Universitat de Barcelona
Facultat de Biologia – Departament d'Ecologia

Nutrient dynamics and metabolism in Mediterranean streams affected by nutrient inputs from human activities

Dinàmica de nutrients i metabolisme en rius Mediterranis afectats per entrades de nutrients procedents de l'activitat humana

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Nutrient dynamics and metabolism in Mediterranean streams affected by nutrient inputs from human activities

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1. General introduction

During the last decades, the amount of land occupied by urban and agricultural activities has increased at the global scale (Walsh 2000, Crouzet *et al.* 2000). This occupation process is expected to continue given that population growth and related activities are predicted to increase during the 21st century (Palmer *et al.* 2005). Urban and agricultural activities generate point and diffuse sources of nutrients, respectively, decreasing the water quality of the receiving freshwater ecosystems, such as streams (Vitousek *et al.* 1997, Crouzet *et al.* 2000). In the developing countries, water quality is an issue of special concern because populations do not have other option than use untreated waters for personal uses (Meybeck 2003), with implications for human health. In the developed countries, water quality issues are related to chemical contamination that limits some water uses or implies increasing water treatment costs.

Pristine streams play an important role in transforming and retaining nutrients from their catchments (e.g., Mulholland et al. 1985; Triska et al. 1989; Munn and Meyer 1990; Martí and Sabater 1996; Peterson et al. 2001). Nevertheless, knowledge regarding how stream ecosystem functions, such as nutrient dynamics and metabolism, are affected by point and diffuse sources is still limited (Gibson 2004, Inwood *et al.* 2005, Meyer *et al.* 2005, Walsh *et al.* 2005). Point and diffuse sources of nutrients from human activities can influence physical, chemical and biological attributes of receiving streams (Paul and Meyer 2001). It is likely that the influences on these attributes will also affect ecosystem functions (Meyer *et al.* 2005). Improving existing understanding about the biogeochemistry of human-altered streams (i.e., receiving anthropogenic nutrient inputs) would allow not only to predict how increasing nutrient inputs should alter stream water quality, but would also provide insights on their capacity to retain and transform nutrients. This capacity is likely to contribute to improve water quality in streams and downstream ecosystems, and thus, provides ecosystem services (Constanza *et al.* 1997, Meyer *et al.* 2005). Therefore, improving existing understanding on how human-altered streams process nutrients can also contribute to develop ecologically sound management strategies to reduce the impacts of human activities on stream ecosystems. Humans depend on water availability for municipal, industrial and agricultural uses, and to provide recreational areas. Therefore, improving such understanding is needed to combine increasing human population and related activities with maintenance of the natural services of streams upon which humans depend (Palmer *et al.* 2005).

Given the burgeoning problems associated with land use-based human activities and the growing need of understanding the interactions between human landscapes and freshwater ecosystems, the European Community developed the Water Framework Directive (WFD 2000/60/EEC). The WFD aimed to establish adequate policy practices to prevent further deterioration of these ecosystems within the human landscape, and to protect and enhance a good ecological status—defined as that status showing low levels of distortion resulting from human activity, but deviating only slightly from those normally associated with stream under undisturbed conditions (WFD 2000/60/EEC). Within this directive, a good ecological status of these ecosystems should be achieved by 2015. To meet this WFD purpose, a number of European research projects have been developed over the last decade to provide ecological understanding on the effects of human activities on freshwater ecosystems. Among them, the STREAMES project (*Human effects on nutrient cycling in fluvial ecosystems: The development of an Expert System to assess stream water quality management at reach scale* Ref.: EVK1-CT-2000-00081; URL: http://www.streames.org) was developed to assess the influences of nutrient inputs from human activities on functional aspects of fluvial ecosystems by comparing them with reference sites (i.e., not receiving anthropogenic nutrient inputs). This dissertation has been developed within the context of the STREAMES EU project.

The STREAMES project aimed to evaluate the effect of large stream nutrient loads on stream nutrient retention, and to examine the relationships between stream nutrient retention and several physical, chemical and biological structural or functional parameters that may constrain (i.e., nutrient sources from the catchment) or control (i.e., in-stream processes) nutrient retention capacity in human altered streams, with particular emphasis on streams from the Mediterranean region. The final goal of the project was to develop an Expert System (ES) for stream managers from either private or public water quality agencies. An ES is a computer application designed to simulate the decision-making processes that would otherwise require extensive human expertise or elaborated calculations, as it is the case for water quality management. The structure of the ES presents two main independent modules: the Knowledge Base (KB) and the Inference Engine (IE). The KB contains the overall knowledge of the process (in our case, stream nutrient management) codified by means of heuristic rules (a rule is a set of conditions and conclusions linked to a given hypothesis). The bottleneck of the KB development is the knowledge acquisition process (Comas *et al.* 2003). Three types of knowledge can be distinguished: general knowledge related to the domain, heuristic knowledge and empirical knowledge. In the STREAMES project, the empirical knowledge was obtained from experiments conducted in 11 human-altered streams located through Europe, which provided data on physical, chemical and biological (including both community structure and ecosystem function) parameters. This dissertation presents the results from two of these streams.

The STREAMES-ES was developed to operate at the reach scale (i.e., thousands of meters), because this is the scale at which local managers are usually able to operate. This was the focal scale at which the empirical research of this project was conducted. Nevertheless, due to the hierarchical structure of the stream ecosystems, patterns and processes occurring at this scale are constrained by elements from larger scales (e.g., the catchment scale). Likewise, mechanisms controlling processes at the reach scale operate at a smaller scale (e.g., the sub-reach scale). Thus, some of the specific objectives addressed in the STREAMES project were tested also at the catchment and sub-reach scales. Research activities addressing objectives at each scale were grouped into individual workpackages. Figure 1.1 shows the three scales at which the project was conducted and the connections between them; it also highlights the research of interest that was considered within each scale. This dissertation was developed within the framework of the workpackages 2 and 3. The overall goal of the workpackage 2 was to examine the effects of high nutrient loads on stream nutrient transport, transformation and retention. The overall goal of the workpackage 3 was to examine the role of stream biota on the control of nutrient retention. Most of the study reaches selected to accomplish these objectives were located in third-order streams (Fig. 1.2). This size was chosen because

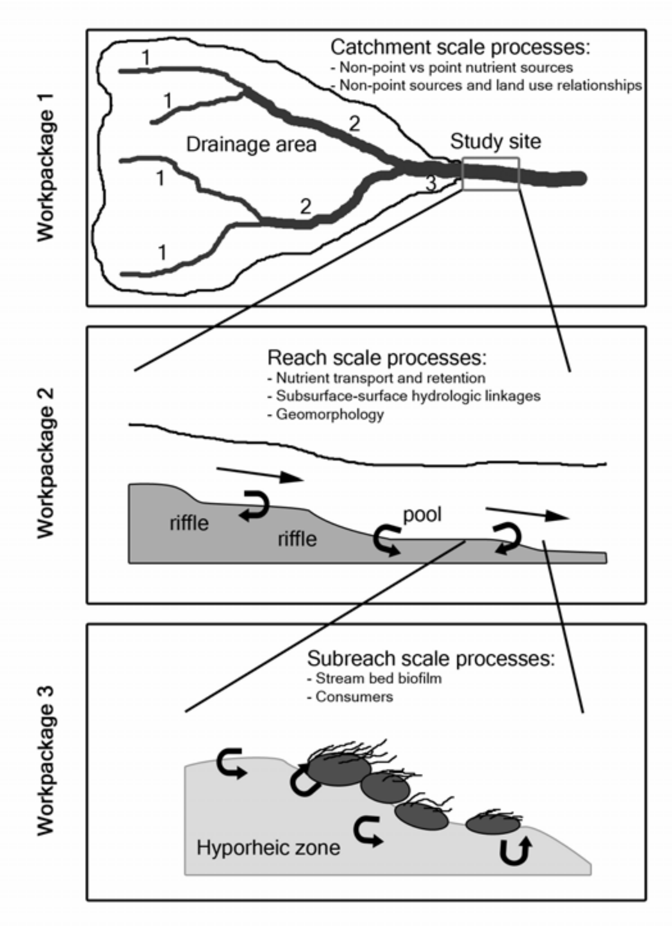

Fig. 1.1. Scales of study at which the empirical research was conducted in the STREAMES project. Each scale corresponds to one workpackage. The figure also highlights the study key words within each scale.

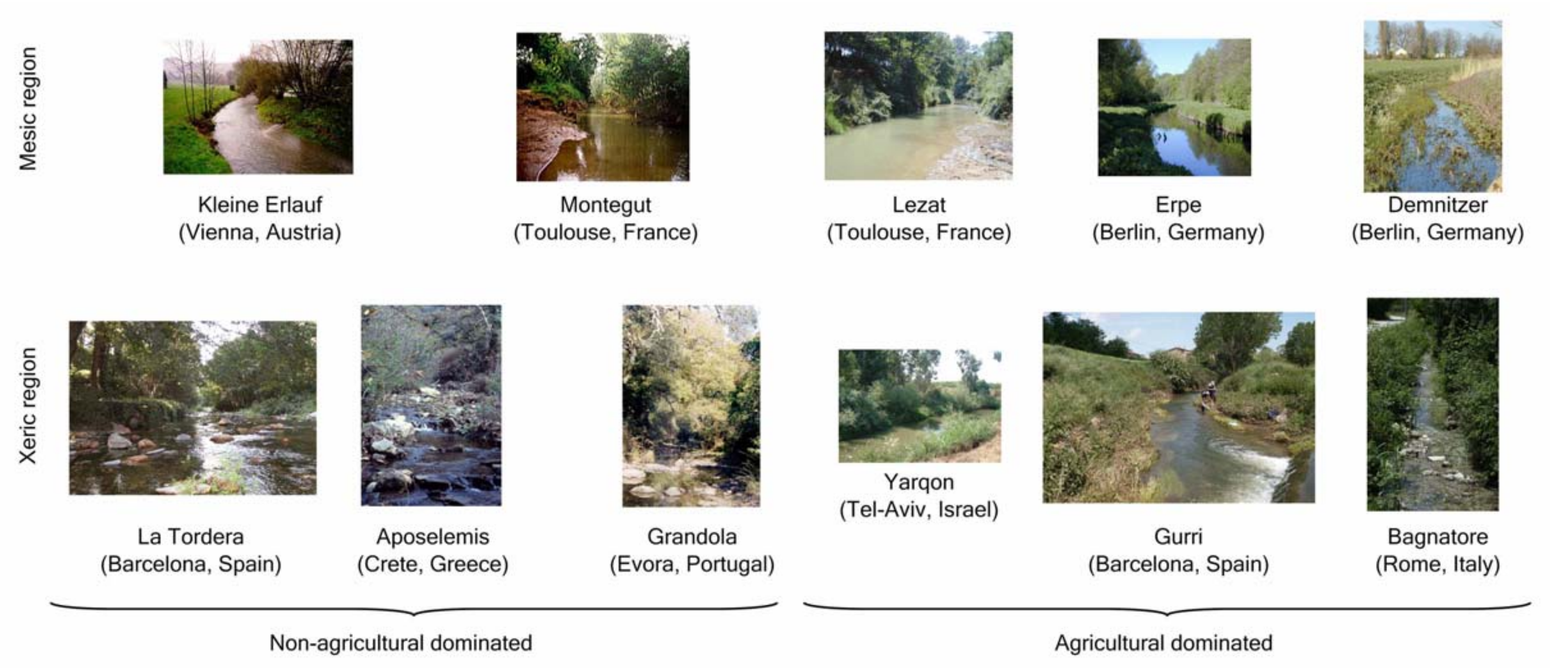

Fig. 1.2. Study streams of the STREAMES project.

these streams account for the greater proportion of the total stream length, and are very vulnerable to human activity (Paul and Meyer 2001). All selected reaches are characterised by having nutrient loads that are higher than expected by their location within the catchment (i.e., reaches with low water quality). Most of the countries participating in this project were located in the Mediterranean region. In these xeric areas (i.e., arid and semi-arid), human effects on water quality are hypothesised to be more evident than in mesic areas (Gasith and Resh 1999). This is because streams in xeric areas have an irregular hydrologic regime and availability of water can be scarce. Nevertheless, the project also included some streams from countries located in mesic regions (Germany, Austria and France) to enlarge the range of water quality conditions and their associated problems. Such a broad variety of study cases were selected to result in a more robust KB for the ES. In particular, this dissertation is focused on two Mediterranean streams, La Tordera and Gurri (Fig. 1.2). La Tordera and Gurri drain a forest- and an agricultural-dominated catchment, respectively. We selected these streams with contrasting land uses to have a study scenario with point source inputs as the main anthropogenic influence, and other scenario with diffuse sources from agriculture in addition to the point source. Within this context, the specific goals of this dissertation were to:

1. Assess the in-stream capacity to modify dissolved nutrients in transport along a reach located downstream of a wastewater treatment plant (WWTP) input (Chapter 4).

2. Examine the influences of a WWTP input on in-stream nutrient retention using different metrics (i.e., uptake length, mass transfer coefficient and uptake rates; Chapter 5).

3. Examine the influences of a WWTP input on denitrification potential rates, as well as factors controlling and limiting these rates upstream and downstream of the point source (Chapter 6).

4. Compare photosynthesis-irradiance responses between upstream and downstream of a WWTP input, and examine the effects of the point source on daily rates of whole-stream metabolism (gross primary production, respiration and net ecosystem production) and the GPP:R ratio (Chapter 7).

5. Examine the relation between the different studied pathways of N cycling (e.g., uptake, denitrification) and the coupling between N uptake and metabolism, by synthesizing the results from the previous chapters to provide a global picture of stream N biogeochemistry under contrasting scenarios of human-alteration (Chapter 8).

Recent literature has described riverine changes driven by human development through a set of syndromes (Meybeck 2003, Walsh *et al.* 2005). Meybeck (2003) characterized river syndromes such as flow regulation, fragmentation of river course, neo-arheism (i.e., reduction of river flow due to water diversion and water use for irrigation), chemical contamination, acidification, or microbial contamination. The urban stream syndrome was latter identified to describe the ecological degradation of streams draining urban land (Walsh *et al.* 2005). Initially, the urban stream syndrome was characterized by flashy hydrographs, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, and reduced biotic richness with the dominance/presence of more tolerant species (Paul and Meyer 2001, Walsh *et al.* 2005). More recently, the syndrome has been complemented with and additional symptom that refers to the alteration of functional attributes, such as nutrient retention (Meyer *et al.* 2005). These authors suggest that inputs from wastewater treatment plant effluents (i.e., point sources) are among the causes of this symptom (Meyer *et al.* 2005). Results from this dissertation aim to examine in detail the effects of WWTP inputs on stream biogeochemical processes and metabolism in two streams draining catchments with contrasted land uses, to gain ecological insights on this human-derived ecosystem syndrome.

2. Description of the experimental design

Field sampling strategy

The 11 study streams of the STREAMES project were selected to cover a broad range of problem scenarios mostly related to inputs of nutrients from both point and nonpoint anthropogenic sources (Fig. 2.1). The selection was based on the combination of descriptors such as dominant direction of surface-subsurface

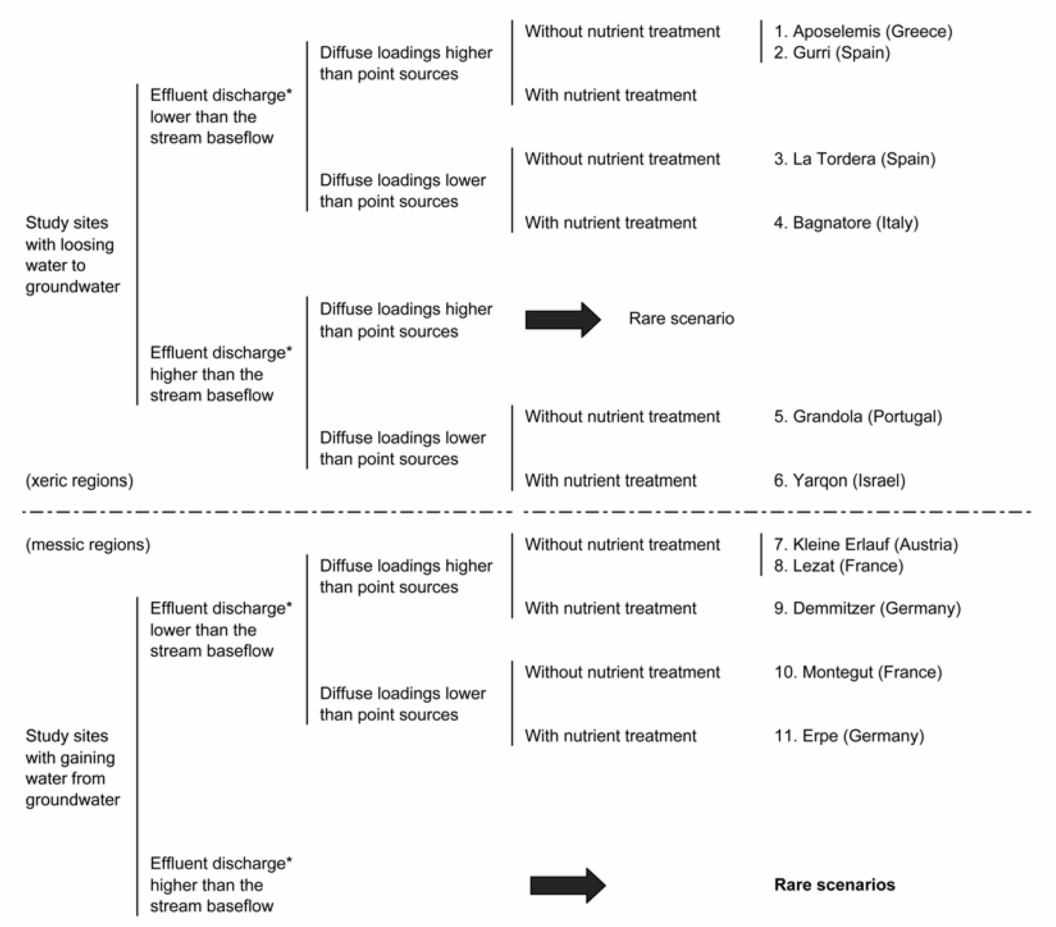

Fig. 2.1. Nested combination of the 4 descriptors selected to identify the study problem scenarios used in the STREAMES project to acquire the empirical knowledge for the Expert System. The figure also shows the stream name and the country of the partner institution that studied each scenario. * The effluent discharge comes from wastewater treatment plants (i.e., point sources).

water interaction, relative importance of point versus nonpoint nutrient sources, magnitude of point sources flow relative to stream baseflow, and whether mechanisms of nutrient removal from point sources prior to discharge into the stream were implemented.

The field sampling setting was common for all the study streams from the 8 participant countries in the STREAMES project. In particular, to conduct the tasks of workpackages 2 and 3 (i.e., the basis for the empirical knowledge from the streams to fuel the Expert System Knowledge Base), two reaches were selected in each study stream: one upstream and one downstream of a wastewater treatment plant (WWTP) input. Figures 2.2 and 2.3 show the location

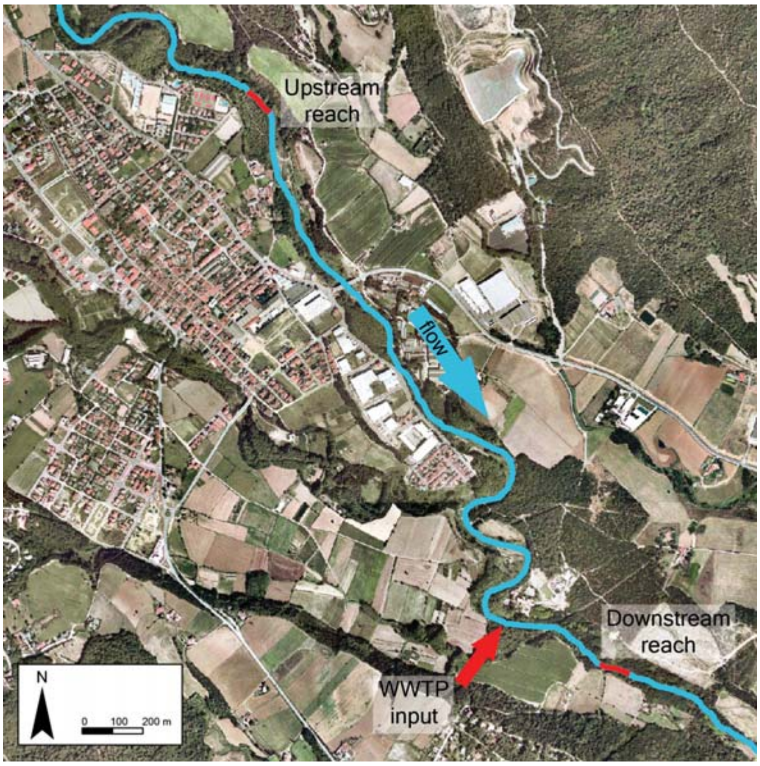

Fig. 2.2. Aerial photograph of La Tordera stream, one of the two study streams of this dissertation. La Tordera drains a catchment dominated by forest, and the existing urban activity is concentrated in the lower part of the basin. The course of the stream, the upstream and downstream reaches, and the point source input are highlighted.

of the upstream and downstream reaches in the two study streams of this dissertation, as well as the point at which the WWTP input enters these streams. This setting allowed to examine the effects of point sources (i.e., WWTP inputs) of nutrients on structural and functional aspects of each particular stream. In addition, a reach that was longer than the downstream experimental reach and that started just below the WWTP input was also selected (referred to as *gradient* reach in Fig. 2.4). The downstream reach was included as part of this longer

Fig. 2.3. Aerial photograph of Gurri stream, one of the two study streams of this dissertation. This stream drains a catchment dominated by agricultural activity. The course of the stream, the upstream and downstream reaches, and the point source input are highlighted.

reach. Information from this reach allowed to examine the recovery capacity of the stream below the input from the point source. To characterize each reach in terms of hydromorphologic features, several transects were defined along the reaches (6 at the upstream and downstream reaches and 10 at the gradient reach; Fig. 2.4).

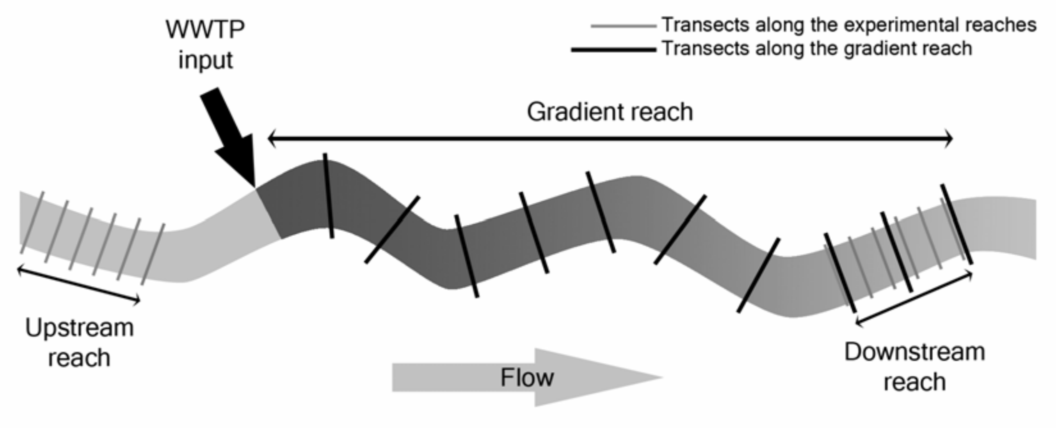

Fig. 2.4. Scheme of the field sampling setting. Transects selected along the upstream and downstream reaches are represented with grey solid lines, and those selected along the gradient reach are represented with black solid lines.

Field work planning

In each selected stream, a minimum of 6 samplings were done on different dates during 2002-2003 encompassing changes in environmental conditions. Each sampling date consisted of at least 3 days of field work, in which we conducted different experiments and samples collection in the upstream, downstream and gradient reaches (Table 2.1). Table 2.2 describes the samples that were collected and the measurements and experiments that were done. The results from the field samplings permitted us to estimate the parameters needed to achieve the proposed objectives.

Table. 2.1. Schedule of the sampling and experiments during each sampling date to obtain the samples and data needed for the study.

		Tasks			
	Location	Morning	Afternoon	Evening	Night
Day 1	Upstream reach (see Fig. 2.4)		Nutrient additions: $NH_4^+ + PO_4^{3-}$ and $NO_3^- + PO_4^{3-}$ Butane addition	Metabolism	Metabolism
	Gradient reach (see Fig. 2.4)			Hydromorphological transects and collection of water samples	
	Downstream reach (see Fig. 2.4)	Collection of biofilm samples		Hydromorphological transects	
Day 2	Upstream reach	Metabolism	Metabolism	Hydromorphological transects	
	Downstream reach		Nutrient additions: $NH_4^+ + PO_4^{3-}$ and $NO_3^- + PO_4^{3-}$ Butane addition	Metabolism	Metabolism
Day 3	Upstream reach	Collection of biofilm samples		Collection of sediments and stream water for laboratory denitrification assays	
	Downstream reach	Metabolism	Metabolism		

Table. 2.2. Description of the sample collection and parameters measured in each of the experiments (i.e., tasks) conducted on each sampling date. Further details on each particular methodology are provided in chapters 4-7. *Continued*

Task	Samples collected	Parameters measured
Nutrient additions: constant rate Addition of NH_4^++PO_4^{3-}+Cl^-	Water samples before the additions: At the 6 sampling sites for PO_4^{3-}, NH_4^+, Cl^- (3 replicates). At the head (1) and the bottom (6) of the reach for DOC (5 replicates).	Water chemistry in terms of concentrations of inorganic nutrients and DOC. PO_4^{3-} and NH_4^+ uptake length, mass transfer coefficient and uptake rate (i.e., nutrient retention metrics).
	Water samples (3 replicates) from the solution added. Continuous measurement of conductivity during the addition at the bottom of the reach.	Hydraulic parameters at the reach scale from conductivity measurements: Average water velocity. Discharge.
	Water samples at plateau conditions during the additions: At the 6 sampling sites for PO_4^{3-}, NH_4^+, Cl^- (5 replicates).	
Butane addition: constant rate	Water samples before the additions for butane blank analysis: 3 samples along the experimental reach. Water samples at plateau: At the 6 sampling sites for butane analysis (3 replicates per site).	Reaeration coefficient.
Nutrient additions: slug addition of NH_4^++PO_4^{3-}+Cl^- and NO_3^-+PO_4^{3-}+Cl^-	Water samples from the solution added.	NH_4^+, NO_3^- and PO_4^{3-} uptake length, mass transfer coefficient and uptake rate (i.e., nutrient retention metrics).
	Water samples over the course of slug pulse passage: At sampling site number 6, collection of samples at even intervals (10-60 seconds, following the frequency of conductivity changes over time).	Hydraulic parameters at the reach scale from conductivity measurements: water velocity and discharge.
	Continuous measurement of conductivity during the addition (every 5 seconds).	These data were compared to data from additions at constant rate.

Table 2.2. *Continued*

Hydromorphological measurements.	Measurements at each transect: Stream wet width. Velocity, depth, and substrata type every 20 cm at cross-sectional transects. Surface conductivity in the middle of the transect.	Reach average width, depth and velocity at each transect. Percentage of substrata types.
Water chemistry longitudinal gradient.	Collection of water samples: At each of the 10 transects (3 replicates), the WWTP effluent, the tributary (in La Tordera), and upstream of the effluent input for NH_4^+, NO_3^-, PO_4^{3-}, DOC and Cl^- analyses. Measurement of conductivity and temperature: At each of the 10 transects (3 replicates), the WWTP effluent, the tributary (in La Tordera), and upstream of the effluent input.	Effects of solute inputs from the point source on stream water chemistry. Longitudinal patterns in water chemistry: NH_4^+, NO_3^- and PO_4^{3-} processing lengths and mass transfer coefficients.
Biofilm collection.	Collection of samples at 6 transects in the upstream and downstream experimental reaches for: Biofilm and filamentous green algae. Measurement of reach coverage of primary producers based on visual estimates.	Samples will be used to estimate: Chlorophyll *a* Biomass Percentage coverage of primary producers along the reach.
Metabolism	Continuous measurements of DO and water temperature every 10 min over a 24h period at the head (1) and bottom (6) of each experimental reach. Light measurements: Continuous measurements of PAR every 10 minutes during daytime at the middle of the reach (site 3).	Daily and instantaneous rates of net and gross ecosystem primary production. Daily and instantaneous rates of ecosystem respiration.
Denitrification laboratory assays	Collection of sediments at the upstream and downstream experimental reaches. One corer at each of the 6 sampling transects. Collection of aprox. 2 L of water from each experimental reach.	Potential denitrification rates.

3. Study sites

The study was conducted in La Tordera and Gurri streams, both located in Catalonia (NE of Spain; Fig. 3.1). The two streams are located relatively close (c.a., 40 km apart) and their hydrological regime is influenced by the Mediterranean climate of the region. This climate is characterized by minimum air temperatures during winter and maximum during summer, and by precipitation mostly occurring in spring and fall. This climate conditions influence the hydrologic regime of these streams (Fig. 3.2). Low flow occurs mostly in summer

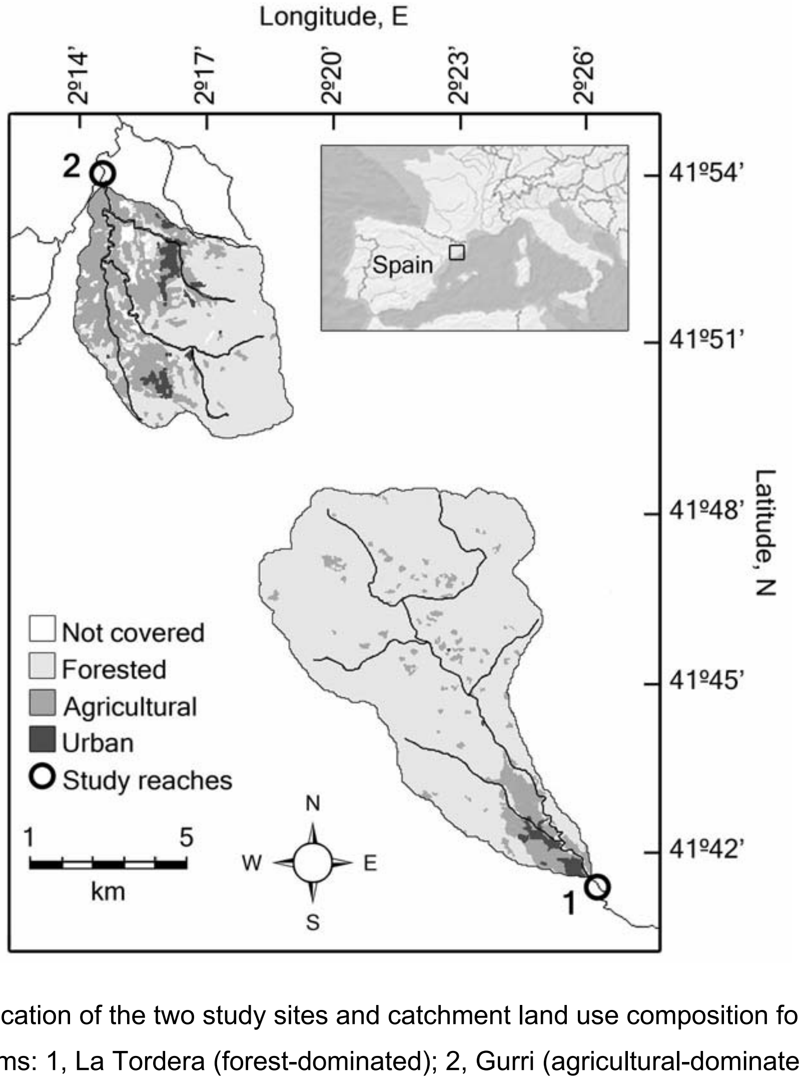

Fig. 3.1. Location of the two study sites and catchment land use composition for the two study streams: 1, La Tordera (forest-dominated); 2, Gurri (agricultural-dominated).

and these streams become usually intermittent for some period during this season. Peak flows occur during spring and fall as a result of heavy rainfalls. Nevertheless, in the two streams discharge can vary orders of magnitude within a hydrological year and between years.

Major differences between the two streams are related to the geology and land use composition of their catchments. The sub-catchment located upstream

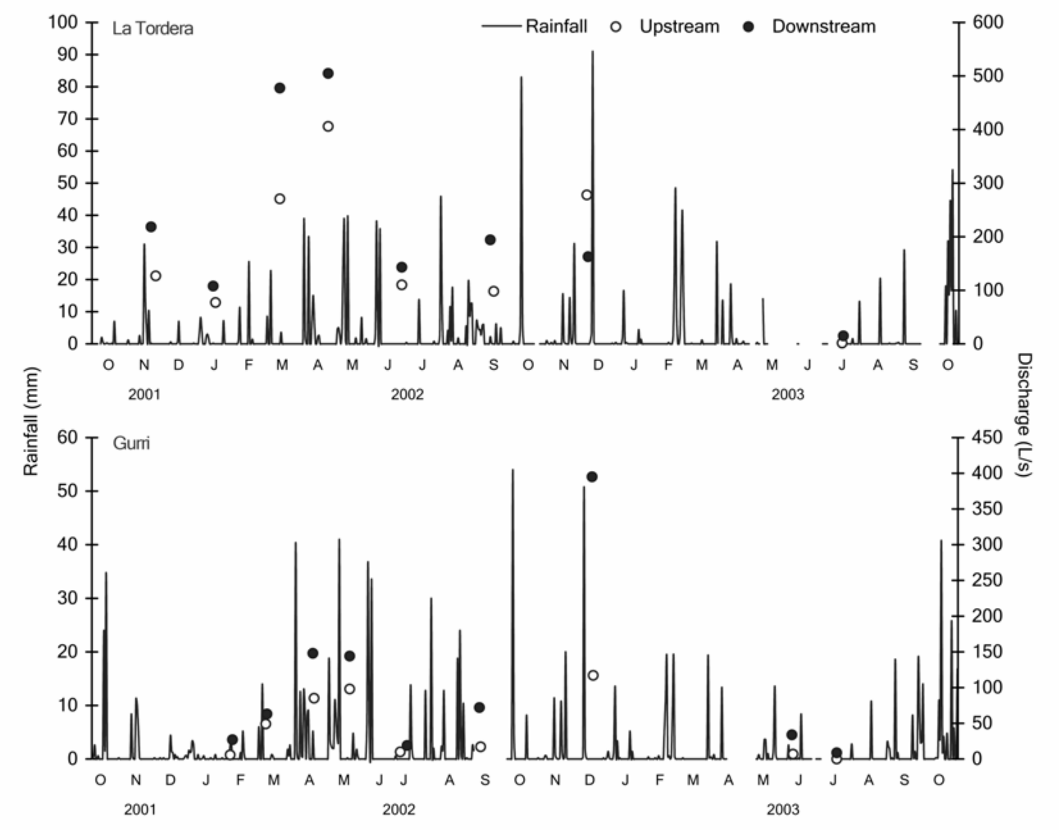

Fig. 3.2. Continuous measurements of precipitation (mm) during the study period in La Tordera and Gurri streams. The figure also shows stream discharge (L/s) measured on each sampling date at upstream (open circles) and downstream (solid circles) reaches. Precipitation data from the meteorological stations of Sta. Maria de Palautordera (La Tordera stream) and of Vic (Gurri stream); provided by the Catalan Meteorological Service.

of the WWTP input (thereafter referred to as catchment) in La Tordera is mainly siliceous, whereas in Gurri is calcareous. In La Tordera, land uses within the catchment (7024 inhabitants and 80 Km^2) are dominated by forests of evergreen holm oak (*Quercus ilex*), pine (*Pinus sylvestris*), and oak (*Quercus humilis*) with some open land (87.4 %). Agricultural practices account for a small proportion of the catchment area (10.8 %) and urbanization (1.8 %) is concentrated in the lower part of the basin, surrounding the study area. In contrast, land uses in Gurri's catchment (5270 inhabitants and 38 km^2) are dominated by agricultural practices (60.7 %) and to a lesser extent by sparse forest (35.2 %) of pine (*Pinus sylvestris*) and oak (*Quercus humilis*). Urbanization accounts for a small percentage (4 %) and is dispersed throughout the catchment.

The WWTPs that discharge into La Tordera and Gurri streams treat 5808 and 11666 inhabitant-equivalents, respectively; where 1 inhabitant-equivalent is the biodegradable organic matter load equivalent to a BOD_5 of 60 g O_2 day^{-1}. Both WWTPs perform a biological treatment with activated sludge, but lack the technology to actively remove nitrogen or phosphorus. Hence, the effluents have relatively high concentrations of these elements and are comparable between the two study streams (Table 3.1). The major difference between the outfalls was the proportion of DIN as NH_4^+-N and NO_3^--N, that indicated that the plant in the agricultural site had a high capacity to nitrify (mean ± SE % of DIN as NO_3^--N was 97.9 ± 0.9), whereas did not in the forested stream (mean ± SE % of DIN as NH_4^+-N was 87.2 ± 5.5). A small tributary joins the main course of La Tordera 20 m downstream of the WWTP outfall. Hence, the WWTP outfall and the tributary inputs were considered together as the point source of nutrients for the downstream study reach in La Tordera stream. Discharge of this tributary accounted for a 20 ± 5 % of the discharge of the point source during the study. Nutrient concentrations (mg/L) of the point source (i.e., WWTP effluent plus the tributary) were calculated by dividing the sum of their nutrient loads (mg/s) by the sum of their discharges (L/s). To conduct this study we selected reaches located upstream and downstream of the point source in La Tordera and Gurri streams.

Table 3.1. Range and mean ± standard error (SE) of nutrient concentrations and molar ratios between nutrients in the WWTP effluents discharging into La Tordera and Gurri streams (*n* = 6). Degree of significance of independent samples *T*-test comparing these parameters between the two effluents is given.

	La Tordera		Gurri		
Parameter	Range	Mean ± SE	Range	Mean ± SE	*P*
Conductivity (μS/cm)	548-1131	931 ± 92	1139-2670	1909 ± 254	0.005
NH_4^+-N (mg N/L)	2.65-24.14	13.90 ± 3.80	0.01-0.39	0.10 ± 0.06	0.005
NO_2^--N (mg N/L)	0.003-0.140	0.064 ± 0.022	0.02-0.13	0.06 ± 0.02	0.818
NO_3^--N (mg N/L)	0.08-2.41	0.91 ± 0.37	6.12-9.70	8.20 ± 0.64	< 0.0005
DIN (mg/L)	3.69-24.27	14.87 ± 3.51	6.51-9.81	8.36 ± 0.61	0.098
SRP (mg/L)	0.01-4.88	1.53 ± 0.80	0.20-0.88	0.49 ± 0.13	0.226
DOC (mg/L)	4.78-14.77	8.87 ± 1.41	3.36-5.85	4.76 ± 0.41	0.018
DIN:SRP	6-2205	568 ± 354	16-73	50 ± 10	0.174
DOC:DIN	0.50-1.52	0.85 ± 0.15	0.40-1.04	0.69 ± 0.08	0.360

The selected study sites were located at 200 and m a. s. l. in La Tordera, and at 500 m a. s. l. in Gurri. Upstream reaches were about 3 and 1 Km above the WWTP input in La Tordera and Gurri, respectively, to avoid its influence. Downstream reaches were located few hundred meters from the point source input to avoid the confounding effects of strong gradients in ambient nutrient concentrations measured below the source (Merseburger *et al.* 2005). Upstream and downstream reaches showed a run-riffle sequence (Fig. 3.3). The reaches selected to examine net changes in nutrient concentrations below the point source in the two study streams (i.e., gradient; Chapter 4) showed a run-riffle sequence with few shallow pools (Fig. 3.3). All reaches showed low channel sinuosity and a slope close to 1 %. No tributaries joined the stream along any of the selected reaches. In each stream, the upstream and downstream reaches were comparable in terms of channel morphology, substrata type and canopy cover. Similar channel morphology between the upstream and downstream reaches is reflected by significant positive relationships between stream discharge (as independent variable) and width of the wet channel, water depth and velocity (as independent variables) for the two reaches of La Tordera (Fig.

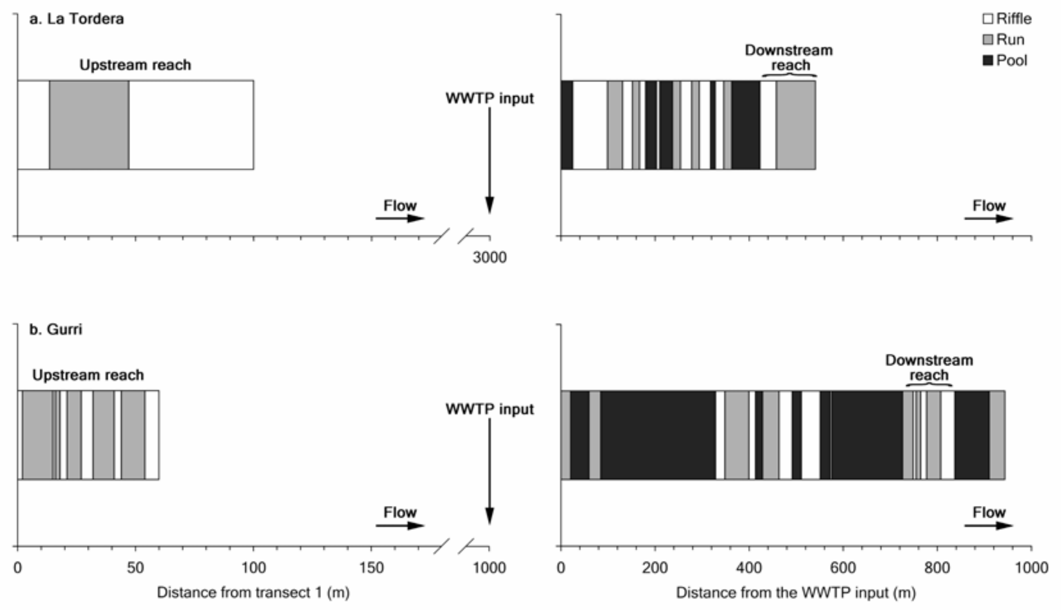

Fig. 3.3. Sequence of riffles, runs and pools in the study reaches in (a) La Tordera and (b) Gurri streams. The distance between the upstream and downstream reaches and the WWTP input is indicated.

3.4) and Gurri (Fig. 3.5). The exponents (i.e., slopes) of these potential relationships sum 1 in the two streams, and indicate that increases in stream discharge were more reflected in increases in water velocity and depth than in width of the wet channel. Hence, the channel morphology was constrained in the two reaches of La Tordera and Gurri streams. In La Tordera, substrata type consisted mostly of cobbles, boulders, pebbles and gravel (Fig. 3.6), and riparian vegetation was well developed along the two reaches. In Gurri, bedrock was the dominant substratum type with few patches of fine sediment (Fig. 3.7). In this stream, canopy cover in the downstream reach was slightly sparser than in the upstream reach.

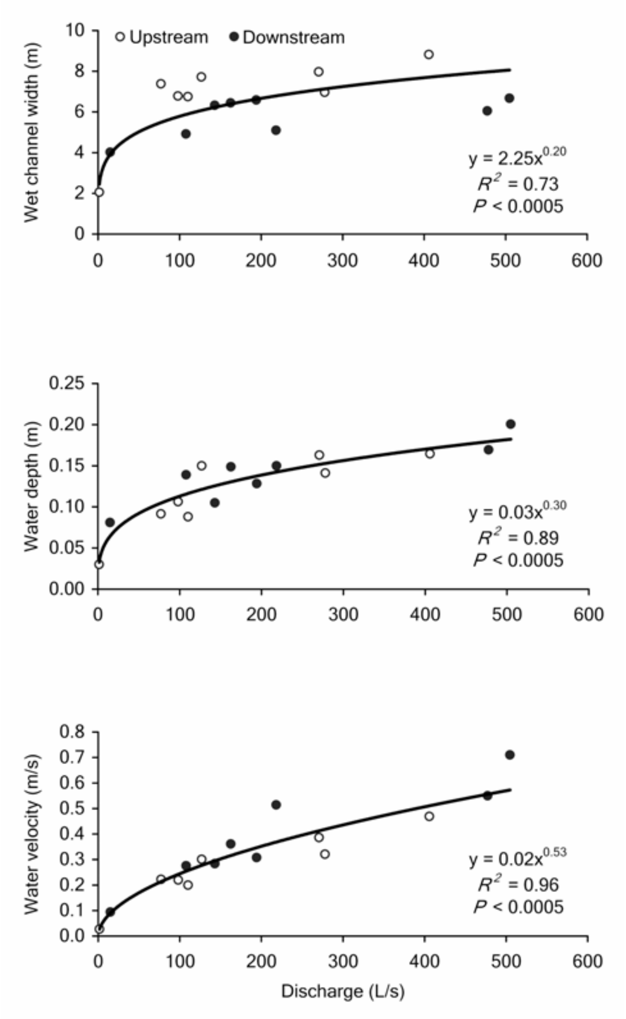

Fig. 3.4. Relationships between stream discharge (as independent variable) and width of the wet channel, water depth and water velocity (as dependent variables) for La Tordera stream (upstream, *n* = 8; downstream, *n* = 9). Solid lines represent these relationships for the upstream and downstream reaches combined. Equation and statistics (R^2 and *P)* of these relationships are shown.

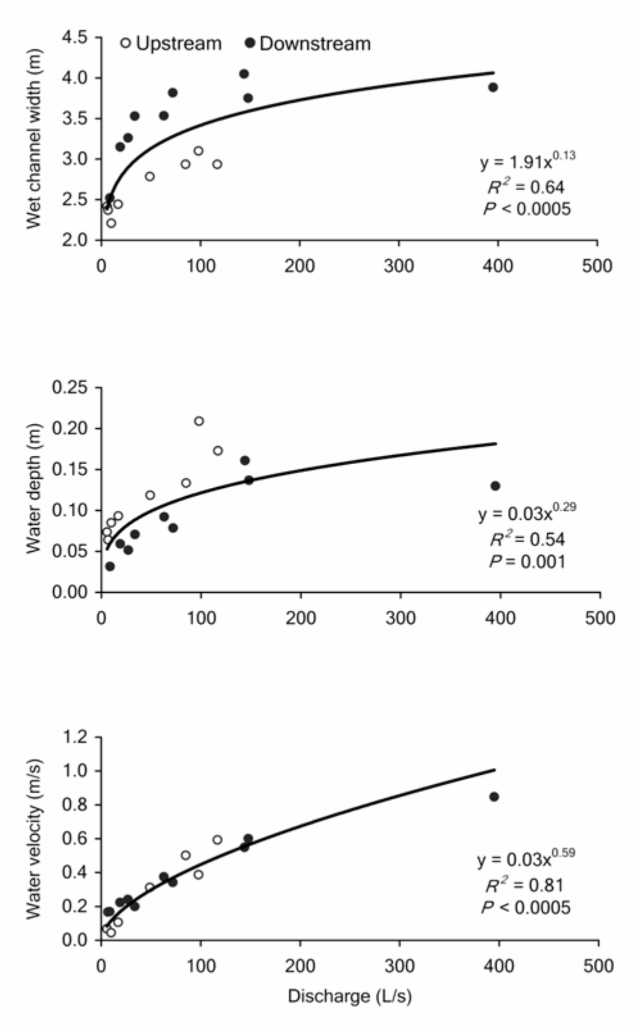

Fig. 3.5. Relationships between stream discharge (as independent variable) and width of the wet channel, water depth and water velocity (as dependent variables) for Gurri stream (upstream and downstream, *n* = 8). Solid lines represent these relationships for the upstream and downstream reaches combined. Equation and statistics (R^2 and *P)* of these relationships are shown.

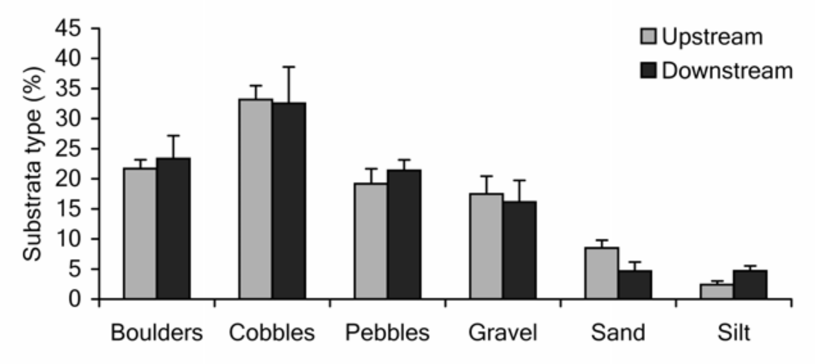

Fig. 3.6. Mean (± SE) percentage of substrata type composition in the upstream and downstream reaches of La Tordera stream. Differentiation criteria according to a modified Wentworth scale (Allan 2001): < 1 mm, silt; 1-4 mm, sand; > 4-16 mm, gravel; > 16-64 mm, pebbles; > 64-256, cobbles, and > 256 mm, boulders.

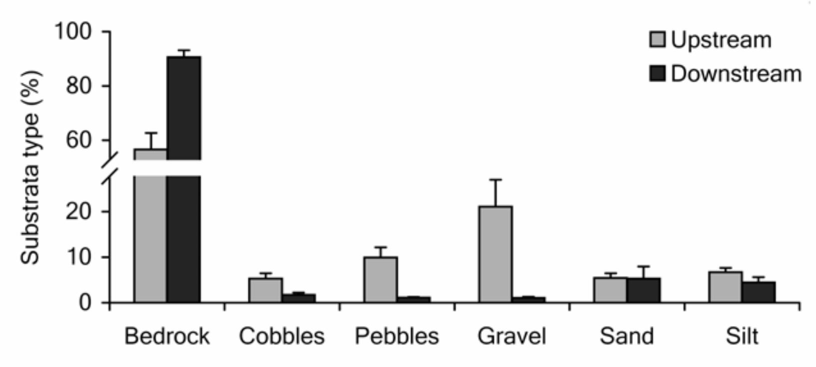

Fig. 3.7. Mean (± SE) percentage of substrata type composition in the upstream and downstream reaches of Gurri stream. We used the same criteria than in Fig. 3.6 to distinguish between cobbles, pebbles, gravel, sand and silt.