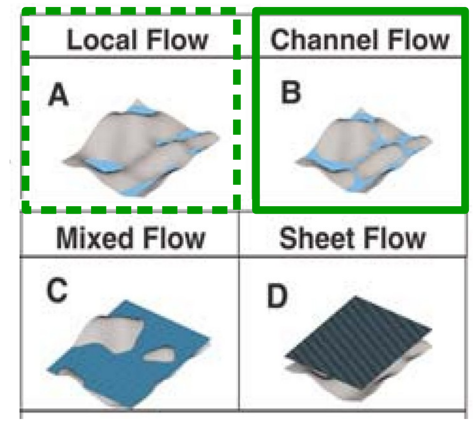
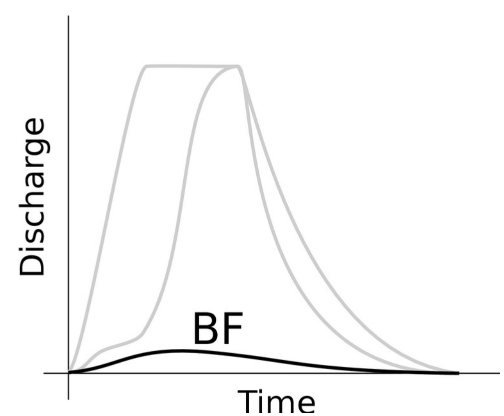
$s = 0.05, \lambda = 1.2071\ m$





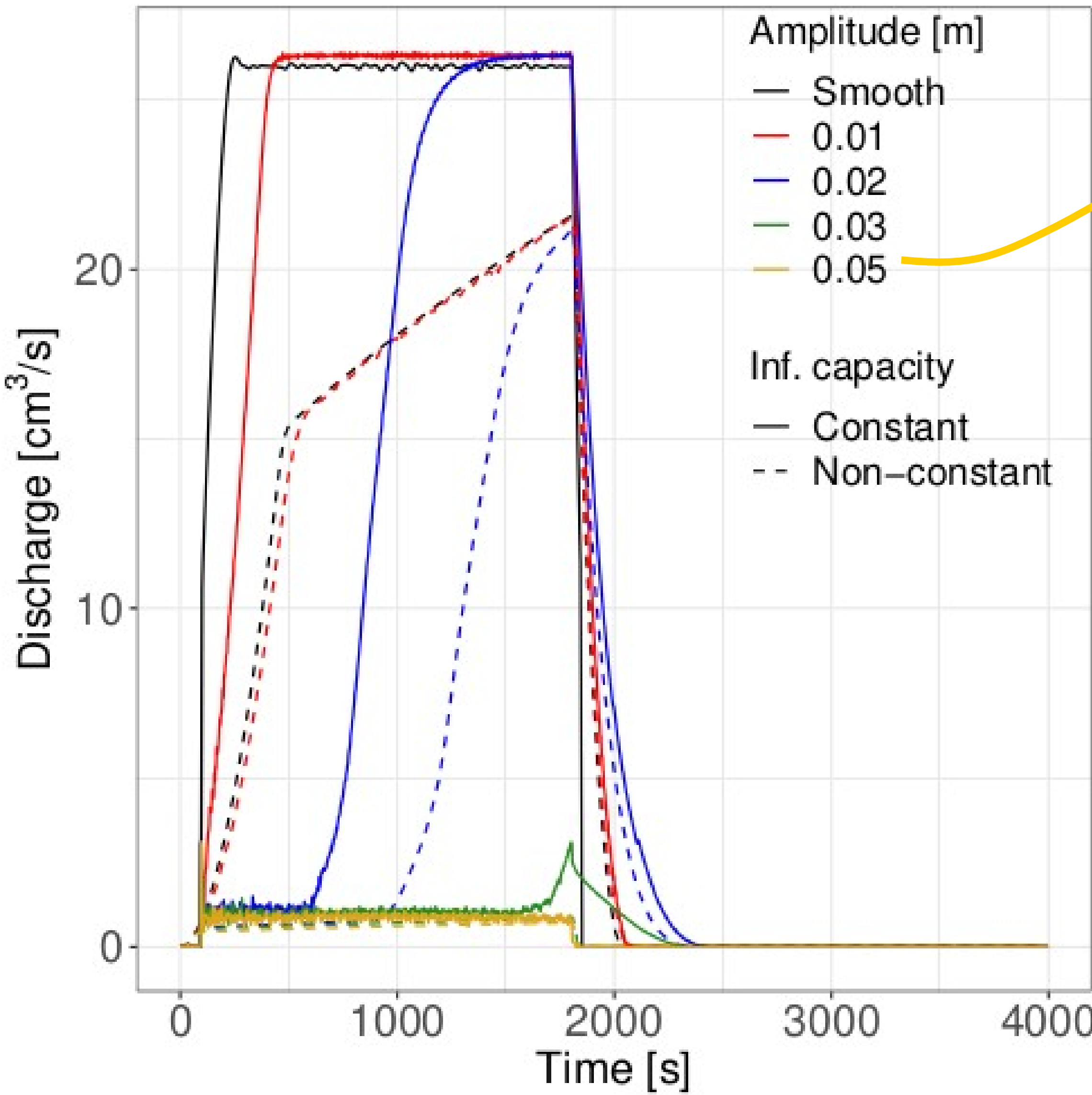
Water depth

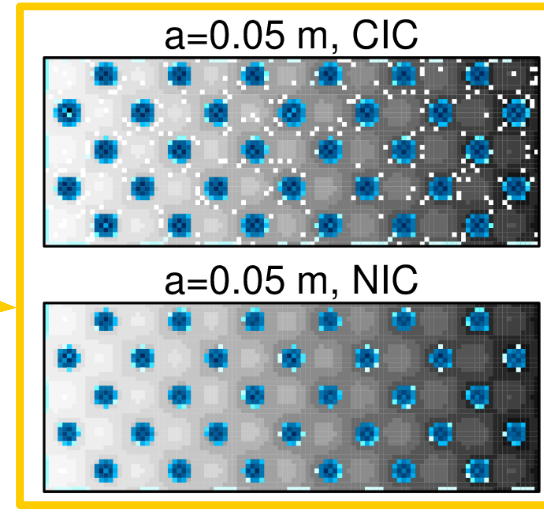




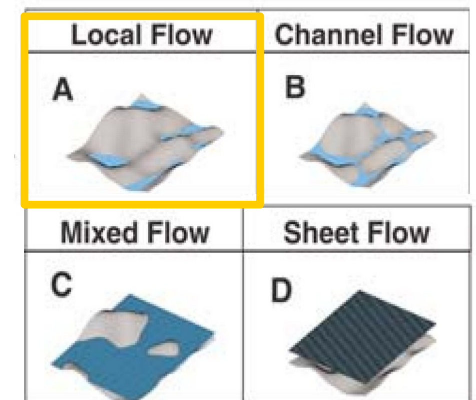
Hydrographs and regimes

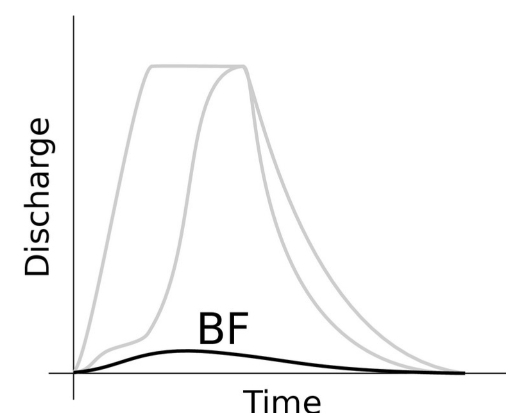
$s = 0.05, \lambda = 1.2071\ m$



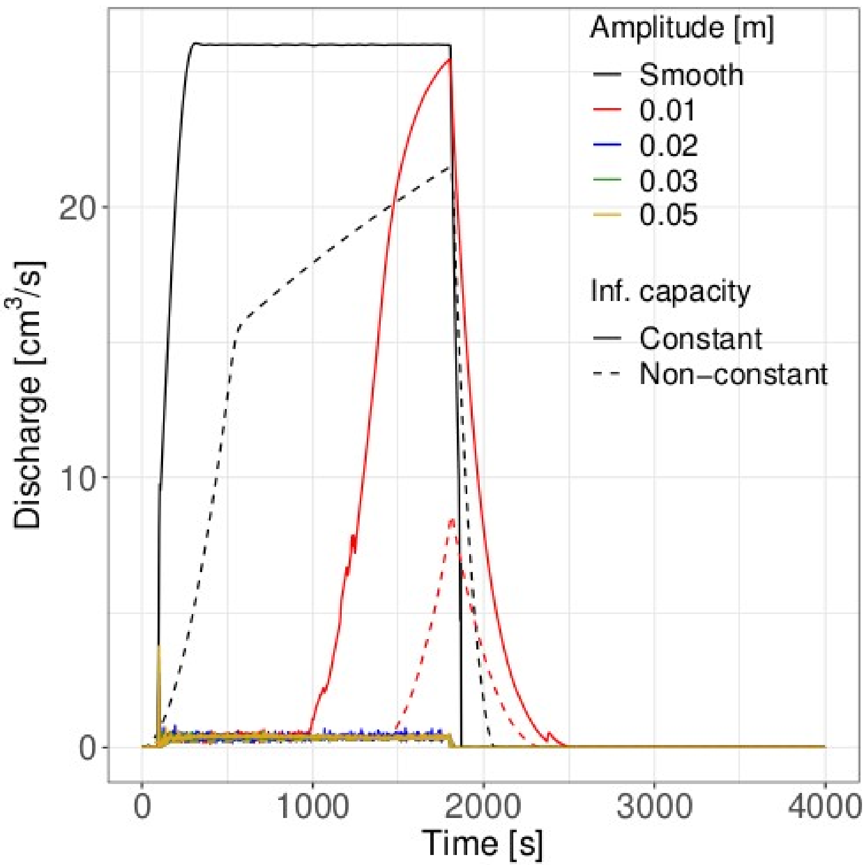


Water depth

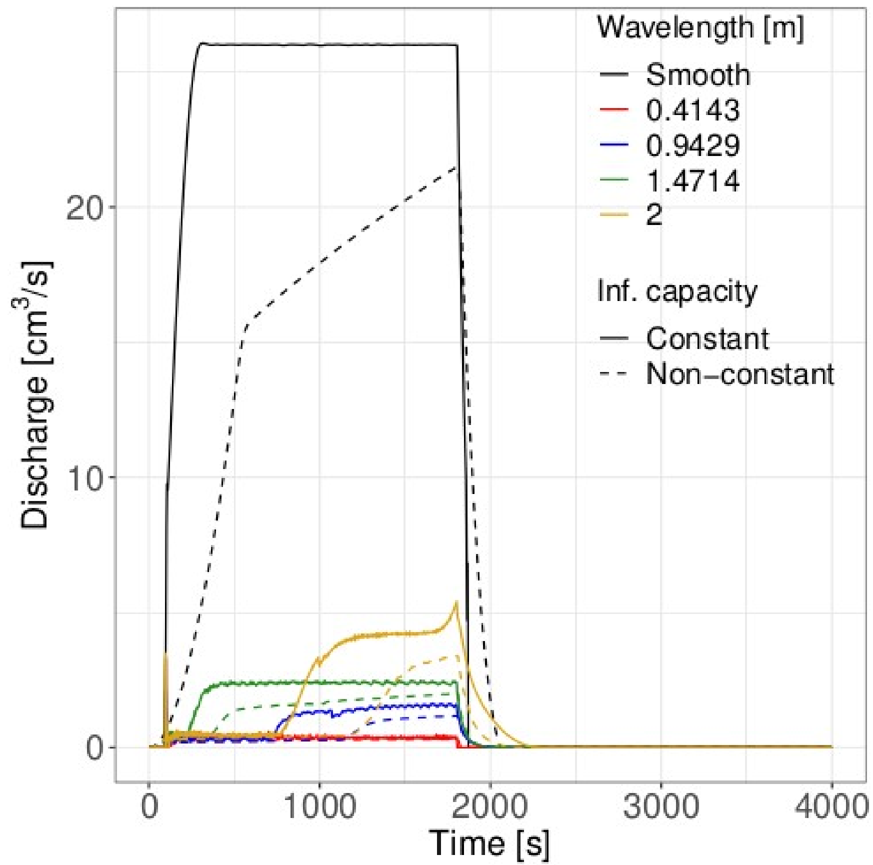




Further examples



(a) $s = 0.03$, $\lambda = 0.4143\,m$



(b) $s = 0.03$, $a = 0.03\,m$

For different surfaces, same characteristic regimes appear, under different conditions

Transient Depth: CIC

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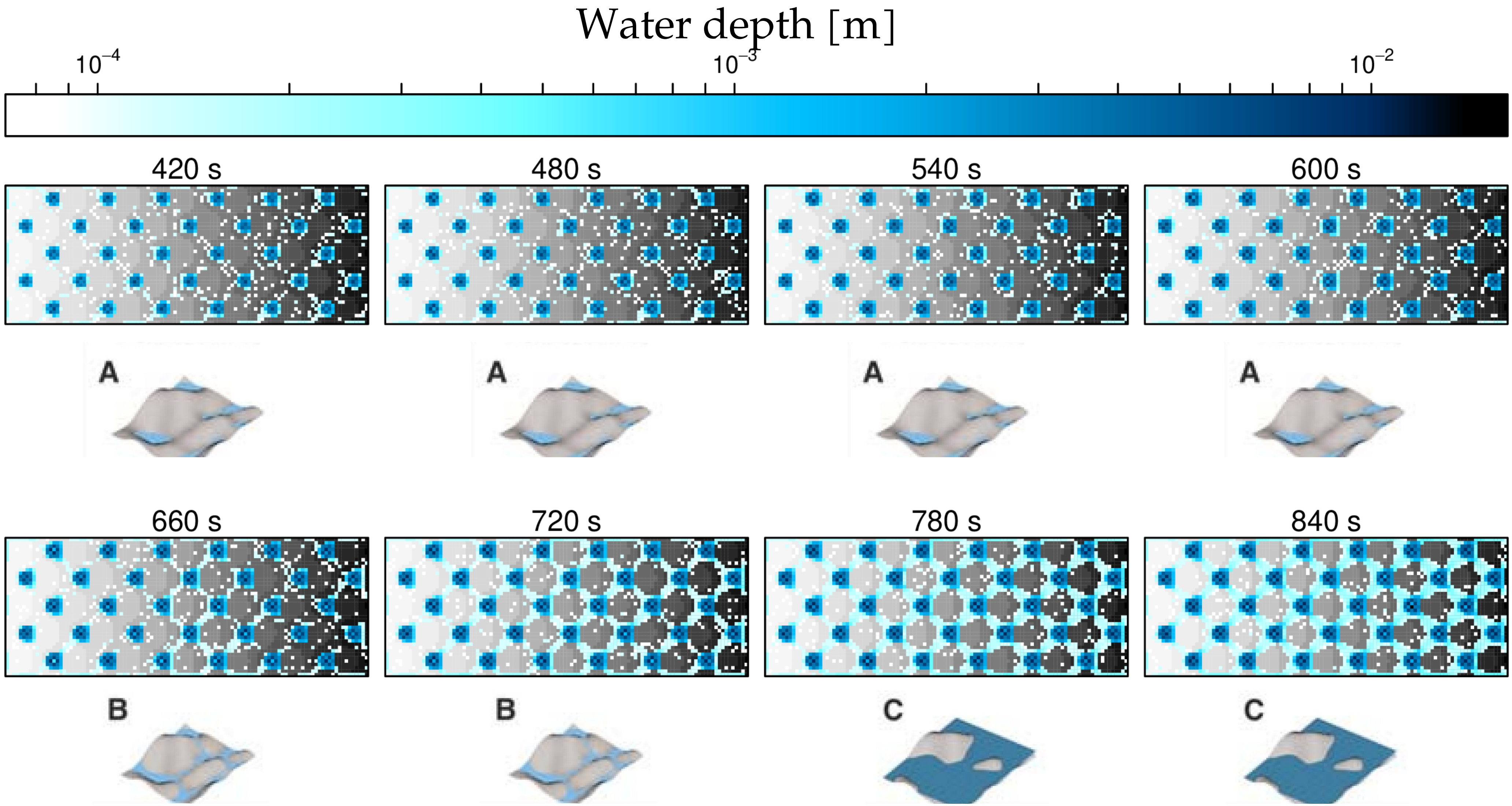
s = 0.05, λ = 1.2071 m and a = 0.02 m



For the same surface, slight differences in hydrodynamics and connectivity exists between constant (CIC) and non-constant (NIC) infiltration capacity

Transient depth, NIC

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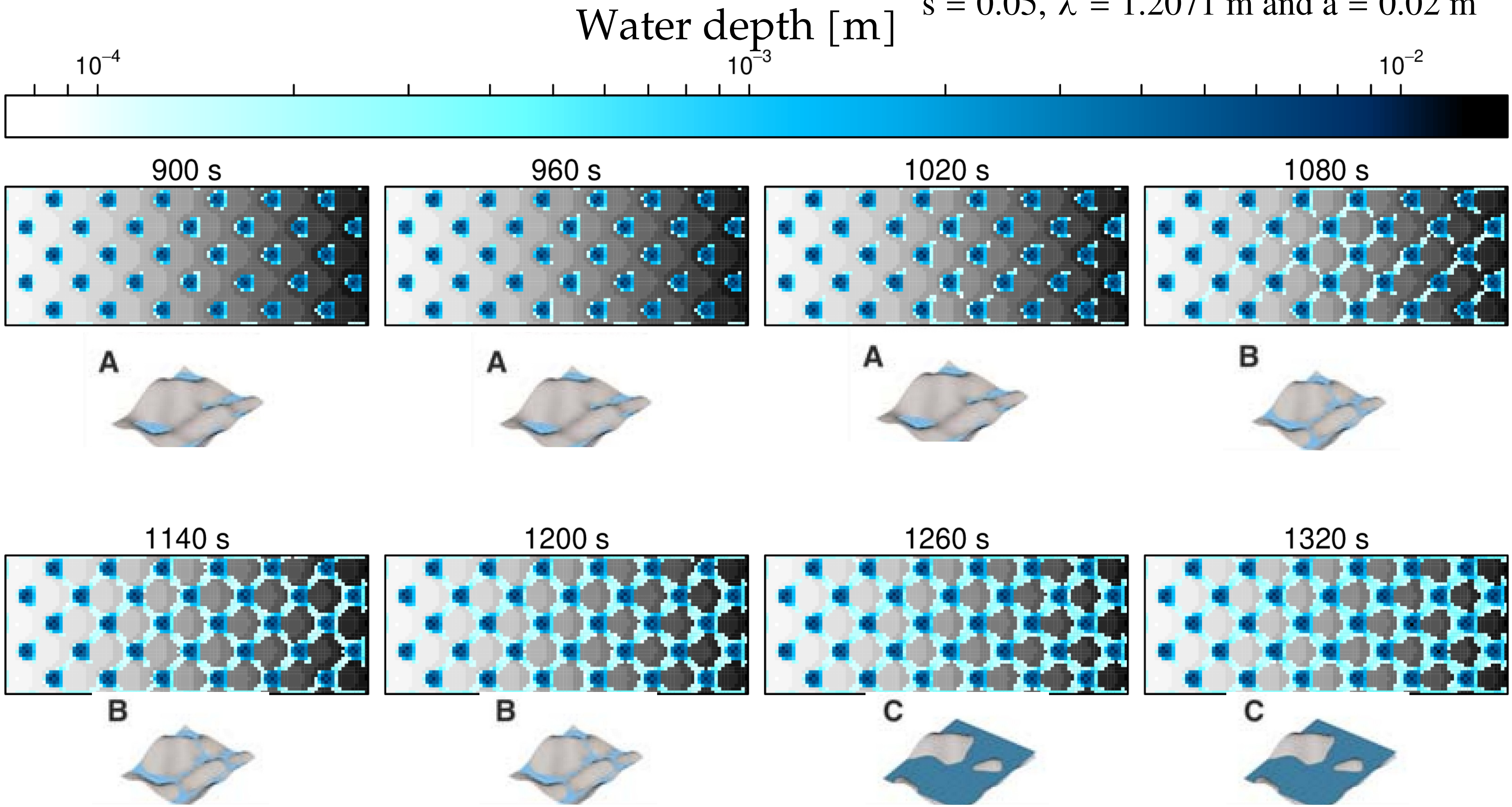
$s = 0.05$, $\lambda = 1.2071$ m and $a = 0.02$ m



For the same surface, slight differences in hydrodynamics and connectivity exists between constant (CIC) and non-constant (NIC) infiltration capacity

Depth fields at end of rain

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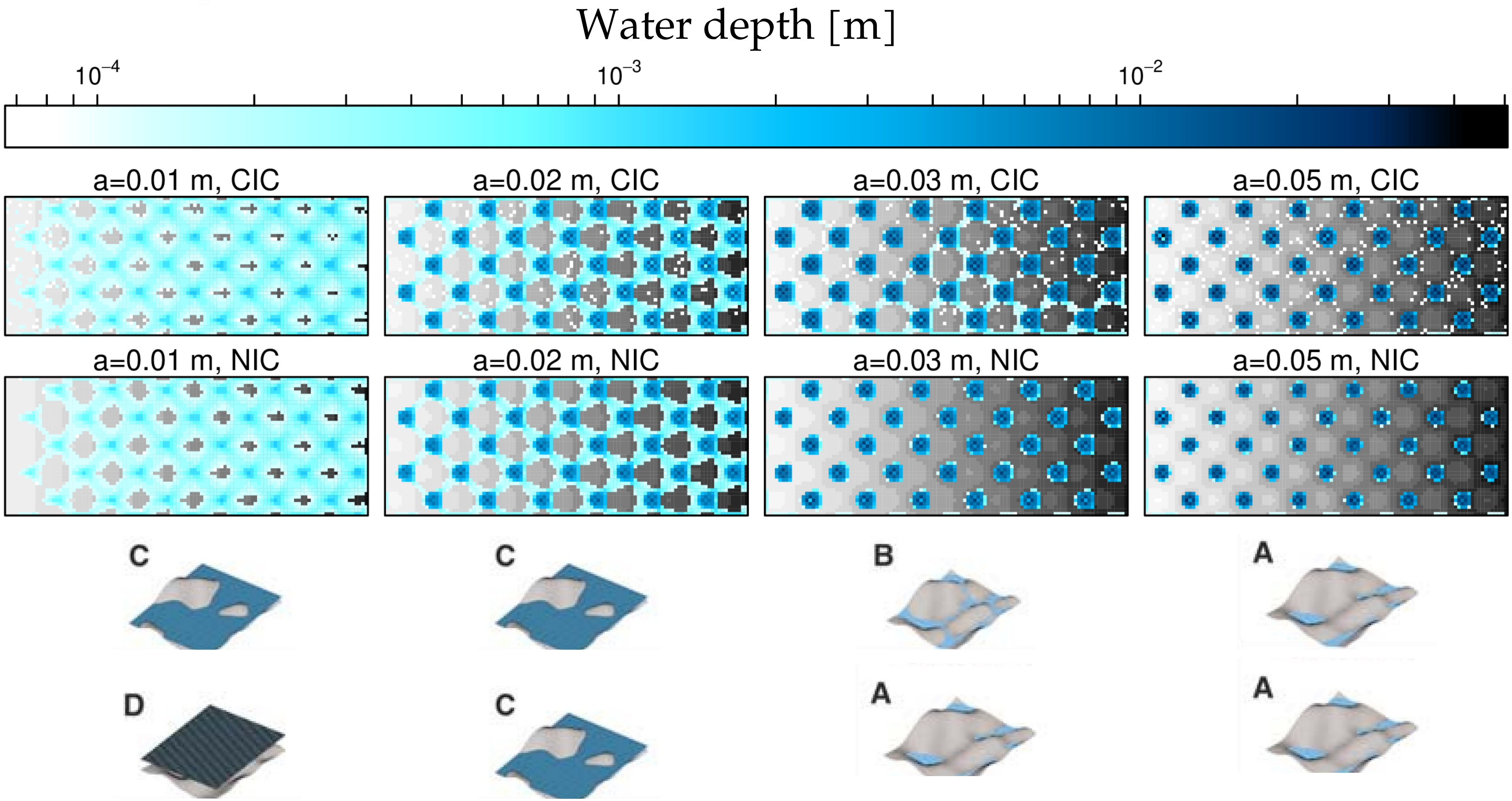
$s = 0.05, \lambda = 1.2071\ m$



The most developed hydrodynamic fields clearly illustrate regimes, and correspond strongly to hydrograph types

Accumulated infiltration

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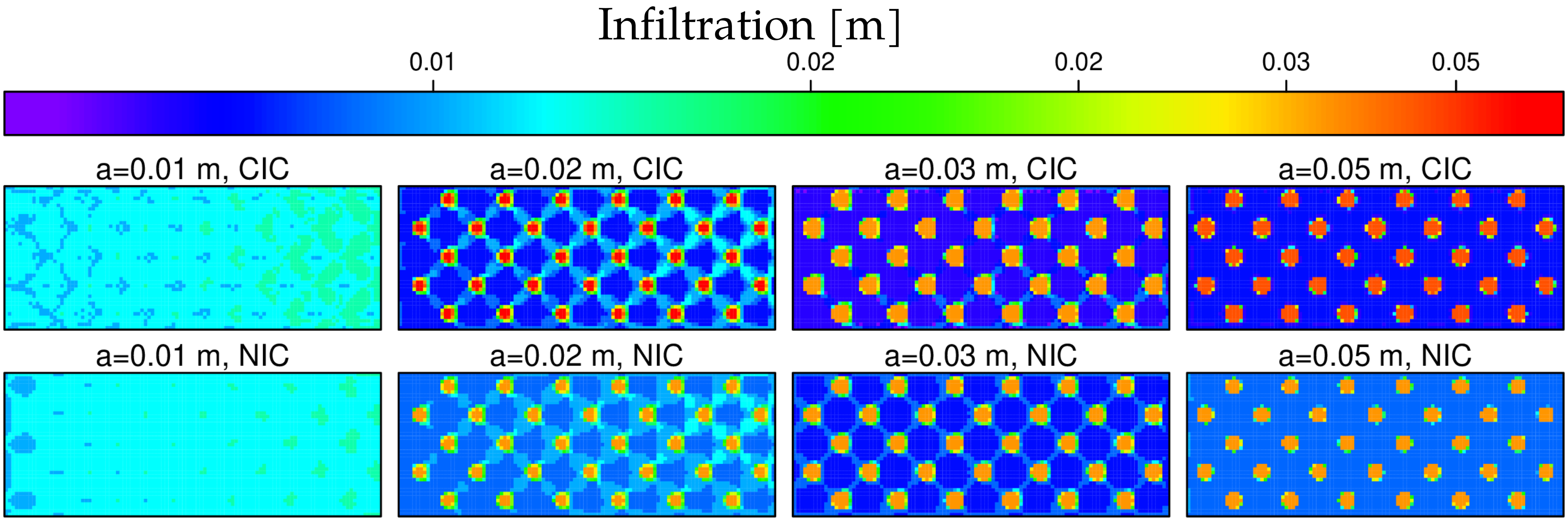
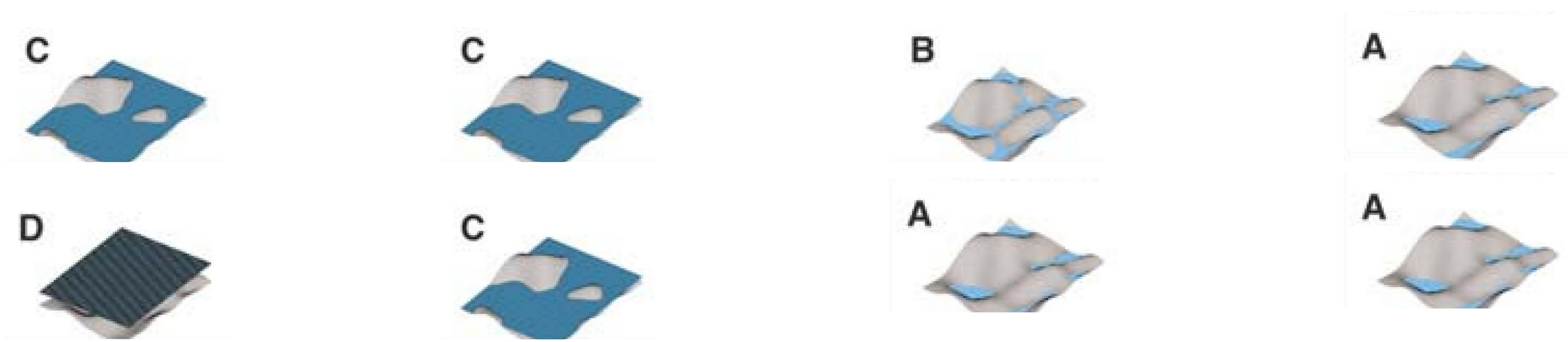
$s = 0.05,\ \lambda = 1.2071\ m$





The different surface hydrodynamics and regimes are clearly mapped into different infiltration patterns, which can be captured by infiltration indicators

Results: infiltration ratio sensitivity

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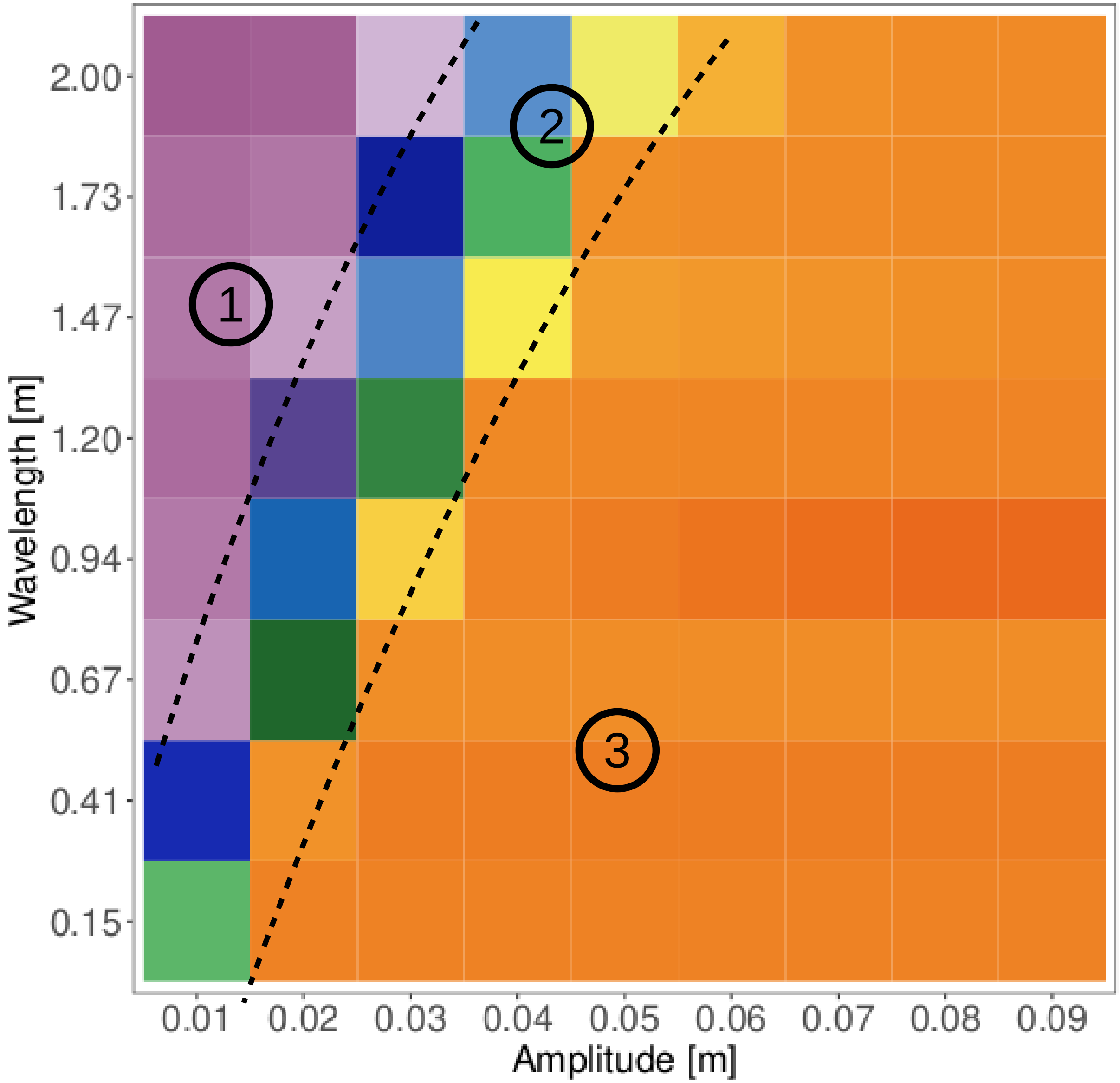
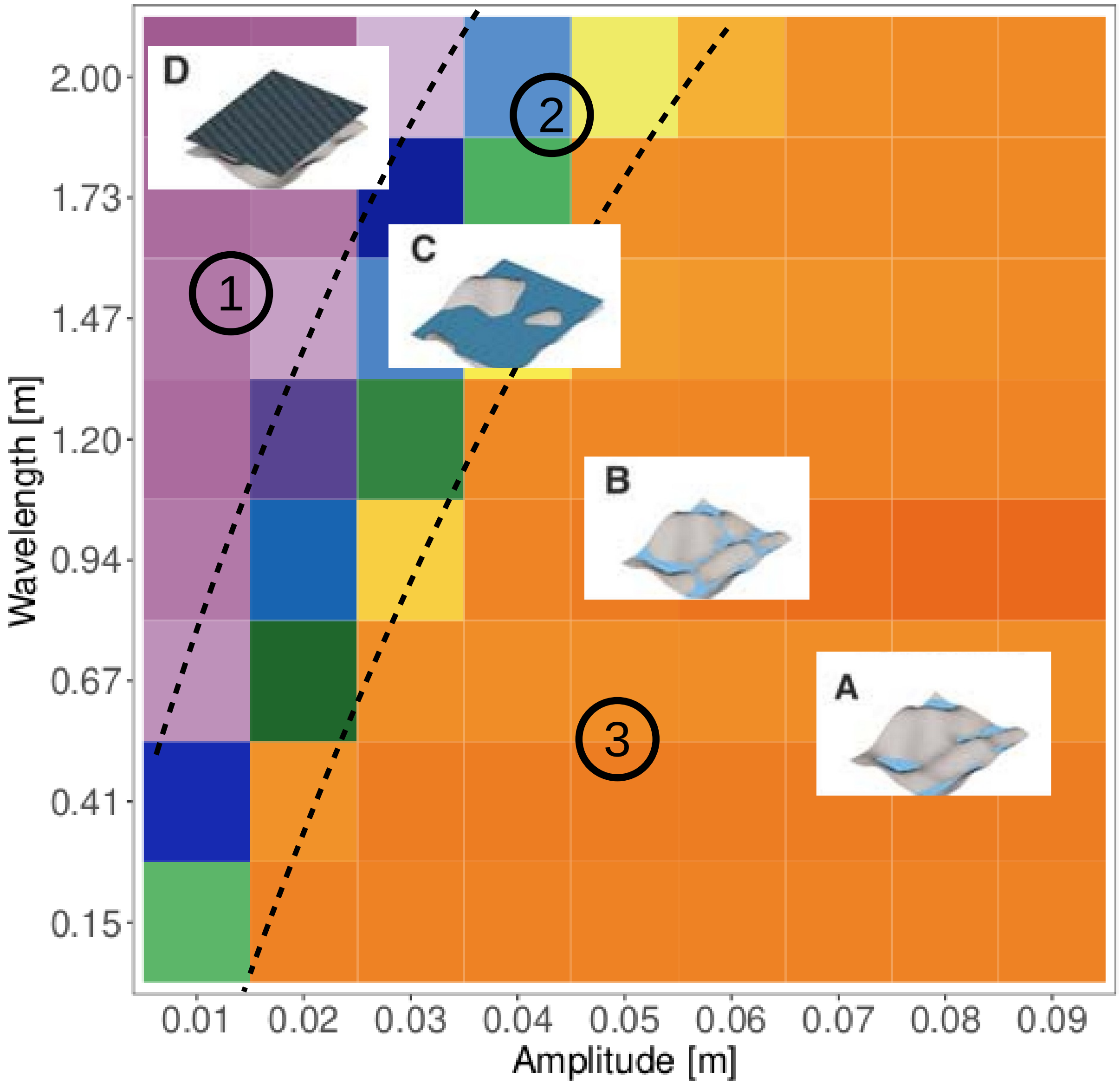


$$\tilde{I} = \frac{I_{\mathrm{MT}}}{I_o}$$

1. Insensitive to MT
2. Very sensitive to MT
3. High increase in infiltration, but not sensitive to MT features

The infiltration enhancement of MT (in comparison to a smooth surface) shows three distinctive regions in response to amplitude and wavelength

Results: infiltration ratio sensitivity



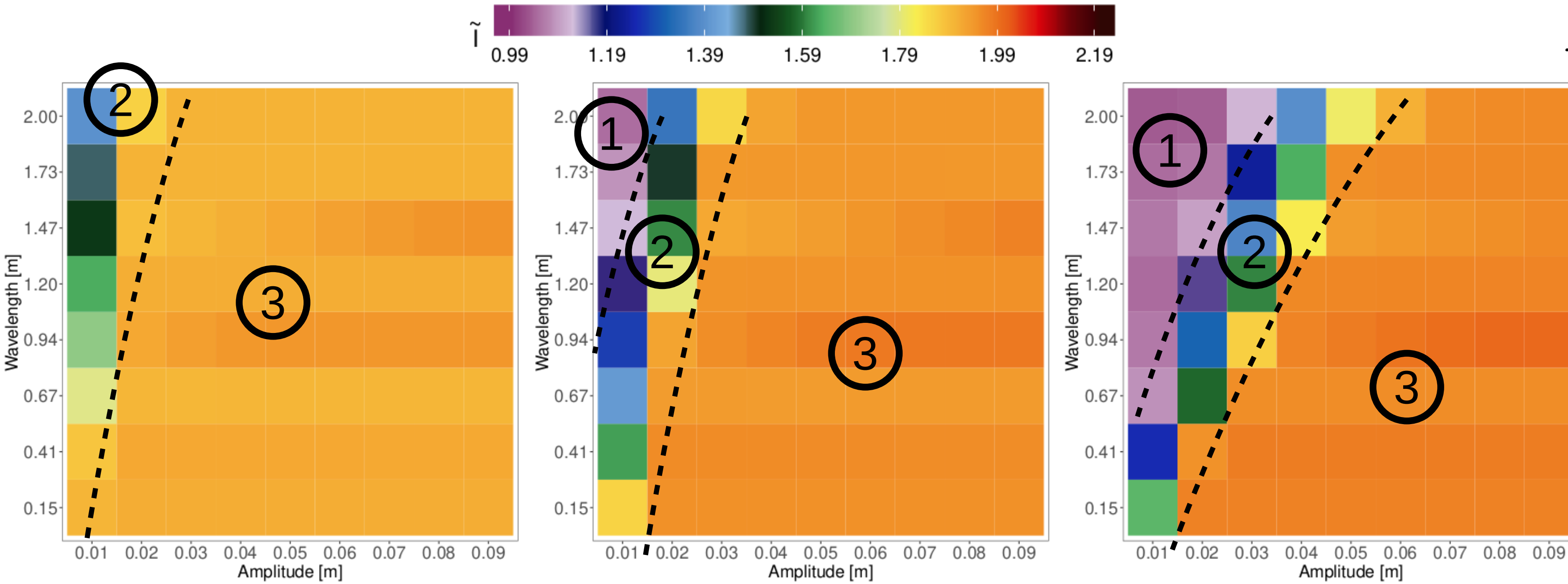
$$\tilde{I} = \frac{I_{\mathrm{MT}}}{I_o}$$

1. Insensitive to MT
2. Very sensitive to MT
3. High increase in infiltration, but not sensitive to MT features

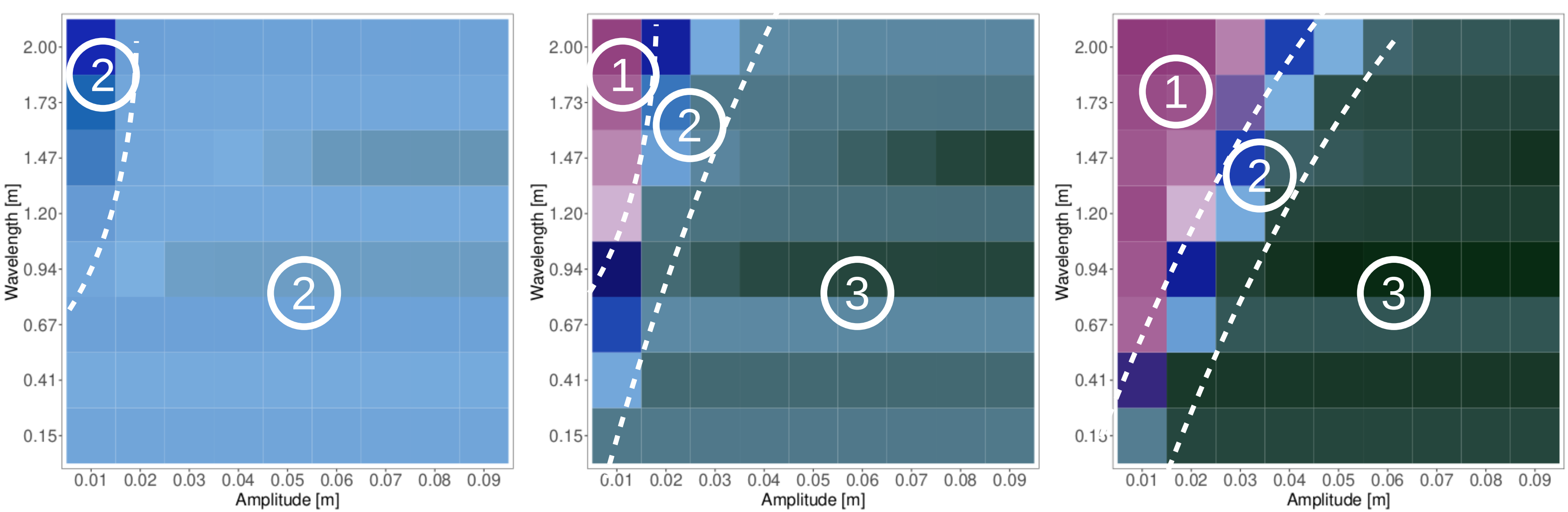
The infiltration enhancement of MT can be related to the conceptual regimes identified by Thompson et al. (2010).

Results: infiltration ratio sensitivity

$$\tilde{I} = \frac{I_{\mathrm{MT}}}{I_o}$$



(a) s = 1%, CIC (b) s = 3%, CIC (c) s = 7%, CIC



(d) s = 1%, NIC (e) s = 3%, NIC (f) s = 7%, NIC

Results: ration of enhancements

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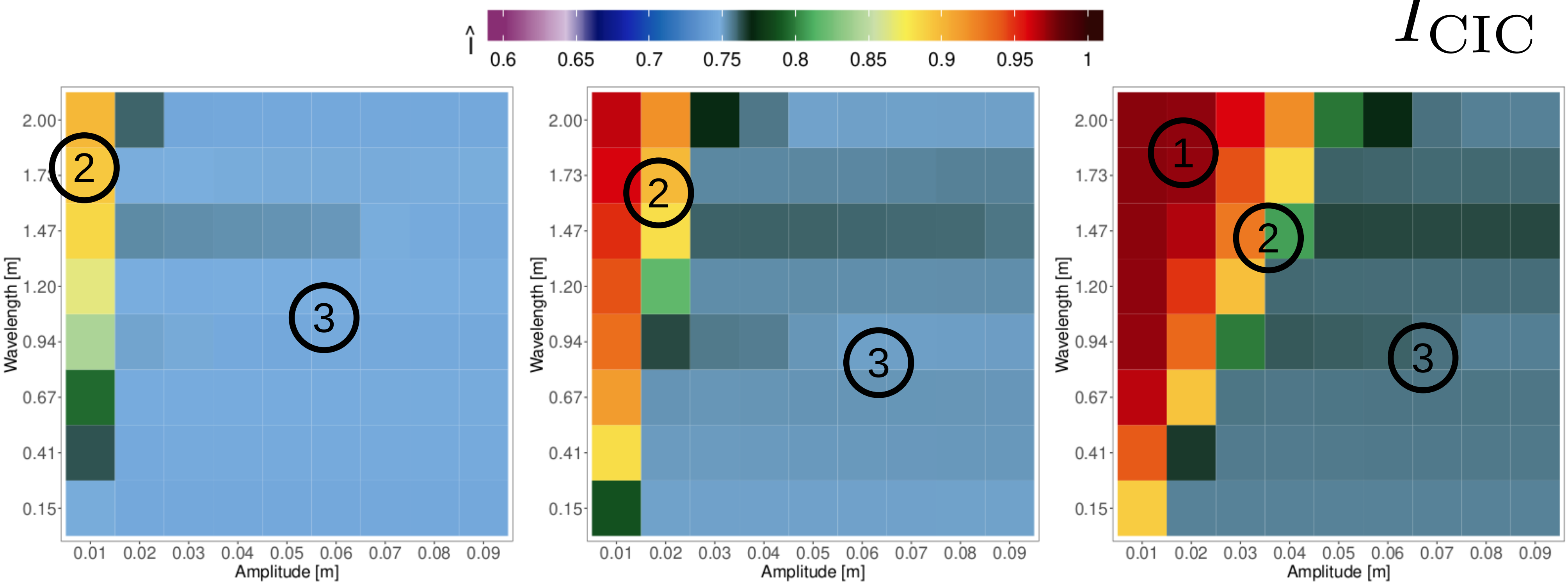
The ratio of enhancements shows also three regions.

$$\hat{I} = \frac{\tilde{I}_{\mathrm{NIC}}}{\tilde{I}_{\mathrm{CIC}}}$$



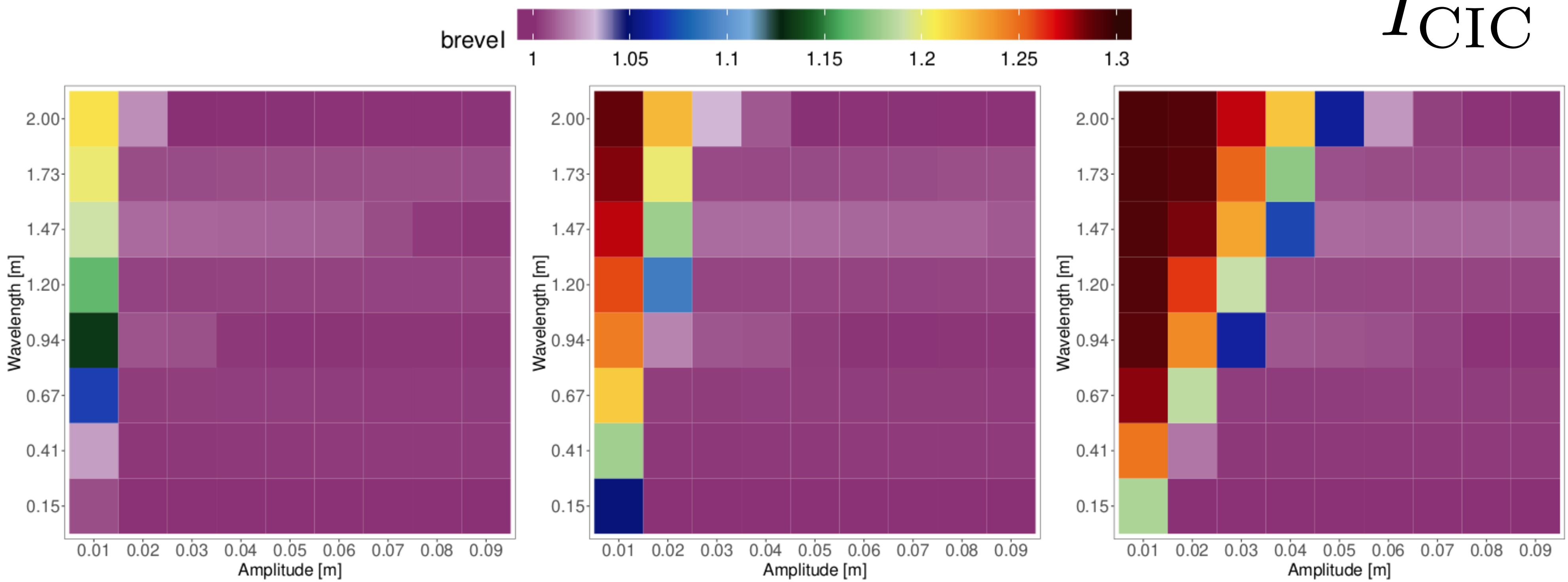
(b) $s = 1\%$ (c) $s = 3\%$ (d) $s = 7\%$

1. Infiltration insensitive to infiltration capacity curve
2. NIC slightly reduces enhancement.
3. NIC reduces enhancement

Results: ratio of infiltration

The ratio of infiltration shows also three regions.

$$\breve{I} = \frac{I_{\mathrm{NIC}}}{I_{\mathrm{CIC}}}$$



(b) $s = 1\%$ (c) $s = 3\%$ (d) $s = 7\%$

1. NIC increases infiltration volume. Not very sensitive to MT features
2. NIC increases infiltration volume, very sensitive to MT
3. Infiltration curve plays no role. MT dominated, but insensitive to features

Microtopography relations

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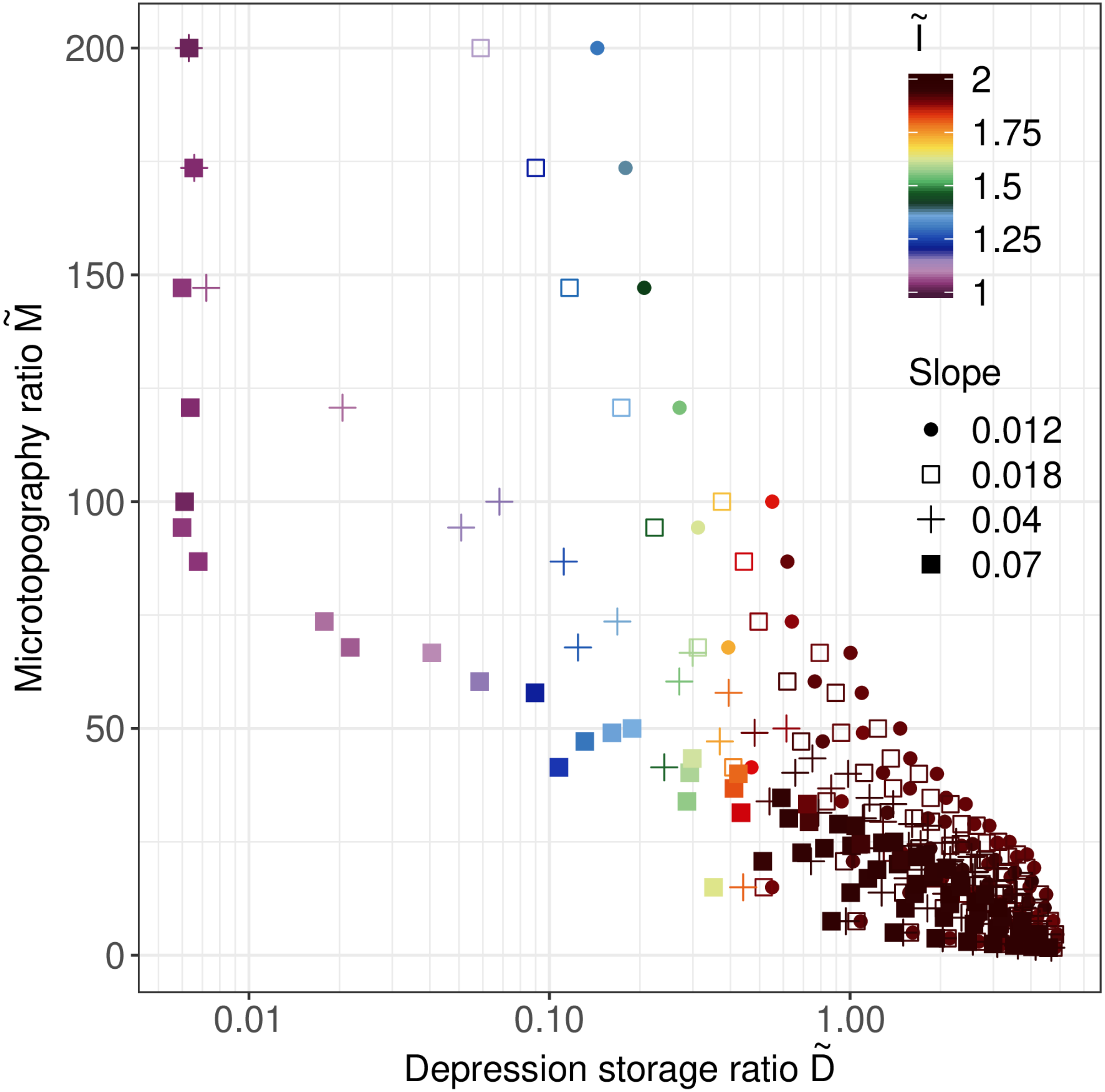

Microtopography relations

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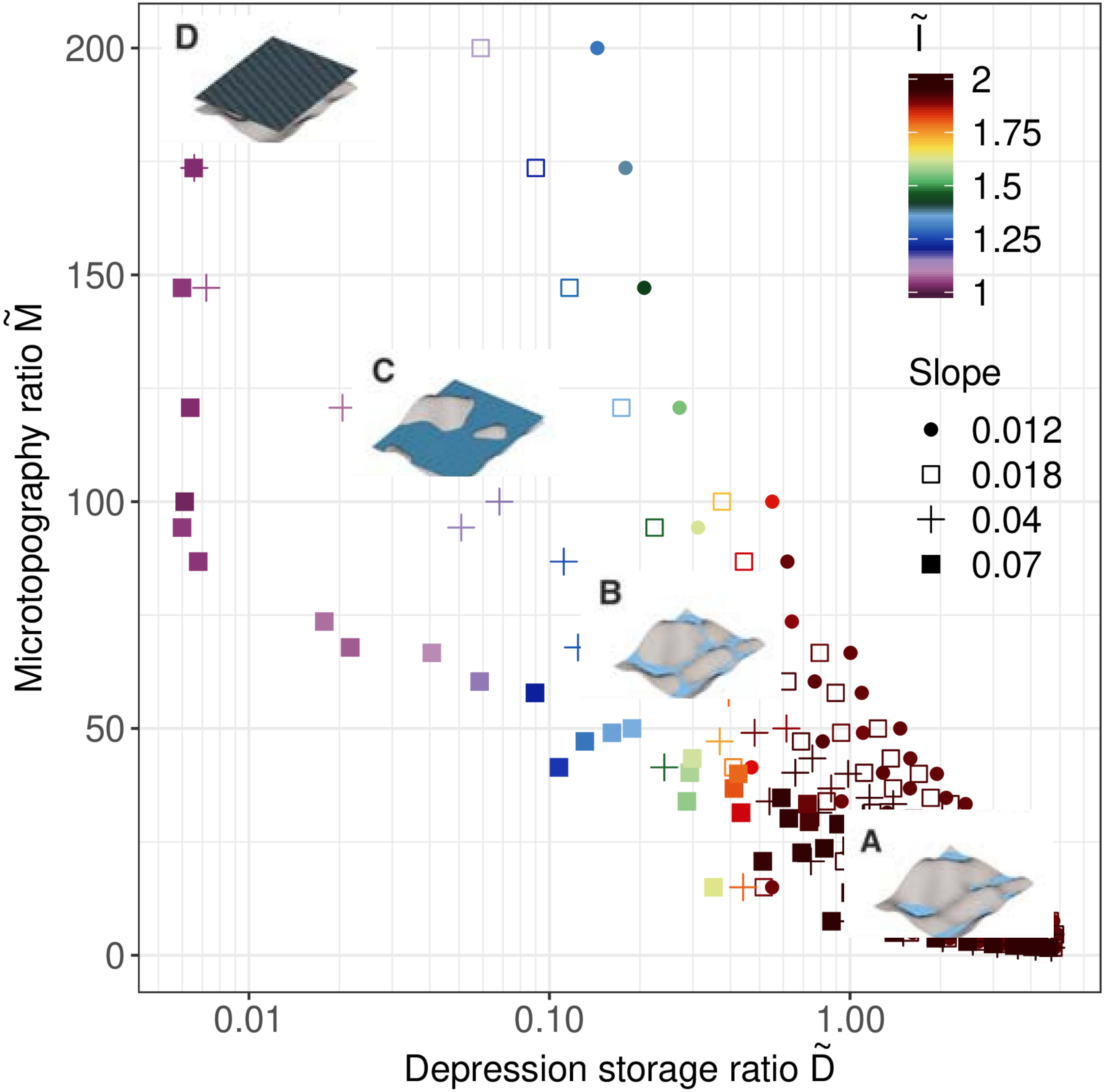

Microtopography relations

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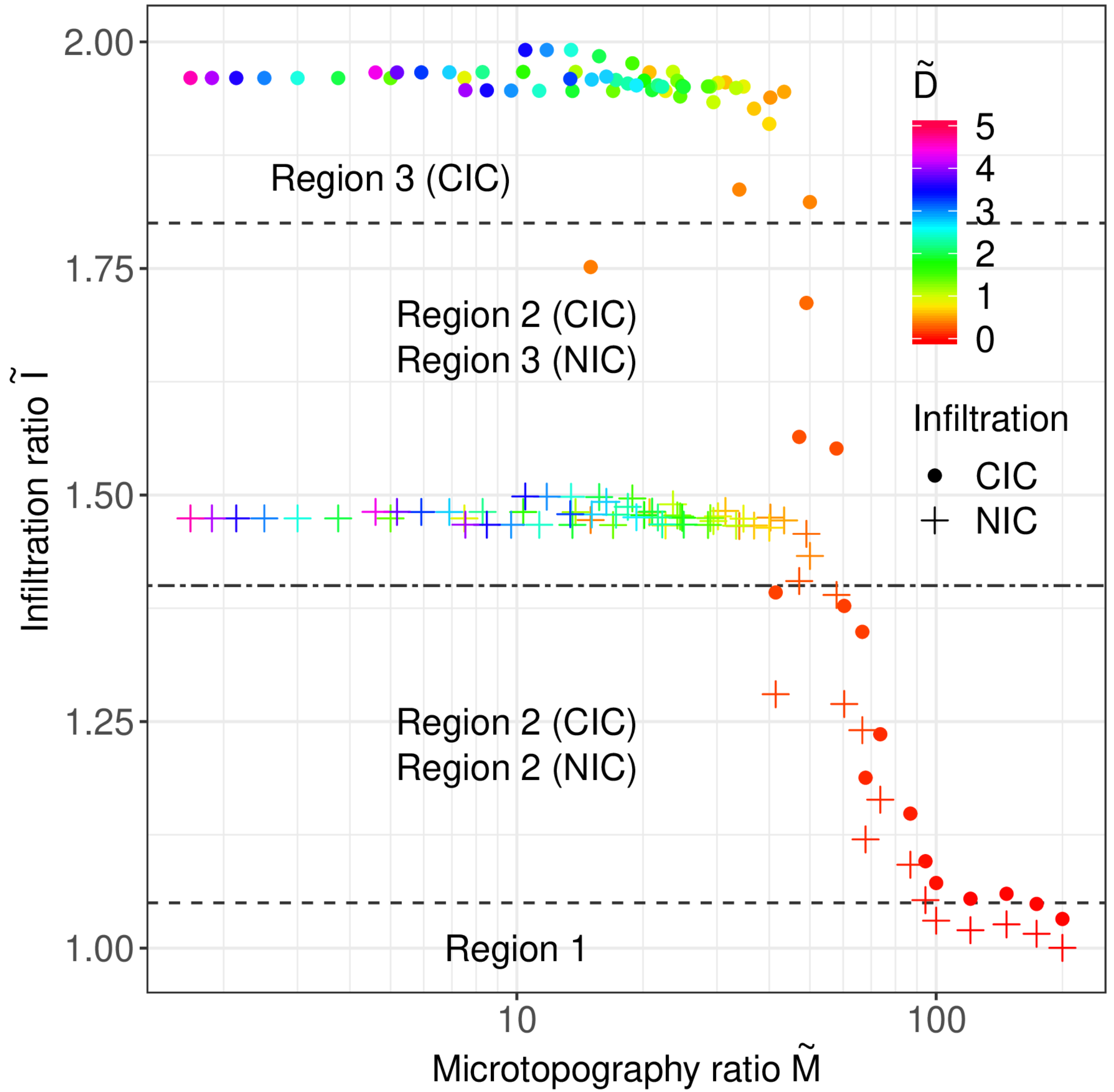

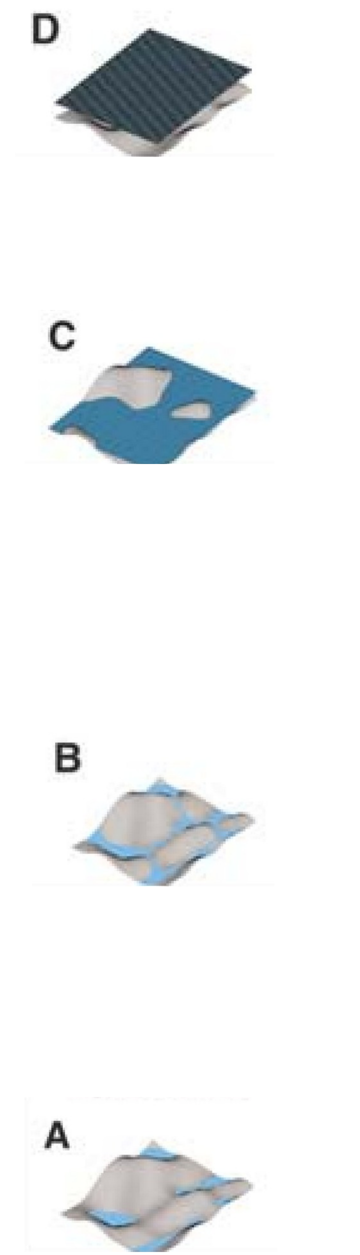

Microtopography relations

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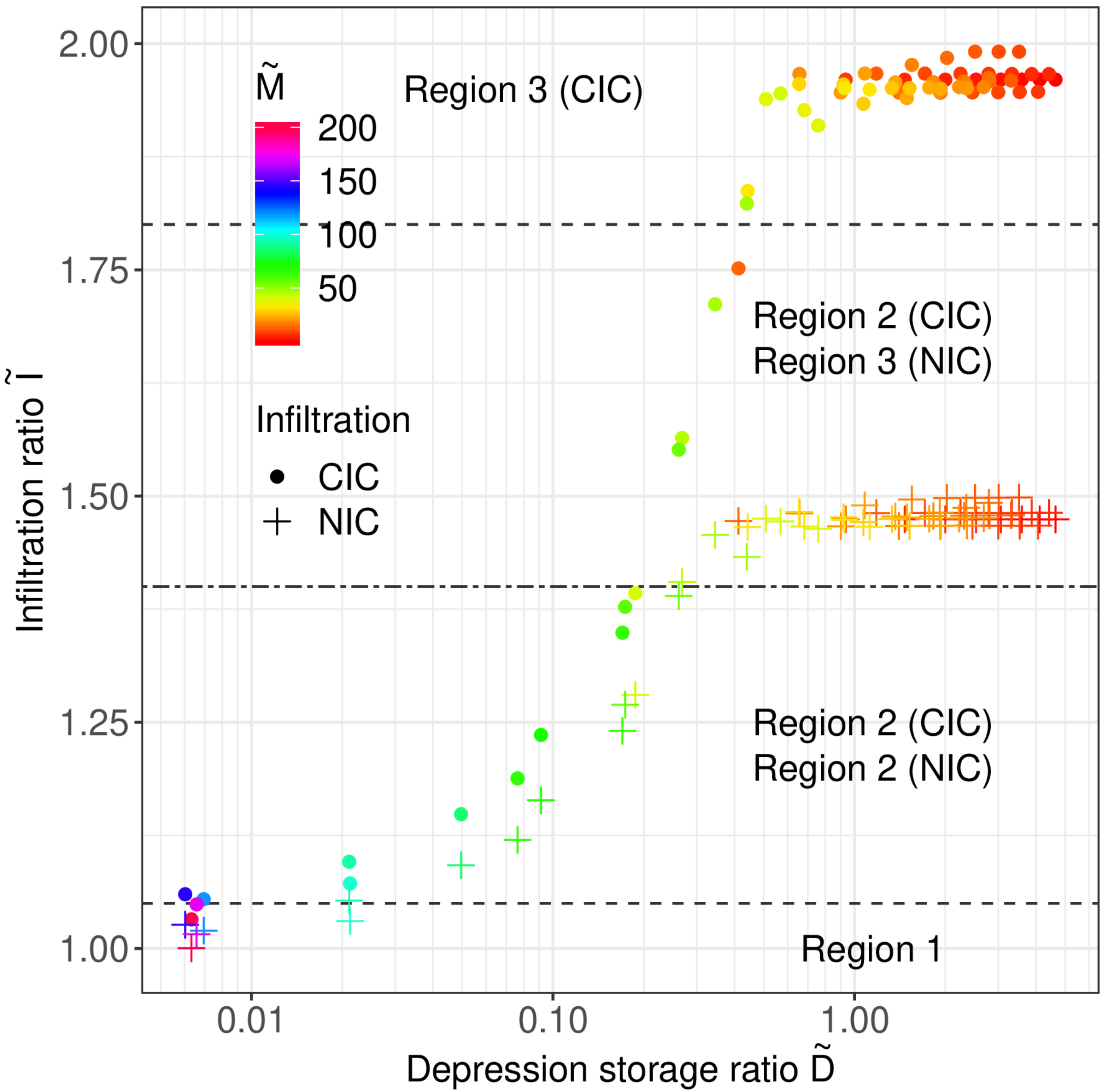
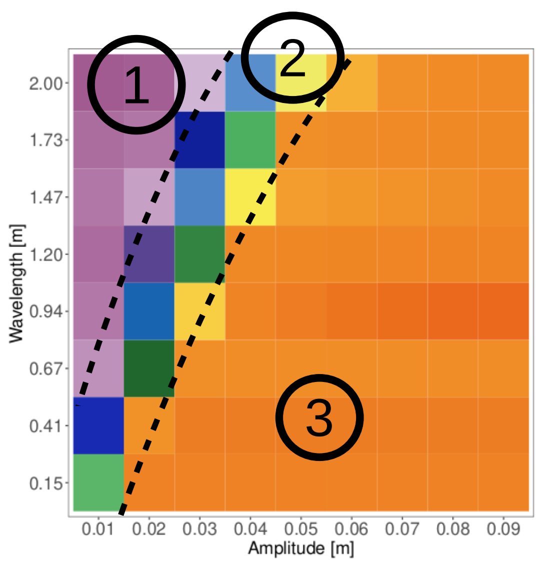
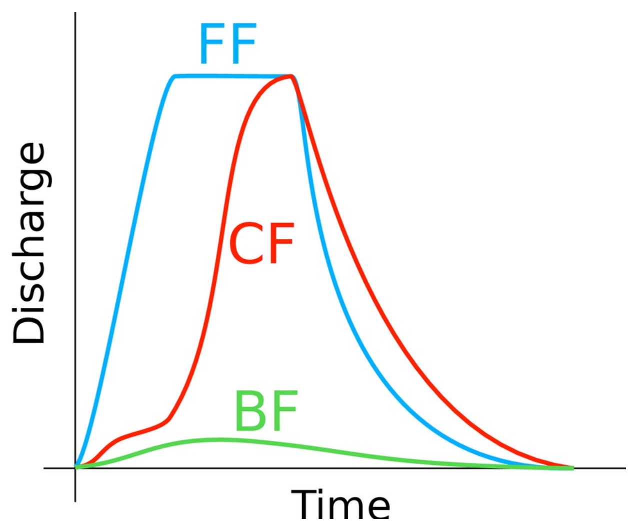


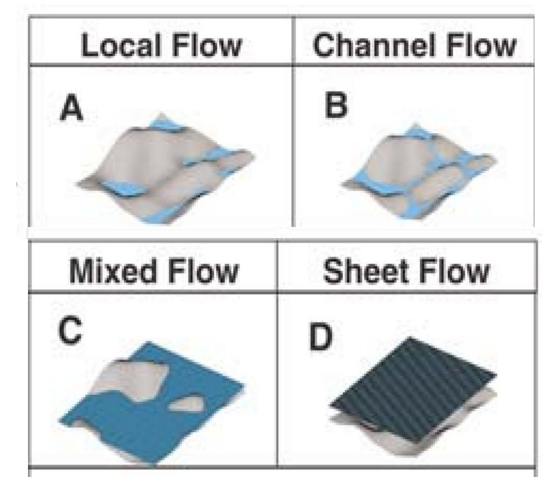
Summary

Region	Indicators $\tilde{I}$	Indicators $\hat{I}$	Indicators $\breve{I}$	Sensitivity to MT	Sensitivity to Inf. cap.	Hydrograph	Developed flow regime
①	≈ 1	≈ 1	≈ 1.3	–	+	FF	$\mathcal{D}/\mathcal{C}$
②	1 – 2	0.65 – 1	1 – 1.3	++	++	CF	$\mathcal{B}/\mathcal{C}$
③	$\rightarrow 2$	$\rightarrow 0.65$	≈ 1	+/-	+/-	BF	$\mathcal{A}/\mathcal{B}$

FF: Full flow, CF: Connected flow, BF: Boundary Flow. $\mathcal{A}$: local flow, $\mathcal{B}$: channel flow, $\mathcal{C}$: mixed flow, $\mathcal{D}$: sheet flow







Conclusions

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1) Microtopography can strongly affect runoff generation and hydrological partitioning in complex, non-linear ways.

2) Thee characteristic regions can be identified in terms of sensitivity to MT (amplitude and wavelength. The position of these regions depends on slope. Therefore, there are micro and macro topography influences (multiscale!).

3) The three regions are the result of characteristic flow regimes, which summarise complex surface distributions and flow connectivity.

4) The hydrodynamic regimes manifest as characteristic hydrograph types.

5) The shape of infiltration capacity in time interacts with MT and modulates its effects.

6) The sensitivity to MT and infiltration capacity is different in the MT region

7) Implications for modelling exist. Under region 1, MT can be neglected. Under region 2, it cannot be neglected, and under region 3 it is easily mapped into static proxies (e.g., depression storage).

Region	Indicators			Sensitivity to		Hydrograph	Developed flow regime
	$\tilde{I}$	$\hat{I}$	$\check{I}$	MT	Inf. cap.		
①	≈ 1	≈ 1	≈ 1.3	–	+	FF	$\mathcal{D}/\mathcal{C}$
②	1 – 2	0.65 – 1	1 – 1.3	++	++	CF	$\mathcal{B}/\mathcal{C}$
③	→ 2	→ 0.65	≈ 1	+/-	+/-	BF	$\mathcal{A}/\mathcal{B}$

FF: Full flow, CF: Connected flow, BF: Boundary Flow. $\mathcal{A}$: local flow, $\mathcal{B}$: channel flow, $\mathcal{C}$: mixed flow, $\mathcal{D}$: sheet flow