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TAGLIAMENTO River

Photo by: K. Tockner

DRAVA River

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Tagliamento River

Drava River

TAGLIAMENTO RIVER

TOPIC 2: General overview and landscape prospective

By Klement Tockner

Environmental setting

The 'Fiume Tagliamento' is the dominant river system of the Friuli region in northeastern Italy. From north to south (a linear distance of < 100 km), the Tagliamento traverses four major regions: (i) the Julian and Carnian Alps, (ii) prealps, (iii) the upper and lower Friulian plain, and (iv) the coast. This steep environmental gradient from north to south is associated with climatic differences; e.g., annual precipitation ranges from 3,100 to 1000 mm per year and mean annual temperature from 5 to 14 °C. The southern fringe of the Carnian and Julian Alps frequently receives very intensive rainstorms, resulting in severe erosion, especially in the alpine area. Torrential rainfalls, steep slopes, and extensive sediment sources generate high floods and massive sediment transport rates. The frequent reworking of the valley floor by floods constrains human habitation within the river corridor.

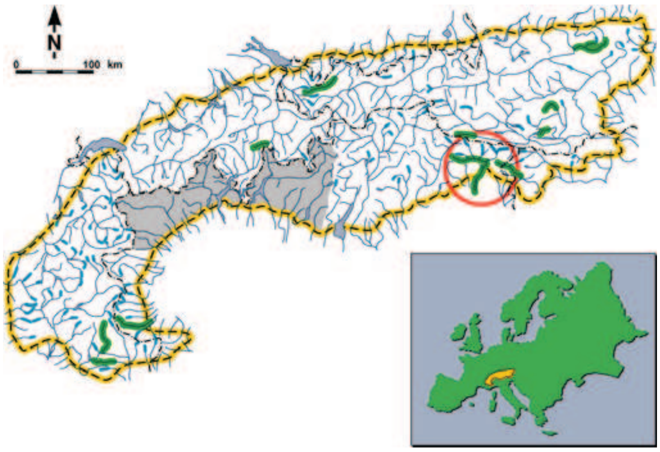
Geology and glacial history

The alpine area of Friuli mainly consists of limestone, with a spatial sequence of Silurian, Devonian, Triassic, Jurassic and Cretaceous formations north to south (Astori, 1993; Martinis, 1993). A precise delineation of the watershed of the Tagliamento is almost impossible due to the high complexity of groundwater drainage through the limestone karst. Limestone is occasionally intermixed with layers of gypsum that lead to high sulphate concentrations in the Tagliamento (Arscott et al., 2000). The catchment is tectonically active, continuously developing faults and overthrusts. Many tributary streams, like the Fella, have sharp bends following the direction of these faults (Fig. 2).

The prealpine mountains mainly consist of limestone (Jurassic-Cenozoic) and Flysch s.s. (calcareous flysch, molasse). The Friulian plain consists primarily of Tertiary and Quaternary sediments. The upper plain consists of a vast alluvial aquifer several hundred meters deep, and is composed of fluvioglacial sediments of high permeability (Ward et al., 1999b). To the south the aquifer sediments are intermixed with layers of marine deposits (sand and clay), which reduce permeability and result in upwelling of groundwater ('Linea delle risorgive', see: Fig. 1).

The lowest glaciers of the Eastern Alps are located in the Julian Alps on the northern slopes of Mt. Canin (2587 m a.s.l.), with the termini of the glaciers at altitudes < 2000 m a.s.l. Within the last decades, however, the glaciated area has decreased from about 10 km^2 to 3 km^2 (Mosetti, 1983). Harsh environmental conditions also are reflected by the position of the tree line at about 1500 m a.s.l., 300-500 m lower than in the central Alps (Gentilli, 1971).

Map: Near-natural river segments (green and blue segments) in the Alps (after CIPRA 1994). Tagliamento encircled.



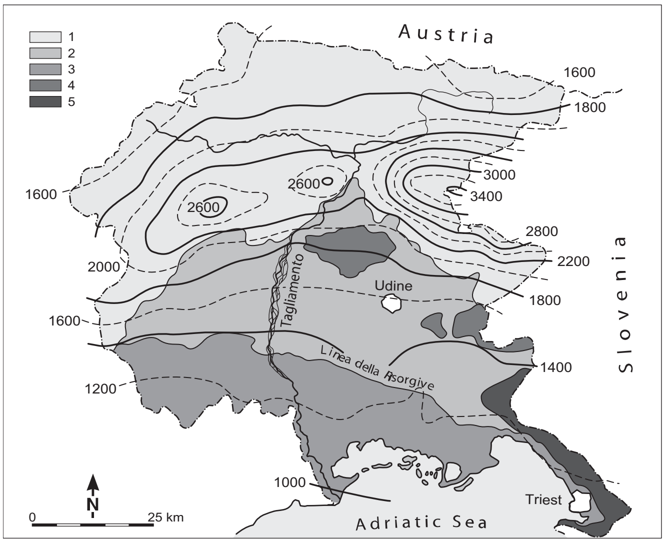


Figure: Climatic setting of the Tagliamento catchment within the region of Friuli-Venezia Giulia, Italy. Average annual precipitation (1951-1970) is given by isohyets in mm. 1: Alps and prealps; 2: Upper Friulian plain; 3: Glacial moraines; 4: Lower Friulian plain; 5: Karstic area (Based on Regione Autonoma Friuli-Venezia Giulia, 1982).

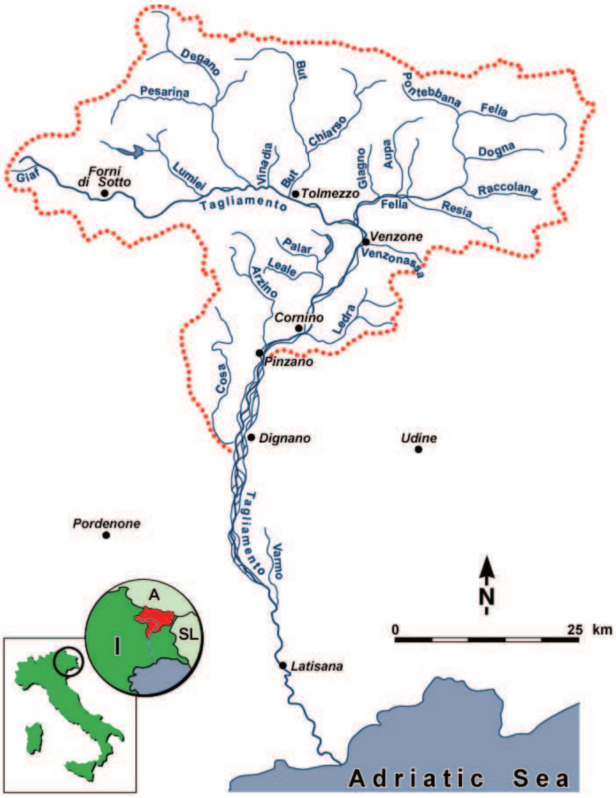


Figure: Catchment map of the Tagliamento, with major tributaries and towns. Inset shows the location of the river in Italy (I), near the borders of Austria (A) and Slovenia (SL) (modified after Ward et al., 1999b).

Table 1: The river corridor of the Tagliamento: Summary statistics (modified after Ward et al., 1999a,b; Gurnell et al., 2000a).

Active corridor area	61.7 km^2
Gravel area (excl. Water)	38.7 km^2
Island area	10.6 km^2
Water area	12.4 km^2
Riparian forest area[1]	32.0 km^2
Riparian corridor area[2]	≥ 150 km^2
Number of gravel bars	950
Number of islands[3]	652
Length of riparian ecotone[4]	670 km
Length of shoreline	940 km

1: Marginal band of riparian woodland which is periodically reworked by lateral displacement of the active zone (Gurnell et al., 2000a).
2: The riparian corridor includes the active zone, the riparian forest area, and the topographically low area on either side of the river (to a maximum of 2 km).
3: Vegetated islands of > 0.01 ha.
4: Including the perimeter of islands and the riparian zone along the lateral flood plain (Ward et al., 1999b).

Table 2: Tagliamento catchment: Total number and length (km) of stream segments, and proportion (%) of temporary sections calculated for each stream order. n.d. = not determined (after Döring et al. 2007).

Stream order	**Number of stream segments**	**Average stream segment length (km)**	**Total stream segment length (km)**	**Relative proportion (%) that falls dry**
1	1663	0.8	1405	63.2
2	416	1.5	631	53.4
3	90	3.6	320	63.0
4	21	7.4	155	n.d
5	6	14.1	85	32.0
6	2	8.0	16	0.0
7	1	114.0	114	20.0
Total	**2199**		**2726**	**54.0%**

Catchment description

The Tagliamento is a 7th order river (46° N, 12°30’ E) that flows unimpeded by high dams for 172 km to the Adriatic Sea. The Tagliamento drains an approximately 2580 km^2 area. It is a mountainous river with more than 70% of the catchment located in the Alpine area. The highest peak in the catchment is Mt. Coglians (2781 m a.s.l.). The mean altitude of the catchment is 987 m a.s.l. Areas above 1000 m a.s.l. (ca. 50% of the Tagliamento catchment), are practically uninhabited (Steinicke, 1991).

The total stream network length for the entire catchment is 2726 km, corresponding to an average stream density of 0.85 km km^{-2} (Table 1). First and second order stream segments account for 75% of total length and 95% of all stream segments, respectively. Most of these low order segments are intermittent and dry at the surface during low flow periods in winter and summer (Hormann, 1964).

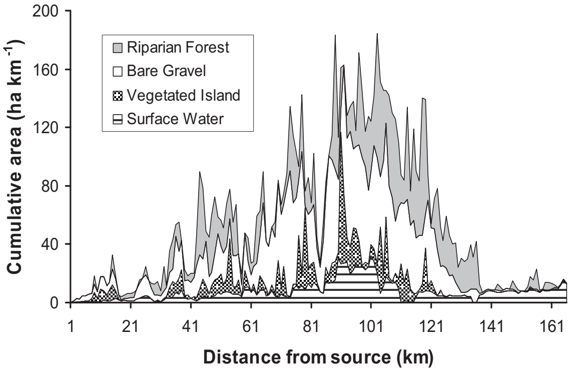


Figure: Distribution of four major landscape elements along the river corridor (based on the analysis of information derived from 1:10000 scale maps, 1984-1985)(Gurnell et al., 2000a).

Hydrology

The Tagliamento is characterised by a flashy pluvio-nival flow regime, with an average discharge of ca. 90 m^3 s^{-1} at Pioverno. The 2, 5 and 10 year floods are estimated to be 1100, 1600 and 2150 m^3 s^{-1} (Maione and Machne, 1982). Mosetti (1983) calculated an average total annual discharge (1929-1939) of 3.83 km^3 at Pioverno (range: 2.64-5.18 km^3, catchment area: 1900 km^2), and 4.72 km^3 at Pinzano (2300 km^2). As described above, the Tagliamento is influenced by both Alpine and Mediterranean snowmelt and precipitation regimes. As a result, it exhibits a bimodal flow pattern with peaks in spring and autumn.

In unconfined floodplain sections, maximum annual amplitudes of surface water levels are about 2 m. Even small fluctuations in discharge, however, lead to marked areal expansions and contractions of surface waters, a characteristic of many alluvial rivers (Tockner et al., 2000; Van der Nat et al. 2002). In the artificially-constrained section downstream of Latisana, however, water level fluctuations of ≥7 m occur.

The Tagliamento River transports large amounts of sediments and deposits them after leaving the Alps, forming an unconfined alluvial corridor. Downstream of the bedrock constrained knickpoint at San Pietro (section I) the river loses surface water into the alluvial aquifer which is dominated by highly permeable gravel. The aquifer extends 5 km to the West and 20 km to the East (Ward *et al.* 1999). Under low flow conditions, a portion of the river in this segment lacks surface flow (maximum dry distance: 23 km). This is a natural feature of Mediterranean rivers which has been exacerbated by water abstraction. To the south, the alluvial sediments downstream of river-km 114, are intermixed with layers of marine deposits (linea delle risorgive), acting as a aquiclude which results in massive upwelling of Tagliamento River water (study section II). Only a small fraction of this water returns to the Tagliamento River itself, since it also feeds other rivers. For example, the Fiume Stella located to the east of the Tagliamento River receives a major portion of its discharge from Tagliamento River water draining through the alluvial aquifer (Ward *et al.,* 1999). Downstream of the bridge at Varmo the braiding river transforms into a meandering river (downstream end of section II).

Human impacts

Although the Tagliamento is considered to be the most natural river system in the Alps, it is not without human impacts. Major human influences on the main river corridor are (i) water abstraction in the upper Tagliamento valley, (ii) organic pollution, and (iii) gravel exploitation. Many small tributaries contain drop structures to inhibit erosion and channel incision (Stefanini, 1982). Water is abstracted for hydropower generation in the upper area, altering the flow regimes of the Degano, the Lumiei, and sections of the main stem Tagliamento (Table 2). Downstream of the weir at Caprizzi (for location see Fig. 2), the Tagliamento frequently loses surface flow over a distance of 25 km. Additionally, a maximum of 23 m^3 s^{-1} is abstracted for irrigation purposes at Ospedaletto south of Pioverno (Canale Ledra). Nevertheless, large tributaries like the Fella, But and Arzino are characterised by a natural flow regime. In addition, the flood dynamics of the main stem of the Tagliamento is largely unaffected by water abstraction. The Tagliamento suffers from organic pollution between Tolmezzo and its confluence with the Fella, and in the chanalised section downstream of Latisana; however, water quality has improved considerably in recent years (Provincia di Udine, 1997). There are lateral dams along some sections (e.g. between Pioverno and Pinzano; and downstream of Dignano). However, they are far outside the active corridor and primarily used to protect agricultural land.

The Corridor

The river corridor, which is morphologically intact along virtually its entire length, is the feature that makes the Tagliamento unique in the Alps. The corridor has escaped massive river engineering and floodplain development schemes, thus retaining the functional characteristics of a near-pristine system: strong longitudinal, lateral and vertical connectivity, high habitat heterogeneity, and a characteristic sequence of geomorphic types.

Geomorphological Diversity

The riparian corridor consists of five major landscape elements: surface water, bare gravel, vegetated islands, riparian forest and topographical low areas that are unforested. The first three landscape elements form the active corridor with a total area of 61.7 km^2. The river retains an intact riparian margin, with a total area of 32 km^2, throughout almost its entire length. Considerable parts of topographically low areas, adjacent to the meandering and regulated sections in particular, are under other land uses, primarily agriculture. These lowland areas tend to be situated on the more stable terraces along the edges of the corridor, although they are partly inundated during major floods. In summary, the riparian corridor of the Tagliamento is about 150 km^2 (excluding tributary corridors), comparable in size to some of Europe's national parks such as the Alluvial Zone National Park, Austria (93 km^2), the Swiss National Park (169 km^2), and the National Park `Neusiedlersee`, Austria, (200 km^2).

Flow and flood pulses

Flooding represents the major physical disturbance along river corridors (flood pulses *sensu* Junk et al., 1989). Rivers also experience frequent but smaller water level fluctuations ("flow pulses" *sensu* Tockner et al., 2000) that occur well below bankfull discharge. Although not responsible for rapid morphological restructuring, these flow pulses are important for creating and maintaining habitat heterogeneity and for ecosystem processes (Benke et al., 2000; Arscott et al., 2002; Van der Nat et al., 2002).

Along the Tagliamento corridor, aquatic habitat change caused by flooding was investigated in five different reaches, ranging from near the headwaters to near the mouth (Arscott et al., 2002). The highest degree (62%) of aquatic habitat turnover occured in a braided headwater section. The degree of habitat turnover decreased with decreasing elevation to ~20% in the meandering reach close to the mouth. In contrast to turnover rate, braiding, sinuosity, and aquatic habitat composition changed little in response to flooding. Floods changed the configuration of floodplain habitats, whereas habitat composition and heterogeneity remained relatively stable. These results support the applicability of the shifting mosaic steady-state model to riverine flood plains (Bormann and Likens, 1979). These results also highlight the importance of floods in maintaining habitat diversity in dynamic flood plains.

We investigated inundation processes in a bar- and island-braided flood plain (Van der Nat et al., 2002). Despite complex inundation patterns, a linear relation between water level and the arcsine square root of inundated area existed in both reaches. A second-order polynomial relation existed between water level and shoreline length. Using these relations as simple predictive models, we converted several years of water level data into predictions for degree of inundation and shoreline length. Simulated degree of inundation strongly resembled the hydrograph. Complete inundation of the active flood plain occured 3-4 times per year; however, the degree of inundation was highly dynamic during most of the year. Simulated shoreline length averaged 171 $m\ ha^{-1}$ (12.8 $km\ km^{-1}$) with a maximum of 197 $m\ ha^{-1}$ (14.7 $km\ km^{-1}$). During major flood events, shoreline length decreased to 28 $m\ ha^{-1}$ (2.1 $km\ km^{-1}$). A braiding index and upstream surface hydrologic connectivity were positively related to water level, whereas total area of isolated waterbodies was negatively related to water level (Van der Nat et al., 2002).

Large-scale expansion-contraction dynamics

Downstream of the bedrock constrained knickpoint at San Pietro (section I) the river loses surface water into the alluvial aquifer which is dominated by highly permeable gravel (Fig. 2). The aquifer extends 5 km to the West and 20 km to the East (Ward *et al.* 1999). Under low flow conditions, a portion of the river in this segment lacks surface flow (maximum dry distance: 23km). This is a natural feature of Mediterranean rivers which has been exacerbated by water abstraction. To the south, the alluvial sediments downstream of river-km 114, are intermixed with layers of marine deposits (linea delle risorgive), acting as a aquiclude which results in massive upwelling of Tagliamento River water (study section II) (Figs. 1 and 3). Only a small fraction of this water returns to the Tagliamento River itself, since it also feeds other rivers. For example, the Fiume Stella located to the east of the Tagliamento River receives a major portion of its discharge from Tagliamento River water draining through the alluvial aquifer (Ward *et al.,* 1999). Downstream of the bridge at Varmo the braiding river transforms into a meandering river (downstream end of section II).

In the upper part (29km) of this river section (losing zone), surface flow decreased on average by 2.5 m^3s^{-1} per river km. In the lower part (12.5 km) (gaining zone), surface flow increased by 0.3 m^3s^{-1} per km. The losing zone was subject to extensive longitudinal expansion and contraction dynamics. We surveyed the longitudinal extent of the dry channels using differential GPS. During summer 2003, the river fell dry up to 23 km. Frequent irregular flow pulses caused by local weather events rapidly decreased the length of the dry channel (up to 3 km h^{-1}); the subsequent contraction was much slower (<0.5 km h^{-1}).

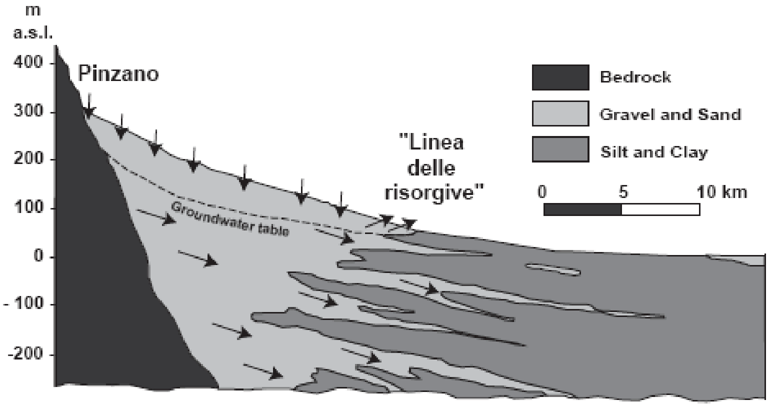


Figure: Schematic view of the main study segment between the knickpoint at Pinzano (river-km 85) and the linea delle risorgive (river-km 114). After Doering et al. (2007). In the upper part (29km) of this river section (losing zone), surface flow decreased on average by 2.5 m^3s^{-1} per river km. In the lower part (12.5 km) (gaining zone), surface flow increased by 0.3 m^3s^{-1} per km. The losing zone was subject to extensive longitudinal expansion and contraction dynamics. We surveyed the longitudinal extent of the dry channels using differential GPS. During summer 2003, the river fell dry up to 23 km. Frequent irregular flow pulses caused by local weather events rapidly decreased the length of the dry channel (up to 3 km h^{-1}); the subsequent contraction was much slower (<0.5 km h^{-1}).

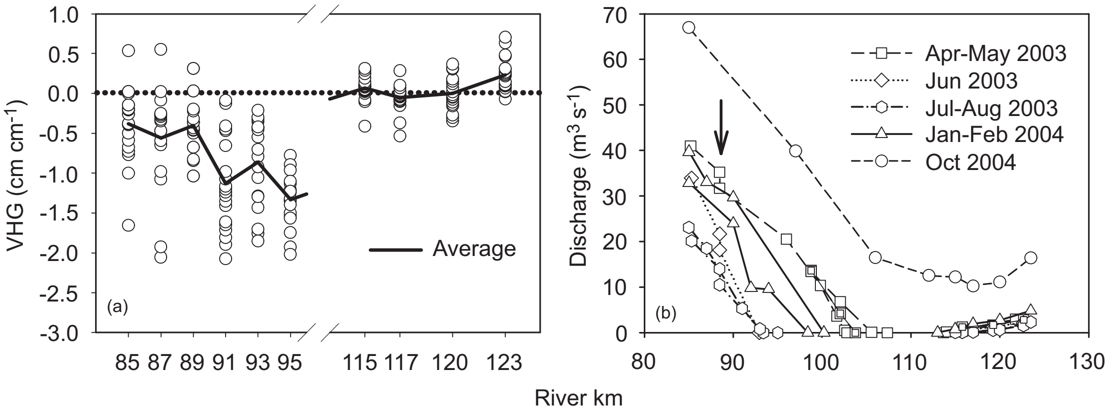


Figure: (a) Vertical Hydraulic Gradient (VHG; cm cm^{-1}) along section I (n=183) and section II (n=129) (July 2003 to April 2004). (b) Surface discharge (m^3 s^{-1}) along section I and section II (April 2003 to October 2004).

Physico-chemical characteristics

Chemical composition of surface waters reflects the geological setting of the catchment. The Tagliamento is classified as an 'alkaline river' with a pH > 7.5, a specific conductance of > 250 μS cm^{-1} and a predominace of Ca^{2+} (about 100 mg L^{-1} upstream of the confluence with the Fella River), Mg^{2+} (20 mg L^{-1}) and HCO$_3^-$ (ca. 160 mg L^{-1}). Along the river, specific conductance decreased from 2000 μS cm^{-1} in the uppermost headwaters to about 450 μS cm^{-1} in the lower reaches. High specific conductance mainly results from the weathering of evaporitic sediments (gypsum). Sulphate concentrations of up to ≥ 2000 mg L^{-1} are classified as extreme values compared to usual concentrations in perennial world rivers and streams (Meybeck, 1996). Concentrations of phosphorus and ammonium were very low along the entire river. Concentrations of nitrate (NO_3-N), however, increased from upstream to downstream with peak values of over 1.6 mg L^{-1}. Dissolved organic carbon (DOC) concentrations were relatively constant at about 1.0 mg L^{-1}. Particulate organic carbon (POC) ranged from 0.18 mg L^{-1} at low flow to 12.1 mg L^{-1} during high flow.

Tagliamento: Reference Ecosystem of European Importance

The Tagliamento River in Italy offers the rare opportunity to investigate natural processes at a scale that can be studied nowhere else in Europe. This remarkable river corridor exemplifies the ecological processes and patterns that must have characterised Alpine gravel bed rivers. The Fiume Tagliamento is clearly a river ecosystem of European importance, since it constitutes a unique resource as a model reference catchment. Therefore, the present authors have initiated a major research programme which integrates hydrology, geomorphology and ecology of the Tagliamento River corridor (Edwards et al., 1999; Gurnell et al., 2000a,b, 2001; Kollmann et al., 1999; Tockner and Ward, 1999; Arscott et al., 2000, 2001; Ward et al., 1999b, 2000). The outcome of the research programme is intended not only to advance knowledge of natural rivers, but will also provide the scientific basis for more sustainable management of functional processes. We wish to establish a hierarchical landscape perspective for riparian ecosystems as an essential basis for developing catchment-wide restoration and conservation strategies that include (i) preservation of unconstrained riparian corridors, (ii) maintenance of flow variability, and (iii) preservation of the capacity of the system to undergo change. It is already clear that the factors controlling ecosystem processes or biodiversity patterns operate across a range of spatio-temporal scales that transcend traditional river management programmes.

Specifically, three major aspects are deemed essential for understanding Alpine braided gravel bed rivers: (i) viewing river-floodplain ecosystems as hierarchical ecosystems containing nested spatial and temporal scales, (ii) linking terrestrial and aquatic ecosystems, (iii) investigating the actual processes of island dynamics. River-floodplain ecosystems are expanding, contracting, and often fragmented ecosystems (Stanley et al., 1997; Ward et al., 1999c; Malard et al., 1999; Tockner et al., 2000). These changes in size are thought to control habitat availability and environmental conditions as well as faunal/floral composition and ecological processes. The expansion and contraction cycle is a fundamental property of all floodplain ecosystems, although, it has been generally neglected by stream ecologists. We propose that the Flood Pulse Concept could be adapted to accommodate the characteristics of river-floodplain systems outside tropical climates, particularly those in the temperate zone. Furthermore, water level fluctuations well below `bankfull` may dominate ecosystem processes and the distribution of biotic communities ('flow pulse' vs. 'flood pulse'; cf. Puckridge et al., 1998; Tockner et al., 2000). The present authors are particularly interested in the dynamics of vegetated islands on the active flood plain and their role in maintaining biodiversity (Ward et al., 1999b). The fact that anthropogenic impacts have eliminated islands from many rivers makes an understanding of their role even more crucial. Islands not only provide information of recent geomorphic history and processes but island dynamics may also serve as an ecosystem-level indicator of the condition of riverine corridors (Ward et al., 2000, 2001).

However, the Tagliamento is a highly endangered ecosystem. The regional government is planning 14 km^2 large flood retention basins in the most natural section. About 30 mill m^3 of material, mainly gravel, will be excavated. These retention basins should protect urban areas along the channelized downstream section of the river against floods of up to 100-yr events. In addition, a highway following the main stem of the river and new industrial areas will severely impact the corridor. The future conservation of the Tagliamento will be a benchmark for the European Water Framework Directive (WFD). If we are not able to protect the last semi-natural rivers, the discussions on restoration projects remain useless. Therefore, scientists are working closely together with conservation agencies in order to develop a sustainable management plan for the Tagliamento River, which is called the "King of the Alpine Rivers".

TOPIC 3: River morphology and dynamics

by Nicola Surian

The Tagliamento River has a length of 178 km and a drainage basin of 2580 km^2 (Fig. 1). The river has its source at 1195 m a.s.l. near Mauria Pass, it drains from the Eastern Alps and from the Prealps, and has its mouth in the Adriatic Sea. Basin relief is 2696 m. The main tributaries of the Tagliamento River are the Fella River (drainage basin area: 706 km^2), the But Torrent (337 km^2), and the Degano Torrent (325 km^2).

The morphology of the river is quite different along its course. In the upper course, from the source to Socchieve, the Tagliamento has the typical character of a mountain stream, that is a relatively steep slope (between 0.01 and 0.1) and a narrow channel made of coarse material (gravels, cobbles and boulders). This first reach is followed by a long reach, about 90 km long, where the river has a braided morphology. This second reach, from Socchieve to S. Paolo, can be divided into two sub-reaches: an upper one, from Socchieve to Pinzano, where the river is more or less still confined by the valley sides, and a lower one, from Pinzano to S. Paolo, where the river flows in the alluvial plain with less lateral constrictions. The width of the active braided channel is from several hundred metres up to more than 1 km, except for a few narrow sections (e.g. Venzone and Pinzano), the slope is between 0.002 and 0.01, and the bed is mainly composed of gravels and cobbles. Downstream of S. Paolo the morphology of the river changes quite rapidly: within a few kilometres the river changes from braided to single-thread and becomes much narrower (channel width is 100-200 m). In this third reach, which extends down to Latisana, the channel slope decreases significantly and the channel is made of finer material (fine gravels, sand and silt). In the last reach, from Latisana to the mouth, the river has few natural characteristics: artificial levees were constructed quite close to each other and thus the morphodynamics are very much restricted.

From a morphological point of view the second and, at a minor extent, the third reach of those described above are worth of some more explanations. The 90 km long reach with braided morphology is unique in the Alps: many other rivers in this mountain region used to have a braided morphology but most of them have, at different degrees, lost their original aspect (Surian and Rinaldi, 2003). As explained in the next section, also the Tagliamento has significantly modified its aspect in the recent past, but has still preserved a clear braided morphology. Such morphology is mainly due to a high sediment production within the drainage basin and to the absence or limited lateral constrictions. The valley bottom is quite wide and even though protection structures exist (levees, groynes), both in the mountain reach (from Socchieve to Pinzano) and downstream in the alluvial plain (from Pinzano to S. Paolo), there is still enough space for river to develop a braided morphology. The configuration of the channel is very unstable since the Tagliamento, as well as others braided rivers, modifies its features (the single anabranches, bars, islands and banks) frequently and at high rates (e.g. bank retreat of some tens of metres during a single flood are not uncommon) (Fig. 2). Some research in progress focuses on such morphological variation at reach scale in relation with flows of different magnitude. Besides sediment supply, lateral mobility and flows of a certain magnitude, there is a fourth element that is needed to preserve the present braided morphology: vegetation, and specifically large woody debris. Several studies have clearly illustrated that large woody debris is a key component of this river, in particular in the formation of islands (e.g. Gurnell et al., 2000 and 2001).

The reach from S. Paolo to Latisana is also of value from a morphological point of view. Here the river is sinuous and characterized by a relatively natural dynamics, that is migration of bends and point bars. An historical analysis on the last 200 years has pointed out that banks retreat with rates of the order of 6-8 m/year and some meander cut-off have occurred. Such dynamics are also possible since levees are about 2 km far apart and there are few bank protections.

Channel changes over the last 200 years

Investigation of recent channel changes is worth to understand the present river dynamics and, eventually, to predict future morphological evolution. In fact when a river modifies significantly its average characters (width, slope, sinuosity, etc.) is commonly an evidence of instability due to natural or human causes.

The analysis carried out using historical maps, aerial photographs, cross-sections and by geomorphological surveys shows that remarkable channel changes have occurred over the last 200 years in the Tagliamento River (Surian, 2002; Surian, 2006; Surian et al., 2008). For instance, in the braided section between Pinzano and Casarsa average channel width decreased from 1970 m (in 1833) to 740 m (in 1993), that is a reduction of 62 %. Channel narrowing was not a constant process: it was less intense during the 19th century and the first half of the 20th century in comparison with the second half of the 20th century (Fig. 3). This process was likely over about 10-15 years ago, since a phase of slight widening was documented for this last period of time (an average widening of 28 m between 1993 and 2007). Also the braiding intensity, that is the number of individual anabranches in a river section, decreased significantly: from 11.0 in the early 19th century to 2.4 in 2007 (in the reach Pinzano –Dignano). Incision was associated to channel narrowing: it was of the order of 1-2 m in the braided reach, but up to 4 m in the single-thread reach (downstream of S. Paolo). Such phase of incision has been followed by a phase with the channel exhibiting equilibrium or sedimentation.

Some reaches of the Tagliamento has undergone remarkable morphological variations over the last 200 years, but, if some of those are due the natural dynamics of such a river (bar and island formation/erosion, bend migration, etc.), others are evidence of an unstable condition of this fluvial system. In particular evidence of such condition are narrowing and decrease of braiding intensity in the braided section and narrowing and incision in the sinuous section. How these morphological adjustments can be explained ? The main causes of those adjustments are the construction of levees and other protection structures and sediment mining. Most of the levees and other protection structures (e.g. groynes, walls, etc.) were carried out during the 19th century and the first half of the 20th century and had a direct effect on river morphology, in particular on channel width. Gravel mining was very intense along the Tagliamento and its main tributaries during the 1970s and the 1980s (some tens millions m^3 of gravels were extracted from channel beds), and altered significantly the sediment budget of the river.

Finally, a comparison with other Italian rivers is worth to put the Tagliamento in a wider context and to evaluate recent channel changes and present morphology. Figures 4 and 5 show how channel width and braiding index have changed in five Italian braided rivers (Tagliamento, Piave, Brenta, Trebbia and Vara) during the last 200 years. The way these two characteristics have changed is quite similar in all the five rivers, as well as in most Italian rivers (Surian and Rinaldi, 2003): both channel width and braiding index have significantly decreased, in particular during the second half of the 20th century. Two aspects may be pointed out comparing the Tagliamento with the other rivers. The first is that the narrowing that took place from the early 19th century to the 1990s was smaller in the Tagliamento (58%) than in other rivers (e.g. 69% and 85%, respectively in the Piave and Vara) (Fig. 4). The second concerns the braiding intensity: notwithstanding a remarkable decrease the Tagliamento still preserves a significant braiding intensity (3.1 in 2001), whereas in the other four rivers braiding index is equal or less than 1.5 (Fig. 5). Thus this historical perspective, shows that the Tagliamento underwent significant channel adjustments but still has a very wide multi-thread channel which represents, likely, the best example of braiding in Italy.

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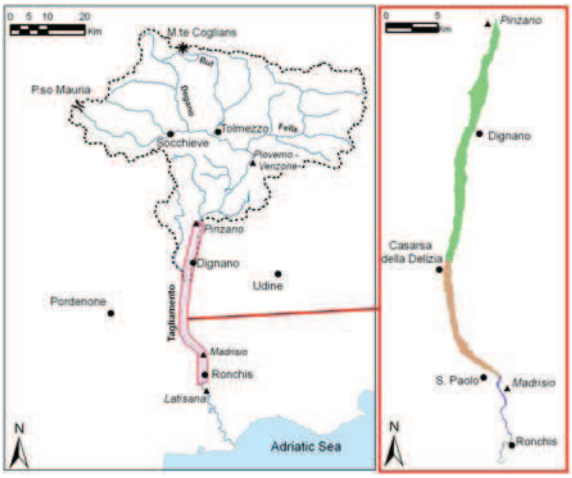


Figure 1. General setting of the study reach

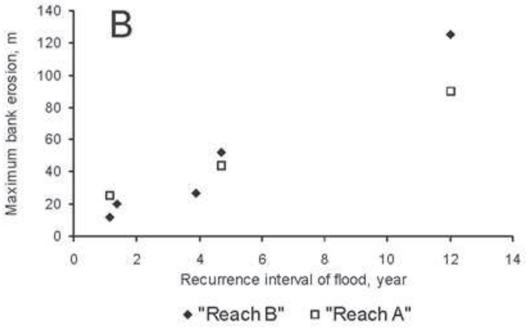


Figure 2. Relationship between the recurrence interval of the largest floods that occurred from 1997 to 2007 and the maximum bank erosion measured in a braided reach ("Reach A") and in a single-thread reach ("Reach B")

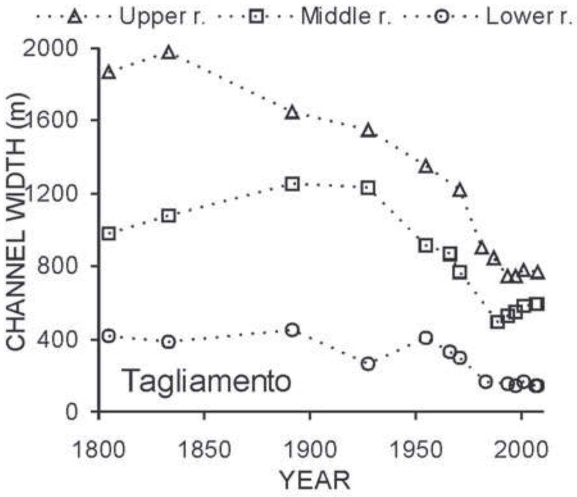


Figure 3. Historical trends of width adjustment in the Tagliamento between Pinzano and Casarsa ("upper reach"), Casarsa and S. Paolo ("middle reach"), and S. Paolo and Ronchis ("lower reach").

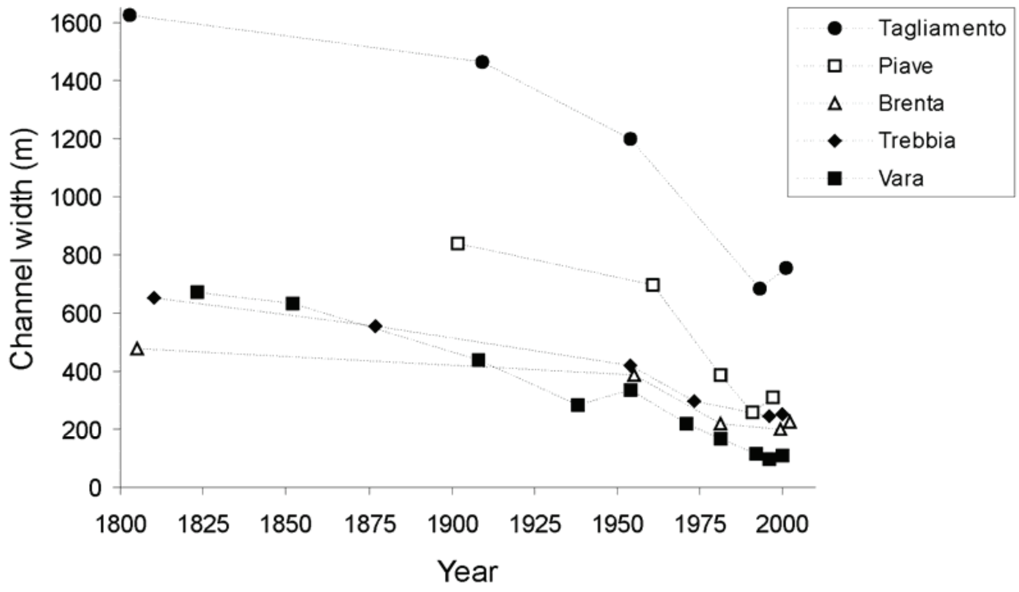


Figure 4. Changes in channel width during the last 200 years in five Italian braided rivers (from Surian and Rinaldi, 2004).

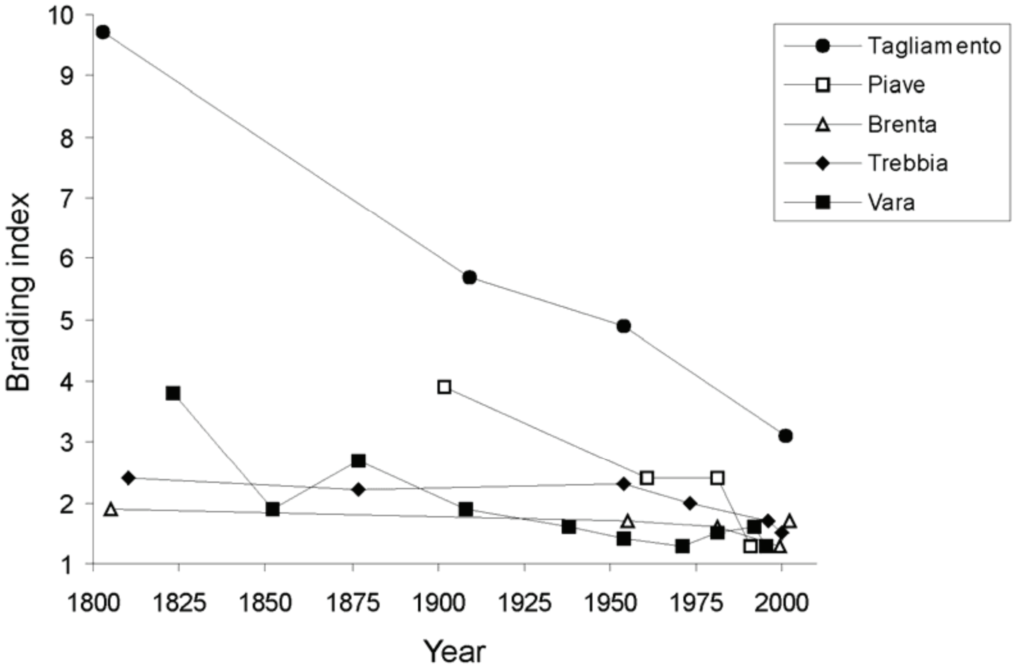


Figure 5. Changes in braiding index during the last 200 years in five Italian braided rivers (slightly modified from Surian and Rinaldi, 2004).

TOPIC 4 : Island Dynamics in a Braided River: Flagogna Reach, Fiume Tagliamento

By Angela Gurnell, Luca Zanoni, Walter Bertoldi

Wood and Island Development

There has been extensive research on the roles of downed trees in river channels of forested headwater catchments where dead wood induces hydraulic, morphologic and textural complexity. In such situations, logjams can form stable structures that control local water depths and flow velocities and provide long-term bank protection for mature forest patches within the river corridor. In larger rivers, accumulations of dead wood often form jams on bar surfaces. Vegetation can develop from seeds deposited in the protected lee of the wood jams with the potential to form wooded islands or to extend floodplains. From our observations on the Tagliamento River, we have demonstrated that regrowth from living driftwood dramatically accelerates this process of island formation, optimizing conditions for island development and persistence within river corridors characterised by rapid channel migration and frequent disturbance by floods (Fig 1).

Along the Tagliamento, rates of tree growth from living wood can be 4 times faster than growth from seeds and small vegetative propagules (Fig 2). This process allows the rapid development of wooded islands, which typically develop and are turned over by floods within 24 years (Fig 3). The availability of riparian species capable of regenerating in this way is obviously a key component of this system but appropriate local conditions are also required, especially adequate moisture levels (Fig 2). On the Tagliamento, dynamic braided reaches lacking islands occur where regrowth from driftwood is severely limited by locally arid conditions caused by deeper alluvial groundwater levels and rapid drainage from surface waters.

Wood as a driver of physical complexity

Trees transported by floods become snagged on river bars, typically with their root bole oriented upstream. The hydraulic impact of an individual tree creates a set of closely linked topographic habitats on what would otherwise be a relatively homogeneous and smooth surface of bare sediments (Fig 4). Deep hollows are often scoured at the upstream flow divergence around the tree's root bole; scouring exposes lag deposits of coarse sediment; and plumes of sands are deposited in the sheltered area bordering, and in the lee of, the tree's stem and canopy. Large wood pieces and large sediment particles become trapped, forming jams against the upstream face of the root bole, reinforcing the hydraulic impact of the tree. The jam of wood and coarse sediment around the root bole, adjacent scour hole, and sand plume may grow over a sequence of inundations. Given suitable tree species and environmental conditions, some wood pieces and the core deposited tree may sprout within the first growing season, developing root networks that reinforce the accumulating sediments and a canopy that further enhances the hydraulic impact of the tree. As a result, the area of hydraulically-induced scour, sedimentation and growing vegetation may enlarge to form a patch of vegetation or 'pioneer island' (Edwards et al., 1999); and such pioneer islands may continue to grow and coalesce to form larger, more mature islands (Gurnell. et al., 2001).

Individual deposited trees, pioneer islands and more mature islands all support the same suite of linked habitats but the relative size of these habitats increases with the size of the vegetated area (Fig 4). For example, deposited trees and pioneer islands (length typically < 30m) are often associated with small shallow scour holes supporting ephemeral ponds. Established islands (length typically > 100m) are often associated with large, deep scour holes extending below the alluvial water table and sustaining ponds for prolonged periods. These ponds provide an important addition to the range of habitats within the active tract. They are different to those associated with remnant cutoff channels, contributing thermal heterogeneity by damping diel fluctuations. Along the middle Tagliamento, scour pools associated with wood accumulations at the head of islands have a lower average daily temperature (18^{o} C) and lower diel variation (5 ^{o} C) than ponds located on open gravel (20.5 ^{o} C and 9.5 ^{o} C, respectively) (Karaus et al., 2005, Fig 4). Because scour and deposition of sediment during bar-inundation can cause rapid creation, infilling and lateral displacement of the low-lying ponds around the margins of aggrading islands, the turnover of ponds is an order of magnitude more rapid than islands (Van de Nat et al., 2003).

Whereas individual trees and islands have an important local effect on flow resistance and bar surface form, clusters of deposited trees can have an important aggregate effect across entire bars. We hypothesise that as the density of snagged trees and pioneer islands increases across a bar surface, their aggregate effect on flow resistance can change a bar surface from a fine sediment source to a fine sediment sink during flood events. An intermediate density of trees would maximize habitat diversity by causing the scouring of fine sediments along high-velocity flow pathways between zones of closely-spaced trees, vegetated patches and islands; and local sedimentation within these hydraulic dead zones.

Wood and biocomplexity

It is well established that wood jams in streams provide: flow and habitat heterogeneity; refugia for fish and invertebrates; sites of biofilm production that serve as food for grazing organisms; high organic matter retention; nursery habitat for fish; and perches for birds and other animals. Within large dynamic rivers, such as the Tagliamento the suite of habitats created around individual deposited trees and islands form complex patches of high bio-diversity within a relatively barren landscape of exposed sediment. Seed germination and sprouting wood produces a diverse vegetation cover on the aggrading sediment surfaces. In addition, the rootwad of deposited trees often contains soil, established plants and a seed bank, which increases plant species diversity and dramatically accelerates and strongly influences the initial trajectory of succession not least because some species may be 'alien' to the particular location along the river continuum (Tockner et al., 2003).

As deposited trees evolve into pioneer islands the number of plant species increases with vegetated area. On the Tagliamento, Kollmann et al. (1999) surveyed 89 recently deposited trees (< 1 year since deposition) and 22 pioneer islands (2-5 years) and showed that, on average, 17.3 (standard deviation 1.1) plant species were associated with the former and 26.2 (2.1) species with the latter. They also showed that the association between the number of plant species and feature area was sustained across the developmental sequence of island types (deposited tree - pioneer island - building island - established island).

Ponds associated with islands produce large amounts of algal biomass that may drive metabolism and provide habitat for a high proportion of juvenile fish. However, it is the physical proximity of the different habitats (scour holes, accumulations of sediment of different calibre, wood jams, vegetated patches that is of particular significance. For example, islands provide a source of organic matter for adjacent ponds and are a habitat from which the pond can be recolonised; ponds are a food source for island fauna and algae can be an important food source for grazers; and the range of linked habitats are important for amphibians. Snags and islands provide stable habitat for invertebrates and are often areas of high secondary production which may be important as drift. The islands are characterised by a high proportion of rare species of some taxa, such as ground beetles (Carabidae) that have high dispersal capacity, but the highest abundance is found along shorelines (up to 150 Ind. m^{-2} on the Tagliamento) where prey organisms, i.e. emerging insects and aquatic drift, are concentrated. Concerning amphibians, in one 2 km^2 reach of the Tagliamento including 82 waterbodies within the active zone, amphibian richness within a given habitat was significantly related to distance from islands (Tockner et al., 2005).

At a large scale, one simple index that appears to be helpful in demonstrating the impact of islands and channel complexity is shoreline length, which has been positively correlated with both the abundance and diversity of animals. Table 1 provides comparative data for two adjacent reaches of the Tagliamento River (a bar-braided and adjacent island-braided reach whose cross sections are shown in Figures 8 i and ii) and provides indices of their overall physical complexity and richness, and diversity of animal species. It is also important to realise that any particular bar will not sustain the same position along the spectrum described above indefinitely. In particular, a bar surface that has been the subject of heavy accumulation of fine sediment and vegetation growth can be reset to a lower cover of vegetation and fine sediment during large erosive floods. In natural settings, rivers have space to move, so that at the landscape scale different zones of the river corridor can support different densities of snagged trees, vegetated patches and islands. The spatial distribution of both individual features and zones of features of different age, profile and density are highly dynamic. Dynamic zones can be present within and between reaches and are subject to major contrasts in habitat turnover rates that promote significant variations in biodiversity. For example, along the middle Tagliamento, aquatic habitat change caused by individual floods was observed to be 35% in the island-braided compared to 56% in the bar-braided reach described in Table 1, illustrating that woody vegetation slowed turnover in these habitats, whereas habitat composition remained relatively stable (Arscott et al., 2002).

Management implications

Our observations on the Tagliamento River demonstrate the important role played by the transport and deposition of downed riparian trees, and especially species that can resprout, in enhancing biocomplexity within valley corridors along large, multi-thread gravel-bed rivers. They create biocomplexity from the scale of the individual tree to the entire river corridor. Islands and their associated ponds are a dominant habitat couplet within the otherwise bare expanse of gravels; the range of meso-habitats associated with this primary couplet (e.g. log piles, sand-drapes, algal mats, and patches in different stages of succession) contribute to the high physical complexity of island-dominated reaches. The large size, braided pattern, relatively unmanaged riparian woodland and large wood load of the Tagliamento River may be unique within Europe and we have proposed that the future conservation of the Tagliamento should provide a benchmark for the European Water Framework Directive (Tockner et al., 2003). However, we also believe that our observations are transferable to other multi-thread and meandering systems and are applicable to restoring reaches of larger rivers. We contend that island-braiding, although rare today, would have been a common style of river channel along large, gravel-bed rivers before the period of river engineering and flow regulation for water supply, flood control, hydro-electric power production and navigation. The loss of island-braided reaches is not only related to increased intensity of river exploitation and management over the past 200 years (Surian and Rinaldi, 2003, 2004), it is likely to have been part of a longer, slower change in large river dynamics whereby island complexes disappear from sections starved of wood (Zanoni et al., 2008). Wood-cored islands of the type described in this paper are dynamic structures that can only exist where there is space for habitat turnover and a supply of downed trees of species capable of regrowth, as well as suitable environmental conditions for regrowth (Gurnell and Petts, 2006). In river restoration, a relaxation in the intensity of river margin management could provide the space to regenerate riparian woodland and a sustainable supply of large wood to yield significant enhancement in the biocomplexity of any large-river system. Island development through incorporation of trees and wood, would have a major impact in enhancing habitat and biodiversity at both local and reach scales, especially where the tree species concerned are capable of sprouting from driftwood.

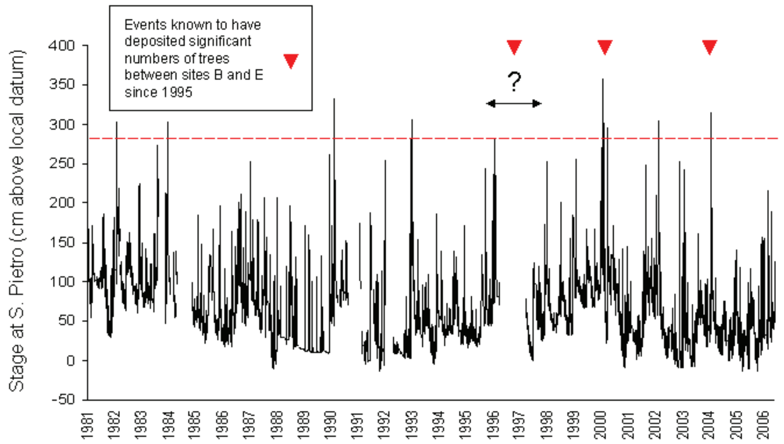


Figure 1: Variations in river stage at San Pietro (close to the Pinzano gorge)

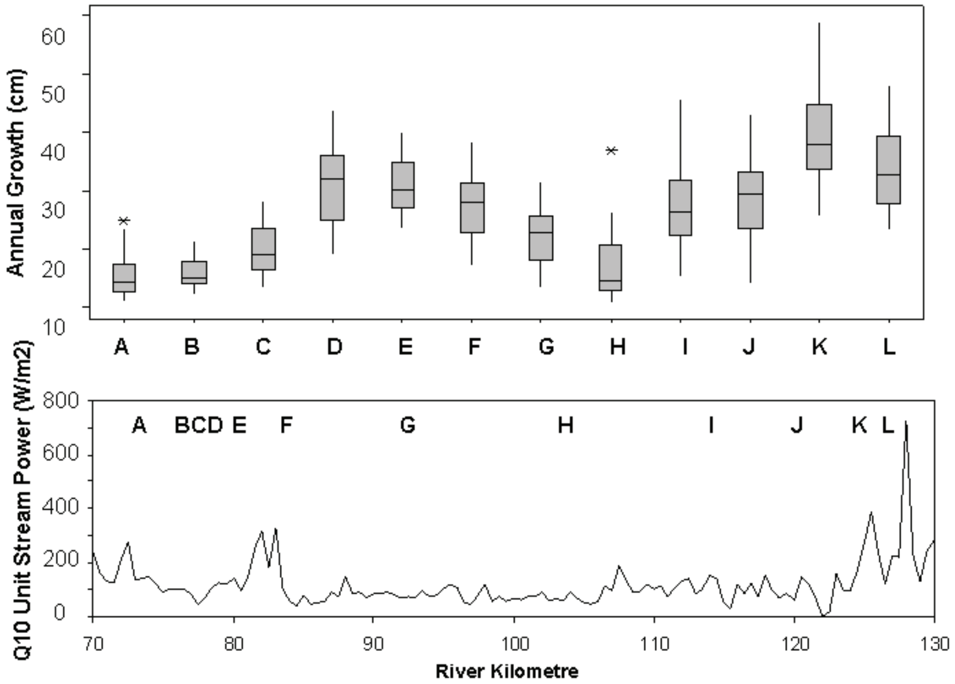


Figure 2: Annual tree growth and unit stream power, Cornino - Mussons

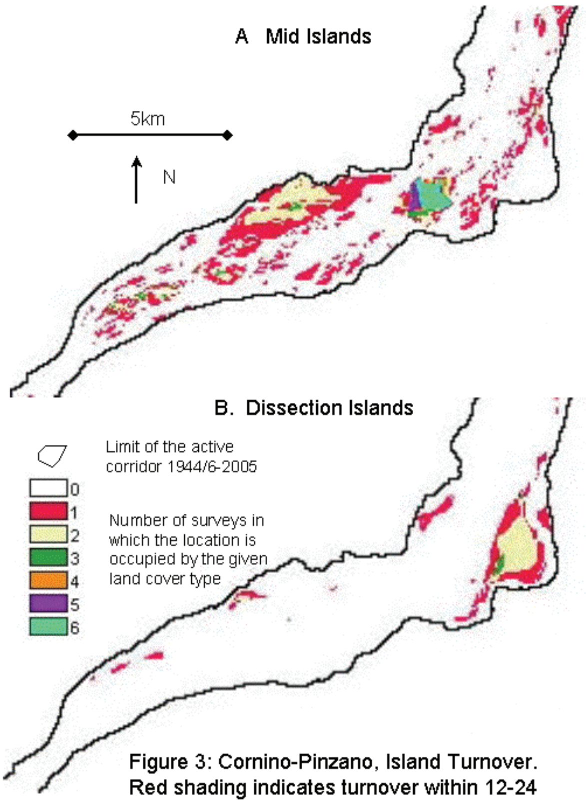


Figure 3: Cornino-Pinzano, Island Turnover. Red shading indicates turnover within 12-24 years.

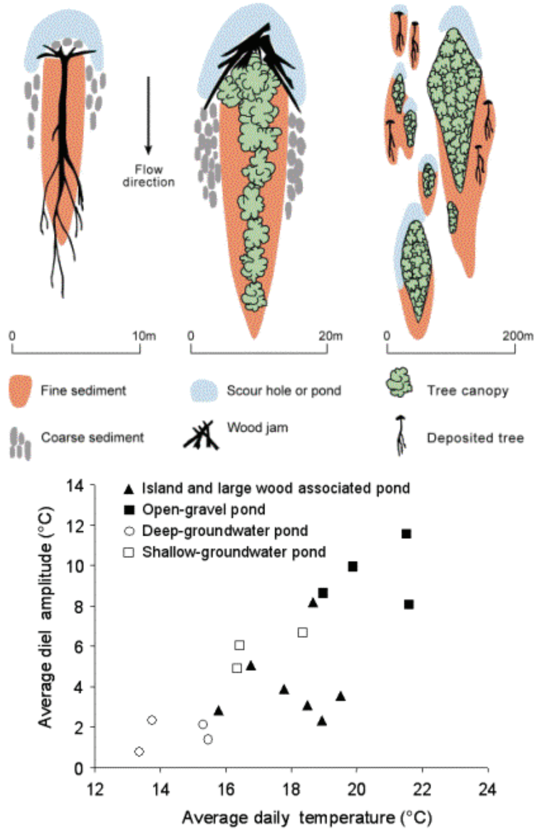


Figure 4: Wood and Physical Complexity

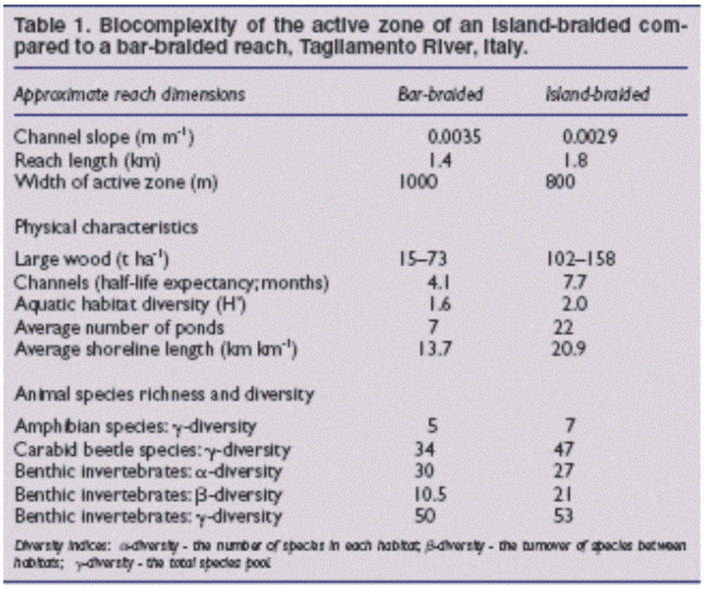


Table 1. Biocomplexity of the active zone of an island-braided compared to a bar-braided reach, Tagliamento River, Italy.

Approximate reach dimensions	*Bar-braided*	*Island-braided*
Channel slope (m m^{-1})	0.0035	0.0029
Reach length (km)	1.4	1.8
Width of active zone (m)	1000	800
Physical characteristics		
Large wood (t ha^{-1})	15–73	102–158
Channels (half-life expectancy; months)	4.1	7.7
Aquatic habitat diversity (H')	1.6	2.0
Average number of ponds	7	22
Average shoreline length (km km^{-1})	13.7	20.9
Animal species richness and diversity		
Amphibian species: γ-diversity	5	7
Carabid beetle species: γ-diversity	34	47
Benthic invertebrates: α-diversity	30	27
Benthic invertebrates: β-diversity	10.5	21
Benthic invertebrates: γ-diversity	50	53

Diversity indices: α-diversity - the number of species in each habitat; β-diversity - the turnover of species between habitats; γ-diversity - the total species pool

DRAVA RIVER

TOPIC 1: fish migration facility – power plant Villach

By Gerald Kerschbaumer

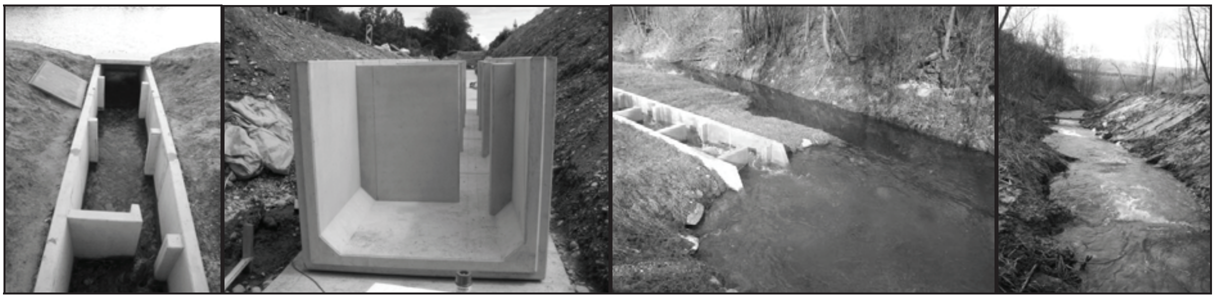
The fish pass at the power plant in Villach addresses the recreation of length continuum for migration possibility of several fish species. The fish pass is a combination of a vertical slot pass and a nature like bypass channel, including an innovative attraction flow facility. The effectiveness is controlled by means of an intensive monitoring.

Characterisation of the fish pass

- Vertical Slot fishway constructed by pre-fabricated parts:
  - 143 m length
  - 47 pools and 7 resting pools
  - 1.5 m width
  - mean discharge: 275 l/s (minimum 200 l/s)
- natural bypass channel
  - 300 m length
  - constructed within a pre-existing brook
  - additional 50 l/s from the brook
- additional attraction flow
  - siphoning system (100 l/s are taken out from above the weir)
  - water jets create an additional attraction flow (1.3 m³/s) due to the Venturi principle
  - bypass channel entrance 150 m below the weir

fish pass channel entrance

additional attraction flow by a combination of a siphoning system and Venturi-injectors

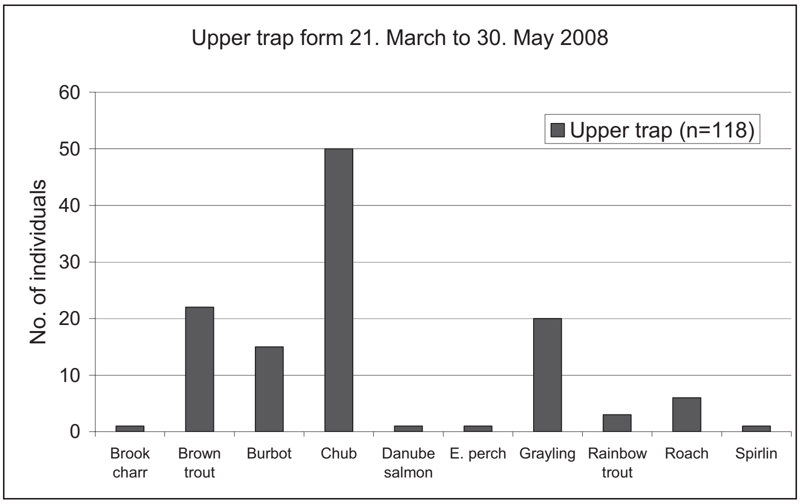


Vertical slot fishpass and natural bypass channel section.

Monitoring the effectiveness

To assess the overall functionality of the construction several monitoring methods are applied:

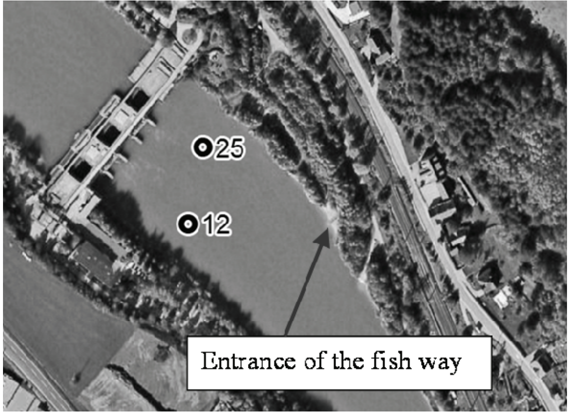
- Traps at the upper and lower end of the fish ladder
- telemetry
- marking experiments
- electro fishing



fish catches at the upper trap between march and may 2008

colour marking

fish catches at the upper trap between march and may 2008



Positions of two nase approaching the weir as documented by radio telemetry.

TOPIC 2: River restoration project - Kleblach-Lind

By Helmut Habersack

High floods at the end of the 19th century and again in the 1960s required solutions for flood control and to minimise river bed aggradation. To achieve these objectives, a variety of bank protection measures was performed, and the river bed was channelized. This caused uniform river widths of c. 50 m and an average water depth of c. 4.5 m at the mean annual flood (300 m3 s−1). These measures, together with catchment-wide changes, caused economical and ecological problems.

In order to improve the ecological functioning of the Drava river and to minimise river bed degradation, several river bed widening measures were implemented since 1999. In Kleblach-Lind 2 km of the Drava River have been restored.

Measures:

- initiation of side channel
- river bed widening
- self dynamic bank erosion

Main goals:

- stabilisation of the river bed by increasing the bed width
- initiation of natural morphological developments
- initiation of improved habitats for plants and animals
- improvement of flood protection

1999

2002

2003

2007

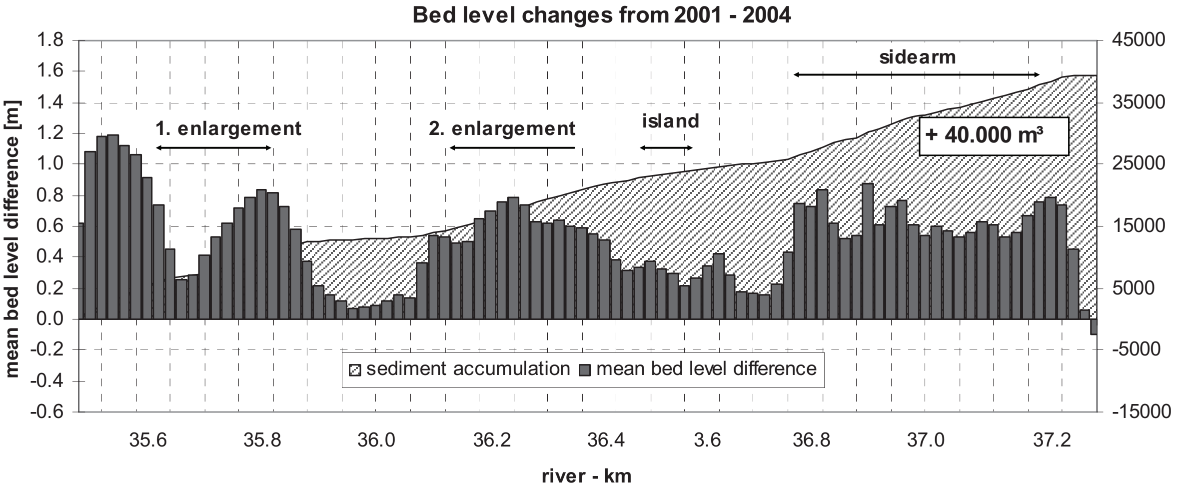
Monitoring

An intensive monitoring program was developed to check the achievement of defined goals:

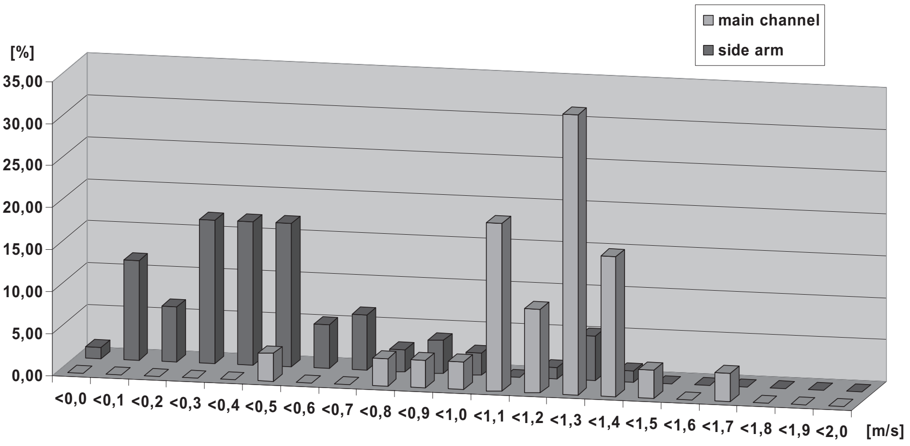
- Geodetic surveys
- echo sounder measurements
- Surface layer analysis, underwater camera system, volumetric sampling
- Two-dimensional flow velocity measurements (Delft P-EMS)
- Numerical simulations

Results

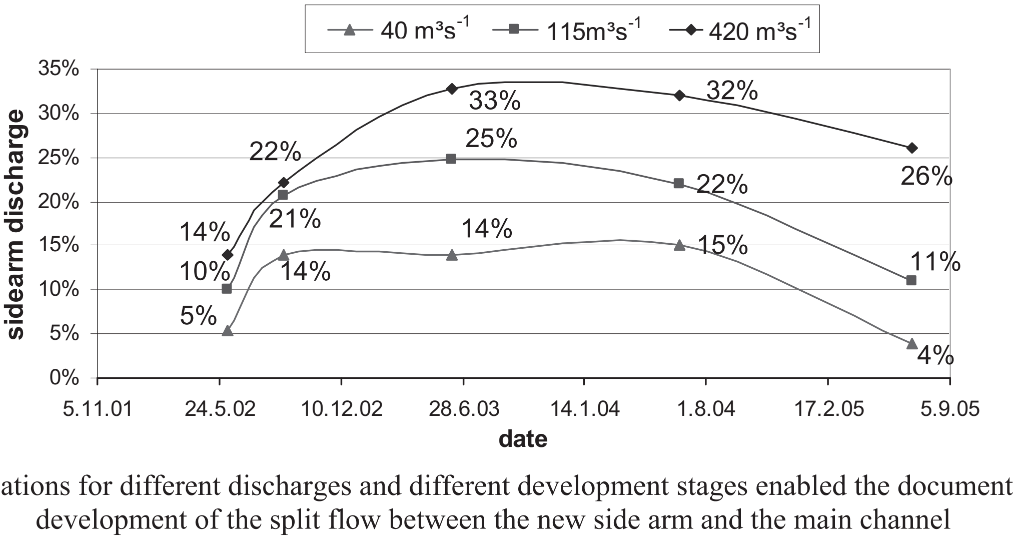
- Bed aggradation replaced the previous degradation in the enlarged area
- Different aims can be reached concurrently: flood protection, riverbed stabilization, as well as valuable new habitats for endangered animals and plants
- For the Upper Drau restoration measures, the density of juvenile fish species has increased and habitat quality has already clearly improved



Bed aggradation in the restored river section



comparison of the flow velocities distribution between main channel and side channel

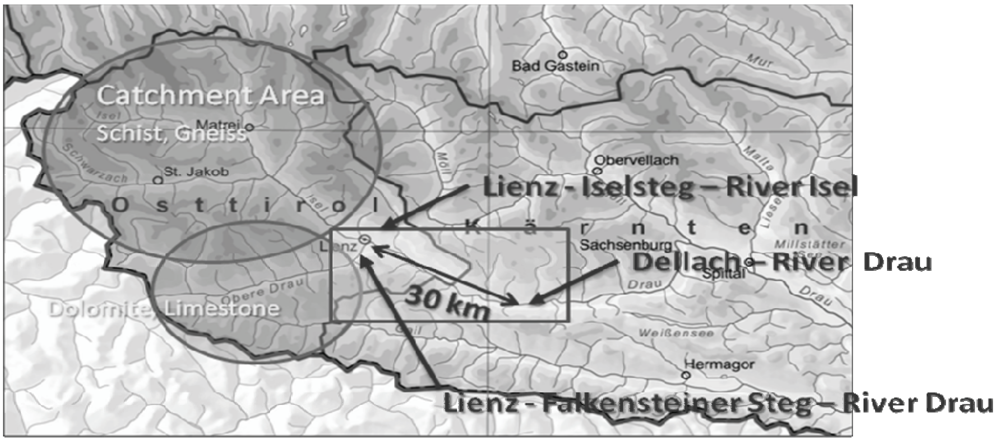


Several simulations for different discharges and different development stages enabled the documentation of the development of the split flow between the new side arm and the main channel

TOPIC 3: Bed load measurement site – Dellach/Drautal

By Helmut Habersack

At the beginning of 2006 a system of bed load measurement devices were installed at the free flowing reach of the river Drava and its most important tributary Isel. The measurement system is situated in three locations distributed over both rivers (distance 40 kilometres).

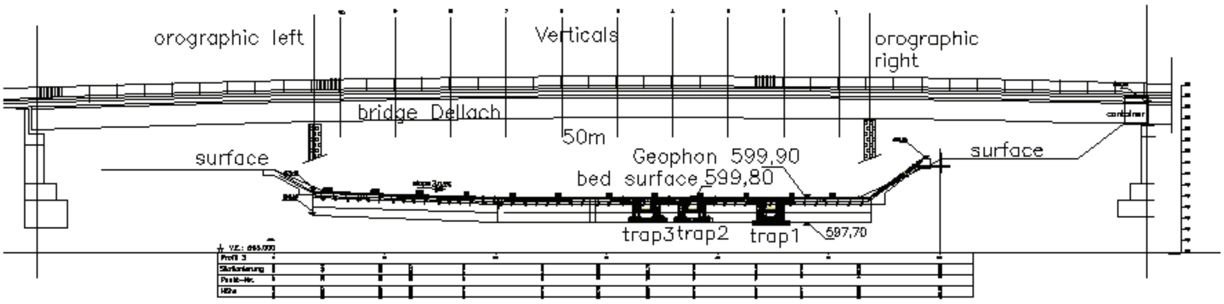


Two of the study sites (Dellach at the river Drau and Lienz at the river Isel) are supplied with:

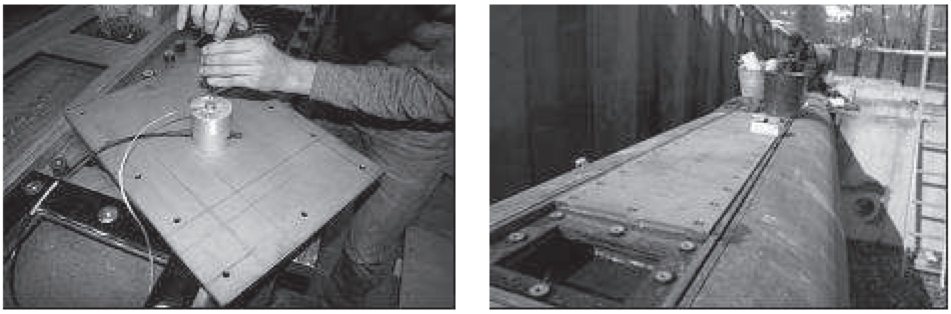
- geophone installations
- different types of bed load traps
- mobile bed load sampling facilities
- related measurement devices (suspended load measurements, flow velocity measurements, water gauges, etc.)

A third study site, installed 2002 at the upper branch of the river Drau at Falkensteiner Steg, is also equipped with geophones, a velocity measurement system and a water gauge.

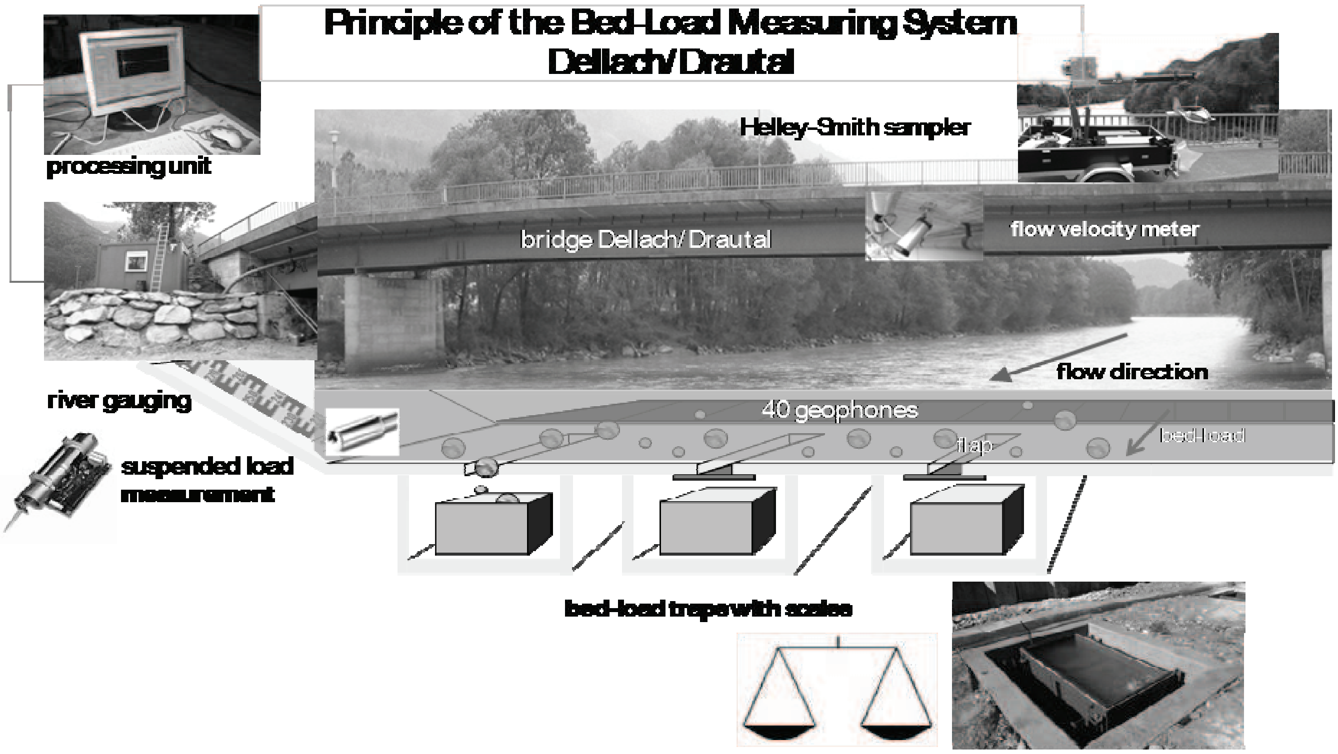
Together with hydrological, geological, meteorological and other related data e.g.: information about sediment sources, sediment dredging, etc. this allows observing the transport processes in detail in the study reach. Within the study especially the initiation of motion of the bed load and the bed load transport processes (cross sectional variation, periodicity in bed load movement) are analysed.



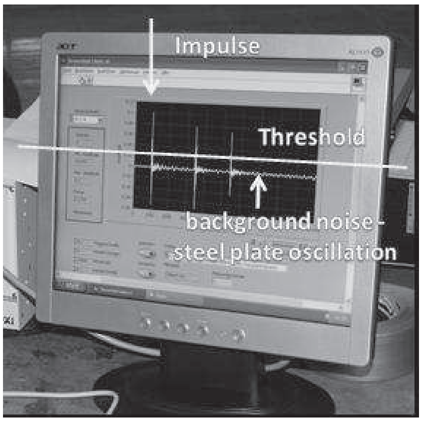
cross section Dellach/Drautal



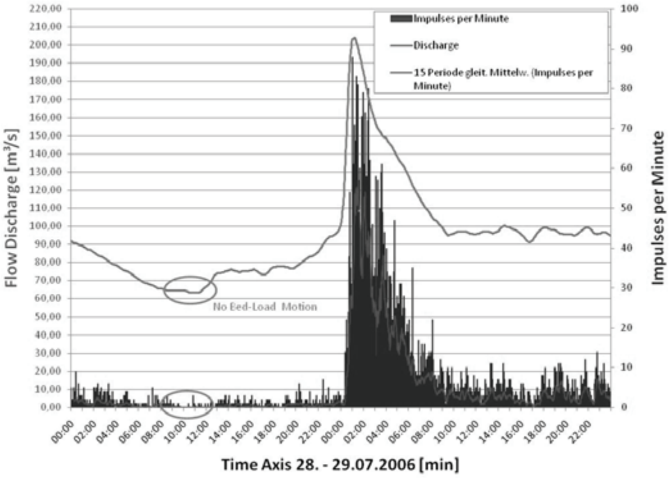
Geophone installation



principle of bed load measuring system



Geophone Impulses over a certain threshold



Geophone Impulses per Minute