IV.1

PREDICTING PATTERNS OF RIPARIAN FOREST RESTORATION.

Van Looy K., Severyns J., Jochems H. and De Smedt F. 2005. Predicting patterns of riparian forest restoration. Large Rivers Vol. 15, No. 1-4, Arch. Hydrolbiol. Suppl. 155/1-4, p. 373-390.

Kris Van Looy*, Jo Severyns**, Hans Jochems* & F. De Smedt**
* Institute of Nature conservation, Kliniekstraat 25, 1070 Brussels
** Free University Brussels, Departement of hydrology and hydraulic engineering, Pleinlaan 2, 1050 Brussels.

Abstract

The river's morphodynamic processes are an intrinsic aspect of riparian forest development. Sedimentation and bar formation are prerequisites for the stages of germination and growth of riparian forests. Furthermore, the mechanical disturbance of plants by erosion and abrasion, define the boundary conditions of establishing riparian forests. A field survey and hydraulic modelling of a 17 km river stretch revealed the patterns and processes of forest development in relation to hydromorphological and biological characteristics. These patterns were introduced in a modelling and prediction of riparian forest development within spatio-temporal sequences. The determined physical and biological components in forest restoration allow us to give guidelines for restoration strategies and plans at the different scale levels.

Introduction

The restoration of riparian forests is one of the main objectives of river rehabilitation projects around the world. In unmodified river systems, riparian vegetation exhibits a zonation from the river channel to the uplands along an elevation gradient (Lyon & Sagers 1998, Pabst & Spies 1998, Pautou & Wuillot 1989, Siebel & Bouwma 1998). Where regulation and engineering works disturb the regular flooding and vegetation patterns of the fluvial system (Bravard et al. 1986, Carbiener & Schnitzler 1990, Carter Johnson 1997, Shafroth et al. 2002), rehabilitation projects focus on enabling river dynamic processes that maintain the floodplain habitat heterogeneity. For the regeneration of riparian forests, flooding events are documented as an essential feature (Schnitzler 1997, Baumgärtel & Zehm 1999, Hughes et al. 2001, Bovee & Scott 2002). From the river manager's point of view flow resistance in space and time is a crucial aspect for riparian forest restoration. Therefore the prediction of forest development with emphasis on age structure and location is an important element in restoration programmes. Softwood forests contribute, by their rapid growth and strong flow resistance, to raising bar and island levels by retaining sand and gravel. The bars and islands in formation grow regularly in width and height with continuing accumulation of trapped sediment and an encroachment of willow thickets.

Hydraulic modelling is an extremely expanding science with strongly reliable measurements of flow resistance and erosion-sedimentation processes under specific riverbed conditions. The integration of vegetation dynamics in these modelling approaches is still unexplored. Aim of the research was to identify spatial and temporal patterns of riparian forest development, applicable in modelling of forest development. In this paper the role of morphodynamic processes in the development of the Salici-Populetum river forests is quantified in critical ranges/thresholds of hydraulic parameters, allowing predictions of forest development after restoration.

Material and method

Studied river reach

The Meuse is a rain-fed river, originating at an altitude of 409 m above sea level at the Plateau of Langres in the North of France and discharging into the North Sea some 900 km further downstream. The mostly rocky underground of the upstream part of the catchment, explains the rain-fed character with high discharge fluctuations for the Common Meuse. The Common Meuse is the 45 km Flemish-Dutch border section of the Meuse between Maastricht and Maaseik. It is a unregulated gravel bed river with a high slope (0.45 m/km). Discharge levels for the Common Meuse range from 10 m^3/s during dry periods to 3.000 m^3/s in periods of heavy rainfall in the catchment. The studied reach is a 17 km stretch of the Common Meuse between Smeermaas and Maasband.

For the Common Meuse, a large-scale restoration project is defined aiming to rehabilitate the river's gravel bed and to restore flood contact with the alluvial plain (Van Leussen et al. 2000, Pedroli et al. 2002, Van Deursen et al. 2001). River regulation activities and fragmentation of valley ecosystems were identified as strongly affecting diversity and composition of the Common Meuse river forests (Van Looy et al. 2003) and immediately threatening gene flow and genetic diversity resources (Bunn & Hughes 1997, Imbert & Lefèvre 2003). Despite the absence of flow regulation and shipping on the Common Meuse river stretch, bank reinforcement and former gravel mining in the river bed resulted in a strong decline of the morphological activity and of the presence of bars and islands (Micha & Borlée 1989). However, since 10 years the bank management changed with the adoption of the restoration programme and the growing awareness of new approaches in flood management. For this research bank erosion and forest settlement were allowed within safety limits. With the major flood events of 1993 and 1995, the morphological activity of the river reach showed a strong revitalisation in the elevation and reforestation of bars and islands.

Field and map survey

The development of pristine riparian forests of Salix and Populus species on the deforested Common Meuse stretch were surveyed for its morphological and biotic characteristics. The recruitment and age of willow and poplar trees was recorded for four consecutive years (1998-2001) along the study reach. All banks and bars were visited in September and all woody species were identified and measured. The age of the trees on bars, islands and the riverbank zone was determined on morphological aspects (year sprouts for young trees and ring detection with Pressler bore for older trees). Individual trees and seedlings were mapped. For developing forests, the coverage and age-classes of the different species were recorded.

Along with the woody species, erosion-sedimentation rates of bars and islands were described for the 4 years. The highest point of the bar was marked (at a tree) and the difference over the years was described as sedimentation (for elevation) or erosion (for lowering).

From bed profile measurements (1930-1987-1997) and aerial photographs (1990, 1995, 1996 and 2000) the age of bars and islands was investigated, together with the delineation of earlier bank line position (from the profiles), in order to describe the bank retreat process.

Spatio-temporal sequences

The regeneration of riparian forest can be determined in spatio-temporal sequences; this proved a valuable approach in integrated process and pattern analyses (Klein et al. 1995, Bartha et al. 1997, Ward & Stanford 1995, Pautou et al. 1997, Chiarello & Barrat-Segretain. 1997, Verheyen & Hermy 2001).

Temporal and spatial sequences were derived from the field and map survey.

From a GIS Digital Terrain Model interpretation of the topography and the accurate Q/h water level relationship, the field survey information could be translated in input data for the hydraulic model. With the field survey covering the whole riverbank zone of the stretch, sufficient data of presence and absence were present for the modelling and to calibrate the observations.
As spatial sequences for the softwood forest development in the Common Meuse were described the islands, lateral bars, point bars, levees and flood channels. Temporal sequences of forest development include the germination phase (year 1), the establishing phase (2-3 year) with the development of dense thickets; the survival phase (4-10 year) of thicket to young forest with groups of different age classes; the forest phase (> 10 year) is settled forest on elevated islands and bars in the river bed or higher on the banks and in the floodplain.

Hydraulic model

The hydraulic model SCALDIS (Mwanuzi & De Smedt 1997, Mwanuzi 1998) was used for the hydromorphological modelling. SCALDIS is a 2-dimensional numerical model, based on the finite elements concept. For the model, the river bed is divided in a grid with grid cells of 200 m length and a width varying of 10-100 m. For the riparian zone and the lower floodplain the grid cells had a width of 10 to 20 m. SCALDIS allows the calculation of water level (h), hydraulic radius (R), stream velocity (v) and shear stress (τ) for each grid cell at a given discharge, based on the Manning equation. Figure 4.1 shows the riverbed in profile with the significant water levels for the modelling. For the shear stress at specific elevation z in the riverbed τ_Z [N/m^2], the following formula was derived:

$$\tau_z = \frac{\tau}{R}(h - z)$$

The erosive capacity can be calculated by comparison of the shear stress τ_Z with the critical shear stress τ_C for bedload transport. The critical shear stress τ_C [N/m^2] is defined in the Shields formula for coarse gravel beds:

$$\tau_c = \theta g(\rho_s - \rho)d_{50}$$

with θ the dimensionless critical shear stress or Shields parameter, ρ_S the sediment density (≈2.65r) [kg/m^3] and d_{50} the median bedload grain size [m].

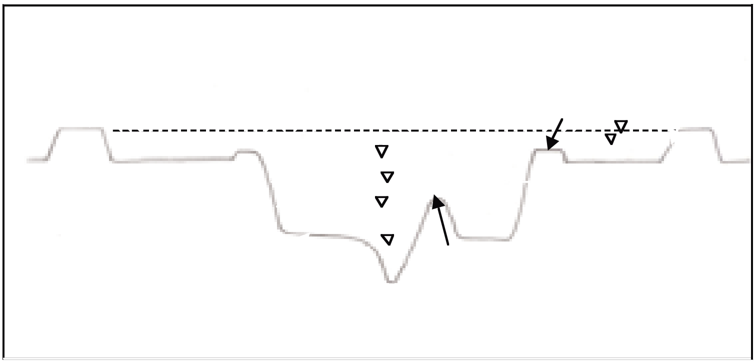

Figure 4.1 Riverbed profile with critical water levels for morphologic development (z3000 is the 3000 m^3/s water level).

Table 4.1 Critical shear stress tc for gravel bedload and armoured layer erosion.

θ	τ_c [N/m^2]		Bedload transport
	bedload	armoured layer	
< 0,03	< 7,3	< 17	No bed movement
0,03 – 0,06	7,3–14,6	17–34	Partial bed movement
> 0,06	> 14,6	> 34	Active bed movement

For the dimensionless critical shear stress three reference values are used for the description of the rate of bed transport (Lisle et al. 2000). The bed layer of the Common Meuse has a gravel fraction with a mean sediment diameter of 15 mm. The armouring of the bed layer results in higher critical shear stresses for bed movement than expected based on the mean perimeter of the bed fraction (Wörman 1992; Raudkivi 1998). For the armoured layer a d_{50}-value of 35 mm was used (Van Manen et al. 1994). Table 4.1 gives the thresholds for the critical shear stress for substrate and armoured layer erosion, calculated with equation (3) for the three q-reference values.

As roughness parameter in the modelling an n-value of 0.030 $s/m^{1/3}$ for the open gravel bed was retained after calibration, for the floodplain an n-value of 0.040 $s/m^{1/3}$. For the resulting forest in the riparian zone a value of 0.10 $s/m^{1/3}$ was used, as it is suggested for dense shrub and forest (Chow 1982). In the description of sedimentation and erosion processes, two additional parameters were derived from the critical shear stress; the entrainment potential as the proportion of actual to critical shear stress and the shear stress gradient, the ratio of change along the stream. The field survey of the distribution and clearing of forest development was analysed for the specific hydraulic conditions of shear stress and bedload with the τ_Z and τ_C formulas.

Results

Spatio-temporal sequences

Erosion-sedimentation rates differ strongly over the area during the survey. Some wooded bars gain 0.5 m a year, while others get washed away completely (table 4.2). The largest bars and islands are associated with larger bed widths and riffles (figures 4.2 and 4.3). No correlation was observed between shear stress values (minima/maxima) and the presence of bars, only shear stress gradients and width/depth ratio's showed correspondence to the position of bars with higher erosion-sedimentation ratio's (figures 4.5 and 4.6). Especially the shear stress gradient over the river stretch accords to the zones with active bar formation and sedimentation/erosion processes. Just downstream gradient peaks active bar formation takes place. High W/d-ratio (> 20 for the Common Meuse) do not always correspond to morphological activity, as at many locations bank protection prohibits bar formation. Nevertheless the criteria for W/d-ratio (> 20) and shear stress gradient (> |0.02|) together give a strong tool to detect and predict morphological activity, necessary for bar formation and riparian forest development processes. Hydrological conditions differ strongly from year to year and the regeneration of riparian forest consequently occurs in waves, as recruitment and settlement depend on early season conditions and annual peak flows (Van Splunder 1998). For the surveyed reach, seedling survival was successful at the majority of the bars in 1999 and 2002, not in the years with higher summer peaks 1998, 2000 and 2001 (see figure 4.4). Higher winter peak flows were responsible for the reduction of older phases. The forest recruitment and bar formation can be erased up to the survival phase quite frequently, whereas the developing forest is gradually elevated by sedimentation (figure 4.2, table 4.2).

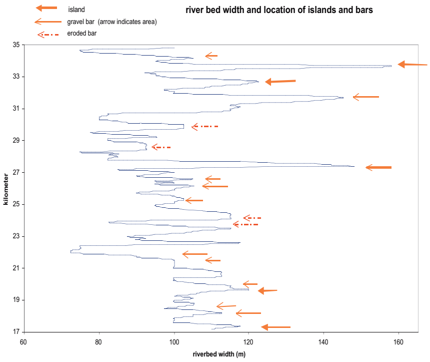

Figure 4.2 Location of bars related to the bed width of the Common Meuse summerbed. The bars that eroded in the winter peak of 1998-1999 are indicated. Numbers of the bars correspond to table 2, arrow length is an indication of bar length (ranging from 100-500 m).

Table 4.2 Bars and islands with field and map survey characteristics. The erosion-sedimentation ratio is the field measured height of erosion (-) or sedimentation (positive) for that period.

				Bed width change [m]		Erosion sedimentation ratio [cm]	
Bank type	**Location**	**Number figure 3**	**age [y]**	**'87-'97**	**'30-'97**	**'98-'99**	**'99-'00**
Islands	Smeermaas	1	20	0	17	0	0
	Hocht	3	8	5	10	30	-40
	Maaswinkel	13	15	10	10	20	5
	Meers2	14	30	0	50	0	0
Lateral bars	Borgharen	2	4	0	5	20	10
	Hocht	3	3	0	0	20	-10
	Herbricht2	5	4	0	0	20	0
	Herbricht3	5	5	0	0	-20	5
	Geulle	6	2	2	2	40	10
	Kotem1	7	8	10	10	30	0
	Kotem2	8	3	10	10	0	-10
	Maasband	15	5	10	10	-5	0
Point bars	Kotem-Hal2	11	5	0	10	-90	-20
	Itterse Weert1	4	4	0	0	10	0
	Itterse Weert2	4	5	0	0	30	0
	Herbricht1	5	5	0	0	40	-10
	Kotem-Hal1	10	8	-10	0	-20	-10
	Meers1	12	7	10	10	30	0
	Elsloo	9	5	50	50	30	0

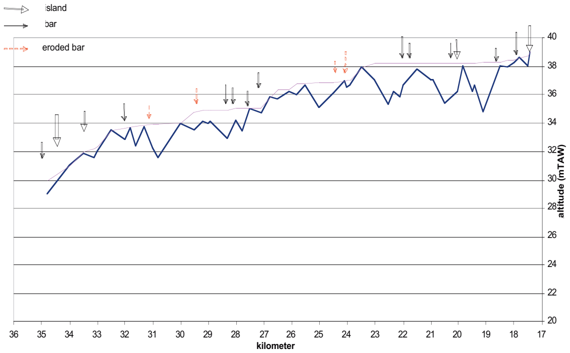

Figure 4.3 Longitudinal profile of summer bed and low flow (minimal discharge of 10m3/s) and the location of bars and islands. Length of the arrow is an indication of the bar length (between 100-500 m).

Table 4.3 Spreading of the temporal sequences over the bar types in the survey (number of bars with sequence present).

		seedlings	establishing	thicket (survival)	woodland
Point bar (7)	1998	7	2	1	0
	1999	5	1	0	0
	2000	2	1	0	0
	2001	2	2	1	0
	2002	4	2	1	0
Lateral bar/ island (12)	1998	12	9	6	2
	1999	9	7	5	3
	2000	3	7	5	3
	2001	2	7	7	3
	2002	5	7	7	3

Important observations are the small summer peaks of 1998, 2000 and 2001 which disrupted the longer low flow period for germination on most of the bars, resulting in less seedling sequences in table 3 (numbers for 1998 were collected before September peak flow). The high winter peaks for the surveyed period resulted in a strong reduction of temporal sequences starting from a rich situation in 1998 after a few years with less pronounced winter peaks.

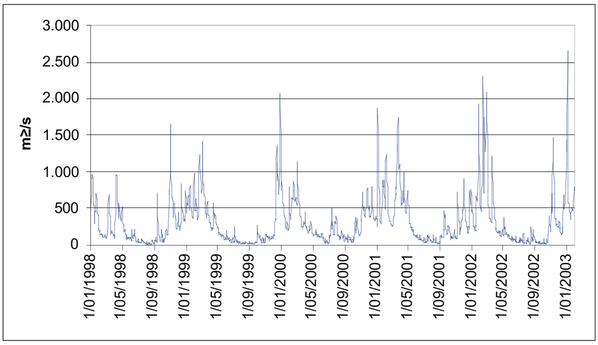

Figure 4.4 Average daily discharge values for the Common Meuse over the survey period.

The critical boundary conditions for the germination phase were derived from the observation of summer peak effect on young seedling growth, allowing the identification of the critical shear stress for seedlings. A 350 m^3/s peak washed away all seedlings on the bars below the z100-line, the line corresponding with the 100 m^3/s discharge level. The mean values of shear stress tz at the critical discharge levels over the surveyed lateral and point bars were derived from the model, and retained as critical shear stress for the first temporal sequence (table 4.4). The calibration of the stand conditions under these hydraulic stresses, gives by recalculation of q values between 0.025-0.054 stating the boundary condition for bedload movement (table 4.1). This gives a validation of the model assumptions and shows the mobilisation of the substrate and the resulting derouting/abrasion as the critical parameter in the forest development.

Table 4.4 Critical shear stress ranges for the forest development phases.

Phase	**Shear stress range [N/m^2]**		**Measured at discharge [m^3/s]**	**Recurrence of this discharge in 10 year period**	**Measured at elevation**
Germination	0.3 - 4.5	point bar			
	0.3 - 6	lateral bar	350	18.3	z100
Establishing	9 - 11.5	point bar			
	11.5 - 13	lateral bar	800	20.6	z250-350
Survival	13 - 17	point bar			
	13 - 22	lateral bar	1500	5	z250-350
Riparian forest	< 30	point bar			
	< 33	lateral bar	3000	0.2	z250-800
Germination floodplain	0.3 – 0.76	flood channel			
	0.76 – 2	levees	1500	5	z800
Settlement floodplain	2 – 4.5	flood channel			
	4.5 – 11.5	levees	2000	1	z800
Floodplain forest	< 10	flood channel			
	< 13	levees	3000	0.2	z800-1500

For the further temporal sequences, the critical water levels and shear stresses were derived from the observation of abrasion of shrubs and forests at certain discharges, by calculating the critical shear stresses (lower and higher boundary conditions and mean values) at the specific locations. These critical boundaries result in the definition of ranges for the spatio-temporal sequences (table 4.4).

Future germination and growth

The hydraulic modelling gives a valuable tool in the prediction of riparian forest development, with the determination of morphologically active zones and spatio-temporal sequences of development.

The riverbed zones with high shear stress gradients do not alter/change drastically in the restoration project from the present situation, as there will be no measures in the gravel bed. With the bank lowering measures, a few peaks become a little lower and a few are more pronounced. The W/d-ratio criterion is reached in 80% of the stretch after restoration, so for the future development, the shear stress gradient is more discriminating for the possibilities of bar formation. Figure 4.7 shows the critical shear stress ranges for riparian forest development at a two year recurrent peak flow in the future situation after restoration measures, with delineation of the morphologically active zones. In Figure 9 the result of the modelling of forest development sequences is shown for the future situation.

Discussion

Many authors point out critical conditions of hydro regime and reversible processes and patterns for riparian forest development (Amoros et al. 1987, Auble et al. 1994, Girel et al. 2001, Hughes et al. 2001). The integration of hydromorphic and biotic sequences for modelling and prediction of forest restoration in the river system was yet never really achieved.

The hydromorphic regime was determined as driving force for the allocation of the forest development stages. Hydraulic stress in the germination phase was detected in the delineation of bedload movement. For the establishing phase, mortality was linked with the execution of excessive forces on the trees, resulting in abrasion. The hydrograph of the research period (figure 4.4) explains this criterion. Flood duration of individual peaks never exceeds critical periods of 2 weeks, nor does annual flood duration attain critical levels of >100 days as critical range for softwoods of Salix and Populus. Therefore the morphodynamics act as sole criterion in riparian forest development for this river stretch. This observation contrasts to other river surveys where flood duration was attributed equal explanatory value as morphodynamics (Naiman et al. 1997, Van Splunder 1998, Friedman & Auble 1999).

For an adequate prediction of forest development for flow resistance matter, the distinction of spatio-temporal sequences in the modelling is primordial. Especially the distinction of a geomorphic and biotic component in the development is an essential step in the elaborated method. The better allocation of forest development, improves the quality of flow resistance modelling. The with this approach obtained outcome showed a significant water level decrease (average of 9 cm over the whole reach) at normative discharge, in comparison to the generally used modelling approach with randomly generated forest patches. The discussion on forest development and flow resistance came to a better consent with this approved model application.

From the presented analysis we can derive some guiding principles for restoration approaches. The geomorphic component needs a management strategy at river reach scale allowing lateral dynamics of free eroding banks and shifts in channels, providing for sufficient sediment supply and morphological activity in the river bed. For the biotic component, the provision of natural flow conditions, with necessary dynamics to create and control reforestation prevails. At the reach scale, the provision of space and freedom for the river is crucial to maintain and create the spatio-temporal sequences in a viable way. Especially a detailed target setting at the site level risks endangering the goals of riparian forest restoration. For a sustainable forest development, all the spatio-temporal sequences need to be present in a viable way to provide for a sufficient seed rain, gene pool and habitat for specialist species at reach level. Recent investigations showed the aspects of gene flow and connectivity as crucial aspects in the restoration of riparian forests of Populus nigra, with emphasis on the problematic situation of fragmentation and isolated stands in the lowland reaches (Imbert & Lefèvre 2003). Black poplar was identified as recruitment-limited rather than dispersal-limited in the lower river reaches where pioneer habitats are limited. The problem of fragmentation was documented for the Common Meuse river forest (Van Looy et al. 2003), as were the genetic problems for Populus nigra, where preservation of present stands and even reintroduction proved necessary to restore the species gene pool (Vanden Broeck et al. 2004). For this reintroduction a variety of locations was selected, well connected to the river and as close as possible to the locations indicated as potential sites for riparian forest development in this modeling. So, conclusions from the presented approach can be drawn towards a dynamic approach of restoration efforts.

Acknowledgment

This study was funded by the Flemish government nature development research programme VLINA (VLINA0012).

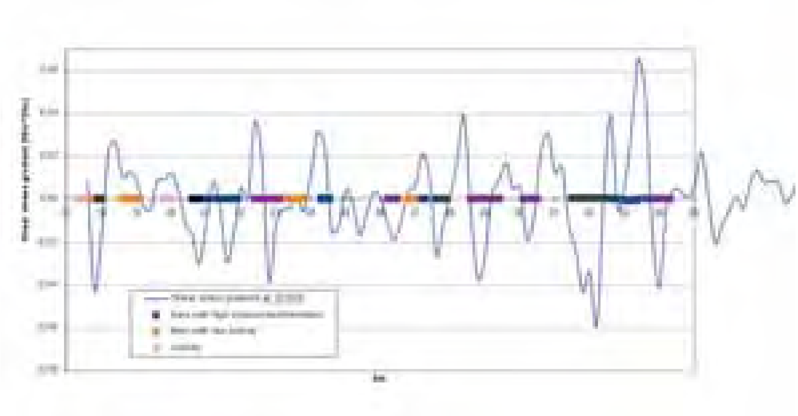

Figure 4.5 Shear stress gradient at bankfull discharge (1500 m^3/s).

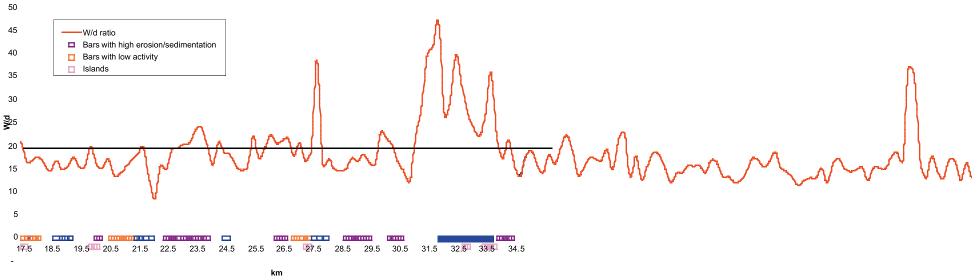

Figure 4.6 Width/depth ratio over the river stretch with the location of the bars and islands.

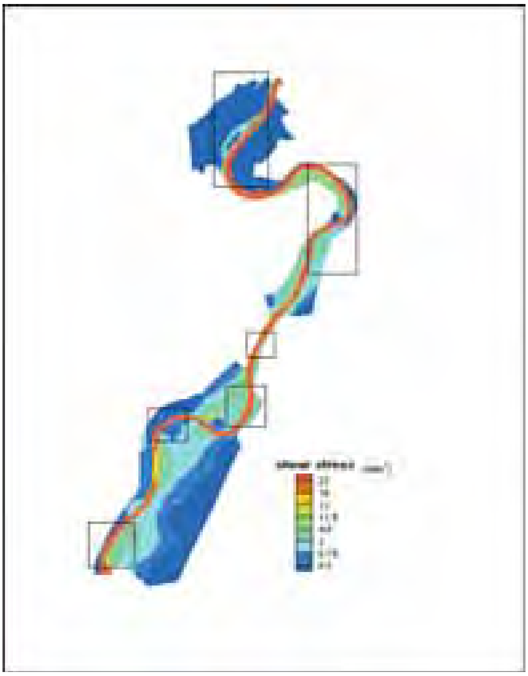

Figure 4.7 Shear stresses at peak discharges (2000 m^3/s) for the future situation after rehabilitation measures of river stretch km17.4-34.8.The boxes delineate the morphological active zones of the riverbed as determined in figure 6-7.

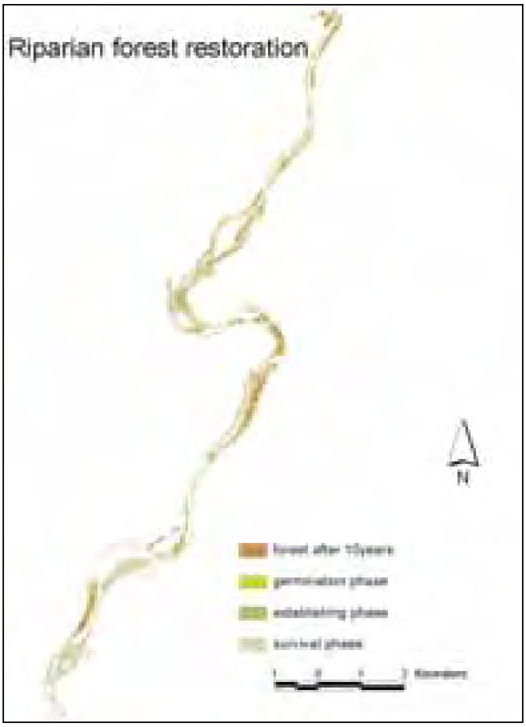

Figure 4.8 Model prediction of forest development after restoration measures for the study area. The temporal sequences are presented, with the summary 10 year forest as overlap of the three sequences.