Hydrogeomorphological processes and plant invasion. What interactions in the case of Asian knotweeds along the Herault River (France)?

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RESEARCH ARTICLE

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Hydrogeomorphological processes and plant invasion. What interactions in the case of Asian knotweeds along the Herault River (France)?

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Abstract

Considered one of the five major threats to biodiversity worldwide, Invasive Alien Species (IAS) particularly threaten riparian ecosystems. Among the IAS found on riverbanks, Asian knotweeds (*Reynoutria* spp. including *R. japonica* Houtt.; *R. sachalinensis* [F.Schmidt] Nakai and the hybrid *R.* x *bohemica* Chrtek & Chrtkova) can barely be controlled as, once established, they disperse easily along stream banks via rhizome or stem fragments transported by water. However, the hydrogeomorphological processes underlying the establishment of Asian knotweeds are poorly understood. The objective of this study was to describe and model the hydrogeomorphological preferences of Asian knotweeds along a Mediterranean river. Based on exhaustive presence/absence surveys, we implemented two models related to the presence of Asian knotweeds: (1) at the river reach scale and (2) at the finer scale of the alluvial bar. Areas of low curvature identified as convex banks and the central parts of alluvial bars appear to be more susceptible to knotweed establishment. Highly disturbed areas were less favorable to maintaining plant species, including Asian knotweeds, while less disturbed areas with denser plant cover were more favorable to Asian knotweeds. The results seem to indicate a trade-off hypothesis in the knotweed establishment strategy between hydrogeomorphological constraints and strong interspecific competition. Analyzed in the light of the current literature, our final models are designed to integrate hydrogeomorphological processes in order to provide an operational tool to help river managers locate the areas most susceptible to knotweed invasion and with important implications for managing these species in riparian ecosystems.

KEYWORDS

establishment strategy, *Fallopia* spp., floods, hydrogeomorphological processes, plant invasions, Polygonum cuspidatum, *Reynoutria* spp.

1 | INTRODUCTION

The 2019 report by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) indicated a sharp rise in the number of invasive alien species (IAS), with an increase of over 70% since 1970, and listed biological invasions as one of the five major global threats to biodiversity (IPBES, 2019). Rivers and riparian habitats have been widely documented as some of the most threatened by invasive plant species (Tabacchi et al., 1996; Tickner et al., 2001). Despite recent advances in the development of conceptual frameworks that link hydromorphological processes to plant invasions (Solari et al., 2016; Staentzel et al., 2017; Tickner et al., 2001), there remains a pressing need to gain a deeper understanding of the processes facilitating the arrival, establishment, and dispersal of IAS along riverine ecosystems in order to limit their spread.

Among IAS found on riverbanks, Asian knotweeds (*Reynoutria* spp. including *R. japonica* Houtt.; *R. sachalinensis* [F.Schmidt] Nakai and the hybrid *R. x bohemica* Chrtek & Chrtkova), are responsible for a variety of impacts on safety and biodiversity (Lavoie, 2017). Moreover, once established, these species become extremely difficult to control because their high underground biomass favors their regrowth (Gerber et al., 2008). Preventing their establishment is by far the most cost-efficient management approach, but requires prior knowledge of the ecological conditions that favor the species' dispersal and establishment with the aim of prioritising the monitoring. Recent research suggests the importance of hydrological regime and hydrogeomorphological processes on the distribution of Asian knotweeds at the stream scale, particularly in their transport and establishment (Matte et al., 2021; Navratil et al., 2021). Therefore, identifying the hydromorphological conditions suitable for their establishment and dispersal appears as an essential line of research.

At the river reach scale, hydromorphological conditions play a crucial role in determining the establishment and growth of vegetation on riverbanks and bars (Jones & Mulholland, 1999; Mitsch & Gosselink, 2000). More specifically, in external bends where erosive and shear forces put the sediment in motion environments are not conducive to the establishment of vegetation (Gurnell et al., 2016). In contrast, alluvial bars and convex sections (the deposition zones in alluvial landscapes) favor the establishment of vegetation by promoting sediment accretion. The local hydraulic and hydrogeomorphological conditions of these deposition areas, that is, low velocities, low erosive force, lower water levels facilitating the accumulation of propagules, promote invasion by IAS (Gurnell, 2007; Mahoney & Rood, 1998). As river flow and floods act as major dispersal vector for Asian knotweeds and river-induced disturbances create vacant niches, creating or renewing a mosaic of habitats available for colonization (Tickner et al., 2001), we can hypothesized that their propagules depend on deposition process to establish. Their presence along a river reach should consequently be conditioned by river curvature, with convex deposition section being more favorable and sensitive to invasion by these IAS than concave section prone to more erosive forces.

More locally, the hydrogeomorphological conditions can also vary within a deposition zone due to heterogeneous abiotic and biotic conditions, creating stable, vegetation-dominated areas and active, frequently flooded areas (Curtis & Guerrero, 2015; Gurnell et al., 2016). In the context of alluvial bars, it has been observed a gradient of exposure, with upstream areas more prone to severe flood-disturbances compared to the more stabilized and vegetated internal and downstream areas. This exposure gradient is expressed in the longitudinal and transverse directions and influences species occurrence depending on their tolerance to abiotic constraints (Hortobágyi et al., 2018). As well, newly arrived propagules should find more constraining biotic conditions in stabilized vegetated areas where competition should be more intense. As species sensitive to competition (Dommanget et al., 2013), this should result in less frequent Asian knotweeds in the vegetated areas of the alluvial bars. We therefore hypothesized that the presence of Asian knotweeds is the result of a compromise between abiotic constraints on the one hand (disturbances) and biotic constraints on the other (competition), which should result in a higher probability of presence at intermediate position along these two gradients.

Using the results of an exhaustive inventory of the presence of Asian knotweeds along the Hérault River (France), we investigated the hydromorphic preferences of *Reynoutria* spp. (i) at the river reach scale according to the bank curvature and (ii) at the more local alluvial bar scale testing the trade-offs among interspecific competition, and flood-disturbance frequency that condition their distribution along the two crossing axes upstream—downstream and close-to-the-stream—far-to-the-stream. We then discuss our results in the light of the available scientific literature with the objective of synthesizing existing knowledge.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was carried out in 2015 on the Hérault River located in the south of France (Gard and Hérault administrative divisions). The Hérault River has a total length of 147.6 km and its watershed has an area of 2550 km^2 (Banque Hydro – MEDDE, 2021). The study focused on a 33-km reach of the river invaded by Asian knotweeds from just upstream of Saint-André-de-Majencoules to the meanders near Brissac (Figure 1).

The mean daily discharge of the Hérault River at Laroque, the nearest downstream hydrometric measuring station, was 19.10 m^3/s since the beginning of the measurement history (DREAL Languedoc-Roussillon, 2021). The months with the highest daily flows were November (32.10 m^3/s) and January (31.70 m^3/s), while those with the lowest average daily flows were July (4.48 m^3/s) and August (3.55 m^3/s) (DREAL Languedoc-Roussillon, 2021). The Hérault River has a Cevenol river regime, characterized by violent annual flooding episodes. In total, 70% of the Hérault's floods events occur in only 2 months of the year (September and October). In 20 years (1995–2015), there were three remarkable flood events: the first one in 1997 reached a flow of 999 m^3/s (50-year event), the second in 2003

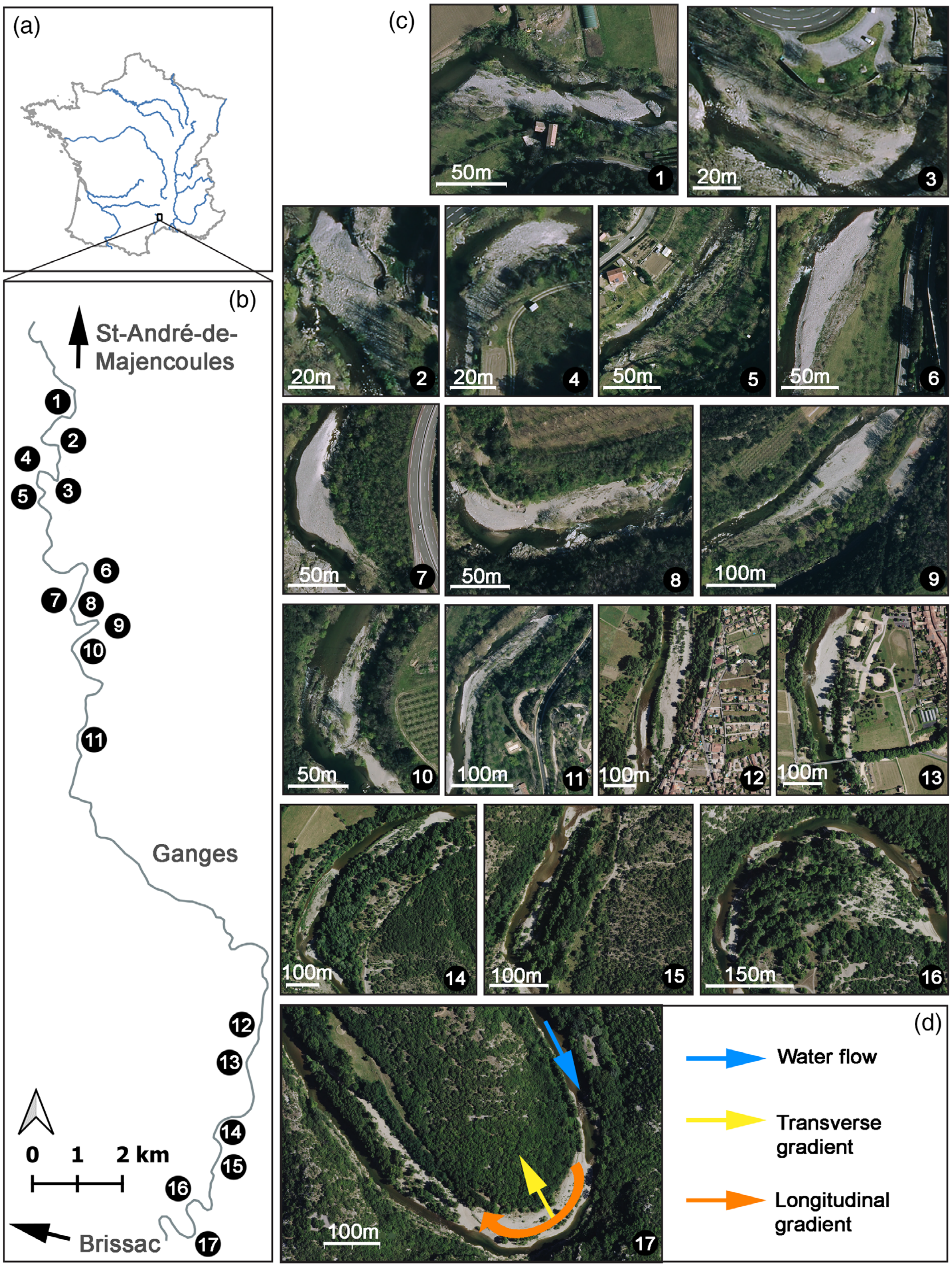

FIGURE 1 The study area along the Hérault River (France) and the seventeen alluvial bars studied. [Color figure can be viewed at wileyonlinelibrary.com]

reach 671 m^3/s (10-year event) and the last one in 2011 reached a flow of 680 m^3/s (10-year event).

2.2 | Asian knotweed inventory

Our dataset was based on a series of inventories that a private firm (Concept Cours d'Eau Scop Aquabio) carried out on a linear survey of about 37 km in September 2015. The full exhaustiveness of the inventory was ensured only on the left bank of the river due to the inaccessibility of some parts of the right bank. Nonetheless, it is important to note that some sections of the right bank were also explored with accuracy. Each inventoried stand was geolocated (Trimble GPS Pathfinder XC and GeoXT6000). Dispersal by flood was identified as the main factor in the spread of the knotweeds, although anthropogenic introductions were also observed. In the study, only

Asian knotweed patches that were obviously of natural origin were retained by an analysis of the surrounding environment and identification of potential anthropic sources (works, roads, etc.).

The field dataset was coupled with High-Resolution aerial ortho-photographs (20 cm/pixel) and Color InfraRed ortho-photographs (IRC) at 50 cm resolution dated June 2015 for the Hérault and April 2015 for the Gard (IGN, 2015).

2.3 | River reach scale

The distribution of Asian knotweeds at the river reach scale was analyzed through aerial imagery on the Hérault River left bank where an exhaustive survey was available. We first assessed river curvature from the stream centerline. To do this, we defined the primary wetted channel thanks to the segmentation algorithm of the open libraries in the Orfeo Tool Box (OTB) on QGIS (Grizonnet et al., 2017). The centerline was then digitized according to the Vonoroi diagram approach based on the geographic center of the primary wetted channel from both banks of the stream as seen in the 2015 IRC aerial images (Lewandowicz & Flisek, 2020). Full details of our approach are given in Appendix S1. We then assessed the curvature of the river from the centerline following Camporeale, Perona, Porporato and Ridolfi's (Camporeale et al., 2005) definition, in which curvature c is determined using a three-point algorithm on the centerline. The centerline is considered as discrete with equidistant discretization points according to the following equation:

$$c=\frac{\partial\theta}{\partial s}=\frac{(\arcsin\alpha^{\beta})}{|\alpha||\beta|\Delta s}=\frac{\alpha_y\beta_x-\alpha_x\beta_y}{\Delta s^3},$$

where α and β are the vectors from point $i-1$ to i and from point i to point $i+1$, respectively. In this study, the interpolation distance was 100 meters. According to this definition, the curvature is positive in the meanders curving clockwise downstream (with concave sections on the left bank) and equal to zero at the inflection points.

2.4 | Alluvial bar scale

Seventeen bars (Figure 1) were selected. Presence of Asian knotweeds was the main criterion for selection (Figure 2). The borders of the banks also had to be sufficiently clear to allow their delimitation from high-resolution images. Finally, since the field survey was mainly conducted on the left bank, the bars were preferentially located on the left bank in order to ensure that the survey data would be complete. Even so, two of the 17 bars selected were located on the right bank; however, these two exceptions were also subjected to exhaustive surveys. The selected bars presented a certain heterogeneity in sediment grain size, surface area and shape, although these variables were not recorded.

Each selected alluvial bar was divided into nine equal units along two orthogonal gradients: a longitudinal upstream—downstream gradient and a transverse gradient (Figure 1). Proposed by Hortobágyi et al. (2018), this approach allows for variations in disturbance regime and in abiotic and biotic conditions on the alluvial bar. Each Asian knotweed stand was associated with one location on each gradient: upstream, central or downstream for the longitudinal gradient and close, middle or far-from-water for the transverse gradient.

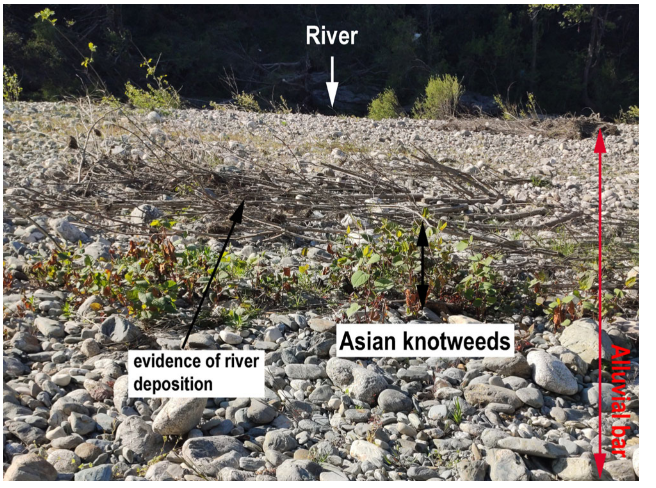

FIGURE 2 Example of an Asian knotweed stand linked to the process of deposition on an alluvial bar on the Hérault River (France). ©Marie DIDIER (2021). [Color figure can be viewed at wileyonlinelibrary.com]

2.5 | Statistical analyses

We used a statistical modeling approach to determine whether river curvature and position on the alluvial bank shape Asian knotweeds presence along the Hérault River.

For the river reach scale analysis, the effect of curvature on Asian knotweeds presence was tested with a logistic regression. The effect of distance to the most upstream station was also considered in the model to take into account the decrease in propagule pressure with distance. The variance inflation factor between curvature and distance to the most upstream location was below two, indicating a lack of collinearity. The variance explained by the model was estimated with McFadden's R^2 (McFadden, 1974).

For the alluvial-bar scale analysis, we used logistic regressions to test the main effects of the two gradients and the interaction effects between them. Because the areas defined by the gradients were not spatially independent, we used General Linear Mixed Models (GLMMs) in which the term "coordinate X" was included as a random effect (lme4 package). Since there was some heterogeneity in the banks studied, a second random effect "site" was considered ($n=17$). A "site" was defined as a location belonging to the same alluvial bar. Four candidate models (in addition to the null model) were constructed. The variance explained by the models was estimated with the marginal coefficient of determination for the fixed-effect parameters alone (Nakagawa et al., 2017). To identify the most parsimonious regression model, we used Akaike's information criterion (AIC).

The statistical analyses were performed with R version 4.0.4 (R Core Team, 2020).

3 | RESULTS

3.1 | River reach scale: Influence of bank geometry on the presence of Asian knotweeds

A total of 604 observations of Asian knotweeds out of 613 inventoried have been retained, all of obvious natural origin. These geolocalized observations were coupled according to the location to the 370 values of curvatures calculated on the 37 km of the Hérault River. The bank geometry of the river reach considered with curvature values is detailed in Figure 3. On the left bank, concave banks were identified by positive curvature values while convex banks were identified by negative curvature values (Figure 3a,b). In 2015, Asian knotweeds observations were more associated with negative curvature values.

Table 1 shows the results of the logistic regression testing the effect of curvature on the presence of Asian knotweeds. According to this model, which had an R^2 of 0.143, bank curvature had a significant effect on the presence of Asian knotweeds on the Hérault River ($p < 0.01$). The effect was negative on banks with positive curvature, identified as concave, reflecting a lower probability of the presence of Asian knotweeds. According to these results, the lower the curvature value, the higher the probability of Asian knotweeds presence. Distance from the most upstream invaded location also had a significant effect on the probability of Asian knotweed presence ($p < 0.001$). The probability of Asian knotweed presence decreases as you move downstream.

3.2 | Alluvial bar scale: Establishment preferences

On the 17 alluvial bars selected where the species were present, Asian knotweeds were more frequently situated on the central area of the alluvial bar than on the upstream area along the longitudinal gradient.

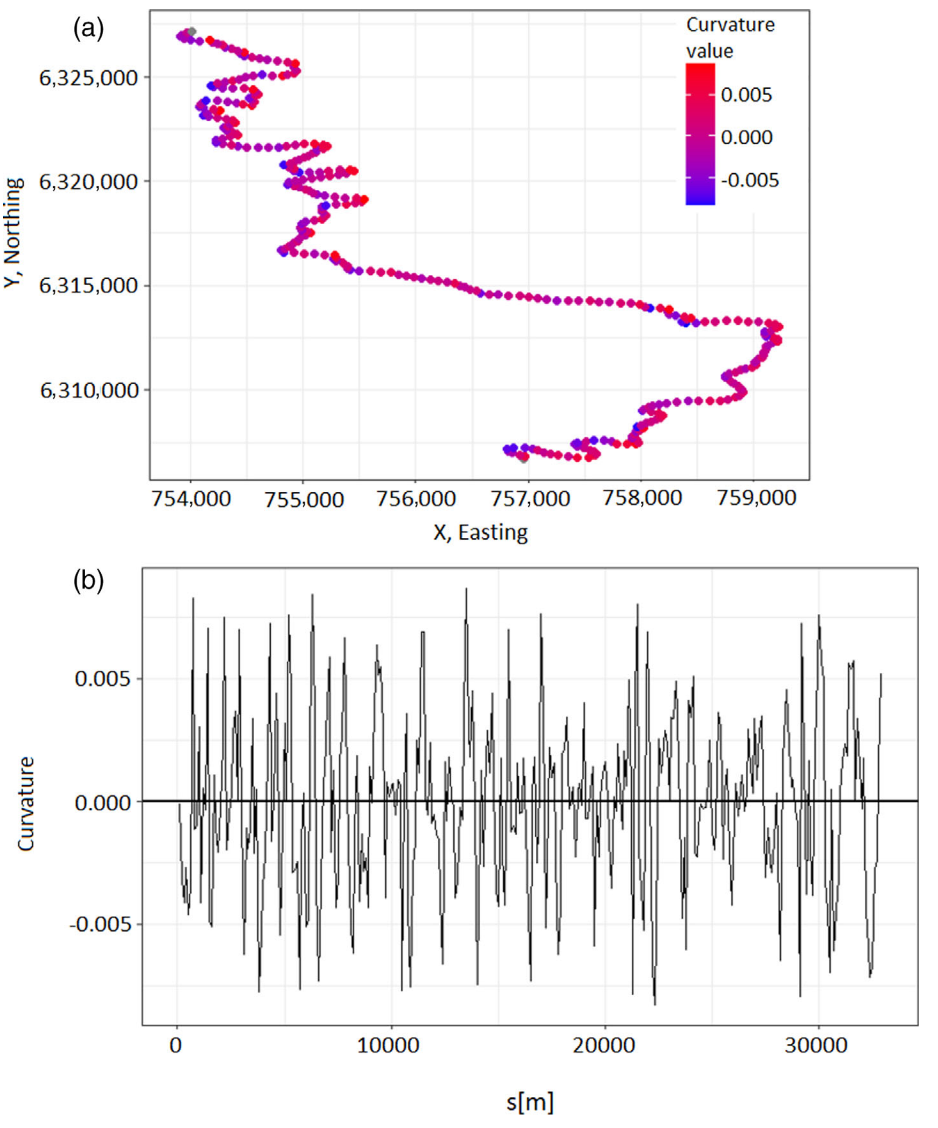

FIGURE 3 (a) Channel axis configuration of the Hérault River (France) and (b) the corresponding curvature. s stands for the distance to the most upstream invaded point. [Color figure can be viewed at wileyonlinelibrary.com]

Asian knotweeds were also more numerous in the areas closest to and mid-distance from the water compared to areas farthest from the water along the transverse gradient. Out of a total abundance of 227 knotweed stands, 19.82% were located on the upstream part of the bars, 45.82% on the central part and 34.36% on the downstream part. On the same individuals, 42.29% of them were present on the closest part to the water, and respectively 36.12% and 21.59% on the middle part and farthest part.

The most parsimonious candidate model was the one considering only the longitudinal gradient, with a marginal coefficient R^2_{GLMM} of 0.051. Detailed results of the logistic regression are shown in Table 2. According to the logistic regression, the upstream zone of the bank was associated with a statistically significant lower probability of Asian knotweed presence compared to the central and downstream zones ($p < 0.001$ in Table 2, Figure 4). The results of our analysis show that the central parts of the alluvial bars present the highest probability of presence for knotweeds, with a value of 0.568 (Figure 4). In contrast, the upstream zones exhibit a significantly lower probability of presence (divided by almost 3), with a predicted value of 0.294. The downstream part of the alluvial bars presents a probability of presence of 0.431. The model indicated no significant difference between the central and downstream zones.

4 | DISCUSSION

Our study used for the first time field data to model hydrogeomorphological preferences of Asian knotweeds at two scales along a Mediterranean European river in an innovative approach that had to our knowledge never been applied to an invasive alien plant case. The study of interactions between vegetation and hydrogeomorphological processes is a scientific front whose stakes are fundamental to understanding and then predicting the phenomena of alien plant invasions as many of them occur along riverbanks. Here we discuss our results

TABLE 1 The logistic regression model testing the effect of curvature and the distance to the most upstream-invaded point on the presence of Asian knotweeds on the Hérault River (France).[b]

Variable	Coefficient	SD	Statistic	*p*-value	95% confidence interval		Significance[a]
Curvature	−1.078e+02	3.510e+01	−3.073	0.002	−1.778e+02	−3.989e+01	**
Distance to upstream	−9.558e-05	1.404e-05	−6.808	9.91e−12	−1.239e-04	−6.881e-05	***

[a]Significance: ***$p < 0.001$, **$p < 0.01$.
[b]The R^2 of the model is 0.143.

TABLE 2 The top-ranked logistic regression model predicting Asian knotweed presence at the alluvial bar scale on the Hérault River (France).[b]

Variable		Coefficient	SD	Statistic	*p*-value	95% confidence interval		Significance[a]
Longitudinal gradient (vs. central)	Upstream	−1.151	0.417	−2.756	0.005	−1.970	−0.332	**
	Downstream	−0.552	0.399	−1.381	0.167	−1.336	0.231	

[a]Significance: ***$p < 0.001$, **$p < 0.01$.
[b]The R^2_{GLMM} of the model is 0.051.

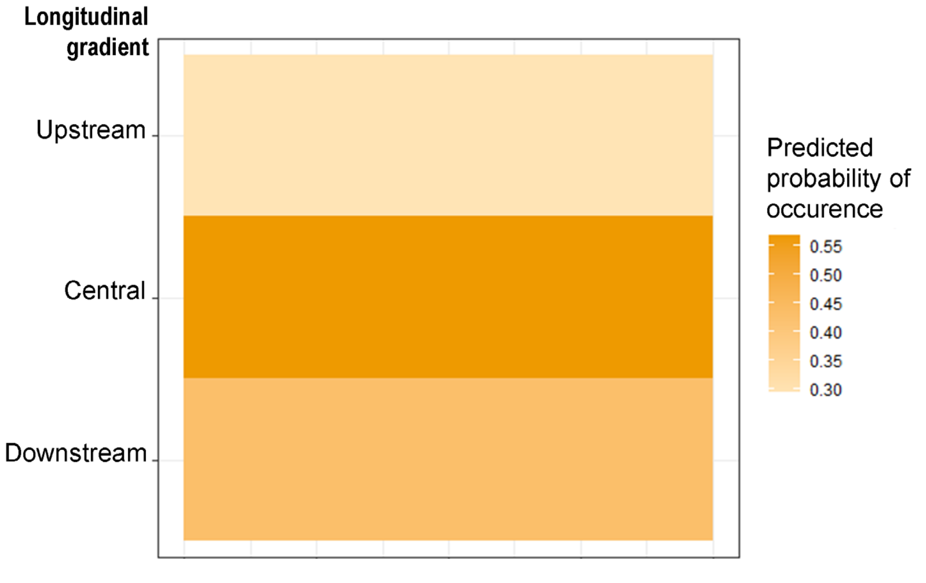

FIGURE 4 Predicted probability of occurrence along the longitudinal gradient on the Hérault River (France) according to the logistic regression. [Color figure can be viewed at wileyonlinelibrary.com]

based on the scientific literature on the subject in order to better understand their scope for Asian knotweeds and to highlight future research areas.

4.1 | Influence of bank morphology on the presence of Asian knotweeds

The meander geometry of river banks appears to significantly influence the rate and pattern of Asian knotweed invasion. Our research has revealed that convex sections are the preferred areas of distribution for these invasive species. The slower flow velocities in these areas facilitate the arrival and deposition of sediments and/or dead wood that may contain propagules (Hooke, 1975), resulting in knotweeds often being inventoried in river deposit zones. The deposited sediment provides, in parallel, the necessary substrate and nutrients for the establishment and growth of propagules contributing to the recruitment of the young clones. These findings suggest that convex banks with low hydrogeomorphological constraints are particularly susceptible to invasion at the river scale due to low erosive and shear forces, and serve as ideal habitats for the establishment of pioneer species like Asian knotweeds (Descombes et al., 2016).

In meander concave sections, high flow velocities combined with shear stresses result in increased sediment mobilization and bank erosion, creating conditions that are unfavorable to vegetation and hindering the establishment of plant species (Gurnell et al., 2016). These local constraints may limit the recruitment of Asian knotweed propagules by preventing their deposition. In uninvaded areas, the hydrogeomorphological features associated with this geometry pose physical challenges to seedling establishment. However, once an area has been invaded by Asian knotweeds, these same hydrogeomorphological features, especially high erosive stresses, could further exacerbate the invasion by removing propagules from established stands and sweep them to uninvaded downstream areas, potentially leading to exponential spread (Bailey et al., 2009; Colleran & Goodall, 2014; Mandák et al., 2004). These results foreshadow the existence of complex interactions between hydrogeomorphological constraints and the distribution of invasive species in river systems. As modeled by Gurnell et al. (2016), there are dynamic zones within river corridor where different hydrogeomorphological processes dominate so that plant and hydrogeomorphological processes interact in different ways. With regards to Asian knotweeds, the probability of establishment may be reduced in most constraining zones, without completely preventing the establishment of a stand. Meanwhile, the same erosive forces can contribute to invasion dynamics by facilitating the detachment and transport of propagules (Lamberti-Raverot et al., 2017).

Futhermore, our findings at this scale show a decreasing probability of Asian knotweed presence downstream that reflect a decrease in propagule pressure along the river. Boyer and Barthod (2019) pointed out that the density of Asian knotweed clones should be negatively correlated with the downstream distance to other clones. The most successful establishment of these flood-transported species occurs at fairly small distances from the parent plant, probably within only a few hundred meters (Boyer & Barthod, 2019; Duquette et al., 2016). Thus, at the initial stage of colonization Asian knotweeds can maintain themselves at a low level of population for a few years with a discrete downstream spread until hydrogeomorphological processes through flooding generate a significant flow of propagules, and exponentially accelerate the colonization in terms of time and distance (Boyer & Barthod, 2019). The natural progression of Asian knotweeds appears to be closely linked to river hydrogeomorpology.

The significant results obtained in our study are consistent with the results of Descombes et al. (2016), who present river curvature as an explanatory factor for the presence of Asian knotweeds along a stream although this has not been identified as the most determinant. Instead, distance to the river was identified as the predictor that consistently better explained knotweed dispersal. What aligns with the low goodness of fit of our model (< 15%) indicating that other unaccounted-for factors conditioned the presence of these species at the scale of the watercourse. One of the key contributions of our study is the examination of a unique river system with extreme flood events, which can greatly impact the pattern of distribution and spread of these invasive plant species. Our approach complements the existing literature by providing finer-scale insights, at a smaller scale of 100 m, and contributes to a better understanding of the ecology of knotweeds. The plant species and communities found in river corridors reflect three broad sets of hydrogeomorphological constraints, including climate, water availability and fluvial disturbance (Gurnell et al., 2016). While our paper considered fluvial disturbance, further investigation of micro-conditions, climate and water availability at the river reach scale could lead to work toward developing a more performant model and an operational tool to help river managers define the sensitivity level of their watersheds to Asian knotweed invasion. It should help guide river managers in identifying locations where more surveys and effort may be needed at the stream scale (Dommanget et al., 2019).

4.2 | Occurrence of Asian knotweeds on a single alluvial bar

Significant variations in the location and spatial extent of Asian knotweed establishment on the Hérault River alluvial bars was observed. The presence of Asian knotweeds was significantly dependent on the longitudinal gradient of the alluvial bar, but not on the transverse gradient. Although Asian knotweeds established at all locations along the longitudinal and transverse gradients, establishment on the most exposed upstream areas near the active channel remained marginal, with the lowest probability of occurrence.

Disturbances of both natural and anthropogenic origin have been recognized as facilitators of the process of Asian knotweed invasion (Lavoie, 2017; Matte et al., 2021). At a finer scale, our distribution analysis reveals that the establishment and maintenance of Asian knotweeds at the alluvial-bar scale are limited by high-level disturbances related to hydrogeomorphological constraints. Characterized by particularly high levels of disturbance, the upstream areas are the most unstable; vegetation establishment, including Asian knotweed, is limited as the areas are subject to regular hydrogeomorphological disturbances such as submergence, shear stress, erosion and burrowing (Curtis & Guerrero, 2015). Despite the high phenotypic plasticity and adaptability of Asian knotweed, its establishment on these areas appears to be constrained by the nature and intensity of the disturbances occurring there.

In contrast, the central portion of the bank had the highest probability of occurrence, while the downstream area had an intermediate probability. According to the "fluvial biogeomorphic succession" model proposed by Gurnell et al. (2016), the vegetation succession associated with the bar stabilization process leads to locally vegetated areas with high vegetation cover and aboveground biomass. This theory posits that a higher vegetation density characterizes the downstream portions of alluvial bars due to stabilization with more stable conditions and low levels of disturbance. The lower probability of presence of these species compared to the central areas could then be related to the lower probability of depositional events, including propagules deposition, but also of greater interspecific competition among the plants, especially for light. Indeed, although Asian knotweeds can grow in a variety of light regimes, they find optimal growth conditions in open areas (Descombes et al., 2016). These findings are consistent with field studies and the literature, which identifies Asian knotweeds as heliophilic pioneer species that thrive best in open areas rather than in the shade of dense trees or shrubs (Navratil et al., 2021; see Dommanget et al., 2013, 2019). Asian knotweeds prefer sites with high light availability, close to a river that creates new primary areas through sinuous expansion and the deposition of diaspores in the sediment (Descombes et al., 2016). The highest probability on central part of alluvial bars suggests a trade-off in the Asian knotweed establishment strategy between hydrogeomorphological constraints in upstream areas and strong interspecific competition in downstream areas. Abiotic conditions and hydrogeomorphological constraints in the upstream parts of the alluvial bar appear to be less favorable for the survival of Asian knotweed species, while high interspecific competition downstream may limit their presence, likely due to light competition (Dommanget et al., 2013). As a result, the central zone appears to be the preferred location, providing a balance between hydrogeomorphological constraints and interspecific competition for the best environment.

In this study, the model's ability to explain the presence of Asian knotweeds was limited, with a goodness of fit below 10%. This may be due to the limited number of samples available for analysis, the stochastic nature of hydrological events affecting the distribution of these flood-transported species and/or a failure to consider other important factors, such as biotic interactions and hydrological attributes such as slope, soil properties, and bar elevation. As Solari et al. (2016) noted, it is important to consider soil properties when modeling the relationship between riparian vegetation and hydromorphology. As instance, fine-grained sediment deposition is a fundamental hydrogeomorphological process that creates and maintains riparian habitats (Corenblit et al., 2009). Nevertheless, Descombes et al. (2016) were able to effectively study the relationship between *R. japonica* and hydrogeomorphological processes by using variables such as distance to the river and stream curvature as proxies for soil properties. It is crucial to acknowledge the heterogeneity among the selected bars in this study along the upstream-downstream axis of the river. The areas designated after dividing the alluvial bars into two different gradients exhibit heterogeneity, which could lead to potential discussion as the elevation above the water's edge may vary and the impacts of water flow and floods on the transport of Asian knotweed could also differ.

4.3 | Perspectives

Global warming will probably cause an expansion of Asian knotweed populations (Groeneveld et al., 2014) and the species are likely to become a major threat to rivers. This research improves our understanding of the interactions between hydrogeomorphological processes and Asian knotweeds invasions, and is an important step toward answering managers' operational questions. However, this paper also supports the need to account for more hydrogeomorphological variables in a more quantitative and precise manner. Further work could result in the creation of predictive, "invasive risk" maps along rivers to better target and prioritize management actions. Although recent studies have highlighted the impact of Asian knotweeds on river systems (Matte et al., 2021), the interactions between hydrogeomorphological processes and Asian knotweeds remain poorly understood. For instance, the tolerance of Asian knotweeds to submergence, erosion or shear stress has only rarely been mentioned in the literature, and then without supporting evidence, even though this is an essential element that could help explain the establishment of Asian knotweeds at the local scale.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Bailey, J. P., Bímová, K., & Mandák, B. (2009). Asexual spread versus sexual reproduction and evolution in Japanese knotweed sl sets the stage for the "Battle of the clones". *Biological Invasions*, *11*, 1189–1203.

Banque Hydro – MEDDE. (2021). Synthèse de la Banque Hydro – L'Hérault à Agde (Bassin Rond) (Y2372010). Accessed July 07, 2021.

Boyer, M., & Barthod, L. (2019). Un sac, des gants, un croc de jardin: le déterrage précoce, une technique douce contre l'envahissement des rivières par les renouées asiatiques. *Sciences Eaux Territoires*, *1*, 56–61. https://doi.org/10.3917/set.027.0056

Camporeale, C., Perona, P., Porporato, A., & Ridolfi, L. (2005). On the long-term behavior of meandering rivers. *Water Resources Research*, *41*(12), 1–13. https://doi.org/10.1029/2005WR004109

Colleran, B. P., & Goodall, K. E. (2014). In situ growth and rapid response management of flood-dispersed Japanese knotweed (*Fallopia* japonica). *Invasive Plant Science and Management*, *7*(1), 84–92.

Corenblit, D., Steiger, J., Gurnell, A. M., Tabacchi, E., & Roques, L. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processes and Landforms*, *34*(13), 1790–1810. https://doi.org/10.1002/esp.1876

Curtis, J. A., & Guerrero, T. M. (2015). *Geomorphic mapping to support river restoration on the Trinity River downstream from Lewiston dam, California, 1980–2011 (Open- File Report No. 2015–1047)*. U.S. Geological Survey.

Descombes, P., Petitpierre, B., Morard, E., Berthoud, M., Guisan, A., & Vittoz, P. (2016). Monitoring and distribution modelling of invasive species along riverine habitats at very high resolution. *Biological Invasions*, *18*(12), 3665–3679. https://doi.org/10.1007/s10530-016-1257-4

Dommanget, F., Evette, A., Breton, V., Daumergue, N., Forestier, O., Poupart, P., Martin, F. M., & Navas, M. L. (2019). Fast-growing willows significantly reduce invasive knotweed spread. *Journal of Environmental Management*, *231*, 1–9. https://doi.org/10.1016/j.jenvman.2018.10.004

Dommanget, F., Spiegelberger, T., Cavaillé, P., & Evette, A. (2013). Light availability prevails over soil fertility and structure in the performance of Asian knotweeds on riverbanks: New management perspectives. *Environmental Management*, *52*(6), 1453–1462. https://doi.org/10.1007/s00267-013-0160-3

DREAL Languedoc Roussillon. (2021). SYNTHESE: Données hydrologiques de synthèse (1969–2021) (Station Y2102010). Accessed July 07, 2021.

Duquette, M. C., Compérot, A., Hayes, L. F., Pagola, C., Belzile, F., Dubé, J., & Lavoie, C. (2016). From the source to the outlet: Understanding the distribution of invasive knotweeds along a north American river. *River Research and Applications*, *32*(5), 958–966. https://doi.org/10.1002/rra.2914

Gerber, E., Krebs, C., Murrell, C., Moretti, M., Rocklin, R., & Schaffner, U. (2008). Exotic invasive knotweeds (*Fallopia* spp.) negatively affect native plant and invertebrate assemblages in European riparian habitats. *Biological Conservation*, *141*(3), 646–654. https://doi.org/10.1016/j.biocon.2007.12.009

Grizonnet, M., Michel, J., Poughon, V., Inglada, J., Savinaud, M., & Cresson, R. (2017). Orfeo ToolBox: Open source processing of remote sensing images. *Open Geospatial Data, Software and Standards*, *2*(1), 1–8.

Groeneveld, E., Belzile, F., & Lavoie, C. (2014). Sexual reproduction of Japanese knotweed (*Fallopia* japonica s.l.) at its northern distribution limit: New evidence of the effect of climate warming on an invasive species. *American Journal of Botany*, *101*(3), 459–466. https://doi.org/10.3732/ajb.1300386

Gurnell, A. M. (2007). Analogies between mineral sediment and vegetative particle dynamics in fluvial systems. *Geomorphology*, *89*(1–2), 9–22. https://doi.org/10.1016/j.geomorph.2006.07.012

Gurnell, A. M., Corenblit, D., García de Jalón, D., González del Tánago, M., Grabowski, R. C., O'hare, M. T., & Szewczyk, M. (2016). A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. *River Research and Applications*, *32*(2), 142–163. https://doi.org/10.1002/rra.2928

Hooke, R. L. B. (1975). Distribution of sediment transport and shear stress in a meander bend. *The Journal of Geology*, *83*(5), 543–565. https://doi.org/10.1086/628140

Hortobágyi, B., Corenblit, D., Steiger, J., & Peiry, J. L. (2018). Niche construction within riparian corridors. Part I: Exploring biogeomorphic feedback windows of three pioneer riparian species (Allier River, France). *Geomorphology*, *305*, 94–111. https://doi.org/10.1016/j.geomorph.2017.08.048

IGN. (2015). BD ORTHO HR®.

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. In S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, et al. (Eds.), (p. 56). IPBES secretariat. https://doi.org/10.5281/zenodo.3553579

Jones, J. B., & Mulholland, P. J. (1999). *Streams and ground waters*. Elsevier.

Lamberti-Raverot, B., Piola, F., Thiébaut, M., Guillard, L., Vallier, F., & Puijalon, S. (2017). Water dispersal of the invasive complex Fallopia: The role of achene morphology. *Flora*, *234*, 150–157.

Lavoie, C. (2017). The impact of invasive knotweed species (*Reynoutria* spp.) on the environment: Review and research perspectives. *Biological Invasions*, *19*(8), 2319–2337. https://doi.org/10.1007/s10530-017-1444-y

Lewandowicz, E., & Flisek, P. (2020). A method for generating the centerline of an elongated polygon on the example of a watercourse. *ISPRS International Journal of Geo-Information*, *9*(5), 304. https://doi.org/10.3390/ijgi9050304

Mahoney, J. M., & Rood, S. B. (1998). Streamflow requirements for cottonwood seedling recruitment—An integrative model. *Wetlands*, *18*(4), 634–645. https://doi.org/10.1007/BF03161678

Mandák, B., Pyšek, P., & Bímová, K. (2004). History of the invasion and distribution of *Reynoutria* taxa in The Czech Republic: A hybrid spreading faster than its parents. *Preslia*, *76*(1), 15–64.

Matte, R., Boivin, M., & Lavoie, C. (2021). Japanese knotweed increases soil erosion on riverbanks. *River Research and Applications*, *38*(3), 561–572. https://doi.org/10.1002/rra.3918

McFadden, D. (1974). Conditional logit analysis of qualitative choice behavior.

Mitsch, W. J., & Gosselink, J. G. (2000). The value of wetlands: Importance of scale and landscape setting. *Ecological Economics*, *35*(1), 25–33.

Nakagawa, S., Johnson, P. C., & Schielzeth, H. (2017). The coefficient of determination R 2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface*, *14*(134), 20170213. https://doi.org/10.1098/rsif.2017.0213

Navratil, O., Brekenfeld, N., Puijalon, S., Sabastia, M., Boyer, M., Pella, H., Ledot, J., & Piola, F. (2021). Distribution of Asian knotweeds on the Rhône River basin, France: A multi-scale model of invasibility that combines biophysical and anthropogenic factors. *Science of the Total Environment*, *763*, 142995. https://doi.org/10.1016/j.scitotenv.2020.142995

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing .

Solari, L., Van Oorschot, M., Belletti, B., Hendriks, D., Rinaldi, M., & Vargas-Luna, A. (2016). Advances on modelling riparian vegetation-hydromorphology interactions. *River Research and Applications*, *32*(2), 164–178. https://doi.org/10.1002/rra.2910

Staentzel, C., Arnaud, F., Combroux, I., Schmitt, L., Trémolières, M., Grac, C., Piégay, H., Barillier, A., Chardon, V., & Beisel, J. N. (2017). How do instream flow increase and gravel augmentation impact biological communities in large rivers: A case study on the upper Rhine River. *River Research and Applications*, *34*(2), 153–164. https://doi.org/10.1002/rra.3237

Tabacchi, E., Planty-Tabacchi, A. M., Salinas, M. J., & Décamps, H. (1996). Landscape structure and diversity in riparian plant communities: A longitudinal comparative study. *Regulated Rivers: Research & Management*, *12*(4–5), 367–390. https://doi.org/10.1002/(SICI)1099-1646(199607)12:4/5<367::AID-RRR424>3.0.CO;2-X

Tickner, D. P., Angold, P. G., Gurnell, A. M., & Mountford, J. O. (2001). Riparian plant invasions: Hydrogeomorphological control and ecological impacts. *Progress in Physical Geography*, *25*(1), 22–52. https://doi.org/10.1177/030913330102500102

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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