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A REFERENCE RIVER SYSTEM FOR THE ALPS: THE 'FIUME TAGLIAMENTO'

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ABSTRACT

A major deterrent to a full understanding of the ecological ramifications of river regulation at the catchment scale is a lack of fundamental knowledge of structural and functional attributes of morphologically intact river systems. For example, both the River Continuum and the Serial Discontinuity Concepts, in their original formulations, had the implicit assumption of a stable, single-thread channel from headwaters to the sea. The Fiume Tagliamento traverses a course of 172 km from its headwaters in the Italian Alps to the Adriatic Sea. No high dams impede the river's passage as it flows through the characteristic sequence of constrained, braided, and meandering reaches. The Tagliamento, the only large morphologically intact Alpine river remaining in Europe, provides insight into the natural dynamics and complexity that must have characterized Alpine rivers in the pristine state. The Tagliamento has a flashy pluvio-nival regime (mean $Q = 109\ m^3\ s^{-1}$, with flood flows up to $4000\ m^3\ s^{-1}$). Thousands of newly-uprooted trees were strewn across the active bed and floodplain along the river's course following a major flood in the autumn of 1996. The active floodplain is up to 2 km wide and contains a riparian vegetation mosaic encompassing a range of successional stages. Up to 11 individual channels per cross section occur in the braided middle reaches. Islands are a prominent feature of the riverine landscape and island dynamics are postulated to play a key role in determining pattern and process across scales. Future studies will examine the roles of island dynamics and large woody debris in structuring biodiversity patterns of aquatic biota and successional trajectories of riparian vegetation. The high levels of spatiotemporal heterogeneity exhibited by the Fiume Tagliamento provide a valuable perspective for regulated river ecologists and those engaged in conservation and restoration. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: Alpine rivers; braided rivers; European rivers; Fiume Tagliamento; floodplain vegetation; islands; river corridors; riverine landscapes

INTRODUCTION

The rivers of Europe have been regulated for centuries, initially with embankments to protect against flooding and channel modifications to facilitate navigation, then more extensively to allow agricultural activities and human habitations on river floodplains, and eventually by construction of dams for water storage, flood control and hydropower production (Whitton, 1984; Petts *et al.*, 1989). The details vary, but the main results have been: (1) to simplify a formerly complex channel morphology, (2) to suppress natural dynamics, (3) to isolate river channels from what remains of their floodplains, and (4) to fragment the riverine environment.

Despite recent interest in the historical conditions of European rivers lotic ecologists do not fully appreciate the extent to which managed rivers deviate from the natural state. For example, both the River Continuum Concept (Vannote *et al.*, 1980) and the Serial Discontinuity Concept (Ward and Stanford,

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1983), in their original forms, had the implicit assumption that unmodified rivers consist of a stable, single-thread channel from headwaters to the sea. A major deterrent to a complete understanding of the ecological ramifications of river regulation at the catchment scale is a lack of fundamental knowledge of the complexity and dynamics of morphologically intact river systems. Although it is neither possible, nor necessarily desirable, to restore highly regulated rivers to their pristine state, a better understanding of the natural spatiotemporal heterogeneity is a prerequisite for effective ecosystem management (e.g. Stanford and Ward, 1992; Ward, 1998).

An important theme of this paper is that valid reference river systems are needed, even if these exist only as theoretical constructs. We have, however, located a river in the Alps, the Fiume Tagliamento, that provides considerable insight into the natural dynamics and complexity that must have characterized many rivers, not least Alpine ones, in the pristine state. A holistic research program has been initiated that includes hydrologists, geomorphologists, plant ecologists, zoologists, botanists, stream ecologists, and groundwater ecologists. The ensuing material is a first description of the spatio-temporal heterogeneity of this remarkable river ecosystem, supplemented with comparative data from other European rivers.

LAST FRAGMENTS OF NEAR-NATURAL RIVER SEGMENTS

Only remnants of natural or near-natural river reaches remain in the Alps (Figure 1). The remaining semi-natural reaches are primarily in the headwaters. Additionally, there are a few canyon stretches that are relatively pristine and, because of their high aesthetic value, remain unregulated. Examples include the

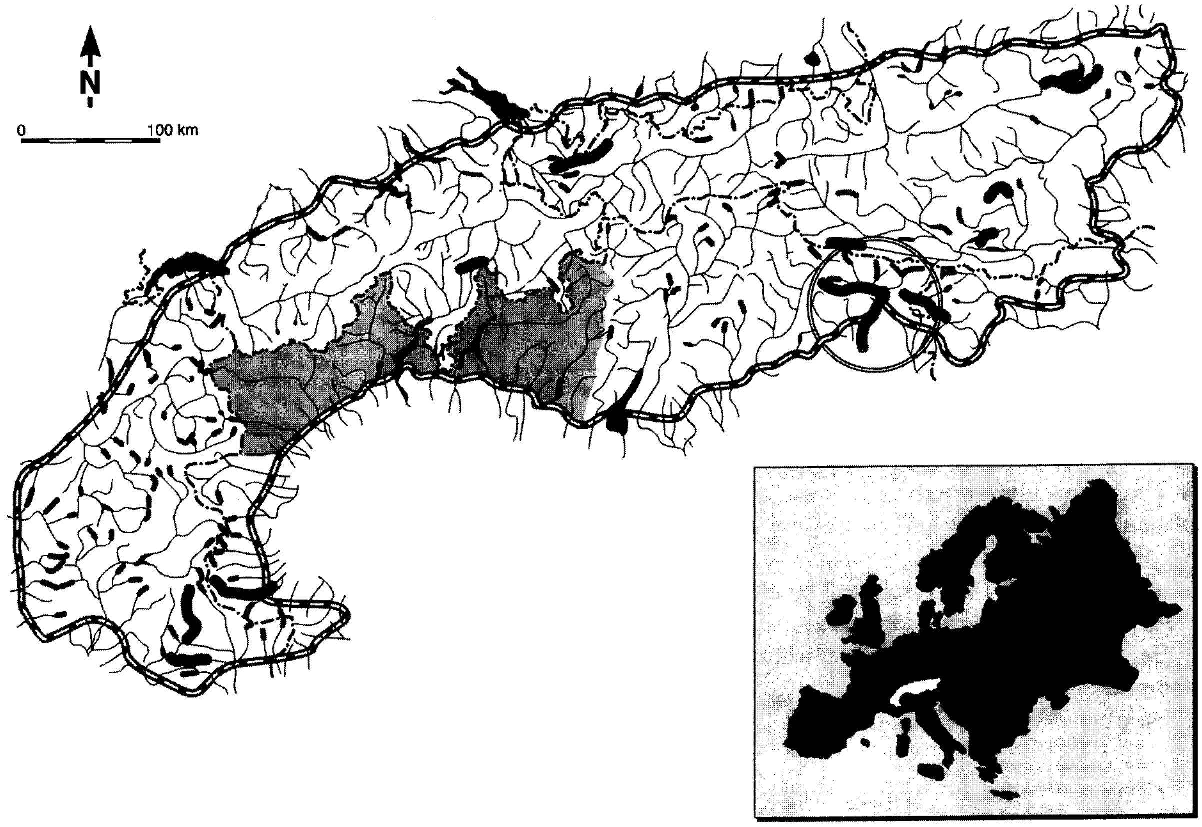

Figure 1. The remaining natural and semi-natural river segments in the Alps (inset shows location of Alps in Europe). Grey shading indicates areas for which sufficient data are not available. The Fiume Tagliamento (Italy) is in the center of the encircled area. Redrawn from Martinet and Dubost (1992)

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Table I. An inventory of the last natural and semi-natural river stretches in the Alps (after Martinet and Dubost, 1992)

	Alps	Austria	Italy	France	Switzerland	Germany	Slovenia
Total rivers length (km)	13 150	3850	3780	2680	2090	400	350
Unpolluted stretches (%)	18	10	23	20	36	13	5.7
Stretches upstream of water abstraction (%)	21	24	10	26	10	2.5	77
(Semi-) Natural stretches (%)	9.6	6.8	9	18	4.9	2.5	5.7

Soca River in Slovenia (partly protected by a national park) and the Salza River in Austria. Very few natural braided reaches remain along European rivers, one of the rare examples being a segment of the Lech River in Tyrol (Austria). An average of < 10% of the total length of Alpine rivers is in a semi-natural condition, ranging from 2.5% in Germany to 18% in France (Table I). We were, therefore, surprised that an essentially intact river system, containing extensive braided reaches, exists in Italy, a country in which only 9% of the length of Alpine rivers retain a natural or near-natural state.

FIUME TAGLIAMENTO

The Fiume Tagliamento is considered the 'last large natural alpine river in Europe' (Müller, 1995) and can, therefore, serve as a model river ecosystem for the Alps. Its headwaters are situated in the limestone Alps of north-east Italy, from which it flows to the Adriatic Sea, traversing an idealized sequence of constrained, braided, and meandering reaches. The river is not entirely without human impact, however. Water is abstracted from some locations and in the last few kilometres near the sea the channel is constrained by embankments. Nonetheless, the Tagliamento retains an essentially pristine morphological character (Figure 2), with a highly complex channel morphology structured by a dynamic hydrologic

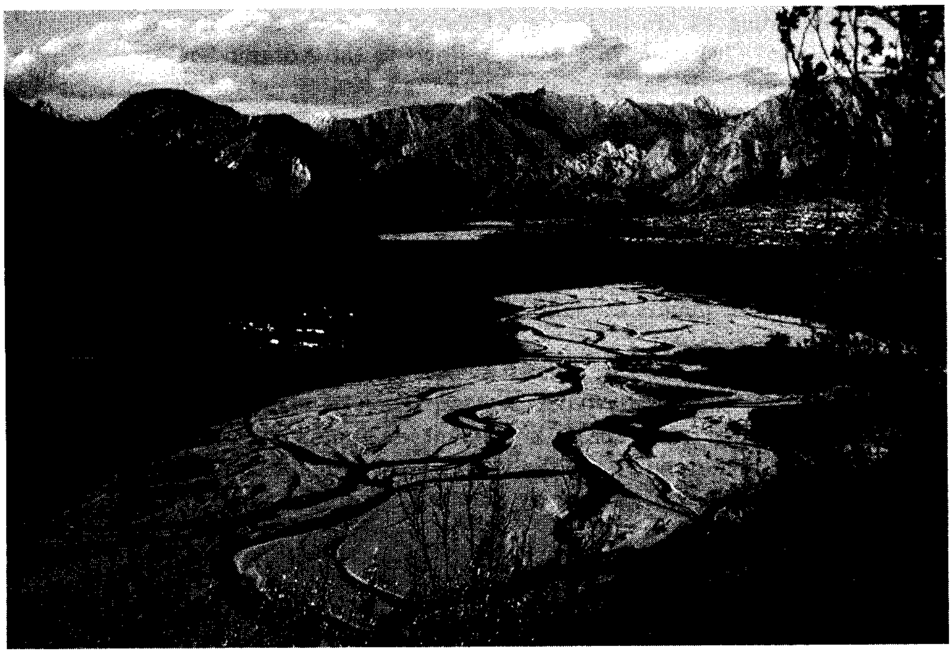

Figure 2. Upstream view of the Fiume Tagliamento from Monte Ragogna showing the dynamic braided channel morphology that characterizes extensive reaches of this river system. This is the section between Venzone and Cornino (river km 60–77) (photo by K. Tockner)

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Table II. Catchment statistics of the Fiume Tagliamento, Italy

Stream order	7
Catchment area (km^2)	2580
Mean altitude (m a.s.l.)	1159
River length (km)	172
Slope (%)	
Upper section	10
Middle section	1
Lower section	0.1
Discharge (Q_{80} in m^3 s^{-1})	
Forni di Sotto	3
Amaro	31
Ragogna	78
Camino al Tagliamento	36
Varmo	32
Specific discharge (L km^2 s^{-1})	45.6
Average precipitation (mm year^{-1})	2150

regime. In addition, the Fiume Tagliamento provides an immense river corridor, covering an area of about 150 km^2 (excluding tributary corridors), connecting the Mediterranean with the Alps. This riverine landscape, therefore, has ecological importance far exceeding its role in sustaining aquatic biocoenoses.

Catchment characteristics

The Fiume Tagliamento is a 7th order stream located in north-eastern Italy (Friuli-Venezia Giulia; 46° N, 12°30′ E; Table II). The catchment is divided into three sub-basins (Figure 3). The upper basin, Alto Tagliamento (211 km^2; 32.5 km long), extends from the source at 1195 m a.s.l. (Passo della Mauria) to the confluence with Torrente Lumiei. The middle section of the catchment, Medio Tagliamento (2082 km^2; 63.5 km long, including 14 km in Pinzano Canyon), extends downstream to Pinzano. The lower section, Basso Tagliamento (287 km^2; 76 km long), flows to the Adriatic Sea.

The Tagliamento 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) and the mean altitude is 1159 m a.s.l. For the first 60 km the river flows in an easterly direction, then it turns to the south after the confluence with its major tributary, the Torrente Fella. Near Gemona, glacial moraines (Würmian) force the river to turn westward for a few kilometres and separate the Tagliamento valley from the Udine basin. The average slope is 10% in the uppermost part, 1% from the confluence with the Torrente Fella to the confluence with the Torrente Cosa, and 0.1% in the lowest (meandering) section. The upper catchment area is tectonically active with mainly dolomitic limestone bedrock. The lower basin consists of Tertiary and Quaternary sediments.

Petts (1990) refers to forested river corridors as a 'lost resource'. The river corridor of the Tagliamento contains a diversity of plant community types. A comparison of plant communities in the Tagliamento and two other braided Alpine rivers across a gradient of human impact demonstrates (1) an overall decrease in the number of communities, (2) the loss of several major community types, (3) the addition of ruderal communities, and (4) replacement by plantations, with increasing impact (Figure 4).

Hydrodynamics

The Fiume Tagliamento is characterized by a flashy pluvio-nival flow regime (Figure 5), with the highest average discharges in spring (snowmelt runoff) and autumn (rainy period). At Pioverno (catchment area = 1866 km^2) average discharge is 91 m^3 s^{-1}. The catchment above this location has a mean altitude of 1171 m a.s.l., with an average annual precipitation as high as 2150 mm, an average air

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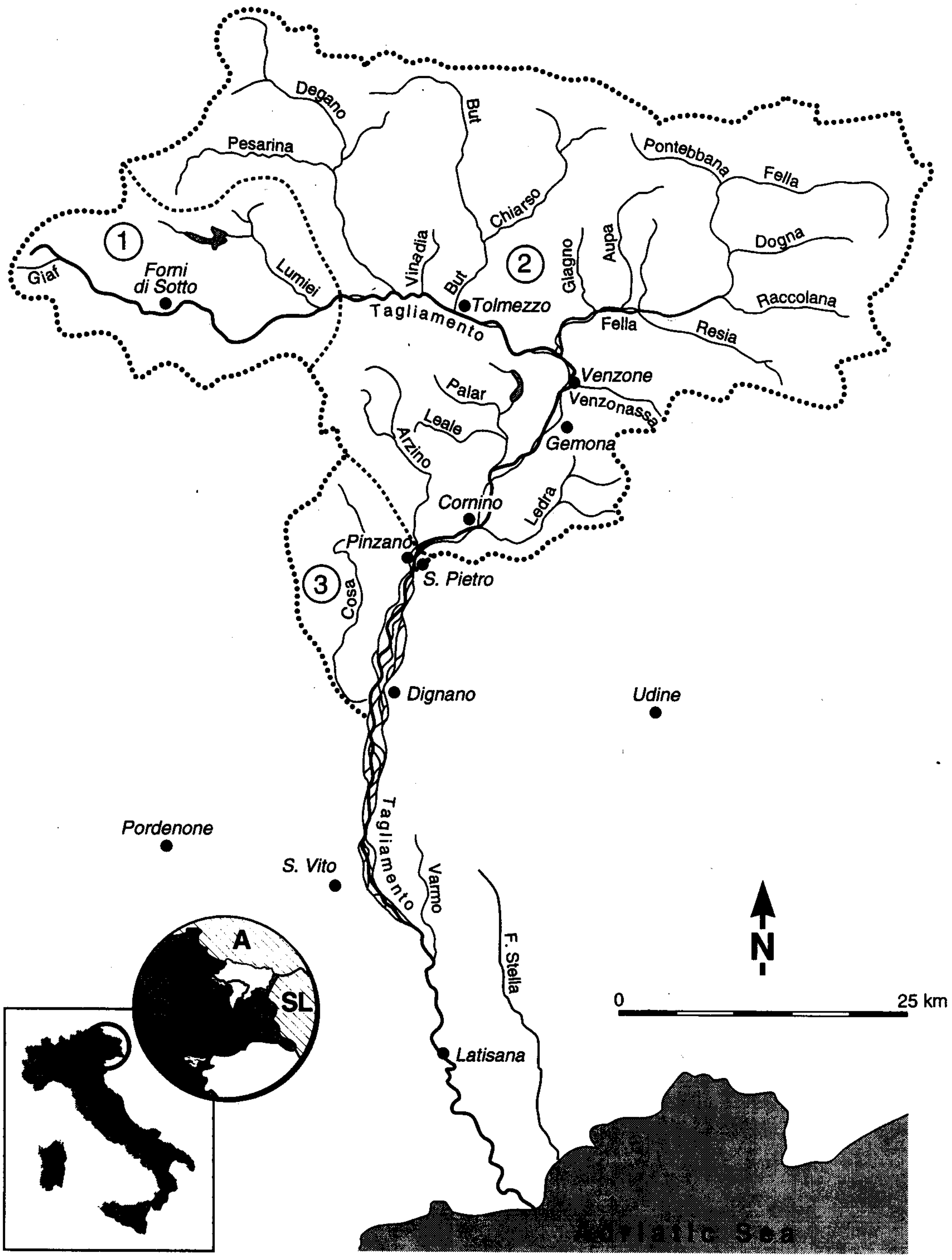

Figure 3. Catchment map of the Fiume Tagliamento, with towns, major tributaries and location of the three sub-basins (1–3). Inset shows the location of the river in Italy (I), near the borders of Austria (A) and Slovenia (S)

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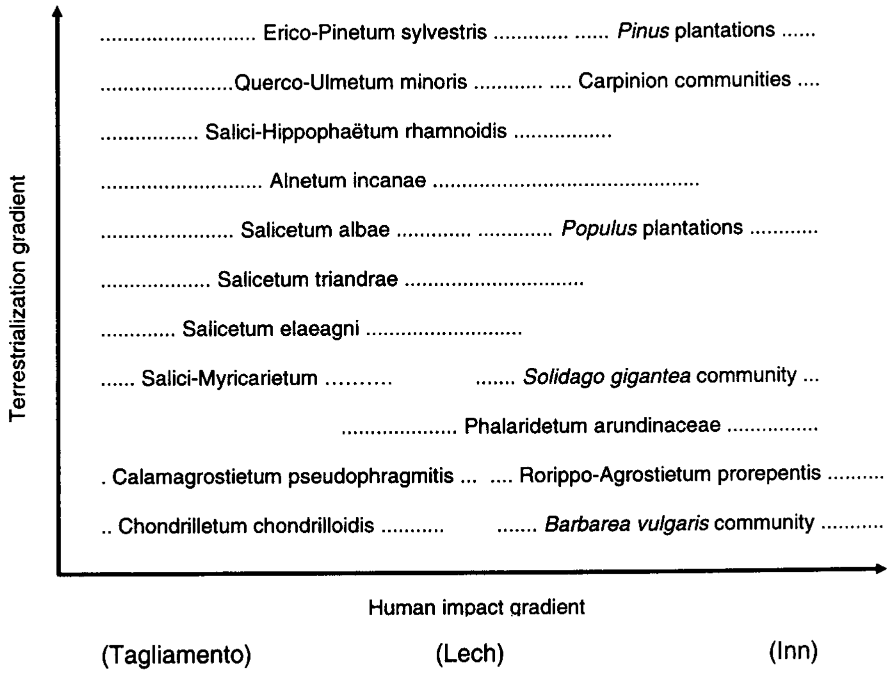

Figure 4. Changes in the abundance of plant communities in three braided Alpine rivers representing a gradient of human impact. Based on Lippert *et al.* (1995) and Müller (1995). Nomenclature follows Oberdorfer (1994). The Querco-Ulmetum minoris community is represented in the Tagliamento by the *Fraxinus ornus–Ostrya carpinifolia* assemblage

temperature of 6.2°C, and with a mean evaporation rate of 637 mm (Baumgartner *et al.*, 1983). Annual discharge upstream from the major infiltration zone (S. Pietro) averages 109 $m^3 s^{-1}$, which corresponds to a specific surface runoff of 45.6 $L s^{-1} km^{-2}$. The average monthly flow maximum in November is 149 $m^3 s^{-1}$. Discharge maxima of about 4000 $m^3 s^{-1}$ have been recorded.

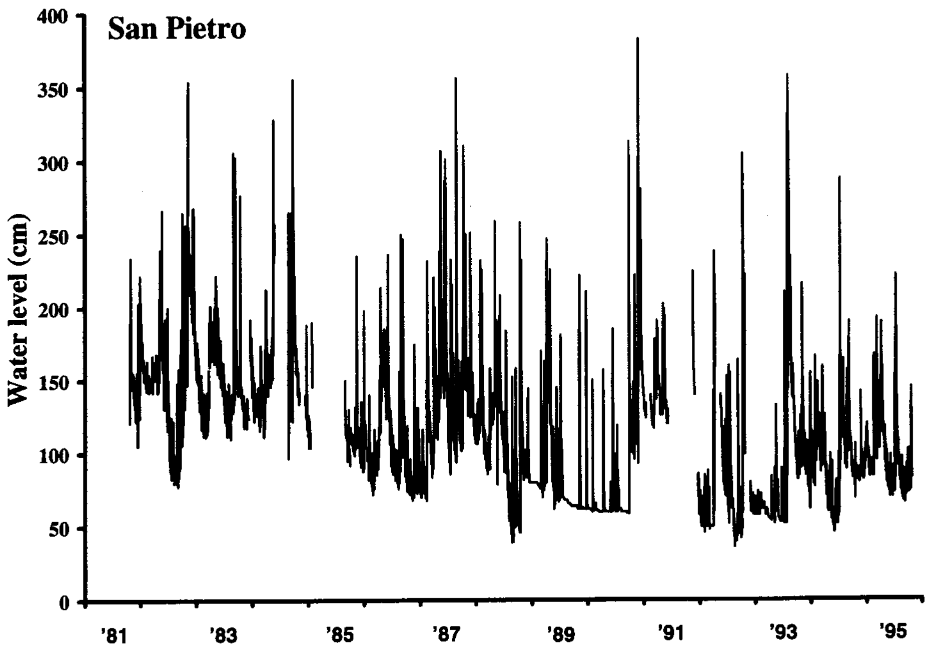

Figure 5. Water level fluctuations of the Fiume Tagliamento at San Pietro for the period 1981–1995

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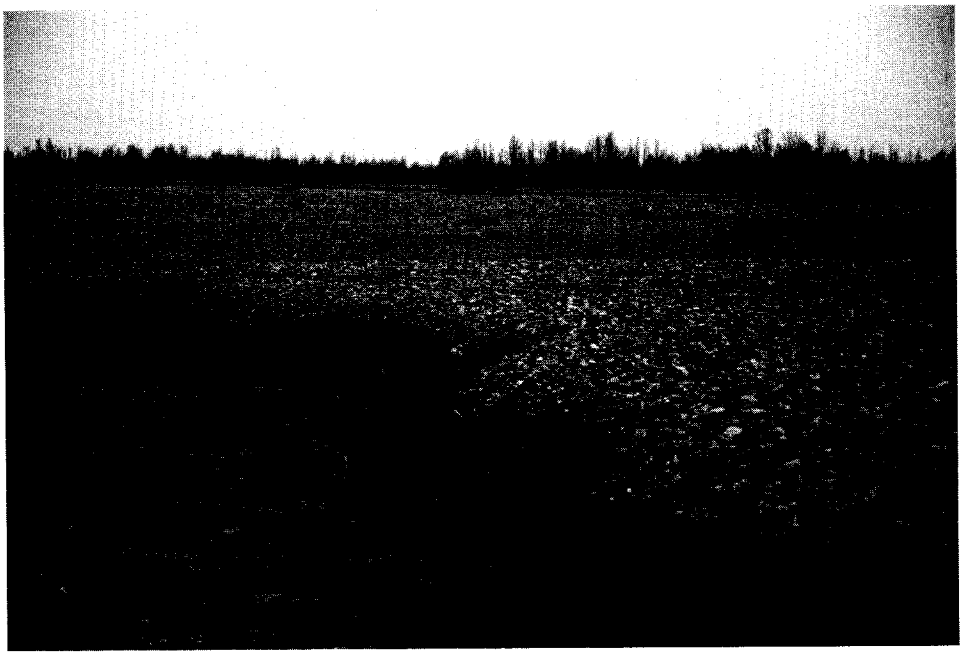

Figure 6. Intercalated large woody debris, buried by advancing gravel sheets during the September 1996 flood of the Fiume Tagliamento (photo by K. Tockner)

We observed a major flood that occurred at the end of September 1996 and surveyed the effects during the following weeks. Thousands of newly-uprooted trees were strewn across the active channel and along the floodplain and island edges; uprooted trees were especially abundant in the braided middle reaches, but also occurred well upstream into the headwaters of the upper basin. Most of the trees and shrubs were oriented with the root wads in an upstream position, the trunk and branches trailing downstream. Such trees may serve as nuclei for the formation of new islands. Smaller pieces of wood, most likely deposited during previous floods, were buried by advancing sheets of gravel (Figure 6). The processes of cut and fill alluviation were evident throughout the catchment, following the subsidence of flood waters.

Downstream of Pinzano, the Tagliamento loses water into a vast alluvial aquifer. Groundwater in the deepest part of the aquifer (250–300 m) is about 40°C, whereas surficial groundwater temperatures are between 11 and 13°C. Deep groundwaters have high chloride concentrations, reflecting ancient sea water infiltration. The alluvial aquifer widens to about 5 km to the west and, on the level of Udine, ca. 20 km to the east. The aquifer is dominated by gravels and is highly permeable. Average subsurface flow velocity is ca. 0.3 m h^{-1} and average porosity is about 10%. To the south of this central depression the aquifer sediments are intermixed with layers of sand and clay, which drastically reduce permeability and result in a massive upwelling of groundwater ('Linea delle risorgive').

Around 60 $m^3 s^{-1}$ of water returns to the river from the aquifer between Tagliamento and Castions di Strada (Fiume Stella: 35 $m^3 s^{-1}$). River discharge (Q_{80}) decreases from 78 $m^3 s^{-1}$ at Pinzano to 32 $m^3 s^{-1}$ at S. Vito al Tagliamento, but increases again to 40 $m^3 s^{-1}$ at the confluence with the Varmo. During dry periods, the Fiume Tagliamento loses between 20 and 30 $m^3 s^{-1}$ between Pinzano and Latisana. Most of the water downwells in the first 2 km. Maximum water loss is 76 $m^3 s^{-1}$; 70 $m^3 s^{-1}$ infiltrates into the aquifer at the left bank and 5.8 $m^3 s^{-1}$ to the right bank. Under low flow conditions, this reach of the river lacks surface flow, a natural feature of many Mediterranean rivers that has been exacerbated by surface water abstraction and groundwater extraction. Cyclic expansion and contraction of surface waters on a seasonal basis appears, however, to be a natural phenomenon in many alluvial rivers (Stanley *et al.*, 1997; Ward *et al.*, 1999).

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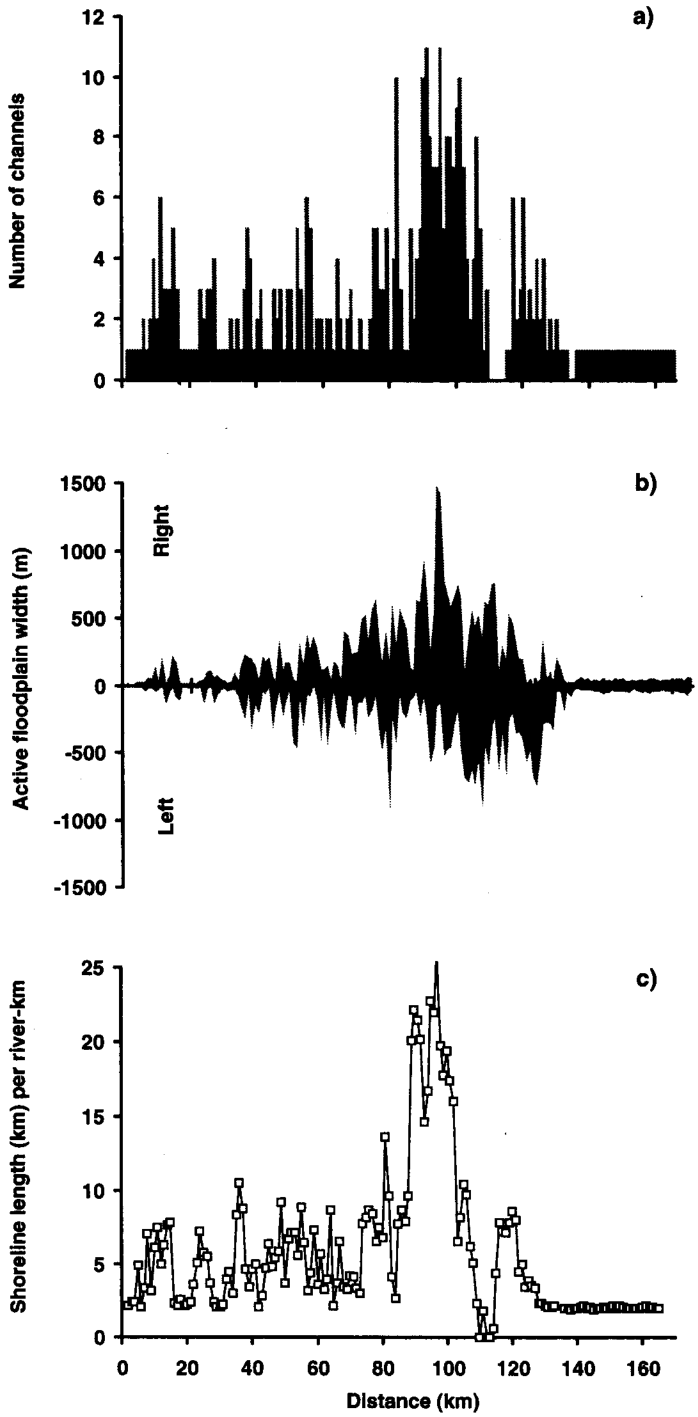

Figure 7. (a) Number of channels per cross section along the course of the Fiume Tagliamento, based on aerial photographs taken on 10 October 1984. (b) Width of the active floodplain (for both sides of the river, starting from the thalweg) along the entire course of the Fiume Tagliamento (based on 1:10000 maps). The active floodplain has been delimited by the extent of unconsolidated gravel. (c) Shoreline length per river kilometre along the course of the Fiume Tagliamento at ca. mean discharge (calculated from 1:10000 maps)

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Channel patterns

The upper basin of the River Tagliamento is characterized by a sequence of braided and constrained segments, each with a length ranging from 1 to 7 km. This alternation of floodplains with constrained reaches, a common feature of alluvial rivers, has been likened to 'beads on a string' by Stanford and Ward (1993). The average number of channels per cross-section in the upper braided section is four (with a maximum of six; Figure 7a). Channel number increases downstream from the knickpoint at Pinzano to a maximum of 11 channels (during mean flow conditions). Downstream from the upwelling area, channel numbers are 3–6, followed by reduction to a single-thread channel in the meandering section. The width of the active floodplain (Figure 7b) bears a close relationship to the number of channels per cross section (Figure 7a), and perhaps better portrays the 'beads on a string' pattern. Note that a rather wide floodplain is present in the channel segment that loses all surface water during low flow conditions (cf. km 112–115, Figure 7a, b).

The length of shoreline (for the wetted channel) per river kilometre along the course of the Tagliamento is plotted in Figure 7c. In the middle braided section, shoreline length in some reaches exceeds 20 km per river kilometre. The alteration of constrained and floodplain reaches is clearly shown for the upper half of the river. In the meandering reach the values are close to 2 km per river kilometre.

In Figure 8, sinuosity is plotted against the braid-channel ratio for the three sections of the Tagliamento. Sinuosity was calculated as channel thalweg length/valley length. The braid-channel ratio is the sum of mid-channel lengths of all channels in reach/length of mid-line of widest channel (calculated after Friend and Sinha, 1993). Locations in the meandering section exhibit sinuosity values from ca. 1.0 to 1.3. The headwaters and the middle braided section exhibit broader ranges of sinuosity, although most values occur within the range of sinuosity encompassed by the braided section. It is the braid-channel ratio that distinguishes the three sections, increasing from 1.0 (single-thread channel) for locations in the meandering section, to ca. 1–5 for the headwater locations, to ca. 1–12 for the middle braided section where single-thread channels in constrained reaches alternate with complex multichannel systems in floodplain reaches.

Islands

The role of islands has been almost totally ignored by stream ecologists. Most of what is known relates primarily to the formation and dynamics of bars and islands from the perspective of hydraulics and fluvial geomorphology (e.g. Church and Jones, 1982; Fetherston *et al.*, 1995; Abbe and Montgomery, 1996). Thorp (1992), who examined the influence of three islands in the regulated Ohio River on macroinvertebrate assemblages, concluded that 'Islands have significant positive effects on invertebrate density and diversity that appear related to changes in physical habitat characteristics'.

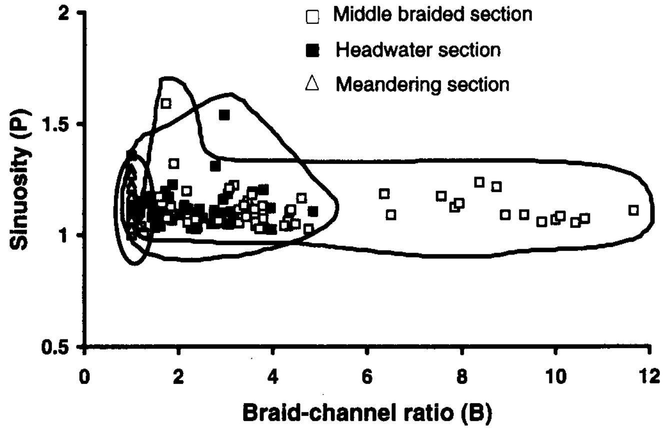

Figure 8. Variation of sinuosity (P) and braid-channel ratio (B) for the headwater, middle braided, and meandering sections. Sinuosity and braid-channel ratio calculated after Friend and Sinha (1993)

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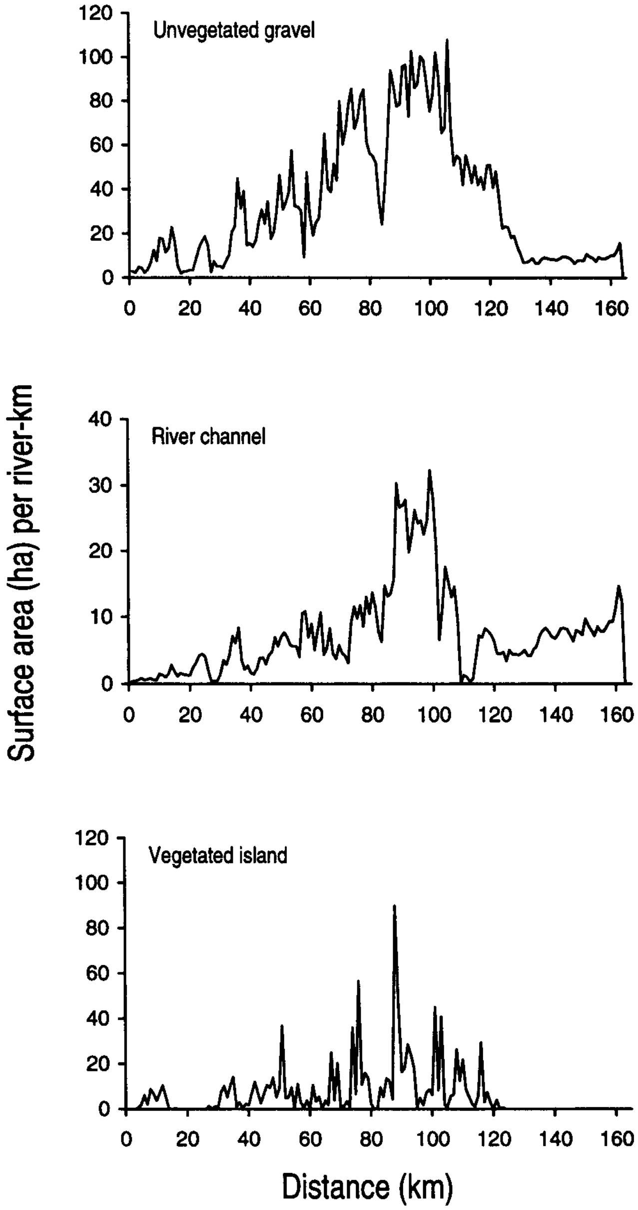

Figure 9. Surface areas per kilometre of unvegetated gravel, the river channel, and vegetated islands along the course of the Fiume Tagliamento. Note that vertical axes have different scales

The river corridor of the Tagliamento, excluding terrace vegetation outside the active floodplain, covers an area of 73.8 km^2. Vegetated islands comprise 8.5%, surface water 16.8% (at mean water level), and exposed gravel devoid of woody plants 74.7% of the area of the active floodplain. The surface area of unvegetated gravel (unconsolidated gravel areas above mean water level) exhibits an essentially unimodal pattem along the river's course, with maximum values in the middle braided section (Figure 9). The surface area of the river channel under summer flows exhibits a similar pattern, except for zero or near zero values in the major downwelling zone. Vegetated islands are prominent features not only in the braided middle section, but also in the upper course of the river.

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The Fiume Tagliamento offers an exceptional opportunity to conduct holistic interdisciplinary studies of the role of island dynamics in river ecosystems. We hypothesize that islands are an emergent property of the interaction between riparian vegetation, wood debris, and the physical system, and that islands significantly influence pattern and process across a range of scales in river ecosystems. A conceptual model of island development has been developed, based on vegetation density and the flow threshold required to reverse the developmental trajectory (Figure 10). According to the predictions of the model, flow regulation leads to a level of stabilization which exceeds that normally occurring in nature. Figure 10 illustrates the possible evolution from a gravel bar to a fully vegetated island through the burial of trees and other large woody debris, the subsequent growth of vegetation from this 'seeds' wood and the development of further vegetation from seeds and pieces of the vegetation buried with the wood or subsequently trapped in sediment deposited around the growing vegetation. The process of vegetation colonization and succession proceeds until a sufficiently large discharge event disturbs and/or destroys this vegetation by the process of erosion and incision or sedimentation and degradation. Thus, the development and persistence of vegetated islands represent the interaction between vegetation development and flood disturbance, with a greater discharge threshold required to disrupt well-established persistent islands. The model conceptualizes a critical point in island development, when islands develop from a transient to a persistent state and when the channel evolves from a braiding to an anastomosing pattern. Once this critical point is reached, a sufficient discharge disturbance to cause reversion to a braided pattern becomes very unlikely. Since the model depends on the occurrence of major flood events to halt or reverse island development, we hypothesize that a regulated flow regime would form an extension of the 'normal' model, whereby the discharge is insufficient to significantly disturb vegetation development; vegetation development proceeds and a single-thread channel develops; and as a result an enormous discharge event would be necessary to cause reversion to a multithread pattern.

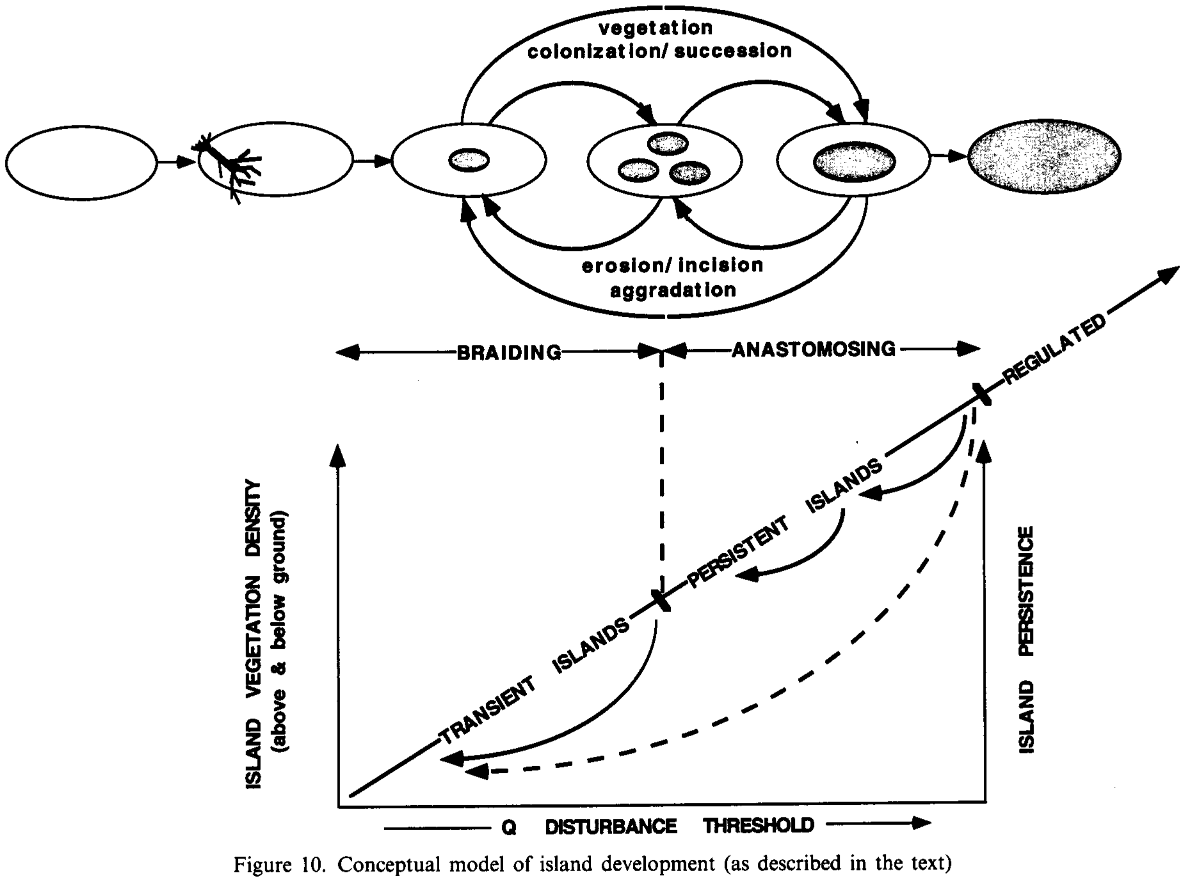

Figure 10. Conceptual model of island development (as described in the text)

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Nadler and Schumm (1981) described how the stabilizing effects of flow regulation dramatically altered the channel morphology of the plains segment of a Rocky Mountain river. In the early 1800s, the plains segment of the South Platte River was a wide, straight, shallow, braided stream with intermittent surface flow and transient bars. By the late 1800s, discharge became perennial, resulting in greater densities of riparian vegetation on the floodplain and on the bars. In the early 1900s, the bars had become vegetated islands. Dams in the mountains stored snowmelt runoff, thereby reducing flood peaks, and the islands became so stable that the channels were no longer dynamic. Eventually all channels except the thalweg were abandoned and islands attached to the lateral floodplain, completing the transformation to a sinuous single-thread channel.

IMPLICATIONS FOR REGULATED RIVERS

The high levels of spatio-temporal heterogeneity exhibited by the Fiume Tagliamento provide a valuable perspective for regulated river ecologists and those engaged in conservation and restoration efforts. In Europe and other areas where rivers have been highly regulated for long periods, we may not fully appreciate the intensity of the natural disturbance regimes under which the riverine/floodplain biota evolved or the role played by fluvial dynamics in sustaining the ecological integrity of rivers as ecosystems. Nor do we necessarily fully appreciate the complexity of the natural riverine landscape. Such understanding is essential for assessing the extent to which riverine ecosystems have been altered by human activities and for designing and carrying out effective managerial strategies.

The Fiume Tagliamento, a morphologically-intact river in the Alps, constitutes an invaluable resource as a model reference catchment. Research has been initiated to investigate the roles played by processes such as succession, disturbance, and island dynamics in structuring the biodiversity patterns of aquatic and riparian biota. Through such investigations we hope to gain insight into ways to better manage regulated rivers as productive and diverse ecosystems, while meeting human needs within river catchments.

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