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Long period morphological dynamics in regulated braided gravel-bed rivers: comparison between Piave River (Italy) and Waitaki River (New Zealand)

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Dedicated to my father and mother

Abstract

Aim of this research has been to make an analysis of long and medium term morphological dynamics that may affect the regulated gravel-bed braided rivers as the Piave river (Italy) and the Waitaki river (New Zealand).

The Piave river (drainage area around 4000km^2), is one of the largest rivers in the north-east of Italy, the study reach is, mainly, 37 km long, and represent the intermediate course of the river within the mountain district. In addiction were been study different sub-reaches until a minimum of around 1,5 km long.

The Waitaki river (drainage area around 11000 km2), is a large gravel-bed river draining the eastern slope of Southern Alps, South Island, New Zealand, has been analyzed along a 13 km long subreach.

The flow regime and the sediment supply of these rivers have been considerably altered by hydroelectric dams, flow diversions and, along the Piave river, gravel mining. In addiction, river dynamics have been affected by the construction of stream-bank protection structures.

To document these changes, an historical analysis was performed using aerial photographs, cross section survey data and a LiDAR dataset.

Morphological features that were examine included planform configuration, active corridor extension, channel width, channel top depth, flow area, number of channels and bed elevation.

Vegetation features that were examine included, instead, areal island cover extension and different vegetation class extension.

The results indicate as remarkable changes occurred during the study period.

In both river there was a marked tendency to the diminution in the number of channels and in the active corridor extension, just subsequently to the main flood events is possible see an increase in the active corridor extensions.

Along the Piave river was possible see a marked tendency to narrowing and channel incision during the last 80 years.

The island, along both rivers, tend to encroachment and maturation for many years, occupying the active corridor. The island extension could decrease just after considerably flood events (RI > 10 years) or thanks to many close flood events. Regarding islands, has been possible see their tendency to joining with perifluvial vegetation, in consequence of long no-flood periods.

Riassunto

Obbiettivo della presente ricerca è quello di eseguire un'analisi di lungo e medio periodo sulla dinamica della morfologia fluviale riguardante fiumi a canali intrecciati a fondo ghiaioso, sottoposti a regolazione dei regimi idrici, come il fiume Piave (Italia) e il fiume Waitaki (Nuova Zelanda).

Il fiume Piave (area del bacino di circa 4000 km^2), è uno dei principali fiumi del nord-est d'Italia; il tratto analizzato ha una lunghezza di circa 37 km e si trova nella parte centrale del bacino montano. Inoltre, sono stati studiati diversi sottotratti fino ad un minimo di 1.5 km di lunghezza.

Il fiume Waitaki (area del bacino di circa 11000 km2) è il più importante fiume delle Nuova Zelanda per valori di portata, scorre dal versante est delle Alpi del Sud dell'isola del Sud della Nuova Zelanda; il tratto analizzato ha una lunghezza di circa 13 km.

Il regime delle portate e l'apporto di sedimenti di questi due fiumi sono stati considerevolmente alterati dalla presenza di dighe per la produzione di energia idroelettrica e dalla presenza di opere trasversali e di difesa spondale.

Per studiare le variazioni che si sono succedute nel tempo si è eseguita una ricostruzione storica con l'ausilio di fotografie aeree, dati storici di rilievi topografici e un set di dati LiDAR.

Le caratteristiche che si sono analizzate sono l'estensione dell'alveo attivo, la larghezza massima dei canali, la profondità massima dei canali, l'area bagnata dei canali, il numero di canali e le caratteristiche altimetriche del letto del fiume. Si sono, anche, condotte analisi sulla variazione e la dinamica della vegetazione presente in alveo, attraverso la misurazione dell'area delle isole fluviali e l'estensione delle diverse tipologie di vegetazione presente nell'area perifluviale.

I risultati ottenuti indicano come nel corso degli anni considerati vi siano stati delle variazioni considerevoli.

In entrambi i fiumi c'è stata una marcata tendenza alla diminuzione dei numeri di canali e dell'estensione de corridoio attivo, solamente a seguito di eventi di piene rilevanti è stato possibile osservare un aumento dell'estensione del corridoio attivo.

Lungo il corso del fiume Piave è stato possibile osservare una marcata tendenza all'incisione del canale durante gli ultimi 80 anni.

Le isole fluviali tendono a maturare e stabilizzarsi per molti anni, occupando così il corridoio attivo. L'estensione delle isole diminuisce solamente a seguito di eventi di piena con tempi di ritorno marcati (> 10 anni), oppure a seguito di eventi che si succedono frequentemente, anche se di intensità minore. Infine si è potuto notare una tendenza delle isole fluviali a fondersi con la vegetazione perifluviale circostante, limitando ancor più l'estensione del corridoio attivo.

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1. Introduction

The branch of Earth sciences, which studies and interprets the forms of the earth's surface of fluvial origin is known as fluvial geomorphology. It can be defined as the study of the processes that rule production, flow and accumulation of sediments in both river basin and riverbed over a long, medium or short period, and of the resulting formations on the bed and in the flood plain (Sear et. al, 2003).

In a long-term timescale (many centuries)it may be identified a cyclical pattern relating to the external factors of the system, as tectonics and climate, which can act as independent variables.

The medium-term timescale (many decades) examines the changes the fluvial system is subjected to, in relation to the variability of fundamental hydrologic-hydraulic parameters (liquid and solid discharge) and morphometric characteristics relating to the stream that is usually affected by considerable and sometimes even radical changes.

In the end, the short-term timescale is linked to experimental activities, such as pilot basins (Lenzi et al., 1996), physical models studied in hydraulic laboratories or to the direct field study of the effects caused by flood events with a known return period (Lenzi et al., 1990; Lenzi et al.,1997).

Therefore the main objective of fluvial geomorphology is the knowledge and interpretation of fluvial processes, which generate and modify landscape's shapes (Marchetti, 2000). By flowing in a river bed composed of non-cohesive loose substances, the current modifies sections' shape and its planimetric and altitudinal structure, thus originating morphodynamics processes.

The preservation of morphological shape, the change of an already-existing balance or the tendency to establish a new shape of the watercourse are the result of both varied and different fluvial processes (erosion, sediment transportation, sedimentation) and geological, climatic, hydrologic, hydraulic, vegetative and biological factors that could trigger, control or wipe out various fluvial phenomena. Such processes characterize every type of river bed, therefore are not typical of any particular morphological configuration. In fact, there are in nature varied fluvial forms corresponding to different stability conditions of beds, that is the tendency of river beds to be modelled, in relation to the geometric characteristics of the valley and as a response to a certain hydrometric status, to particular flow conditions and depending on the particle size of material transported that forms the bed and on soil composition forming the banks (Lenzi et al., 2000).

Fluvial morphology is defined as the group of the varied forms taken on by the main physiographic elements that characterize a river. The size of these forms, even if they may vary according to different landscape units, remain quite constant in time and lead to create a bed configuration having proper and unique characteristics (Billi, 1995). There are no clear limits among the various morphological typologies but there is a continuous shift from one form to the other. For this reason, in order to be able to define the morphology of a watercourse and the typologies it is made of, one single parameter is not enough, therefore different factors must be examined and taken into consideration, such as:

- *Sinuosity*: it expresses the ratio between the length of the river and the length of the valley axis (Leopold et al, 1964);
- *Grain distribution*: it consists in analyzing the particle size of the material forming the bed;
- *Total sediment transportation*: defined as the sum of two components, that is bed load and suspended load transportation;
- *Braiding*: it is the number of bars or islands situated along a given reach. It is defined as the ratio between the main channel width under flood conditions (when bed sediments are completely flooded) and its width under standard flow conditions;
- *Vertical running off*: it specifies whether the stream flows deeply incised in the valley's plain or in its sediments. It is normally expressed by the ratio between the width of the flooded area and the width of the open channel, which corresponds to the bankfull discharge (Kellerhals et al., 1972; Rosgen, 1994);
- *Width-Depth ratio*: it describes the size and the form factor as the ratio between the bank and bank width of the channel, and the corresponding mean depth (Rosgen,1994);
- *Planimetry*: it explains how a watercourse flows into its drainage area;
- *Gradient*: it is a very important aspect in the determination of the hydraulic, morphological and biological characteristics relating to a watercourse;
- *Longitudinal section*: it is the change in height of a stream which explains how the river can be divided up into morphological categories according to the gradient;
- *Cross section*: it indicates the incision degree of a channel and the extent of the most important hydraulic variables.

These sets of variables, which are typical of every fluvial environment, can be divided up into reference variables or boundary conditions

- Reference variables are the main elements causing the change in fluvial environment. They are represented by solid and liquid discharge systems.
- Boundary conditions are the parameters that describe the physical conditions by which a river flows. They are mainly represented by the particle distribution of the material that forms riverbed and banks, by the lithological and geomorphological characteristics of the fluvial basin, by the gradient and the topography typical of the valley, by the main characteristics of riparian vegetation and obviously by human influences.

The type and the extent of phenomena causing river regulation must be always referred to a specific timescale that, in the specific field of fluvial geomorphology, can be divided up into 3 different levels: long, medium and short (Figure. 1.1).

a) The long timescale, called also "geological", concerns the changes occurred in a time interval of million years that had been often caused by factors not directly linked to the fluvial system, as tectonic movements and climatic changes.
b) The medium timescale, or historic scale, describes the changes occurred in a time interval that ranges from decades to centuries. This is the most representative phase in the study of fluvial morphology.
c) The short timescale gathers up the events that caused changes in the fluvial environment during a short period of time, that is a couple of years.

As regards the "short" time interval, man is the main morphogenetic factor of a fluvial system, as he causes important changes in the rate of flow and sediment transportation that subsequently affect riverbed dynamics,too. (Castiglioni e Pellegrini, 2001).

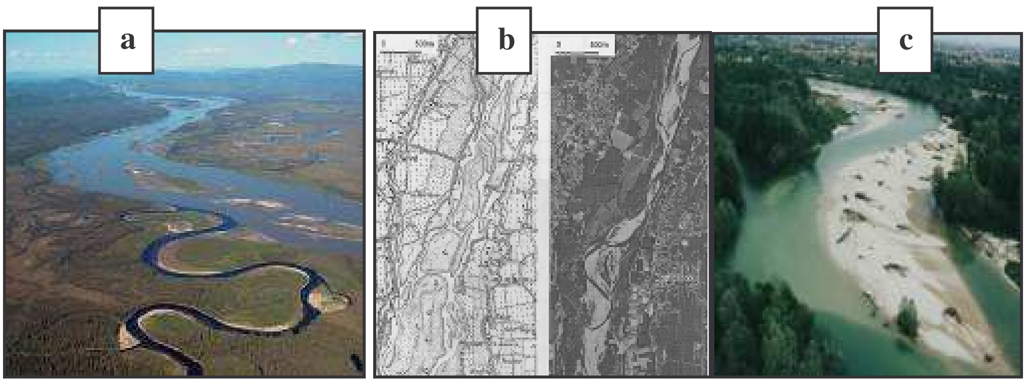

Figure 1.1: examples of modifications occurring over different timescales: a long, b medium, c short

A river is defined as stable or as in dynamic equilibrium if, considered in a medium timescale, it maintains its distinctive shape and size (width, depth, bottom slope, etc.) almost unchanged, although it progressively changes its course. On the contrary, if the distinctive parameters of the watercourse are subjected to substantial changes, due to natural or human-caused phenomena that could change its equilibrium status, the river becomes unstable. This aspect depends on the way watercourse responds to different bad conditions that can lead to change processes affecting the fluvial system. That is to say that changes in altitude (incision or sedimentation), changes in the bed's shape or in the planimetric course occurring over different timescales (medium or short) and under different spatial conditions (local scale or concerning the entire fluvial system) and which can differ as opposed to the ongoing phenomena they are subjected to (Figure 1.2).

Figure 1.2: example of unstable rivers. The fist picture shows a tract in which incision phenomena prevail; the second is related to sedimentation

The *Water Framework Directive* (Directive 2000/60/CE) first introduced the new term "Hydromorphology". Hydromorphology integrates the geomorphologic approach with the analysis of the changes the rivers undergo, as a consequence of the changes in their discharge system induced by the presence of artificial works in the bed and by the continuous drawing of water and aggregates for human purposes (AdBPo, 2008).

Fluvial geomorphology together with hydromorphology does contribute to determine which are the forms and the processes characterizing a watercourse, by analyzing them within different spatial areas (basin, reach, surrounding environment) and according to different timescales. Furthermore it helps to recognize the important characteristics typical of the fluvial system such as sedimentation, erosion areas and the sediment balance. It also allows to understand the influence of the processes affecting the morphological and ecological structure, environmental security and the utilization of involved resources. No less important is the possibility to assess the quantitative and qualitative extent of changes in order to solve them.

1.1 Elements of the fluvial system

Overall a water flow has many features relating to fluvial dynamics. The fluvial system is not merely limited to those areas near the river bed, but it encompasses all the portions of territory which are affected by the stream or have been so in the past.
The main fluvial forms are below described by making reference to the categorization provided by either Hupp & Osterkamp (1996) and Rinaldi (2000).

Channel bed

In a perennial river, it is the area of river bed partially or wholly covered with water for the most part of discharges affecting the stream, corresponding in fact to the section containing the supposed ordinary flood, to be more precise the intermediate discharge that compared to a series of maximum-range discharges reported over one year, is equalled or exceeded as regards 75% of events (Hydrographic Service, 1928).
The water level that reaches the floodplain is defined as the bankfull level which corresponds to the bankfull discharge.
Over base flow periods, water flows inside the ordinary bed along a particular course having a section that is less than the ordinary one, called base flow bed.
The ordinary bed is naturally demarcated by banks and channel shelves.

Floodplain

Is a level surface created by sedimentary depositional processes that borders the river, which is shaped by the progressing sedimentation inside and outside the river bed. In some river beds, one can find some transition forms between bars and floodplain: we talk of bars left by the flow in the course of time that gradually turn to vegetation and then into floodplain (Fig.1.3).
In natural conditions floodplain is affected by 1-3-year-return-period floods. The recurrence interval**,** also known as the return period, is the flood frequency through

which one can estimate the probability of a given flood event having some particular charactersitics, so that the value of discharge is equaled or exceeded in any given year.

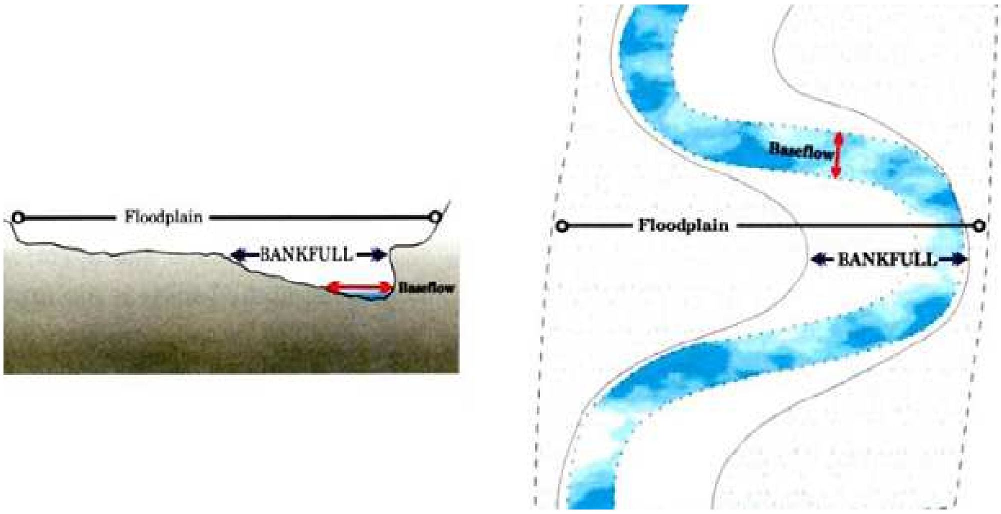

Figure 1.3: example of a cross section area and relative layout drawing which noticeably depict the base flow, the bank full and floodplain.

Bar

We talk of sedimentary bodies present inside the bed having no perennial vegetation; it is the lowest topographic surfaces extending along the active bed, being slightly over the baseflow.

Bar movement performs through destruction, regeneration or migration (upstream erosion and under current aggradation). Sometimes their mobility reduce due to vegetation, being subordinated to their position inside the bed, anyway (Lenzi et al. 2000).

The most frequently overflown bars, composed of materials and with no proper vegetation, are subject to sediment movements by the current which dislodges vegetation on its surface. A non- vegetated bar is also called active bar.

In long-lasting bars, which are more raised, one can find lighter sediments allowing the development of vegetation. Vegetation in turn does contribute to steady the bar itself by increasing the resistance to motion, thus decreasing stream velocity over it by contributing to deposit additional light sediment according to a positive feedback process.

There are several typologies of bars closely related to fluvial morphology (Figure 1.4).

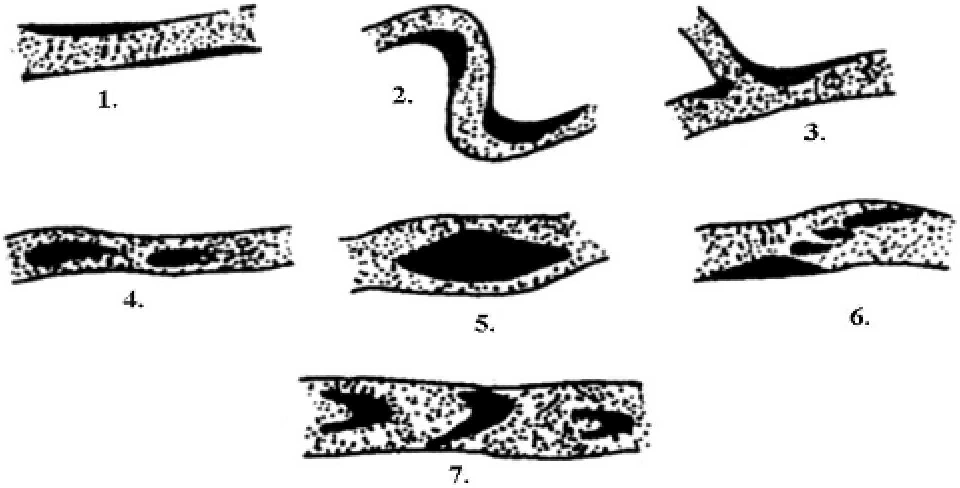

Figure 1.4: example of fluvial bars: 1 – lateral bars; 2 – meander bars; 3 – merging bars; 4 – longitudinal bars; 5 – diamond-shaped bars; 6 – diagonal bars; 7 – sand dunes

Alternating lateral bar are typical of straight rivers or low-sinuosity ones (Fig. 1.5); instead, meander bars are typical of those rivers having a higher sinuosity ratio, which tend to evolve in the interior point of curves in which stream has a lower energy; instead, lateral bars and diamond-shaped ones are typical of braided rivers.

Figure 1.5: example of lateral bar in the Fanes river (BL) (Lenzi et al., 2000)

<u>Island</u>

It is created in a suitable environment comprising the partial cover due to either light sediment and bed portions in which vegetation can grow (pioneer islands). These islands are to be found in particular by gravel bars set at higher positions, thus denoting better balance conditions. It is the result of both a progressing growth of vegetation and the accumulation of light sediment as a consequence of woodland which settles the sediment (see in detail section 1.5).

Riffle

It represents the topographic “top-level part” of a bed longitudinal profile, created by sedimentary depositional processes, which are composed of clastic rocks and rude material, such as small rocks lacking in fine sediment (sand).

It can be found in many typologies of rivers, in particular the gravel ones excepting those having highest gradients (>3-5%), where one can see the formation of real steps.

Over moderate and base flow periods, depending on the local increase in bed gradient, they have a minor effective depth of the stream and higher velocity which exceeds the adjacent pools. Over ordinary floods as well, water level becomes more uniform, thus velocity differences result to be lower.

Step

These are real steps created and shaped by the current itself through deposition or determined by factors which can not be adjusted by the current such as rock steps or log steps. All the typologies of steps can be found in mountain rivers in which particle size of the bed has bulky elements which can originate the steps as well as the surfacing of rock substrate and the presence of bulky woody material.

Pool

These are areas relating to the bed in which the minor effective depth of the current exceeds the adjacent areas (as riffles or steps), that are caused by the localized erosion action caused by a current exceeding energy as opposed to average slope conditions. Pool hydrodynamics and shape are determined by the creation of secondary currents (vertical and horizontal axis-shaped twirls) following the strong velocity gradients caused by a current disturbance at head, such as a rock channel shelf, a step, a riffle or a bar (Figure 1.6)

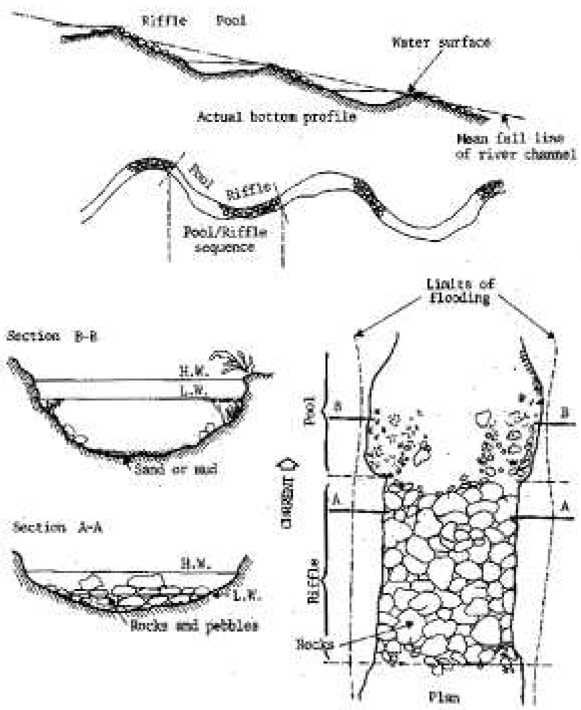

Figure 1.6: outline of a riffle -pool sequence

<u>Terrace</u>

It is a sublevel surface bordering the fluvial erosion slope due to an increase in erosion action (incision) of the river following a deposition phase due to either human activity or climate change (Fig.1.7). The rivers changes its altitude position by creating a new floodplain suitable for the new bed altitude. The abandoned floodplain is called terrace, which can be however flooded by flood events, that would depend on how height the terrace is.

Figure 1.7: outline of fluvial terrace

The formation of a new floodplain is related to fluvial movements, either vertical or lateral, while the terrace is gradually eroded by mentioned movements.

Channel shelves and banks

These are surfaces having a certain gradient or real differences in height dividing the different fluvial forms. The former is created through the fluvial erosion, whereas the latter creates a particular form of fluvial aggradation due to the overflow from river bed during some particular events (Marchetti, 2000).

Meanders

These are curves that take twists and turns along the river course. Meander movement occurs through the fluvial erosion that occurs at curve's outside bank expense, where the stream reaches its maximum velocity. The erosion of outside bank contrasts with the sedimentation process of the inside bank, in which velocities are lower (Fig 1.8).

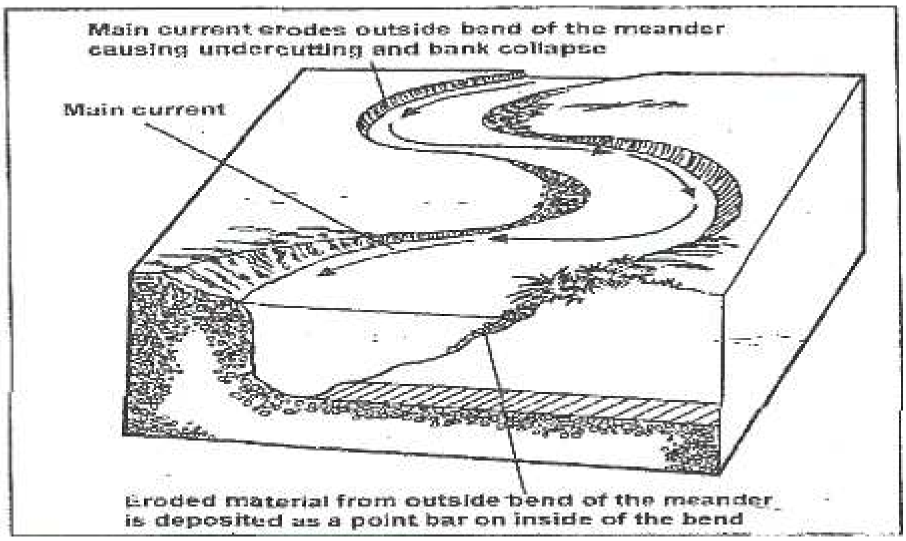

Figure 1.8: flow direction lines relating to a meander

1.2 Classification of channel patterns

1.2.1 Leopold and Wolman's classification

Straight, meandering and braided patterns were described by Leopold and Wolman in 1957.

In Table 1.1 is possible see the main characteristics of the Leopold and Wolman classification:

Table 1.1: summary of selected terms describing alluvial channel patterns

Channel Pattern	Description
Straight	Single channel, sinuosity <1,5, alternating bars
Meandering	Single channel, sinuosity >1,5, usually dominated by suspended sediment load
Braided	Multiple flow paths separated by transient bars, relatively stable bars, or islands

1.2.1.1 *Straight channels*

In the field it is relatively easy to find illustration of either meandering or braided channels. The same cannot be said of straight channels. In fact, truly straight channels are so rare among natural rivers as to be almost nonexistent. Extremely short segments or reaches of the channel may be straight, but it can be stated as a generalization that reaches which are straight for distances exceeding ten times the channel width are rare.

Often streams of this straight class area in the headwater areas, and dissipate hydraulic potential energy through a series of high friction steps and scour pools. Straight channels area considered relatively stable.

1.2.1.2 *Meandering river*

Often, stram of this nature are I the more genle sloping and wide valleys, where the stream can laterally migrate across the valley, eroding floodplain on the cut-bank side, and building floodplain on the point bar side. The meanders help the stream to dissipate hydraulic potential energy through scour and turbulent eddies. Meandering channels are considered intermediately stable with semi-cohesive bank material, moderate and suspended sediment.

1.2.1.3 *Braided river*

A braided river is one which flows in two or more anastomosing channels around alluvial island. Braided reaches taken as a whole are steeper, wider and shallower than undivided reaches carrying the same flow. Braided pattern should developed after deposition of an initial central bar. The bar consisted of coarse particles, which could be not transported under local conditions existing in that reach and of finer material trapped among these coarser particles. This coarse fraction became the nucleus of the bar which subsequently grew into an island. The braided pattern is one among many possible conditions which a river might establish for itself as a result of the adjustment of a number of variables to a set of independent controls. The requirements of channels adjustment may be met by a variety of possible combinations of velocity, cross sectional area and roughness. Braiding represents a particular combination, albeit a striking combination, of a set of variables in the continuum of river shapes and patterns.

Braiding is not necessarily an indication of excessive total load.

Braiding channels are considered relatively unstable with non-cohesive bank material and predominantly bedload sediment

1.2.2 Billi's classification

In 1994, Billi grouped the possible morphological typologies of a watercourse (picture 1.9) into 5 main configurations:

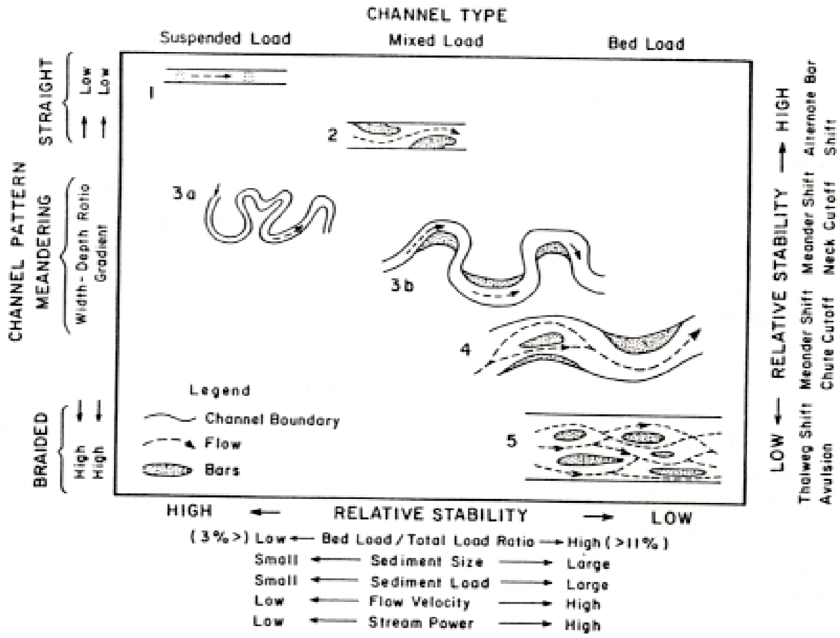

Figure 1.9: scheme of main configurations of the riverbed

1.2.2.1 *Straight rivers*

They are very rare in nature. Generally there are no single channels 10 times longer than the width of riverbed**.** Even when banks are straight, the main channel follows a slight sinuous course, which is due to the presence of alternate bars. Sinuosity (length of the river/length of the valley axis) reaches values close to unity, both in case of moderate and flood flow. Single channels mainly originate in highland areas, where slopes are very steep (3-5%) and there is plenty of coarse-grained sediments (gravel, pebbles and rocks). In mountain regions single channels flow into the narrow bed of V-shaped valleys and generally they are included in an undeveloped alluvial plain. A very common morphological characteristic one may observe in mountain streams is the sequence of *riffle-pools*, that is very steep tracts having moderate water surface elevation followed by flatter stretches having higher water surface elevation. The distinctive alternation of *riffle-pools* is linked to lateral bars and sometimes to longitudinal medians. The portion of the upstream bar (head of the bar) has coarser sediments, as it is directly affected by the current; on the contrary the downstream stretch (tail end of the bar) is characterized by finer sediments. These substances tend to float and during flood events they can move, dissolve and re-create thus constituting a vital and irreplaceable element in river dynamics. When slopes are steeper, more than 4%, and the grain distribution of the river is various, *riffles* shorten and originate step-like morphological unit (*step*). In these stretches the cross section becomes rather terraced; there are *step-pools* sequences, that is bed entities where the step is composed of tightly stuck rock groups extending across the current in such a way to create a sort of terrace, while the *pool* is the space between one *step* and the other at a water surface elevation that varies from upstream towards the downstream side (Montgomery e Buffington, 1997). They are stable structures until floods occur over a return period of 30-50 years. The dynamics of single-channel rivers is quite limited. By considering boundary conditions, which are affect, and the very steep slopes, avulsion phenomena rarely take place. Much more common is river bed and banks' erosion which causes incision and channel shifts, therefore it can endanger hydraulic security systems.

1.2.2.2 *Braided rivers*

Their formation is favoured by high energy conditions and steep slopes, a very variable water discharge, abundant supply and availability of sediments, relevant quantities of bed load transport and non-cohesive banks. They are characterized by very wide beds composed of one or two channels similar in size, and showing *riffle-pool* phenomena. Their length-depth ratio is usually higher than 40 (it can reach even 300) and their gradient is lower than 4%. In braided rivers two bar types, different in altitude, are to be identified. Lower bars are continuously subjected to submersion and erosion phenomena, while higher ones, which are also more stable, are reached by water only during severe flood events. The main distinguishing characteristics of these two bars are referred to the particle size distribution and the presence of vegetation. Bars, which are frequently submerged, are characterized by coarse-grained sediments and lack of vegetation (or poor presence). In more stable bars, which are also higher, finer surface sediments are more abundant, thus favouring the spread of vegetation. Vegetation itself strongly helps to stabilise the bar by increasing its resistance to motion, thus lowering the current velocity above it and favouring in this way further deposition of finer sediments, according to a positive feedback process. *Braided* rivers are characterized by high dynamicity with a continuous displacement of bars and channels during flood events. A further peculiarity of this morphological typology is the difference between low-flow and ordinary overflow channels. During base flow, few channels are filled with water, while by an increasing discharge rate more and more channels collect water until filling the entire flood channel. Under these conditions, sinuosity reaches values close to unity

1.2.2.3 *Wandering rivers*

These are channels characterized by a low or medium sinuosity (1.3 – 1.5) and they belong to the intermediate shape between braided and meandering rivers. They are usually composed of alternate lateral bars, usually half-moon like or more or less diamond-shaped**,** and by one single active channel. There could be also a second channel, usually adhering to one of the banks, which can be active (shear channel) or inactive (dead channel) and with a variable width, but not exceeding that of the main channel. Furthermore there are also secondary transverse channels on the bars. The shear channel forms during strong floods due to the cross shear of lateral bar; it can subsequently obstruct or be abandoned, or, on the contrary, even widen and become the main channel. The dead channel, instead, is the final part of a no-longer-active channel, which is supplied only during floods with stagnant water. The main characteristic of these fluvial systems is the sinuosity variation by changing water discharge. During base or moderate flow, bars emerge and the stream takes on a meandering shape (sinuosity equal to 1.5), which fades also during non-extraordinary floods provided that the water surface elevation is so high to cover a large part of the lateral bars, reaching this way a sinuosity level close to unity, as banks are generally straight and parallel. According to some scientists, wandering rivers represent from an hydraulic and morphological point of view, an unstable and indefinite configuration, which aims at evolving into a meandering or braided river. They are considered as the evolution of braided rivers determined by the anthropic influences. They are very common in Italy and in many mountain areas.

1.2.2.4 Meandering rivers

The planimetric course of this kind of rivers is characterized by curved bends, called meanders, that follow one another in a more or less repetitive and uniform way. Their sinuosity degree (length of the river/length of the valley axis), usually higher than 1.5 and which sometimes can reach also 3 in value, is not affected by the hydrometric level variations of the current. Meandering rivers generally have moderate gradients (even less than 0.1%) and a sandy grain distribution (sometimes even gravelly) and are typical of low gradient valleys.

The inner side of the curve is usually occupied by the meander bar, which has a semi-conical sediment structure with a half-moon shaped base, that is slightly bent towards the outer bank.

The main characteristic of meandering rivers is referred to the high mobility of the channel, which occurs through migration and meander's cut-off. This process can occur during flood events in coincidence with a sedimentation mechanism inside the curve and an erosion process of the outer bank. In this way the meander moves both crosswise and lengthwise as against the valley axis, followed by the corresponding bar. The meander migration brings about a sinuosity increase, which can cause the cut-off of the meander neck. This phenomenon occurs during floods when erosion on the outer side of two contiguous meanders brings the two bends closer. The sheared meander will generate a half-moon shaped lake (oxbow), where the overflow finer sediments are going to settle, until incorporating it in the alluvial plain.

Avulsion phenomena are quite common in meandering rivers. They consist in the abandonment of an old reach as a consequence of bank erosion during floods, with the resulting formation of a new river bed inside the flood plain.

1.2.2.5 *Anastomosing river channels*

They are a kind of braided rivers composed of two or more relatively stable channels; if considered separately, they have a variable sinuosity degree but they may be compared to meandering interconnected channels. The areas comprised among the various branches are not composed of moving bars, but of flood plain portions, which are much more larger than channel width. Channel gradients are very low (less than 0.1%). Anastomizing river channels are a very rare type of watercourse, which originate in areas characterized by quick subsidence conditions, by the raising of basic water level and by other phenomena that favour sedimentation processes. Their dynamics is slower if compared to meandering channels as bank cohesion is very high and determines a great stability of the river bed.

1.3 Dominant and effective discharge

The use of dominant and effective discharge might cause some misunderstandings and perplexities, therefore we need to provide a clear overview on these separate terminologies.

The change in river bed morphology (shape, gradient, sinuosity, cross section) usually augments rapidly as liquid discharge increases. We also need to highlight that over periods the stream is subject to high-level discharges, such periods usually last less than those ones having moderate discharges (Wolman and Miller, 1960), and in any case both erosion succession and solid-load deposition affect the whole succession of high and moderate discharges. As part of this succession, one can see a particular interval of discharges that, due to its duration, has more influence compared to the ones during change and maintenance processes relating to fluvial system structure. The analysis regarding the ratio between the rate of discharges and fluvial morphology in alluvial deposits is usually addressed by introducing the concept of dominant discharge.

In fact, this is the discharge that, amongst the rate of discharges of a given stream, results to be more important in relation to bed modelling. Dominant discharge may be defined as follows:

- It is the most important discharge of all flows as regards a particular fluvial dynamics effect (Caroni and Maraga, 1983); to be more precise, it is a discharge that, when constantly mantained in a channel for a long period, gives the same long-term structure.
- Dominant discharge may be defined as the bankfull discharge, that is such discharge filling the channel up to the top of banks without overflowing (Andrews,1980; Carling, 1998; Hey, 1997). During discharges that are bigger than a bankfull, we observe an overflow and the consequent flood of floodplain.
- Dominant discharge may be defined as the discharge having a recurrence interval equal to 1-2.5 years (Leopold,1994) or 1.5-2 years (Rinaldi, 2000), thus corresponding to ordinary events.

The concept of effective discharge was first introduced by Wolman and Miller in 1960. During their studies concerning magnitude and frequency of geomorphological events, they denied that flood events having maximum load were the ones with a bigger sediment transport, thus affecting bed morphological dynamics, and proving this way that such characteristics were related to flood events having higher frequency.
In fact, the effective discharge is linked to the maximum contribution of the average solid transportation over one year, that is the maximum value of transported solid load which is linked with a certain liquid discharge by its frequency. Therefore this is the discharge transporting the maximum percentage of sediment. It may be calculated through data obtained from both liquid and solid discharge by searching the liquid discharge increase which carries the major fraction of solid transportation over a year.
The effective discharge may be localized by the peak of curve III (Fig.1.11) obtained through integrating both the frequency curve relating to the liquid discharges, and the curve representing sediment production (solid discharge linked to the liquid one). It coincides with the average of discharge increase which can transport the major fraction of annual sediment over a period estimated in some years (Andrews, 1980).
Figure 1.10 provides a graph about the relation existing between sediment transportation, transportation frequency and effective discharge (Wolman and Miller, 1960).

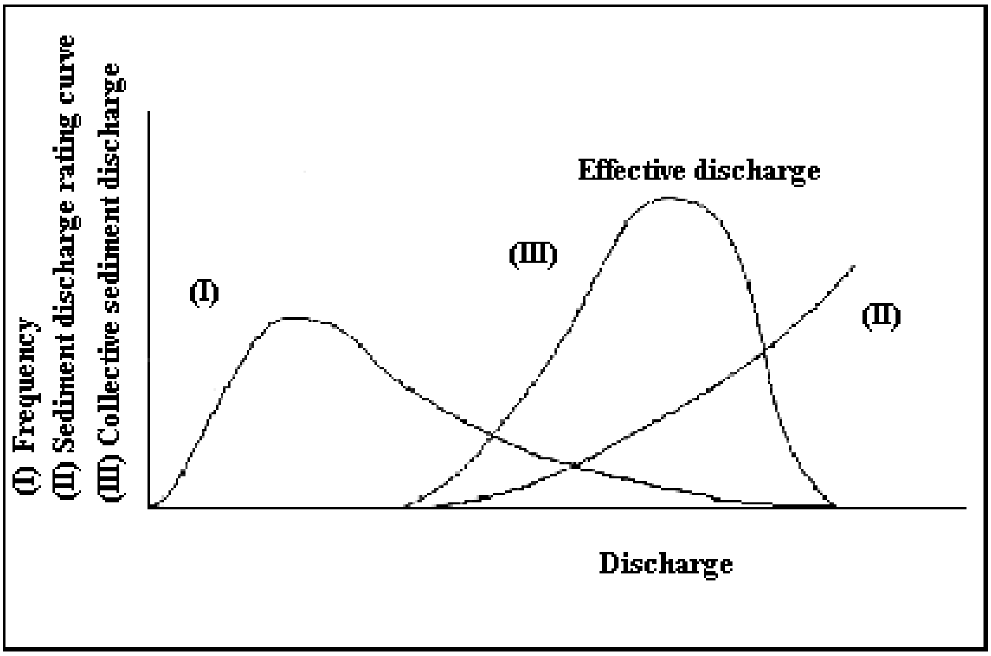

Figure 1.10: hypothesis of intensity and frequency of fluvial modelling depending on dominant role in moderate flows and ordinary floods (Wolman e Miller, 1960)

In above graph, the rate of solid transportation is represented by curve II, whereas curve I represents the distribution of frequencies relating to given liquid discharges previously analyzed. In the final stage, curve III has been obtained by multiplying curve I by curve II. Whether the mobility thhreshold of bed load is relatively low,the effective discharge occurs during the periods of moderate flow or ordinary flood.

Despite conceptual strengtht of the effective discharge, one can notice several difficulties relating to its practical application, which can be linked to the need to have both series of long-term liquid discharges and measurements of solid transportation. Wolman and Miller (1960), beased on many experimental data and studies carried out on Rocky Mountains and in the rivers of U.S west coast, asserted that, in terms of solid trasportation accumulation, flood events having high frequency and low transportation intensity are more important and significant, as reported below:

- Such conclusions remain valid only if bed mobility threshold is very low;
- A bigger variability relating to the system of liquid flows entails a higher percentage of sediment that can be transported by extraordinary floods; thus the role of extraordinary events is more important in semi-arid climates;

- The quantity of sediment transported by extraordinary events increases as basin drainage area decreases.
- A higher variability relating to the system of liquid flows entails a higher percentage of sediment which can be transported by extraordinary floods; thus the role of extraordinary events is more important in semi-arid climates;
- The quantity of sediment transported by extraordinary events increases as basin drainage area decreases.

1.4 Fluvial dynamics and anthropic action

The anthropic action in the fluvial ecosystem has started processes, that usually have the same intensity compared to the natural ones, that led to new evolution tendencies or to the acceleration of the ones in action by overlaying its own effects over the previous ones (Billi,1994). In that case we need to talk of fluvial dynamics, that is the combination of natural and anthropic changes the stream undergoes. Fluvial dynamics entails changes in structure, altitude and planimetric course of a bed, thus comprising the fluvial morphology, but in particular the transition from a configuration to another as adaptation to the new conditions (Billi,1995).

The fluvial system, which comprises a bed, a floodplain and its significant fluvial area (area in which the stream makes its influence felt from a physical and biotic point of view) is an important resource, but when treated in an inopportune way it may turn into a menace for both environment and human activity. A thorough management of the stream implies the knowledge of those processes that adjust the fluvial dynamics in response to natural or artificial input. To understand stream history gets important in order to plan both its evolution tendency and system reaction to any kind of intervention (Cencetti et al., 2005)

Italian rivers have been affected by human intervention in the past, thus causing a significant change in natural evolution tendencies of the system. Especially it caused: the incision of beds of the order of 3-4 meters up to 10 meters in some stretches of the Valdarno river (Cencetti et al., 2005), the constriction of beds even bigger than 50% (the Po river , the Piave river, the Brenta river), changes in bed typology from braided to wandering (an intermediate configuration between aforementioned ones; Surian Rinaldi, 2002) and a decrease in solid discharges (Dutto F., 1995)

The main anthropic activities which caused such effects are as follows: gravel mining, bed settlement and relative road infrastructures have lowered the presence of sediments.
Few italian rivers currently present natural or semi-natural conditions: only less than 10% of the total length of mountain rivers present a semi-natural condition. Bed incision and its narrowing causes social and environmental repercussions, a decrease in biodiversity, damages to buildings and infrastructures as well as a decrease in water accumulation in the groundwater layer**.**
The Italian rivers (in particular the Po river , the Arno, and the Tiber river) have always been affected by changes carried out by human activity from Roman time onward. Until XIX century, most of the projects were closely related to channelization and diversion in order to protect and safeguard buildings and persons from floods, thus ensuring the development of agricultural productivity. In the last years there have been some further anthropic projects, such as the construction of energy-producing and flood lamination infrastructures as well as gravel mining. In fact, this last one caused the change in fluvial systems, particularly intense from 1950 to 1970.
Besides it caused a decrease in solid transportation which started a series of problems relating to vertical erosion, thus causing river bed deepening. There were many consequences related to such processes: the instability of river banks, the undermining of bridge’s piers and the pylons built in the bed, passage of flood waves even if the alluvial planes did not function as natural detention basins. There were also some negative effects on the environment such as a decrease in underground water and a decrease in beach sediments. Such decrease in sediments, due to gravel mining has been widened by dam and embankment construction as well as other infrastructures that created the so-called “sediment traps”. In Italy we count 729 important dams and 8000-9000 small relative infrastructures (Rusconi,1994). In particular way, the catastrophic event occurred in 1966 contributed to increase the projects of new dams in Italy. Such infrastructures have a double effect as on the one hand they decrease both peaks and flood duration, on the other hand they reduce the load of sediments as we move downstream (Walling, 2000). In fact, with the passing of time , such changes caused a progressing decrease in the capacity to catch and store water as we move upstream, whereas we observe a progressing increase in river bed as we move downstream, a generalized erosion and other substantial changes in morphological characteristics of river bed (Basson and Rooseboom,1997).
The changes in soil utilization and urbanization, occurred following the socio-economic development in second post-war period, caused a change in the rate of discharges.

Waterproofing of areas once meant for agriculture, has increased the rate of streams, thus decreasing their seepage capacity and decreasing corrivation time (the necessary time so that a particle can get from basin distant points to closing section), and the effect is that of increasing discharges to a top level during given flood events (Fig.1.11).

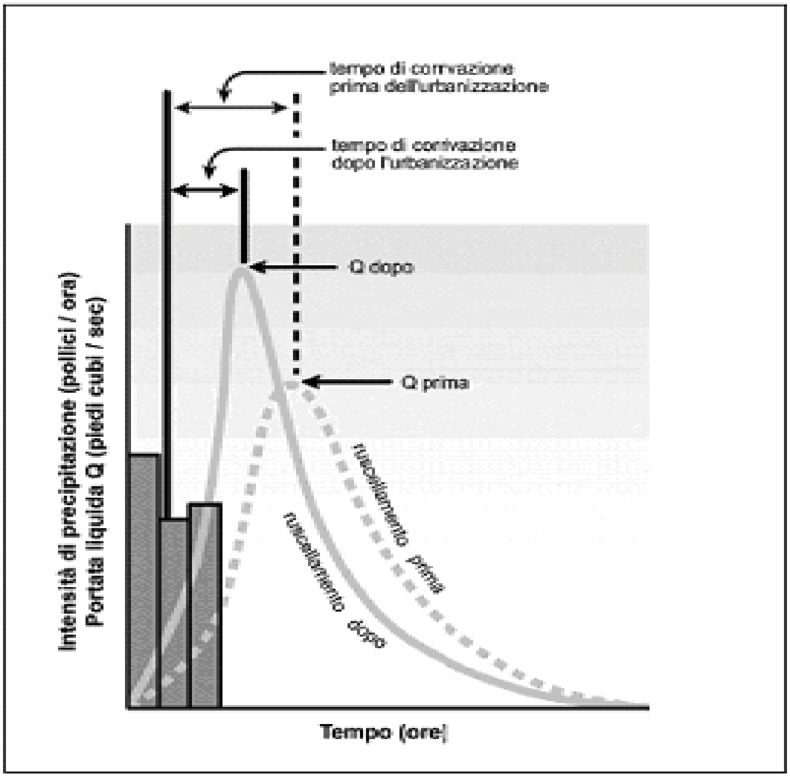

Figure 1.11: effect of urbanization on the rate of discharges increase of values estimated in relation to maximum-level floods (Ann Ist Super Sanità 2005)

1.5 Riparian vegetation and islands

A riparian area could be define as the strip of moisture-loving vegetation growing along the edge of a natural water body. The exact boundary of the riparian area is often difficult to determine because it is a zone of transition between the water body and the upland vegetation. A riparian management zone usually extends from the water's edge to the upland area.

Riverine floodplains are increasingly recognized as expanding, contracting and fragmenting ecosystems (Stanley *et* al., 1997; Malard *et* al., 1999; Tockner et al., 2000). The extent, composition and configuration of aquatic and terrestrial habitats vary in response to the pulsing of discharge (Tockner *et* al., 2006), in fact the vegetation deposition and germination into the river-bed and its survivability are influenced by water discharge, sedimentation and the seasonal phasing of floods and plant reproduction (Johnson, 1997 and 2000).

Riparian vegetation impacts a variety of flow and sedimentation processes and bed/bank proprieties (Tal *et* al.2004).

Vegetation can influence the flow regime in many different manners; it could divert the channel direction and could create a lot of different habitat with a great ecologic value. That great effects variability depends on the different species and different ages on the riverbed vegetation.

Moreover, it is important remark how in many cases there are strongly connection between different ‘effects’. For example velocity reduction within plant communities hinders scour and indeed encourages the deposition of suspended sediment, while velocity reduction in the wakes of copses and large trees can focus bed material accumulation to form proto-islands (Coulthard, 2005), and in turn deposition encourage further vegetation growth, which permits bars and islands to increase in height and attain greater permanency (Hicks *et* al., 2008).

Vegetation that is not removed while young and weakly rooted will become increasingly resistant to scour. The continuum of meandering-braided channels should reflect the ratio of the time required for vegetation to grow to a sufficiently mature state that it can resist scour compared with the average interval between scour events (Paola, 2001).

Therefore, vegetation-driven changes in braided channel morphology are likely to stem from a damping of the work done along channel margins, the progressive isolation of bar and island surface from competent flows, the polarisation of bedload transport process into fewer, more permanent channels, and any down-shift in the frequency of scour-competent floods relative to the time scale of vegetation establishment (Hicks *et* al., 2008).

We can define, briefly, six different function that riparian vegetation serves:

- <u>Bank stabilization and water quality protection:</u> the roots of riparian trees and shrubs help hold streambanks in place, preventing erosion. Riparian vegetation also traps sediment and pollutants, helping keep the water clean
- <u>Food chain support:</u> salmon and trout, during the freshwater stage of their life cycle, eat mainly aquatic insects. Aquatic insects spend most of their life in water. They feed on leaves and woody material such as logs, stumps and branches that fall into the

water from streambanks. Standing riparian vegetation is habitat for other insects that sometimes drop into the water, providing another food source for fish

- Thermal cover: riparian vegetation shields streams and rivers from summer and winter temperature extremes that may be very stressful, or even fatal, to fish and other aquatic life. The cover of leaves and branches brings welcome shade, ensuring that the stream temperature remains cool in the summer and moderate in the winter. Cooler, shaded streams have less algae and are able to hold more dissolved oxygen, which fish need breathe
- Flood control: during high stream flows, riparian vegetation slows and dissipates floodwaters. This prevents erosion that damages fish spawning areas and aquatic insect habitats
- Fish habitat: as dying or uprooted trees fall into the stream, their trunks, root wades, and branches slow the flow of water. Large snags create fish habitat by forming pools and riffles in the stream. Riffle are shallow gravelly sections of the stream where water runs faster.
- Wildlife habitat: riparian vegetation provides food, nesting and hiding places for wild animal, and could be really important for some part of their life cycle

River Islands could be defined as discrete areas of woodland vegetation surrounded by either water-filled channels or exposed gravel (Ward *et al.*, 1999) or as a land mass within a river channel that is separated from the floodplain by water on all sides, exhibits some stability (Osterkamp, 1998), and remains exposed during bankfull flow (whereas a bar would be submerged).

River island have the potential to greatly enhance biodiversity within the riparian zone, because their shorelines are characterized by a mosaic of habitat patches of different age, level of disturbance and geomorphological character, which are uncommon features along heavily managed river banks (Gurnell et al., 2001).

The early classification of straight, braided and meandering channel patterns, which is described by Leopold et al.(1964), implicitly incorporates island development through two processes:

- the evolution of relatively stable medial bars on which vegetation can establish within braided channels;
- the isolation of section of vegetated floodplain to form islands through avulsion and cut-off along meandering channels.

Kellerhals *et al.* (1976) provide a codification of islands within their classification of river features, which reflects the frequency and degree of overlap of islands. They discriminate between occasional, frequent, split and braided island patterns. These seem to reflect the likely variations in island distribution along a continuum from single to multiple thread channels.

The downstream changes in tree species, sediment, climate and subsurface hydrology dictate the strategies available for vegetation establishment and the rate at which the vegetation can develop. If establishment rates are slow, then it is impossible for islands to develop before the vegetation is removed by flood events. As a result, the nature of the colonizing vegetation determines: whether islands develop; their potential size; and their ability to resist erosion by floods within any specific regime of physical processes (Gurnell et al.,2001)

Islands may not be permanent on the geologic time scale due to river meanders, climate changes, etc., but can remain in place over decadal or century time scales and hence exhibit stability. Stability, however, is a term that is not usually defined precisely in the literature. A stable island is one that exists not only in an inter-flood time period, but also remains after the next high flow occurs. Vegetation is generally a good indicator of stability.

Vegetation may also provide a distinction between an island and a bar, but is not necessarily a requirement for a fluvial island. Islands may be composed of material too coarse to allow establishment of vegetation, or they may be located in regions of naturally sparse vegetation (Wyrick, 2005).

1.5.1 Hydrologic and biotic importance of fluvial island

Fluvial islands are important in both hydrologic and biotic capacities, and can therefore be indicators of the general health and energy of the system. Although islands may be generally unstable in the long term, recent histories of magnitudes, frequencies, and durations of water and sediment fluxes can be recorded in the sediment and biota. In some instances, histories of older, extreme events could be preserved as well.

Landforms, including islands, associated with a particular river can provide a detailed account of that river's past and present activity. Because islands separate the total river flow into at least two individual channels, they create varying hydraulic conditions due to different widths, depths, slopes, etc. The type of islands present in a riverine system can help describe the river processes as well. Islands represent a more natural state of a river system. Gurnell and Petts (2002) determined that most European rivers were once island-dominated (pre-1900), but have become devoid of islands following human interference. Away from areas of agricultural or urban development in Europe, islands remain a common feature of riverine landscapes, such as the Fiume Tagliamento in northeast Italy (Ward et al., 1999).

Since islands are separated from the floodplain, they may offer a safe haven for wildlife from many predators. Flow conditions near the island, such as river width, depth, and velocity, will minimize predation and increase species productivity. For this reason, many large rivers have wildlife refuges that include islands. River management that reduces total island area could have negative implications for migratory fowl. Plants have been shown to thrive on islands near heavy grazing lands(Hilbig, 1995). The presence of a certain species of plant on the island can help determine the flow conditions in the area. Some plant species require specific growth conditions, such as inundation duration, gradient, and particle size. Ward et al. (1999) suggest that the key elements of
optimum ecosystem functioning are islands and secondary channels. In fact, Arscott et al.(2000) found that on the Fiume Tagliamento, aquatic habitat complexity was greater in the island-braided section as compared to the island-devoid section. In the same river, Van der Nat et al.(2003) showed that aquatic habitats were more stable in regions of vegetated islands even as compared to bar-braided regions. Stanford et al. (1996) shown as islands are most likely to occur in areas of dynamic fluvial processes that would provide for high species diversity within a wide range of riparian habitat.

1.5.2 Influence of dams on fluvial island

Nearly all large rivers are flow-regulated to some degree. This can have implications for fluvial island development and stability. Dams reduce flood peaks, increase baseflow, and store sediments (especially coarser material). The sediment transported past a dam can be only a fraction of the normal sediment load.

The reduced flow peaks downstream of a dam eliminate most processes of channel erosion, overbank deposition, and sediment replenishment. This also generally reduces the biologic habitat, diversity, and interactions between biotic and hydrologic processes. While dams can reduce the erosion and destruction of fluvial islands, they also promote bank attachment by decreasing the sediment supply and reducing the downstream transport capacity which lead to deposition of tributary input sediment.

Dams, however, can also be the cause of island development. The erosional flows downstream of a dam could scour around some centralized topography (Wyrick, 2005).

1.5.3 Causes of Island formation and erosion

Osterkamp (1998) considered all the processes involved with islands in more detail, he proposed that islands could be separated into at least eight categories based on their formation processes:

Avulsion

During a high flow event, a river may excavate a shorter path, particularly across a bend, thereby leaving two flow channels after the river stage has receded. These avulsive types of islands may form through such mechanisms as toppling of riparian trees and flow diversion by debris dams. One example of this island type was described in the Little River valley in northern Virginia by Kochel et al. (1987), where log jams during a low frequency storm event trapped gravel within the channel up to an elevation of 1.5 meters higher than the surrounding floodplain, causing the flow to avulse around part of the floodplain to form a new island. Log jams have also been documented on the Morice River in British Columbia that diverted flood flows across the floodplain, creating a nickpoint retreat that resulted in an avulsion and a new island (Gottesfeld and Gottesfeld, 1990).

Gradual degradation of channel branches

The gradual-erosion type of island usually results from steady evacuation over years or centuries of sand/gravel flood deposits or glacial outwash sediments, or from other processes of accelerated upland erosion, bank failure, or abundant supply of stored bed sediments. Transport of bed sediments in anabranches by regulated streamflow may lead to the formation of fluvio-deltaic islands, which are formed by the sorting of coarse sediments delivered by high-energy tributaries to low-gradient main stems that cannot mobilize the incoming coarse material. Divided flow in the main stem, splitting around the coarse material, may result in the formation of islands through deposition on the coarse material and/or incision of the flanking channels.

Lateral shifts of channel position

Lateral-shift islands are created by channel migration and meander cutoff or by interactions at the confluence of multiple meandering streams. Numerous examples of this type occur along the Mississippi River downstream of Memphis, Tennessee, especially near the confluences of the White and Arkansas Rivers (Osterkamp, 1998).
This type of island is also common in braided channels, such as the Platte River or the Wisconsin River.

Stabilization of a bar or riffle

Bar/riffle-stabilization islands form from long term aggradational and sorting processes of coarse bed sediments or by redistribution of sand and gravel in streams having large bedload fluxes. An extended period of low-flow allows for riparian vegetation to encroach onto depositional surfaces.
Hooke 'S (1986) analysis of English rivers concluded that it takes one to three years for vegetation to sufficiently stabilize exposed bars. If flows remain low for a long enough period of time, vegetation may accumulate on its surface and stabilize the emergent island against future higher flows.

Structural features

The structural-feature type of islands forms almost exclusively in non-alluvial, often bedrock, channels of karstic, glacial, or volcanic ash geology. Structural-islands may emerge as the river preferentially erodes through bedrock fractures.

Rapid incision of deposited sediments during flood recession

Flood-deposit islands form during the rapid evacuation of sediment during a flood, mass movement, or general landscape instability. Dewatering and accelerated incision of fresh flood-deposited sediment can cause upstream migration of multiple headcuts during flood-peak recession that may isolate higher central topography. The main difference between these type of islands and avulsion islands is that flood-deposit islands are formed by erosion of newly-deposited sediments, whereas avulsion islands are composed of older-deposited floodplain material. These types of islands are most common along small streams that are substantially altered during short time periods, such as Plum Creek, near Denver, during the 1965 Flood (Friedman et al., 1996). These types of islands are
not restricted by spatial scales, however, as other examples of this case involve islands that are deposited during unique extreme flow events and are made up of material that is unmovable during normal river flows.

Lee deposition

Lee-deposition islands are common in widened, braided channels of all sizes where steady sediment evacuation, usually as bedload, occurs. Immediately downstream of a channel obstruction or snag, a local zone of shallow depth, reduced velocity, and accumulating sediment may develop and quickly become vegetated. Instream woody debris has been shown to be important in nucleating and maintaining mid channel islands in Pacific Northwest mountain streams (Grant et al., 2001; Ward et al., 2002).

Mass movement

Mass-movement islands usually occur in lowlands that are catastrophically altered by extreme events such as debris avalanches. Other examples that may not be quite so extreme include islands formed by rockfall, soil slump, and bank failure.

Reservoir installation

When a dam, whether man-made or natural, is emplaced, it ponds water upstream. If there is a sufficient water level rise, high riparian topography may become isolated as the valleys are flooded. These islands may or may not be composed of bedrock. Because the erosive power of rivers are reduced drastically within a reservoir, these types of islands are highly stable and may only cease to be islands if the dam is removed or the water surface elevation is droppe

Osterkamp (1998) described several scenarios in which islands could disappear.
Perimeter sediment deposition could eliminate an island by several methods. The first method is by preferential in-filling of one of the side channels that effectively raises the bed level in one anabranch but not the other, and thereby shifts the flow into a single path. The second method is by sedimentation around the whole perimeter of the island until it eventually coalesces with other nearby islands or the floodplain, again forcing the flow into a single path. A third method of island elimination is by the flow preferentially incising one of the side channels and leaving the other anabranch 'high and dry'. This is common downstream of dams after peak flows have been reduced. If a low flow regime persists for long enough, vegetation may accumulate between an island and its floodplain.
The meandering nature of a river can cause it to laterally migrate and abandon one of the anabranches around an island. Floods can eliminate an island by two methods. The first is by simply increasing the flows to levels high enough that the entire island is eroded away. The second is by changing the main direction of

the flow during a flood, thereby altering the angle of attack from the water and gradually wearing away the island by abrasion.

1.5.4 A conceptual model of island development

Figure 1.12 depicts a conceptual model of island development, which incorporates the traditional view of island development, since it allows islands to evolve (i) on open gravel surfaces within the active zone and (ii) as a result of dissection of the floodplain. However, the model has a number of important features, which highlight the role of riparian vegetation and wood debris.

It incorporates the range of ways in which riparian woody vegetation can establish on open gravel surfaces including: growth from diffusely distributed propagules; growth from propagules that have accumulated within the shelter of vegetation debris, particularly accumulations of dead wood; and regeneration through the sprouting of living vegetation debris pieces, accumulations and entire trees that have been deposited on the open gravel during flood events.

It allows a range of trajectories of island development that reflect the trapping of sediment, dead and living wood, and vegetation propagules to promote the lateral and vertical growth of islands.

It provides a conceptual link between islands that develop on gravel bars and those that are excised from floodplains, by permitting islands that develop on open gravel areas to attach to the floodplain and by allowing for alternating phases of growth and dissection of islands.

The fundamental elements of the model in Figure 1.12 embrace the range of processes: (i) which lead to the local availability of seedlings and/or vegetative regeneration that can develop into shrub and tree cover; (ii) which provide suitable sites within which sexual or vegetative recruitment may successfully lead to an established tree cover; and (iii) which are capable of destroying the tree cover to ensure that the islands do not continue to develop until they merge to form mature floodplain forest confining a single-thread river system. Figure 1.12 illustrates the various processes that transform an open gravel area (left side of Figure 1.12) through alternative pathways of vegetation development, via pioneer and building islands into a tree-covered component of the contemporary floodplain (right side of Figure 1.12). An alternative pathway to island development (from the right to left side of Figure 1.12) is through the dissection of the contemporary floodplain, with the potential for total erosion of the resultant islands to bare gravel. The conceptual model illustrates the interplay between processes of aggradation (upper half of Figure 1.12) and degradation (lower half of Figure 1.12), which can lead to the development of complex islands. It also illustrates the importance of the erosion, transport and deposition of entire trees and smaller wood pieces to the proposed trajectories for vegetation establishment (Gurnell et al., 2001).

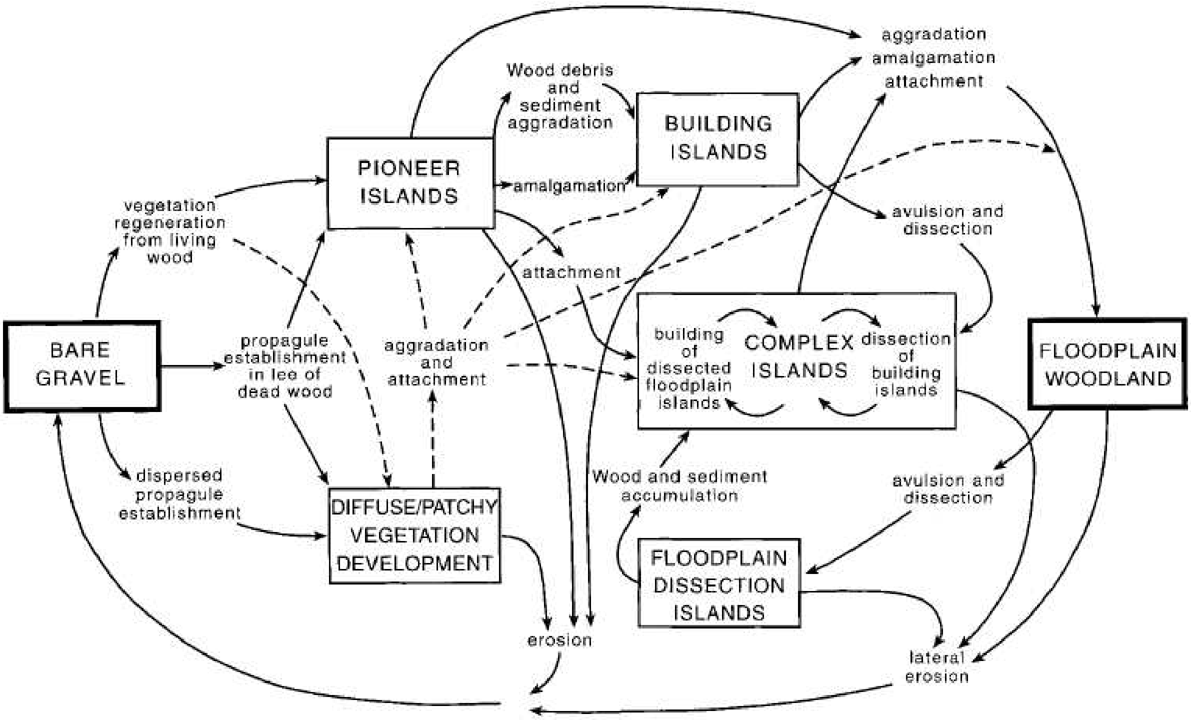

Figure 1.12: a conceptual model of island development for the Fiume Tagliamento. The solid arrows represent the most commonly occurring pathways (Source Gurnell et al., 2001)

1.6 Characteristics of braided gravel-bed rivers and evolution trajectories

Braided gravel-bed rivers are defined as streams which flow in multiple and migrating channels across an alluvial gravel bed, containing numerous and changing bars, ponds and islands (Gray & Harding, 2007). Braided gravel bed rivers are very common in temperate regions, and high precipitation mountain valleys (Tockner et. al, 2003). The proximity of mountains brings to this type of rivers large amount of coarse sediment supply, as well as rapid and frequent variations of flow discharge, and thus braided gravel bed rivers present high amount of energy which make them respond dynamically to any change.

Dominant characteristics of a natural braided gravel bed river are:

- Channel pattern: channels, bars and islands are continuously reshaped depending on the severity of the storm peak flow.
- Longitudinal profile: often present a concave profile. The braided reaches have a relative steep slope (up to 1%). Running downstream, generally many braided rivers experiment a transition to single streams.
- Cross sections normally are characterized by bed elevations in the middle of the active channel. Natural braided gravel bed rivers usually exhibit wide floodplains (Galay et al., 1998).

It is a distinctive characteristic of braided gravel bed rivers vertical profile to be constituted, under the active channel, by a hyporheic layer (area saturated in water) and a layer of unsaturated gravel (hypogeic zone) (Tockner et. al., 2006) (Fig. 1.13).

- Sediment size: gravel sediments are the result of glacial activity, highly erodible bedrock and active mountain building (Gray & Harding, 2007). It is typical of braided gravel bed river to change its bed material into sand as the stream gets close to the mouth, suggesting that at a certain threshold gravel transport is null. To be considered as a gravel river, the bed material must be between 2 to 64 mm.

- Deposition during large floods: a characteristic process in braided rivers is deposition of bed material during the rising state of a flood followed by a rapid degradation during the falling stage. According to Wyżga & Zawiejska (2005), in wide multithread reaches where already bars and island are present, the unit stream power is lower than in narrower, single-thread or channelized reaches, making the first more favourable sites for material and large wood debris depositions.

- Biodiversity: braided gravel bed river due to its variety of zones -ponds, riffles, backwaters, islands, groundwater, riparian forest, hypogeic zones-, they host a rich diversity of small habitats with fast turnover rates (Tockner et. al., 2006). Within these habitats we can found a variety of aquatic, amphibious and terrestrial organisms (Van der Nat et. al., 2003). Floods periodicity and specially groundwater levels are the dominant controls in ecological processes (Church, 2002).

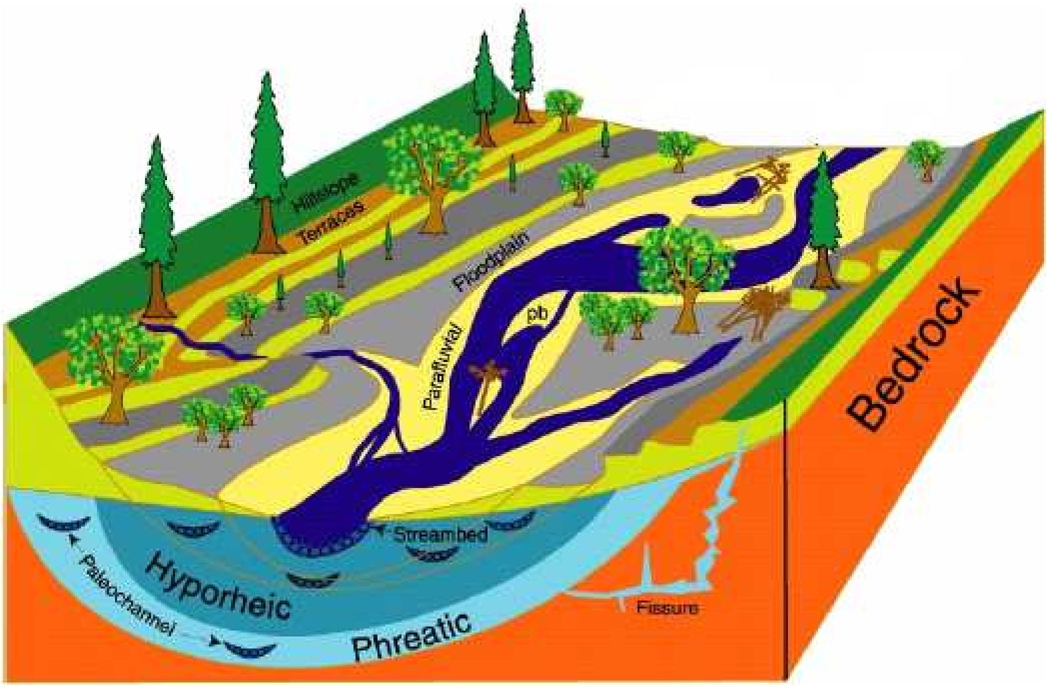

Figure 1.13: braided gravel-bed floodplain structure. Modified from Tockner et. al.(2006)

Over the past 50 years, there has been considerable international research into the conditions that cause some rivers to braid and others to meander. The synthesis of this research is that a river's planform reflect a balance between processes that tend to widen and de-stabilise the channel by eroding its banks (and releasing bed-material) and processes and characteristics that tend to inhibit this.

Braiding is encouraged by a combination of high flow strength, erodible bank material and an adequate supply of bed-material from upstream and/or the eroding banks to sustain the braiding process. Meandering channels occur where bank strength is large enough and flow strength low enough to constrain bed-material release from bank storage. The upshot is that channels are prevented from widening to the extent where bars become emergent and braiding features develop. Bank strength can be provided by deposition of cohesive fine sediments from suspension or by the binding and protective action of riparian vegetation. Often, these two factors reinforce: vegetation slows flow velocities, thereby increasing fine sediment deposition, while fine sediment provides a suitable substrate for seeding vegetation (Hicks et al., 2006).

Natural river corridors depend upon fluxes of water, sediment and organic matter from headwaters to river mouth and between river channels and floodplains. These fluxes support heterogeneous landscapes and give rise to a wide spectrum of river planform styles. Changes in climate and the direct and indirect activities of humans have led to major changes in water and sediment fluxes, which have resulted in changed river

corridor characteristics worldwide (Gurnell et al., 2009) as, for example, the impact of dams (Petts and Gurnell, 2005).
The importance of vegetation is increasingly being demonstrated by modelling studies (Kean and Smith, 2004; Millar, 2000) and by flume experiments (Tal et al., 2004; Tal and Paola, 2007) are indicating the overriding impact of vegetation in driving transitions from multi-thread to single thread channel patterns.
Riparian vegetation impacts a variety of flow and sedimentation processes and bed/bank proprieties (Tal *et* al.2004). Vegetation can variously influence the flow regime: it could divert the channel direction and could create a lot of different habitat with a great ecologic value.
There can be substantial feedback between these various effects. For example, velocity reduction within plant communities hinders scour and, indeed, encourages deposition of suspended sediment, while velocity reduction in the wakes of copses and large trees can focus bed material accumulation to form proto-islands (Coulthard, 2005). In turn, deposition encourage further vegetation growth, which permits bars and islands to increase in height and attain greater permanency (Hicks *et* al., 2008).
Vegetation that is not removed while young and weakly rooted will become increasingly resistant to scour. The continuum of meandering-braided channels should reflect the ratio of the time required for vegetation to grow to a sufficiently mature state that it can resist scour compared with the average interval between scour events (Paola, 2001).
Therefore, vegetation-driven changes in braided channel morphology are likely to stem from a damping of the work done along channel margins, the progressive isolation of bar and island surface from competent flows, the polarisation of bedload transport process into fewer, more permanent channels, and any down-shift in the frequency of scour-competent floods relative to the time scale of vegetation establishment (Hicks *et* al., 2008).
Restoration of braided gravel-bed rivers is a complex activity which should depend on (i) the river state in relation to its temporal trajectory of geomorphological evolution, (ii) the existing and potential ecological values and benefits and (iii) human needs for safety from floods and protection of economic interests (Piegay et al., 2006).
The erodible corridor concept consists of defining a corridor in the alluvial plain within which managers will not control erosion using engineered protections (Piegay et al., 2005). Application of this concept has several geomorphic and ecological benefits,

which must be balanced with the economic benefits derived from protecting property and infrastructure outside the corridor (Surian et al., 2009).

In order to set restoration goals it is worth avoiding the identification of a reference state (Kondolf et al., 2007). Pragmatically, two main goals should be (i) stopping channel incision where it is still occurring and (ii) promoting channel widening, especially where remarkable changes in planform configuration have taken place.

Considering that channel adjustment is driven by the imbalance between driving (stream power) and resisting (sediment supply and material size) forces, sediment management will be the key issue in achieving the proposed goals, accompanied by allowing rivers to recreate their cross-sections. Indeed, two broad categories of interventions can be envisaged, i.e. basin and reach-scale measures. The former implies mitigating the sediment 'starvation' typical of reaches downstream of reservoirs, which trap all the sediments conveyed from the upper basin (Surian et al., 2009). Solutions to such problem are technically restricted—flushing operations can transfer fine sediments, whereas in the study cases, gravel-size material is the issue—and entail the mechanical by-passing of dams through gravel collection in the upper part of the reservoir and from the river delta and its transfer downstream of the dam (Palmieri et al., 2001). Tightly coupled to this intervention should also be gravel extraction, which—rather than being carried out in river reaches as is still commonly done—would have much less adverse effects if operated on gravel deposits upstream of reservoirs, since these sediments have already been subtracted from the river dynamics (Surian et al., 2009).

Other possible causes of reduced sediment transfer are torrent control works (Liebault and Piegay, 2002), which are built in the steep tributaries to prevent channel incision and excessive bed-load transport during high magnitude flood events (conventional bed sills and check dams). Even though the impact of these structures on sediment yield must be several orders of magnitude smaller than hydropower reservoirs because of their relatively low storage volume, the adoption of open check dams (e.g. with slit-type openings) should be favoured in the future.

In fact, these structures feature a hydrodynamic filtering mechanisms (e.g. Armanini et al., 1991; Catella et al., 2005) which enables the self-cleaning of gravel deposited in the retention basins during moderate flows, thus allowing at least a partial sediment transfer downstream. Different kinds of filters (horizontal, vertical and inclined elements with unique or multiple slope) adopted in the design of open check dams, are a widely used new approach for torrent control in the Italian alpine region (D'Agostino et al., 2004).

The establishment of an erodible river corridor (Piegay et al., 2005) along the entire channel network could accompany the interventions at the basin scale, because gravel-size sediment mobilized from bank erosion processes in upstream reaches would supply the river segments located downstream. However, in the study basins, significant erodible areas can be realistically located only in those reaches where human infrastructure is absent or of low value. Therefore, the definition of an erodible river corridor is inevitably a reach-scale restorative intervention (Surian et al., 2009).

The delimitation of floodplain areas where a river is allowed to erode in the future is fundamental to any direct interventions at the reach scale, such as the removal of bank protections (e.g. ripraps and groins). would also have the side effect of supplying the channel with large wood, which represents another important factor for enhancing the restoration of island-braided systems (Ward et al., 2000; Gurnell et al., 2005; Gurnell and Petts, 2006), and is currently restricted in its supply in most of the study river reaches because of human interventions (Pecorari et al., 2007; Pecorari, 2008). However, it is important to point out that such reach-scale interventions do not represent a long-term solution, even though they may provide a short-term source of gravel. The ideal strategy in most of the study rivers would be to act simultaneously at both basin and reach scale (Surian et al., 2009).

Given the complexity of the mutual relationship between water-sediment fluxes and channel morphology in braided rivers, there is always a certain degree of uncertainty when assessing the river's response to an external force. This means that each restoration project is very site-specific, and that none of them can be used as a reference case (Surian et al., 2009).

2. Objectives of the research

Aim of this research has been to make a profound study of long and medium term morphological dynamics that may affect the regulated gravel-bed braided rivers.
For this purpose in the Piave River and in the Waitaki River (New Zealand), two basins have been identified in order to carry out research activities. These two important rivers have been singled out as they have similar characteristics from a morphological point of view as well as from an anthropic impact and flow regulation point of view. In fact, both are gravel-bed braided rivers having a bed mainly composed of sedimentary rocks with similar slope (of the order of 0,3-0,36%) and both catchment areas of mentioned two rivers have been affected by many anthropic interventions aiming at producing hydroelectricity.
In order to better comprehend the complex dynamics that is possible observe along water courses having such characteristics, different analyses have been carried out in order to have a general overview of the hydro system as a whole, without exclusively focusing on few parameters, but trying to consider all possible connections existing between the different factors interacting in the shape of riverbed morphology.
Therefore three main aspects relating to a braiding river have been taken into consideration: sedimentary shapes, liquid flows and vegetation. In fact, such aspects cause the most important and significant morphological changes.
In order to achieve a complete characterization, several types of analyses and observations have been carried out so as to allow observing riverbed dynamics on the whole, by considering the different time and space scales. In that sense, the reach of the Piave River, 37 km long (Soverzene - Busche) and the reach of the Waitaki River, about 13 km long (Kurow – Otekaieke) have been analyzed and studied.
Subsequently some subreaches have been identified in order to carry out more detailed and accurate analyses and observations. In the end, even mentioned subreaches have been singled out on the basis of their characteristics, in particular those that better reflect the examined characteristics on a much deeper scale.
With a view to general analysis relating to riverbed dynamics, a huge amount of emphasis has been put on the importance and influence of vegetation inside riverbed, without leaving out the connections with other factors (sedimentary shapes, liquid flows etc.) but making use of their comprehension in order to better interpret the data obtained through the analyses on the different types of vegetation linked to the fluvial forms.

The aim of this study has been to analyze the evolutive tendencies of fluvial islands, the role that vegetation can perform into the general overview of fluvial dynamics and the problems arising inside the system due to an excessive or limited vegetation in riverbed.
The last aim of this study has been to obtain results that might provide an accurate and critical analysis upon the situation concerning the morphological changes and riverbed dynamics of abovementioned rivers, acquired knowledge that may be useful in order to better manage the fluvial system as a whole.

3. Study Areas

3.1 The Piave river basin

The Piave river is the Italian study site of the present research. In the following paragraphs, the main characteristics of the Piave river and its basin are reported,

3.1.1 Overview of the Piave river

The Piave river originates in the Carnic Alps, to the south of Mount Peralba, in the area of Sappada town (Belluno), at an altitude of 2037 metres above sea level, and it flows into the Adriatic sea to the southeast of Venice lagoon, near the port of Cortellazzo (Venice).

The basin of the Piave river (Fig. 3.1), extends inside the provincial territories of Belluno, Bolzano, Pordenone, Trento, Treviso e Venice. Its total surface is equal to 4.126 km^2 and it flows for 220 km.

Figure 3.1 : hydrografic chart of Piave basin (Bondesan et al., 2000)

The following table (3.1) shows the percentage of the main tributaries in the motane basin (Bondesan et al., 2000).

Table 3.1: percentage of tributary basin as opposed to the totality of the Piave mountain basin

Tributary	Basin Area (%)
Cordevole	24
Boite	11.2
Maè	6.7
Ansiei	6.7
Sonna	3.8

Natural lakes are Alleghe (0,45 km^2) and Misurina (0,15 km^2) in the Dolomiti (province of Belluno), lake S. Croce sul Tesa (136 km^2) and the two lakes near

Revine (0,5 e 0,4 km^2). 11 reservoirs are present for hydroelectric power production, as reported in table 3.2.

Table 3.2: list of artificial basins inside the Piave river with their surface and their tributaries.

Reservoir	River	Basin Area (km^2)
Comelico	Piave	372
S.Caterina	Anisei	225
Pieve di Cadore	Piave	818
Valle	Boite	380
Pontesei	Boite	323
Val Gallina	Val Gallina	151
Fedaia	Avisio/Cordevole	14.4
Cavia	Biois	2.2
Mis	Mis	108
Stua	Caorame	27
Ghirlo	Cordevole	419

The glaciers of the Piave basins are north of the river, where the highest peaks are to be found (Bondesan et al., 2000). The most important glaciers extend in the group of Pale di San Martino, in the group of Popera, in the group of Marmarole and Mount Sorapis, in the group of Antelao, in the group of Tofane and Mount Cristallo, in the group of Mount Civetta and Mount Pelmo, along a total surface equal to 3.6 km^2.

3.1.2 Morphological characteristics of Piave River

Depending on a large variability of the geographical areas the river flows through (Alps, Prealps, hilly area, low and high plain, coastal area), the morphological characterization of the Piave fluvial system is considerably diversified.
According to characteristics such as width, gradient, particle size etc., Surian (2000) suggests to divide the river, as we move downstream, into three parts: the first from the spring to Longarone, the second from Longarone to Ponte di Piave, the third from Ponte di Piave to the mouth.

In its first reach, the Piave is a real torrent that has steep gradients and a bed relatively narrow, surrounded by high mountains. At high altitudes, stream velocity is of the order of some m/s, whereas its width changes up to many meters. Downstream from Perarolo, in some reaches, its width increases up to 400 metres.

Bed gradient in the first 7 km has maximum values (8,8 %), whereas in the subsequent kilometres as far as Perarolo it is included between 1,0 % and 3,2 %, whereas as regards the stretch between Perarolo and Longarone one can observe values between 0,5% and 0,6% (Vollo, 1942).
Bed sediments north of said stretch are very rude (high concentration of blocks and gravel), whereas between Lozzo di Cadore and Longarone we can find more gravel.Between Lozzo di Cadore and Ospitale di Cadore, the average diameter of gravels is about 17 mm, whereas larger size blocks exceed 200 mm (Dal Cin, 1967).

In the intermediate reach, which is about 110 km long and it is included between Longarone and Ponte di Piave, the river flows in a torrential manner, given that it maintains its considerable gradients included between 0,7% and 0,2%. Bed width ranges between many meters up to 3 km.
Downstream from Longarone, although the morphology of two slopes does not change, the bed extends and it mostly has a considerable width; therefore the river keeps flowing at high velocity along e broad bed composed of small rocks and gravel, thus taking on a braided morphology.
The particular instability of mentioned stretch typology causes a change in the branch course, thus changing again both channels and bars on the bed.
Particle size characteristics of the bed are quite homogeneous, whose diameter ranges from a minimum of 13 mm to a maximum of 82 mm, but usually included between 20 mm and 50 mm (Surian, 1998).

In the end, near Ponte di Piave, both its torrential characteristics and gravels disappear, therefore the Piave takes on a typical lowland character. In this last stretch we observe a notable decrease in gradients, so much so that they decrease below 0.1‰ near the mouth.
Depending on the gradient, velocities gradually decrease toward the mouth until they reduce during ordinary base flow to 0.2-0.3 m/s. Such decrease also depends on the tidal flow whose influence is quite intense as far as Zenson, about 30 km from the mouth.
From Ponte di Piave to San Donà di Piave, the river takes on a typical meander morphology, being artificially adjusted from San Donà di Piave to Eraclea, by

maintaining its high sinuosity, in its last kilometers, as far as the mouth (Bondesan et al., 2000), being more elevated than the plane level.
Particle size of mentioned stretch is composed of small sediments such as sand and silt. Over base flow periods, these materials are covered with rock deposit and clay which are detached and transported toward the sea during given flood events.

3.1.3 Climate and rainfall in the Piave basin

The entire Piave basin is in humid and temperate continental climate zone, which is typical of many other areas to the south of the Alps.
Winter is usually the less rainy season. In spring we may observe the usual and typical climate changes relating to such season: wet days are followed by dry and thunderstorms start to appear. Rainfalls get more and more copious. Summer begins in June, one of the two periods having heaviest precipitations over the year, causing some atmospheric disturbances; then weather instability is followed by long warm periods. Autumn may start either in the early September or in October; when it starts, the season is followed by grey, long and wet periods. In fact, autumn months are followed by heavy rainfalls that reach their peak in November.
Rainfall in the Piave basin is subject to many changes from place to place depending on orographic slope exposure, and in the plain, on distances from both mountains and sea. We have to highlight that rainfalls increase, as opposed to the plain, with a peak in basin's middle, referable to Prealps area.
The annual average rainfall referred to the whole basin, as regards the 60-year study (1928-1987) is about 1350 mm. In the areas where rainfalls are relatively low (north-west part of the basin), rainfall is equal to 1000 mm, whereas in heavy rainfall areas (east-central area of the basin) values range from 1500 to 1900 mm, getting also to areas in which values are equal to 2000 mm. Over some years, rainfall may also range significantly as opposed to average value, for example over 1983 and 1960 values referred to annual precipitations have been respectively 993 mm and 1969 mm (Fig. 3.2).

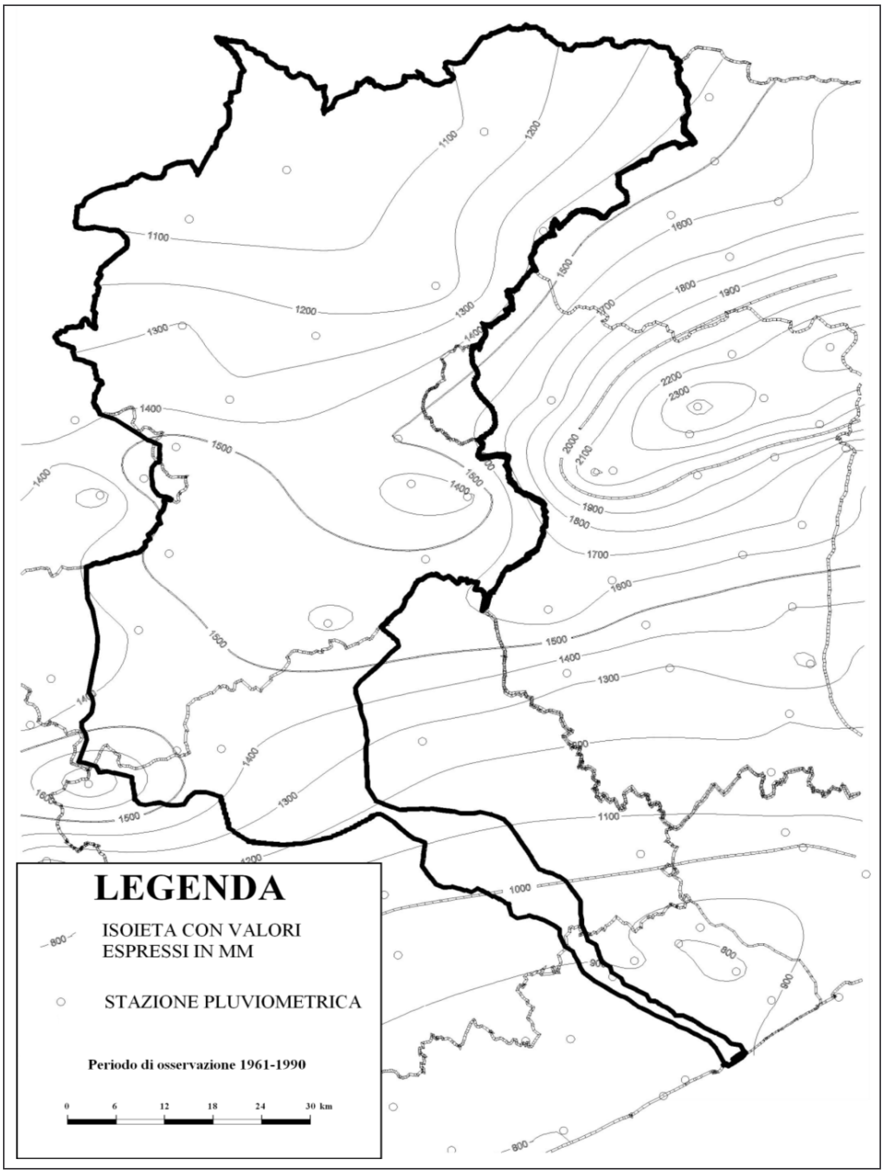

Figure 3.2 : annual average precipations between 1961-1990 (from AdB, 2001)

3.1.4 Morphological changes of the bed over the last century due to anthropic interventions

A timeline for human activity on the Piave fluvial system can be split into three periods (Surian, 1999). During the first period, from the fourteenth century to the early twentieth century human activity was limited, thus river morphology maintained more or less its natural characteristics.

In the early mid-twentieth century, both morphology and dynamics of river bed have been subject to deep changes that are attributable to several anthropic interventions (hydroelectric power plants, diversions, embankments and weirs) carried out along the water course and in its hydrographic basin (Surian, 1999).

The increase in hydroelectric power production and the irrigation development were considered the most significant and crucial important purposes to the economic development, almost all interventions were carried out without weighing up negative consequences arising from that action in the immediate period and in a medium- and long-term period (Borgarelli, 2007).

The utilization of the Piave to energy and irrigation purposes has been justified by the considerable quantity of water supplied by the river. This has led to the creation of a well-constructed network of diversions and artificial channels connecting all reservoirs, energy power plants and water distribution plants. Mentioned complex network was engineered in 1905 by SADE Energy Company *(Società Adriatica di Elettricità)* by carrying out important works that, in the following years, led to the excessive utilization of the Piave and its tributaries (Fig. 3.3). The landscape of Belluno valleys was radically transformed. Rivers and torrents were dammed, new artificial lakes were created, kilometres of galleries were drilled through the mountain in order to carry away the high pressure waters.

Figure 3.3: mosaic work depicting the hydroelctric power production network in the Piave mountain basin, near the "Achille Gaggia" power plant located in Soverzene (BL)

The current artificial network contains around 50 water intakes taking water from the upper torrents (about 2 billion m^3 a year), a well-constructed by-pass network of underground pipings that manly extend over 200 km, 11 medium-size basins (table 3.2), 30 production plants and many other related control systems. ENEL Power Company obtains 7 % of nation's hydroelectric energy from the Piave (Fig.3.4).

At present the plants regarding the Piave are as follows:
Piave-Ansiei plant that includes Comelico and S. Caterina reservoirs as well as Pelos plant;

- Piave-Boite-Maè-Vajont plant that includes Pieve di Cadore, Vodo di Cadore, Valle di Cadore, Pontesei, Vajont and Val Gallina reservoirs as well as many plants like Soverzene one, that is main plant.
- Piave-Santa Croce plant that includes Santa Croce, Lago Morto and Lago del Restello reservoirs , Soverzene dam and many plants located chiefly in the area of Fadalto.

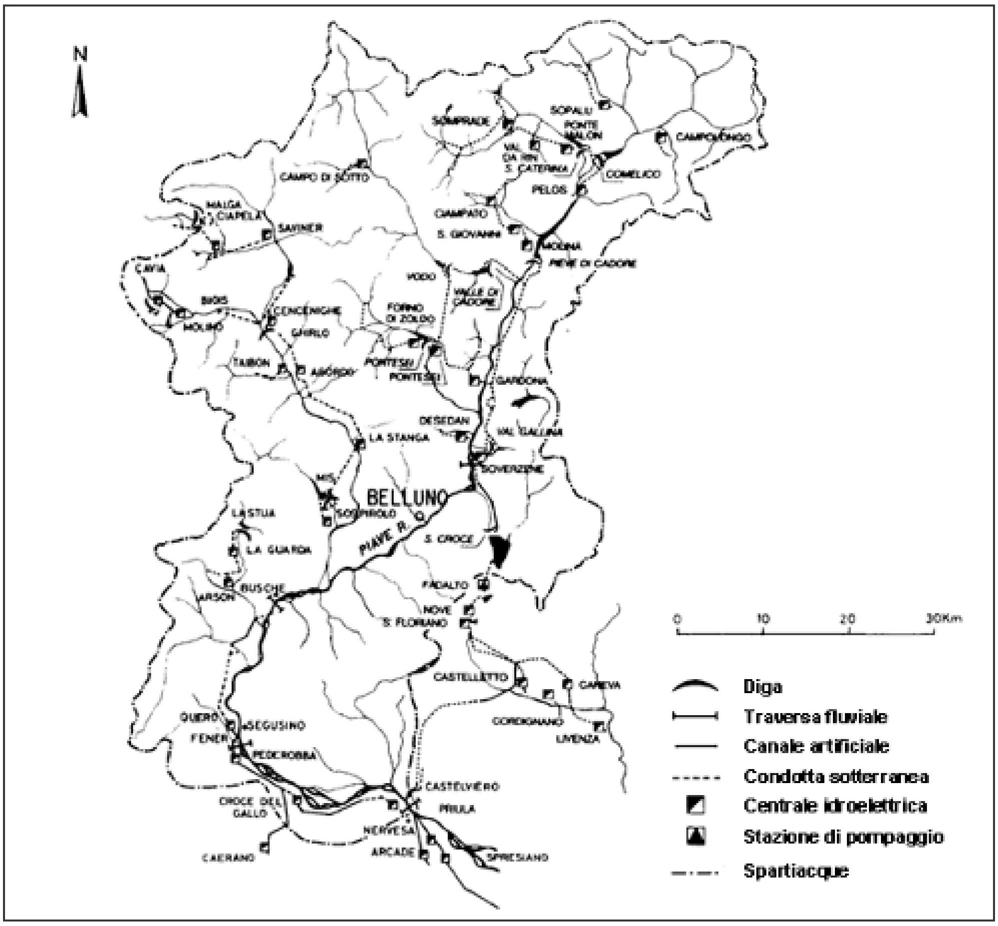

Figure 3.4: outline upon the electric power plants and irrigation works along the Piave river (Surian, 1999)

Human activity on the river increased in the 1950's when in addition to the construction of projects intended for energy production, irrigation and flood control systems, there was an excessive increase in gravel removal from the river bed, in particular in the low-mountain strip of the river, that substantially changed rate of flows and solid transportation (Surian, 1999). The removal of material has caused many changes that affected wider stretches as opposed to the location of removals, corroborated by an increase in upstream erosion and a decrease in downstream sediment deposition.

Besides human activity, over the centuries, has drastically affected vegetation inside the fluvial system, causing drastic decreases in trees along the bed and in particular in the banks.

The deep change in the soil utilization has affected the presence of sediments in the basin during this time interval. From the sixties and over all the mid-twentieth century, the entire mountain area of the basin underwent a considerable depopulation that came with the abandonment of traditional agricultural activity which led to the increase in woodlands that caused a decrease in sediment from the slopes (Lega Ambiente, 2006).

At present, the Piave river has a considerably modified flow and its annual average discharge, measured near Nervesa, is about a third of the one the river had in natural condition (Surian, 1998).

Surian's (1998, 1999) study upon the morphological changes that arose over the last century, through the analysis of both historical cartography and aerial views, highlighted a considerable decrease in river bed width that in some stretches underwent a considerable reduction, more than a half as opposed to its initial sizes, in particular between the seventies and the early nineties. Furthermore such study has also defined the degree of braiding, which has in turn decreased to values near 3 and as low as values not far from 1,5. This caused a change in the planimetric system of the stream in some stretches that take on a braided character, and in some stretches having less channels as well as considerable wondering.
Bed incision is an action that is highly affected by the decrease in sediment availability, which is due to flood control systems and fluvial infrastructures. Unlike other water flows subject to high anthropization, bed incision has been relatively moderate.; maximum values (2-3 meters) have been measured immediately downstream of transverse structures (Bondesan et al.,2000).

3.1.5 Main flood events in the study period

The historical analysis of the main flood events that affected the Piave basin is very important in order to understand the changes occurred in its bed.

The focus has shifted to the floods that affected water flow morphology in the stretch and in the time interval that was studied by the AdB (2001) and Borgarelli (2007).

River changes were studied over the period 1930-2002. Large floods occurring over this period are listed in Table 3.3.

Table 3.3: mainly flood events along the Piave River during the study period (Da Canal, 2006)

Year	Discharge(m^3/s)	Return Period
1960	1605	9.5
1963	755	2.2
1965	2599	43.1
1966	4091	279.4
1972	1080	3.8
1975	770	2.2
1976	1456	7.4
1977	775	2.2
1978	1419	6.9
1980	1565	8.9
1981	1000	3.3
1987	1073	3.8
1989	856	2.6
1990	881	2.7
1992	879	2.7
1993	1752	12.1
1994	818	2.4
1996	1132	4.2
1998	1300	5.7
1999	1150	4.3
2000	1282	5.5
2002	1775	12.5

3.1.6 The study reach and subreaches

The study area includes a reach of the Piave river extending along 37 km between the town of Soverzene, north-east of Ponte nelle Alpi, and weir of Busche (Fig.3.5).

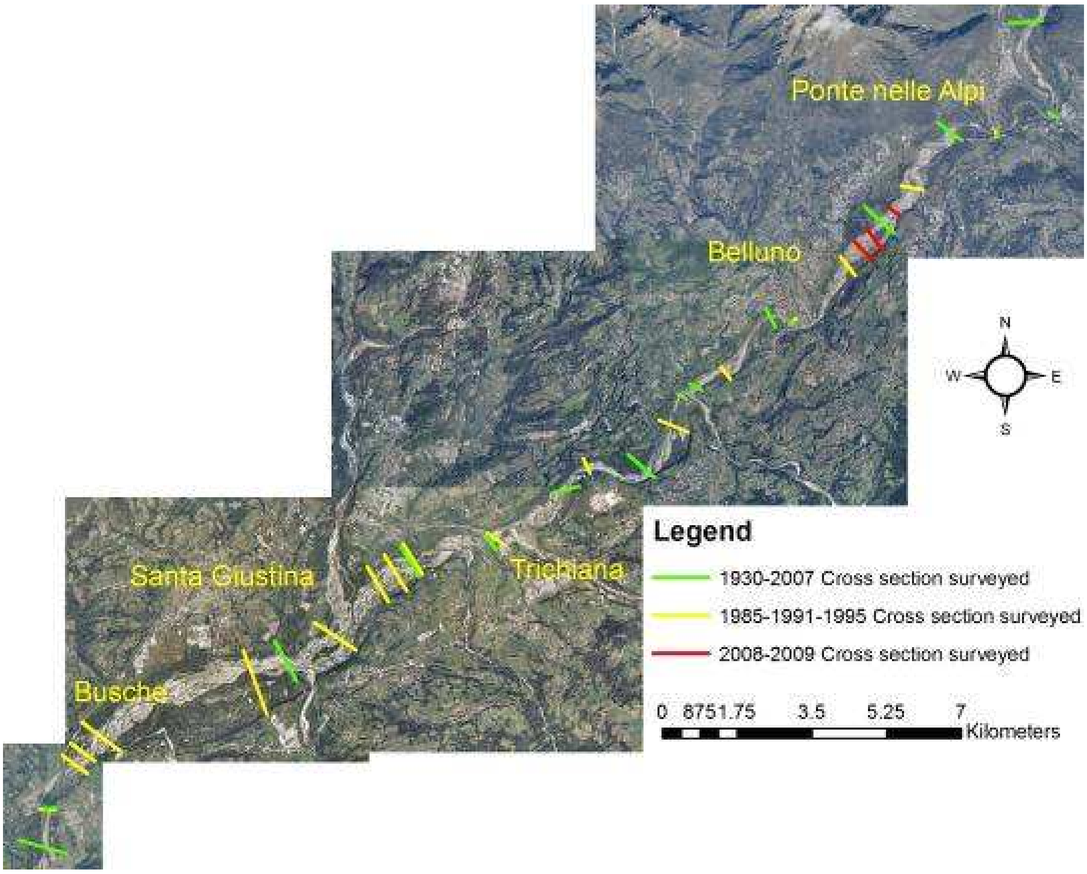

Figure 3.5: study reach from the area north-east of Ponte nelle Alpi to weir of Busche .

Along said reach there are three right-side tributaries (Cordevole, Ardo and Caorame) and five left-side tributaries (Limana, Cicogna, Ardo, Terche and Rimonta) (Tab.3.4).

Table 3.4: drainage basin area of Piave tributaries(Source Surian et al., 2009)

Tributary	Drainage basin area (km^2)	Bank side
Cordevole	876	right
Ardo	40	right
Caorame	97	right
Limana	27	left
Cicogna	60	left
Ardo	36	left
Terche	45	left
Rimonta	41	left

With the 37-km long study reach, two level of sub-reaches of different spatial scale were then analysed, with different aims.

At the upper level, five subreaches (range of length 3-15 km) were identified to analyze the morphological evolution in detail (Fig. 3.6). These five subreaches were created based on their prevalent morphological typology: braided, alternate bar and wandering.

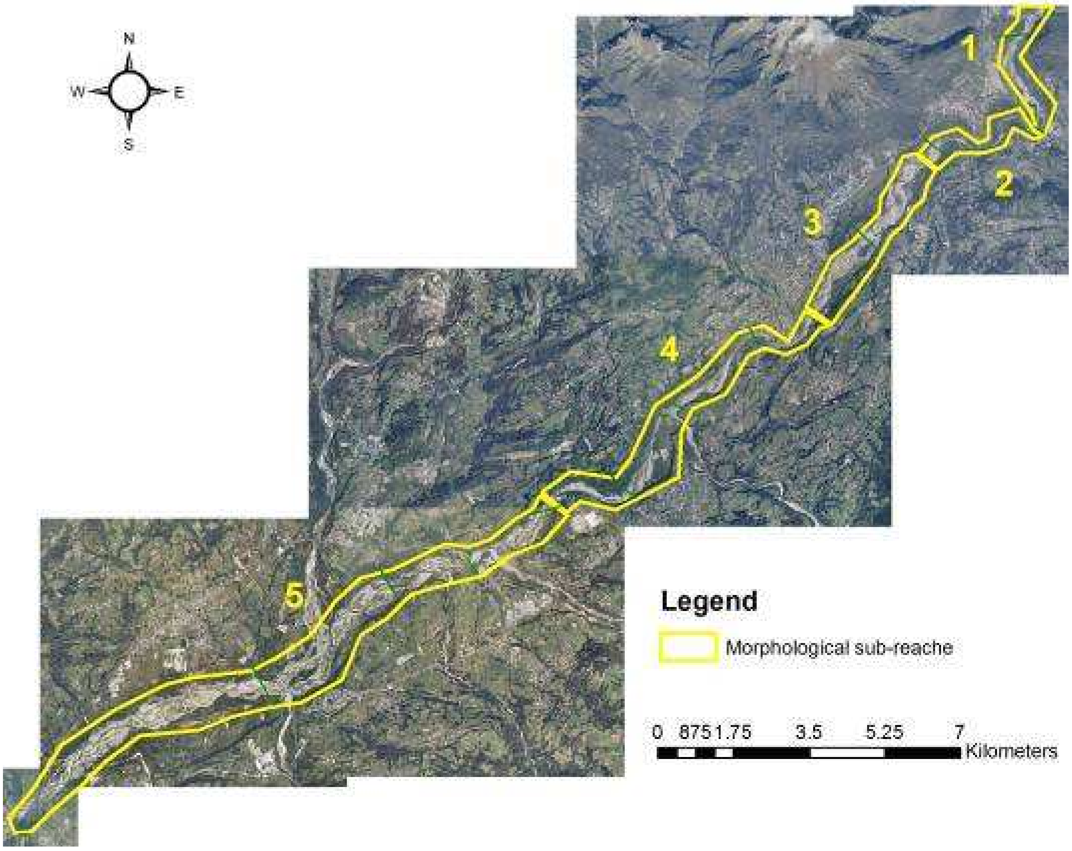

Figure 3.6: subdivision of the study reach in the sub-reaches characterized by prevalent morphological characteristics

The smaller scale of analysis consists of a sub-reach 1.3 km long, shown in Figure 3.7, where most of the field work was carried out (see chapter 5.5).

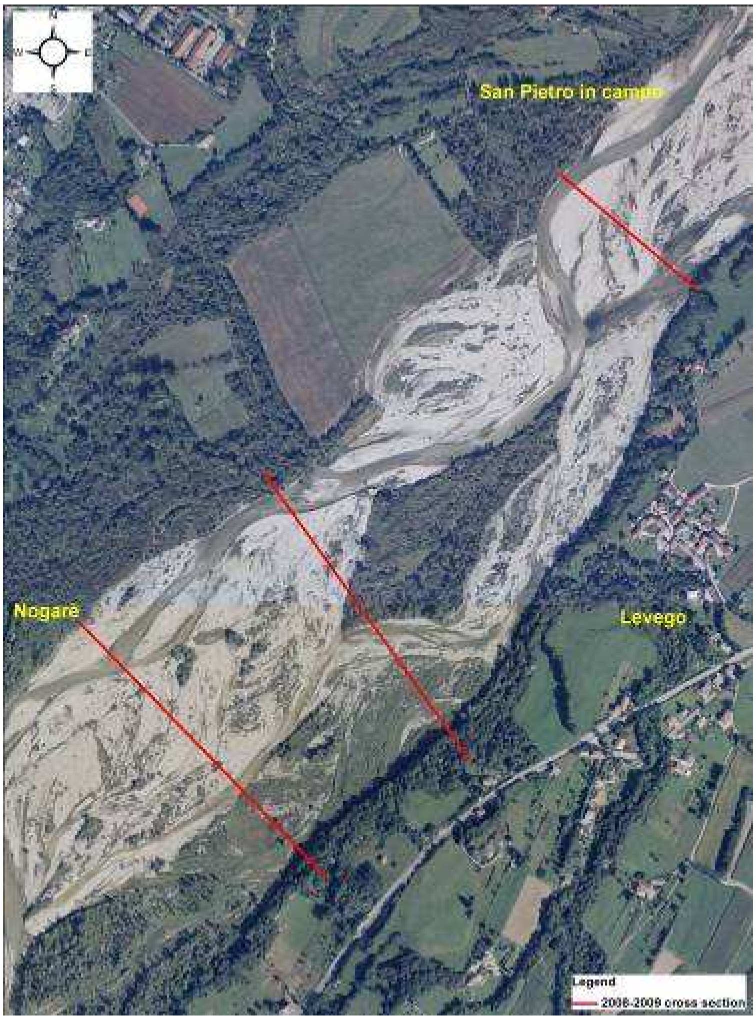

Figure 3.7 : the smaller sub-reach from San Pietro in Campo to Nogarè

3.2 The Waitaki River

The Waitaki River is located in the South Island (Fig. 3.9) of New Zealand (Fig. 3.8). It is the country's largest braided river by discharge (mean discharge ~ 358 m^3/s) and a major source for hydroelectric power, it has got a total area of about 11000 km^2 (Fig.3.10).

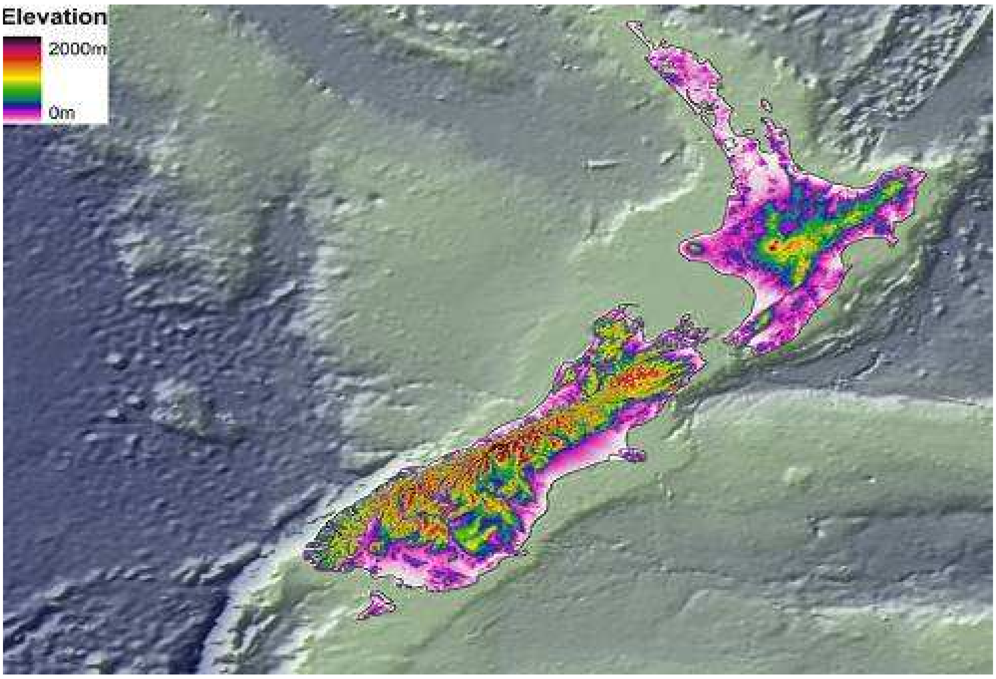

Figure 3.8 : New Zealand

Figure 3.9: South Island of New Zealand

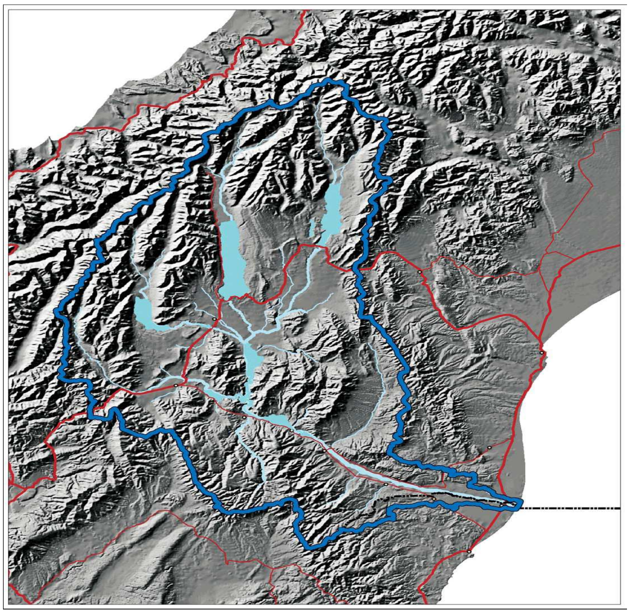

Figure 3.10: the Waitaki river basin

3.2.1 Overview of the Waitaki river

Aoraki/Mt Cook and the mountains of the Southern Alps/Kā Tiritiri o te Moana dominate the Waitaki catchment. Flows of ice, water and eroded rock have formed the glacial lakes and braided rivers of the Mackenzie and Ahuriri basins; carved a gorge through the Benmore, Kirkliston and Hawkdun ranges; and culminate in the extensive braided Lower Waitaki River. The continuing uplifting and weathering of the mountains by rain, snow and ice provide constant flows of water and gravel down the river and its tributaries to the sea. Tributary rivers and streams join the flow from the mountains, providing connections to wetlands, springs and aquifers. The Waitaki River reaches widths of up to one kilometre before meeting the Pacific Ocean north of Oamaru.

The Waitaki catchment, with its extreme variation in topography and climate, provides a diverse range of freshwater habitats and species, and a strong sense of place for people. The catchment is home to a large number of indigenous fish and birds, including the black stilt - one of New Zealand's rarest and most specialised braided riverbed birds.

Just over 5,000 people live in the catchment, with many more returning to visit year after year. The rivers and lakes are popular recreation resources for a range of activities.

Aoraki/Mt Cook and the Waitaki River are the ancestral mountain and river of Ngāi Tahu. The upper catchment and Aoraki/Mt Cook National Park are nationally and internationally recognised nature and tourism locations.

Water in the catchment provides essential supplies to towns and communities, including Oamaru and parts of Waimate District, and is a very important source of electricity and hydro-electricity storage nationally. It also provides for significant irrigation on land both in and out of the catchment. Hydropower works include three dams along the middle gorged section of the Waitaki Valley and a network of canals, control structures and power stations that utilize the storage from three natural lakes and from other three artificial lakes in the upper basin. Thanks to those construction is possible define two different basins, the upper Waitaki and the lower Waitaki.

The upper Waitaki (Fig. 3.11) consist in six different lakes (Fig. 3.12), three of them are natural as lake Tekapo, lake Ohau and lake Pukaki and other three artificial lakes as lake Benmore, lake Aviemore and lake Waitaki.

Figure 3.11 : the upper Waitaki basin in the southern Alps of New Zealand

Figure 3.12: the upper Waitaki basin in the Southern Alps of New Zealand

The most important tributaries are the Hakataramea, Otakaieke and Maerewhenua Rivers.

The tributaries of the Lower Waitaki have a low mean flow but high flood flows (MWD, 1982). Their floods, resulting from south to south-easterly storms, do not usually coincide with main river floods from the upper catchment. Many of the tributaries also dry up in summer. The upper catchment experiences a different climatic regime than the lower catchment and the natural lakes exert a damping and lagging effect on the upper catchment runoff. A consequence is that flood runoff from the tributaries and from the tributaries and from the upper river is often out of phase.

Since the construction of Waitaki Dam between 1934 and 1937, and more particularly since the construction of control gates at Lakes Pukaki (1947) and Tekapo (1951), the river flows to the Lower Waitaki have been controlled, resulting in a generally steadier river flow and there has been no gravel input from the upper catchment. It is only under special circumstances that flows at Waitaki Dam are reduced below 120 m^3/s (Hicks et al., 2003).

This Hydro-control has reduced the mean annual flood from an unregulated state flow of 1250 m^3/s to a flow of 800 m^3/s (Pickford and Rogers, 1990).

3.2.2 Basin and river morphology

The Lower Waitaki River is defined as that reach of the river extending from the Waitaki Dam (Fig. 3.13) downstream to the river mouth east of Glenavy Township, a river distance of some 70 km (Fig. 3.14).

Figure 3.13: the Waitaki dam, delimitation between upper and lower Waitaki basin

Figure 3.14: the Lower Waitaki, see from downstream

The geologic setting of the lower Waitaki Valley has been described in several reports (McLean, 1977; Macfarlane, 1982 and Hall, 1984). The Lower Waitaki River occupies a fault-angle depression between the Mesozoic greywacke hills of South Canterbury and the more extensively metamorphosed schist hills of North Otago. The valley fill comprises a sequence of Quaternary river and glacial outwash gravels that overlies Upper Tertiary sedimentary strata, which in turn overlies the Mesozoic basement. From Black Point towards the coast, the valley widens onto a broad Quaternary alluvial fan (Fig. 3.15) that laps onto the adjacent coastal plains. The Tertiary strata and older basement are disrupted by faulting and folding, while the Quaternary gravels have also been deformed but to a relatively minor extent.

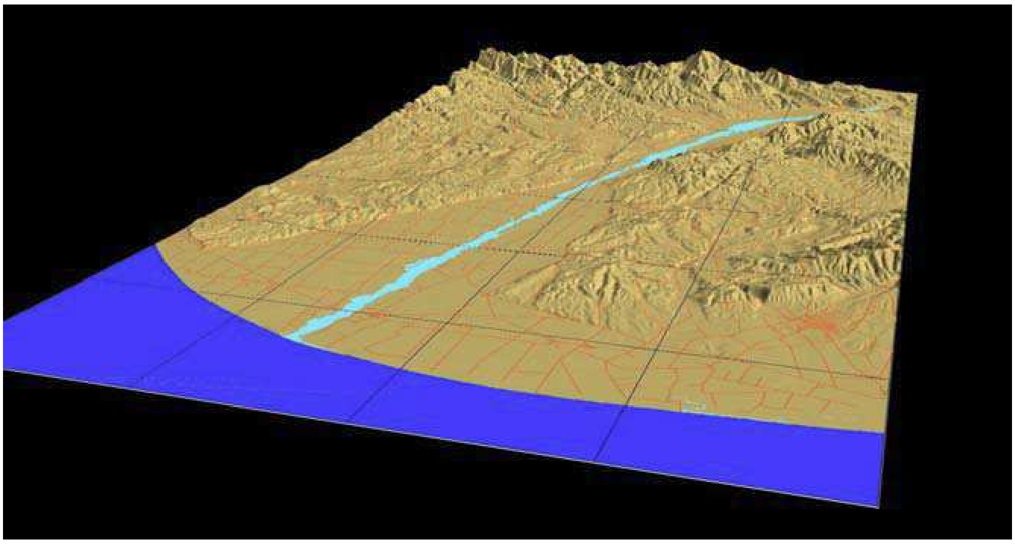

Figure 3.15: the lower Waitaki valley and alluvial fan (source: Tonkin & Taylor 2003)

The Tertiary strata include a sequence of generally soft marine sediments and more resistant limestones, and youner terrestrial sediments. Generally, they crop out along the valley margins and in the tributary valleys.

The quaternary deposits have been subdivided into recent gravels, which underlie the active riverbed and the adjacent floodplains, and Pleistocene gravels, which form terraces above the level of the river and its tributaries and also generally underlie the recent riverbed gravels. The Quaternary deposits reflect Pleistocene glacial activity, when glaciers from the Southern Alps repeatedly extended into the McKenzie Basin and which resulted in the periodic supply of large volumes of gravel down the Waitaki Valley. This has led to the construction of the broad alluvial fan downstream from Black Point, the accumulation of alluvial gravels and tributary fans in the more confined valley upstream from there, and also the development of flights of terraces when the river has incised into these deposits at times of lower sediment supply and/or rejuvenated grade (Hicks et al., 2003).

The catchment land cover (Tab. 3.5) is varied, reflecting the underlying geology and climatic features of the area and a history of land use modifications.

Table 3.5: Land cover of the Waitaki catchment (Source - New Zealand Land Cover Database 2 (Snapshot 2001/2))

Land cover	**Percentage of total catchment area**	**Predominant location**
Rock	11.50%	Alpine areas
Permanent snow and ice	2.50%	Alpine areas
Alpine and sub-alpine herb-fields, shrub land	5%	Alpine areas
Indigenous forest	1.50%	Upstream of the glacial lakes
Depleted tussock grassland	11.50%	Ahuriri and Mackenzie basins
High producing pasture	10%	East of Waitaki Dam and Hakataramea catchment
Lake, ponds and rivers	6.50%	Throughout catchment
Tall tussock	25%	Throughout catchment
Low producing pasture	21.50%	Throughout catchment
Scrub, matagouri	2%	Throughout catchment
Exotic forest	1%	Throughout catchment
Other	<1% each	

3.2.3 Morphological characteristics of Waitaki river

The Lower Waitaki River (Fig. 3.16) runs between Waitaki Dam and the coast. Between Waitaki Dam and just upstream of Kurow, the river fills a single channel confined by a bedrock gorge. From approximately one km upstream from Kurow the valley widens and the river becomes braided. It then remains braided to the mouth.

At present, at normal flows (typically around 300 m^3/s), the braided reach typically shows a dominant, main channel that meanders across the open gravel fairway with a wavelength of approximately 2 km. smaller flows area carried by side braids that pass through the vegetated fairways margins. The average valley gradient down the braided reach is 0.0033. Upstream from Black Point the bed width is some 0.8 km wide and the gradient is slightly flatter, at 0.0030; downstream from there, where the valley broadens substantially, the bed width ranges from 0.8-1.6 km, the gradient is slightly steeper at 0.0036 and the braiding is more intense (Graynoth, 1981).

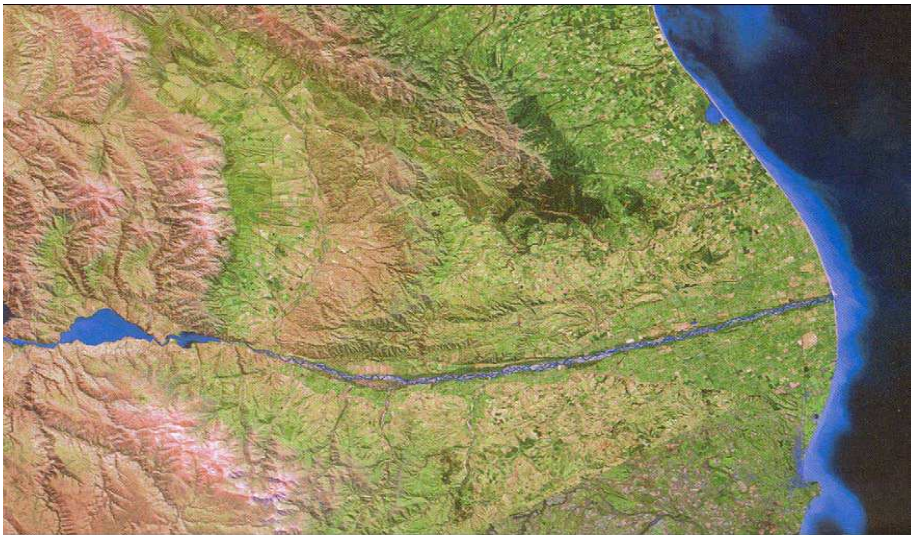

Figure 3.16 : the Waitaki River flowing from the Waitaki Dam to the sea

The predominantly gravel riverbed is often unstable along the main channel, where there is fast flowing water. However, along the quiet backwaters, the beds are frequently sufficiently stable to allow the establishment of semi-aquatic and aquatic vegetation. An area of approximately 12000 ha on the floodplain is subject to periodic flooding and erosion by the Waitaki River (MWD, 1982).

The bed-material of the Lower Waitaki is dominated by greywacke gravel, with a subsidiary fraction (18%) of fine-medium grade sand. The overall median size is 22 mm, while the median size of the gravel fraction (coarser than 2 mm) is 32 mm.

A coarsened surface layer, or armour (median size of about 80 mm), is a characteristic of much of the lower Waitaki bed. Finer gravel patches (median size of about 30 mm) tend to appear only on the surface of mobile gravel lobes or sheets, which are the main manifestation of gravel transport. The cobbly armour is particularly noticeable in channels, both large and small and on bar surfaces that have been scalped of their sand and finer gravel fractions by high flows. The armour size is coarser in the Kurow Gorge compared with in the braided reaches downstream (Fig. 3.17).

Figure 3.17: armoured strata exposed in eroding bank along the Waitaki River

Armour development is a reflection of a low gravel supply relative to the river's potential to transport bedload. Although there are no long-term records of armour development, it is likely that the extent of armouring has increased following hydro dam construction, due to the termination of bedload supplied from the upper catchment. Equally, though, the Lower Waitaki should have already been armoured to some degree before any hydro-development, since the natural lakes intercept the bulk of the sediment generated catchment-wide. Indeed, calculations of bedload transport capacity using bedload formulae indicate that the Lower Waitaki has the potential to transport several times its pre-dam supply.

In some circumstances, reduced transport capacity may match a reduced upstream supply and a river may rapidly advance to an equilibrium state. In extreme circumstances, the river may not even be able to transport all the bedload supplied by its tributaries. If this occurs, the growing tributary deltas will tend to push the main river against the opposite bank. Another possibility though is that the river may simply continue to pass its bedload at rates controlled by the bedload supply rather than its transport capacity (Hicks et al., 2003).

The suspended sediment load of the lower Waitaki derives from the upper catchment, from the tributaries and from sediment flushed from the bed material during floods. The natural lakes and hydro-lakes act as sediment traps so that only suspended fine silt and clay, finer about 0.02 mm diameter enters the Lower Waitaki from upstream (Kirk, 1983). For this reason, while the lower river tributaries may only supply 5% of the water flow in the river, they contribute a much larger proportion of the suspended load and dominate the coarser fractions of the suspended load. The Lower Waitaki bed material may be regarded as a temporary source of suspended load – it yields a “flush” of fine sediment (Fig. 3.18) when the bed material is mobilised during high flows and re-absorbs fine sediment during flow recessions.

Figure 3.18: fine sedimenta long the Waitaki River

Generally, the upper catchment may be viewed as delivering a base load of clay and fine silt that tends to follow a broad seasonal pattern. Superimposed on this is the coarser, peakier suspended load sourced from flood runoff in the lower river tributaries (Hicks et al., 2003).

3.2.4 Riverbed vegetation

Early European settlers first introduced crack willows to the Waitaki Valley as a source of shelter and fuel. With construction of the Waitaki power station, fluctuating river flows were able to move willow debris onto the braided river island and river margins. They became established there because the new flow regime lacked the extreme seasonal variations that would usually flush the debris out of the bed or would allow grazing of riverbed sites during prolonged spells of lower winter flows (Hicks et al., 2006).
As a consequence, the Lower Waitaki River became choked with crack willow, broom, gorse and tree lupin, particularly after the drop in rabbit numbers in the early

1950s. As they were colonised by willows, riverbed island and bars were stabilised and flows tended to be redirected towards the river margins. This led to the erosion of surrounding land as the flood flows tended to break away from (Fig. 3.19) the main path of the river (Aberle et al., 2003).

Figure 3.19: broom and gorse adjacent to the fairway along the Waitaki River

3.2.5 Riparian vegetation control

The earliest photographs of the river, taken around 1900, show very little sign of willow or other woody week growth. By the late 1950s, however, much of the river bed was infested with crack willow. The invasion of this weed into the river bed proper reduced the available waterway area (through its bulk), and encouraged sedimentation to occur on islands. These changes caused the river to seek alternative routes around the willow thickets, resulting in active and in some cases spectacular erosion of the riparian margins. In 1961 the Ministry of Works, acting on behalf of the Waitaki Catchment Commission, commenced an extensive willow clearance operation within the riverbed to cut a 400 m wide central corridor through these infestations. This was achieve by teams of bulldozers dislodging the willows and pushing them outwards to form windrows along the river margins. Follow-up spraying was undertaken to arrest re-growth within the fairways. Such spraying continues to the present day.

Given the nature and extent of this operation, widespread disturbance of the river bed and its armoured surfaces is to be expected. Further to that, the removal of willow and other woody weeds on the islands would have made available to the river in high flow extensive deposits of sands and silts that had accumulated over time on the willow infested island.

In the 1970s, the Waitaki Catchment Commission, with the assistance of the South Canterbury Catchment Board, promoted and implemented the Lower Waitaki River Control Scheme. These works sought to confine the active river bed within a 400 m fairway using series of rock-armoured gravel groynes supported with willow plantings. A variety of willow species including crack willow were utilised in this operation. Major flow diversions were needed to divert the river away from areas where these banks were to be constructed or maintained, or at least to ease the erosive effects of direct attack by the river. Other activities included some areal spraying with herbicides and the physical removal of stranded willows (termed "snagging").

By the early 1980s, it became evident that this approach was both impractical in this river and not sustainable from a funding point of view. The cost of maintaining the groynes was becoming prohibitively expensive and the prospect of reduced Government subsidy required a major rethink. It was considered that a more passive approach was required, to be achieved by a relaxation of the fairway boundaries out to 800 m width.

In effect, this involved abandoning or reducing in size the existing groynes and concentrating primarily on using willows to hold the borders and spraying to control the other woody weeds (mainly gorse and broom) within the fairway. Flow diversion was actively discouraged unless needed to establish or effect repairs to protection works. Aerial spraying of the river island was routinely undertaken by helicopter, with bulldozers still used for snagging (Hicks et al., 2006).

Aberle et al. (2003) evaluated the efficacy of this type of program, in particular the adequacy or otherwise of the 400 m cleared fairway may be inadequate for the purpose intended and may over time induce pressure on the riparian boundaries.

This suggests that any reduction in effort on actual clearance activities arising from cost increases can only exacerbate the problem.

As shown by Thompson et al. (1997), accumulated silt, sand and periphyton can probably be moved by moderate-sized flows. The duration of the flushing flows should be long enough to mobilise fine sediments to cleanse the gravel bars but not mobilise the armoured substrate that would destabilise the channel pattern. They consider that a flow of 480 m3/s should be adequate to mobilise sand and fine gravel over a large portion of the channel bed. They consider that larger flows would be required to keep the beaches and bars free of vegetation.

They consider that flows less than about 800 m3/s are not likely to destabilise the braided channel pattern but flows larger than 1250 m3/s certainly would. They note that, ideally, the flow required for destabilising the braiding and removing the vegetation should be as close to the minimum flow needed as possible. This is because larger flows may also alter the course of the river. Moreover, releasing flows higher than necessary would mean using water that could be used to generate additional electricity.

They suggest the following flood regime as a first estimate:

- monthly peak floods of 600 m3/s to limit periphyton and silt accumulation
- every 3 years release flood flows of 1250 m3/s for 3 days to maintain a bare gravel, braided and destabilise riparian shrub-land

Unfortunately that kind of management was not well applied every three years, so the last induced flow (2009 January) had not the expected effects, leaving a lot of vegetated bars and a lot of fluvial island well stabilized.

3.2.6 The study reach

In this study we focused our attention along the sub-reach from the small village of Kurow downstream to the Otekaieke river tributary (Fig. 3.20).

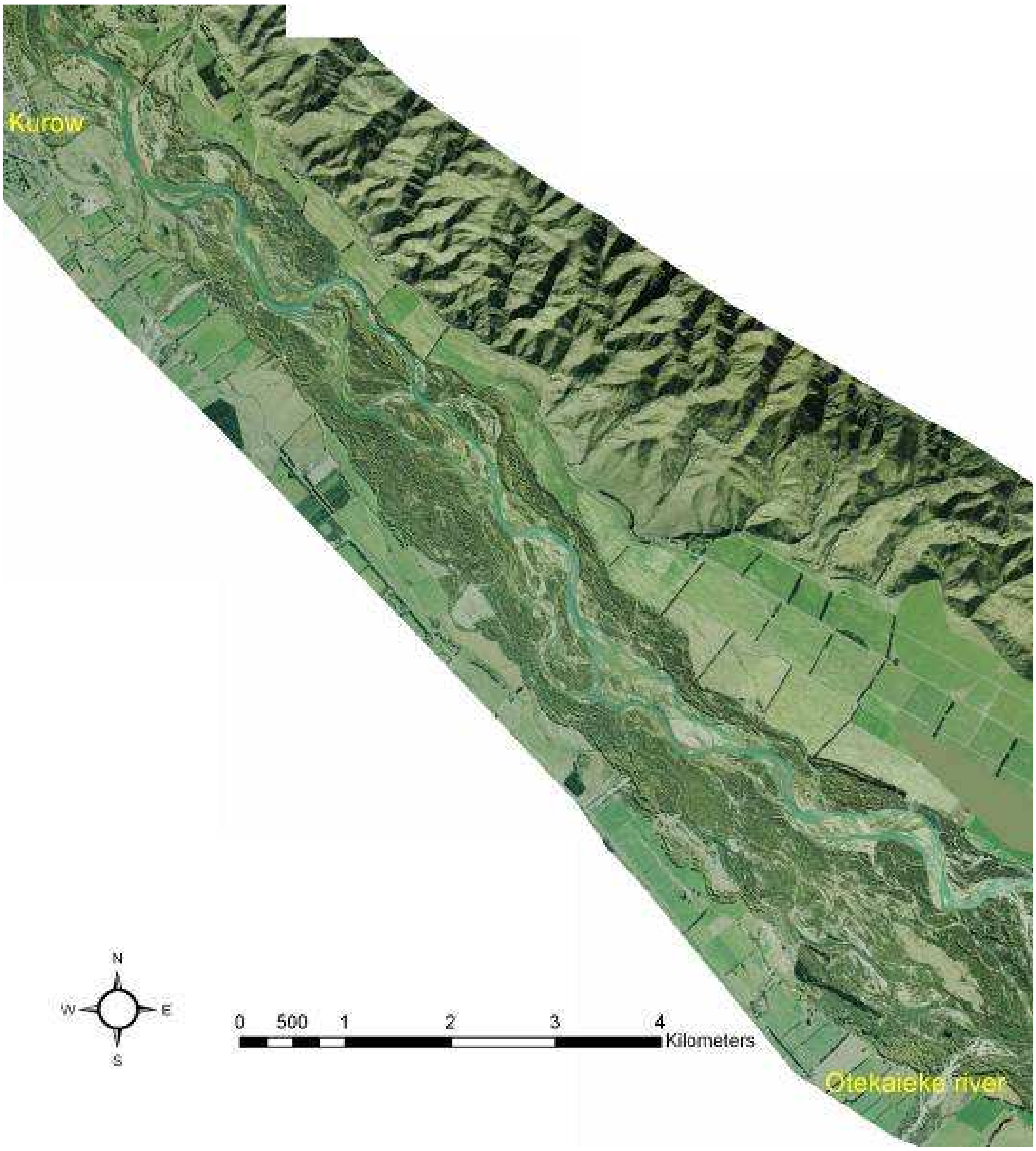

Figure3.20: the Waitaki River sub-reach, from Kurow downstream to the Otekaieke tributary confluence

Table 3.6 shows the main characteristics of the study reach:

Table 3.6: main characteristics of the Waitaki river study reach

Lenght	12.5 km
Slope	0.24%
Max width	0.50 km
Min width	2.5 km

4. Materials

During this study we made use of different technologies and materials in order to better study and analyze all the elements relating to the subject under consideration, to be more precise the content of this study.The utilization of these different technologies and materials has been dictated by different needs, different lines of study and different study environments.

So LiDAR technology has been used to carry out an elevation analysis of fluvial island evolution and the overlying woody and brush vegetation along the study reach under consideration relating to the section of the Piave River. Besides LiDAR has been used to integrate elevation data that are useful to better comprehend the morphological evolution through the study of cross sections. For this purpose the different Digital Terrain Models (DTM) have been created, by which it has been possible to obtain abovementioned data.

Instead, DGPS system has been used during all surveys on location, in all accurate analyses in order to provide a geographical localization of any different type of relief, and during the demanding and complicated cross section survey. The choice of such system and its utilization has been dictated exclusively by observations relating to the accuracy and the effectiveness of data we have been able to obtain, since such system is considered the most accurate and reliable for the purposes of this study. Then all the data gathered through DGPS system, obtained by DTM created by LiDAR data, have been analyzed and used through the use of the HEC-RAS simulation software in order to observe the changes along the territorial study depending on different discharge conditions.

Finally,we made use of many aerial photographies in order to study the different planimetric characteristics of both varied morphological elements and fluvial islands.

As below reported, we briefly illustrate the operation’s principles and the characteristics of all materials used during this study.

4.1 LiDAR: the technology

The development of airborne laser scanning goes back to the 1970s with early NASA systems. Although cumbersome, expensive, and limited to specific applications (such as simply measuring the accurate height of an aircraft over the earth’s surface), these early systems demonstrated the value of the technology.

These systems operate by emitting a laser pulse.

By precisely measuring the return time of a laser pulse, the “range” can be calculated using the speed of light. This is similar to using a total station surveying instrument. The advent of GPS in the late-80s provided the necessary positioning accuracy required for high performance LIDAR. It wasn’t long until rapid pulsing laser scanners were developed and linked to the GPS system. The systems became complete with ultra-accurate clocks for timing the LiDAR return and Inertial Measurement Units (IMU) for capturing the orientation parameters (tip, tilt, and roll angles) of the scanner.

A modern LiDAR system has a rapid pulsing laser scanner (with continuous wave lasers which obtain range values by phase measurements), precise kinematic GPS positioning, orientation parameters from the IMU, a timing device (clock) capable of recording travel times to within 0.2 of a nanosecond, a suite of robust portable computers, and substantial data storage (100 GB per mission).

From the earliest applications of airborne laser scanning, the mapping community was aware that vertical accuracies of a 15 cm Root Mean Square Error (RMSE) were possible, with horizontal accuracies about two times the footprint. Maximizing this technology greatly reduces the time and fieldwork required by most traditional methods.

4.1.1 System Component

Modern LiDAR systems are the result of rapid advances in technology during the last several years. The following are components of the AeroScan LiDAR system, used in many different studies:

4.1.1.1 *The scanner*

High-performance scanners are capable of emitting up to 15,000 pulses per second with a variable-scanning angle of 1° to 75°. With continuous wave laser pulses, multiple return values for each pulse may be recorded – up to 5 return values per pulse. Operating in the near infrared (1064 nm), pulse values may be recorded after diffusion and reflection on the ground.

GPS and IMU technology is integrated into the scanner, as well as a robust timing mechanism (clock). In addition to recording returned pulse range values, some scanners also provide signal intensity, amplitude, and pulse angle.

4.1.1.2 <u>*GPS, IMU and Timing Clock*</u>

Precise kinematic positioning by differential GPS and orientation parameters by the IMU of the canner is critical to the performance of the LiDAR system. The GPS provides the coordinates of the scanning laser source and the IMU provides the direction of the pulse. With the ranging data accurately measured and time-tagged by the clock, the position of the “return point” can be calculated.

4.1.1.3 <u>*Software*</u>

The four primary components of a LiDAR system (Scanner, GPS, IMU and Clock)
each operate within an independent plane-of-reference (Fig.4.1). As a result, the assembly of components requires sophisticated software for accurate intercommunication. The delivery of each pulse carries a time tag, position value, and orientation parameters.
Multiple returns from each pulse require cataloging and a nearly perfect storage protocol. In some cases the hardware manufacturers provide a complete system with software; the highest performance systems usually require custom software for component integration.
Computer Support: Each primary component (scanner, GPS, clock and IMU) requires dedicated computer support. In addition, another computer supports the aircraft navigation, and yet another acts as a server managing data storage.

Figure 4.1: AeroScan LIDAR System, showing the Scanner, IMU, and supporting hardware.

4.1.2 System operation

4.1.2.1 *Bore Sighting the System*

Once the system is assembled, a "bore sight" is required for calibration. By collecting LIDAR data of a pre-measured target, the internal referencing of the system is odeled, so that the configuration of the components is known. These values are used in post-processing to calculate the accurate location for LIDAR return values to an external referencing system. Each time the system is removed, a new bore sight is required.

4.1.2.2 *Data Collection*

LIDAR data collection begins with a well-defined flight plan meeting the project's requirements. The average post-spacing of the points must be at a density to support the level required for a Surface Elevation Model (SEM). Changing the flight altitude of the aircraft or the scan angle of the scanner allows for modifying the density of the post-spacing. Urban areas with tall buildings and steep terrain require special consideration to avoid holes in the data.

For the kinematic GPS, a base station of known location with a multi-channel GPS must be initialized with the GPS receiver on-board the aircraft. This initialization lock must remain in place during the entire flight. For this reason, very shallow turns are made between flight lines during data acquisition.

LIDAR data may be acquired quite rapidly: a system emitting 15,000 pulses per second with the capability to record 5 returns per pulse could potentially capture 75,000 values per second. In reality, the number of returns from such a system collecting data for a Northwest forest is closer to 35,000 values per second. At 900,000 pulses per minute, a typical 3-hour mission results in about 162 million pulses.

Since LIDAR is an active illumination system (Fig. 4.2), data can be captured in all 'clear' conditions – day or night. This factor is very useful in taking advantage of good weather conditions and the opportunity to capture data at night in busy air space around airports. As mentioned, most terrain mapping

LIDAR systems use a near infrared laser, so pulses hitting standing water are completely absorbed.

Upon landing after a mission, the system is de-initialized (LIDAR system is turned off), and quality assurance of the data begins. Since all of the data collected are georeferenced, it can be viewed in-situ using GIS software to verify coverage of the site. Also, to validate the accuracy of the collection, known survey data and a check of the bore site should be completed in-situ. Without proper quality assurance at this phase, the absolute accuracy of the data collected should be suspect.

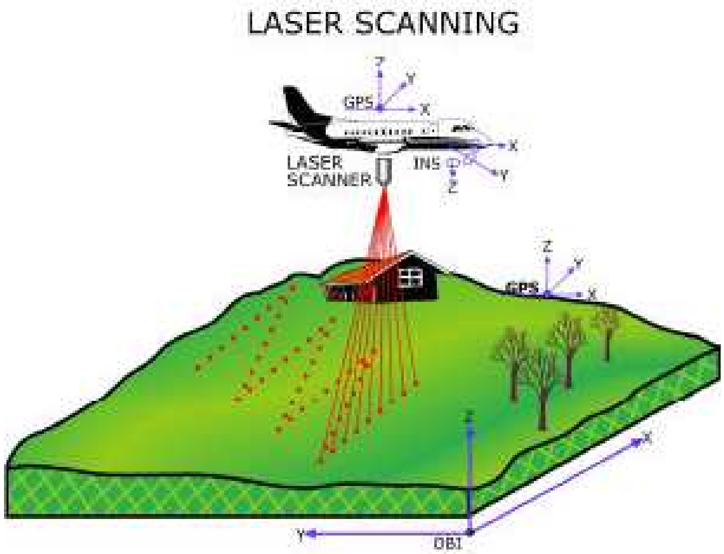

Figure 4.2: the operational characteristics of LIDAR data collection. The red dots represent, LIDAR points hitting the ground at a specified post-spacing, in a wave-like scanning pattern.

4.1.3 Processing methodologies

Data Pre-Processing: LIDAR data processing is composed of two phases. First, the data must be filtered for noise, differentially corrected (as with any high accuracy GPS survey), and assembled into flight lines by 'return layer'. This processing computes the laser point coordinates from the independent data parameters: scanner position, orientation parameters, scanner angular deflection, and the laser pulse time of flight, or slant range. LIDAR data sets are remarkably large. Therefore, it is common to validate data coverage in near real-time, before completing a mission (Figure 3). Most LIDAR providers assemble the returns as a basic ASCII file of x, y, and z values, which have been transformed into a local coordinate system. A typical flight line, six miles long with a 40° scan width, produces an ASCII file of about 5 MB for 1st return values only. Very robust data processing software and hardware is a fundamental requirement to work with data sets of this size.

Data Post-Processing: The LIDAR data must undergo further analysis to derive the final products: DEM, DSM, or intermediate return information. These surfaces are derived using skilled technical staff and GIS modelling software. Current aerial photography, satellite imagery, and existing maps are required to derive these products with a high confidence level. Figure 4 is a Triangulated Irregular Network (TIN) of 'first-return' LIDAR data for a forested site.

If current imagery is not available, collecting georeferenced 4096 x 4096 pixel digital imagery integrated to the same IMU and ABGPS as the scanner) with a calibrated camera/lens is effective. This imagery may be quickly ortho-rectified using the captured orientation parameters (without aero triangulation) and the LIDAR DEM. Imagery allows for efficient processing with higher confidence. Mapping forests exhibiting a diversity of management treatment options are processed quite effectively through the combination of digital imagery and LIDAR.

Figure 4.3 is a digital orthophoto of a forested site, which was generated from an image flown before the LIDAR data collection. The orientation parameters from this image, and the LIDAR DEM were used to rectify the image.

Firms providing LIDAR services typically have a suite of in-house algorithms for deriving the canopy layer, or DSM, and a bare earth DEM. These software modules analyze the multi-surfaces mapped by the multiple return LIDAR data sets. The processing for bare earth begins with the LIDAR points with the highest likelihood of being on or near the earth's surface. The LIDAR Analyst proceeds by moving from the "known to the unknown", making reference to the imagery, and removing above ground points selectively.

Figure 4.4 is a TIN of the bare earth DEM for a forested site. For this four square mile area, much of which is covered with mature forest. The LIDAR point density supported 20' contours. Most of the area contained 10' supplemental contours (USGS).

As a final check, representative sites within the project area should be verified photogrammetrically on a stereo plotter. LIDAR points are easily visible on the 3D stereo model for analysis, and from this check, an accuracy statement for the data set can be developed for the final Report of Survey

Figure 4.3*: a digital orthophoto of the site in Figure 4 (source USGS).*

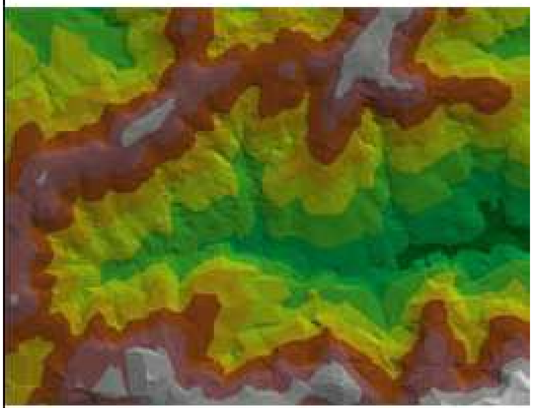

Figure 4.4: a TIN generated from a bare earth DEM(source USGS).

Data Delivery: Data delivery is typically in a format ready-for-use in GIS or CAD software in the correct coordinate system. Existing accuracy standards should be utilized to the greatest extent possible: the ASPRS large-scale Mapping Standard and the National Spatial Data Accuracy Standard. For example, if the density of ‘ground points’ does not support the accuracy required, these areas should be annotated and noted for low confidence.

To accompany the deliverables (typically a bare earth DEM, canopy layer, and a SEM) a Record Of Survey should outline the procedures for data collection and postprocessing, the intended post-spacing, flight parameters, kinematic GPS reports, and referencing of the base station.

4.2 Digital Terrain Model (DTM)

The digital representation of ground surface topography is very important to comprehend and study geomorphological and hydrological processes, in particular in the mountain basins, in which morphology plays an important role as regards hydrological response. From base information supplied by topography and more detailed information that directly ensue from reliefs (ground utilization, lithology, etc), one can obtain synthesis maps that constitute the potential indicators of processes (Cazorzi et al., 2000).

DEM is the acronym of Digital Elevation Model , that is a model that allows to represent a geographic area analyzed through a grid split into many same-size small cells (matrix representation or raster) or into triangular irregular network (*TIN*).In a raster model (Fig. 4.5), each cell contains only one value that encoders in alphanumeric form one attribute that is linked to the portion of the area represented by the same cell. The cells of a matrix are identified through a pair of coordinates (xy) which indicate the position as opposed to a reference system. As regards each cell, altitude can be considered as constant or it can be linked to its centre of mass, and in other points z will be considered as an interpolated value. In this way, areas of the territory having the same characteristics coincide with same-value cells. TIN (*Triangular Irregular Networks*) is a representation model in which the area under discussion is split up into a connected series of variable-size triangles, set unevenly in the space (tessellation) (Fig. 4.6).

DTM are usually composed of georeferenced matrices relating to terrain elevation values : data contained into said matrices can be usually arranged into square grids (DTM in raster format) or whose vertices are positioned on importance points (Fig. 4.7). DTM enables to calculate a series of attributes such as gradient, exposure, curvature and a series of topographical indices. DTM in raster format, are produced through interpolation starting from the points obtained through survey (Gps, LiDAR, Radar, Satellite).

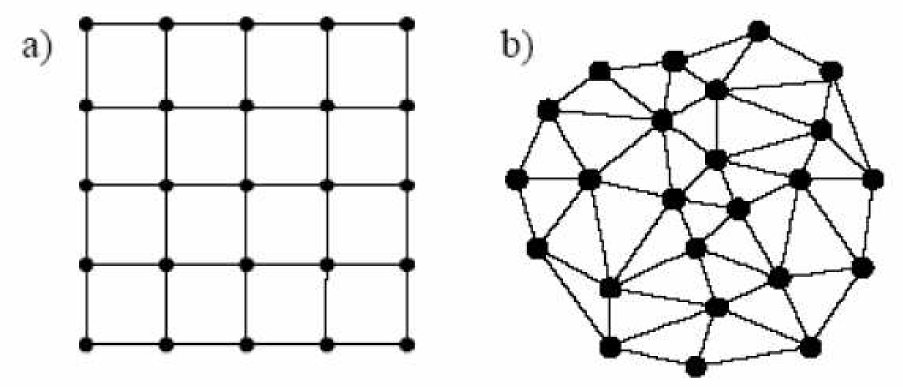

Figure 4.5: example of DEM models with raster (regular grid) (a) and TIN (irregular grid) (b)

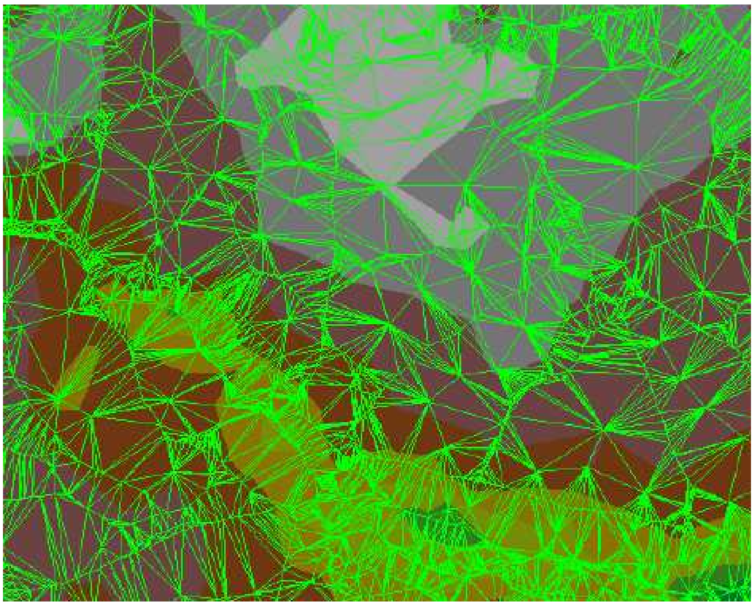

Figure 4.6: example of a triangular irregular network (TIN)

Unlike a DEM, in which a cell coincides with a unit numerical value defining an altitude, in a DSM (*Digital Surface Model*) the altitude can either indicate the effective altitude in a terrain or the height of either a tree or a building.

DTM is the acronym of Digital Terrain Model, and unlike *DSM* it exclusively relates to terrain, to be more precise it only represents those surfaces lacking in vegetation. It is a static representation of a continuous surface of terrain through an elevated number of known points in coordinates x,y,z related to a reference arbitrary system, a model allowing to represent details such as rivers and lakes. *DTM* is the base element to the numerical representation of terrain morphology and it is probably the most commonly used starting point to the measurement, analysis and modelling of slope hydrologic processes (Cavalli, 2006).

Such representation models besides describing terrain course, they enable to calculate several parameters such as area, volume, altitude, gradient, lines of maximum surface flow etc. It is clear that the characteristics of used starting points and interpolation methods determine the level of detail and the level of accuracy in resultant model.

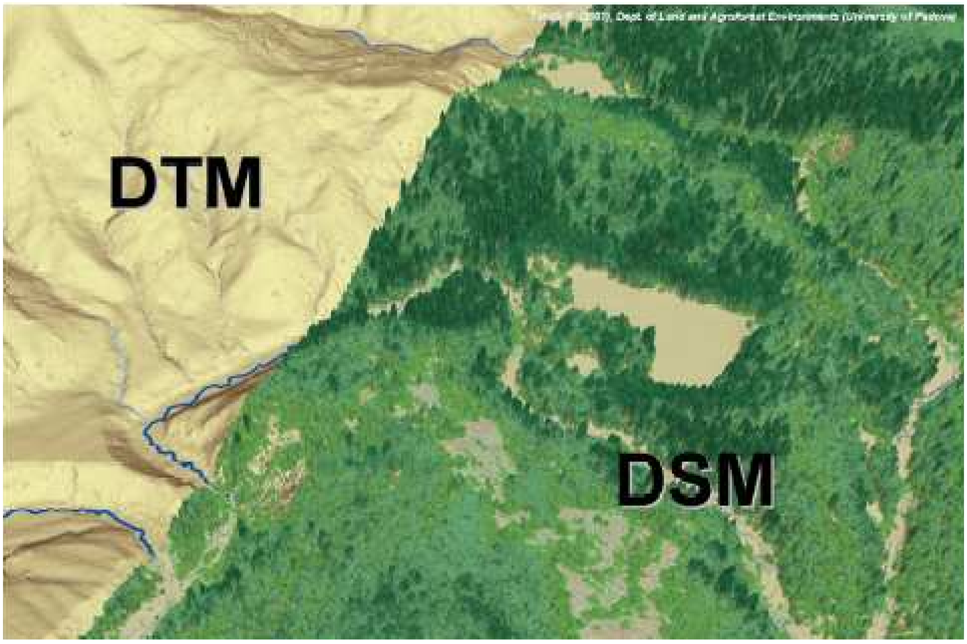

Figure 4.7: differences between DTM (Digital Terrain Model) and DSM (Digital Surface Model) as modified by Tarolli 2007

4.3 Differential Global Positioning System (DGPS) technology

The Global Positioning System *(GPS)* is composed of a constellation of 24 satellites that provides real-time or pre-recorded, anywhere and anytime, positioning, timing and navigation services of any user. The GPS provides the position on an ellipsoid having a three-dimensional geodetic datum called World Geodetic System (*WGS84*), which was developed in 1984 by the United States Defence Mapping Agency (*DMA*), valid end efficient all over the world. Such geodetic datum is a reference system that allows to define in mathematical terms the position of points on the Earth's surface or close to it.

The system development program was created by the Department of Defence in 1973 to enable U.S. Armed Forces vessels, aircrafts or vehicles to be located anytime and anywhere all over the world. Although it was originally intended for military purposes, the system's designers also made it suitable for civilian use, even if less accurate.

Many civilian applications benefit from GPS: in fact, it is currently a mainstay of transportation systems for aviation and maritime operations, used by mining and petroleum industry to locate off-shore rings, vessels and vehicles; besides it is used as anti-theft device (car alarm) and to support both assistance and civil defence means. The system can be used when exploring isolated areas, enabling the user to be located anytime and anywhere; the introduction of Differential Global Positioning System *(DGPS)* enabled to reach an accuracy so as to be used as static or dynamic positioning system in geodetic, geophysical, hydrographic and cartographic measurements.

4.3.1 GPS functioning

Operation's principle of GPS is based on triangulation method used in surveying and geodesy to determine the position of reference points. By using the triangulation method we obtain two points, but one of these is to be excluded because its position is either inside the Earth or into space, having a high velocity motion.

The Figure 4.8 presents schematically the triangulation method used in the Global Positioning System.

In theory, three measures are enough to determine accurately the position, but there are four unknown quantities to resolve:

- Latitude (x)
- Longitude (y)
- Altitude (z)
- Time (t)

therefore, four satellites are required.

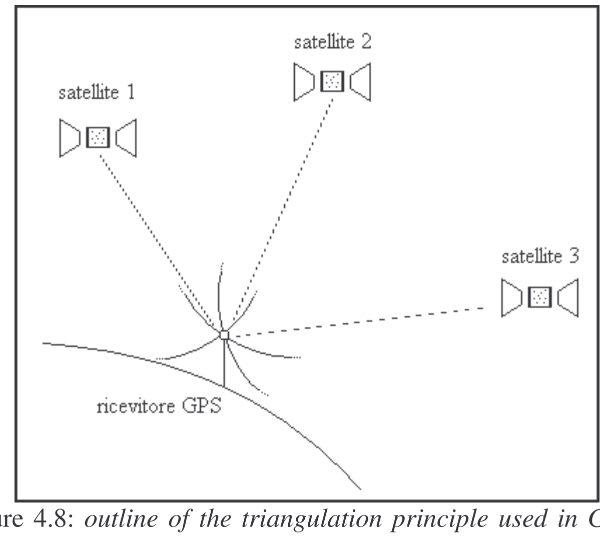

Figure 4.8: *outline of the triangulation principle used in GPS to determine the position of a point on the earth's surface through the measurement of the distance between the point and three satellites that orbit.*

Point determination is based on the measurement of travel time of the signals emitted by a number of satellites towards the receiver. To be more precise, we need to calculate the distances between the receiver and at least four satellites accurately positioned in order to carry out a positioning fixing (intersection of four spheres with Ri radius) that will provide the user with the position and determination time:

Ri = c∆T

c = speed of light (c = $300*10^6$ m/sec);
∆T = time used by signal to get from satellite to receiver

The signal emitted by the satellite is a spherical wave that propagates into space. One can represent such wave through a sphere in which, in every instant t_1, its radius is described as the distance that the signal covers into space and the satellite is in the middle of such sphere.
However, we can not consider the problem exclusively from a geometry point of view, as the distance Ri is calculated on moving objects (satellites move at very high relative velocities), through different clocks having different features and precisions from each other. When calculating the distance Ri (called pseudo-distance) there is an additional parameter, namely the time, whose measurement is rounded and imprecise. The receiver knows, based on the definition, the emission time of each satellite time signal, and it measures the reception time of the same signal through its internal clock.
The Ri is called pseudo-distance because the distance satellite-receiver is achieved by the precision of clock time difference. Such difference, whose value is rounded, represents the fourth unknown quantity of a system of equations for determining the point P0 that will have the following coordinates: x0, y0, z0 and t.
At this point, it is clear how the accurate determination of the variable t affects the accurate determination of point coordinates. The development of very accurate systems requires systems having a very precise and constant internal clock, so this feature makes the instrumentation more or less expensive, providing the degree of precision. In order to obtain a reliable measurement, we need to know exactly when

the signal has been transmitted, therefore an excellent clock is required. Satellites have four atomic clocks on board that use the oscillations of caesium and rubidium atoms, precise but rather expensive; as regards the receivers, a constant clock is enough because through the information provided by the fourth satellite, it is possible to synchronize receiver's clock and to resolve the unknown quantity of time. To sum up, all of the clocks are synchronized with each other.

A perfect synchronization is very important because a little imprecision when measuring time can cause a notable error in position determination.

4.3.2 Causes of error in position determination

GPS measurements are affected by many different types of errors due to many causes. The error typology and relative cause are linked to the possibility to intervene on the observation regarding its elimination or decrease.

All errors may be quantified in terms of the effects of satellite-receiver distance. Errors prevent GPS maximum potential from being reached, therefore they must be eliminated or at least minimized.

- Instrumental errors: they are caused by satellite and receiver operating modes, and these errors are due to intrinsic precision that systems can provide in their different measurement modes; they can be divided into:
  - Satellite clock phase biases;
  - Error of receiver's clock which can be eliminated by carrying out simultaneous observations on 4 satellites at least;
  - Poor satellite "health" eliminated by excluding observations from that satellite.
  - Receiver "noise" that can not be virtually eliminated.

- Model errors (biases) – Systematic errors common to both pseudo-range and phase measurements. They can be referred to:

  - Indeterminate satellite orbit, due to difficultly in modelling all non-gravitational forces that perturb satellite motion.
  - Synchronization errors of receiver and satellite clocks (Offset).
  - Signal perturbation during atmospheric propagation (atmosphere biases).
  - Carrier-wave ambiguity biases: they refer to phase measurements only.

- Observation errors – Accidental errors occurring in the signal acquisition by the receiver. Some of these errors can not be completely eliminated, but they can be minimized through appropriate techniques and procedures. Below we mention some errors:

▪ Cycle slips: it is a reception breakdown from the satellite while carrying out measurements; they are due to high signal noise and temporary obstruction of the line of sight between the satellite and receiver.

▪ Multipath: it is a process that worsens the ratio signal/noise, which is referred to the contemporaneous reception of the signal directly from the satellite or to other signals reflected by surfaces surrounding GPS antenna (trees, buildings, road signs (posters), metal-works, pylons, etc.). In order to decrease the effect, it is important to position the station away from surfaces reflecting the signal or using particular antennas opportunely shielded or carrying out long enough measurements so as to compensate such effects.

▪ Change in phase centre of the antenna. It occurs when similar but differently oriented antennas create different measurements. Such problem can be decreased by using antennas of the same type and oriented towards the same direction.

- Signal encryption and intentional degradation. The United States Department of Defence that manages the GPS system, reserves the right of exclusive use or degradation of GPS signal at any time. Degradation can be carried out in two different ways:

▪ Anti-Spoofing (AS). It is the overlap of an additional unknown pseudo-casual code on code P, so that the precision positioning is made impossible to non-military users.

▪ Selective Availability (SA). It refers to the degradation of information contained inside the navigation message D (worsening of transmitted ephemerides and satellite clock adjustment parameters). It was eliminated on May 2, 2000, by a decree issued by the President of the United States of America. However, the United States reserve the right to restore it at any time, if required for reasons of military security.

4.3.3 Differential Global Positioning System (DGPS)

4.3.3.1 *Absolute positioning*

The absolute positioning is widely used worlwide by most users. In fact, just one receiver can provide the geographical coordinates of one point after being turned on and after the tracking of satellite orbits by the system. One feature of differential GPS (DGPS) is characterized in that the positioning precision of one point increases depending on tracking time.
Such procedure is defined as "absolute positioning localization", to be more precise it is independent of any differential infrastructure on which angle and distance differences are carried out. The receiver, as opposed to the signals received, calculates and visualizes an instant position. The coordinates will be displayed as geographical coordinates in the GPS reference system (geocentric ellipsoid) WGS84 or in the UTM local system. The downside relating to such method is the impossibility to reduce errors over a certain threshold defined by physical laws and the system structural limits.

4.3.3.2 *Differential positioning*

The Differential Global Positioning System (DGPS) has been in use in the United States since January 1996.
The differential method enables to decrease all errors previously described. The principle on which various differential systems are based is to adjust errors caused by signal delays, by measuring them in a point of known coordinates.
If two receivers are reasonably close on the earth (a distance no more than 200 Km), the signal that both receive will have potentially travelled by following the same course through the atmosphere, therefore it will potentially have the same error.
It is a procedure on which the coordinates of a point are determined as opposed to a reference station positioned in a known point. Therefore it will be possible to correlate systematic errors of fixed reference station to the rover one.
The fixed station receives the same signal from rover station but, instead of using the signal during time to calculate the position, it uses the knowledge of its

position to calculate the error during time. It calculates the estimated signal delay and it compares it with the signal delay received. The difference is the correction factor of systematic errors that station transmits to the receiver. This way all errors due to SA and the errors referable the ephemerides and the clock are completely annulled; errors caused by ionospheric and tropospheric propagation have a considerable decrease, even if in a lower way as the distance from reference station increases. In the figure 4.10, the functioning principle relating to differential correction system is presented schematically.

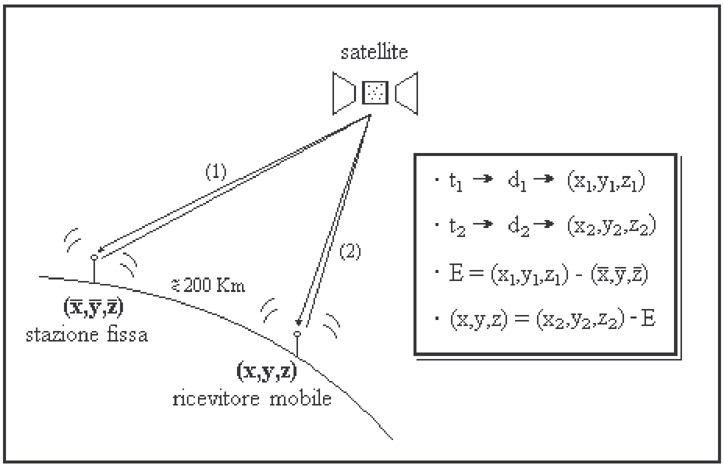

Figure 4.10: o*utline regarding the functioning principle of DGPS differential correction system*

As reference station can not know which available satellites the rover receiver is using to calculate its position, the fixed receiver quickly interrogates all visible satellites and it calculates each error of them; it transmits information to the navigator via radio frequency signals in standard format, which applies the correction factor to the signal received by the corresponding satellite.

One of the problems relating to such differential correction algorithms is referred to georeferencing, that is the control of satellite data correspondence as opposed to cartographic representation: the satellite detects the position through a “spherical representation" of planet, whereas on the map such position must be represented on a plane , thus it can not be directly used.

The combination of GPS, DGPS differential correction system and georeferencing system enables the system to reach a precision around 2 m (Venturino, 2003).

A differential reference station includes:

- Multi-channel GPS receiver
- Computer to calculate corrections
- Modem
- Radio frequency transmitter

The first three devices are assembled inside the receiver, therefore the station is very compact and easy to move. The exact position of station must be entered manually during initialization phase, or in the self-positioning systems, it is directly computed by the receiver through the use of special techniques. The station calculates corrections to distances relatively to all visible satellites and it transmits to users, the receiver adds up corrections to measured distances and it calculates user's correct position. The outcome of processing includes the coordinates of the measured point in the WGS84 international system, which can be used in a subsequent positioning on the known point.
The use of this technique requires two possible uses (Gabrielli, 2003):

1. The differential-method and post processing GPS: one can carry out surveys in the country, then a dedicated software correlates the raw data measured by the rover and the reference; such method is called DGPS (*Differential - GPS*);
2. The real time differential GPS: such method is usually called RTDGPS (*Real Time Differential - GPS*); it differs from the previous one because the adjustments between stations occur during measurement through a radio link between reference and rover.

We need to highlight that only when using the differential GPS, one can obtain precisions of the order of one meter and centimetre, up to very special cases in which precisions are close to the millimetre. There is a downside relating to such technique given that one must provide with two GPS receiver, or to acquire reference data from fixed stations functioning as service to record GPS signals regarding a specific area.

4.3.4 Coordinate acquisition method

Coordinate acquisition methods used in GPS applications (Gabrielli, 2003) are:

- **Static Methods**: such method is used in surveying where a centimetric or subcentimetric precision is required (the sample time of satellite signal is around 60 seconds per each reading), the two receivers are mounted on topographic tripods and positioned on topographical network nodes having a distance up to around 20 Km. It is important to know that unlike traditional survey methods based on optical methods, the two receivers do not need to be reciprocally visible. In this case initialization time is around 30-90 minutes depending on used instrument and environmental conditions. The static method is used in geodesy (or in high-accuracy surveying), in this case distances may range up to some hundreds of kilometres and initialization time may range up to some hours.
- **Rapid baseline static method.** Such method (also called rapid static, because its rapid sample time of satellite signal, around 15 seconds per each reading), very similar to the previous one, in which precisions are nearly the same, 1-2 centimetres, but having much faster initialization times (around 2 or 3 times faster), is used in baselines (distance between two receivers) faster than the previous one, usually up to 5 km (max. 10 km). Such method is by far the most used based on its rapid acquisition times.
- **Kinematic Method, Stop & Go**. Such method makes this instrument unique and irreplaceable as regards certain types of applications.

In the kinematic DGPS, the range relating to optimal functioning is around 5 km (max.10 km), such type of survey is particularly useful for GIS applications, in fact, the definition of areas (polygons) can be continuously done in Stop & Go applications. We remind that, according to definition, a GIS allows topological transformations of polygons, lines, and points. This is the procedure to follow; after initializing the instrument and after resolving ambiguities, we move one the two receivers by keeping the satellites lock. The technique involves observations of a series of points with common ambiguity.
The ambiguity is resolved generally at the first point, at the start of the series. During the course, the kinematic chain must not be disconnected (for example the loss of satellites below four); should said event occur, a new initialization would be required.

The Stop & Go method differs from the complete kinematic because through this system during rover shift (receiver used for the movements), trajectories done are not recorded, but only positioning points.

4.4 HEC-RAS Hydrological simulation software

The HEC-RAS model is a one-dimensional hydraulic model that can be used to analyze river flows. Version 3.1.3 of the HEC-RAS model was released by the U.S. Army Corps of Engineers Hydrologic Engineering Centre in May 2005 and 4-8 supports water surface profile calculations for steady and unsteady flows, including subcritical, supercritical, or mixed flows. Profile computations begin at a cross-section with known or assumed starting condition and proceed upstream for subcritical flow or downstream for supercritical flow. The model resolves the one-dimensional energy equation. Energy losses between two neighbouring cross sections are computed by the use of Manning's equation in the case of friction losses and derived from a coefficient multiplied by the change in velocity head for contraction/expansion losses. For areas where the water surface profile changes rapidly (e.g., hydraulic jumps, bridges, river confluences), the momentum equation is used (US Army Corps of Engineers 2001).

The Hydrologic Engineering Centre River Analysis System (HEC-RAS) is intended for calculating water surface profiles for steady gradually varied flow in nature or man-made channels. This water surface engineering software package (Army Corps. Eng. (1995)) will replace the HEC-2 backwater and ultimately
the HEC-6 erosion and sedimentation programs. HEC-RAS program will import HEC-2 input data files and perform a hydraulics analysis yielding the same results as the HEC-2 model.

The HEC-RAS computer model has a large number of options, such as mixed flow regime analysis, allowing analysis of both sub- and supercritical flow regimes in a single computer run, culvert and bridge routines allowing for multiple openings of different types and sizes, quasi 2-D velocity distributions, and xyz graphics of the river channel system.

HEC-RAS operates under the MS-Windows environment (version 3.1 or Windows 95) and provides state of the art Graphical User Interface (GUI) graphics for both input and output.

4.4.1 Model users background

A description of the HEC-RAS model and its use is given in a site example. There will be little instruction on the hydraulics to determine the computer input parameters. The user should have taken a first course where open-channel hydraulics are discussed. A number of references (Chow (1959), French (1985), Linsley, et. al. (1992)) are given for review purposes.

4.4.2 Hydraulic analysis

The HEC-RAS model can handle a full network of channels, a branching system, or a single river reach. The steady flow component is capable of modelling subcritical, supercritical and mixed flow regime water surface profiles.

The solution of the one-dimensional energy equation is used as the basic computational procedure. The flow in natural and man-made channels is estimated by the use of the one-dimensional Manning Equation (see Chow (1959)). Energy losses are evaluated by friction and contraction/expansion (coefficient multiplied by the change in velocity head). Where the water surface profile is rapidly varied, the momentum equation is utilized. By the use of these equations, the program can handle hydraulic jumps, hydraulics of bridges, and evaluate stream profiles.

The program can also be used to determine the effects of various obstructions such as bridges, culverts, and structures in the flood plain. Flood plain management and flood insurance studies to evaluate floodway encroachments may be evaluated by the steady flow system component of the program. Also, capabilities are available for assessing the change in water surface profiles due to the channel improvements, levees, and ice cover.

Special features of the steady-flow component include: multiple plan analysis; multiple profile components; and multiple bridge and/or culvert opening analysis.

4.4.3 Data requirements

The function of the HEC-RAS program is to determine water surface elevations at all locations of interest.

The data needed to perform these computations are separated into geometric data and steady flow data (boundary conditions).

4.4.4 Geometric data

The basic geometric data consists of establishing how the various river reaches are connected (River System Schematic); cross section data; reach lengths; energy loss coefficients (function losses, contraction and expansion losses); and stream junction information. Hydraulic structure data (bridges, culverts, etc.) will be covered in this module (see the illustrative examples for details).

4.4.5 The river system schematic

The schematic defines how the various river reaches are connected. The program can handle simple single reach modules or complex networks. The river system schematic is developed by drawing and connecting the various reaches of the system within the geometric data editor (see the following sections on input data and the illustrative examples). This schematic data must be the first input into the HECRAS model.

Each river reach on the schematic is given a unique identifier. Each cross section in a reach must use the unique “reach” identifier as well as a “river station” identifier. The user is required to draw each reach from upstream to downstream, in what is considered to be the positive flow direction. The connection of reaches are considered junctions and must be numbered. Junctions should be established at locations where two or more streams come together or split apart. Junctions should not be established with a single reach flowing into another single reach.

4.4.6 Cross section geometry

Boundary geometry for the analysis of flow in natural streams is specified in terms of ground surface profiles (cross sections) and the measured distances between them (reach lengths). Cross sections should be perpendicular to the anticipated flow lines and extend across the entire flood plain (these cross sections may be curved or bent).

Cross sections are requires at locations where changes occur in discharge, slope, shape or roughness; at locations where levees begin or end and at bridges or control structures such as weirs. Each cross section is identified by a Reach and River Station label. The cross section is described by entering the station and elevations (x-y data) from left to right, with respect to looking in the downstream direction. When numbering River Station Identifiers, assume the higher numbers are upstream and the lower numbers are downstream within a reach.
Each data point in the cross section in a given station number corresponding to the horizontal distance from a starting point on the left. Stationing must be entered from left to right in increasing order (see the illustrative example for the details).

4.4.7 Reach length

The reach length (distance between cross sections) should be measured along the anticipated path of the centre of mass of the left and right overbank and the centre of the channel (these distances may be curved).

4.4.8 Manning's n

The value of *n* depends on: surface roughness; vegetation; channel irregularities; channel alignment; scour and deposition; obstructions; size and shape of the channel; stage and discharge; seasonal change; temperature, and suspended material and bedload. Three values of *n* will be selected for each cross section in the following illustrative example; *n* for the left and right overbank and *n* for the centre of the channel, see Chow (1959) and French (1985) for selection of numerical values of *n*.

4.4.9 Contraction and expansion coefficients

Contraction or expansion of flow due to changes in the cross section is a cause of energy loss between cross sections. The loss may be computed from the contraction and expansion coefficients specified on the cross section data editor. Refer to references Chow (1959) and French (1985) for these coefficients.

4.4.10 Stream junction data

Junction data consists of reach lengths across the junction and tributary angles (only if the momentum equation is selected). In the following illustrative examples, the energy equation was used to model the junction. The energy equation does not take into account the angle of any tributary. In most cases, the amount of energy loss due to the angle of the tributary flow is not significant.

4.4.11 Flow regime

The flow regime must be specified on the Steady Flow Analysis window of the user interface.

Computations are used upstream for subcritical flow and downstream for supercritical flow. In cases where the flow regime will pass from subcritical to supercritical or supercritical to subcritical, the program should be run in a mixed flow regime mode.

4.4.12 Boundary conditions

Boundary conditions are necessary to establish the starting water surface elevations (WS) at the ends of the river system. The WS is only necessary at the downstream end for subcritical regime, the WS is only necessary at the upstream end for the supercritical regime, and the WS is necessary for both downstream and upstream for the mixed flow regime. Boundary conditions are not necessary at junctions.

4.4.13 Discharge data

Discharge information is required at each cross section starting from upstream to downstream for each reach. The flow rate can be changed at any cross section within a reach.

5 Methods

There have been many methods of analysis depending on the topics we have considered and analyzed, the type of parameters considered as well as the materials and the systems (devices) used.

We briefly illustrate below all application and analysis methodologies used during this study, which have been carried out on location and in laboratory.

In Table 5.1 there is a summary of all field-use methodologies and their localization:

Table 5.1: field-use methodology and their localization

Method	Waitaki River Study reach	Piave River-		
		Whole study reach	Ponte nelle Alpi Belluno sub-reach	San Pietro in campo-Nogarè sub-reach
Interpretation of aerial photos	X	X	X	-
Cross-cections from LiDAR DTM	-	X	X	X
Cross-ections from DGPS surveys	-	X	-	X
DTM detrendization for relative island elevation	-	-	X	-
HEC-RAS modelling	-	X	-	X
Field measurements on islands characteristics	-	-	-	X

5.1 Identification of geomorphological and vegetation features from aerial photos

Planform changes of river features over the last 60 years and island dynamics and changes were analyzed on six aerial photos along the Piave River (1960, 1970, 1982, 1991, 1999, and 2006) and eight along the Waitaki River (1956; 1964; 1966; 1985; 1994; 1995; 1996; 2001 e 2008). The maps range in scale from 1:25,000 to 1:26,000, whereas the aerial photos from 1:8,000 to 1:33,000. Photos were scanned at a resolution of 600 dpi in order to obtain an average virtual resolution of 1 m or smaller. Aerial photographs were rectified and co-registered to a common mapping base at 1:5,000 by a GIS software (Esri ArcGIS 9.2). Approximately 30 ground-control points were used to rectify each single frame, and second order polynomial transformations were then applied, obtaining root mean square errors (RMSE) ranging from 2 to 4 m.

The active channel was calculated using the different aerial photographs runs and correspond to the area of water and sediment bars lacking pluriannual vegetation, i.e. shrubs and trees.

Assuming the conceptual model of island dynamics (Edwards et. al. 1999), a milestone of our study process was to establish a criteria for distinguish between vegetated bars and pioneer islands. When regeneration reaches at least 3 meters high (between 3 to 5 years after the first new shoots), we expected that bar vegetation is structured enough to be considered as a pioneer island. We based our criteria upon the visual monitoring of LWD deposited in high bars through 1999 and 2003 aerial photographs (Pecorari, 2008); tree height information was provided by analysing 2003 DSM data.

The survival of saplings depend on the right balance between a high elevation site - less disturbed by small floods - depth and fall rate of the water table - higher is the gravel bar where the vegetation is growing, higher the distances to reach the subsurface water table necessary to survive to drought periods. *Populus nigra* fragments grow better in location where water table is stable and are formed by a coarse gravel substrate with presence of finer sediment (Francis et. al., 2004).

The next fundamental step was to identify and distinguish among pioneer, young and stable islands. The basic factors in characterized island types are maturity of the vegetation and size (Kollman et. al. 1999). It is assumed - model of island formation from buried LWD (Gurnell & Petts, 2006) - that older the vegetation is, older is the island and higher is the accretion of sediments, hence bigger the island should be. We employed three dimensional data (DSM and DTM) which are a valuable complement to aerial photographs (Zanoni et al., 2008).

In the aerial photos, distinction between arboreal and shrubby vegetation was made estimating vegetation height based on canopy texture, shape and shadows. A height of about 3-5m was assumed to separate the two classes.

We defined as follows:

- Pioneer islands: We considered pioneer island those gravel bars that present a patchy vegetation cover with spots of vegetation around 3-5 meters,
- Young islands are an intermediary step towards the consolidation as established island. Young islands are the result of the progressive development of the vegetation and recruitment of fine sediments,

consequently it is expected that young islands present higher ground elevations and bigger area than pioneers.

- Stable island: Those established islands with a high dense vegetation cover and an average of 15 to 20 years old (Gurnell & Petts, 2002). In an natural braided gravel bed river, these landforms rarely survive more than 20 or 25 years (Gurnell et. al., 2001). The totality of stable islands in our study reach seems to be formed by three of the processes described by Osterkamp (1998): following the progressive enlargement of young islands; islands formed by avulsion during a flood event; lateral channel migration during normal discharge that may isolate a central surface

For the Waitaki River, photograph runs in 1956, 1966, 1994, 1995, 1996 and 2008 were used, and these captured changes due to two large floods that occurred in November 1994 (~1500 m^3s^{-1}) and in December 1995 (~3000 m^3s^{-1}). For the Piave River analysis, photograph runs for 1960, 1970, 1982, 1991, 1999 and 2007 were used, and they captured the effects of the great flood that occurred in November 1966 (over 4000 m^3s^{-1}, return period of about 200 years).

Significant planform features were digitized on rectified photos in order to derive planform characteristics for each image. Measurements are affected by errors due to both rectification and digitization processes. An error assessment was carried out, based on (a) RMSE values, which can be an acceptable proxy of the average error of geo-rectification; (b) previous studies that took into account both geo-rectification and digitization errors (e.g. Gurnell, 1997; Winterbottom, 2000; Zanoni et al., 2008); (c) some field measurements with GPS that we carried out to assess the position of digitized features. Through such analysis, maximum errors of 6 m were estimated for measurements on aerial photographs.
Aerial photographs from the two study rivers were used to measure historical changes in planform characteristics and the contraction and expansion of the riverbed vegetation. Six different photo runs for each river. For the Waitaki River aerial photographs, contact prints were scanned at 0.5 m pixel resolution (Hicks *et* al., 2003), while for the Piave River the pixel size varied between 0.5 m and 1.33 m.

For the Waitaki River, photograph runs in 1964, 1966, 1985, 1994, 1996 and 2001 were used, and these captured changes due to two large floods that occurred in November 1994 (~1500 m^3s^{-1}) and in December 1995 (~3000 m^3s^{-1}) (Hicks *et* al., 2003). For the Piave River analysis, photograph runs for 1960, 1970, 1982, 1991, 1999 and 2007 were used, and they captured the effects of the great flood that occurred in November 1966 (over 4000 m^3s^{-1}, return period of about 200 years).

The georeferenced digital imagery was then analysed with ESRI Arcview 9.2 software, using a semi-automated approach. This involved setting-up a series of quasi-parallel transect lines spaced at 500 m intervals along the study reaches. Each transect was digitised into segments according to the ground cover, which (after Hicks *et* al., 2003) was manually classified and recorded as either

- Flowing channel
- Non-flowing water (e.g., backwaters and ponds)
- Pasture (including cultivated farmland and hillslopes)
- Tall vegetation (e.g., trees such has willows) higher than 3-5 meters
- Low vegetation (e.g., bushes and shrubs) lower than 3-5 meters
- Vegetated Island, higher than 3-5 meters
- Sparse vegetation (i.e., patchy scrub growing on gravel bars)
- Bare gravel
- Tributary bed
- Urban

Up to 117 transects were measured along the Waitaki River, depending on the coverage of the aerial photography, while along the Piave River the analyzed transects varied from 57 to 66 depending on aerial photograph coverage.

The analysis aimed to quantify changes in riverbed vegetation cover and wetted channel width with time, and to capture any accompanying changes in braiding characteristics (Hicks *et* al. in 2003).

All the Piave photos represent low flow conditions (Tab. 5.2), whereas the Waitaki photo-runs represent different flow conditions (Tab. 5.3). Will be very important keep under strong consideration the different discharge conditions during the data analysis.

Table 5.2: Piave river discharge data

Year	Discharge (m^3/s)
1960	23
1970	24
1982	22
1991	25
1999	27
2006	32

Table 5.3 : Waitaki river discharge data

Year	Discharge (m^3/s)
1956	426-451
1964	25
1966	331-463
1985	440
1994	340-385
1995	464-521
1996	420-435
2001	90
2008	145

5.2 LiDAR data

This method was applied in the Piave river only.

An airborne LiDAR flight carried out by “Autorità di Bacino dell’Alto Adriatico” during fall 2003 (adopting orthometric elevations, estimated vertical error ± 20cm). Point density of 2-3/m^2 was reached after filtration.

In order to create DTM accurately it has been required to analyze the effective density of dataset points obtained through the use of *Spatial Analyst Density* application of *ArcMap 9.2 software* (Fig.5.1). The DTM was created at 0.5-1 m resolution using the tool “3D-analyst” of ArcGIS 9.2

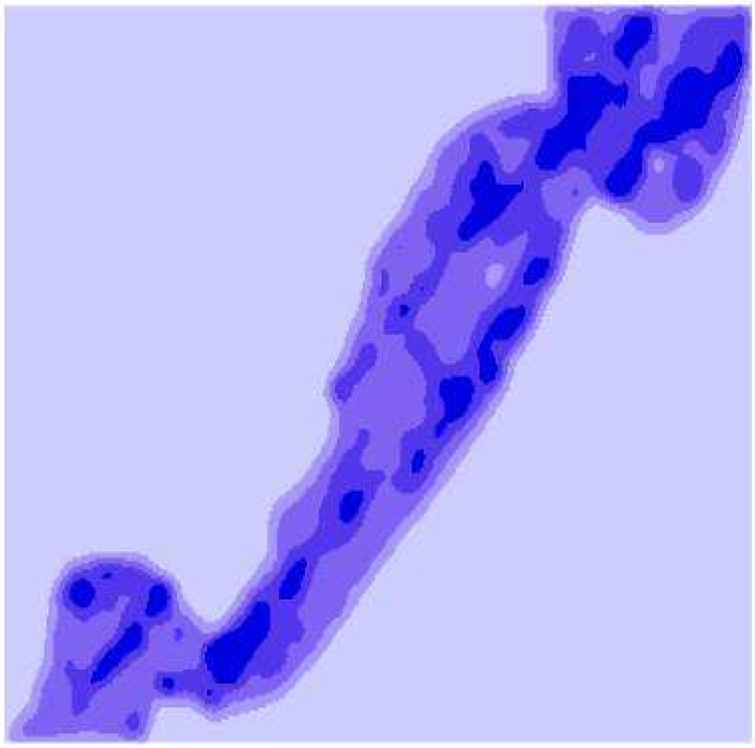

Figure 5.1: density map of points obtained through LiDAR survey relating to a reach of the Piave river obtained through Spatial Analyst Density application.

This has been carried out because, once determined point density regarding varied DTM sections, one could avoid errors when extrapolating profile and sections having effective density less than that assigned as a dimension of the generating cell of the same digital model. In fact, for example, if we create a DTM with a cell dimension of 0.5 m but the effective density is lower than this value, we will find areas in which they will be created through the interpolation of points that were not measured, thus observing a decrease in precision of the digital model to obtain.

For this purpose, density maps have been created through the use of *Raster Calculator application of Spatial Analyst, ArcMap 9.2* (Fig.5.2), in order to detect potential areas of low density near cross sections we intended to extrapolate from the model, so as to calibrate and determine accurately the dimension of the cell.

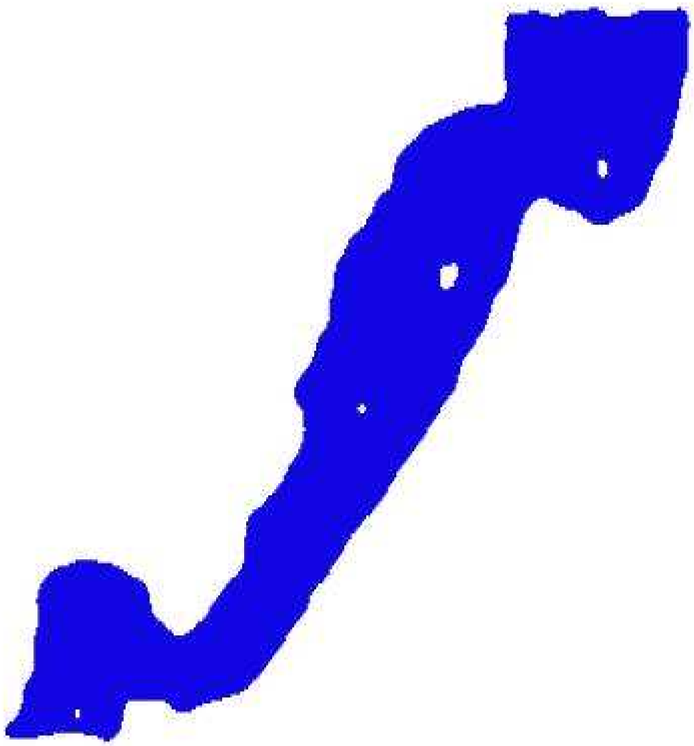

Figure 5.2: localization of areas having density lower than 0.5 (white areas), obtained through the use of di Spatial Analyst Raster Calculator, ArcMap 9.2

By doing so we could create five different DTM, four of these created with a cell dimensions of 0.5 m and one with a cell dimension of 1.0 m.

A problem found by analyzing the DTM relates to the quality of certain areas. Macroscopic errors are due to the so-called jamming operations (Fig.5.3) carried out by the U.S. military staff of Aviano Air Base (Pordenone) in order to disturb in some areas the satellite signal through the use of radio devices for reasons of military security. As we have not been able to solve this problem, we could not use data relating to these areas affected by such disturbance operations.

Figura 5.3: DTM dell'intera area di studio del fiume Piave con evidenziazione della zona sottoposta a jamming nel periodo in cui è stato effettuato il volo di rilievo con laser scanner

5.3 Topographical surveys, LiDAR data and cross-section elevation

These methods were applied in the Piave river only.

Cross-sections surveyed in 1929 within the study reach by the "Magistrato alle Acque di Venezia" (the former management agency of the river) were acquired and utilized for the analysis of long-term vertical bed adjustment and their geographical position implemented in the GIS project. These cross sections were re-surveyed in 2007 using a DGPS system (Fig. 5.4), and a virtual vertical error < 2 cm was assured by post-survey data filtering. 2007 ellipsoidal elevation (WGS-84 reference system) were then converted to orthometric elevations (i.e. to the same datum used in 1929 surveys) by the software VERTO2 provided by of the Italian Military Geographical Institute (IGM), whose precision is claimed to be ±4cm.

Figure 5.4: differential global positioning system instruments

In addition, the topographic survey carried out by the “Genio Civile di Belluno” in 1985, 1991 and 1996 at eleven cross-sections (Table 5.4) was also acquired and will be used to infer recent channel elevation variations. Unfortunately, only two of these cross sections correspond to those surveyed in 1929-2007, i.e. a complete set entailing both long- and short-term variations is available only for 2 sites.

In order to determine how channel bed evolved after 1996 at these cross-sections for which DGPS survey of 2007 was not available, we used the DTM from the LiDAR survey, and cross-sections were then extracted from the DTM in correspondence to the those of the 1980s-90s. LiDAR-derived cross-sections suffer from the inability to correctly represent inundated areas where water depth is > 20-30 cm, nonetheless the LiDAR survey was carried out during low flow conditions such that only a minor fraction of each cross-section is not correctly captured.

For each available cross-section dating from 1929, 1985, 1991, 1996, 2003 and 2007, the mean elevation of the active channel (i.e. excluding floodplains and islands) was calculated based either on survey point description (for 1929 and 2007) or on visual identification from aerial photos (for the others). In the subsequent analysis, cross-sectional elevations from 2003 (LiDAR) and 2007 (DGPS) will be both used as a reference to the “present day” conditions, because between these two surveys no relevant flood events occurred and the active channel width did not show marked variations. Preference to 2007 elevation data – where available – will be granted because of the possible error associated to the missing sensing of the bottom of the low-flow channel.

Table 5.4: list of the cross-sections used and their survey year

Cross Section Code	Distance from upstream(km)	Year
S-1	1.26	1929, 2007
S-2	2.84	1985,1991,1996, 2003
S-3	3.99	1929, 2007
S-4	5.21	1985,1991,1996, 2003
S-5	8.00	1929, 2007
S-6	9.74	1985, 1991, 1996, 2003
S-7	10.54	1929, 2007
S-8	10.98	1929, 2007
S-9	11.68	1985, 1991, 1996, 2003
S-10	12.96	1929, 2007
S-11	14.56	1985, 1991, 1996, 2003
S-12	15.19	1929, 2007
S-13	17.45	1929, 1985, 1991, 1996, 2007
S-14	19.45	1929, 1985, 1991, 1996, 2007
S-15	21.98	1985, 1991, 1996, 2003
S-16	23.35	1929, 2003, 2007
S-17	28.12	1929,1985,1991,1996,2007
S-18	28.69	1929,1985,1991,1996,2003
S-19	29.01	1985, 1991, 1996, 2003

5.4 DTM detrendization

The water surface was taken as base-line to obtain a rough mean DTM which represents the average slope of water channel. Based upon the high resolution DTM of the study area (cell size = 1m), a shape file was created including 80 points (approx. 1 point every 100 m) located within the water flow and especially in areas of changing channel gradient. A raster slope layer based upon these 3D points was then realized, by applying an interpolation method available in ArcGIS 9.2 Spatial Analyst: Natural Neighbour.

The natural neighbour method is appropriated for calculating a grid of values from clustered scatter points (Childs, 2004). Natural Neighbour Interpolation uses the ratio between the Voronoi tassels of the point to be estimated and "borrowed" area from the other tassels from the existing points (Boissonnat, 2002).

The basic equation in 2D is:

$$Z(x,y) = \Sigma\, wi\, f(xi,yi)$$

where $Z(x,y)$ is the estimated value of point (x,y), wi are the weights assigned and $f(xi,yi)$ are the known values of (xi,yi). Weights, wi, are determined using the Delaunay triangulation.

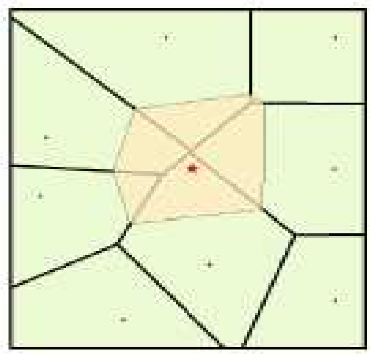

Figure 5.5: E.g. of 2D natural region

The last step in order to create a Detrended DTM (Fig. 5.8) is subtract the original DTM minus the new mean DTM obtaining a detrended DTM which is the baseline point for our work (Fig. 5.6 and Fig. 5.7), such calculation was done with Spatial Analyst Tool (Raster Calculator).

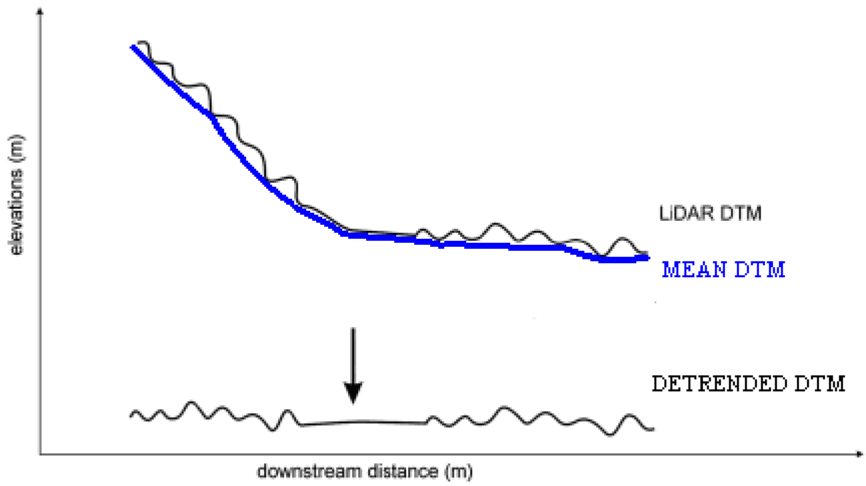

Figure 5.6: example of the Detrended DTM calculation. Modified from Cavalli et. al.(2008).

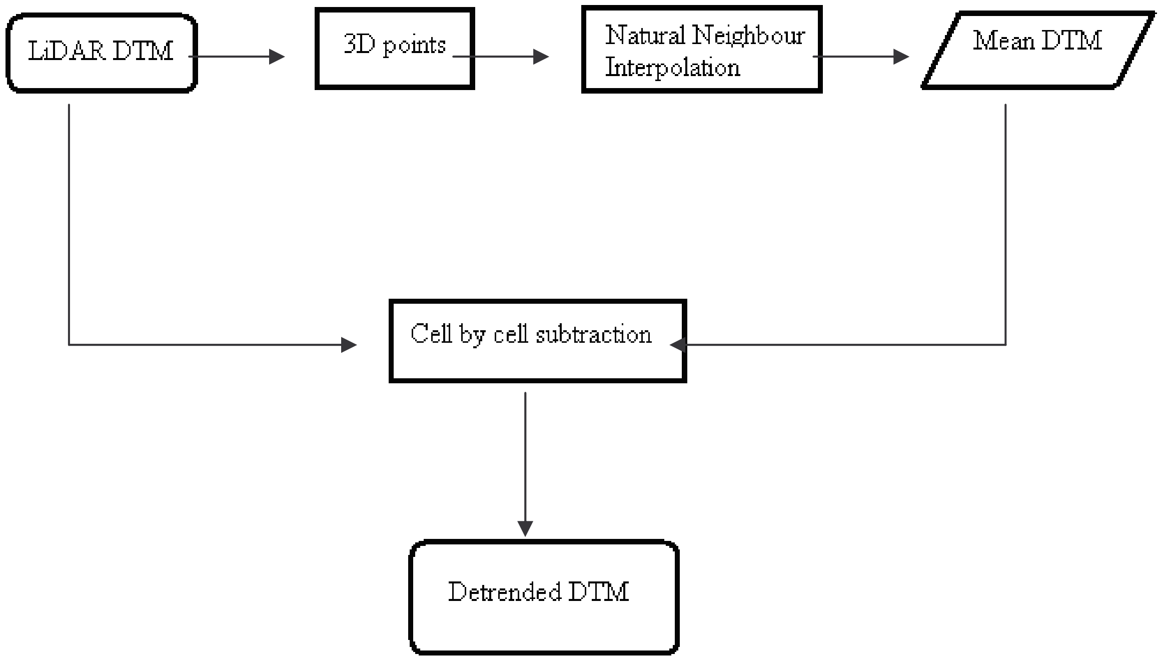

Figure 5.7: flowchart of the calculation of the detrended DTM.

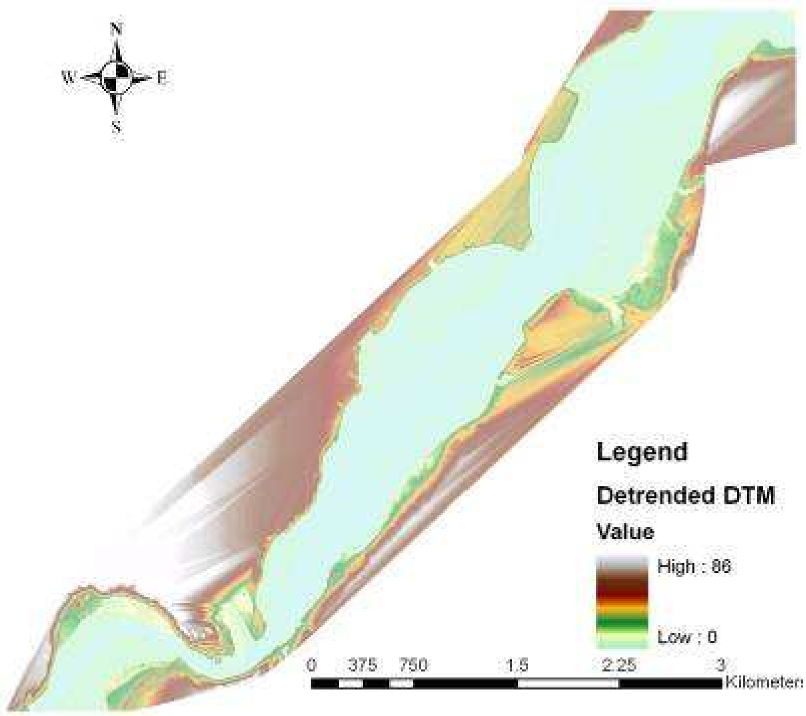

Figure 5.8 : detrended DTM.

The DTM represent the elevation of bare ground, the DSM (Fig. 5.9) represent the elevation of the surface intercepted in the first return, and so it records elements - canopies, bridges, buildings, etc- above the bare ground.

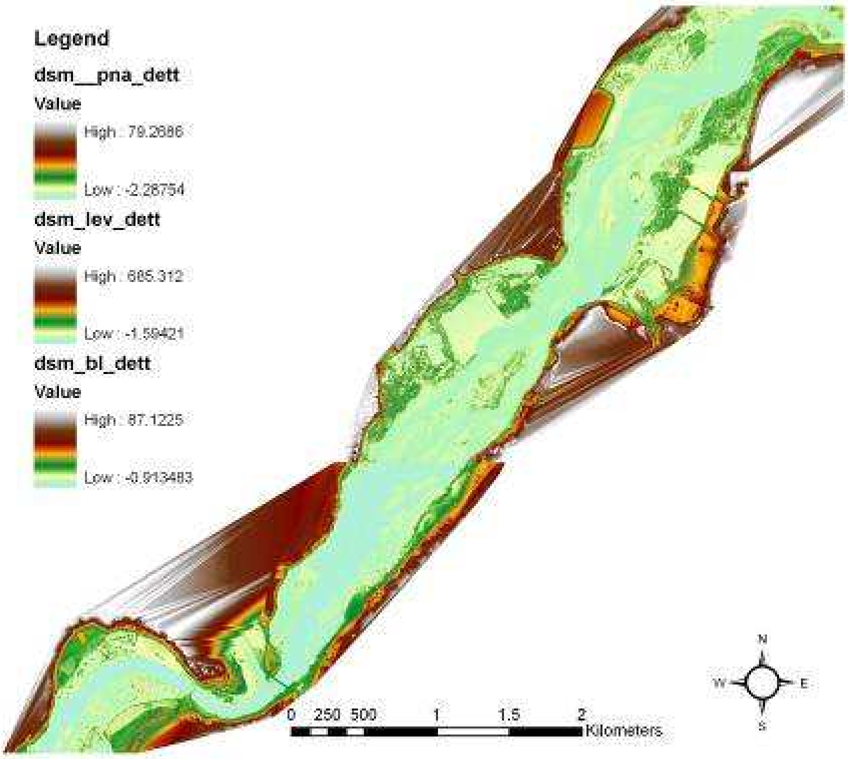

Figure 5.9: DSM of the study reach

Therefore the raster subtraction of the original DTM layer minus the DSM layer generates the Canopy Height Model (Fig. 5.10), in which every pixel means the foliage height above the terrain of the vegetation cover (Barilotti et. al., 2009). It may be assumed that the LiDAR canopy height is similar to the real one. However, past studies demonstrated that the height value showed by single trees is often lower in a CHM than by field measurements carried out with a clinometer. This error occurred due to the narrow apex of the trees -especially in softwood trees-, for this reason, the laser pulse could miss the tree top (St-Onge et. al., 2001).

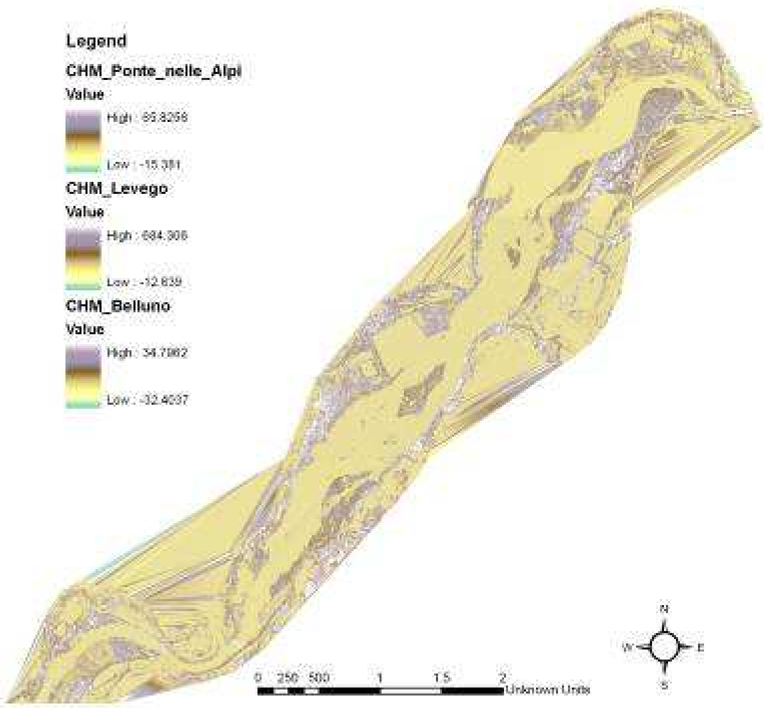

Figure 5.10: CHM of the area.

Applying the Spatial Analyst Zonal Statistics of ArcGIS, we were able to match every island polygon with the detrended DTM and with the CHM. Hence, we obtained the maximum, minimum and mean elevation of island ground; also maximum and mean height of the island vegetation.

5.5 Field activities at the subreach scale in the Piave River

Several field observations and measurements were carried out in the subreach "San Pietro in campo – Nogarè" (see section 3.1.6) in the period Summer 2008 – March 2009.

This subreach was chosen for its morphological characteristics, such as the presence of many islands of different types, including the largest island encountered in the Piave study reach (Fig. 5.11).

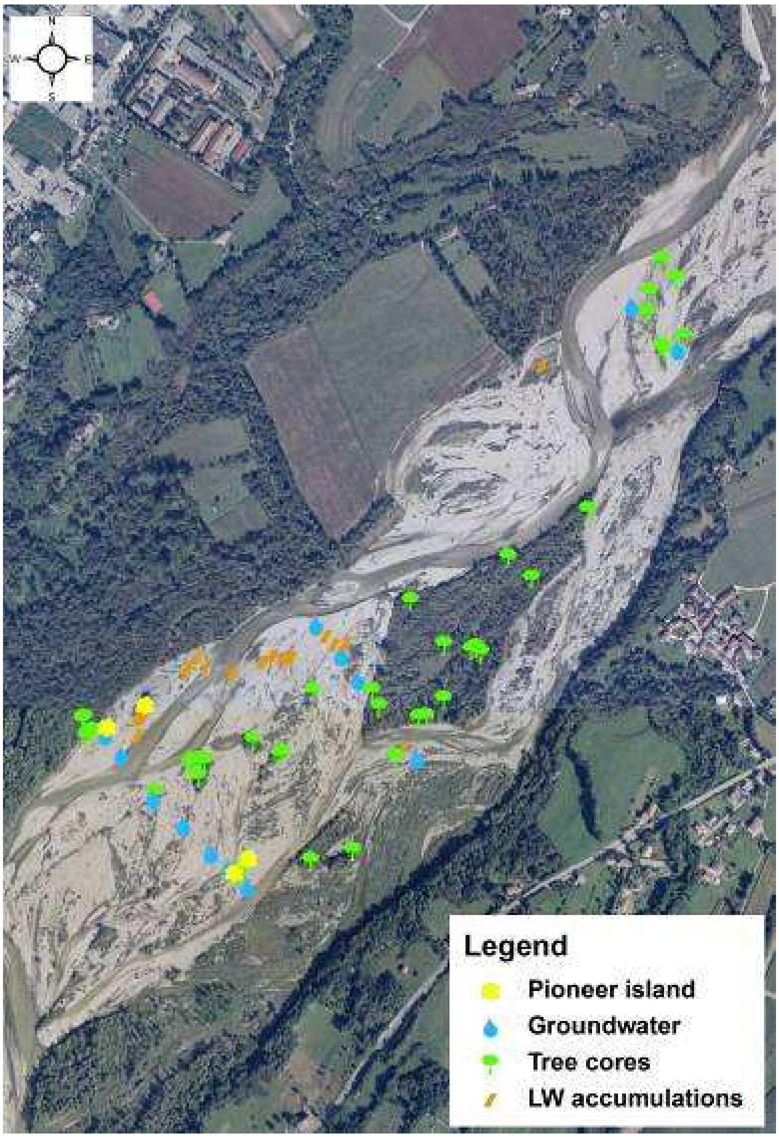

Figure 5.11: the subreach in which more detailed analyses have been carried out

The age of trees (Fig. 5.12) growing on islands was determined through the use of a Pressler gimlet on a sample of 47 trees (Fig. 5.13), ranging from 6 cm to 57 cm in diameter and from 4 m to 30 m in height.

Figure 5.12: trees growing on Island along the subreach

Figure 5.13: sampling with Pressler gimlet

The groundwater distance below bars and islands during summer low flows was determined by digging 13 holes in the gravel bed along the cross-sections and measuring by DGPS the elevation of the water table (ranging from 5 cm to more than 1 m). Finally, fine sediment (i.e. sand) depth deposited on islands was measured by a stadia rod at 37 locations (Fig. 5.14), by digging trenches in the sand substrate down to the underlying gravel substrate (ranging from 0 cm to more than 1 m).

Figure 5.14: fine sediment depth measurements

6. Results

6.1 Historical changes in river vegetation and morphology

Figures 6.1, 6.2, 6.3 and 6.4 show the riverbed cover classification trends for the Waitaki River and for the Piave River , respectively

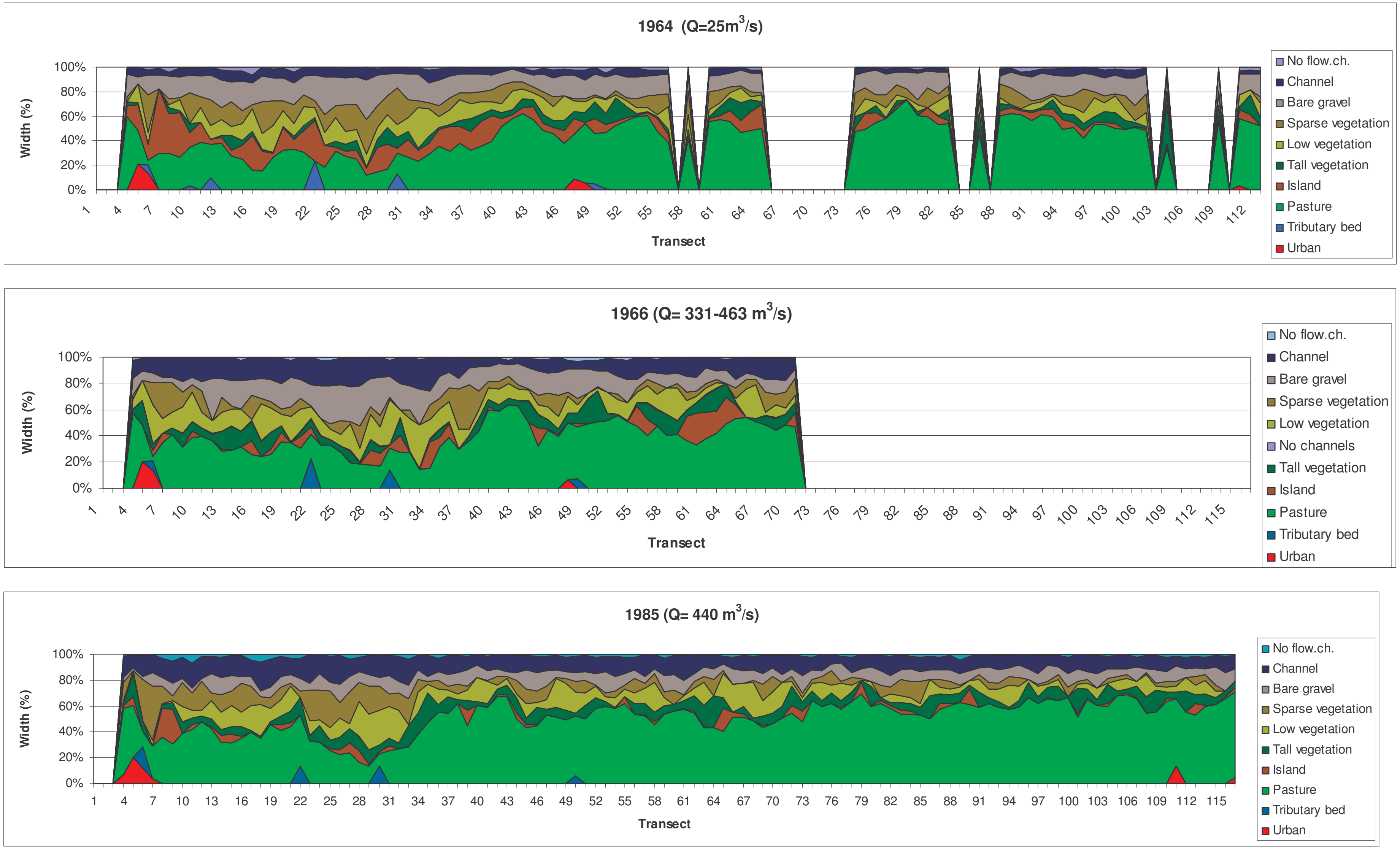

Figure 6.1: results of riverbed classification analysis along the Waitaki River; white gaps indicate no photographic cover(source Hicks et al , 2003).

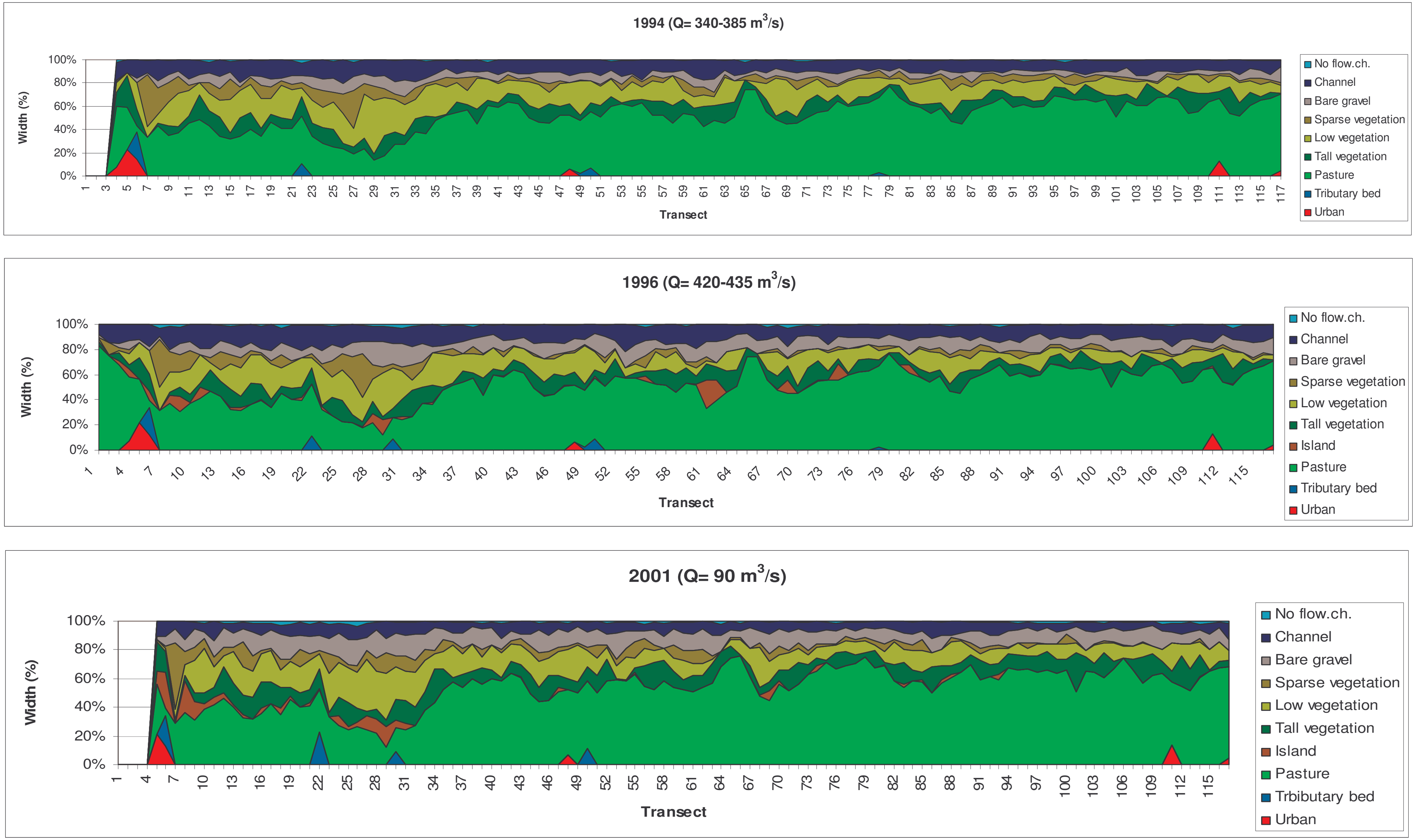

Figure 6.2: results of riverbed classification analysis along the Waitaki River; white gaps indicate no photographic cover(source Hicks et al , 2003).

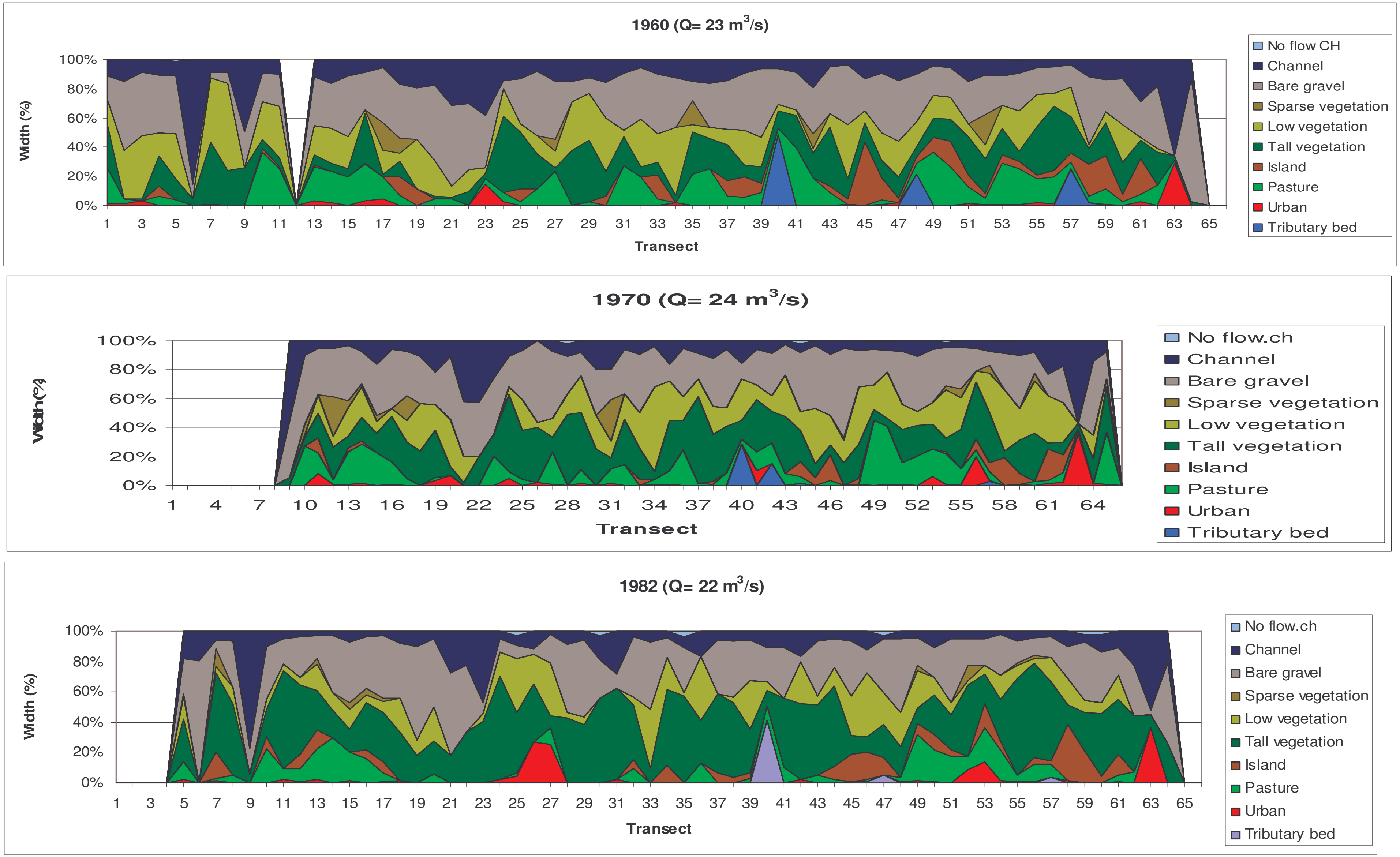

Figure 6.3: results of riverbed classification analysis along the Piave River; white gaps indicate no photographic cover.

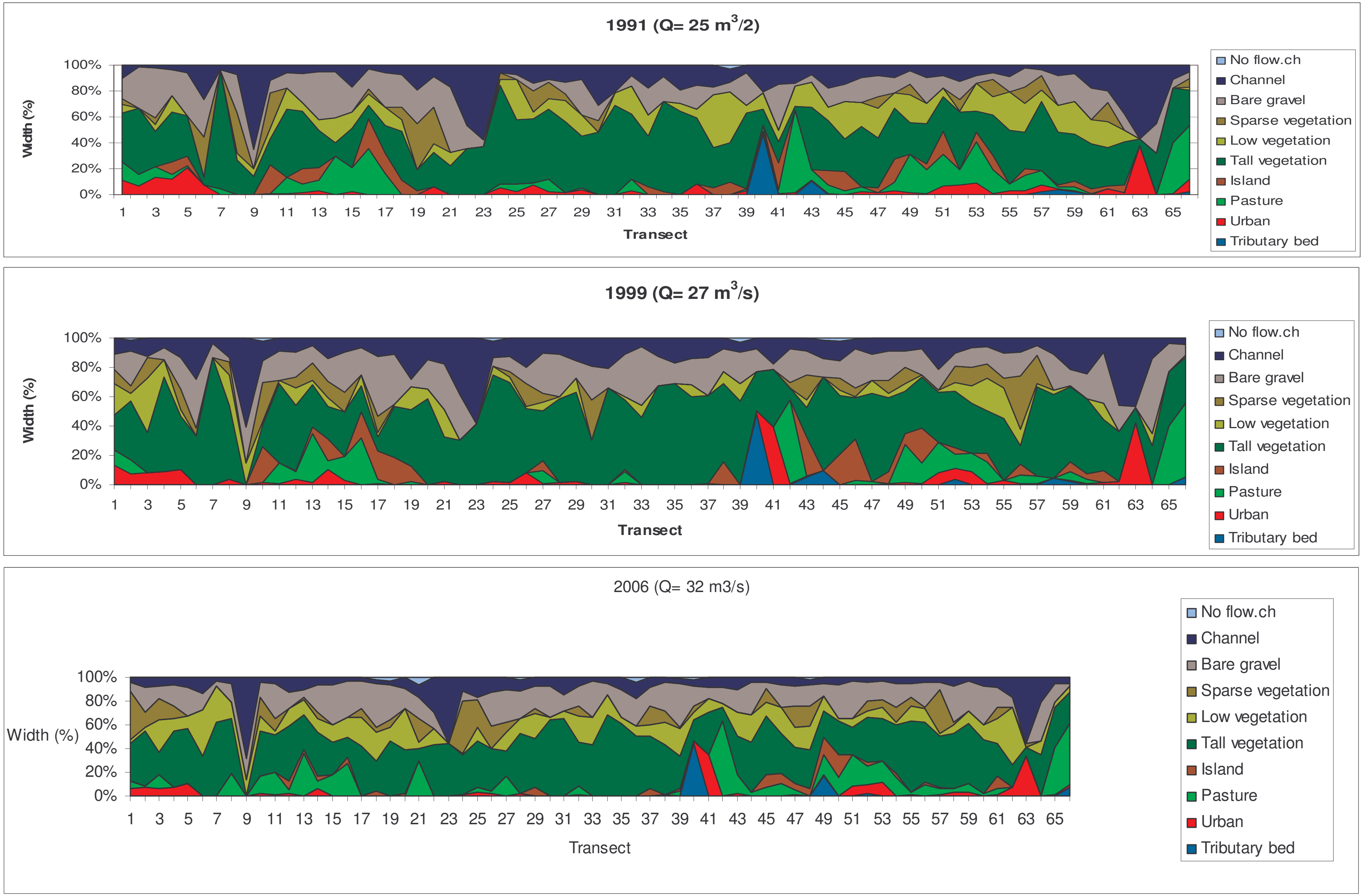

Figure 6.4: results of riverbed classification analysis along the Piave River; white gaps indicate no photographic cover.

6.1.1 Waitaki river

6.1.1.1 *Riverbed cover variations*

In Table 6.1 and Figure 6.5 is possible see the cover variation trend along the Waitaki River in the period included from 1964 to 2001.

Table 6.1: cover classes along the Waitaki river

Year	Urban	Gravel	Water	Vegetation
1964	0.48	16.60	6.58	76.34
1966	0.48	15.11	14.18	70.23
1985	0.41	8.79	13.68	77.12
1994	0.46	5.64	11.38	82.52
1996	0.45	9.46	12.92	77.17
2001	0.44	10.59	7.48	81.49

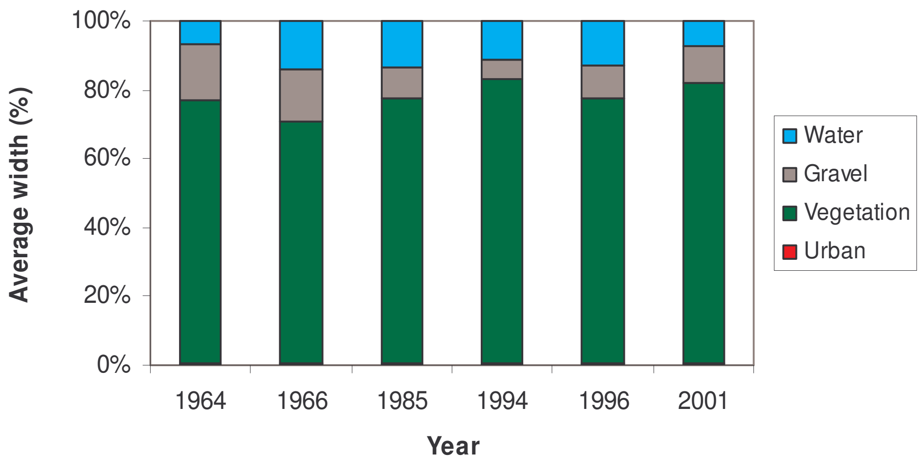

Figure 6.5: cover class variation along the Waitaki river

Within the Waitaki River corridor "Vegetation" cover has always been > 70%. This high total vegetation width is misleading because the sections extended out either side into the adjacent pasture land, beyond the river corridor, by an arbitrary distance as Hicks et al. (2003). What is thus relevant is the relative change in vegetation cover, not the absolute percentage.

However, a first contraction phase took place from a value of 76.3% in 1964 to 70.2% in 1966. After that period there was great expansion period until 1994 (82.5%). From 1994 there was another contraction period to the value of 77.2% in 1996. Finally, during the last five years analyzed, there was again an expansion phase until the value of 81.5% in 2001.

Complementary to “Vegetation”, “Gravel” extent show a long and strong contraction period, starting in 1966 reaching a valus as low as 5.64% in 1994. An expansion phase is evident afterwards (up to 10.6%).

An expansion in the “Water” extent from an value of 6.6% in 1964 to 14.18% in 1966 is shown. Subsequently, a long contraction period until 1994 is observed, followed by an expansion to 12.9% in 1996, and finally a very strong contraction for 2001(7.5%) is evident. During the study period there was not significant variation in the “Urban” extent, with very low values in the order of ~0.45%.

6.1.1.2 *Vegetation cover variations*

A more detailed classification of the riverbed vegetation cover, and analysis of how this has changed, provides further insight into the morphological role of the riverbed vegetation.

Table 6.2: vegetation cover classes present along the Waitaki River between 1964 and 2001

Year	Average Pasture percent	Average Island percent	Average Tall vegetation percent	Average Low vegetation percent	Average Sparse vegetation Percent
1964	58.0	11.2	7.4	11.6	11.8
1966	55.3	6.6	10.3	17.6	10.3
1985	66.9	2.6	9.8	11.9	8.9
1994	63.0	1.5	10.7	18.7	6.1
1996	67.4	1.7	10.9	15.7	4.3
2001	66.1	1.6	12.1	15.6	4.6

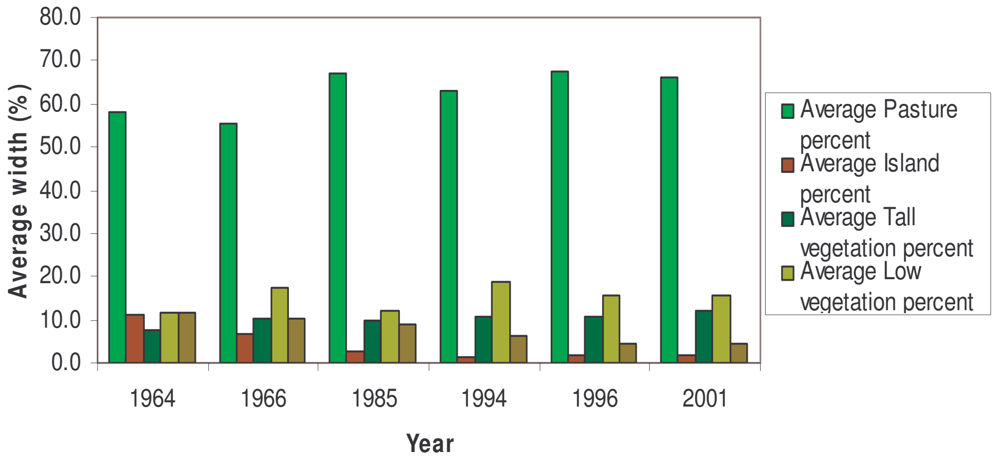

Figure 6.6: vegetation cover trends along the Waitaki River between 1964 and 2001

Along the Waitaki River, the "Pasture" cover showed an overall increasing trend from 1964 to 2001 (Table 6.2 and Figure 6.6), reflecting conversion of braid-plain to productive farmland. Average-height and "Tall vegetation" also increased overall. The apparent reduction in the width of "Islands" from 1964 to 1985 is probably more a reflection of differences in discharge on the days when the photography was done (25 m^3/s in 1964 compared with 440 m^3/s in 1985). Since 1994 the width of islands fluctuated from 1.5 to 1.7% in 1996 and to 1.6% in 2001. "Tall vegetation" cover has tended to increase (7.4% in 1964, 12.1% in 2001). This has been at the expense of "Sparse vegetation", which declined from 11.8% in 1964 to 4.6% in 2001. The cover of "Low vegetation" has fluctuated but shows no apparent trend.

6.1.2 Piave River

6.1.2.1 *Variations in the river corridor along the entire study reach*

Table 6.3 and Figure 6.7 report the variations within the river corridor occurred in the Piave River.

Table 6.3: cover classes along the Piave River

Year	Urban (%)	Gravel (%)	Water (%)	Vegetation (%)
1960	1.25	32.03	15.19	51.53
1970	1.99	31.33	12.26	54.42
1982	2.42	28.91	11.58	57.08
1991	3.43	17.02	14.50	65.05
1999	3.28	19.11	15.01	62.60
2006	2.73	19.55	10.44	67.28

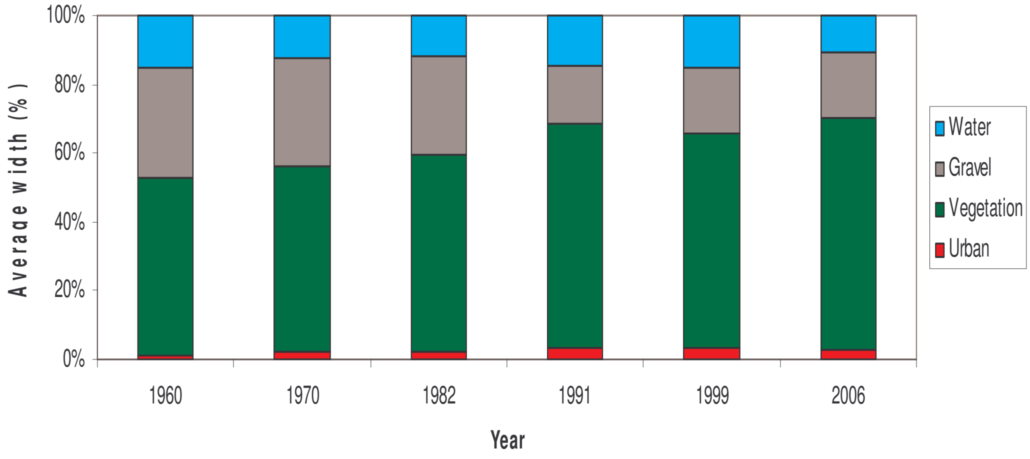

Figure 6.7: average percent width variation on the riverbed cover classification along the Piave River

"Vegetation" cover has increased from 51.5% in 1960 to 65.% in 1991; after that there was a period of slight contraction to a value of 62.20% in 1999 and more recently there was a vegetation expansion up to 67.3% 2006

Other interesting variation was recorded about the "Gravel" extension variation. In fact there was a great decrease from 32% in 1960 to a minimum value of 17.% in 1991. Then there was a little expansion period up to 19.5% 2006.

As to the "Water" extent variation, it shows a decrease from 15.2% in 1960 to 11.58% in 1982. Afterwards there was an expansion back up to 15% in 2000, and recently another contraction period is visible (10.4% in 2007).

It is worth to stress that the "Gravel" extent decrease between 1982 and 1991 (Fig…) corresponds to the sharp vegetation cover expansion and to the considerable water area expansion.

6.1.2.2 <u>Vegetation cover variations</u>

A more detailed classification of the riverbed vegetation cover, and analysis of how this has changed, provides further insight into the morphological role of the riverbed vegetation.

Table 6.4: vegetation cover classes present along the Piave River

Year	Average Pasture percent (%)	Average Island percent (%)	Average Tall vegetation percent (%)	Average Low vegetation percent (%)	Average Sparse vegetation Percent (%)
1960	20.25	9.15	34.38	33.80	2.43
1970	17.48	4.17	41.68	33.34	3.33
1982	10.73	7.22	60.46	20.47	1.13
1991	11.39	6.06	57.87	17.21	7.47
1999	8.93	6.57	66.82	9.96	7.73
2006	11.93	2.65	55.64	20.48	9.30

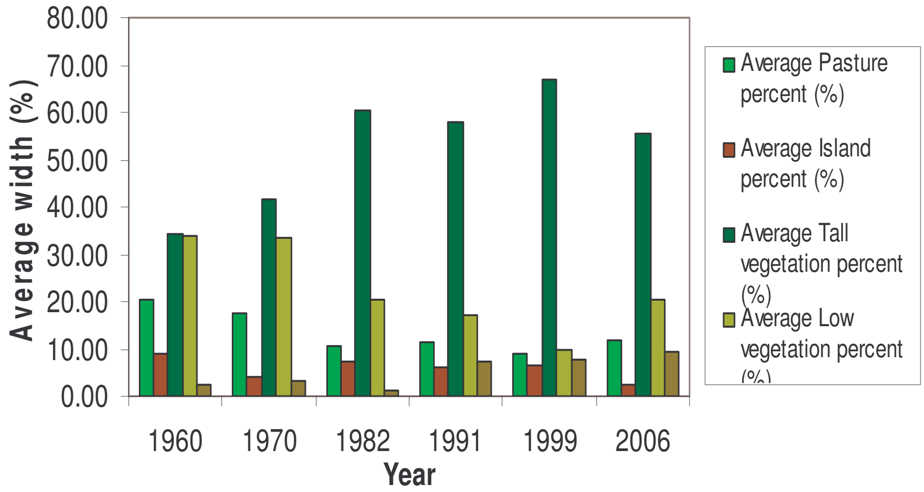

Figure 6.8: vegetation cover trends along the Piave River

In the Piave River (Table 6.4 and Figure 6.8), there was an expansion in "Tall vegetation" from 1960 (34.4%) to 1982 (60.5%), followed by a period of smaller oscillation around 55-65% until 2007. "Low vegetation" cover followed the opposite pattern, contracting from 33.8% in 1960 to 10% in 2000 and afterwards expanding to 20.5% in 2007. "Pasture" extent initially contracted from 20.2% in 1960 to 10.73 in 1980; after that period there was substantially an equilibrium condition. "Sparse vegetation" increased from 1960 (2.4%) to 2006 (9.3%), with a great contraction step in 1982 (1.1%). "Islands" contracted from a value of 9.1% in 1960 to a value of 4.2% in 1970, subsequently there was an expansion period up to 7.2% in 1980 and an equilibrium phase until 2000 (6.6%), with a recent contraction period until the value of 2.65 in 2007

In order to delve deeper into the analysis, more detailed analyses relating to the Piave study reach have been carried out. In fact, the study reach has been divided up into three different subreaches to better analyze and observe the changes in those reaches having a braiding and wandering morphology. In fact, upstream reach and downstream one have a braiding morphology, whereas the one between mentioned reaches has a wandering morphology (Fig. 6.9)

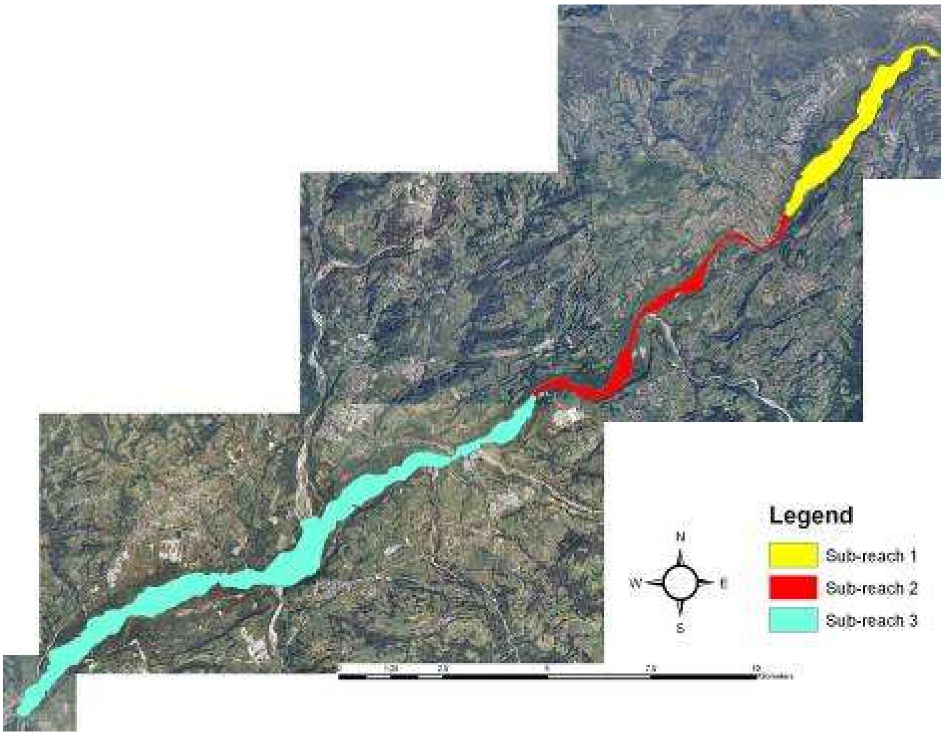

Figure 6.9 : Piave study reach, in evidence the three different sub-reaches

6.1.2.3 <u>*Subreach 1:*</u>

The subreach 1 has a predominant braiding morphology, but we need to point out that such reach flows between two high terraces which somehow delimit its possible divagation.

6.1.2.3.1 *Riverbed cover variations*

In table 6.5 and in figure 6.10 is possible see the cover variation trend along the subreach 1 along the Piave River in the period included from 1960 to 2006:

Table 6.5: changes in cover along subreach 1 of the Piave river

Year	Water	Vegetation	Gravel	Urban
1960	17.74	51.43	29.87	0.96
1970	13.43	49.97	34.82	1.78
1982	11.84	53.27	34.10	0.78
1991	11.22	61.30	23.22	4.26
1999	14.71	63.69	17.92	3.68
2006	9.84	68.24	19.52	2.40

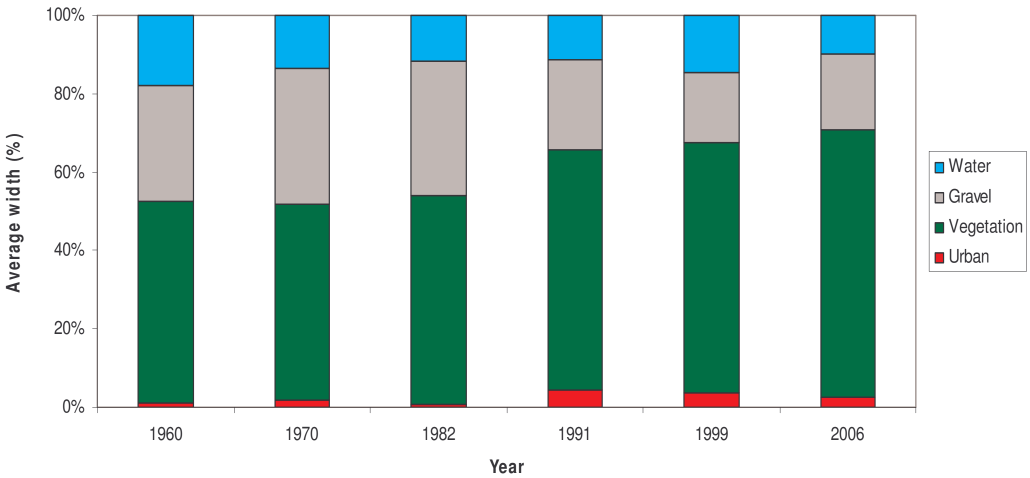

Figure 6.10: riverbed cover variation along the Piave River sub-reach 1

"Water" extent cover present a costant decrease phase from 1960 (17,74%) to 1991 (11,22%), after there was an expansion period until 1999 (14,71%) and finally a new contraction phase up to 9,84% value in 2006. The "Gravel" extension had an initial expansion between 1960 (29,87%) and 1982 (34,10%) followed by a strong decrease phase up to the minimum value recorded in 1999 (17,92%), and a final slight increase in 2006 (19,52%).

As to the "Vegetation" extent variation, a constant increase was recorded over the entire period from 1960 (51.43%) to 2006 (68.24%), except for a slight decrease in 1970 (49.97%).

6.1.2.3.2 *Vegetation cover variations*

A more detailed classification of the subreach 1 vegetation cover, and analysis of how this has changed, provides further insight into the morphological role of the riverbed vegetation.

Table 6.6: change in vegetation cover along the subreach 1of the Piave River

Year	Pasture	Island	Tall Veg.	Low Veg.	Sparse Veg.
1960	21.97	3.80	24.78	46.52	2.93
1970	23.17	2.62	34.76	29.12	10.33
1982	17.97	7.02	53.57	18.05	3.39
1991	13.64	9.32	50.83	11.70	14.51
1999	10.29	8.70	56.36	13.79	10.86
2006	11.92	1.90	51.99	24.36	9.83

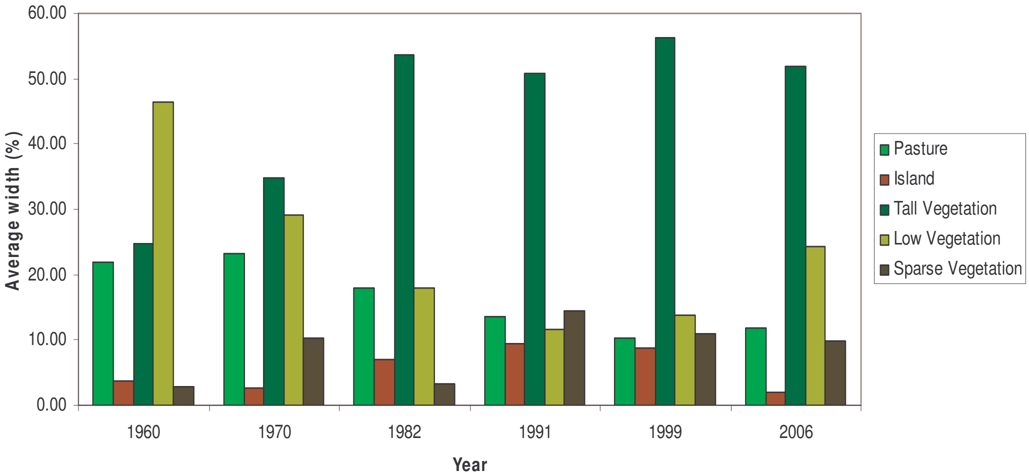

Figure 6.11: change in vegetation cover along the subreach 1of the Piave River

In the subreach 1 (Tab.6.6 and Fig. 6.11) there was an expansion in "Tall vegetation" from 1960 (24,78%) to 1982 (53,37%), followed by a period of a slight decrease until 1991 (50,83%), a further and strong expansion until 1999 (56,36%) and a final decrease until 2006 (51,99%). As regards "Low vegetation" cover, a progressive and constant decrease was recorded from 1960 (46,52%) to 1991 (11,70%) and afterwards there was a strong increase until 2006 (24,36%). "Sparse vegetation" has increased from 1960 (2.9%) to 1970 (10.3%), after that has decreased until 1982 (3.4%); the there was a another great expansion up to 1991 (14.5%) and a final decrease phase until 2006 (9.8%). Moreover, by analyzing the change in "Pasture" extent, it is possible see a slight increase between 1960 (21,97%) and 1970 (23,17%), a progressive decrease until 1999 (10,29%) and a slight increase until 2006 (11,92%).

"Fluvial island" extent present a long expansion phase until 1991 (9,32 %) followed by a strong decrease until 2006 (1,90%).

6.1.2.4 Subreach 2

The subreach 2 of the Piave River has a predominant wandering morphology, in which the main channel flows in a well-delimited reach, in particular in its left bank.

6.1.2.4.1 Riverbed cover variations

In table 6.7 and in figure 6.12 is possible see the cover variation trend along the subreach 2 along the Piave River in the period included from 1960 to 2006:

Table 6.7: change in cover along the subreach 2 of the Piave River

Year	Water	Vegetation	Gravel	Urban
1960	16.38	51.35	31.21	1.06
1970	14.43	53.78	31.13	0.67
1982	13.86	56.76	25.79	3.59
1991	18.98	66.33	12.76	1.94
1999	18.38	60.35	20.04	1.22
2006	14.53	67.39	17.53	0.55

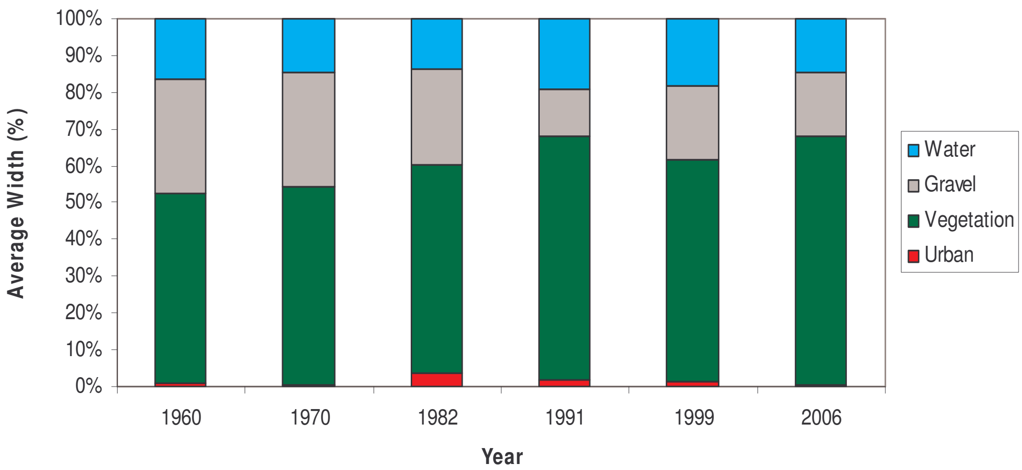

Figure 6.12:change in riverbed cover along the subreach 2 of the Piave River

"Water" extent cover has decreased from 1960 (16,38%%) to 1982 (13,86%), after that there was an increase period until 1991 (19,98%) and the same value remained almost constant until 1999 (18,38%), finally there was a strong and sudden decrease until 2006 (14,53%). "Gravel" cover extension had a constant and quite strong decrease from 1960 (31,21%) to 1991 (12,76%) followed by a strong increase phase until 1999 (20,04%) and a subsequently decrease phase untill 2006 (17,53%).

Instead, as regards “Vegetation” cover extent, there was a constant and rapid increase from 1960 (51,35%) to 1991 (66,33%) and, after a rapid decrease until 1999 (60,35%), there was a final strong increase until 2006 (67,39%).

6.1.2.4.2 Vegetation cover variations

By analyzing the trend in vegetation (Tab. 6.8 and Fig. 6.13) it is possible observe a constant increase in “Tall vegetation” from 1960 (39,4%) to 1999 (86,4%), corresponding to a constant decrease in “Low vegetation” between 1960 (34,85%) and 1999 (6,26%). Between 1999 and 2006 there was a turnaround with a slight increase in “Low vegetation” (15,35%) and a stronger decrease in “Tall vegetation” (65,86%).

“Pasture” extent has decreases from 1960 (18,15%) to 1999 (1,58%), followed by a final increase phase until 2006 (5,13%).

“Fluvial island” extent has decreased from 1960 (4,87%) to 1970 (0,48%), then there was a moderate increase phase until 1982 (2,44%) and a further, slight decrease until 1991 (1,19%). Finally has decreased until 1999 (0,77%) and a increased until 2006 (1,22%).

“Sparse vegetation” has increased from 1960 (2.85%) to 1970 (3.09%) and decreased until minimum value in 1982 (0%), then there was a long expansion phase until 2006 (12.43%).

Table 6.8: changes in vegetation cover along the subreach 2 of the Piave River

Year	Pasture	Island	Tall Vegetation	Low Vegetation	Sparse Vegetation
1960	18.15	4.87	39.28	34.85	2.85
1970	13.53	0.48	51.13	31.77	3.09
1982	3.68	2.44	70.13	23.75	0.00
1991	2.68	1.19	74.80	17.06	4.28
1999	1.58	0.77	86.41	6.26	4.98
2006	5.13	1.22	65.86	15.35	12.43

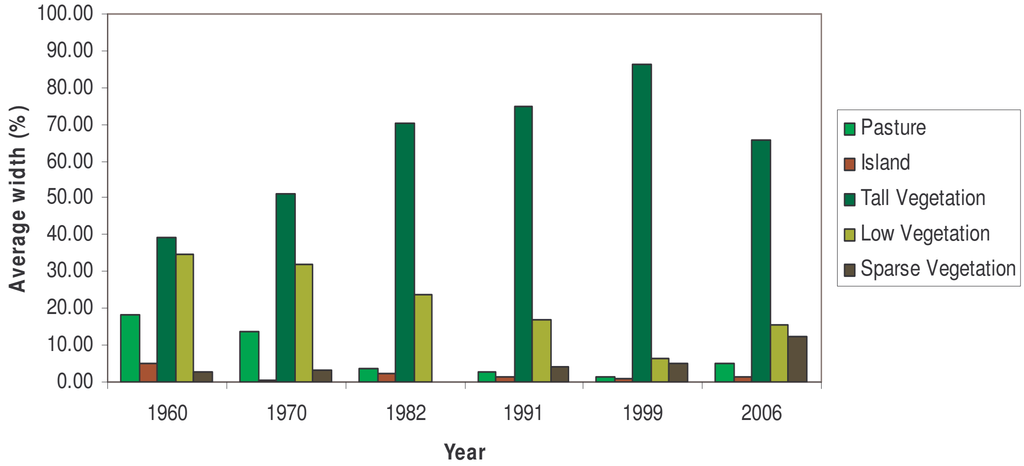

Figure 6.13: changes in vegetation cover along the subreach 2 of the Piave River

6.1.2.5 <u>*Subreach 3*</u>

The subreach 3 has a braiding morphology too; in this case the subreach is the less delimited than mentioned three ones; its riverbed width is quite wide.

6.1.2.5.1 *Riverbed cover variations*

In Table 6.9 and figure 6.14, it is possible see changes in riverbed cover from 1960 to 2006:

Table 6.9: changes in cover along the subreach 3 of the Piave River

Year	Water	Vegetation	Gravel	Urban
1960	12.66	51.72	34.05	1.56
1970	10.44	56.72	29.96	2.88
1982	10.25	59.49	27.69	2.57
1991	14.13	66.89	15.25	3.73
1999	13.25	63.16	19.38	4.21
2006	8.46	66.56	20.75	4.23

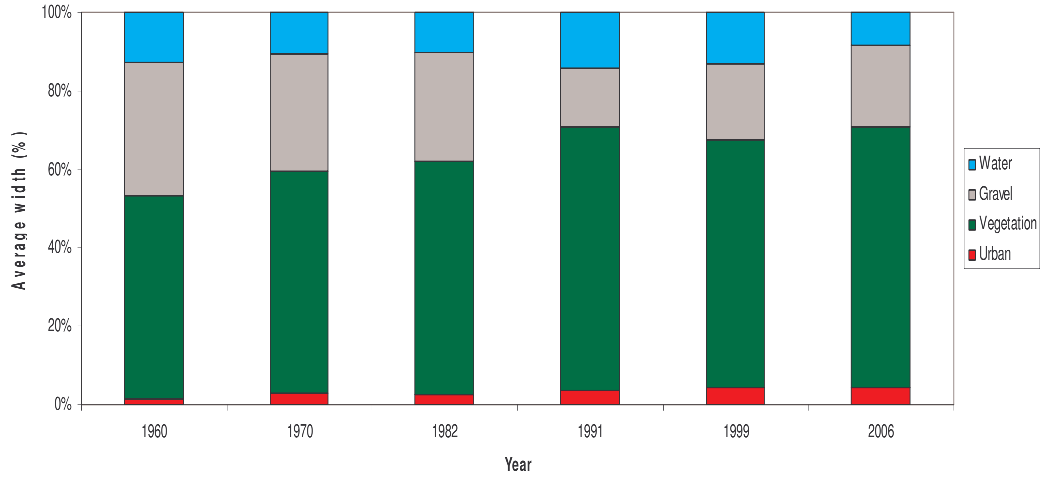

Figure 6.14 : changes in riverbed cover along the sub-reach 3of the Piave River

"Water" extent has decreased from 1960 (12.66%) to 1982 (10,25%), then has increased until 1991 (14,13%), finally has decreased until 2006 (8,46%). Instead, "Gravel" cover has decreased from 1960 (34,05%) to 1991 (15,25%) then has increased until 2006 (20,75%).

As regards "Vegetation" extent there was a constant increase between 1960 (51,72%) and 1991 (66,89%) followed by strong decrease phase until 1999 (63,16%), and a subsequently rapid increase period until 2006 (66,56%).

6.1.2.5.2 *Vegetation cover variations*

"Tall vegetation" has increased from 1960 (34,1%) to 1982 (54,0%), then has decreased until 1991 (48,3%). After 1991 there was a strong increase phase until 1999 (59,7%) and a final decrease phase until 2006 (51,2%) (Tab.6.10; Fig.6.15).

As regards "Low vegetation", there was an initial increase from 1960 (25,3%) until 1970 (37,7%) and a subsequent decrease period until 1982 (21,3%). Then there was an alternate phase, has increased until 1991 (22,0%),has decreased until 1999 (8,09%) and a finally has increased until 2006 (18,9%). "Island" extent has decreased from the maximum cover extent value in 1960 (16,5%) to 1970 (7,3%), then there was a moderate increase until 1982 (11,85%). After that there was a decrease up to the minimum value recorded in 2006 (4,4%), and a slight increase phase until 1999 (9,1%).

"Pasture" cover has decreased from 1960 (21,9%) to 1982 (11,8%), followed by an increase phase until 1991 (18,0%) and a subsequently contraction period until 1999 (14,9%), ending with another increasing phase until 2006 (17,85%). As regards "Sparse Vegetation" , there was a decrease period from 1960 (2,2%) to 1982 (21,3%) and a subsequently expansion phase until 1999 (8,3%). Finally, "Sparse vegetation" has decreased until 2006 (7,7%).

Table 6.10 : changes in vegetation cover along the subreach 3 of the Piave River

Year	Pasture	Island	Tall vegetation	Low vegetation	Sparse vegetation
1960	21.91	16.47	34.06	25.34	2.22
1970	18.25	7.26	35.46	37.68	1.34
1982	11.81	11.85	53.98	21.30	1.05
1991	18.04	7.26	48.32	22.02	4.35
1999	14.89	9.08	59.67	8.09	8.27
2006	17.85	4.38	51.16	18.93	7.68

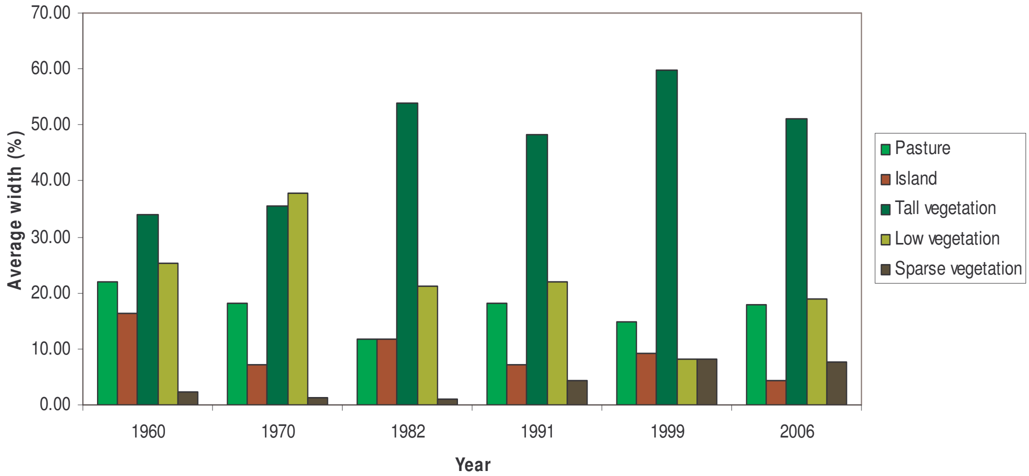

Figure 6.15: changes in vegetation cover along the subreach 3 of the Piave River

6.2 Island dynamics

An island is an area composed of fine sediment, located between channels or exposed gravels, that is covered with woody vegetation.
As previously described, three types of fluvial islands have been identified according to their evolution, maturity and structural characteristics:

- Pioneer
- Young
- Stable

As already stated, all the analyses we carried out have been compared to the active corridor area, that is the portion of riverbed delimited by the exposed gravels, so as to compare with each other the data relating to observations carried out on the Piave River and the Waitaki river over many years under consideration.

6.2.1 Waitaki river

According to Table 6.11 and Figure 6.16, active corridor area has decreased over years, starting from 1956 (19,3 km^2) until 1994 (14,5 km^2). From 1994 there was an increase phase up to 1996 (14,8 km^2) followed by a slight decrease phase until 2008 (13,8 km^2).

Table 6.11 : active corridor area of the Waitaki River

Year	Active Corridor(km^2)
1956	19.33
1966	16.42
1994	14.52
1995	14.68
1996	14.79
2008	13.84

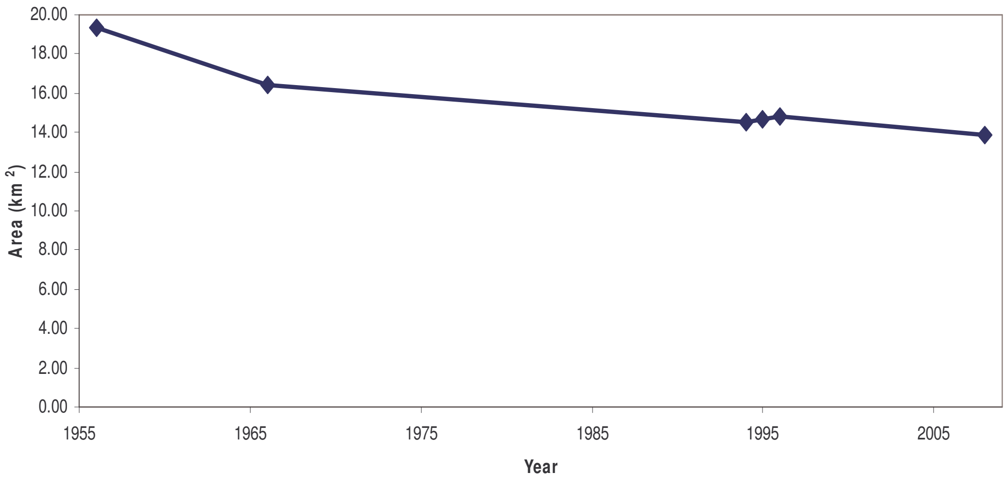

Figura 6.16: change in the active corridor area of the Waitaki River between 1956 and 2008

By considering the trend in percentage area relating to the three different types of fluvial islands (Fig. 6.17; Tab. 6.12), obtained through the percentage ratio between island area and active corridor area, “Stable island” has increased from 1956 (0,7%) to 1996 (3,8%), then there was a constant level until 2008 (3,8%).

As regards “Young island”, after an initial decrease phase from 1956 (2,5%) to 1966 (1,4%), there was an increase period until 1994 (2,2%), then there was a considerable decrease in 1995 (1,6%) and a subsequently considerable increase until 1996 (2,2%), finally there was a decrease phase until 2008 (1,6%).

“Pioneer island” has decreased from 1956 (1,8%) to 1994 (0,7%), then has increased until 1995 (1,0%) and has decreased until 1996 (0,71%). Finally there was another decrease phase until 2008 (0,9%).

Table 6.12: change in percentage area according to the different types of fluvial islands along the Waitaki River

Year	Stable	Young	Pioneer
1956	0.67	2.52	1.75
1966	1.16	1.44	1.62
1994	2.72	2.19	0.67
1995	3.75	1.55	1.01
1996	3.76	2.24	0.71
2008	3.75	1.58	0.89

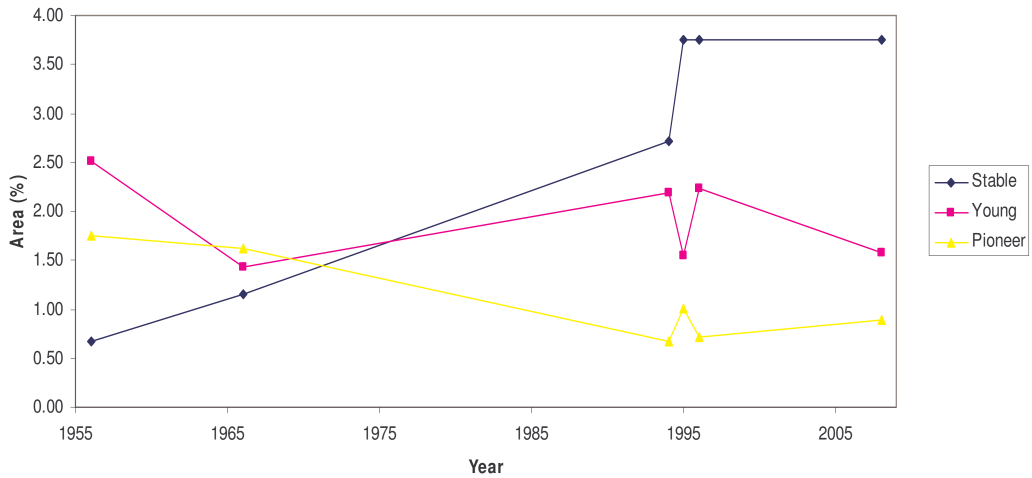

Figure 6.17: change in the area of the three types of fluvial islands over the analyzed time interval along the Waitaki River

Table 6.13 and Figure 6.18 show the number of the different types of islands, normalized to active channel area. “Stable island” has increased from 1956 (3,5 N km^{-2}) to 1994 (12,4 N km^{-2}). Then there was an initial and slow decrease phase until 1995 (11,3 N km^{-2}) then a stronger one until 1996 (7,8 N km^{-2}), followed by a new slow increase phase until 2008 (8,1 N km^{-2}).

"Young island" has increased from 1956 (28,0 N km^{-2}) to 1994 (53,8 N km^{-2}), subsequently has decreased up to minimum value recorded in 2008 (16,1 N km^{-2}). "Pioneer island" has shown an almost constant level between 1956 (144,0 N km^{-2}) and 1966 (145,8 N km^{-2}), followed by a strong decrease phase until 1995 (36,8 N km^{-2}). Then there was a strong increase period up to 1996 (54,3 N km^{-2}) and a subsequent decrease up to the minimum value recorded in 2008 (35,0 N km^{-2}).

Table 6.13: numerical trend in the different types of fluvial island along the Waitaki River

N/km^2	1956	1966	1994	1995	1996	2008
Stable	3.47	12.66	12.40	11.31	7.84	8.09
Young	28.0	28.31	53.79	33.85	33.59	16.11
Pioneer	144.04	145.82	51.87	36.78	54.28	34.97

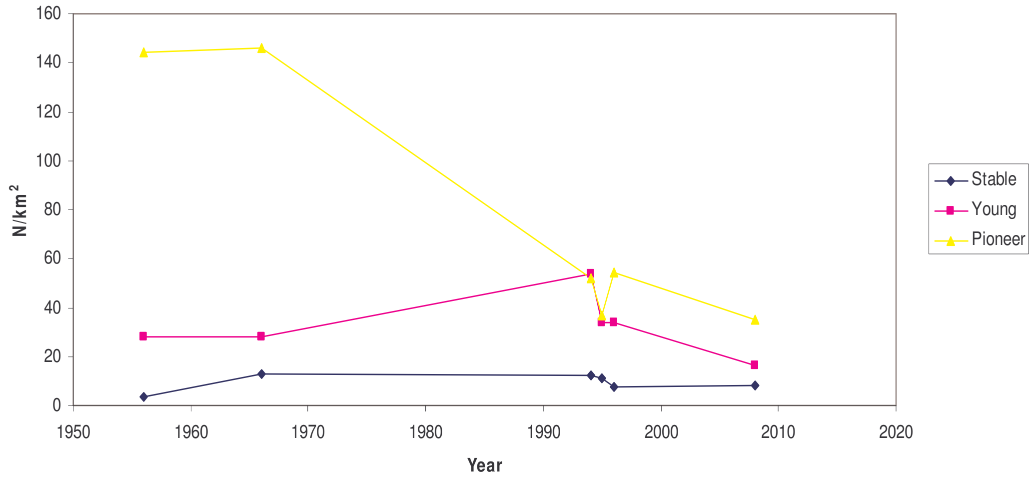

Figure 6.18: variation in the number according to the unit of surface relating to the different types of islands along the Waitaki River

6.2.2 Piave River

According to Table 6.14 and Figure 6.19, active corridor area has increased from 1960 (13,4 km^2) to 1970 (14,2 km^2), then has decreased until 1991 (9,3 km^2) and, finally, has increased up to 2006 (10,6 km^2).

Table 6.14: variation in the active corridor area along the Piave River

Year	Active corridor(km^2)
1960	13.4
1970	14.2
1982	11.0
1991	9.3
1999	9.4
2006	10.6

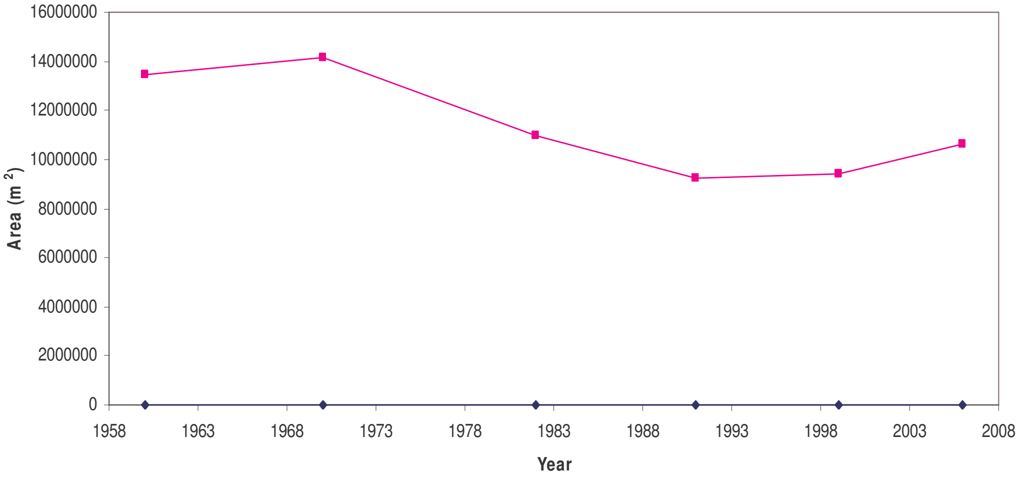

Figure 6.19: variation in the active corridor area along the Piave River between 1960 and 2006

“Stable island” has decreased from 1960 (1,6%) to 1970 (1,5%), then has increased up to 1982 (4,1%). Between 1991 (3,2%) and 2006 (2,3%) there was a fluctuation with a maximum in 2000 (4,0%) (Tab.6.15, Fig. 6.20).

Regarding “Young island” there was a strong decrease from 1960 (5,7%) to 1970 (1,5%), then there was an increase period until 1991 (6,2%), followed by a strong decrease until 2006 (2,8%).

Finally, “Pioneer island” has decreased from 1960 (1,5%) to 1970 (0,4%), then there was an increase phase until 1991 (1,4%) and a finally contraction phase until 2006 (0,9%).

Table 6.15: variation in the percentage area relating to the different types of fluvial islands along the Piave River.

Year	Stable	Young	Pioneer
1960	1.6	5.7	1.5
1970	1.5	1.5	0.4
1982	4.1	5.2	1.4
1991	3.2	6.2	1.4
1999	4.0	3.4	0.9
2006	2.3	2.8	0.9

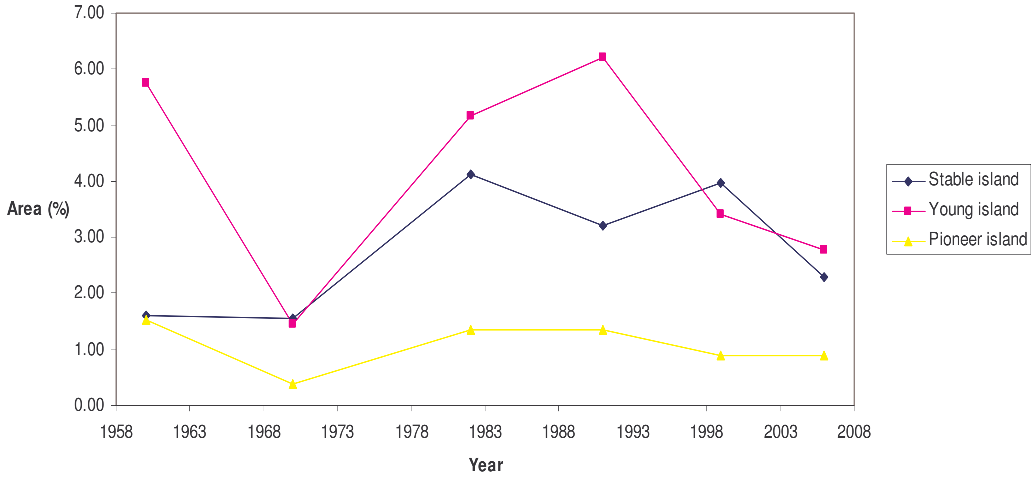

Figure 6.20: variation in the area relating to the three types of fluvial islands over the analyzed time interval along the Piave River.

Table 6.16 and Figure 6.21show the number of the different types of islands, normalized to active channel area. "Stable island" has increased from 1960 (2.5 N km^{-2}) to 1970 (3,0 N km^{-2}), then has decreased until 1980 (1,8 N km^{-2}) and then there was another increase period up to 1991 (2,1 N km^{-2}); after that there was a decrease period until 1999 (2.13 N km^{-2}) and a finally increase period until 2006 (5.27 N km^{-2}).

Regarding "Young island" has increased from 1960 (17,0 N km^{-2}) to 1970 (18,5 N km^{-2}), then there was a strong contraction period until 1982 (8,3 N km^{-2}) and a significant expansion period to 1991 (13,4 N km^{-2}) and a finally decrease period until 2006 (10,2 N km^{-2}).

"Pioneer island" has strongly decreased from 1960 (83,8 N km^{-2}) to 1982 (40,4 N km^{-2}), then has increased up to 1991 (43,5 N km^{-2}), then there was another contraction period until 1999 (25,3 N km^{-2}) and a finally expansion period until 2006 (38,4 N km^{-2}).

Table 6.16: numerical trend in the different types of fluvial islands along the Piave River

N/km^2	1960	1970	1982	1991	1999	2006
Stable	2.5	3.0	1.8	4.2	2.1	5.3
Young	17.0	18.5	8.3	13.4	10.6	10.2
Pioneer	83.8	65.1	40.4	43.5	25.3	38.4

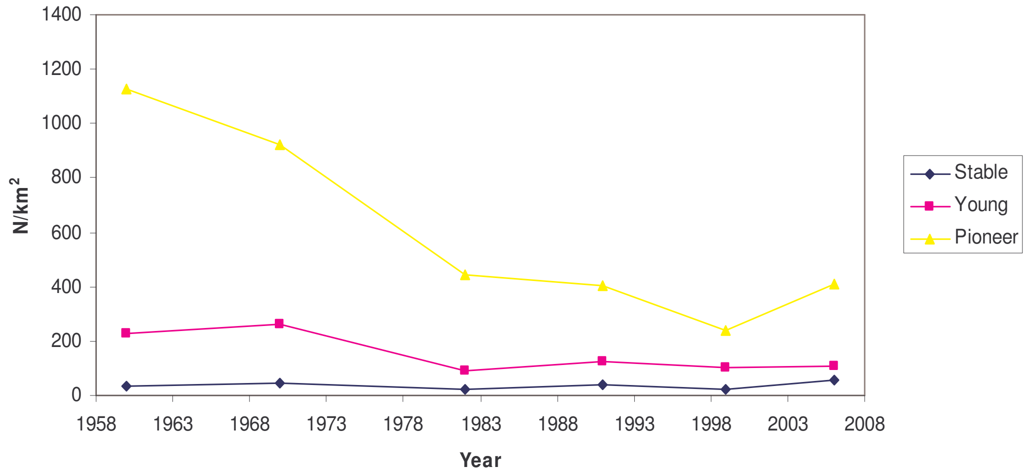

Figure 6.21: *numerical trend, compared to the unit of surface, in the different types of fluvial islands along the Piave River*

In order to better understand the changes along the Piave River, more detailed analyses relating to the study reach have been carried out; by dividing it up into three different subreaches it is possible to better observe the changes in those reaches having a braiding and wandering morphology.

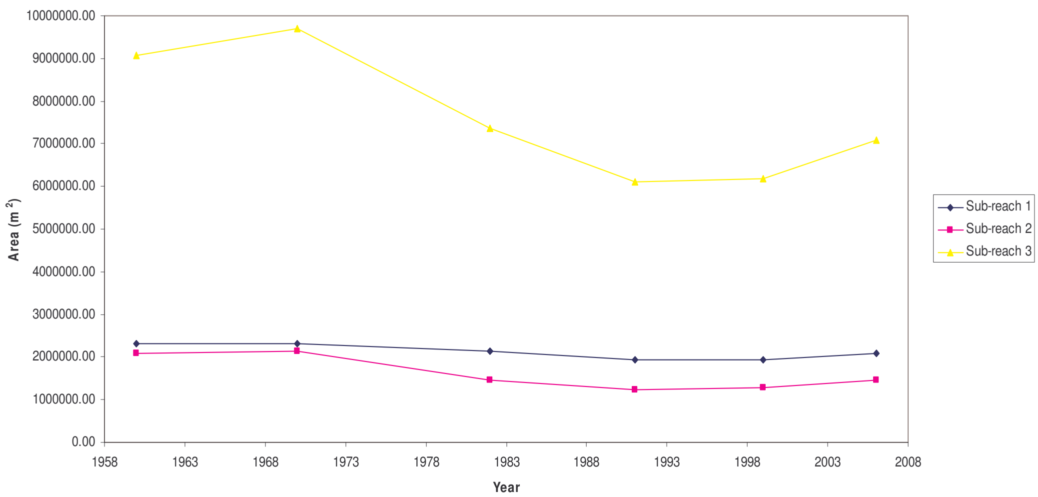

Figure 6.22: variation in the area of different subreaches over the years included in the study interval along the Piave River.

As been possible observe there is no significant change in surface along the subreach 1, remaining quite constant over time (Fig.6.22). Instead, as regards the subreach 2, as been possible observe a slight and constant decrease until 1991, followed by constant trend between 1960 and 1970. From 1991 to 2006 there was a new slow increase in the active area. Finally, the subreach 3 denotes a strong change over the study period under consideration. In fact, after a moderate increase phase from 1960 to 1970, there was a strong and continuous decrease period until 1991, then there was a stable trend from 1991 to 2000, whereas from 2000 to 2006 there was a new increase phase.

6.2.2.1 Subreach 1

Along the subreach 1, a very limited presence of "Stable island" is observed in 1960 (0.8%) and 1970 (0.2%) and a complete absence in 1982. Afterwards there was a quite strong increase in islands extent to the maximum value recorded in 1999 (5.6%) followed by a new decrease in 2006 (3.8%) (Fig.6.23 and Table 6.17).

With regards to "Young island", it is possible to observe, after a decrease between 1960 (2,7%) and 1970 (0,5%), a sharp increase to the maximum value recorded in 1991 (8,5%), followed by a reduction to the most recent value of 2.8% in 2006, very similar to the 1960 extent.

As to "Pioneer island", these represent a very limited area during the entire period under analysis, reaching a maximum in 1991 (2,0%) and a minimum value in 1970 (0,4%).

Table 6.17: : variation in the area of different island types over the years included in the study interval along the subreach 1.

Year	Stable (%)	Young (%)	Pioneer (%)
1960	0.8	2.7	1.2
1970	0.2	0.5	0.4
1982	0.0	3.5	1.5
1991	3.3	8.5	2.0
1999	5.6	5.9	1.3
2006	3.8	2.8	1.1

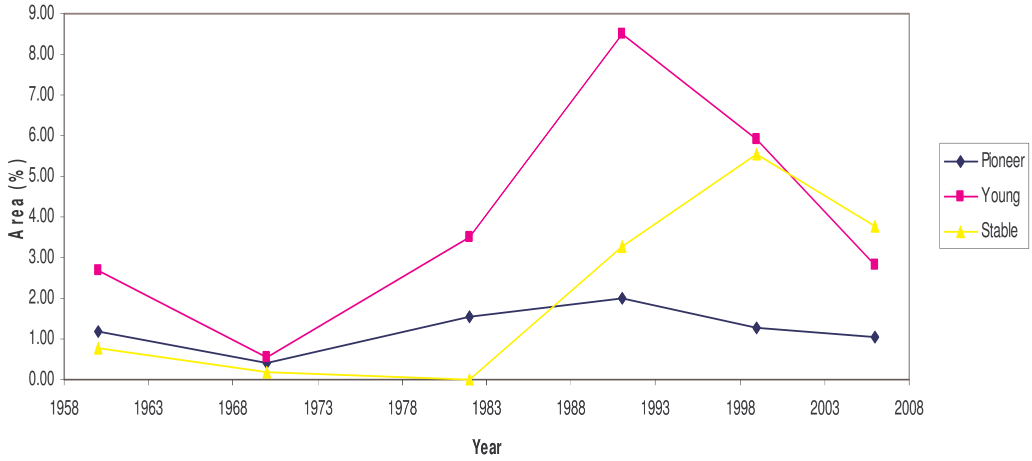

Figure 6.23: : variation in the area of different island types over the years included in the study interval along the subreach 1.

According to the analysis into Table 6.18and Figure 6.24, analysing the number of the different types of islands normalized to the active channel area, a substantial stability of "Stable island" until the recent increase (15.4 N km^{-2}) can be observed. Instead, with regards to "Young island", these decreased between 1960 and 1982, subsequently increased until 1991 (25,2 N km^{-2}), then decreased until 1999 (15,6 N km^{-2}), with a very slight recent increase in 2006.

"Pioneer island" show a noticeable increase between 1960 and 1970, followed by a sudden decrease until 1982 (53,2 N km^{-2}) and a new increase until 1991 (N km^{-2}). More recently, after a reduction until 1999, the relative island number is close to that of 1960 (59,1 N km^{-2})

Table 6.18 : variation in the numerousness, relating to area unit, for every different Island typology along the subreach 1

Year	Stable (N km^{-2})	Young (N km^{-2})	Pioneer (N km^{-2})
1960	2.6	59.8	67.6
1970	4.7	32.3	130.5
1982	0.0	8.9	53.2
1991	6.7	25.2	87.0
1999	3.6	15.6	33.7
2006	15.4	17.8	59.1

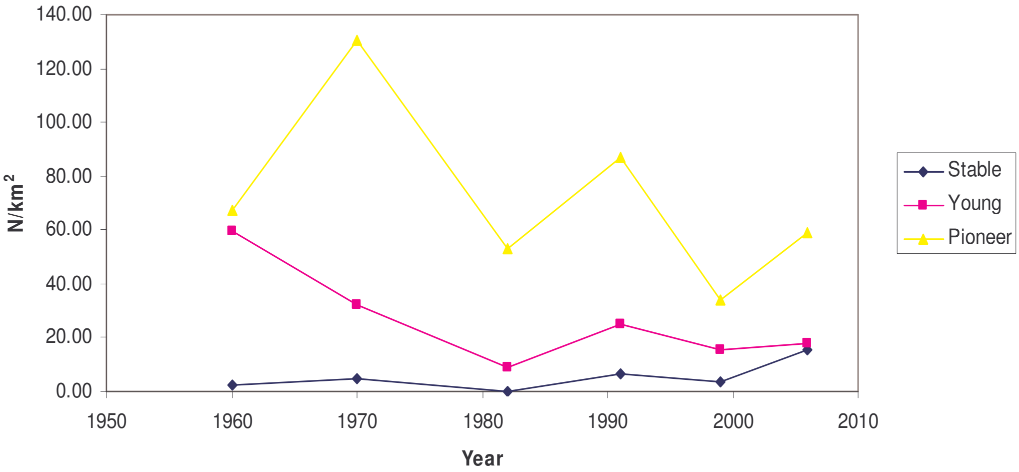

Figure 6.24: variation in the numerousness, relating to area unit, for every different Island typology along the subreach 1

6.2.2.2 Subreach 2

"Stable island" has decreased from 1960 (1,1%) to 1970 (0,7%), then has increased up to the maximum value in 1982 (3,7%), after that there was a constant decrease until 2006 (1,1%) (Tab. 6.19 and Fig. 6.25).

"Young island" has decreased from 1960 (5,6%) to 1970 (1,2%), then there was a slow-decrease period until 1980 (0,9%). After that period, there was another increase phase until 1991 (2,1%) and a subsequent slow and constant decrease period until 2006 (1,7%).

Regarding "Pioneer island" the trend is quite constant with an initial and moderate decrease between 1960 (2,1%) and 1970 (0,2%) reaching the maximum value in 1982 (1,0%), then fluctuating around lower values until 2006 (0,7%).

Table 6.19: *variation in the area of different island types over the years included in the study interval along the subreach 2.*

Year	Stable (%)	Young (%)	Pioneer (%)
1960	1.1	5.6	2.1
1970	0.7	1.2	0.2
1982	3.7	0.9	1.0
1991	2.0	2.1	0.7
1999	1.6	2.0	0.8
2006	1.1	1.7	0.7

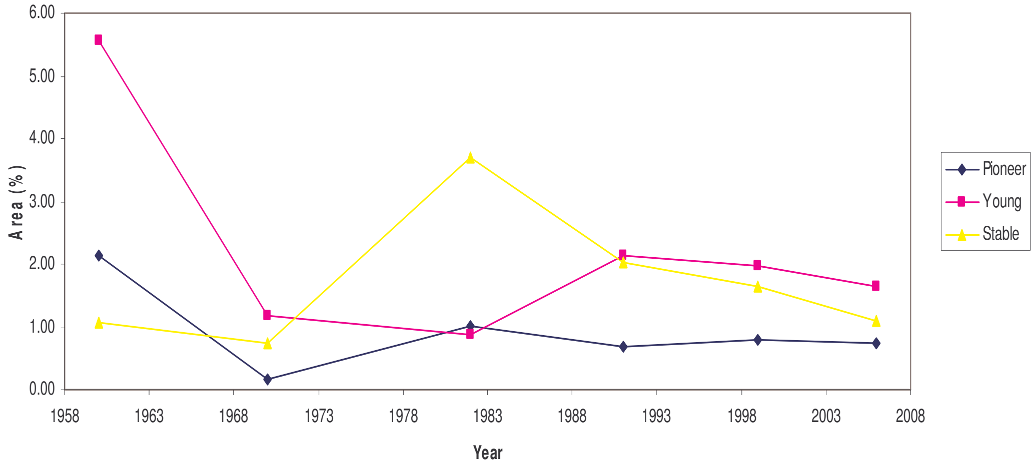

Figure 6.25: variation in the area of different island types over the years included in the study interval along the subreach 2.

"Stable island" has decreased from 1960 (3,9 N km^{-2}) to 1970 (0,9 N km^{-2}), after that there was an increase period until 1982 (2,1 N km^{-2}); subsequently there was a decrease phase until 1999 (0,8 N km^{-2}) and a final strong increase until 2006 (2,7 N km^{-2}) (Tab.6.20 and Fig. 6.26).

Regarding "Young island", there was a decrease between 1960 (28,0 N km^{-2}) and 1999 (3,1 N km^{-2}), then followed by an increase period until 2006 (7,5 N km^{-2}).

"Pioneer island" has greatly decreased from 1960 (107,0 N km^{-2}) to 1999 (20,2 N km^{-2}), followed by an increase phase until 2006 (39,6 N km^{-2}).

Table 6.20: variation in the numerousness, relating to area unit, for every different Island typology along the subreach 2

Year	Stable (N km^{-2})	Young (N km^{-2})	Pioneer (N km^{-2})
1960	3.9	28.0	107.0
1970	0.9	17.4	53.0
1982	2.1	8.2	53.9
1991	0.8	7.4	23.8
1999	0.8	3.1	20.2
2006	2.7	7.5	39.6

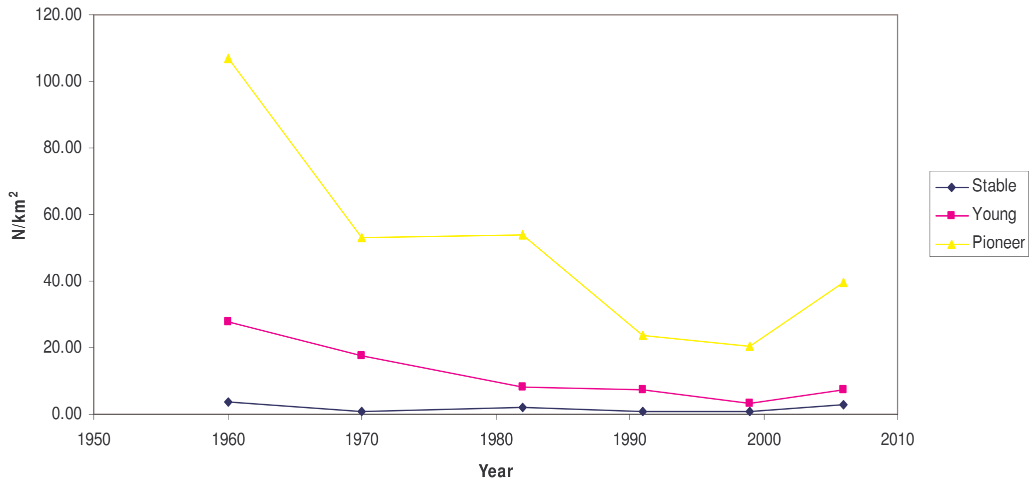

Figure 6.26 : variation in the numerousness, relating to area unit, for every different Island typology along the subreach 2

6.2.2.3 Subreach 3

Regarding "Stable island" there was a constant trend between 1960 (2,0%) and 1970 (2,0%), followed by an increase up to the maximum value recorded in 1982 (5,4%), then there was a progressive decrease until 2006 (2,1%), with a sole value showing an opposing trend in 1999 (4,0%) (Tab. 6.21; Fig. 6.27).

Regarding "Young island" there was a fluctuating trend with a decrease between 1960 (6,6%) and 1970 (1,7%), an increase phase until 1982 (6,5%), a stable phase until 1991 (6,3%) and a final decrease phase until 2006 (3,0%).

"Pioneer island" has decreased from 1960 (1,5%) and 1970 (0,4%), then there was an increase phase until 1982 (1,4%) and a subsequent long decrease phase until 1999 (0,8%) and finally has been constant until 2006 (0,9%).

Table 6.21 : variation in the area of different island types over the years included in the study interval along the subreach 3.

Year	Stable (%)	Young (%)	Pioneer (%)
1960	2.0	6.6	1.5
1970	2.0	1.7	0.4
1982	5.4	6.5	1.4
1991	3.4	6.3	1.3
1999	4.0	2.9	0.8
2006	2.1	3.0	0.9

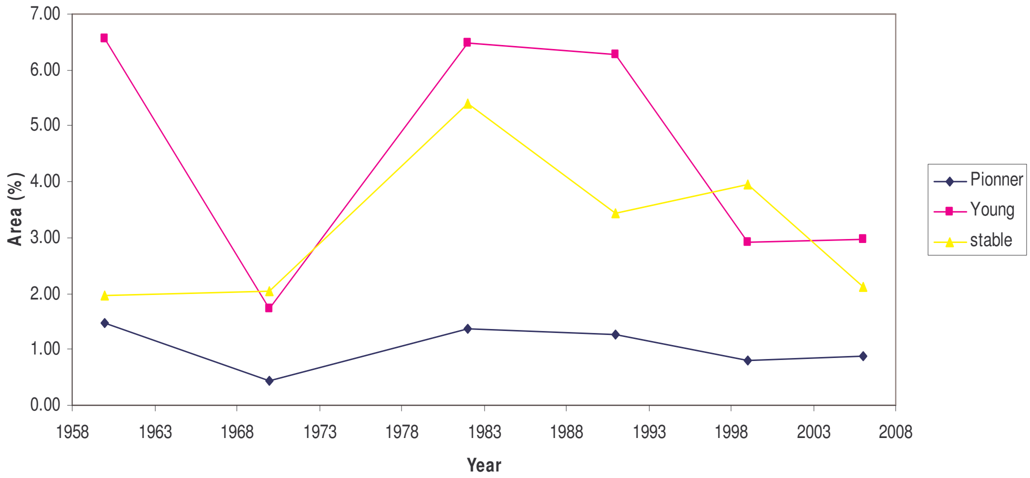

Figure 6.27 : variation in the area of different island types over the years included in the study interval along the subreach 3.

"Stable island" shown continuous fluctuation between similar values, reaching the maximum in 1991 (4,1 N km^{-2}) and the minimum in 1999 (1,9 N km^{-2}) (Table X; Fig. X) (Tab. 6.22; Fig. 6.28).

"Young island" has increased from 1960 (14,6 N km^{-2}) to 1970 (15,4 N km^{-2}), followed by a strong decrease phase until 1982 (8,1 N km^{-2}), then there was a moderate increase up to 1991 (11,0 N km^{-2}) and a subsequent slow and constant decrease phase until 2006 (8,5 N km^{-2}).

"Pioneer island" has decreased from 1960 (82,9 N km^{-2}) to 1999 (23,9 N km^{-2}) then has increased up to 2006 (32,0 N km^{-2}).

Table 6.22: variation in the numerousness, relating to area unit, for every different Island typology along the subreach 3

Year	Stable (N km^{-2})	Young (N km^{-2})	Pioneer (N km^{-2})
1960	2.2	14.6	82.9
1970	3.1	15.4	52.1
1982	2.4	8.1	34.1
1991	4.1	11.0	33.6
1999	1.9	10.7	23.9
2006	3.1	8.5	32.0

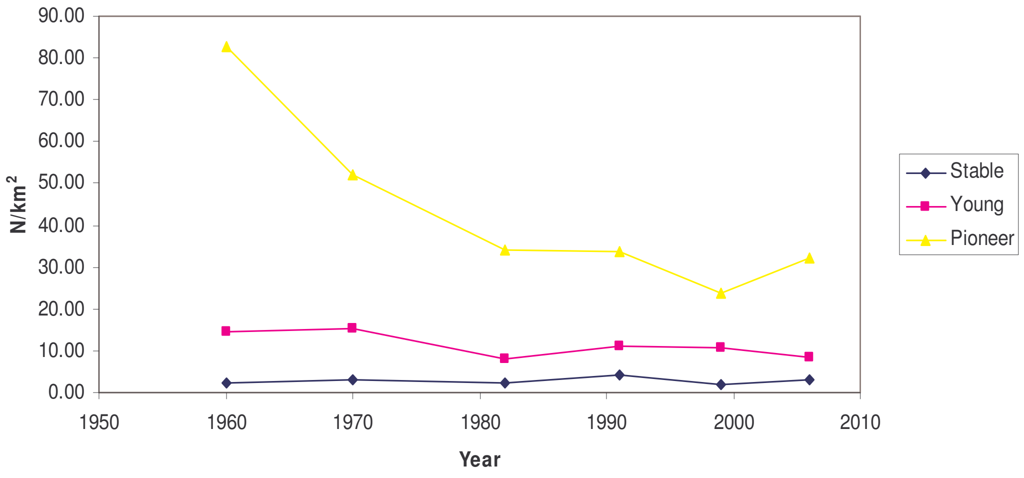

Figure 6.28 : variation in the numerousness, relating to area unit, for every different Island typology along the subreach 3

6.3 Island and floodplain elevation in the Piave River

As described in section 5.4, a detrended DTM, DSM and Canopy Height Model (CHM) were created from a LiDAR survey for the subreach.. in the Piave river. These raster-type data allow to analyze elevation characteristics of fluvial islands, floodplains and their vegetation.

6.3.1 Island elevation

In the sub-reach analyzed 317 islands are present; 75 % are pioneer islands, 17 % are young islands and 8% are stable islands (Fig. 6.29).

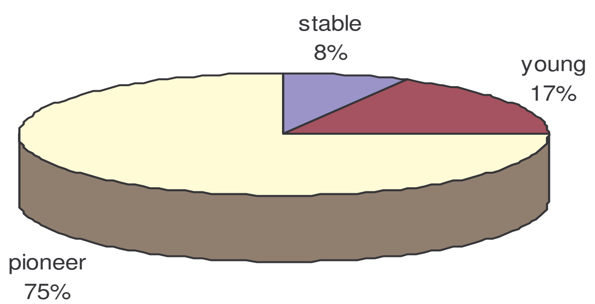

Figure 6.29: types of island in the Piave sub-reach

However, analyzing the area relating to the different types, stable islands turn out to cover 52 % of the whole island area in the subreach (i.e. they are much larger than the other types), whereas young islands cover 34% and pioneer islands the remaining 14 % (Fig. 6.30). Mean areas for each different island type are shown in Tab. 6.23.

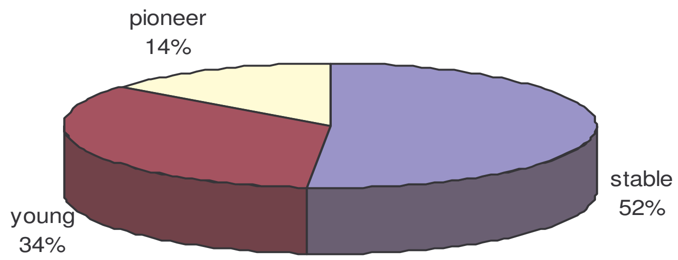

Figure 6.30: *fluvial island area measured along the Piave River study reach*

Table 6.23: mean area for the different island types

Island Type	Mean Area (m^2)
Stable	3668
Young	1139
Pioneer	107

Based on the detrended DTM, several characteristics related to the ground elevation of islands were determined within the perimeter of each of them, i.e. mean, minimum, maximum elevation and elevation range. Elevations are relative to the low flow water elevation (Fig. 6.31).

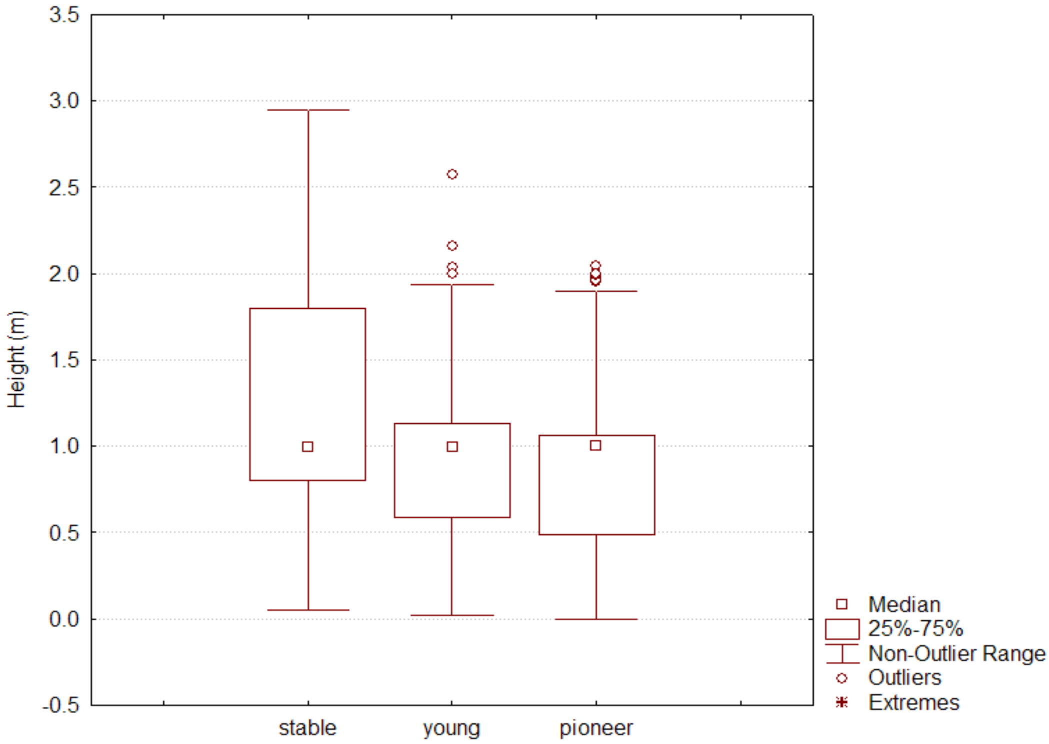

Figure 6.31: mean ground elevation for the three different types of islands along the Piave sub- reach

Figure 6.31 show the distribution of the mean island elevation for the 3 island types. Quite surprisingly, the median value of the distribution does not differ for the three groups. However, the stable islands feature mean elevations up to 3 m, and most values range from 1 to around 1.5 meters, whereas young and pioneer islands show most of the mean elevation at lower values (0.5 m-1.2 m), and the highest islands of these 2 types are at around 2 m (excluding outliers for young type up to 2.5m).

Looking at the maximum ground elevation within each island, stable islands are apparently "higher" than young and pioneer ones. In fact, they feature values up to 4m and a median of 2m. Young and pioneer islands instead feature a median value of 1m and a maximum of 3 m. Most young and pioneer islands highest elevation lies between 1 m-2 m.

6.3.2 Floodplain elevation compared to islands

A further analysis regarding the comparative analysis between island and floodplain elevation was carried out.

Purpose of this part is to compare the mean elevation of the floodplain with the mean elevation of every different island typology (Fig.6.32).

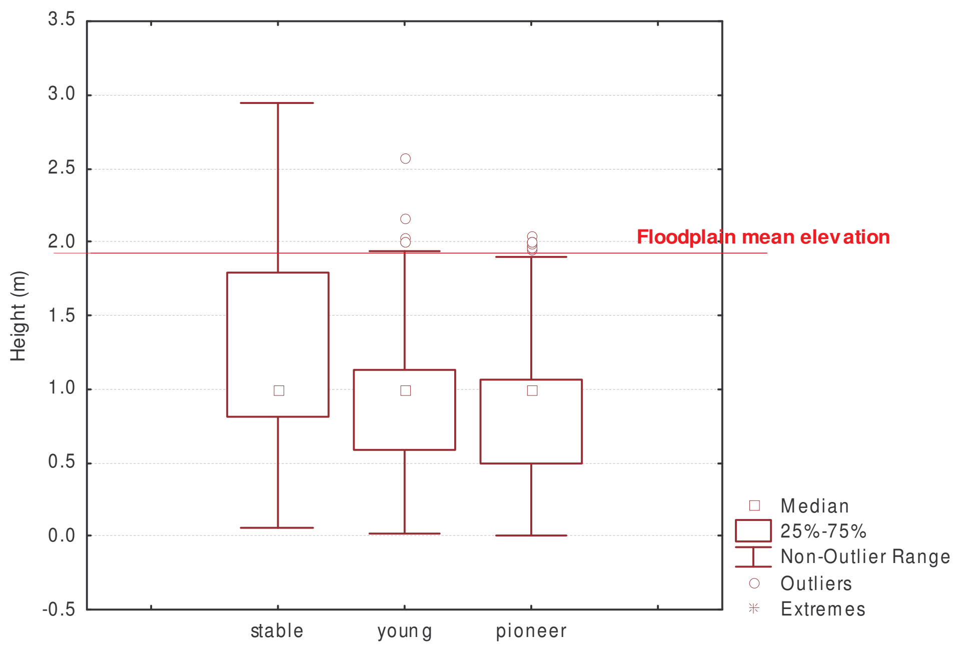

Figure 6.32: island mean elevation compared to floodplain mean elevtion.

La floodplain ha un altezza media di 1,81 m, si nota quindi che la quasi totalità delle isole fluviali (excluding otuliers) presentino un'altezza inferiore a quella della floodplain circostante.

6.3.3 Islands vegetation height

Figure 6.33 reports the maximum vegetation height in the different type of islands.

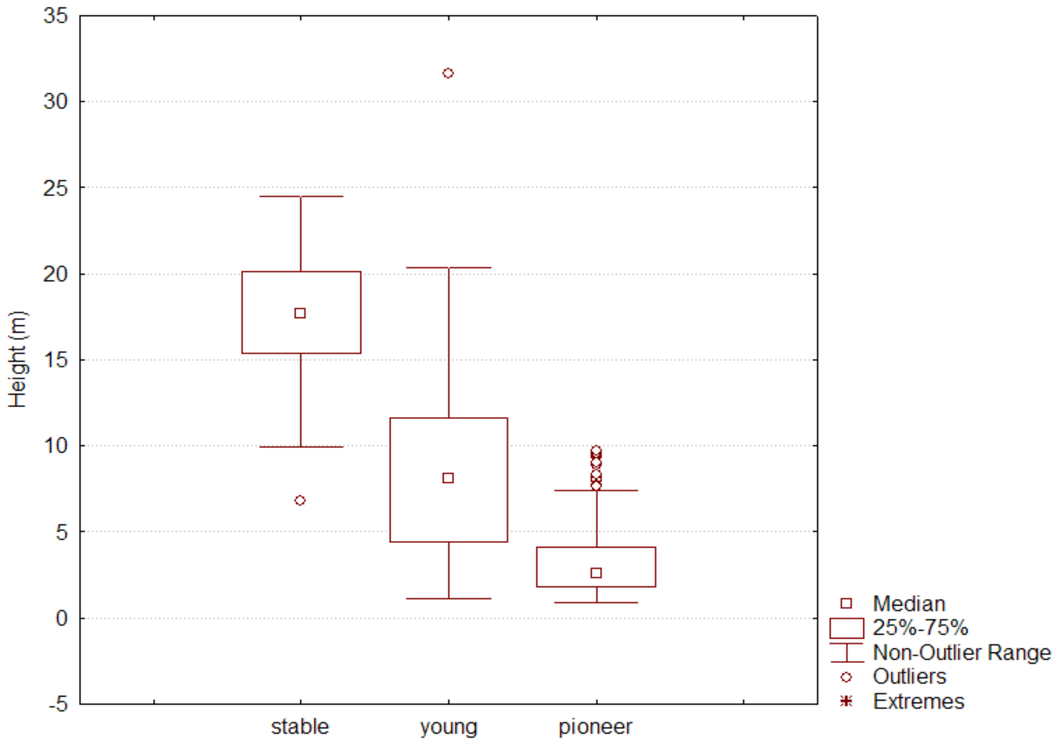

Figure 6.33: maximum vegetation height

A clear distinction according to island types is evident. Stable islands have a median value for the maximum elevation of 17 m, and the majority range from 15 m to 20 m. The maximum value is up to 25 m, and the minimum equals 10 m. Young islands feature instead a median maximum height around 7 m, with most of the values ranging from 5 m to 12 m. Pioneer islands feature a median max height of about 2.5 m, and maximum values (excluding outliers) of about 7m.

Looking at the mean vegetation height (figure 6.34), stable islands feature a median value of 3.50 m, with a dominant range of 3 m - 4 m. Young islands has a median value of 2.20 m, whereas pioneer islands of 0.7 m, but their mean height distribution is more scattered.

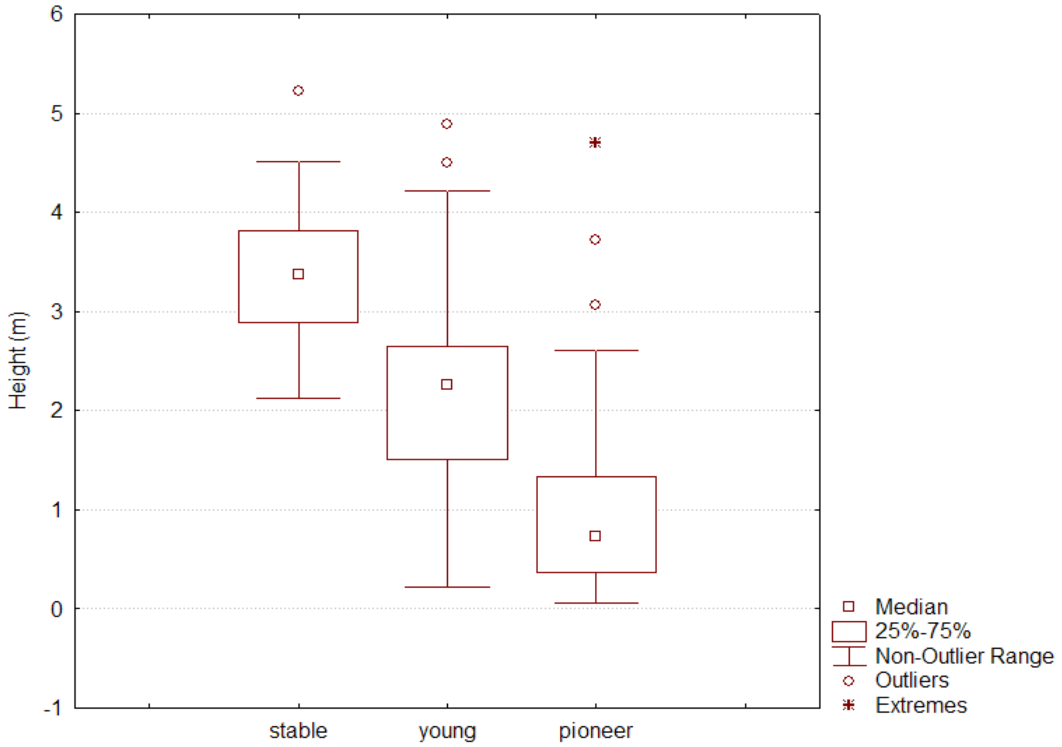

Figure 6.34: mean vegetation height

In Figure 6.35 is possible analyze the relation between tree age and tree height.

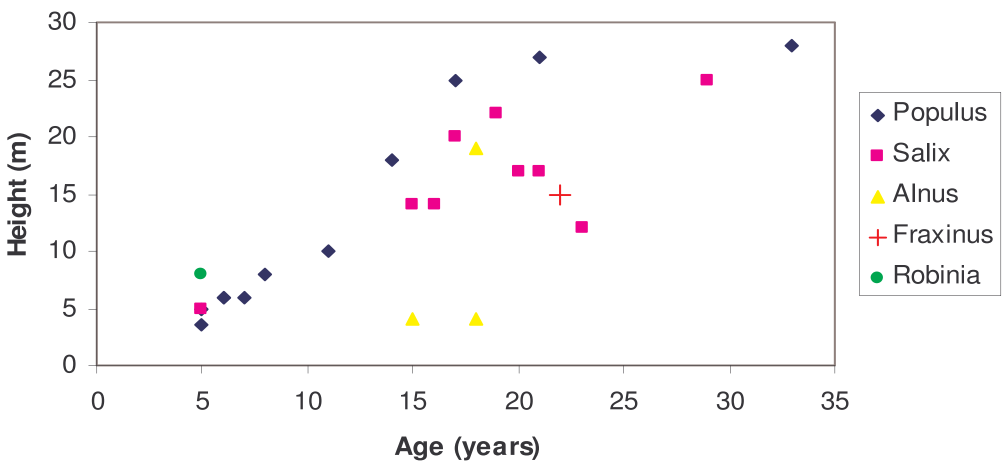

Figure 6.35 : relation between tree heights and tree ages

It is possible see a substantial constancy about the distribution of the different species. Just the Alnus trees present not concordant values.

Regarding the age, is possible see as the holder tree found during the surveys is a Populus tree of about 33 years old.

In Figure 6.36 is possible see the correlation between fine sediment height and the three different Island typologies.

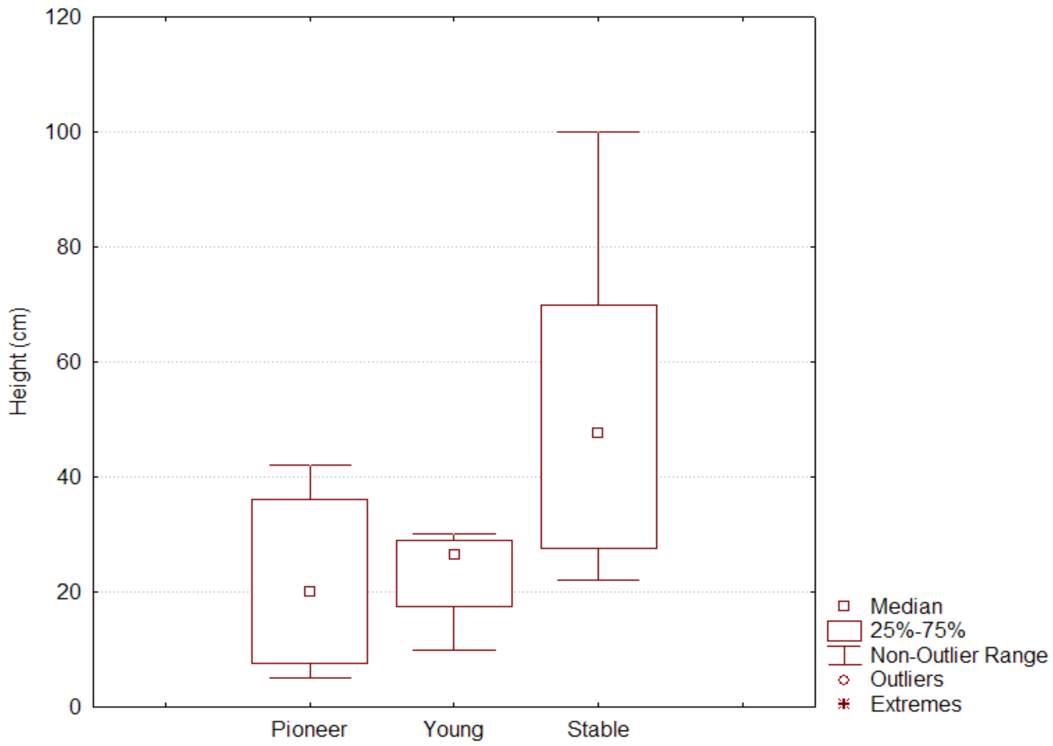

Figure 6.36: correlation between fine sediment height and island typology

Is possible observe as the "Stable Island" present an higher fine sediment layer, with a median value near 50 cm. Then, is possible see as there are not great differences between the "Pioneer island" and the "Young island" fine sediment layer height.

6.4 Long-term variation of hydraulic parameters in the Piave river

Through the use of HEC-RAS software the variations of hydraulic parameters over time (1930 – 2003 – 2007) at 16 cross sections (see Fig. 3.5) were determined. The following flow discharge were used:

- 20 m^3/s (low flow)
- 130 m^3/s (mean natural annual discharge)
- 400 m^3/s (bankfull discharge, RI=1-2 yr)
- 1000 m^3/s (flood estimated RI ~ 10-20 yr)
- 2000 m^3/s (flood estimated RI ~ 50 yr)

6.4.1 Maximum channel depth

Considering a discharge value of 20 m^3/s it is possible see as in 2003 the channels are basically deeper than in 1930, with a maximum value of 1.5 m. There is the same tendency regarding the 2007 channels, with a maximum deeper value of 2.2 m. (Tab.6.24).

Table 6.24: variation of max depth for Q=20 m^3/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-0.7
15	-1.3	-2.1
14	0.4	-
13	-	-1.9
12	-1.0	-0.5
11	0.3	0.4
10	-1.5	-2.2
9	0.3	-1.1
8	-1.0	-1.8
7	0.0	0.6
6	-0.5	-1.7
5	-0.2	0.1
4	-	-0.2
3	-0.2	-1.0
2	-0.7	-2.2
1	0.0	-1.1

Then, considering a discharge value of 130 m^3/s it is possible see as in 2003 the channels are basically deeper than in 1930, with a maximum value of 1.8 m. Regardingi the 2007 channels, is possible see the same tendency, with a maximum deeper value of 1,8 m. (Tab.6.25).

Table 6.25: variation of max depth for Q=130 m³/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-1.8
15	1.5	1.1
14	-1.3	-
13	-	-0.1
12	1.1	0.4
11	-0.4	-0.4
10	1.8	1.4
9	-0.7	-1.3
8	1.3	0.3
7	-0.2	-0.7
6	1.0	0.5
5	0.6	0.1
4	-	-0.2
3	0.5	0.3
2	1.0	0.8
1	0.3	0.4

Considering a discharge value of 1000 m^3/s it is possible see as in 2003 the channels are basically deeper than in 1930, with a maximum value of 2.0 m. Regarding the 2007 channels, is possible see different tendencies, in fact is possible see a maximum deeper value of 2.2 m and an higher value of 1.6 m (Tab.6.26).

Table 6.26: variation of max depth for Q=1000 m³/s. Values with reference to 1930 configuration.

Cross section	**2003**	**2007**
16	-	1.4
15	-0.7	0.7
14	1.4	-
13	-	0.5
12	-0.6	0.1
11	0.4	0.3
10	-2.0	-1.6
9	1.4	2.2
8	-0.9	-0.2
7	1.3	1.1
6	-0.9	-0.5
5	-0.4	0.4
4	-	0.5
3	-0.8	-0.2
2	-0.8	-0.3
1	-0.1	-0.2

Finally, considering a discharge value of 2000 m^3/s it is possible see as in 2003 the channels are basically deeper than in 1930, with a maximum value of 1.5 m. Regarding the 2007 channels, is possible see a predominantly diminution of the channel depth, with a maximum higher value of 2.6 m. (Tab.6.27).

Table 6.27: variation of max depth for Q=2000 m^3/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	0.7
15	0.4	2.4
14	0.5	-
13	-	2.6
12	-0.4	0.4
11	0.2	0.2
10	-1.5	-1.1
9	2.4	2.5
8	-0.4	-0.3
7	2.1	1.3
6	-0.8	-0.3
5	-0.2	0.4
4	-	0.6
3	-0.6	-0.1
2	-0.6	-0.1
1	0.5	0.5

6.4.3 Flow Area

Considering a discharge value of 20 m^3/s it is possible see as there is a decreasing tendency in flow area values for 2003 and 2007, with a reduction of 38.1 m^2 and 37.0 m^2 respectively (Tab. 6.28)

Table 6.28: variation of flow area for Q=20 m³/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-12.0
15	-38.1	-37.0
14	-0.7	-
13	-	3.5
12	-22.4	-25.1
11	22.8	25.7
10	-19.8	-21.2
9	12.7	3.7
8	-6.7	-2.1
7	11.0	-2.8
6	-9.1	6.6
5	24.1	-0.2
4	-	-15.9
3	2.9	2.1
2	-3.2	4.1
1	5.3	4.9

Considering a discharge value of 130 m^3/s it is possible see as there is a decreasing tendency in flow area values for 2003 and 2007, with a reduction of 137.7 m^2 and 138.4m^2 respectively (Tab. 6.29)

Table 6.29 : variation of flow area for Q=130 m³/s. Values with reference to 1930 configuration

Cross section	2003	2007
16	-	-32.8
15	-137.7	-138.4
14	-20.5	-
13	-	-6.0
12	-68.5	-73.5
11	45.5	69.0
10	-46.3	-45.9
9	-3.6	-6.5
8	-16.7	-36.5
7	17.5	-9.6
6	-45.1	-6.2
5	89.8	1.1
4	-	-61.5
3	14.8	4.4
2	-30.2	-8.8
1	-10.1	-12.1

Considering a discharge value of 1000 m^3/s it is possible see as there is a decreasing tendency in flow area values for 2003 and 2007, with a reduction of 265,7 m^2 and 401,9 m^2 respectively (Tab. 6.30).

Table 6.30: variation of flow area for Q=1000 m³/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-401.9
15	-265.7	-120.8
14	-85.0	-
13	-	-48.4
12	-43.4	-95.7
11	43.7	59.8
10	-66.7	-65.7
9	-143.5	-90.6
8	106.9	-90.2
7	153.3	36.6
6	-233.7	-111.0
5	202.1	53.2
4	-	-27.8
3	-31.2	5.8
2	-152.4	-93.7
1	-199.5	-203.6

Considering a discharge value of 1000 m^3/s it is possible see as there is a decreasing tendency in flow area values for 2003 and 2007, with a reduction of 325,1 m^2 and 888,0 m^2 respectively (Tab. 6.31).

Table 6.31: variation of flow area for Q=2000 m³/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-888.0
15	27.4	374.1
14	-325.1	-
13	-	1.2
12	-38.9	-76.8
11	-62.9	-51.8
10	-32.5	-32.5
9	-141.1	-249.6
8	222.8	-142.1
7	275.2	64.6
6	-317.5	-121.2
5	338.5	39.1
4	-	53.0
3	-35.3	23.6
2	-206.6	-123.1
1	-307.0	-298.8

6.4.3 Top width

Considering a discharge value of 20 m^3/s there is not a clear trend along the entire study reach concerning an increasing or a decreasing of the top width (Tab. 6.32).

Table 6.32: variation of top width for Q=20 m^3/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-66.7
15	-43.4	-53.7
14	-16.9	-
13	-	-2.2
12	-33.8	-61.0
11	58.4	82.6
10	1.7	-9.3
9	-51.8	-66.6
8	34.6	15.4
7	5.6	-3.5
6	-1.0	22.4
5	87.7	1.5
4	-	-161.7
3	29.5	18.4
2	18.5	20.0
1	48.7	60.4

Considering a discharge value of 130 m^3/s it is possible see as there is a decreasing tendency in flow area values for 2003 and 2007, with a reduction of 161,6 m and 244,5 m respectively (Tab. 6.33).

Considering a discharge value of 1000 m^3/s it is possible see as there is a stronger decreasing tendency in flow area values regarding 2003 and 2007, with a reduction of 534,9 m and 537,7 m respectively (Tab. 6.34).

Finally, considering a discharge value of 2000 m^3/s, it is possible see a decreasing tendency, smaller then the previous case, in flow area values regarding 2003 and 2007, with a reduction of 630,5 m and 629,8, respectively (Tab. 6.35).

Table 6.33: variation of top width for Q=130 m^3/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-65.2
15	-161.6	-197.2
14	-45.6	-
13	-	-16.2
12	-115.8	-129.7
11	-20.7	56.5
10	-9.6	-8.0
9	-123.2	-118.3
8	32.9	-99.3
7	-9.4	-31.9
6	-92.2	-35.7
5	154.7	-33.3
4	-	-244.5
3	67.2	25.1
2	-21.9	-22.1
1	-47.0	-48.9

Table 6.34: variation of top width for Q=1000 m^3/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-148.3
15	-534.9	-537.7
14	-24.0	-
13	-	-12.6
12	-85.1	-162.2
11	14.3	0.5
10	-2.0	-1.1
9	-317.0	-311.8
8	-12.7	-31.7
7	9.3	8.2
6	-208.1	-194.2
5	-4.6	-36.2
4	-	61.5
3	-116.6	-95.5
2	-105.7	-97.8
1	-488.5	-489.8

Table 6.35: variation of top width for Q=2000 m³/s. Values with reference to 1930 configuration.

Cross section	2003	2007
16	-	-216.7
15	-382.0	-346.2
14	-27.4	-
13	-	1.6
12	-183.2	-224.0
11	1.0	-5.6
10	-1.1	-1.1
9	-147.4	-339.2
8	-15.2	-32.3
7	10.3	7.6
6	-153.8	-145.2
5	24.7	-33.1
4	-	36.1
3	-153.3	-145.1
2	-64.3	-51.2
1	-630.5	-629.8

6.5 Channel number variations

In order to better define and widen the comparison on the historical variations observed along the Piave River and the Waitaki River, some analyses upon the variation in channel number have been carried out, compared to the discharge relating to the photo series used in the analysis. For this purpose we carried out analyses by making use of the research and analysis typology suggested by Hicks et al. (2003). In Figure 6.37 is possible see the distribution of the study transects along the Piave river study reach.

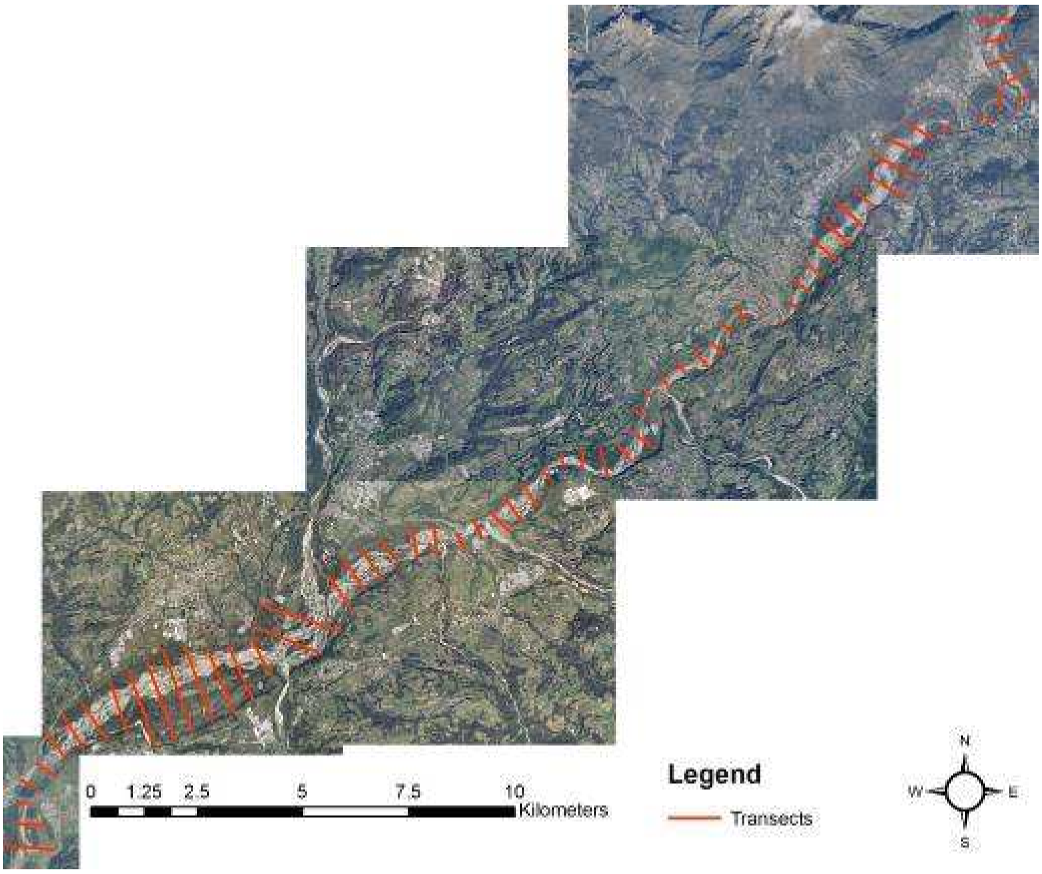

Figure 6.37: transects analysed along the Piave river study reach

It is important to take into account the change in liquid discharge by making reference to photos so as to avoid errors during the analysis, and restricting ourselves to analyzing the sole numerousness of channels; it is also important to analyze the variation in channel number since this is one of the most important parameters in braided rivers.
In figure 6.38, 6.39 and 6.40, 6.41 one may observe the variation in channel number along the Piave Riverand the Waitaki River.

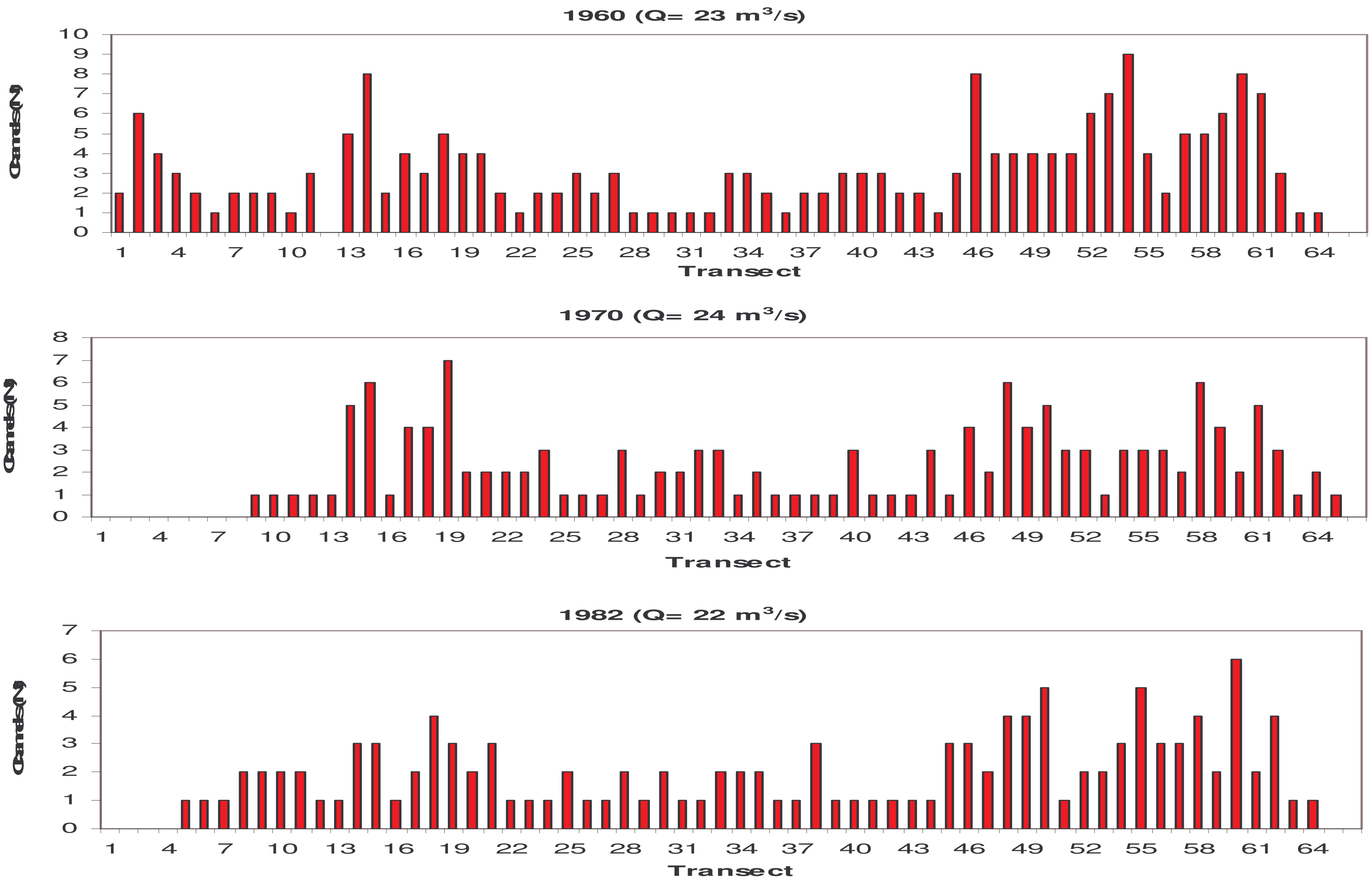

Figure 6.38: *channel number variations along the Piave River study reach, white gaps indicate no graphic cover*

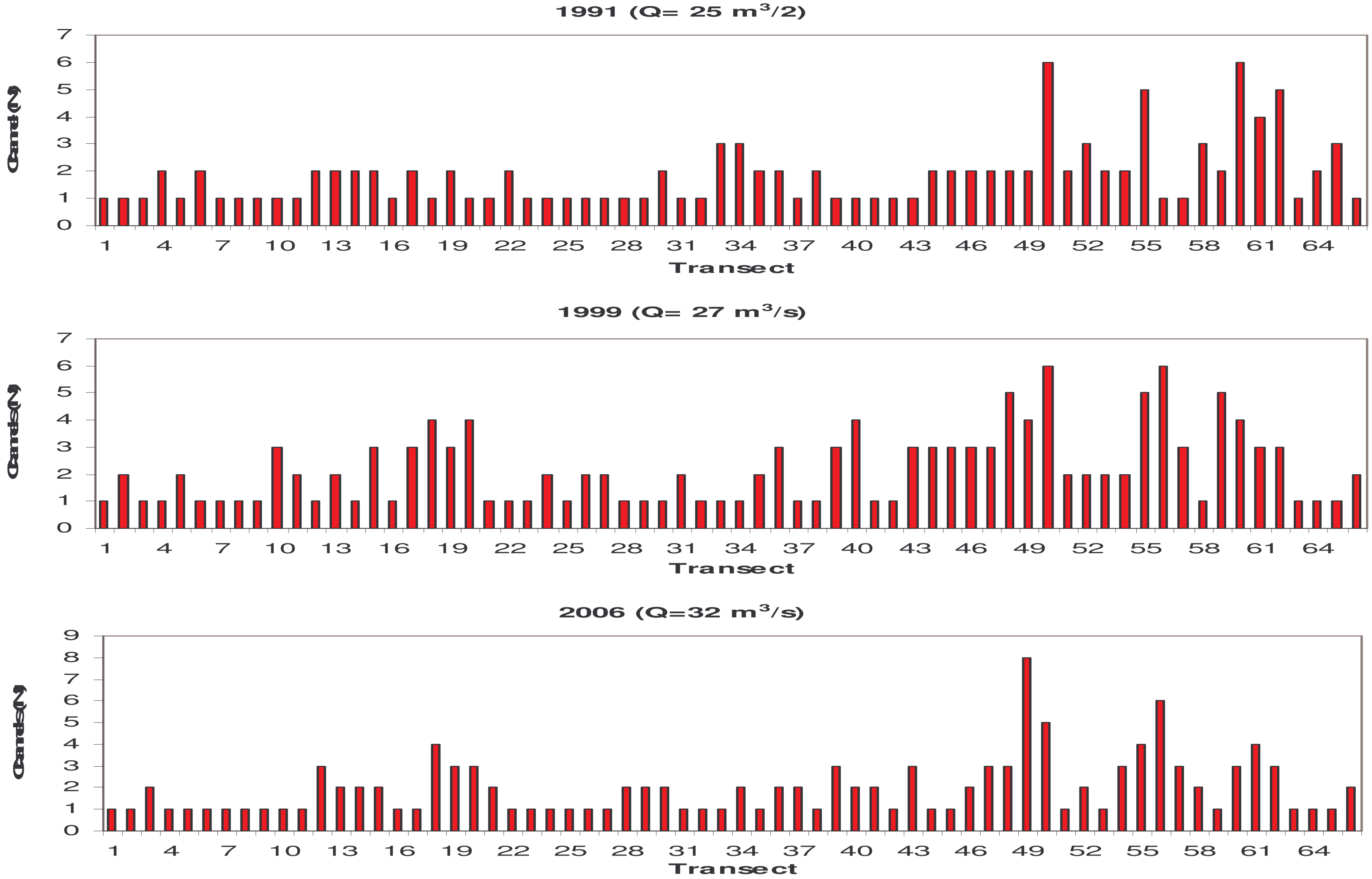

Figure 6.39: channel number variations along the Piave River study reach, white gaps indicate no graphiccover

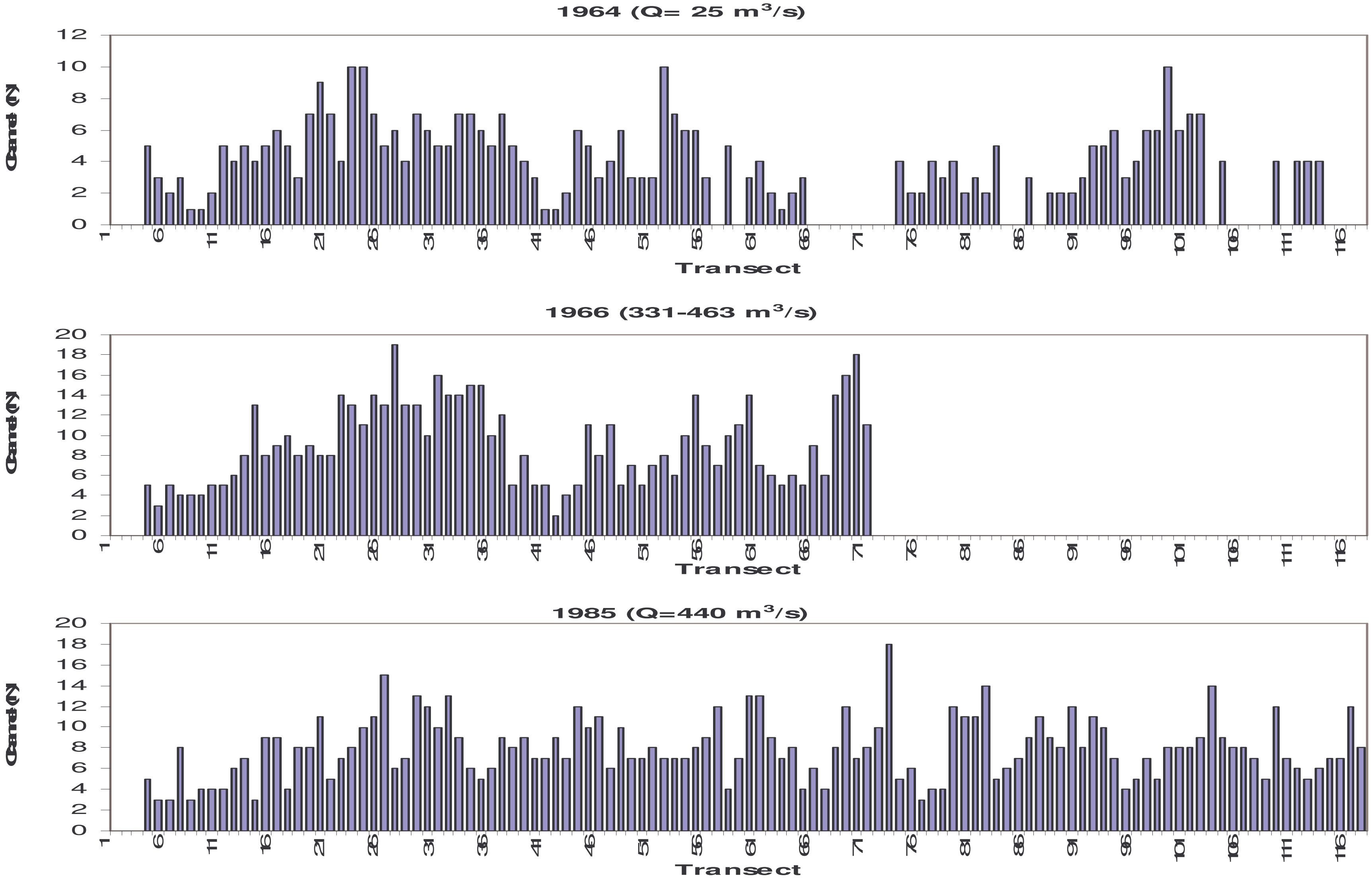

Figure 6.40: channel number variations along the Waitaki River study reach, white gaps indicate no graphic cover(source: Hicks et al., 2003)

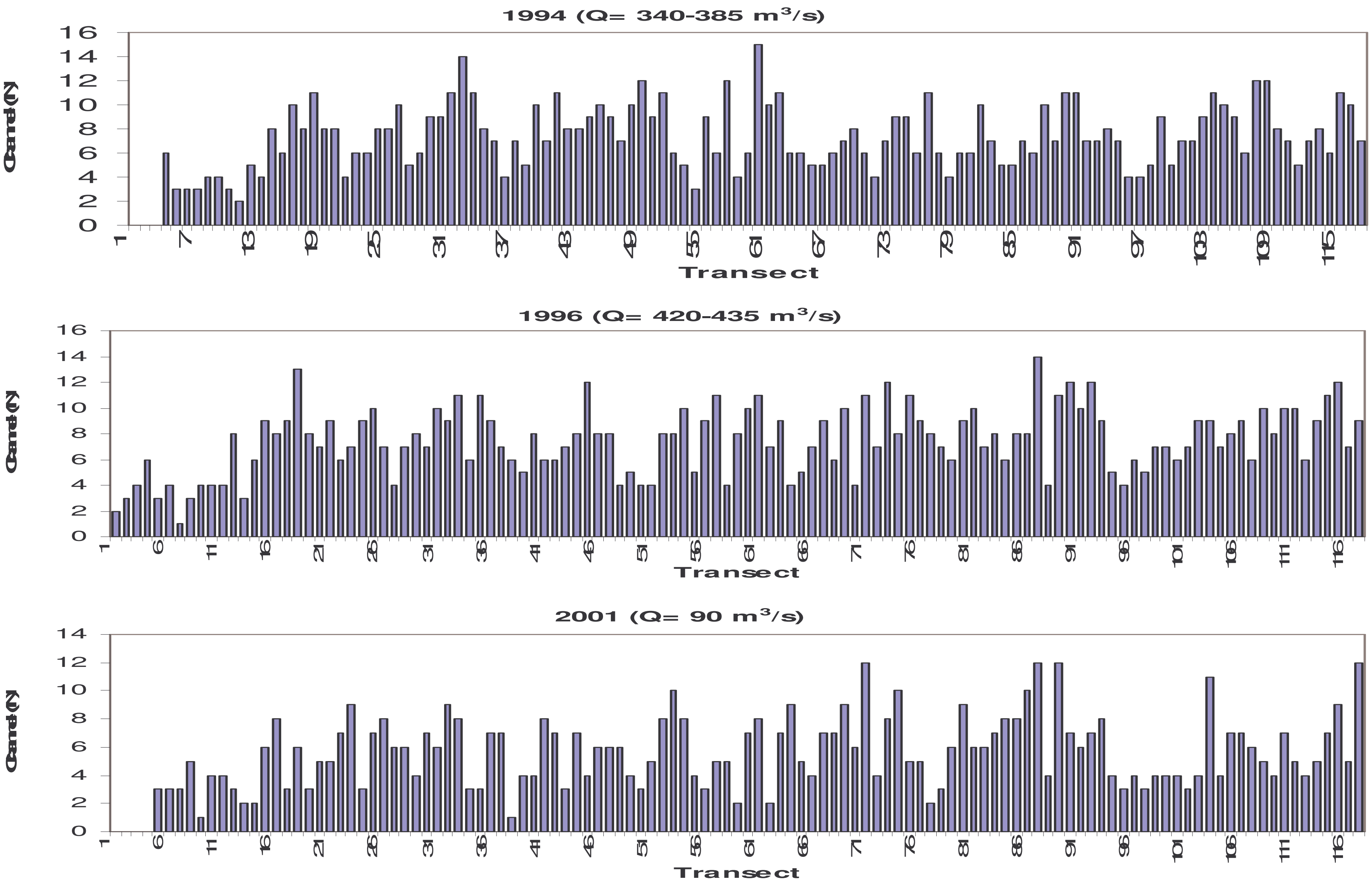

Figure 6.41: channel number variations along the Waitaki River study reach, white gaps indicate no graphic cover(source: Hicks et al., 2003)

In Fig. 6.42 is possible see the channel number variation relating to discharge along the Piave river. Channel number has decreased from the highest value in 1960 to the lower values in 1991 and 1999. Interesting is the 2006 value corresponding to the maximum discharge value and resulting as one of the lower channel number values.

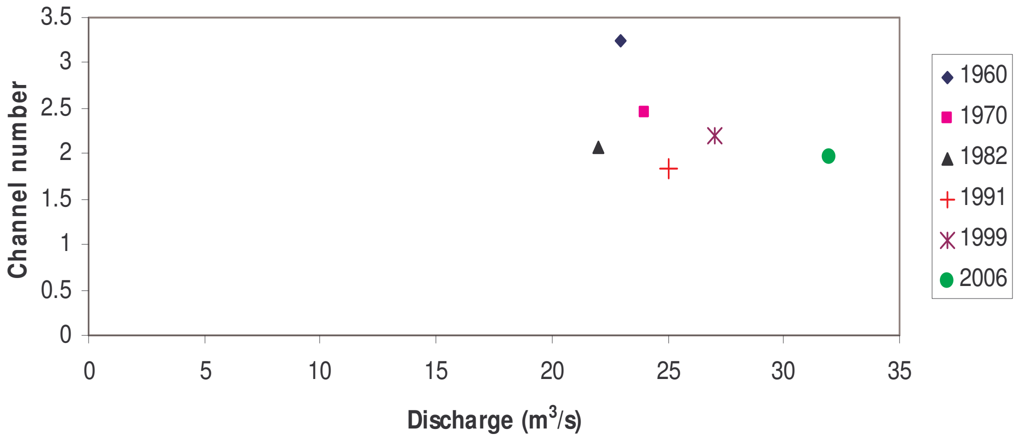

Figure 6.42: channel number variations relating to discharge

In Fig. 6.43 is possible see the channel number variation relating to discharge along the Waitaki river. Channel number has decreased from the highest value in 1966 to the lower values in 1994 and 1996.

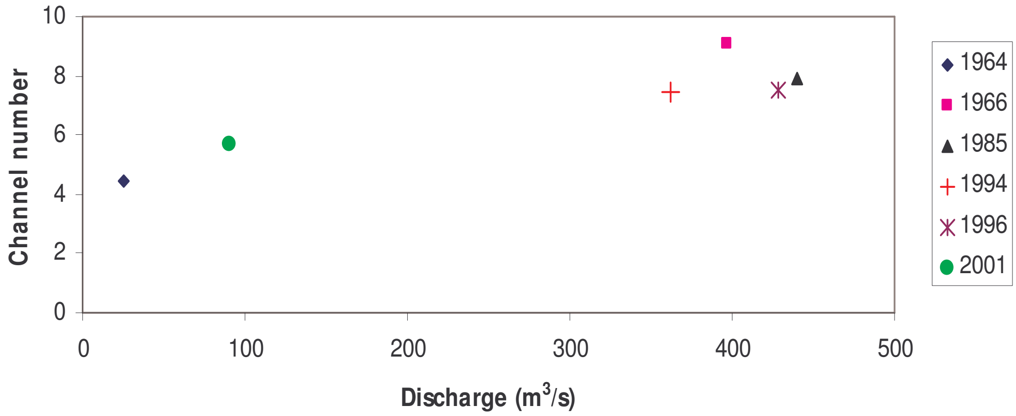

Figure 6.43 : channel number variations relating to discharge along the Waitaki river

6.6 Bed level changes

Figure 6.44 shows the variation of mean cross-section (those described in Fig.3.5) elevations taking as a reference the most recent value, i.e. either the 2007 DGPS survey or the 2003 LiDAR-derived DTM, for each one.

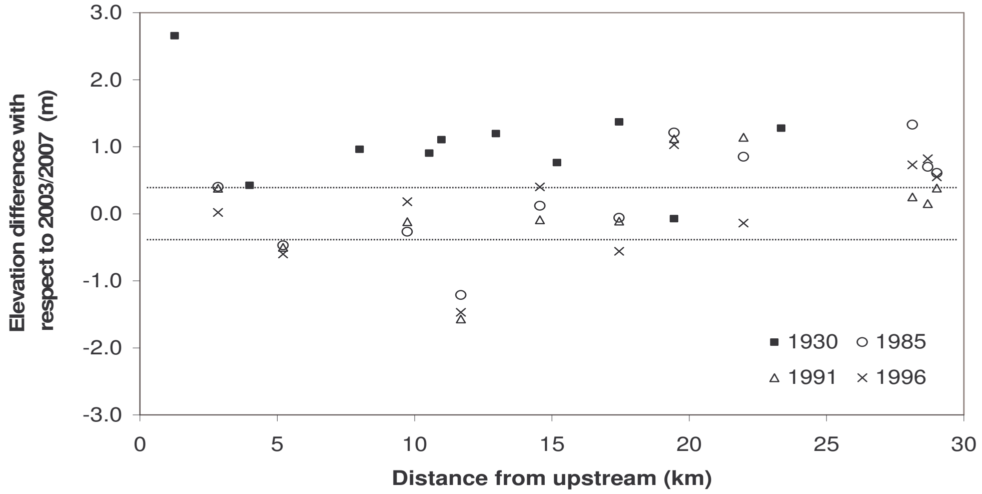

Figure 6.44: variation of mean cross-section elevations

Each cross section is plotted according to its distance from the upstream reach limit (Ponte nelle Alpi). The interchangeable use of either 2003 and 2007 cross-section to serve as a reference to present bed level is allowed by the lack of relevant flood events occurred between the two years as well as of anthropic modifications of the bed (i.e. gravel mining), and confirmed by their comparison were both are available (difference < 20-30 cm, possibily due to the LiDAR inability to detect water-filled channel).

As to the long-term bed changes, it is evident how bed elevation in the 1930s was about 1m higher than today, but the difference is > 2.5 at the very upstream reach limit and it is zero just upstream of the confluence with the Cordevole (cross-section distance of 19 km). More complex is the recent bed adjustment, i.e. after 1985.

Looking at the recent bed adjustments, most cross-sections show 1990s bed elevation similar to present levels, estimating that an overall error of up to ±0.4 m could occur when putting together surveys of different sources and methods. However, three cross-sections located upstream of the confluence with the Cordevole exhibit markedly lower elevations (up to 1.5 m, thus hinting to a recent phase of aggradation), whereas those just upstream and downstream of the Cordevole show higher elevations, up to 1.2 m, indicating a recent incision phase. However, the elevation of the three sections most downstream must be viewed with caution because of their proximity to the Busche weir, built in the late 1950s, which may have likely induced some aggradation due to backwater effects.

Analyzing the trend at each cross-section among the 1985, 1991 and 1996 surveys only, it turns out that the year of lowest bed elevation is not the same along the study reach, generally varying between 1991 and 1996. Locally, bed incised up to 2-2.5m between 1930s and 1990s.

7. <u>Discussion</u>

According to the several analyses carried out during this study, one may obtain a wide range of data relating to the different lines of study we have carried out. All these data allow to obtain important information and a full analysis of the “fluvial system”, since this is the main aim of this study.

7.1 Waitaki river

As is possible observe in Figure 7.1, the Waitaki River is strongly vegetated. It is possible to observe an opposite trend as regards the mean width of vegetation and that of the active channel.

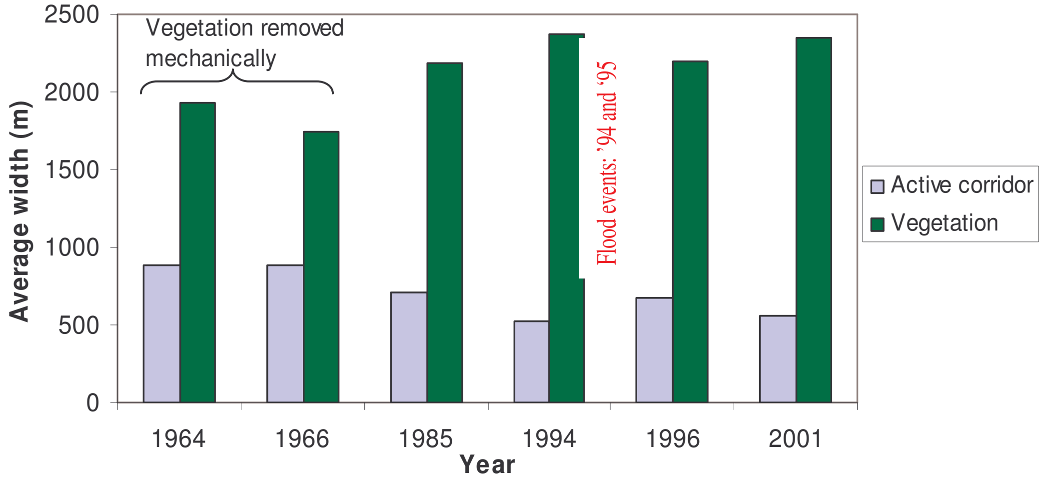

Figure 7.1: variation of the average vegetation and active corridor width along the Waitaki river during the study period

It is possible observe that there are two periods having significant changes, are those included between 1964 and 1966 and between 1994 and 1996. In the first case there is a considerable decrease in vegetation as well as a little increase in the active corridor after the mechanized removal of vegetation. Instead, in the second case, the increase in the active corridor width is due to the two important flood events occurred in 1994 and 1995.
The increase in vegetation occurred between 1966 and 1994 is due to the vegetation enroachment occurred over a stability period without any important flood events, whereas the last period relating to the increase in vegetation is due to a further interval having no important flood events.

The gravel/water balance is closely linked to the discharge referred to the day that aerial photographs were taken, thus it is possible to analyze the sole variation of the sum of the two factors. As regards the sum of mentioned factors, it is possible observe an opposite trend as opposed to that of vegetation.

Pasture cover has a constant increase between 1966 and 2001, thus reflecting a conversion of braidplain to productive farmland.

As regards the variation in the percentage width of islands, one may observe an initial strong decrease due to the mechanized removal and change occured between 1964 and 1966 and a subsequent constant decrease until 1994 due to low flood events capable of changing channels and the perifluvial areas. After the flood events occurred in 1994 and 1995, one may observe a slight but considerable increase due to the possible opening of new channels and to the exposure of new areas having exposed gravels.

Tall vegetation has a constant increase in percentage width over the whole time interval under consideration; this may be can be attributed to the transition of part of the brush and spread vegetation to the most mature class of the vegetation, which is undisturbed due to the low occurrence of floods.

Low vegetation has a quite fluctuating trend with a minimum reached on the basis of one of maximum trends relating to increase in pasture cover, as the conversion of braidplain to productive farmland has been further highlighted. By analyzing the considerable decrease in the percentage width of such class between 1994 and 1996, one may observe that this type of vegetation can be severely affected by quite important flood events capable of removing it from the active corridor.

In the end, as regards spread vegetation, one may observe a constant decrease; this may be due to its removal caused by medium-intensity flood events as well as the inevitabile transition to the tall vegetation class in those farther areas with respect to active channels, thus being less disturbed by currents.

According to a deeper analysis of the fluvial islands along the Waitaki River, it has been possible to closely observe their evolution and their response to events occurred over time. According to the analysis of the change in the active corridor, one may observe a noticeable and constant decrease until 1994; such fact is mainly attributable to an increase in vegetation in the riverbed, subsequently determined by bedriver management through the initial management aiming at maintaining an active area 400 metres wide, and an "abandonment" to the free evolution of the remaining part. After two subsequent flood events occurred in 1994 and 1995, there was a quite limited increase in the active corridor, followed by a new decrease period since there were no further significant flood events capable of removing vegetation or to open, or re-open new channels.

Over the time interval under consideration, one may observe a constant increase in the percentage land mass of stable island that is mainly attributable to both maturation of lower classes and the transition to most mature class due to the lack of events capable of removing or causing a substantial change in mature islands. It is also interesting to observe a considerable increase occurred after the flood event in 1994, which presumably led to the opening new channels in a so-called real floodplain;such fact allowed to reclassify a part of the riparian bush as island. Such analysis is being confirmed by the analysis of the numerousness per unit of surface, in fact one may observe, despite an increase in the percentage land mass , a decrease in the numerousness between 1994 and 1996, thus confirming the opening of new channels that created “macro-islands”.

By keeping such maximum value until 2008, it proves that is quite impossible to remove or to substantially change stable islands over ordinary discharges unlike what may occur over more severe floods.

As regards young islands, one may observe a marked decrease in the percentage land mass between 1955 and 1965, that is presumably due to the mechanized removal of vegetation for the release of the active corridor. It is interesting to note that between 1994 and 1995 there has been a strong decrease in both percentage land mass and numerousness per unit of surface caused by the flood occurred in 1994; instead, after the flood in 1995, one may observe a clear increase in the surface and a level almost stable as regards numerousness so as to prove that the flood occurred in 1995 opened new channels in the floodplain, thus creating new young islands having larger sizes.

Pioneer islands are mainly affected by flood events and ordinary periods, so in this periods they can mature and turn into young islands; otherwise they may merge, causing a decrease in their numerousness.

The subsequent two flood events occurred in 1994 and 1995 have proved that, as expected, these factors brought about an increase in pioneer island numerousness due to the release and deposit of different-size vegetative materials eroded further upstream.

7.2 Piave River

According to our analyses and Da Canal et. Al ones (2010), one may observe, on the basis of an increase in the mean width of vegetation, a decrease in the mean width of the active corridor. One may observe between 1960 and 1970 an increase in the channel active part corresponding to a decrease in vegetation; in fact such change was caused by the flood events occurred in 1965 and 1966. After one may observe a slow and progressive decrease in the mean width of active corridor that may be linked to a further slow and constant increase in vegetation. Between 1991 and 1999 one may observe a decrease in vegetation and an increase in the active corridor, compared to the flood event occurred in 1993.

Along the Piave River one may observe a constant decrease in the gravel-water until 1991, followed by a slight increase and a final new decrease. As regards the Piave River, one may also analyze in depth the change in exposed gravels and active channels, considering the similar discharge values with the exception of the discharge value recorded in 2006, that was slightly above.

Therefore one may observe a clear decrease in the percentage width of exposed gravels between 1982 and 1991, clearly linked to the increase in the percentage width of vegetation and, with reference to 1991 and 1999, a slight increase in the area of wetland. A very interesting value is referable to the percentage width of the area of wetland in 2006. In fact, on the basis of this photographic survey one may observe a maximum discharge value according to the series, but according to the analysis ,one may observe that mentioned year is linked to the maximum increase in vegetation and the lower percentage width of the active part.

As regards the different types of vegetation, one may observe a slight increase in the percentage width of pastures starting from 1999, fact refereable to the possible reuse of those lands that were heavily vegetated in the past. As regards woody vegetation one may observe a constant and noticeable increase until 1999 due to the possible abandonment of forestry jobs and the utilization of bushes along the river; besides fluvial islands tend to merge with the riparian vegetation due to a decrease in exposed gravels.

According to the analysis of the variation in fluvial islands along the Piave River in the time interval under consideration, one may observe that, according to the observations carried out along the Waitaki River, there is a predominant and progressive decrease in the active corridor surface. After the flood occurred in 1966 there was a moderate increase followed by a further increase from 1991, due to a succession of considerable flood events (1993 and 2003) as well as a change in the anthropic management characterized by a control relating to material removal.

Stable islands have an increase in percentage land mass between 1970 and 1982 due to a stability period that corresponds to the decrease in the active corridor. Subsequently one may observe a decrease in the percentage surface because stable islands presumably merged with the perifluvial vegetation. Instead, the varied significant flood events occurred between 1991 and 1999 caused a new increase attributable to the probable reuse of abandoned channels or to the exposure of gravels in new areas. Also in this case, as observed along the Waitaki River, an increase in the percentage surface is not always linked to an increase in numerousness, as this is mainly attributable to the formation of ”macro-islands”.This occurs because close islands tend to merge through the transition of part of younger islands to other classes and/or the opening of new channles in the floodplain.

According to the trend in pioneer islands, one may observe decrease in both land mass and numerousness until 1970 after the floods occurred in 1965 and 1966. Subsequently, as regards the area/land mass, one may observe a increase and a constant trend until 1991 due to low flood events occurred and a significant decrease until 1999 due to a succession of events; in this period one may observe a decrease in the numerousness.

According to the analysis of the variation in the islands regarding the varied subreaches under consideration, one may observe that the sole reach really affected by the change in the land mass of the active corridor is the subreach 3, which is located further downstream. This may be explained as this is the sole wide subreach in which one may observe also considerable divagations.

Along the braiding subreach 1, one may observe that pioneer islands, from a land mass point of view, are affected by floods in which one may observe a considerable decrease with an increase over stable periods. From a numerical point of view, one may observe a nonlinear trend, with an increase after the floods occurred in 1965 and 1966, followed by a clear decrease mainly attributable to the anthropic activity in the seventies and a further decrease in the numerousness due to a succession of flood events (including also those not very heavy) occurred in the nineties.

As regards young islands, one may observe an increase in the land mass corresponding to a decrease in the numerousness, since the varied close young islands merge to form larger island, and a tendency to turn into stable islands after a period of low occurence of floods.

Along the wandering subreach 2, one may observe a progressive decrease in the land mass and in the number of both young and pioneer islands corresponding to a slight increase in the land mass and a subsequent constancy in stable islands. This is clearly due to a progressive decrease in the active land mass, and depending on the wandering typology, a lower interaction of flows with the existing vegetation.

Along the braiding subreach 3, one may observe that after the decrease due to the events occurred in 1965 and 1966, there has been a general increase as regards all the three classes, then followed by a decrease in the land mass and in the numerousness as regards all the types of islands except for a slight increase in stable islands after the events occurred in the nineties. This is referable to the bedriver width along mentioned subreach, in fact through the decrease in the bedriver, the marginal parts have been no longer affected by flows, thus they completely merged with perifluvial vegetation to form a sole body.

Through the altitude analysis of fluvial islands, one may observe the characteristics of island vegetation and soil.

In order to better comprehend the analyses carried out, we made use of data obtained through the surveys (on location).

As we expected, stable islands have a mean and maximum ground height higher than the one of the other two classes under consideration. According to the analyses of the data achieved on location, one may observe that stable islands contain a fine-material layer thicker than the layer of other islands. This may be explained because stable islands have a higher resistance to water flow, thus favoring the deposition of fine material which enhances its condition, by giving it more stability and better vegetative conditions. Another factor that may charaterize the higher ground height of stable islands is attributable to their particular characteristic, since they have a higher resistence to water flow, which by flowing in the close exposed-gravel areas can easily erode the substrate.This erosion causes a further increase in the maximum height of island as opposed to that of channel, factor that explains the maximum heights recorded, that are equal to 4 m.

Instead, as regards pioneer and young islands, one may observe they have a comparable mean and maximum height, but they differ as regards the ground elevation range. In fact, with reference to this datum, pioneer islands have a value between 0 and 1 m, denoting a maturation and stability lower than stable and young islands which have values between 1m and 2m.

In the end, according to the analysis of the vegetation height in the fluvial islands, one may observe a clear differentiation between the three types of islands regarding both mean and maximum height. Such data confirm the data obtained through the surveys, in which the range values observed were similar.Besides,through the dendrochronological analyses, we have been able to date at the predominant age range relating to the different types of

islands. Pioneer islands range between 3 and 5 years, the young ones between 5 and 15, whereas stable ones higher than 15 years. The oldest plant, identified in the area under consideration, can be dated back 33 years, so in the mid-seventies.
According to the analysis of the variation in the channel number, compared to the discharge recorded when photographic surveys were carried out, one may observe a decrease in the mean number of channels along the Piave river over the time interval under consideration. Such data fully correspond to all previous analyses regarding the decrease in the active channel extension and the decrease in channel divagation. The data referred to 2006 is very interesting, because the maximum discharge condition corresponds to the second minimum value according to the mean number of channels, which is only higher than the number of channels recorded in 1991, with a lower discharge.
As regards the Waitaki River,too, one may observe a trend similar to that of the Piave River, with a decrease in the number of channels over last years.
The datum referred to 1964 is very interesting, as it allows us to directly interact with the data of the Piave river, as they have similar values.
This datum allows us to observe that, with the same discharge, there is a higher number of channels along the Waitaki River, therefore the new zealander river tends to take on a braided typology. In fact, by comparing the number of channels to the same discharge value, one may observe that the mean number of channels relating to the Waitaki River is more than double as opposed to the mean number of channels relating to the Piave River.

The evident long-term bed degradation, which is tightly associated to the channel narrowing and vegetation encroachment described in section 6, can be ascribed to an array of factors whose single relevance is difficult to estimate, such as land use variation (i.e. increase in forest cover due to the abandonment of traditional agricultural activities in the more remote areas of the Piave basin after WWII), construction of hydropower dams (i.e. reservoirs created in the 1930s-1950s in the upper Piave trapping a great deal of sediments and thus "starving" the lower river reaches), river training structures (i.e. several long perpendicular groynes built in the 1940s especially in the upstream part of the study reach, which directly caused channel narrowing), and, probably most importantly, gravel mining heavily carried out during between the 1970s and the 1990s.
Recent channel adjustments are more complex and spatially variable, such that a clear trend is less obvious. Even though a general channel widening is apparent between 1990s

and 2007, with an associated reduction in vegetation cover within the river corridor, no clear indications of a widespread, concomitant aggradation phase are observed. This could be partly due to the small magnitude of bed changes compared to the inherent measurement errors, but it might also indicate that the lateral channel mobility needed to re-enlarge the active channel by bank erosion can be restored just stopping further incision – in the case of the Piave river by banning in-channel gravel extraction in late 1990s – even without notable sediment deposition.

The peculiar behaviour of the Piave reaches in the proximity (both upstream and downstream) of the confluence with the Cordevole, i.e. the evidence of a bed level higher in the 1980s and 1990s than today, may be possibly explained in terms of a their aggradational character during very large floods such as the 1966 event. It is possible that during that flood, which featured very intense and prolonged sediment transport both in the Piave and in the Cordevole rivers and which abruptly enlarged the active channel by removing islands and marginal vegetation, gravel deposition took place in the vicinity of the confluence and downstream also for the presence of the weir at Busche, already in place. Subsequently, smaller floods coupled to gravel mining started to incise the bed, which has now reached the present lowest elevation for those reaches.

8. Conclusions

Through the data analysis achieved during this study on two gravel-bed braided rivers, we have been able to obtain important results in order to better comprehend long and medium term dynamics.

Through the comparative study of two rivers, which denote different characteristics as regards basin management, we have been able to better comprehend the responses and to critically analyze the effects relating to the different types of management .

In fact, both rivers have a marked tendency to change from a predominant braided morphology into a wandering one.

The Waitaki River has a stronger tendency to take on a braided morphology due to the same basin management aiming at maintaining a natural condition, whereas in that sense, the management of the Piave River is completely lacking, so at first the Italian river tends to take on a wandering morphology.

The intense river regulation and the presence of anthropic structures along basins caused a strong decrease in sediment transportation, as repeatedly stated, this is the main cause of the change from a braided to wandering morphology.

But the achieved results emphasize that it is impossible to consider a sole factor as the main artificer of the changes we may observe. In fact, it absolutely important to point out the contributory influence that both the change in liquid discharges (therefore its regulation) and in particular the vegetation inside or close to water courses have. Therefore it is clear how the factors affecting the morphological changes are closely linked to each other. We need to point out that a decrease in discharges causes a decrease in sediment transportation as well as a higher tendency of vegetation to settle into riverbed. On the other hand a stable vegetation affects the sediment transportation by stabilizing slopes and sedimentary bodies, thus limiting the erosion and the channel migration. As rivers usually transport sediments, one may observe a higher incision of channels that brings about a further isolation of vegetated sedimentary bodies, which become more and more stable.

The lack, or the decreased frequency of flood events capable of changing the size of channels, makes islands and perifluvial vegetation more and more stable, therefore even when flooded, has a high resistance to water flow.

In fact, one may observe that islands and perifluvial vegetation are only affected by severe flood events, whereas ordinary events can cause few changes in the vegetated areas, as they tend to affect severely young and pioneer vegetation only.

Through the several results obtained during this study, one may observe the morphological tendency relating to gravel-bed braided rivers, which may be summarized as follows:

- Increase in the perifluvial vegetation in the past few decades
- Along the Piave river there was an expansion in the active corridor from 1991
- Sensibility of vegetation over non-ordinary or continuous flood events in boths rivers
- Tendency toward stabilization as regards large-size or mature fluvial islands
- The fluvial islands merge with the perifluvial vegetation
- Tendency to decrease in the active corridor when there is a lack of non-ordinary flood events
- Decrease in the degree of braiding and in the number of active channels
- Tendency toward bed incision (untill 1 m in the past 80 years)

9. References

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