

Electronic Supplementary Material

Cornacchia L, Wharton G, Davies G, Grabowski RC, Temmerman S, van der Wal D, Bouma TJ, van de Koppel J. 2020 Self-organization of river vegetation leads to emergent buffering of river flows and water levels. *Proc. R. Soc. B* 20201147.
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The supplementary materials include the following content:

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S2 Testing for regular pattern formation

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S4 Field measurements on river discharge, flow velocities and water levels

S5 Implications of pattern formation for the resilience of macrophytes to disturbances

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S1 Bifurcation analysis

Our model demonstrates that spatial separation of vegetation into high- and low-density areas is strongly dependent on the water discharge in the stream as a whole. Results of bifurcation analysis with respect to discharge predicts that at low discharge levels, a stable homogeneous equilibrium exists where the entire stream is vegetated (*red line* in **Fig. S1**). At this equilibrium, vegetation biomass decreases linearly with increasing discharge, Q , until plants disappear at $Q \geq 1.2 \text{ m}^3 \text{ s}^{-1}$. However, at a threshold level Q_{T1} ($Q = 0.53 \text{ m}^3 \text{ s}^{-1}$), the homogeneous equilibrium becomes unstable to spatially heterogeneous perturbations, leading to spatial separation into two zones, one characterized by low vegetation biomass and high flow velocities in the middle of the stream, and one

by high biomass and low flow velocities at the edges of the stream. The point QT_1 is the point beyond which the stable heterogeneous pattern of spatial separation develops, similarly to a Turing instability point. Beyond the second point QT_2 ($Q = 1.2 \text{ m}^3 \text{ s}^{-1}$), spatial separation into low- and high-biomass zones is needed for vegetation to persist. From the bifurcation points, unstable nonhomogeneous equilibria originate which link up to a stable nonhomogeneous equilibrium. In this stable nonhomogeneous equilibrium (*solid green line* in **Fig. S1**), plant cover can persist for a much wider range of discharge values, far beyond the value where homogeneously distributed plants would disappear (QT_2). The stable nonhomogeneous equilibrium exists until the limit point LP ($Q = 1.6 \text{ m}^3 \text{ s}^{-1}$), beyond which no vegetation can persist and only a homogeneous state without plants is found. An unstable nonhomogeneous equilibrium occurs within $1.2 < Q < 1.6 \text{ m}^3 \text{ s}^{-1}$ (*dotted green line* in **Fig. S1**). Between these values of discharge, two alternative stable states are found, one characterized by spatial separation of vegetation into high- and low-biomass areas, and the other where vegetation cannot survive. In the graph, the dotted green line represents the threshold biomass under which plant cover will collapse. In general, the model predicts that plant density is higher in the heterogeneous state compared to the homogeneous situation (*green line* vs. *red line* in **Fig. S1**), for all parameter values where spatial separation occurs.

S2 Testing for regular pattern formation

The formation of regular patterns was tested in the cross-stream direction of the simulated domain. We tested the stability of the homogeneous equilibrium to small heterogeneous perturbations before and after the point QT_1 ($Q = 0.53 \text{ m}^3 \text{ s}^{-1}$), which is similar to a Turing instability point. Below this point, we expect heterogeneous perturbations to return to the stable homogeneous equilibrium; however, beyond this point, we expect small perturbations to be amplified, leading to the formation of regular spatial patterns. For simulations performed at $Q = 0.42 \text{ m}^3 \text{ s}^{-1}$, below the point QT_1 , heterogeneous perturbations in plant biomass returned to a stable homogeneous equilibrium (**Fig. S2A**). For simulations performed at $Q = 0.84 \text{ m}^3 \text{ s}^{-1}$, above QT_1 , small perturbations in plant biomass were amplified and led to the formation of regular spatial patterns of vegetation (**Fig. S2B**).

S3 Analysis of Covariance on field velocity measurements

We conducted an Analysis of Covariance (ANCOVA) to quantify the proportion of variance in the observed flow velocity explained by the presence/absence of vegetation, controlling for discharge. To reduce the effect of autocorrelation between points measured in space in the same river, we used the average velocities for each survey date, instead of the single measurement points. The dependent variable was the average flow velocity measured in the vegetated and unvegetated sections of the river in a given survey month. The independent variable was assumed to be the presence/absence of vegetation and discharge was used as a covariate.

Table S1. Analysis of covariance on the effect of vegetation presence on flow velocities, controlling for discharge, for the Bere Stream site.

	df	Sum of squares	F value	p (> F)	Variance explained (%)
Discharge	1	0.25	50.40	< 0.001	13.8
Substrate type (vegetated/unvegetated)	1	1.37	279.55	< 0.001	76.6
Residuals	35	0.17			9.6

Table S2. Analysis of covariance on the effect of vegetation presence on flow velocities, controlling for discharge, for the Frome River site.

	df	Sum of squares	F value	p (> F)	Variance explained (%)
Discharge	1	0.06	32.60	< 0.001	31.7
Substrate type (vegetated/unvegetated)	1	0.09	49.30	< 0.001	47.9
Residuals	21	0.04			20.4

S4 Field measurements on river discharge, flow velocities and water levels

The changes in flow velocity patterns with discharge obtained from our field measurements are shown in **Fig. 2**. In the ‘mixed vegetation’ site, water flow velocities within open and vegetated areas were significantly different (Kruskal-Wallis test, $P < 0.002$, **Fig. 2B**) for all survey months, and discharge was significantly correlated with flow velocity within the stands ($r^2 = 0.77$, $p < 0.0001$) and between them ($r^2 = 0.52$, $p = 0.0005$, **Fig. 2B**). Vegetated flow velocities in the ‘dominant submerged’ site (**Fig. 2C**) were also significantly lower than unvegetated flow velocities (Kruskal-Wallis test, $p < 0.03$) up to discharges of $1.6 \text{ m}^3 \text{ s}^{-1}$. Above these values of discharge, vegetated flow velocities tend to become much higher and not significantly different from the unvegetated ones (Kruskal-Wallis test, $P > 0.05$, **Fig. S3**). For this site, piecewise regression was used due to the presence of a breakpoint, after which flow velocities rapidly increased. This breakpoint was estimated at $1.5 \text{ m}^3 \text{ s}^{-1}$. Below the breakpoint, a significant relationship was found between discharge and flow velocity between the stands ($r^2 = 0.66$, $p = 0.0012$) and within them ($r^2 = 0.56$, $p = 0.005$; **Fig. 2C**). Above the breakpoint, a significant relationship was found between discharge and flow velocity above the stands and between them ($r^2 = 0.85$, $p = 0.002$, **Fig. S3C**), but the linear relationship was very similar to the one for an unvegetated channel. Most importantly, in the two streams as well as in model predictions, the slopes of these relationships are lower than the cross-sectional average flow velocities from each reach survey measurement (**Fig. 2B and C**).

The negative relationship between macrophyte cover and discharge observed in the subset dataset of the ‘dominant submerged’ study site (**Fig. 1C**) is also consistent with the full dataset ($r^2 = 0.80$, $p < 0.001$, **Fig. S3A**). Similarly, the non-significant relationship between discharge and mean total water level for the subset dataset (**Fig. 3B**), is also found in the full dataset under a wider range of incoming discharge ($r^2 = 0.03$, $p = 0.50$, **Fig. S3C**).

S5 Implications of pattern formation for the resilience of macrophytes to disturbances

We used our model to explore the consequences of pattern formation for the resilience of aquatic macrophytes to disturbances. We imposed a disturbance on patterned vegetation at equilibrium

biomass, in which we reduced vegetation density by 50%. In three different simulation runs, we compared the time needed to return to equilibrium. In the first simulation, we reduced the density but we left the patterns intact. In the second simulation, we reduced the density, distributed the remaining biomass equally over the simulated grid, and imposed a deviation in randomly selected cells up to 10% of the biomass. In the third simulation, we reduced the density and homogenized the remaining biomass, removing all spatial variability. We found that recovery to pre-disturbance conditions was quickly reached in the simulation where the patterns were left intact (**Fig. S4, solid line**). The simulation in which vegetation was randomly redistributed showed a strong delay in its recovery (**Fig. S4, dotted line**). However, as soon as patterns re-emerged, vegetation could recover to the initial equilibrium values. Finally, in the simulation with vegetation completely homogenized, vegetation density could not recover to pre-disturbance conditions, as no patterns developed due to the absence of small spatial heterogeneity (**Fig. S4, dashed line**). Hence, our simulations demonstrate that self-organized pattern formation strongly increases macrophyte resilience compared to homogeneously vegetated streams, in response to disturbances that reduce vegetation biomass.

S6 Sensitivity analysis of the effect of parameter values on model predictions

We performed a sensitivity analysis to test the influence of estimated parameter values on the model predictions in terms of vegetation cover, water depths and velocities. The outcome of the analysis is reported in Table S3 below.

Table S3. Sensitivity analysis on the effect of changing parameter values on the vegetation cover, water depth, and flow velocities predicted by the model. The parameter values that provided the best fit between the observed and modelled vegetation cover are indicated in bold.

Parameter	Value	Fit between observed and modelled vegetation cover (R^2)	Water depth [m]	Flow velocity in vegetation ($\pm$ SD) [m s^{-1}]	Flow velocity between vegetation ($\pm$ SD) [m s^{-1}]
m_w	3.8	0.70	0.28	0.11 ± 0.01	0.40 ± 0.02
	4.8	0.65	0.21	0.09 ± 0.01	0.34 ± 0.01
	5.8	0.38	0.18	0.08 ± 0.01	0.28 ± 0.00
r	0.6	0.20	0.18	0.07 ± 0.01	0.26 ± 0.00
	0.8	0.67	0.22	0.09 ± 0.00	0.35 ± 0.01
	1.0	0.70	0.28	0.11 ± 0.01	0.40 ± 0.02
D	0.0001	0.70	0.27	0.11 ± 0.01	0.41 ± 0.02
	0.0004	0.70	0.28	0.11 ± 0.01	0.41 ± 0.02
	0.00085	0.70	0.28	0.11 ± 0.01	0.40 ± 0.02

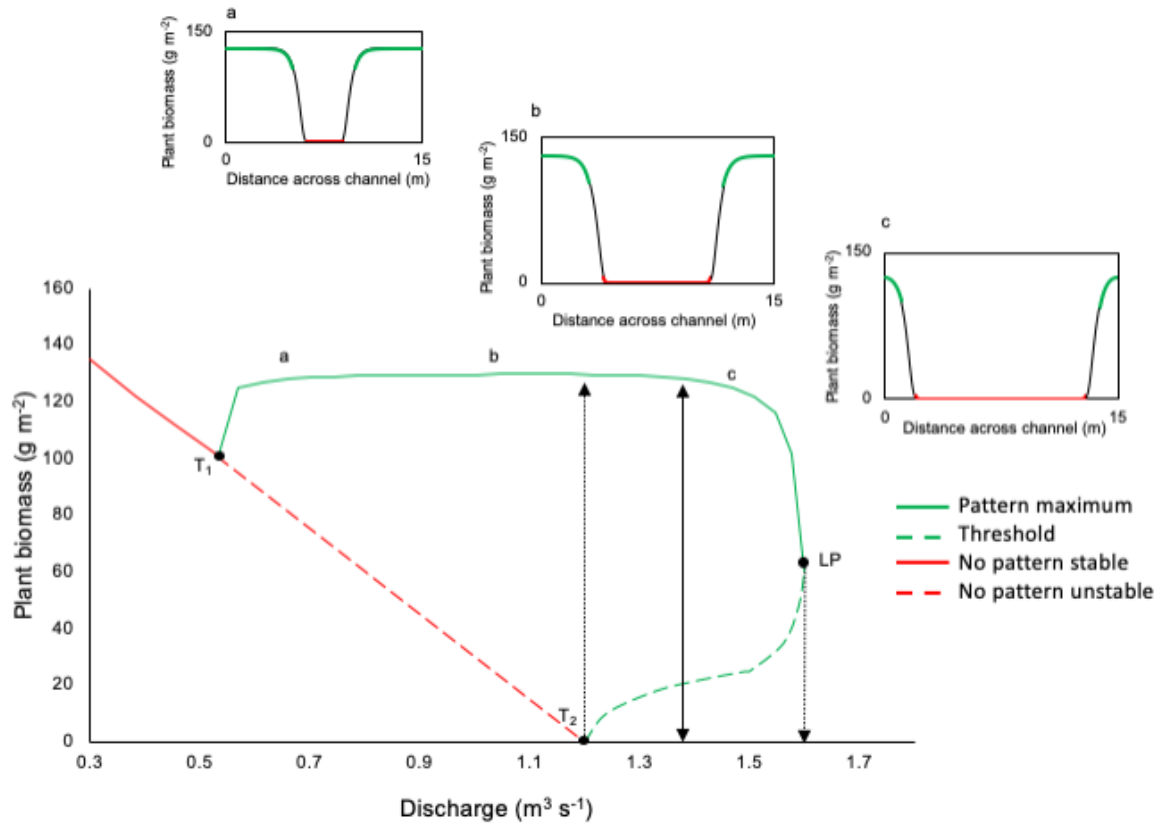


Fig. S1: Bifurcation diagrams of plant density (P) with changes in discharge (Q) based on numerical simulations. Red lines represent the homogeneous equilibrium, green lines show maximum plant density in the nonhomogeneous (spatially separated) equilibrium. Solid lines represent stable equilibria, whereas dotted lines are unstable equilibria. Beyond the point QT_1 ($Q = 0.53 \text{ m}^3 \text{s}^{-1}$), the stable heterogeneous pattern of spatial separation develops, similarly to a Turing instability point. Beyond QT_2 ($Q = 1.2 \text{ m}^3 \text{s}^{-1}$), spatial separation is needed for vegetation persistence. LP ($Q = 1.6 \text{ m}^3 \text{s}^{-1}$) is a limit point, beyond which no vegetation persists. The insets show numerical results of the simulated plant density distribution along the model cross-section for $Q = 0.66 \text{ m}^3 \text{s}^{-1}$ (a), $Q = 1.05 \text{ m}^3 \text{s}^{-1}$ (b), and $Q = 1.47 \text{ m}^3 \text{s}^{-1}$ (c).

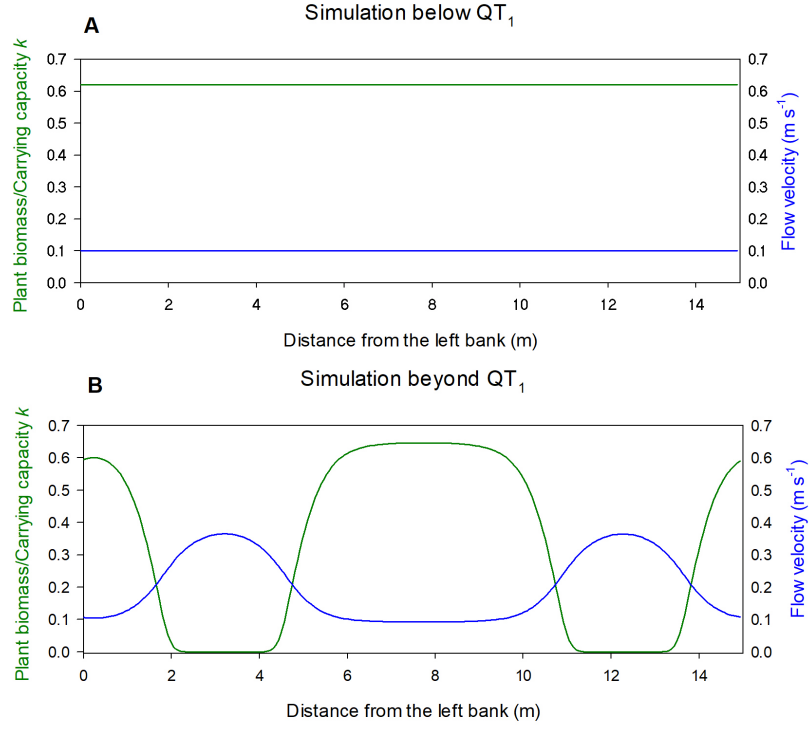


Fig. S2: Simulated spatial patterns of flow velocity (*blue line*) and vegetation biomass divided by the carrying capacity (*green line*) along a model cross-section, performed below (A) and above (B) the threshold in incoming channel discharge QT_1 ($Q = 0.53 m^3 s^{-1}$), similar to a Turing instability point. Below this point, heterogeneous perturbations in plant biomass return to a stable homogeneous equilibrium. Above this point, small perturbations in plant biomass lead to the formation of regular spatial patterns of vegetation.

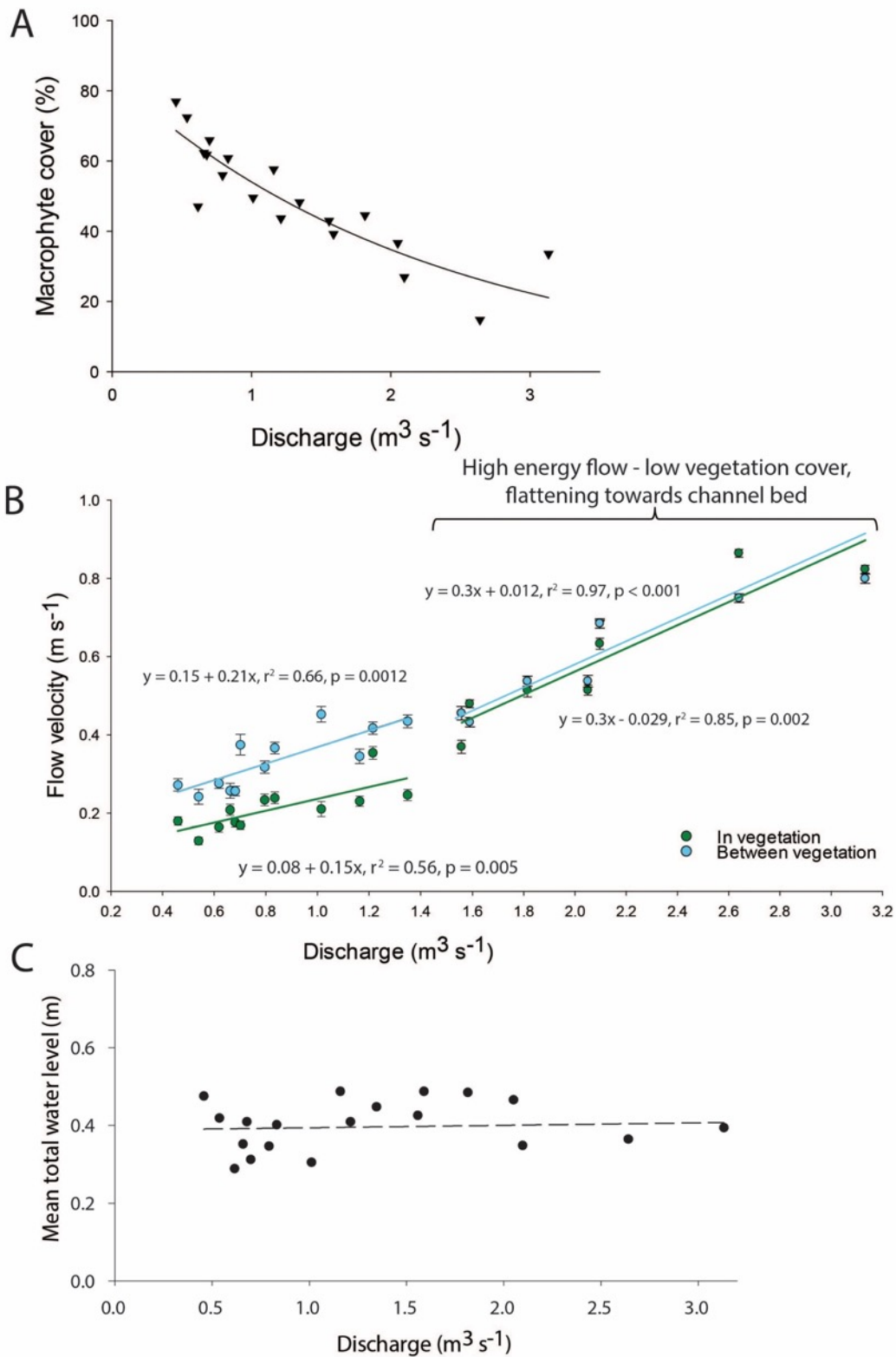


Fig. S3: Full dataset of measured macrophyte cover (A), flow velocities (B) and mean total water level (C) plotted against channel discharge in the ‘dominant submerged’ study site.

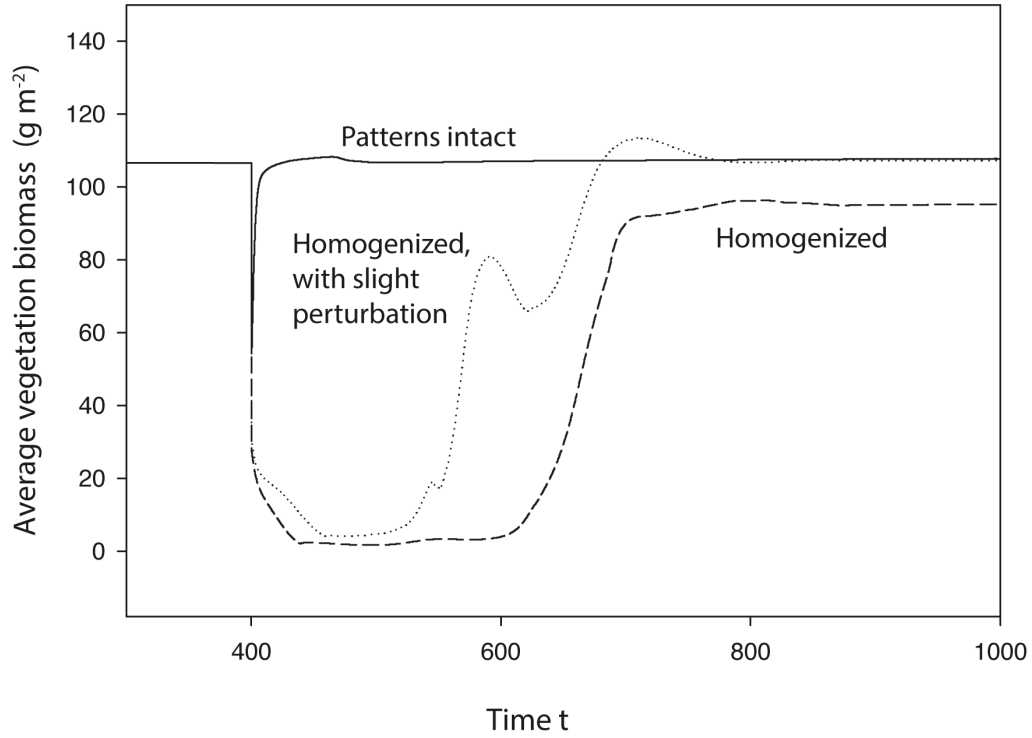


Fig. S4: Results of three simulations describing the recovery of vegetation in the stream after a disturbance in which 50% of the biomass was removed. The solid line represents a simulation in which the patterns were left intact. The dotted line represents a simulation where the remaining biomass was equally redistributed over the simulated grid, and a deviation was imposed in randomly selected cells up to 10% of the biomass. The dashed line represents a simulation where the remaining biomass was homogenized in space, leaving no spatial variability. Parameters as in Table 1, for $U_{in} = 0.25 \text{ m s}^{-1}$.

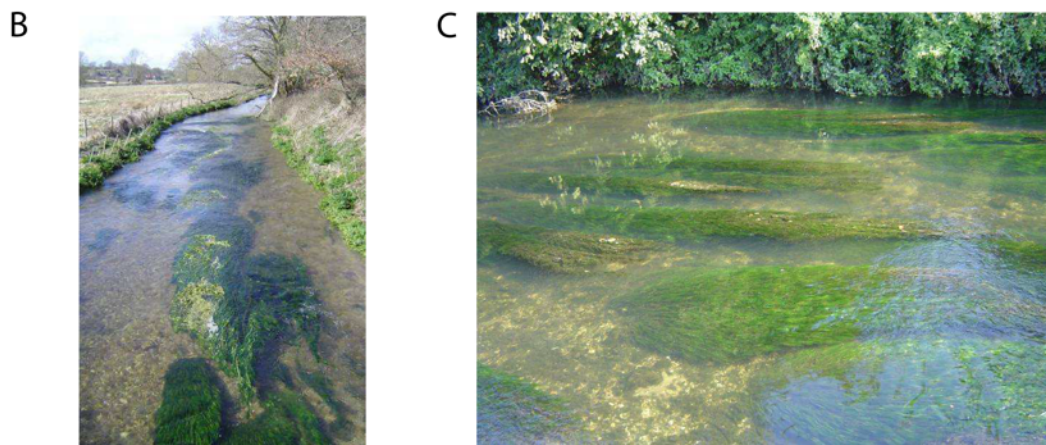
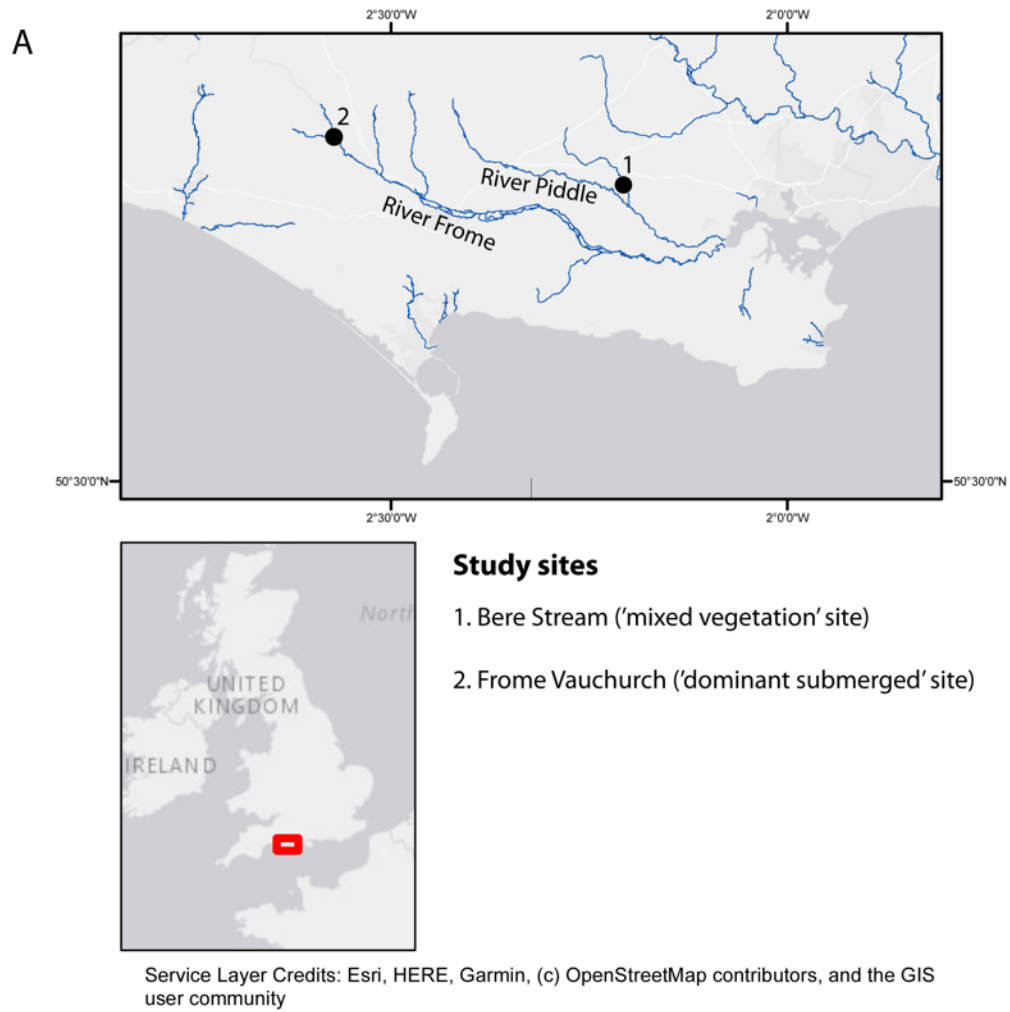


Fig. S5: (A) Location of the study sites in Dorset, UK: the Bere Stream in the River Piddle Catchment and the Frome Vauchurch in the River Frome Catchment. (B) The Bere Stream in March 2009 and (C) the Frome Vauchurch in September 2008: both sites were colonized by multiple *Ranunculus* stands in the middle of the channel. Photos by R. C. Grabowski.

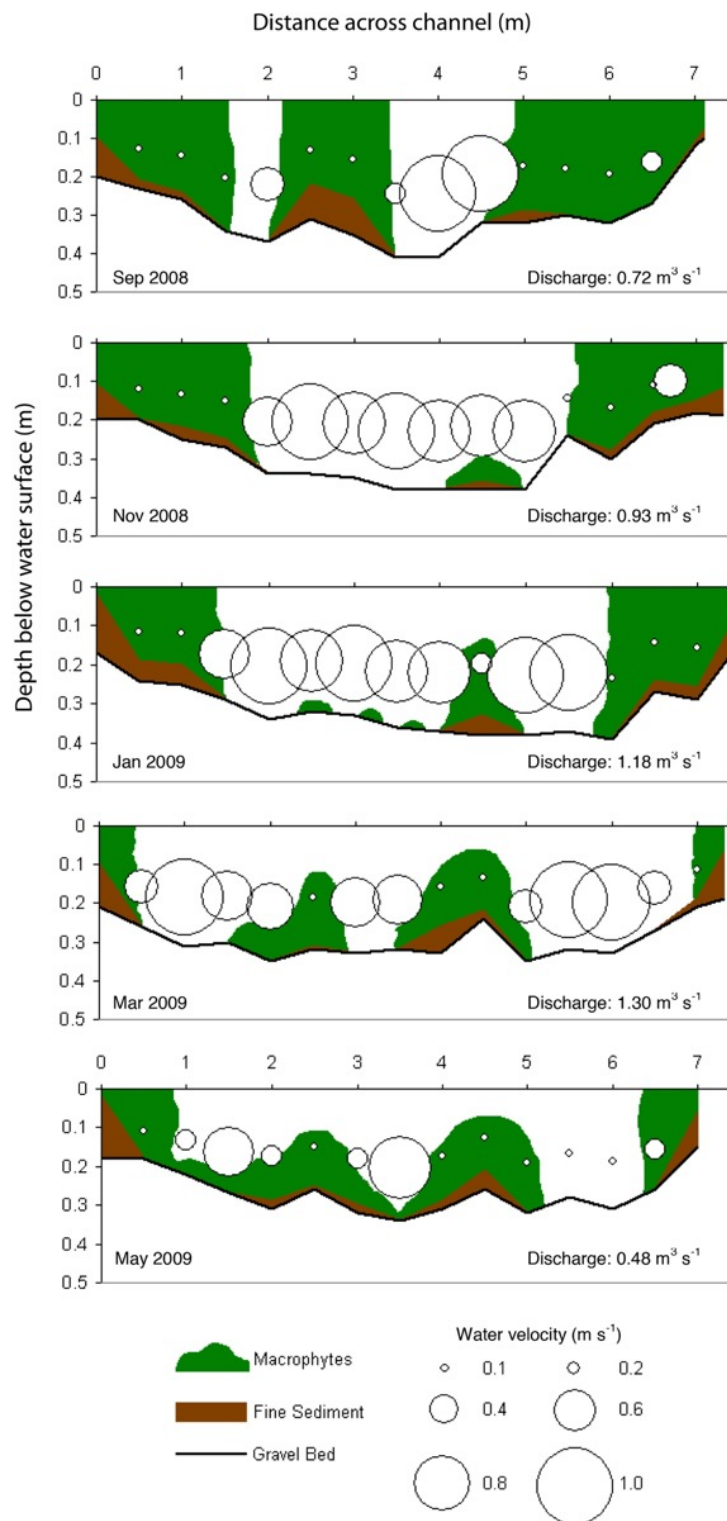


Fig. S6: Plotted cross-section of a sample transect in the Bere Stream (Transect n. 10) showing changes in water depth, fine sediment accumulation, depth-averaged flow velocity, discharge and location of macrophyte patches over time. Modified from [3].

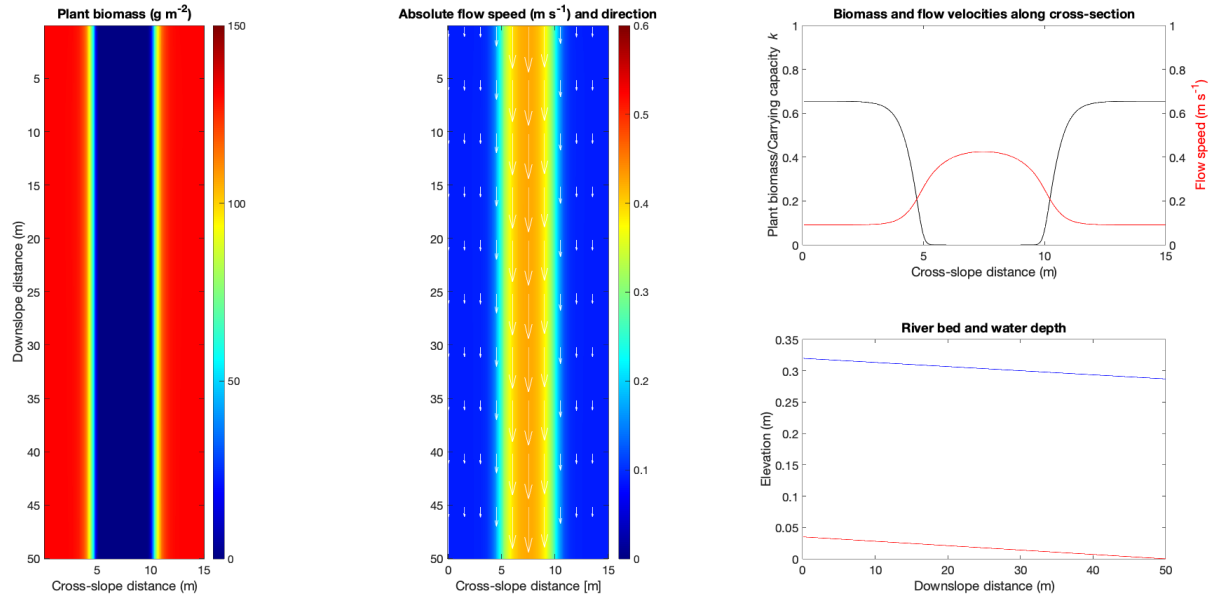


Fig. S7: Visualization of the spatial output of the model. (A) Top view of the simulated plant biomass (g/m^2) and (B) absolute flow speeds (m/s) and direction. (C) Cross-slope view of the biomass and flow velocity distribution. (D) Downslope view of the river bed elevation and water depth (m).

References

1. Grabowski, R. C. 2011 The erodibility of fine sediment deposits in lowland chalk streams (PhD dissertation, Queen Mary, University of London).