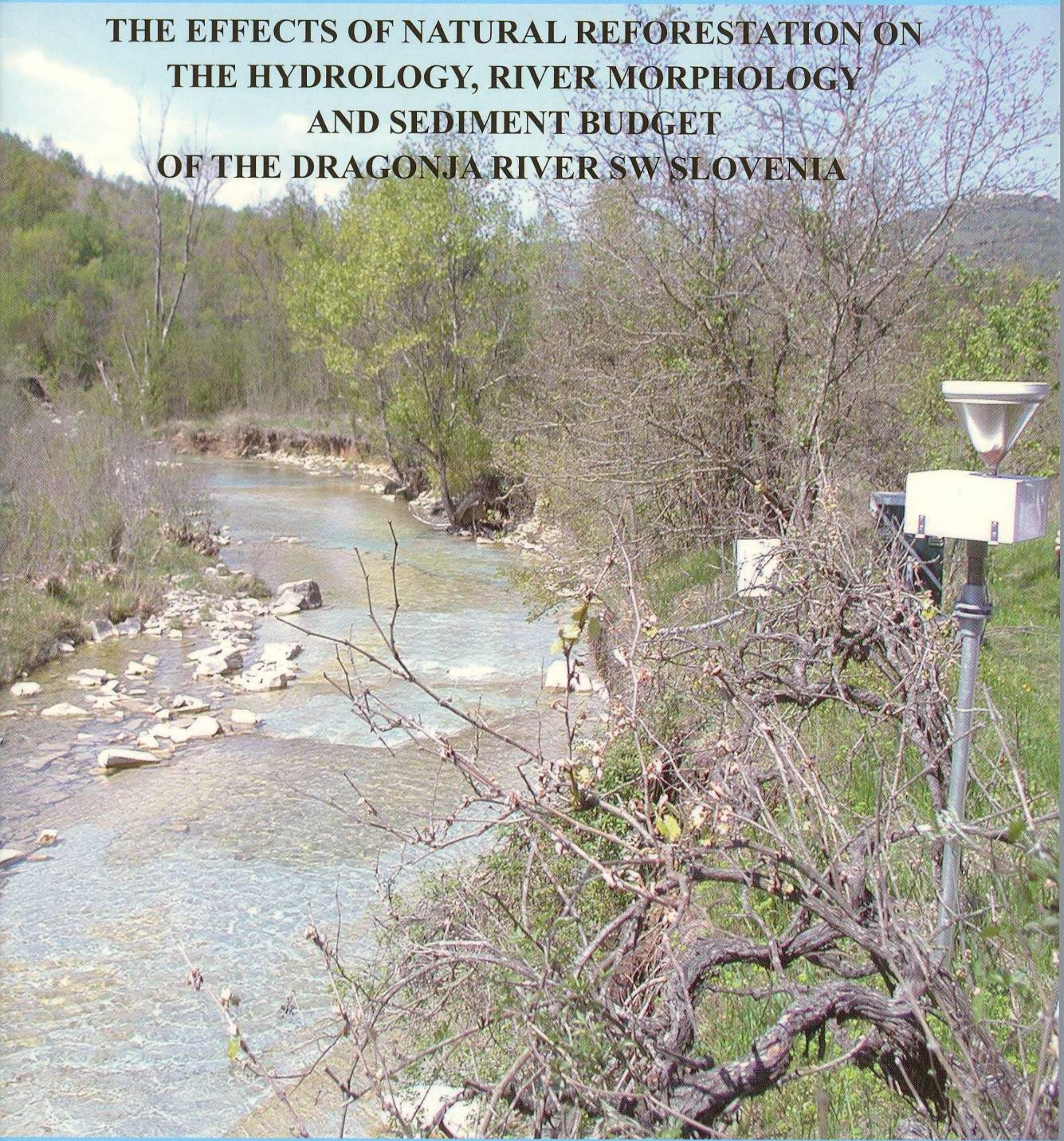
THE EFFECTS OF NATURAL REFORESTATION ON THE HYDROLOGY, RIVER MORPHOLOGY AND SEDIMENT BUDGET OF THE DRAGONJA RIVER SW SLOVENIA



Saskia Deborah Keesstra

The effects of natural reforestation on the hydrology, river morphology, and sediment budget of the Dragonja catchment, SW Slovenia

Invloed van natuurlijke herbebossing op de hydrologie, rivier geomorfologie en het sediment budget van de Dragonja rivier in zuidwest Slovenië.

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The effects of natural reforestation on the hydrology, river morphology, and sediment budget of the Dragonja catchment, SW Slovenia

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geboren te Haarlem

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Voor mijn ouders

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CURRICULUM VITAE

Saskia Deborah Keesstra werd 20 april 1973 geboren te Haarlem. In 1991 behaalde zij haar VWO diploma op het Mendel College te Haarlem. Na een jaartje levenservaring opdoen in Israël ging zij in 1992 op de Vrije Universiteit te Amsterdam Geologie studeren. In 1998 studeerde zij twee maal af, zowel als Geografisch Hydroloog als Toegepast Kwartair Geoloog. Daarvoor ging zij op meerdere stages. Een langdurige stage in Australië, waar een onderzoek ´Using Hydrochemical techniques to estimate Leakage and Recharge in Irrigation Areas (Vic., NSW, Australia)´ werd voltooit als afstudeerproject voor Geografische Hydrologie. Een tweede stage bij de Provincie Noord-Holland: Natuurlijk arseen in ondiepe grond en grondwater in N-Holland, zorgde voor een tweede bul in de Toegepast Kwartair Geologie en een doctoraal veldwerk in de Geul, waar zij (met studiegenoten) onderzoek deed naar de chrono-stratigrafie van de dalsedimenten in de Geul vallei.
Na de studie werkte zij een jaar bij het NITG/TNO bij de afdeling Geo-kartering als medewerker kwaliteitsverbetering gegevensbeheer. Daarna nog een jaar als project medewerker bij De Straat Milieu-adviseurs. In Juni 2000 begon zij als AiO bij de Afdeling Geo-milieuwetenschappen aan de Vrije Universiteit aan het promotieonderzoek waarvan dit boekje het resultaat is. Het onderzoek werd door de Vrije Universiteit gefinancierd.

Saskia Deborah Keesstra was born on the 20th of April 1973 in Haarlem, The Netherlands. In 1991 she graduated from high school at the Mendel College in Haarlem. After a year of life experiences on a Kibboutz in Israel, she went to the Vrije Universiteit in Amsterdam to study Geology in 1992. In 1998 she received her master degrees in Geographical Hydrology and Applied Quaternary Geology. For these master degrees she went on several fieldworks and traineeships. One long (hydrologic) traineeship at the CSIRO in Australia, where she carried out research at the department of Land and Water in Adelaide on Using Hydrochemical techniques to estimate Leakage and Recharge in Irrigation Areas (Vic., NSW, Australia)´. A second traineeship was done at the Province of North-Holland, where she carried out research involving the occurrence of natural Arsenic in the shallow sub surface and groundwater. A quaternary geology fieldwork was carried out in the Geul Valley in the South of the Netherlands, where the chrono-statigraphy of the floodplain sediments were studied.
After receiving the master degrees she went to work at the Dutch Geological survey, where she worked on the improvement of the quality of the coring database. After this she worked for one year at a commercial soil remediation company, De Straat Milieu-adviseurs. In June 2000 she started her PhD research project at the department of Geo-Environmental Sciences at the Vrije Universiteit in Amsterdam, The Netherlands, of which this book is the result. The Vrije Universiteit financed this research.

PART I: INTRODUCTORY CHAPTERS


Chapter 1: Introduction


CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The effects of deforestation, intensification of agriculture and mining on erosion (e.g. Trimble, 1976, 1981; Ehui and Hertel, 1992; Singh, 1999, McDonald et al., 2002), nutrient losses (e.g. Lenhart et al., 2003), slope stability (Vanacker et al., 2003), soil properties (e.g. Pritchet, 1979, Varela et al., 2001), streamflow (Hewlett and Bosch, 1984; Bruijnzeel, 1990) and the hydrological cycle of a catchment (e.g. Gaertner et al., 2001; Benito et al., 2003) have attracted considerable scientific attention. Also the impact of increased agricultural activity on floodplain sediment dynamics and the shape of riverbanks (Gomez et al., 1998; Kondolf et al., 2002, Sloan et al., 2001) and their effects on riverine habitats and biodiversity of the riparian zone have been studied widely (e.g. Rogersa and Schumm, 1991; Orbock Miller et al., 1993; Kazanci et al., 2004).

The effects of the reverse land cover change, i.e. **re**forestation, on the hydrological functioning, sediment budget and morphology of a river and its catchment have received much less scientific attention. However, forest is planted in many places, in order to cope with the fast-growing demand for industrial and fuel wood (Nambiar and Brown, 1997). In addition, abandonment of marginal agricultural land leads to natural regrowth of forest (especially in the Mediterranean area). Finally, large-scale reforestation programmes are being executed to counter widely observed land degradation (United Nations, 1992; ITTO, 2002). Optimisation of water resources (both stream flow and groundwater storage) and the struggle against land degradation are becoming ever more important issues as populations continue to increase and climate tends to become more irregular. Therefore, there is a great need to evaluate how different catchments react to reforestation in terms of their hydrology and sediment budget (Scott et al., 2005; Bruijnzeel, 2004).

It has long been recognized that forest cover influences climatic and soil conditions and therefore the amount of water flow from forested areas. It is also believed that forests tend to equalize the flow throughout the year by increasing the low stages, and decreasing the peak flow by increasing infiltration capacity and underground water storage (Bruijnzeel 2000). However, in many (Mediterranean climate) catchments, a reduced river flow, especially low flows, was found shortly after the introduction or return of the forest (Globevnik et al., 1995, García-Ruiz et al., 1997; Harden and Mathews, 2000). Similarly, the planting of fast-growing trees in natural grassland areas in South Africa produced large reductions in flow (Dye, 1996; Scott and Smith, 1997). Even the partial reforestation of large catchments in the Southeastern part of the United States of America, which were formerly subject to fairly intense erosion, led to decreases in flow, especially during dry years (Trimble et al., 1987). Although reforestation can also be expected to improve the infiltration capacity of the soils, it seems that in the cited cases the increased water use of the forest (evapotranspiration) overrides any increases in infiltration and groundwater storage possibilities (Bruijnzeel, 2004; Scott et al., 2005). The influence of reforestation on catchment runoff behaviour is also dependent on the degree that infiltration characteristics can be improved (Naef et al., 2002). In catchments where infiltration rates are not much affected by the reforestation the runoff change is predominantly caused by the difference in evapotranspiration between the different land-use types (Bosch and Hewlett, 1982; le Maitre et al., 1999; Zhang et al., 1999).

Apart from the changes in the water balance of a catchment, reforestation profoundly changes the sediment supply to rivers, and, ultimately, floodplain sedimentation rates

(Trimble, 1981; Globevnik, 1998; Lach and Wyzga, 2002, Piégay et al, 2004). Furthermore many field measurements and modelling efforts in a Mediterranean climate setting have hitherto concentrated on water erosion processes operating on the runoff plot scale. Apart from several studies in the Pacific North West (Trimble, 1999), erosion and sediment delivery processes following reforestation, operating at other spatial scales (catchment scale) have received little attention in the literature.

Another interesting phenomenon following forest regeneration relates to major changes in fluvial morphology (e.g. Rinaldi, 2003, Liébault and Piégay, 2001, 2002). Various processes interact, such as a decrease in sediment input to the river system, which may induce stream incision, and a diminished sediment transport capacity of the river. The latter is a result of decreased discharge due to the increasing water use of the vigorously growing vegetation. The combined effects are likely to produce a complicated and transient response. The morphological changes of the channel may cause practical problems in terms of bank protection, river engineering and loss of aquatic habitat.

The current research aims to investigate the effects of reforestation on a Mediterranean catchment, the Dragonja Catchment in SW Slovenia on hydrology, fluvial geomorphology and sediment budget.

1.2 Previous research in the Mediterranean region

In several regions in southern Europe a trend of decreasing agricultural activity resulting from socio-economic changes can be observed after the Second World War. This trend is either the result of planned reforestation or nature development, or takes the form of unplanned land abandonment of marginal agricultural areas followed by natural forest regeneration. Despite the large-scale abandonment of many marginal agricultural areas around the Mediterranean Sea, knowledge on the precise hydrological, sedimentological and morphological consequences of large-scale forest regeneration is limited. An outline of the relevant Mediterranean research is given below.

- For southern France, Liébault and Piégay (2001, 2002) state that numerous rivers experienced extensive narrowing and, in some places, also incision and gravel bank immobilization took place over the past two centuries (with a marked acceleration from 1950 to 1970) resulting from a decrease in flood height and frequency (Liébault and Piégay, 2001). They indicate the reforestation of the valley plains in this period as the driving force behind the geomorphic responses (Piégay et al., 2004; Kondolf et al., 2002). Marston et al. (2003) found rapid incision in a rivier in the French Alps. In this catchment the surrounding hillslopes had reforested. In these French catchments humans interfered with the channel form and sediment (e.g. dams, embankments and gravel mining) and the catchments have varying geology, which hinders a one-to-one relation between channel form evolution and the reforestation sequence.
- In Northwestern Spain several researchers found that sediment production is determined largely by the intensity of storms and floods and the erodibility of hillslopes (Pitlick, 1993; Benito et al., 1998). Gonzalez et al., (1997) shows a major change in sediment delivery as a result of land-use change. After total reforestation of a previously severely eroding (250 ha) catchment, all sediment delivery stopped. Also Ruiz-Flaño et al. (1992) show the importance of vegetation cover in the hydrological functioning of a soil, where abandoned fields show a better infiltration rate than fields that are still in agricultural use. García-Ruiz et al. (1995, 1997) demonstrated that

reforestation caused increased infiltration; interception and evapotranspiration, while overland flow decreased. They also state that river incision occurred as the result of changed equilibrium between sediment and water discharge. Lasanta et al. (2000) point out that surface runoff is controlled by the addition (or not) of fertilizer; and sediment concentration is mostly controlled by ploughing. Gallart and Llorens (2004) show a large increase in evapotranspiration as a result of a larger forested area.

- In Italy Rinaldi and Simon (1998) and Rinaldi (2003) found severe incision and channel narrowing as a result of reforestation in combination with gravel mining in the river channel. Significant decreases in sediment delivery from the hillslopes were modelled by Van Rompaey et al. (2005) for a large number of reforested catchments in central Italy.
- An overall study of catchments throughout the Mediterranean by Poesen and Hooke (1997) shows that gully and channel erosion are important sediment sources and that land use changes strongly influence these erosion processes. Brookes et al. (2000) state that the Mediterranean climate is especially vulnerable to vegetation or climate changes as the thresholds to major hydrological or morphological changes are in close range. They constructed a model to simulate the effects of vegetation changes on flow, erosion and deposition processes.
- In Slovenia the first major work on the effects of reforestation in the Dragonja catchment was conducted by Globevnik and co-workers (Globevnik, 1998, 2001a, 2001b; Globevnik et. al, 1995, 1998 and Globevnik and Sovinc, 1998). Another recent study carried out in the Rokava catchment, a sub-catchment of the Dragonja catchment, was carried out by Petkovšek (2002). The results of these studies are given in §1.5.

1.3 Overall Dragonja research project

1.3.1 History of the research project

The Faculty of Earth Sciences of the Vrije Universiteit initiated an inter-departmental collaboration project, titled 'River basin water and sediment transport modelling' in 1999. One of the designated core issues of research for joint hydrological and geomorphological research between the Departments of Quaternary Geology, Hydrology, Environmental Sciences and the Institute of Environmental Studies (IvM), was the study of the impact of land use changes on water, sediment and nutrient fluxes at the meso-scale.
A suitable catchment for this kind of research was found in the 91 km^2 Dragonja catchment in SW Slovenia. The availability of long term hydrologic and vegetation records (1960+; HZM, 2003) provided an ideal situation to study the environmental impacts of land cover change in a meso-scale catchment and to investigate hydrological, meteorological and fluvio-geomorphological processes. After discussions with the department of Civil Engineering and Geodesy and the Water Management Institute in Ljubljana of the University of Ljubljana, the Dragonja research project entitled: '*Integrated assessment of the effects of forest regeneration on river dynamics and functions*: *the Dragonja catchment, SW Slovenia*' was started. As part of this overall project a first proposal for a PhD research project was granted by the Vrije Universiteit, which resulted in this thesis. Forest hydrological aspects associated with the large-scale forest recovery that took place in the catchment since the 1950s are dealt with in a companion study by van der Tol (in prep.). From the Slovene side the two projects were matched by PhD research on hillslope erosion (Petkovšek, 2002) and forest hydrology (Šraj, 2003).

1.3.2 Research aims

The main objective of the larger project: *'Integrated assessment of the effects of forest regeneration on river dynamics and functions: the Dragonja catchment, SW Slovenia'*, is to quantify the effects of natural reforestation on river morphological behaviour and soil-vegetation-atmosphere exchange. Research was carried out along four main themes. The project following the first theme is carried out by Christiaan van der Tol for his thesis at the department of Hydrology and Geo-Environmental Sciences at the Vrije Universiteit. The project addressing the second theme has not been carried out so far. This thesis addresses the research themes 3 and 4 with their respective objectives, with an emphasis on the last theme.

1) Forest hydrology and micrometeorology:
Where the main research goals are

- To study the impact of topography on natural reforestation and evaporation in four different situations (wet *versus* dry and North *versus* South slopes, leaf biomass (stand vigour)) and species composition.
- To study the trade off between growth and water stress on the mentioned forest stands.

2) Soil ecology and nutrient cycling.
Where the main research goals are:

- To determine the forest chronosequence and resulting changes in hydrology, soil ecology and nutrient cycling as a result of the gradual abandonment of agricultural fields (5, 10, 15, and 30-years after abandonment).
- To study the natural development of above- and below-ground (soil fauna) biodiversity as a function of forest age in relation to various key ecological processes such as primary production, decomposition, soil water retention, infiltration, fertility, and carbon and nitrogen mineralization.

3) Catchment hydrology and erosion.

- An overview of the Dragonja catchment in terms of geology, demography and climatology (Chapter 2).
- The hydrological parameters and the effect of reforestation on the hydrological functioning of the catchment are described and assessed in chapter 3.
- The main aim in slope hydrology and erosion is to reconstruct the change in erosion rates on the hillslopes and the changes in total sediment loss of the catchment due to the reforestation of the Dragonja catchment over the period 1954 to 2002. Modelling the past land use situation provides an insight in how these land-use changes affected the erosion rates on the hillslopes and may be used for management purposes. This aspect is addressed to in chapter 4.

4) River morphology and floodplain deposits,

- The main objectives are to study the impact of reforestation on in-channel processes, such as bedload transport, the production of bedload material and the production of suspended sediment (other than from hillslopes). Therefore the in-channel sediment processes and the sediment production processes at present and before the reforestation are qualified and quantified (Chapter 5).
- To study the sediment budget of the river by monitoring the supply and transport of both bedload and suspended sediment material (Chapter 5). Furthermore, the

downstream fining and downstream rounding of the bedload material is discussed (Chapter 6).

- To study the impact of human interference and especially the effects of reforestation on the river and floodplain morphology of the Dragonja river, including the spatial variability of river response to land-use change in the catchment is presented (Chapter 7).
- To evaluate and quantify the sediment storage components of the Dragonja river floodplain by presenting a reconstruction of the development of the Dragonja floodplain over the past 60 years in relation to the cited land use changes. The approach involved dating of floodplain sediments using ^{137}Cs-profiles, measurement of actual sedimentation rates using artificial grass sedimentation mats, and linking this information with the present-day behaviour of the river (Chapter 8).

1.4 A SUITABLE RESEARCH AREA: THE DRAGONJA CATCHMENT

The Dragonja catchment is especially suitable for this research as it has a uniform geology and land use change. Previous studies that looked at the effects of reforestation on stream sediment dynamics pertained to large catchments with rather heterogeneous land cover and/or geology e.g. Liébault and Piégay, 2001; Marston et al., 2003). Besides, in most other studies the effects of land use change are obscured by human influence, like dams or gravel mining in the channel (Rinaldi and Simon, 1998; Liébault and Piégay, 2002). Other studies on the effects of reforestation on hydrology, sediment budget and/or morphology were carried out in a different climatic zone or on relatively small hillslope plots (García-Ruiz et al., 1995, 1997, Lansata et al., 2000).

The Dragonja catchment is a medium-scale catchment, for which a well-documented record of land-use change and discharge measurements is available. This area has been under cultivation for a long period of time, probably already since Roman time. The deforestation caused, as in many other regions (e.g. González-Sampériz and Vicién, 2002; Oldfield et al., 2003), large-scale erosion on the hillslopes and deposition of large volumes of fine sediment in the valley.

In recent times, the morphology of the riverbed of the river Dragonja and its largest tributary, the Rokava, underwent a distinct transformation due to a change in sediment load and river discharge. These changes were induced by the depopulation of the region after the Second World War and the resulting abandonment of agricultural fields and broad scale reforestation. Anthropogenic environmental change in the Dragonja catchment is restricted to agricultural land-use change, as no other human disturbance (e.g. gravel extraction, dams, road construction) obscures the effects of land abandonment (Globevnik et al., 1998; Keesstra and Van Dam, 2002). Furthermore, the Dragonja River represents one of the few remaining streams draining into the Adriatic Sea that has (largely) not been regulated by man (Globevnik and Sovinc, 1998). As such, any changes in channel morphology will reflect changes in the flow regime as caused by changes in climate or land cover. Therefore, the Dragonja catchment seems well suited to gain experimental information on the effects of reforestation on water and sediment delivery to the channel and subsequent sediment dynamics in the valley, and associated morphological changes of the river channel and the floodplain.

1.5 Previous research in the Dragonja Catchment

The first major research conducted in the Dragonja catchment has been carried out by Globevnik and co-workers (Globevnik, 1998, 2001a, 2001b; Globevnik et. al, 1995, 1998 and Globevnik and Sovinc, 1998). Their research shows:

- An overview of the historic background of the region.
- The reforestation sequence (from ca. 20% in 1971 to >60% in 1994) with subsequent decreasing erosion features
- The hydrological changes as recorded at the outlet of the Dragonja (notably a gradual reduction in average annual and dry-weather flows (of 3.5% and 10% per year, respectively)).
- The sediment input as modelled with the Gavrilović formula (1970) for the period 1971-1995 and bedload transport capacity was modelled with the Meyer-Peter-Müller formula (1948).
- The channel narrowing (60 %) and sedimentation in the channel over the period 1971-1996 in the middle and lower reaches of the Dragonja River.
- An inventory of changes in the ornithofauna was made, which concluded that bird species that are characteristic for the cultural landscape were replaced by woodland species.

Another recent study was carried out in a sub-catchment of the Dragonja catchment, the Rokava catchment (Petkovšek, 2003) and was partly conducted in cooperation with the author of this thesis. This work pointed out that:

- The sediment delivery between autumn 2000 and spring 2002 (based on suspended sediment samples) was around 1500 t y^{-1}.
- Cliffs (large bedrock banks) contributed a few 100 m^3 of suspended sediment per year to the stream.
- Annual bedload transport was estimated to about 100 m^3 of bedload sediment per year.
- With the RUSLE model (Renard et al., 1997) the soil loss from different land use types was derived, the highest rates were found in vineyards (50 t ha^{-1} y^{-1}), orchards and fields (20 t ha^{-1} y^{-1}).
- A comparison with the Gavrilović equation (1970) showed that the latter gives the rates that are about half of those of RUSLE.
- The change in erosion rate from the hillslope sources has reduced to 50 % from the sixties till present, while erosion rate from cliffs (referring to the Rokava sub-catchment only) has decreased even more.

To bring the deterioration of biodiversity in Europe to a halt by 2010, the European Union founded the Natura 2000 network (European Commission, 2000). All participating countries agreed to take all measures needed to realise the required habitat zones essential for maintaining biodiversity, taking into account economic, social and cultural requirements. The Dragonja catchment has enjoyed a Natura 2000 status since 2004.

A further point of attention is the fact that the Dragonja River basin is situated right on the border between Slovenia and Croatia. After decades of depopulation and subsequent natural reforestation, the Dragonja area is beginning to be developed again in various ways. As a result, several conflict situations have arisen recently among the different stakeholders in the catchment. Examples of conflicting interests include: (i) the development of the area as both a drinking water supply and food production resource, both on the Slovenian and Croatian sides; (ii) the touristic development of the valley (e.g. a golf resort); and (iii) the maintenance

of nature conservation under the Natura 2000 directives, and the ecological functioning of the saline wetland nature reserve at the outlet of the Dragonja catchment.
Sustainable water management in the area must consider the interests of all stakeholders concerned. Thus, apart from preserving the area's natural (floral and faunal) and cultural heritage and protecting the quality of its water resources, the water and agricultural demands of the more development orientated stakeholders will need to be addressed as well. To meet the demands of all stakeholders, and to meet the directives of the Natura-2000 network, the catchment management requires sound information of the hydrological, morphological, ecological and sediment delivery and deposition functioning of the river is needed.

1.6 Structure of thesis

This thesis is structured in the following way: In the first chapter a general introduction to the project is given, with background information on previous conducted research. This chapter also gives an overview of the aims of this study. In chapter 2 an introduction is given on the study area, with its characteristics on geology, demography and climate. Chapter 3 shows the hydrological parameters and the effect of reforestation on the hydrological functioning of the catchment. In chapter 4 the changing sediment production on the hill slopes is presented using a spatially distributed soil erosion and sediment delivery model WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al, 2001; Verstraeten et al., 2002). The difference between the pre-reforestation situation and the current situation is shown. In chapter 5 the other sources of both coarse and fine sediment are discussed and the way the supply and transport of this sediment changed due to the reforestation. In chapter 6 is explained how bed load material is distributed in the channel and the rounding abrading processes in the channel are described. The changed morphology of the river channel is described and explained in chapter 7. In chapter 8 a reconstruction of the overbank sedimentation before the reforestation is presented and compared to the current situation. The synthesis of main conclusions is given in chapter 9.

Chapter 2: Study area

CHAPTER 2: STUDY AREA

2.1 GEOGRAPHICAL AND DEMOGRAPHIC SETTING

The study area (Fig. 2.1) is located in southwestern Slovenia. The region is part of Istria, which extends further south into neighbouring Croatia. The catchment of the Dragonja is a hilly region with an area of 91 km^2 as measured upstream from the long-term gauging station at Pod Kaštel (Fig. 2.1). The length of the river is 30 km and forms the natural border between Slovenia and Croatia for a large part of its course (approximately 20 km). Near the outlet, the alluvial river valley spreads into salt pans before reaching the Adriatic Sea. The elevation ranges from 452 m in the eastern most part of the catchment down to sea level. The Dragonja River flows from east to west, between 45º 29'N, 13º 51'E in the east to 45º 28"N, 13º 35'E in the west. As a result the hill slopes have mostly northerly or southerly expositions.

The upstream part of the Dragonja catchment consists of two sub-catchments (Fig. 2.1), the Upper–Dragonja sub-catchment (32 km^2) to the south, and the sub-catchment of the Dragonja's largest tributary, the Rokava, with an area of 20 km^2, to the north.

Figure 2.1: The study area: the Dragonja catchment, southwestern Slovenia. (45º28'N, 13º35'E).

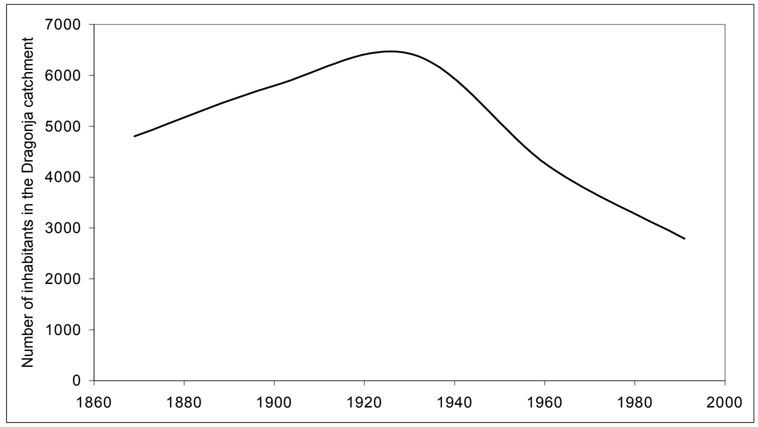


Figure 2.2: Number of inhabitants in the Dragonja catchment over the period 1860 to 1995 (after Globevnik, 2001)

The hinterland of the Dragonja catchment is a rural area. Historically, it was an important food supply area for the cities on the Trieste Bay shoreline. These agricultural activities led to extensive deforestation with accompanying changes in hydrology and geomorphology, including severe erosion. After the Second World War the area depopulated (Fig. 2.2) due to the weak socio-economic potential of the hinterland. The socialist regime of former Yugoslavia stimulated the industry at the coast and many small farmers abandoned their fields and moved to Koper, a coastal city nearby, to work in the newly established industries. In 1995 the number of inhabitants had dropped by 50% compared to the 1930s (Globevnik, 2001b). Moreover, part of the present-day inhabitants work in the above-mentioned industry or in the tourist business at the coast and no longer use land for agriculture. As a result, the abandoned agricultural fields and pastures became naturally reforested over large parts of the catchment (see section 2.4 below). However, in the last few years a new trend developed. Many abandoned houses are being rebuilt as summer and weekend houses by people from the larger cities of Slovenia or even from Italy.

Historically, the delta of the Dragonja River was used for salt making from the 13th century onwards until the mid 19th century (Zagar, 1991). From then on, the salt industry was taken over by mining and the saltpans were abandoned. This resulted in a saline wetland area that now is an important nature reserve for several species of flora and fauna. Since 1993 the wetland area is a national park. The hinterland of the Dragonja catchment has a Natura 2000 status since 2004 (European Commission, 2000).

2.2 Geology

2.2.1 General geological setting

The Dragonja catchment is situated between the Trieste Karst area in the north and the Buje Karst area in Croatia in the south. The substrate is mainly composed of impermeable flysch, in which few karst phenomena occur. Flysch is a general term for deep-water turbidites (Bouma, 1962; Marjanac,1990). This Eocene flysch consists of alternating, calcareous clay, silt and sandstone layers, with some calcareous conglomerates and breccias. The sandstone banks can reach a maximum thickness of 1.5 m. In the southwestern (downstream) part of the catchment, the Dragonja River cuts into an Upper Cretaceous rudist limestone that lies discordantly below the flysch deposits. A reverse fault thrusted the relatively young flysch strata next to the Cretaceous limestones. (see cross section in Fig. 2.3). In the headwaters of the Dragonja catchment the flysch is

gently folded. Further to the west the strata are sub-horizontal to gently dipping towards the north.
The Dragonja valley bottom is covered with alluvium. Consisting mainly of silts and clays with a base of gravels. In some places the river has cut through the alluvial sediments and part of the flysch stratum, which has resulted in a bedrock channel.

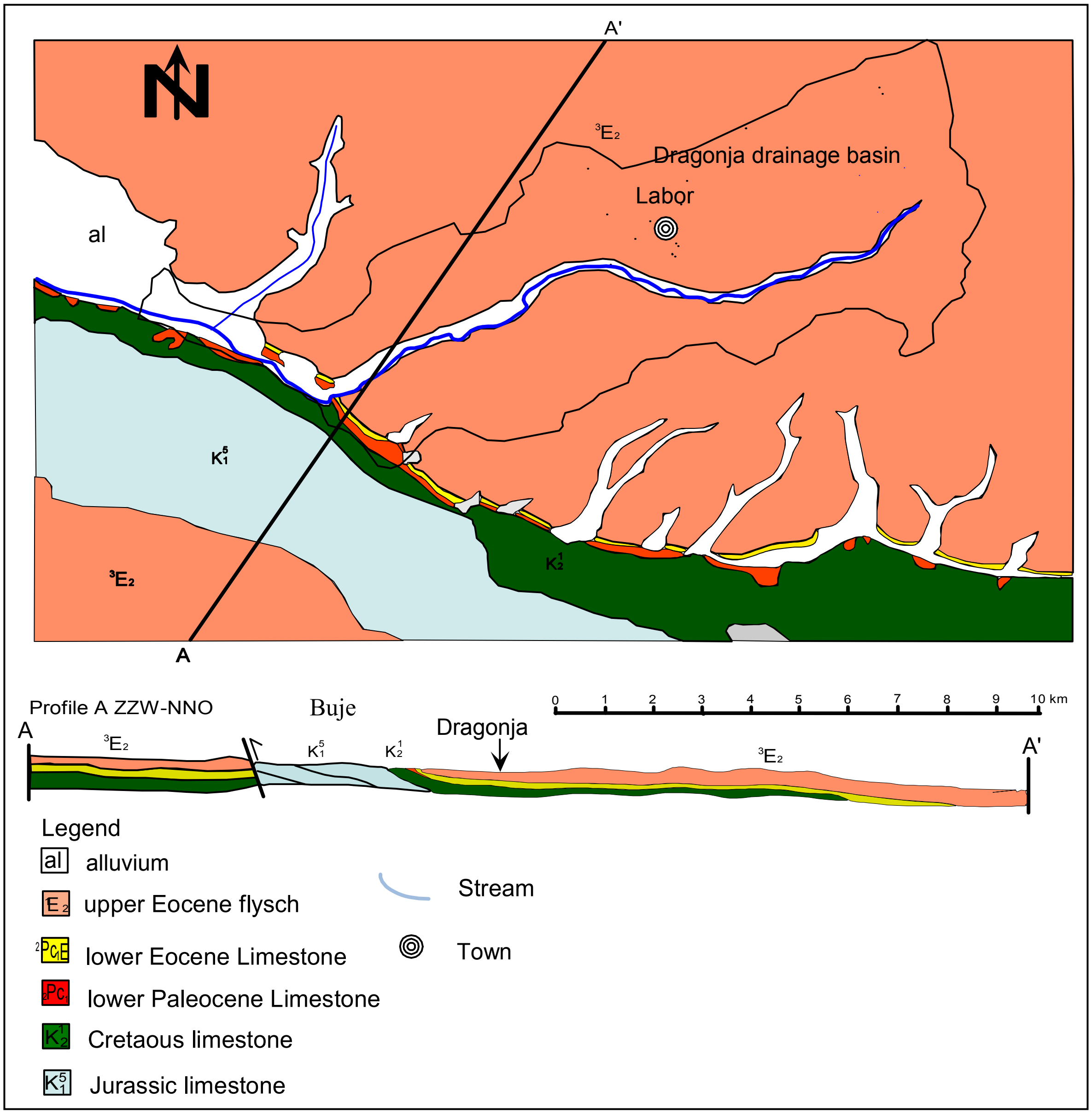


Figure 2.3 Geological Map and cross section of the Dragonja drainage basin (Based on Osnovna geologska karta 1:100,000; Trst L 33-88 Karta in Tolmac, Ljubljana. (1973); after Hobbij and Minneboo, 2001.

2.2.2 Neotectonics

The tectonic structure of the region was formed after the Eocene, as the Eocene Flysch deposits are part of the tectonic structure. During the Oligocene and Miocene the Dinarides were formed. During this period also the faulting at Buje (Fig. 2.3) took place (Matičec, 1994). After this period a relatively quiet tectonic period began. This is substantiated by the absence of large earthquakes in the vicinity of the Dragonja valley (Anderson and Jackson, 1987) and indicates that none of the fluvial morphological changes described further on in the present study should be the result of neotectonics.

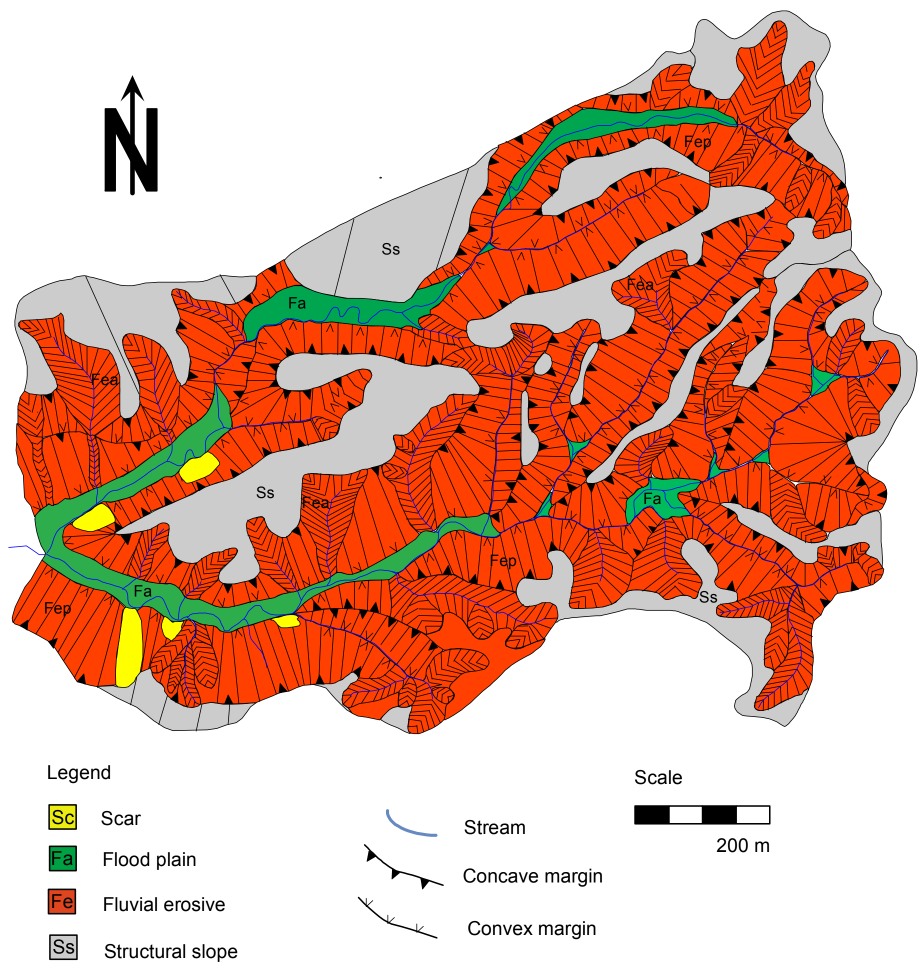


Figure 2.4 Geomorphologic map of the upper Dragonja and Rokava sub-catchments, based on figure 2.3 (geological map) and Drzavna topografska karta (1995) 1:25,000.

2.2.3 Hydrogeology

In general the flysch strata are impermeable and do not allow much groundwater flow. The alluvial aquifer occurs on top of flysch strata that cover the majority of the catchment. Therefore groundwater flow is virtually limited to the alluvial aquifer. However the flysch strata do contain some calcareous breccias, which are said to be susceptible to karstic phenomena and possibly provide a medium for rapid groundwater flow. On at least one location (near the confluence of the Rokava and Dragonja Rivers) a spring with an estimated discharge of 20 l s^{-1} is found, which is considerable, especially during the dry summer months. The limestone in the Croatic part of the catchment has karstic features and is therefore highly permeable. In this part of the catchment many karstic springs discharge to the Dragonja River. Moreover, the lower part of the river flows in a fault valley. No research has been conducted on possible leakage from the alluvial aquifer to the underlying faulted area (see also section 3.4 on catchment water budgets).

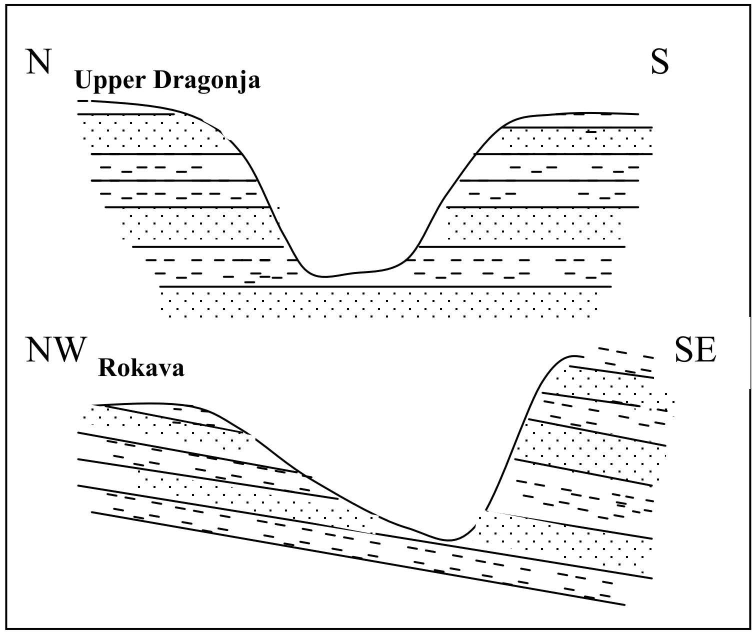


Figure 2.5: Geomorphological differences between the Rokava and Upper-Dragonja sub-catchments as a result of differences in the dip of the underlying flysch bedrock.

2.3 Geomorphology

From an analysis of the Digital Elevation Model (DEM) and the geological map a geomorphological map was constructed (Fig. 2.4., Minneboo and Hobbij, 2001). Generally, the overall geomorphology reflects the underlying geology. Most of the catchment is dissected by the Rokava and Dragonja Rivers. As a result of differences in geology the cross sectional profile of the Upper-Dragonja sub-catchment has a funnel-like shape, where the Rokava sub-catchment has a more elongated shape. The stream pattern in the Dragonja is dentritic, where the Rokava pattern is trellis-like (Fig. 2.1). The limestone in the Croatic part of the catchment has karstic features causing a very different geomorphology. The sub-horizontal to gently south-dipping flysch with its resistant sandstone layers leads to steep slopes. In the Upper-Dragonja sub-catchment, the north- and south-facing slopes have similar steepness. In contrast, the Rokava valley is wider and the north-facing slopes are much steeper than the south-facing slopes. These differences are related to the geological structure, as the south-facing slopes in the Rokava sub-catchment are partly structural (Fig. 2.5).

Figure 2.6: Large bed rock cliff in the Upper Dragonja sub-catchment (Fig. 2.9, site 8, KK). This cliff is actively undercut by the river.

The floodplain is up to 100 m wide in the upper parts to 400 m in the downstream part of the catchment. The adjacent fluvial erosive slopes are up to 200 m high with an average slope of 17º. At some

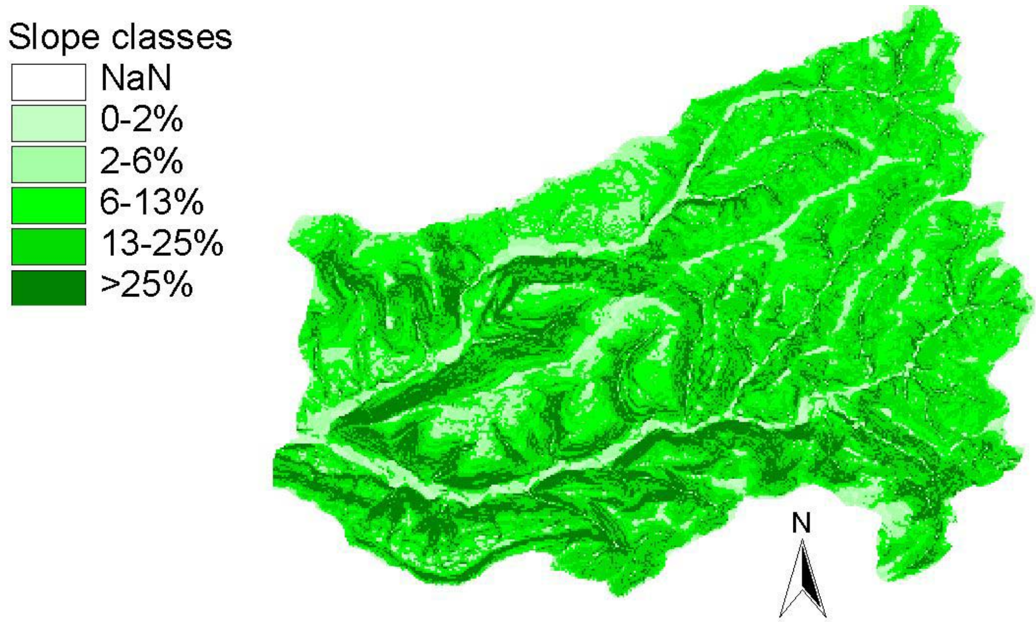


Figure 2.7: Slopes of the Upper Dragonja and Rokava sub-catchment as derived from the DEM. Distinguished slope classes were: 0-2%, 2-6%, 6-13%, 13-25% and >25%.

locations, where the river is actively undercutting the side slopes, large erosion scars are found. The resulting bedrock cliffs can be up to 50 m high and nearly vertical (Fig. 2.6).

The steepness of the catchment is illustrated in Figure 2.7. This slope map was derived from the digital elevation model (DEM), which was digitised from the 1:5000 topographical map (Drzavna topagrafska karta, 1995) using geographical information systems (Arc-GIS, Arc-View and Cartalinx). Slope classes 0-2% and 2-6% are found mostly on floodplains and plateaux ridges, where they coincide with the structural slopes (cf. Fig. 2.4). Slope class 6-13%, which is the most common, is predominantly present on the valley slopes. These slopes are most commonly associated with fluvial erosion. Slope class 13-25% represents the steeper slopes where fluvial erosion occurs, but also slope processes such as rock falls and slumping are important. Slope class > 25% is only locally found at large steep bed rock cliffs where the predominant erosion process is rock fall as a result of fluvial undercutting (cf. Fig. 2.6).

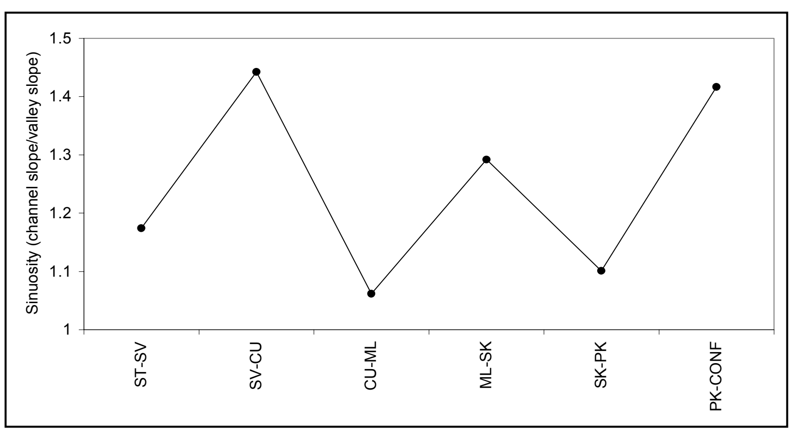


Figure 2.8: Sinuosity of the channel of the Dragonja River calculated from the channel slope divided by the valley gradient. The location of the reaches (x-axis) are given in Fig. 2.9.

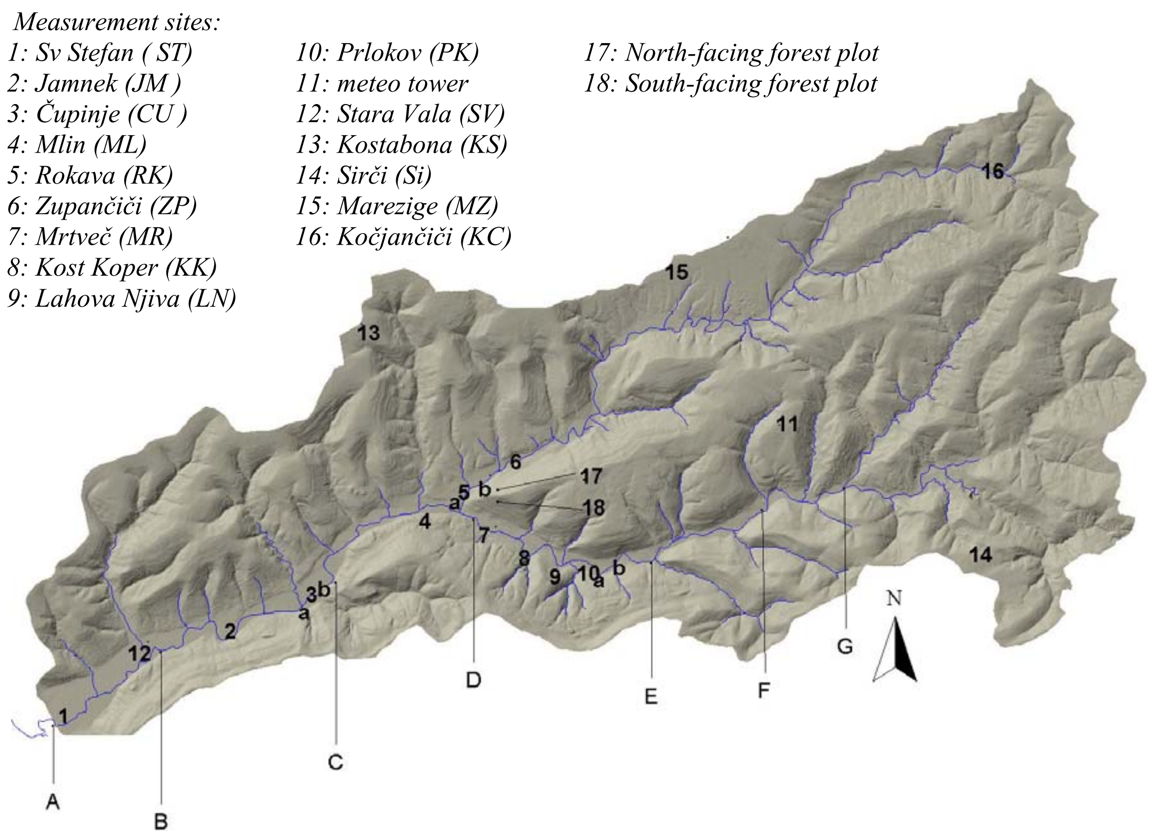


Figure 2.9: Digital Elevation Model of the Dragonja catchment. The thin lines indicate the river course. Letters indicate river reaches with low or high sinuosity: reaches A-B, C-D and E-F: low sinuosity; reaches B-C, D-E and F-G: high sinuosity. Selected sites for stone tracing measurements: 1, 2, 3b, 6,10b. Erosion pin measurements in sedimentary banks: sites 1, 4, 6 and 7). Bedrock bank monitoring with erosion/deposition pins, 3-D photogrammetry (only 5b and 8) and normal photographs: sites 2, 3a, 5b, 8, 9 and 10a. Discharge measurements and suspended sediment sampling: site 1, 5a and 7. Precipitation monitoring: sites 5a, 7 and 11 to 16. At the meteo tower incoming solar radiation, humidity, precipitation wind speed and direction and temperature were recorded. At the forest plots (sites 17 and 18) throughfall, stemflow, interception, soil moisture and incoming radiation was measured.

The length of the riverbed divided by the valley length, results in the sinuosity of the river. Generally the sinuosity of the Dragonja is low and varies between 1.1 and 1.45 (see Figs. 2.8 and 2.9). Sinuosity may be influenced by several parameters: the gradient of the valley, sediment size and the total sediment load of the river (Schumm, 1969). In the Dragonja both gradient and the average sediment size decrease gradually downstream. Therefore these two parameters are probably not the cause of the variable sinuosity (Fig. 2.8). Possibly the observed pattern in sinuosity is linked to the sediment load. The amount of sediment in the river changes along the rivers course, as a result of tributaries delivering sediment to the main river. Perhaps the river stops meandering as a result of large amounts of sediment dumped into the river by tributaries. However this hypothesis remains to be tested.

Generally the Dragonja River has a pool-riffle morphology over most of its course. In the lower reaches the pools and riffles have developed both in sedimentary material. In the middle reaches bedrock underlies the riverbed in the pools. In the upper parts of the river a step-pool regime (Whittaker and Jaeggi, 1982) is found. Some steep tributaries have a straight river plan form. The sandstone beds within the flysch are more resistant to erosion than the silt- and claystones in between. As a result large structural 'terraces' interrupt the hill slopes at some places. These sandstone layers form steps or even waterfalls in the river channel. Also the pool-riffle spacing is related to the occurrence of these sandstone banks as discussed further in Chapter 6.

2.4 Land cover changes

Over the period 1945 to 2002 a general trend of reforestation has taken place in the area. In an effort to reconstruct the reforestation sequence aerial photographs taken in 1954, 1975, 1985 and 1994 were digitised and analysed whereas a field survey was carried out in 2002. Seven land cover types were distinguished: (1) fields, (2) pastures, (3) abandoned field (< 5years), (4) young forest (>5 years), (5) mature forest (>30 years), (6) erosional cliffs and (7) riverbed. A summary description of the respective land cover types is given below:

(1) Fields: vineyards and agriculture, the erodibility of this category varies as a result of diverse ploughing regimes and different ways of farming. Some fields are small and used for hobby farming; others are large vineyards or crops fields (e.g. pumpkins) that are maintained with heavy machinery (Fig. 2.10A). The absence of field borders on the large vineyards, enhance the erodibility on these locations.
(2) Pastures: grasslands were formally grazed by goats, but nowadays only used for haying. This land use type is also diverse in terms of its erodibility as many farmers plough their pastures in spring, thereby creating a situation similar to that in agricultural fields.
(3) Abandoned fields: fields and pastures that were abandoned less than 5 years ago. Species such as Juniper (*Juniper communis*) and blueberry (*Vaccinium carymbosum*) appear in between the grasses (Fig. 2.10B).
(4) Young forest: fields and pastures which were abandoned more than 5 years ago, but not long enough for the development of a dense forest. The vegetation consists of a lot of undergrowth and schrubs in between the trees. The trees generally belong to the *Carpinetum orientalis croaticum* (Oriental hornbeam) (Fig. 2.10C).
(5) (Semi)mature forest: approximately 30 years of vegetation development results in a semi-mature forest. In this region a distinct difference in vegetation species exists between north- and south-facing slopes. On north-facing slopes a mature forest stand largely consists of (Oriental) hornbeam (*Carpinum betulus and Carpinus orientalis),* oak (Quercus cercus) and ash (*Fraxinus ornus*). The average tree height is 12.3 m. On the south-facing slopes (Fig. 2.10D) on the other hand a oak (*Quercus pubescens)* and ash (*Fraxinus ornus*) association dominates (van der Tol, in prep.) The average tree height for the south-facing slopes was estimated at approximately 8 m. In many places the remnants of terraced field can be found. The stone walls are generally in ruins (cf. Fig. 2.10C).
(6) Erosional cliffs: Large bedrock banks along the river and other severely eroding areas in small tributary valleys (see example in Fig. 2.6).
(7) Riverbed: the current riverbed and the former, now largely overgrown riverbed.

Figure 2.10: Examples of land cover types in the Dragonja catchment. A: Small-scale agriculture: vegetable fields and vineyards. B: Abandoned field on a plateau, in the background a mature forest on the adjacent slope. C: Young forest on a steep hill slope with abandoned terraces. D: South-facing slope with mature forest.

The land use analysis shows a dramatic drop in the area covered by pastures and agricultural fields from 1954 to 2002 of more than 70% to 16% (Fig. 2.11) and a concurrent increase in area under forest. Most of the reforestation occurred spontaneously after abandonment of fields. However, in the 1960s and 1970s some severely eroding spots were reforested with pines (Globevnik et al., 1998). When looking at the areas under forest with time, the largest change in forest area took place before 1985. After 1985, land use became relatively stable (Fig. 2.11).

The differences in land use change for the various slope classes distinguished in Figure 2.7, and differences between the Rokava and Upper-Dragonja sub-catchments are studied with GIS-analysis. The results showed (see pie diagrams in Fig. 2.12) that gentle slopes (up to 13%) are better represented in the Rokava sub-catchment and therefore more area is available for (mechanized) agriculture.
Furthermore, for slope class 0-2% a wider and more easily accessible floodplain facilitates a higher percentage of agriculture in the Rokava sub-catchment compared to the Upper-Dragonja sub-catchment. Also in slope classes 2-6% and 6-13%, higher

percentages of the land are still in agricultural use in the Rokava than in the Upper-Dragonja sub-catchment as a result of a more favourable position to the nearest coastal city of Koper. The other slope classes do not show much difference in land use. This resulted in a distinct difference in reforestation sequence between the Rokava and Upper-Dragonja sub-catchments. Overall, 56% (only mature forest) or 73% (young and mature forest) of the Upper Dragonja area was under forest in the year 2002 vs. only 39% (only mature forest)/61% (mature and young forest) in the Rokava sub-catchment.

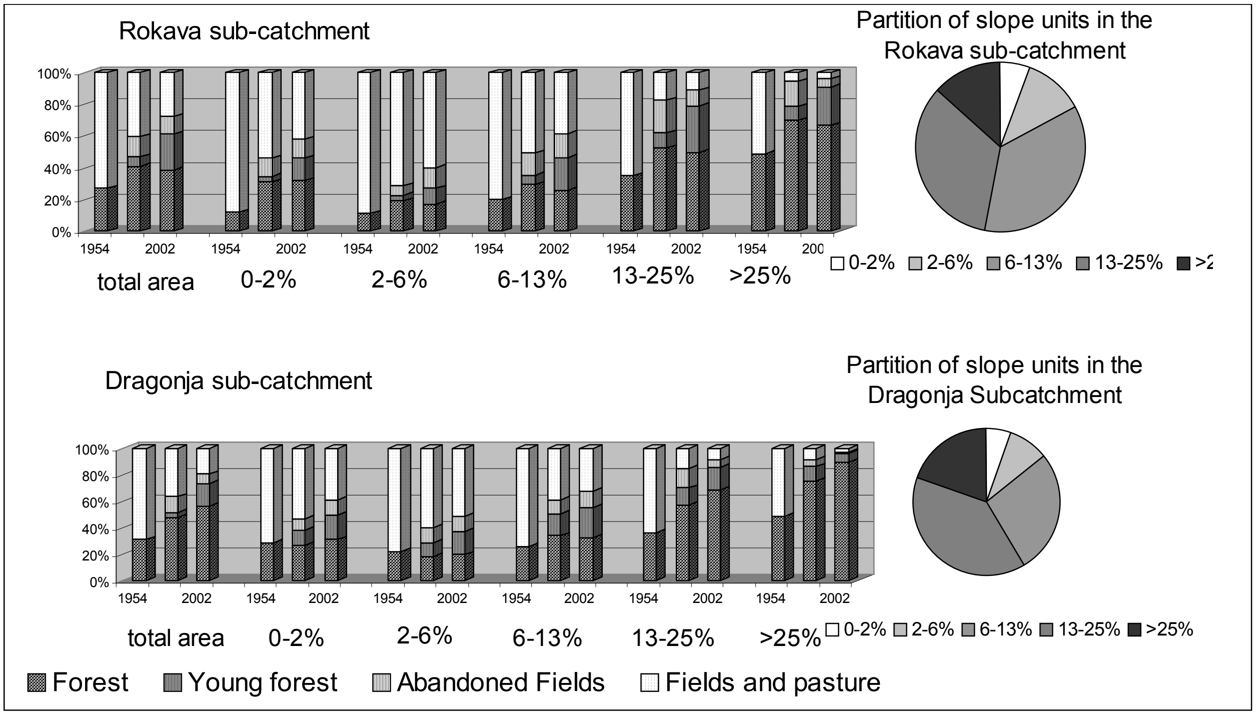


Figure 2.12: Land use change in the Rokava and Upper-Dragonja sub-catchments in 1954, 1975 and 2002 for different slope classes (0-2%, 2-6%, 6-13%, 13-25% and >25%) and the whole catchment. Pie diagrams indicate the partition of the slope units in both sub-catchments. Land use was derived from aerial photographs and field survey, slope classes were derived from a Digital Elevation Model (DEM).

2.5 SOILS

2.5.1 Soil types

As a result of the underlying flysch and the Mediterranean climate, all soils are highly calcareous and consist mostly of carbonate rendzinas (FAO, 1990)/ rendolls (USDA, 1998). At locations where sandstone layers are close to the surface eutric brown soils have formed in the calcareous parent material. In the valleys fluvisols (FAO, 1990) / ustifluvents (USDA, 1998) have developed (Zupancic and Pric, 1999). In the lowest parts of the catchment waterlogged soils are prevailing. At the southern border of the catchment a rendzina on Tertiary limestone is present (Fig 2.13).

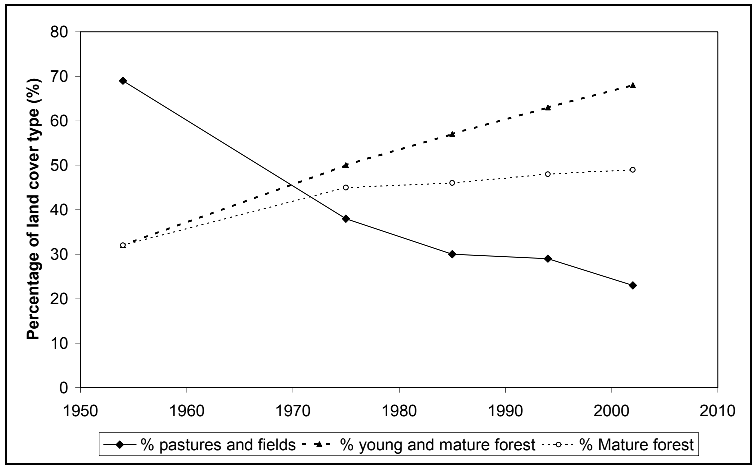


Figure 2.11: Decreasing area of pastures and fields and increasing area under mature forest in the Upper-Dragonja and Rokava sub-catchments over the period 1954-2002 as derived from aerial photograph interpretation and a field survey.

Thickness of the soils varies from more than 1 metre on most of the plateaux to some decimetres or even totally absent on some of the slopes. This is the result of erosion associated with the former land use and natural mass wasting processes. In the valleys the soils are not well developed as a result of high sedimentation rates and ploughing.
During the present study more than 130 soil samples taken throughout the catchment were analysed for texture, $CaCO_3$ content, organic matter content and saturated conductivity. The locations of the sample sites (Fig. 2.14) were selected on the basis of landscape setting (plateau, slope or valley floor) and land use type (fields, pasture, abandoned field, young forest, mature forest and trails). The results of these analyses are summarised below.

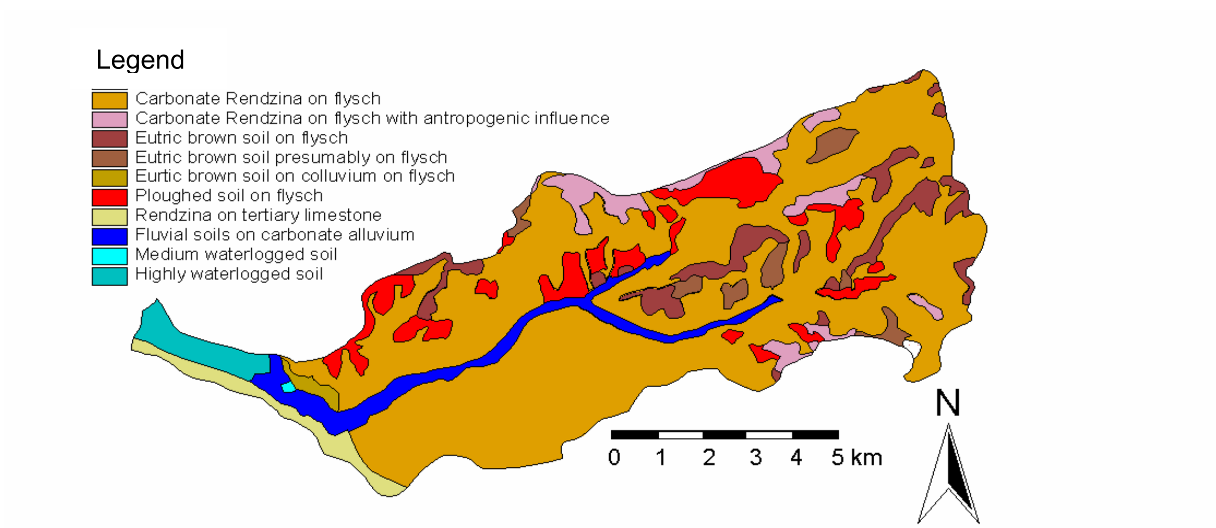


Figure 2.13: Soil map of the Dragonja catchment (Geološki zavod Slovenije, 2003).

2.5.2 Soil texture

Textural analysis was done with a Laser Particle Sizer (A22, Fritsch). The samples were prepared according to the method presented by Konert and Vandenberghe (1997). The customary chloric acid (HCl) was not added to the sample, since that would have dissolved parts of the sediment itself. The texture of most samples was clay to clay loams, although the scatter was considerable (Fig. 2.15). No distinct difference in texture could be distinguished between hillslopes and plateaus. The samples taken from the valley floor were somewhat coarser (Fig. 2.15) (Chapter 3 will give more information on this subject).

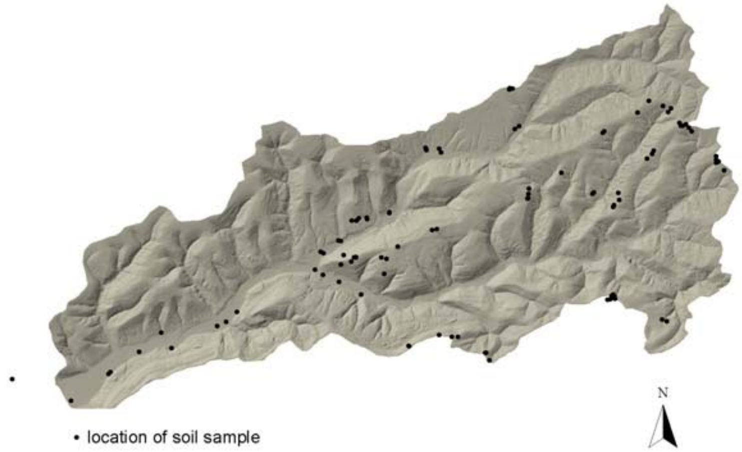


Figure 2.14: Locations of soil sample sites in the Dragonja catchment

2.5.3 Saturated conductivity

The saturated vertical conductivity (K_{sat}) was measured both in the field (double ring-infiltrometer) and in the laboratory. The laboratory measurements were carried out on fixed volume samples with both constant and falling head methods (ANSI/ASTM, 1974).
No significant differences were found between the overall K_{sat} values associated with the contrasting land use types or landscape setting due to the considerable scatter in the data (Fig. 2.16). However the variation in conductivity within some landscape-land use units (e.g. pastures or fields on slopes) was relatively small. Nonetheless some variance in the data may be linked to differences in landscape or land use. K_{sat} values associated with fields in valley or plateau positions were much higher than for fields on slopes, presumably reflecting a contrast in ploughing intensity. Conductivity of pasture soils in valleys and on slopes were very low but high on plateaux sites. Again, this is thought to be the result of the partial ploughing practised on the plateaux. Only trails exhibited even lower K_{sat} values, a phenomenon that is well-known from literature (Reid and Dunne, 1984; Scott et al., 2005; Rijsdijk et al., 2005). On the slopes and plateaux conductivity values increased with vegetation age (though much less so on the plateaux) but no such trend was apparent for the valley locations (Fig. 2.16) During the revegetation sequence the abandoned fields have the lowest average conductivity. At the locations where ploughing was stopped (i.e. on abandoned fields) the bulk density increased and infiltration rates dropped. When trees start to grow the number of macro-pores increases again and the saturated conductivity increases also.

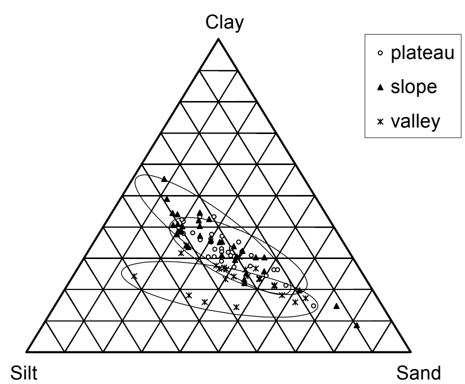


Figure 2.15: Texture of soil samples taken on hill slopes, plateau and valley locations on various land cover types.

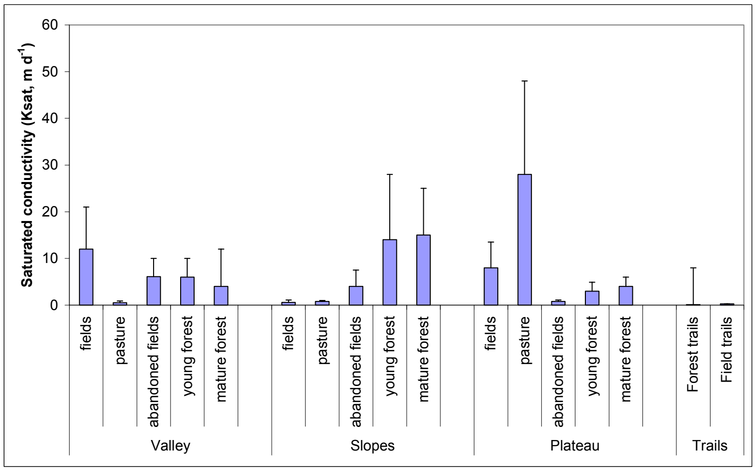


Figure 2.16: Average saturated conductivity (m d^{-1}) for soil samples taken at locations representing different terrain or and land-use combinations. Bars indicate conductivity for samples taken at 0-5 cm and 5-10 cm of depth. Lines indicate standard deviations within the data set.

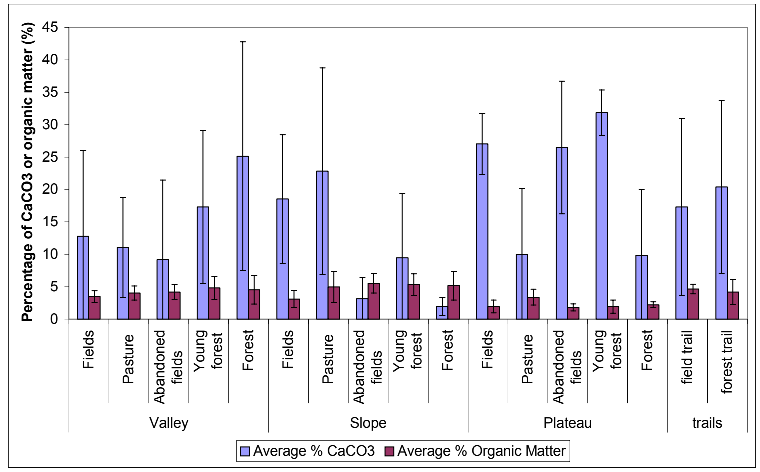


Figure 2.17: Average $CaCO_3$ content and organic matter content in soil samples taken on locations representing different terrain or land use combinations such as 'fields in a valley' or 'abandoned fields on a slope'. Lines indicate standard deviations within the data set.

2.5.4 $CaCO_3$ and organic matter content

The $CaCO_3$ content and organic matter content was measured on the same samples (Fig. 2.17) as those which were used for the saturated conductivity measurements. The $CaCO_3$ content was analysed by dissolving the $CaCO_3$ with an excess of HCl (25 % solution) and measuring the CO_2 gas that forms during the reaction (Scheibler method). The organic matter content was analysed by loss on ignition at 500ºC. The results of these analyses (Fig. 2. 17) show large variations. The $CaCO_3$ content cannot be linked to the different land uses or the landscape setting from where the samples were taken. The organic matter content of fields is somewhat lower than on the other sites. This can be explained by the removal of organic matter from the land by agricultural activities.

2.6 CLIMATE

2.6.1 Introduction

The climate of Slovene Istria can be classified as sub-Mediterranean (Köppen-type C_f), with interacting Mediterranean and continental influences. This means a great variability of weather patterns, even in summer. The climate has been registered for a long period. For nearby Trieste a database of precipitation from 1841 onwards is available (Brunetti, 2000). In the vicinity of the Dragonja catchment data from two precipitation stations are available: for Kubed (from 1925 till 1990 and from 2001 onwards) in the hinterland, and for Portorož -Beli (from 1974-1991) at the coast (Fig. 2.18 and 2.19). Temperature was also measured at the latter site. Wind speed and sun hours were also measured at Portorož from 1961 till 1995.

2.6.2 Precipitation

Characteristic of a C_f-type climate is the relatively frequent rainfall during the summer months. The precipitation is relatively equally distributed throughout the year, with somewhat more precipitation in autumn (Fig. 2.19). The annual precipitation in Slovene Istria varies from 700 mm to 1400 mm and increases with distance from the coast (Fig 2.18).

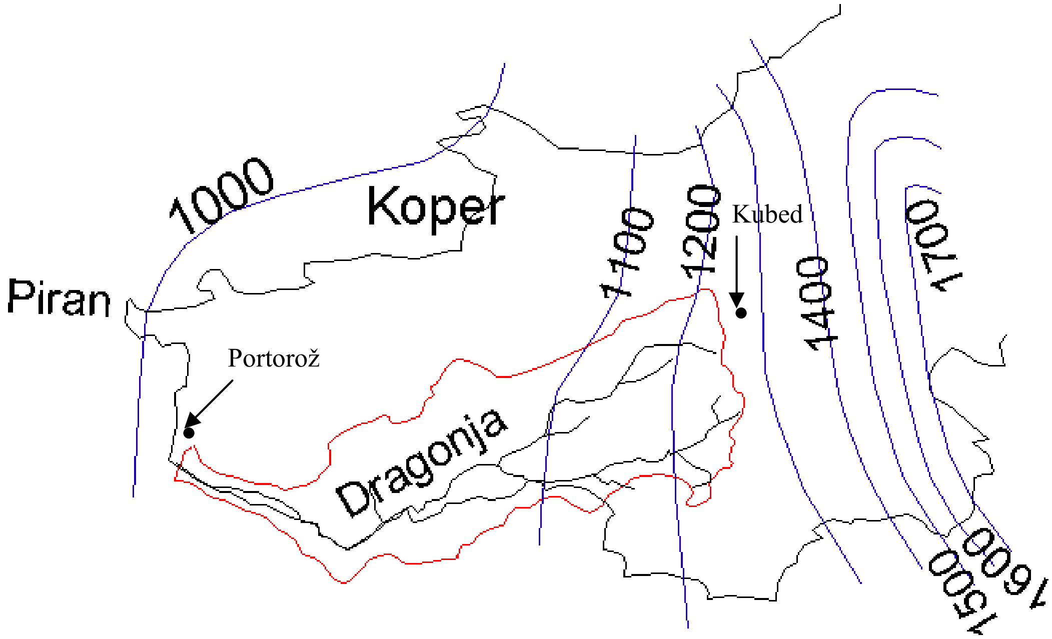


Figure 2.18: Distribution of yearly precipitation from 1958-1987 (after Ogrin, 1995).

Figure 2.18 shows increase in annual precipitation from Portorož -Beli (1047 ± 165 mm) in the western, coastal zone of Istria to 1447 ± 245 mm for Kubed just outside the catchment on the eastern side (all calculated over the period 1961-1990). For both stations precipitation is relatively equally distributed throughout the year and no obvious dry period (Fig. 2.19). The highest amounts of precipitation occur in autumn. A secondary peak occurs in summer (in June for both stations). The highest mean monthly precipitation totals (1961-1990) for Portorož and Kubed were registered in September 1965, respectively 330 mm and 362 mm.
In the city of Trieste, located approximately 40 km north of the mouth of the Dragonja River, daily precipitation has been recorded since 1841 (Brunetti, 2000). The average annual precipitation over the period 1841-2003 is 1042 mm ± 206 mm (Fig. 2.20 left).

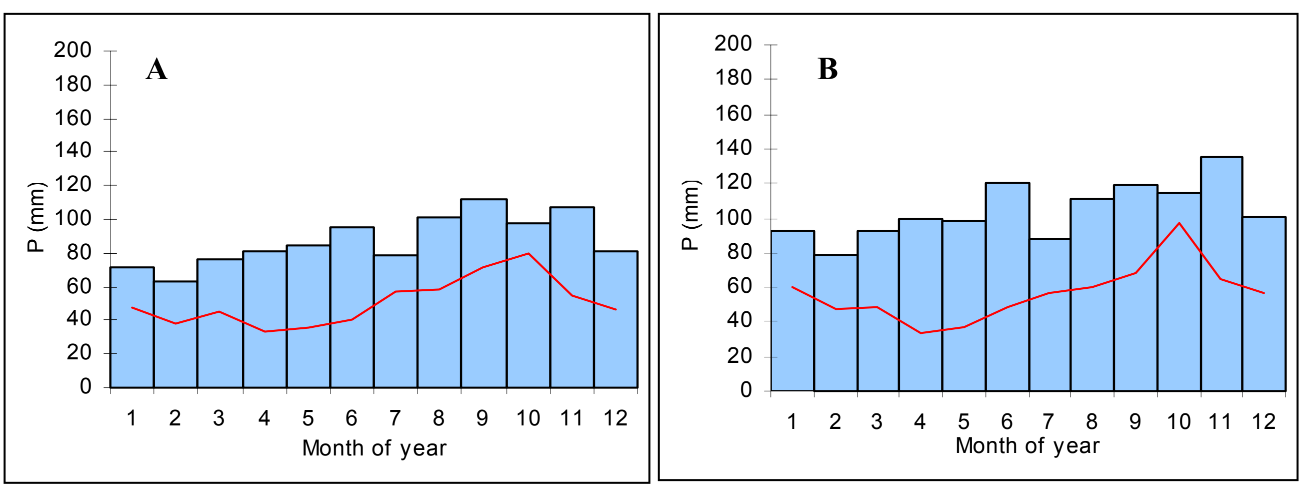


Figure 2.19: Annual distribution of precipitation at Portorož (A) and Kubed (B) averaged over the period 1961-1990; line indicates standard deviation (see Fig. 2.18 for locations; after Ogrin, 1995).

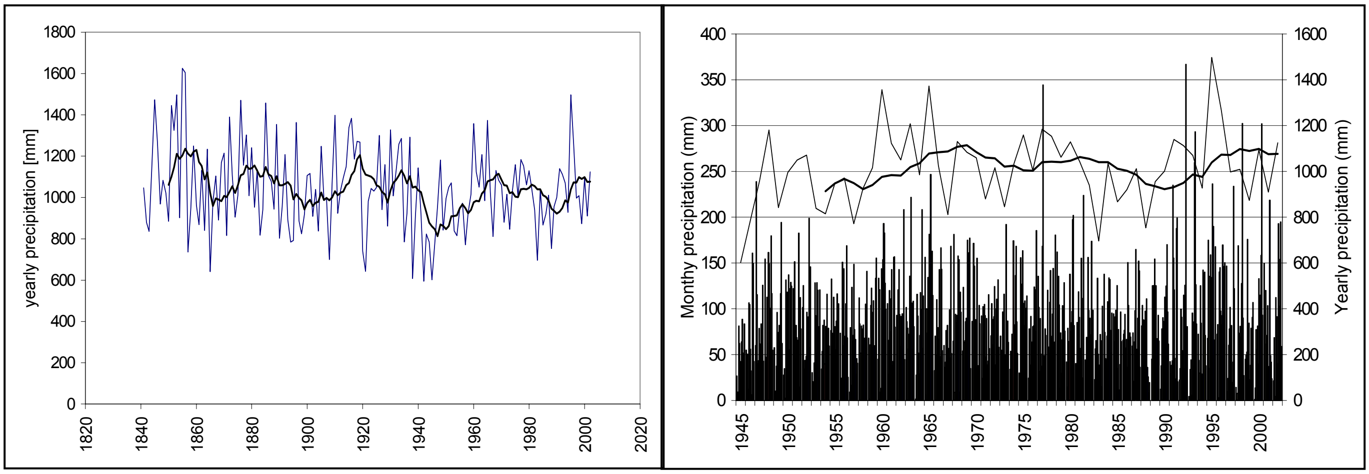


Figure 2.20: Left: Annual precipitation in Trieste, Italy from 1841 until 2003, with 10-year moving average (solid line). Right: Bars giving the monthly precipitation in Trieste, Italy over the period 1945-2003. Line graphs give the annual precipitation and the 10-year moving average (solid line).

Maximum and minimum recorded annual precipitations in Trieste were 1625 mm (in 1855) and 595 mm (in 1942). Rainfall during the 1940s was particularly low, but recovered from the 1960s onwards (Fig. 2.20).
But when looking at the monthly precipitation data measured at Trieste (Fig. 2.21), less heavy rainfall (> 200 mm month^{-1}) occurred in the period during which most of the reforestation in the Dragonja area took place (1945-1985). It is unknown which implications this finding has had on the morphological evolution of the river channel which is discussed in Chapter 6.

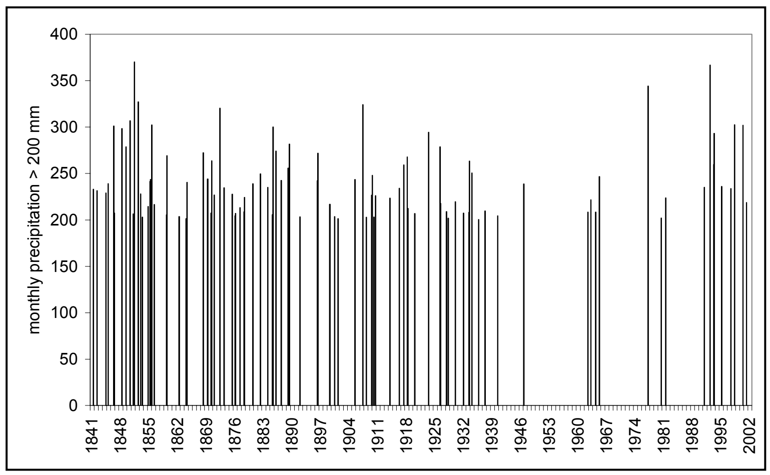


Fig. 2.21: Monthly precipitation in Trieste exceeding 200 mm over the period 1841-2002 (after Bruneti, 2003).

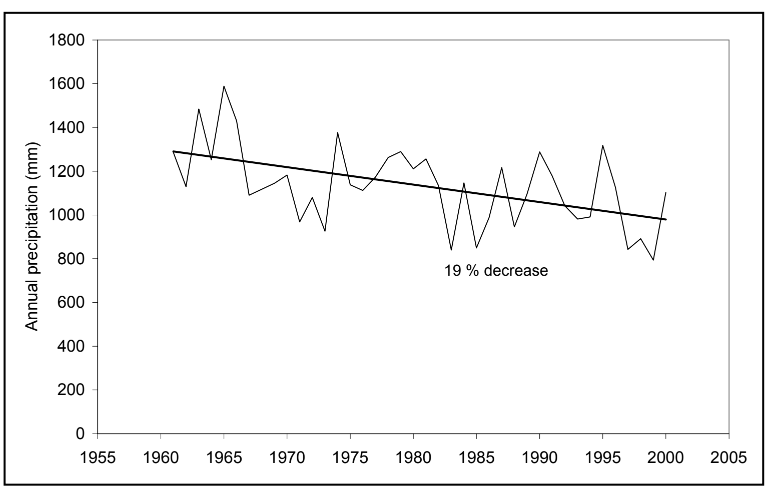


Figure 2.22: Annual precipitation from 1960 to 2000 measured at the Dragonja outlet (Portoroz-Beli station). Over measured period a decrease of 19 % was recorded.

Even though the precipitation in Trieste does not show a decrease in annual precipitation over the period 1961-2003, the precipitation at Portorož shows a drop in annual precipitation of 19% over the period 1961 and 2002, from an average of 1275 mm y^{-1} over the period 1961-1970 to 1025 mm y^{-1} over the period

1991-2000 (Fig.2.22). The implications of this finding for the area's hydrological functioning are discussed in Chapter 3.

2.6.3 Temperature

The average annual temperature at the coast (Portorož) is 13.5 ± 0.4 °C and 11.5 ± 0.3 °C at the eastern upper end of the catchment (Kubed) measured over the period 1961-1990. The extreme daily average temperatures vary from -10°C to 35°C (HMZ, 2003; Ogrin, 1995). Maximum mean monthly temperatures occur for both stations in July, ranging from 22.6 ± 1.1 °C for Portorož to 20.7 ± 1.1 °C for Kubed. The lowest mean monthly temperatures occur in January, 4.9 ± 1.7 °C and 2.9 ± 1.7 °C for Portorož and Kubed, respectively (Fig. 2.23). The lower average temperature at Kubed is due to the higher altitude of this station. The climate at Portorož is more maritime than the climate at Kubed where the extremes lie further apart.

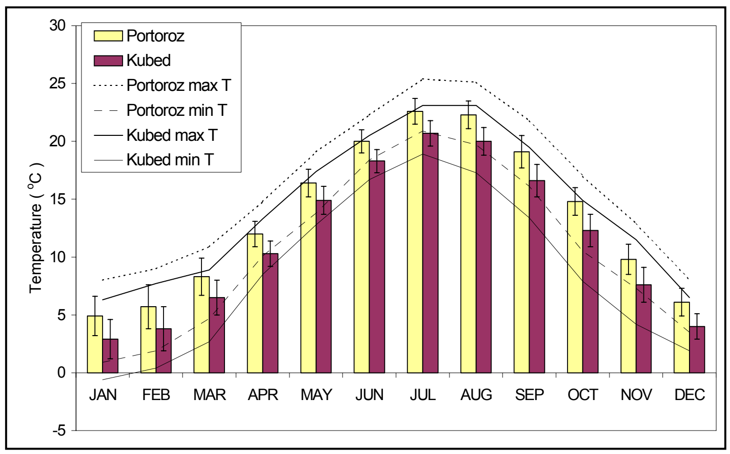


Figure 2.23: Average monthly temperature with standard deviation, maximum and minimum monthly temperature in Portorož and Kubed over the period 1961-1990.

2.6.4 Wind

At Portorož the dominant wind direction is Northeast, with an annual frequency of 36 % over the period 1976-1990 (Fig. 2.24). The wind from the northeast, locally called the Bora is most dominant during the winter period when it may be very strong and brings cold and dry weather conditions. The second dominant wind direction is from the South-East, which is most common during autumn and spring. Locally this type of wind is called the Jugo, and it usually brings relatively warm and wet weather. Wind speed was measured on a meteo-tower established during the present study in the centre of the Dragonja catchment near Boršt (see Fig. 2.9 for location) from 2002 to 2004. The highest wind speeds were recorded in winter; especially December and

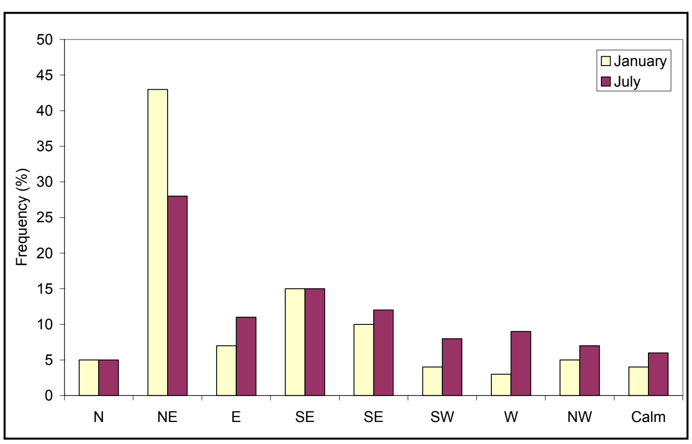


Figure 2.24: Frequency of wind directions in winter (January) and summer (July) conditions measured at Boršt.

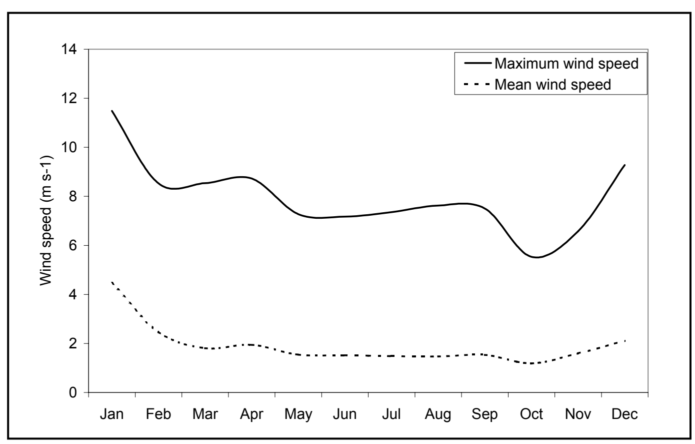


Figure 2.25: Annual variation in maximum and mean wind speeds measured in the period 2002-2004 at Boršt.

January have high average and maximum wind speeds. Mean wind speeds do not vary much during the remaining part of the year. However maximum wind speeds show a distinct low in October (Fig. 2.25).

2.6.5 Radiation

The incoming short radiation, 350-1100 nm, and net radiation were measured at the Boršt meteorological station between October 2000 and September 2004. On average the incoming radiation was 412 Wm^{-2} with an annual amplitude of 300 Wm^{-2}. The net radiation had an average intensity of 220 Wm^{-2} and an amplitude of 205 Wm^{-2}. The distribution over a year shows the maximum radiation in June and July. Minimum radiation was measured in December and January (Fig. 2.26). The anomalies in the expected sinus form of the graph are probably caused by an exceptionally cloudy April 2004 (C. van der Tol, personal communication).

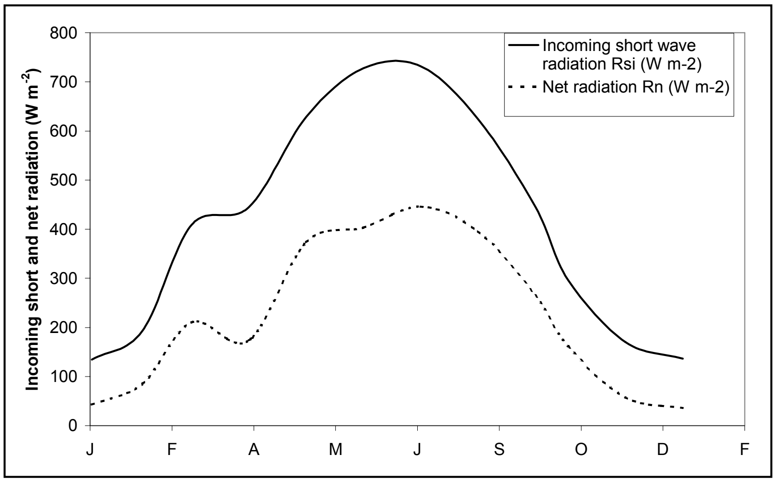


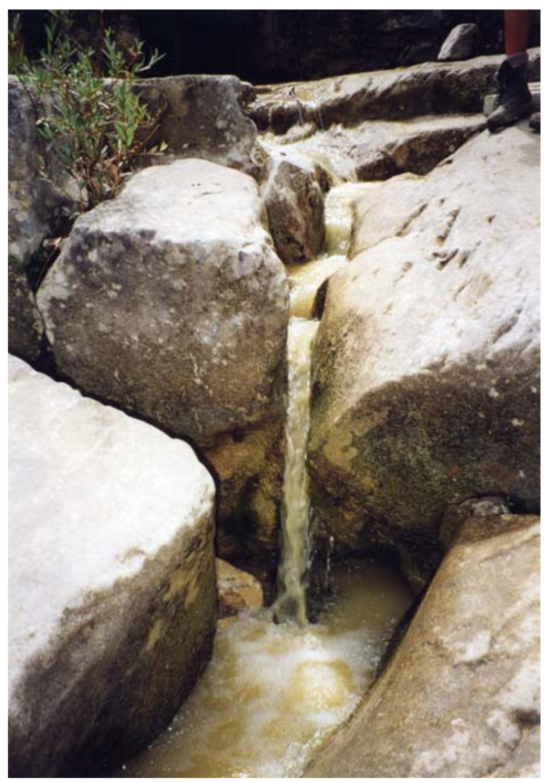
Figure 2.26: Annual variations in incoming short wave radiation on the north and south plot measured over the period 2002/2004 at Boršt (Fig. 2.9).

2.6.6 Potential evapotranspiration

The quotient ET/E_0 (evapotranspiration divided by the potential evaporation) indicates if a catchment potentially looses part of its water to the underground. In a normal water balance this quotient should always be below 1. If this quotient is above 1, this is a clear indication for strong leakage in the underground.

In the Dragonja the E_0 calculated according to the directions of Penman is 1054 mm y^{-1} over the period October 2000 to September 2004 (Penman, 1948) The evapotranspiration (ET) was calculated from the simple water balance calculation ET= P-Q from the long-term measurements period 1960-2002. The average ET over this period was 630 mm y^{-1}. Hence, the ET/E_0 calculates to 0.60, which does not indicates that the catchment looses a major part of its water in the underground. However, this does indicate that the catchment suffers from drought stress during the summer months. In Chapter 3 a more detailed description of the water balance of the catchment is given.

Chapter 3: Hydrology



CHAPTER 3: HYDROLOGY

3.1 INTRODUCTION

In this chapter the hydrology of the Dragonja catchment, notably its water budget and response to precipitation, and changes therein due to the progressive reforestation, is described and analysed as a preliminary to the subsequent chapters on geomorphological processes and the sediment budget. An analysis of the long-term precipitation and stream flow data (1960-2002) collected by the Slovene authorities is presented first. Next, the present-day situation is described using data collected over the period October 2000 to September 2004, when our field survey was conducted.

3.2 LONG-TERM TRENDS IN PRECIPITATION, DISCHARGE AND EVAPORATION (1960-2002)

The C_f-type climate indicates relative frequent rainfall during the summer months. The precipitation is relatively equally distributed throughout the year, with somewhat more precipitation in autumn. The annual precipitation in Slovene Istria, measured at Portorož and Kubed (see Fig. 2.9 for locations) varies from 700 mm to 1400 mm and increases with distance from the coast. The precipitation at Portorož shows a drop in annual precipitation of 19% over the period 1961 and 2002, from an average of 1275 mm y^{-1} over the period 1961-1970 to 1025 mm y^{-1} over the period 1991-2002 (see Fig. 2.22 and Fig. 3.1).

From an analysis of the discharge measured at the outlet of the Dragonja catchment, at Pod Kaštel, it is evident that the river's discharge has been reduced significantly since 1960 (Globevnik, 2001b), although the situation seems to have stabilised more or less from the mid-1980s onwards (HMZ, 2003; Fig. 3.1). During the period 1960 - 2002, peak, mean and minimum discharges all dropped to less than half their values of the time prior the reforestation. Especially the low discharges have changed dramatically: mean maximum flow, mean annual flow and mean minimum flow decreased by 53%, 79% and 85% respectively. However, reductions in average annual discharge after 1985 were marginal at 5% (Fig. 3.1). The average discharge at the outlet over the period 1960- 2002 was 1.59 m^3s^{-1} versus only 0.97 m^3s^{-1}over the period 1986-2002. The number of days without any flow ($Q<0.01$ m^3s^{-1}) increased from 7.5 days y^{-1} (period 1960-1970) to 32 days y^{-1} (period 1992-2002) throughout the reforestation period. Most high discharges were recorded in autumn, i.e. September and October. Occasionally a large flood occurs in the summer time.

The hydrological record at Pod Kaštel suggests 1-, 10- and 50-year recurrence interval floods to have a magnitude of 28, 65, and 105 m^3 s^{-1} respectively calculated over the period 1960-2002. However, when the return periods for the same magnitude floods are calculated over the periods 1960-1986 and 1986-2002 they increase from 0.6 to 1.9 years for the 28 m^3 s^{-1} flood and from 9.5 to 29 years for 65 m^3s^{-1}. For the period 1960 to 1986 a flood with a magnitude of 105 m^3 s^{-1} was estimated to occur every 38 years. For the period 1986-2002 it was not possible to make an estimation for a 105 m^3s^{-1} flood reoccurrence, as it was too far out of the range of the dataset.

Table 3.1: r^2 of relation between monthly discharge and precipitation over the period 1961-2002 and the percentage of discharged precipitation per month (monthly discharge divided by monthly precipitation).

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
r^2	0.64	0.26	0.60	0.41	0.44	0.20	0.35	0.28	0.24	0.46	0.62	0.44
%Precipitation discharged	87	75	74	72	49	33	17	12	18	33	49	64

There is a large variation during the year in the percentage of monthly precipitation that is transformed into discharge (Table 3.1). On average, high percentages of precipitation are discharged in winter and spring, but in summer almost no precipitation is discharged by the river, with the exception of occasional very large storms, which can cause destructive summer floods. These large seasonal differences in hydrological behaviour are due to differences in the functioning of the vegetation through the year, which affects soil water storage patterns.

Firstly, trees transpire only during their growing season (April-October). Secondly, trees intercept rain with their leaf area, especially during low intensity storms. Again, interception evaporation is much smaller during the leafless period than during the growing season. Thus, in winter, when the leaves are absent, transpiration is negligible and limited to a few evergreens. A third important factor is the catchment's wetness status. In summer the soil can be very dry after a long dry period; the soils then take up the precipitation like a sponge, leaving little or no water to be discharged as stormflow. However if several storms pass by over in a short period, the soil becomes progressively wetter and the same amount of precipitation can cause a very different response in terms of discharge (Mathys et al., 1996). Another, rather minor factor is the higher soil evaporation due to higher temperatures and solar radiation in late spring and summer, especially on irrigated valley bottom land.

Comparing annual precipitation and streamflow totals it is clear that the overall decrease in precipitation does not correspond with that in streamflow totals (Fig. 3.1). The

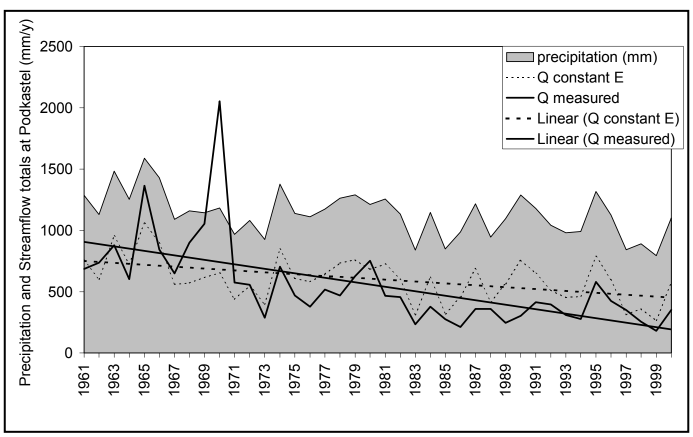


Figure 3.1: Annual precipitation (area graph), and measured discharge at the outlet of the Dragonja Catchment (measurement station Pod Kaštel, solid line graph), with linear trend line. Dotted lines represent the theoretical discharge for constant evaporation (based on the 1961 situation): with linear trend line.

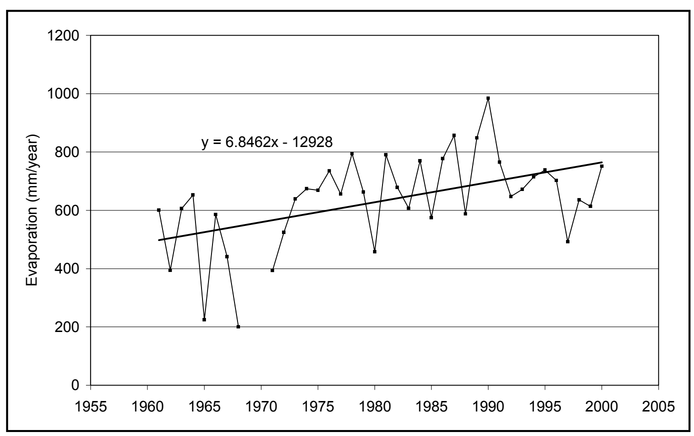


Figure 3.2: Annual evaporation (ET) calculated from the simple water balance ET = rainfall (P) minus discharge (Q). Based on data from Pod Kaštel (Q) and Portorož (P).

precipitation dropped about 19% over the period 1960-2002, where as the mean discharge decreased by 79%. The percentage of precipitation that is discharged by the river dropped even more than the annual precipitation: from 67% (1961-1969) to 34% (1991-2002). To further explore the reduction in discharge a simple catchment water balance was calculated for each year over the period 1960-2002. The catchment water balance in its simplest form is given by:

$ET = P - Q$

Where ET is the actual evapotranspiration, P the precipitation and Q is streamflow, all in mm y^{-1}.

The apparent evaporation (P – Q) in 1960 amounted to 390 mm. By 2000 the ET had increased to 750 mm (Fig. 3.2). Based on the precipitation and discharge measurements made in the more forested upper part of the catchment from October 2000 to September 2001 an even larger evaporation total was derived, in the order of 1000 mm y^{-1}.

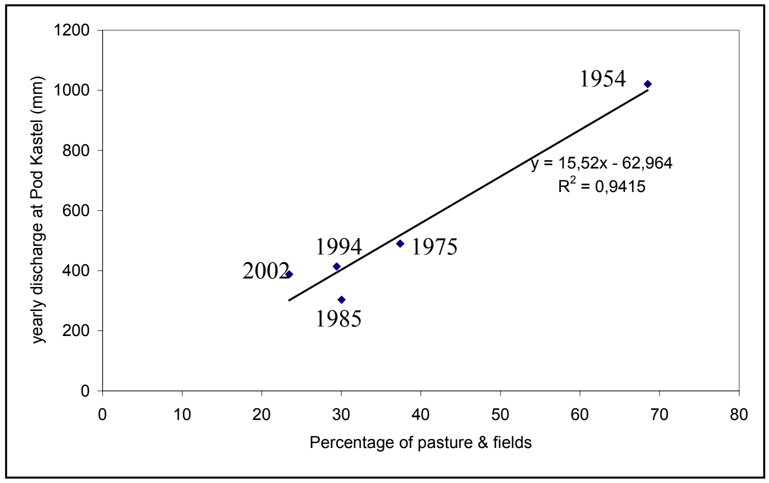


Figure 3.3: Relation between annual average discharge at the Pod Kaštel measurement station and the percentage of field and pastures in the upper part of the catchment in 1954, 1975, 1985, 1994 and 2002.

The diminished discharges of the Dragonja River must therefore be primarily the result of the increase in evapotranspiration due to the increased rainfall interception and transpiration of the reforested areas. Major reductions in annual streamflow following reforestation have also been reported for other areas with a Mediterranean (e.g. Spain, Gallart and Llorens, 2004; South Afrika; Scott and Lesch, 1997; Scott et al, 2005) or warm temperate climate (e.g. South Central USA, Trimble et al., 1987).

Further support for this interpretation comes from the observation that streamflow totals are positively related to the area under fields and pasture (i.e. inversely related to the area under forest; Fig. 2.3)

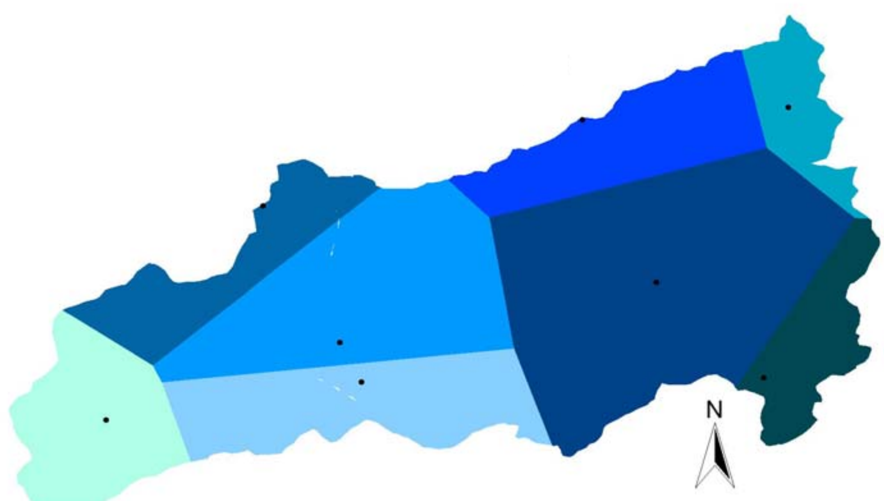


Figure 3.4: Thiessen polygon map of the precipitation measurement sites. Dots indicate tipping bucket rainfall recorders.

3.3 Hydrological behaviour of the Upper-Dragonja and Rokava sub-catchments

3.3.1 Methods

As a preliminary to the study of the sediment budget of the tributary catchments Upper-Dragonja and Rokava (cf. Fig. 2.1) and to put these short-term measurements in perspective, rainfall inputs and streamflow response of these headwater areas were monitored between October 2000 and October 2004. However, because of frequent equipment malfunctioning after the first year the following analysis had to be restricted to the period October 2000 to October 2001.

The precipitation was measured at 8 locations using tipping bucket rainfall recorders that were custom built by the Vrije Universiteit. The locations are indicated in Fig. 3.4, and correspond to sites 5a, 7, 11 to 16 in Fig. 2.9. Water levels in the Upper Dragonja and Rokava Rivers just above the confluence (sites RK and MR in Fig. 2.9) were measured every 10 minutes with a pressure transducer (Druck Ltd. PDCR-830 connected with a 21X Campbell Scientific Inc. data logger). Water levels were converted to discharge using rating curves derived for the respective channel sections (Fig. 3.5) Discharge amounts were determined by the area velocity method at low to intermediate flows (Ott-nautilus current meter) and by the float method during high stages (Ward and Robinson, 1990). The two streamflow stations were also equipped with automated water samplers (ISCO Elscolab 6712 portable sampler) programmed to take a 500 cc sample for every 5 cm rise or fall in river stage. The samples were analysed for suspended sediment concentration by drying the sample on a stove, weighing it and dividing the result with the sample volume. Further details on this subject can be found in Chapter 5. A meteo tower installed near the village of Boršt on the central plateau (site 7 in Figure 2.9)

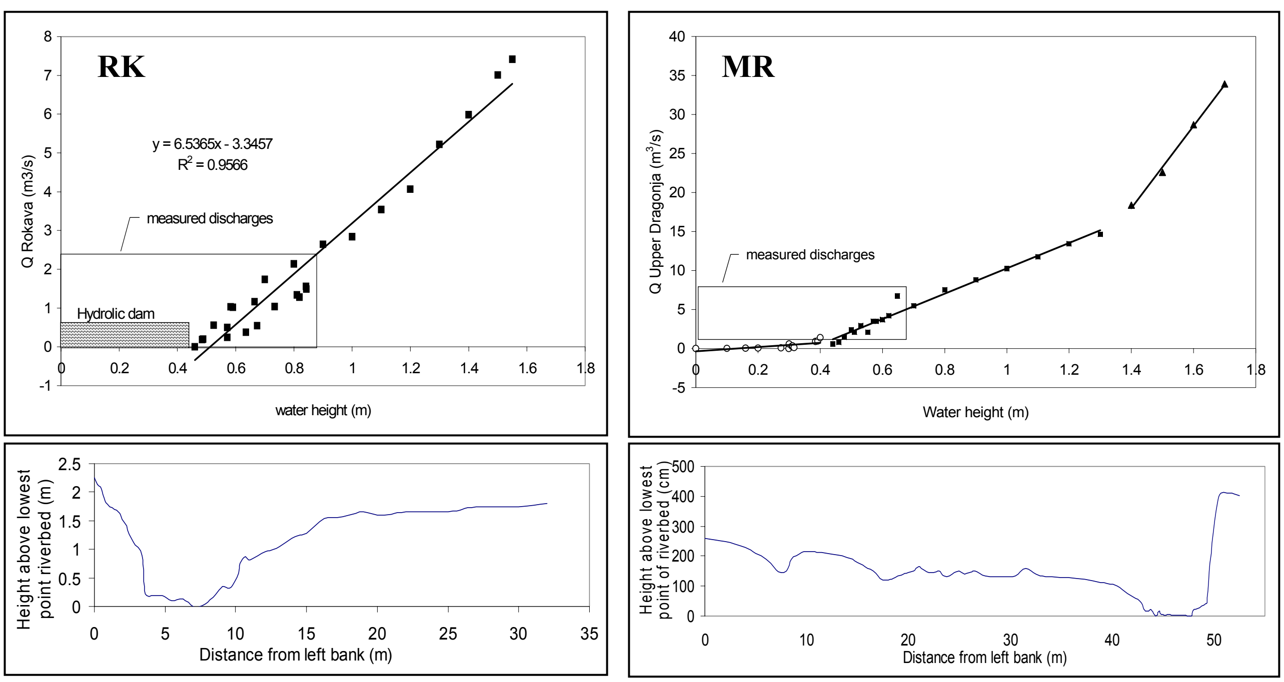


Figure 3.5: Top: Stage-discharge relations for stream gauging stations at the outlets of the Rokava (RK) and Upper-Dragonja (MR) sub-catchments. Bottom figures show the wetted perimeter of the cross sections as measured with a levelling device in 2002.

monitored solar radiation (Pyranometer, Li-Cor LI-200X), humidity and temperature (Humicap, Vaisala HMP45C), wind speed and wind direction (Vector Instruments Anemometer (A100R3) and potentiometer (W200P)) every 30 minutes. On two steep forested hillslopes (Fig. 2.9, sites 17 and 18) of different aspects (north- and south-facing slopes) plots of 1500 m^2 (north-facing) and 650 m^2 (south-facing) were equipped with a full forest hydrological set-up, including throughfall gutters (equipped with tipping bucket systems) and totalisers, stem flow (equipped with tipping bucket systems), litter traps and soil moisture probes (Trime-MUX6 and Campbell Scientific Inc. SC615/616). A full analysis of these data can be found Te Linde (2001) and Van der Tol (in prep).

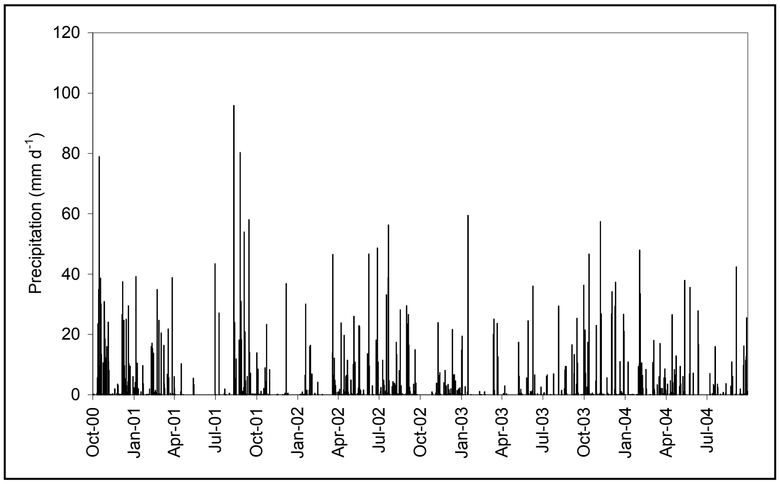


Fig. 3.6: Daily precipitation data measured from October 2000 to October 2004 averaged over all 8 gauging sites (Fig. 2.9).

3.3.2 Precipitation characteristics

The Thiessen polygon map (Fig. 3.4) shows the areas for which each of the rain gauges was assumed to be representative. For the sediment delivery modelling performed in Chapter 4 the average of the measured daily precipitation totals was used (Fig. 3.6). The positive trend in precipitation towards the East as presented by Ogrin (1995, Fig. 2.18) was also found in our measurements. The average annual precipitation for the whole 4-year period was 1075 mm, which is slightly lower than the long term average rainfall measured in Kubed (1447 ± 245 mm) but slightly more than at the coast at Portorož -Beli (1047 ± 165 mm). The distribution of precipitation over the year (average for the 4 years of precipitation measurements) shows that 34% falls in autumn (Sept-Nov), 23% in the winter period (Dec-Feb), 19% in Spring (Mar-May) and 24% in summer (Jun-Aug). On 77% of the days in the period October 2000 till October 2004 less than 1 mm of precipitation was recorded. Storms of more than 20 mm d^{-1} occurred on 5% of the available days. Storms with an intensity of more than 50 mm d^{-1} occurred on 0.5% of the available days. Figure 3.7 shows

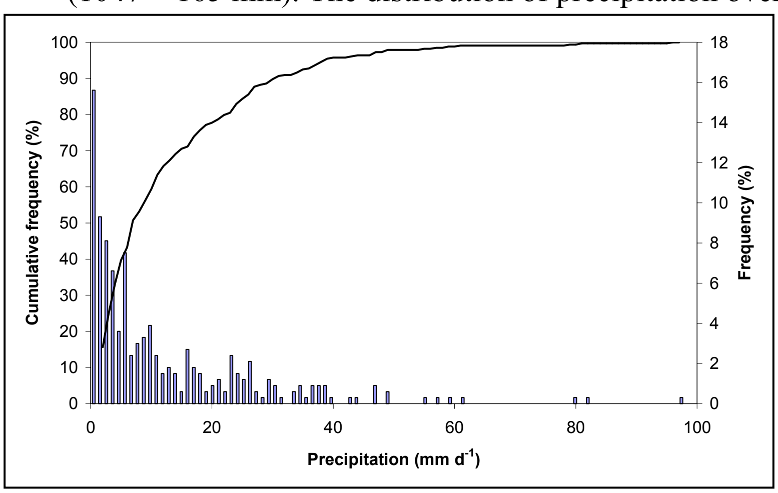


Fig. 3.7: Frequency and cumulative frequency of precipitation events (> 1 mm d^{-1}) in the period October 2000 until October 2004.

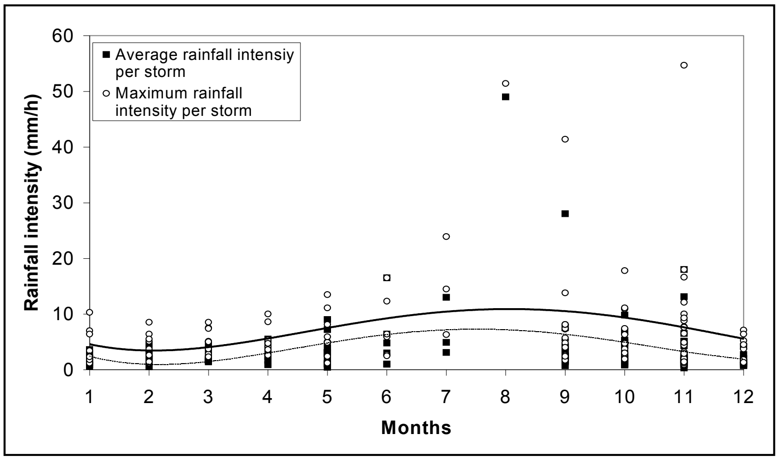


Figure 3.8: Average and maximum hourly intensities during storm events measured in the period October 2000-September 2001 at measurement site Rokava, Fig 2.9 for location. All measured intensities grouped per month to even-out exceptional events.

the frequency distribution of the precipitation on days with more than 1 mm of precipitation.
In winter and spring frontal type rainfall prevails, which generally has low intensities, typical 1-10 mm h^{-1}. In summer and autumn more local convective type rainstorms occur, which often have higher intensities (typical 10-20 mm h^{-1}, with occasional maximum hourly values of 50 to 60 mm; Fig. 3.8).

3.3.3 Discharge

Most of the discharge occurs in winter and very little at the height of summer (Fig. 3.9). This reflects the seasonal variation in evapotranspiration (low in winter, high in summer) and therefore the seasonal variation in soil water storage. In summer the precipitation of an average storm (ca. 20 mm) is not converted into significant discharge. The high soil water absorption, storage capacity and interception by the fully developed tree canopy prevent this. Comparison of the measured saturated conductivity measurement conducted on samples taken from different locations in the catchment (see Fig. 2.18), with the precipitation intensities (Fig. 3.8) suggests that on most locations, with the exception of trails, an average storm with a maximum intensity of 25 mm h^{-1} can be absorbed by the soil. During exceptionally intensive and voluminous storms (with an intensity of more than 50 mm h^{-1}), infiltration-excess overland flow occurs.

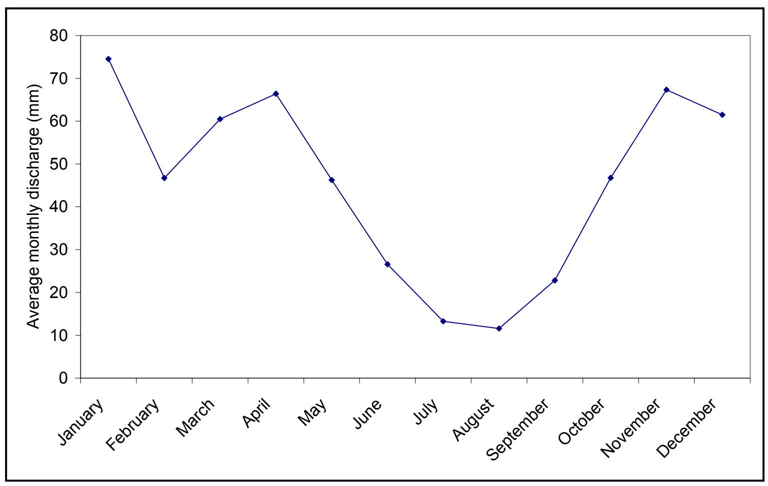


Figure 3.9: Average monthly discharge (mm month^{-1}) calculated over the period 1960 to 2002 measured at Pod Kaštel.

Because the Rokava and Upper-Dragonja sub-catchments reforested differently, also the hydrologic response to precipitation is different. The difference between the Rokava and Upper-Dragonja catchment in the effect of reforestation on the water balance is evident from several hydrological parameters (measured form October 2000 to September 2001).

Discharges were generally low; base flows at gauging sites RK and MR ranged from 200 $l\ s^{-1}$ in winter and fall to no flow in summer. Maximum-recorded peaks in the period October 2000 to September 2004 at the RK and MR sites were 9.4 m^3s^{-1} and 46.5 m^3s^{-1}. However, the extreme event recorded at MR (the Upper Dragonja River; 46 m^3s^{-1}) was not recorded in the Rokava branch.
The relation between the quick and delayed flow shows the difference between the more extensively forested Upper-Dragonja and the Rokava catchment that still has a lot of agriculture. Quickflow events were separated from baseflow using the straight-line technique (Hewlett and Doss, 1984). The slope of the separation line between quick and delayed flow shows a generally steeper slope for the Upper-Dragonja, indicating a relatively shorter period of quick flow. On average, quickflow event of more than 0.5 m^3 had an average duration of 58 h in the Rokava versus 25 h for the Upper Dragonja. The Rokava discharges on average 58% of the total runoff as quickflow. In the Upper Dragonja this value is 45%.
Also the amount of precipitation converted to discharge differ. Over the period October 2000 to September 2001 the average percentage of precipitation discharged by the river was 26 % for the Rokava sub-catchment and 22 % for the Upper Dragonja sub-catchment (Table 3.3). This indicates a larger storage capacity and/or a higher evapotranspiration in the Upper Dragonja. Also the percentage of precipitation discharged as quickflow is higher in the Rokava sub-catchment, 15 %, compared to 10 % for the Upper-Dragonja sub-catchment.
The reservoir constant, 1/k (calculated over the period October 2000 to September 2004), indicating the recession rate of the groundwater reservoir supplying the base flow were 16 days for the Upper Dragonja sub-catchment (measured at site MR) and 12 days for the Rokava sub-catchment (measured at site RK).

An analysis of the Antecedent Precipitation Index (API), which is a general term for the wetness of the catchment at the beginning of a storm (Ward and Robinson, 1990), is important to describe the response of the catchment in terms of percentage of precipitation converted to storm discharge. Especially in summer the API controls this mechanism, which is reflected by the high variance in discharge /precipitation ratio during the summer months (Table 3.1). The two sub-catchments also reacted in different ways for comparable levels of API. The Upper-Dragonja sub-catchment discharge levels were somewhat lower than those of the Rokava sub-catchment for the same API (Hendriks, 2002). This indicates a better infiltration capacity or higher interception in the Upper-Dragonja catchment, of which both can be the result of the higher percentage of forest.

3.4 Water balance

Precipitation and discharge data for the period October 2000 until September 2001 were used to derive tentative water budgets for the Upper Dragonja and Rokava sub-catchments (Fig. 3.10).

In this water balance calculations a simple formula was used:

$$P = Q + ET + \Delta S$$

Where Q is discharge, P is precipitation, ET is the evapotranspiration and ΔS is the change in soil and groundwater storage (all in mm y^{-1}).

For the precipitation input the weighted (cf. Fig. 3.4) amounts recorded at the 8 rainfall stations were used. The 'direct' application of the measured rainfall minus measured streamflow suggested annual evapotranspiration totals of 1180 and 1240 mm for the Rokava and Upper Dragonja sub-catchments, respectively assuming change in soil water storage ΔS ~ 0 or on an annual basis (Ward and Robinson, 1990). The derived apparent ET totals include a leakage term (L) of unknown magnitude.
In a parallel study, Van der Tol (in prep.) has quantified interception evaporation (E_i) and transpiration (soil water uptake (E_t)), plus soil evaporation (E_s) in forest plots on the

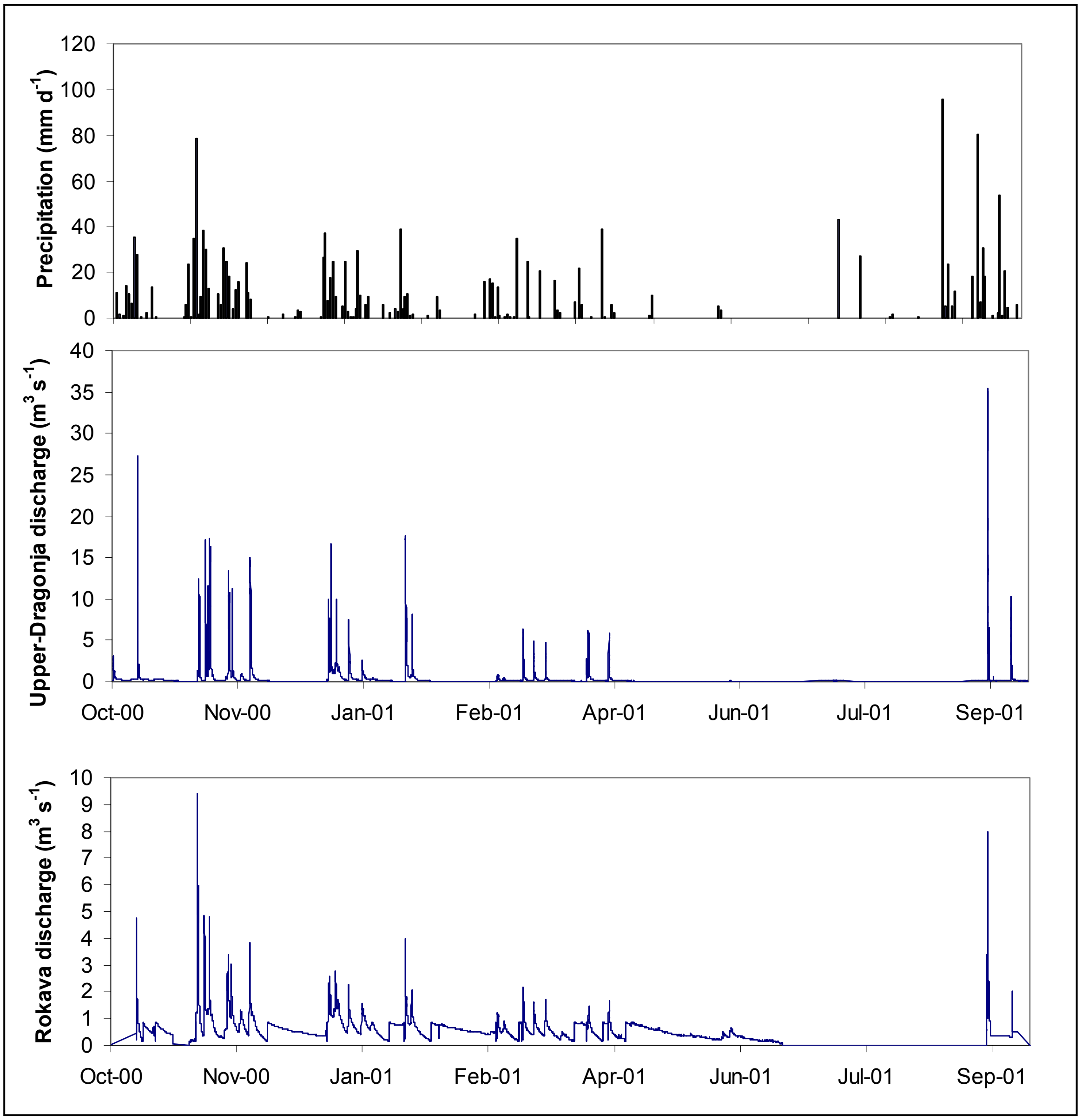


Figure 3.10: Discharge and precipitation at measurement sites RK and MR in the period October 2000 to September 2001. RK represents the discharge of the Rokava tributary; MR of the Upper-Dragonja River, 400 m upstream from the confluence with the Rokava River (see Fig. 2.9, sites 5a and 7).

north- and south-facing slopes (Table 3.2). This knowledge can be used to derive an estimate of the deep leakage term L in the water budget equation (since $ET = E_i + E_t + E_s$ and now known approximately). There is a distinct difference in hydrological behaviour between north and south facing forested slopes (Table 3.2). Features like tree height, stem density and diameter as well as species composition and leaf area index (LAI) all differ considerably (Te Linde, 2001). The evaporation components (E_i, E_{trans} and E_{soil}) for the two sites were measured over the period October 2000 to October 2004 (van der Tol, in prep.).

Table 3.2: Water balance (in mm y^{-1}) for 100% forest land use on south and north facing slopes from October 2000 to September 2001. Discharge and precipitation measured in 2000-2001. Interception and transpiration measured from 2001 to 2004. Soil transpiration was derived from literature. The surplus was interpreted as recharge.

	South facing slopes	*North facing slopes*	*Average*
Interception ($E_{interception}$)	560 (35% of P)	480 (30% of P)	520
Transpiration (E_{trans})	350	400	375
Soil evaporation (E_{soil})	150	100	125
Sub-total Evapotranspiration	1060	980	1020
Precipitation (P)	1590	1590	1590
Precipitation surplus (P-ET)	530	610	570

Average interception loss from deciduous forest was 35% of incident rainfall on south-facing slopes and 30 % on north-facing slopes. Average soil evaporation (E_{soil}), which is linked to solar radiation, was estimated at 150 mm y^{-1} on south-facing slopes and 100 mm y^{-1} on north-facing slopes. Average transpiration (E_{trans}) is 350 mm y^{-1} for south-facing slopes and 400 mm y^{-1} for north-facing slopes. This lower E_{trans} on the south-facing slopes is caused by a lower LAI and the south-facing slopes experience more drought stress in summer, which induces lower transpiration rates. Moreover, on south-facing slopes leaves sprout later than on north-facing slopes, whereas, in exceptionally dry years, leaf fall starts earlier on south-facing plots again, as a result of drought stress (van der Tol, in prep.). However, the higher temperatures and radiation load of the south-facing slopes also caused a somewhat higher interception evaporation that compensated the lower transpiration (Table 3.2). Thus, at the forest plot scale total evaporation is about 1020 mm y^{-1}, with a slightly higher value (1060 mm y^{-1}) derived for the warmer south-facing forest than for the cooler north-facing forest (980 mm y^{-1}). Subtracting total ET from incident rainfall (a high 1560 mm in the wet year 2000-2001) gave a surplus of 530 mm (south-facing) versus 610 mm (north-facing) per year. These amounts represent the water available for lateral downhill drainage (throughflow) plus any (vertical) deep leakage towards the groundwater table.

To derive the water budgets for the two sub-catchments and estimate the leakage term, plot-based estimates of ET and its components were used together with evaporation estimates for a non-forest cover (grassland; Van der Tol, personal communication; Table 3.3).

The Rokava sub-catchment has a somewhat smaller percentage of forested area (61%) than the Upper-Dragonja sub-catchment (70%). Moreover, large parts of the forested hill-slopes in the Rokava catchment have a north-facing aspect (70 %), whereas in the Upper-Dragonja area approximately only half of the forested slopes are north-facing. Both features should cause a larger potential evaporation rate for the Upper-Dragonja. However, as shown in Table 3.3, differences in ET between the two areas were marginal (880 versus 895 mm). Assuming $\Delta S = 0$ it flows that the respective leakage terms amount to ca. 300 and 345 mm y^{-1} in the Rokava and Upper Dragonja sub-catchments, or ca. 1 mm day^{-1}, which is an acceptable value in this type of terrain (Ward and Robinson, 1990).

However, the high precipitation in the studied hydrological year (1590 mm), may have caused a large difference in catchment wetness at the beginning and end of the measurement period (i.e. $\Delta S \neq 0$). Estimating ΔS on the basis of rainfall inputs during the two weeks prior to the beginning and end of the year gave approximate value of 50 mm for both sub-catchments giving alternative estimates for L of 250 and 295 mm y^{-1}.

Table 3.3: Water balance (in mm y^{-1}) for Rokava and Upper-Dragonja sub-catchments over the period October 2000 to September 2001.

	Rokava sub-catchment		*Upper-Dragonja sub-catchment*	
Interception ($E_{interception}$)	61% Forest 70% S, 30% N	310 mm	70% Forest 50% S, 50% N	365 mm
	49% Non-forest	80 mm Total: 390 mm	30% Non-forest :	50 mm Total : 415 mm
Transpiration (E_{trans})	61% Forest 30% S, 70% N	235 mm	70% Forest: 50% S, 50% N	280 mm
	49% non-forest: no difference S/N	120 mm	30% non-forest no difference S/N	75 mm
Soil evaporation (E_{soil})	30% S, 70% N	135 mm	50% S, 50% N	125 mm
Precipitation (P)	1590 mm			1590 mm
P-ET(E_i+E_{trans}+E_{soil})	710 mm			695 mm
Discharge (Q)	410 mm			350 mm
Recharge (Δ S)+ Leakage (L)	300 mm			345 mm

PART II: SEDIMENT GENERATION

Chapter 4: Changing sediment generation due to natural reforestation in the Dragonja catchment, SW Slovenia

CHAPTER 4: CHANGING SEDIMENT GENERATION DUE TO NATURAL REFORESTATION IN THE DRAGONJA CATCHMENT, SW SLOVENIA

ABSTRACT
Under the influence of socio-economic changes in many regions in Europe, a trend of decreasing agricultural activity is observed since the Second World War. The resulting reforestation profoundly changes water and sediment supply to river channels, deposition rates on the floodplains and erosion rates on the hill slopes. We studied these changes in the 91 km^2 Dragonja catchment in southwestern Slovenia.
With the spatially distributed erosion and sediment delivery model WaTEM/SEDEM, the hill slope sediment delivery to the river channel was calculated on the basis of parameters (soil and precipitation parameters, a DEM and land use) measured in 2002 and land use maps based on aerial photographs from 1954, 1975, 1985 and 1994. For two independent calibrations WaTEM/SEDEM modelled a sharp decline of 69 % +/- 3% in total hill slope sediment delivery from 1954 to 2002.
As the sub-catchments Rokava and Upper-Dragonja did not reforest in the same way, the sediment yield response is different as well. Separate calculations show the same reduction (45 %) in sediment yield from 1954 to 1975. After 1975 the sediment yield stayed stable in the Rokava sub-catchment. In the Upper-Dragonja the trend continued, to a total reduction of 76 % of sediment outflow since 1954.
The sources of fine sediment were determined by analysing the hysteresis of the discharge waves, and the suspended sediment texture. The sediment that leaves the catchment originates from three sources, hill slopes, erosional bedrock banks and sedimentary riverbanks.
Hysteresis analysis indicates that little sediment comes directly from the hill slopes into the channel (clock-wise hysteresis). In contrast the analysis of the suspended sediment texture suggests that during a discharge wave the suspended sediment originates predominantly from the hill slopes. During low stage the sparse sediment in the water column largely originates from large bedrock banks. The sedimentary riverbanks are not an important source of suspended sediment.
Despite the discrepancy between the two methods it can be concluded that most suspended sediment originates from the hill slopes but is not transported to the river channel during the beginning of a storm. The sediment is first transported to the base of the valley, and during a later stage in the same storm or a next one it is transported to the river channel.

Keywords: Dragonja, Slovenia, hill slope erosion, land use change, natural reforestation, effect of hysteresis, WaTEM/SEDEM

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4.1 INTRODUCTION

The effects of deforestation and intensification of agricultural land on erosion (e.g. Singh, 1999), nutrients (e.g. Lenhart et al., 2003), slope stability (Vanacker et al., 2003) and soil properties (e.g. Varela et al., 2001) have been studied widely. However the effects of reforestation has received much less attention. Under the influence of socio-economic changes in many regions in Europe a trend of decreasing agricultural activity is seen. This trend induces either planned reforestation and nature development in catchments, or unplanned land abandonment and natural reforestation. This reforestation profoundly changes water and sediment supply to the rivers, the deposition rate on the floodplains and the erosion rate on the valley slopes (e.g. Piégay et al, 2004). We studied and modelled these changes in erosion on the hill slopes in the Dragonja River, southwestern Slovenia. Erosion modelling in a similar setting, in terms of climate and geomorphology, has been performed before (e.g. Erskine et al, 2002 and Martínez-Casasnovas and Sánchez-Bosch, 2000), however, in most instances the input parameters are not as detailed or not available for the whole catchment. Furthermore, modelling the response of hill-slopes in terms of erosion due to reforestation, as performed in this study, has not been undertaken before.

Figure 4.1: The study area: the Dragonja catchment, Southwestern Slovenia (45°28'N, 13°35'E). The black dots indicate the location of the precipitation gauges.

As a result of several decades of depopulation, the previously severely eroding 91 km^2 Dragonja drainage basin (Fig. 4.1) has seen a steady increase in the proportion of (mostly broad-leaved) forest. With the return of the forest, profound changes in the flow regime and the morphology of the main river have taken place. Notably a gradual reduction in average annual and dry-weather flows (3.5% and 10% per year, respectively), and a 68% decrease in channel width in the middle reaches between 1954 and 2001 have occurred (Keesstra et al., 2005=chapter 7).
Both the reduced water and sediment flow rates pose a potential threat to the continued functioning of wetland reserves near the outlet of the drainage basin and limit the possibilities for renewed agricultural development in the area. In addition, a significant change in river channel form has been observed, which greatly influences the aquatic habitat of the Dragonja River. Recently, in 2004, the Dragonja valley has obtained a Natura-2000 status (European Commission, 2000), the management the catchment according to the Natura-2000 directives will require sound information on the hydrological, geomorphological and ecological functioning of the area.

The aim of this study is to reconstruct the change in erosion rates on the hill slopes and change in total sediment loss of the catchment due to the reforestation of the Dragonja catchment over the period 1954 to 2002. The erosion rates on the hill slopes and the amounts of sediment being delivered to the rivers were calculated using a spatially distributed soil erosion and sediment delivery model WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al, 2001; Verstraeten et al., 2002)). The sediment yield of a catchment provides useful information about the net erosion intensities within catchments (Walling 1994). Modelling the past land use situation provides an insight in how these land-use changes affected the erosion rates on the hill slopes. These insights can be used for management purposes.

4.2 Study area

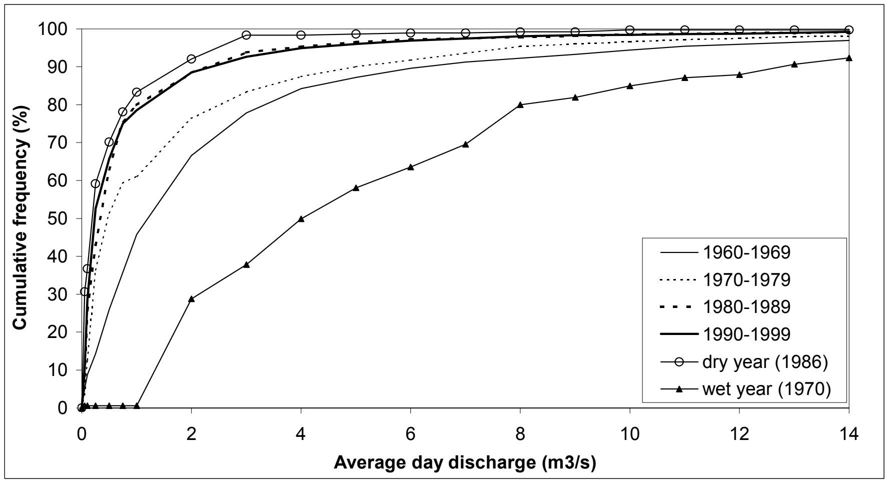

Figure 4.2: Flow curves of the daily discharges at Pod Kaštel, near the outlet of the Dragonja River (HMZ, 2003).

The Dragonja catchment is situated in the south-western part of Slovenia. The river is 30 km long and the catchment is approximately 91 km^2 (Fig. 4.1). The elevation of the drainage basin ranges from 400 m at the headwaters to sea level at the river mouth. The Dragonja debouches into the Adriatic Sea. The upstream part of the Dragonja River consists of two sub-catchments, the Dragonja sub-catchment (32 km^2) and the Rokava sub-catchment (20 km^2). The geology of the catchment is largely uniform. The substratum of the catchment is composed of sub-horizontal to gently north dipping Eocene flysch, consisting of highly calcareous soft silt and clay stone with sandstone layers up to 1.5 m thickness (Melik, 1960; Orehek, 1972). The overall morphology of the catchment is characterized by long flat ridges and plateaus with steep slopes at the margins of the valleys. The soil is mostly a carbonate rendzina, with the exception of the valley floors, where a fluvisol (FAO, 1990), an ustifluvent (USDA, 2003) has developed. On places where a sandstone layer is very close to the surface, a brown eutric soil has developed.

All soils are highly calcareous (Zupancic and Pric, 1999). The thickness of the soils varies from more than 1 meter on the plateau to zero on the slopes, partly as a result of erosion associated with former agricultural activities.

The climate of Slovene Istria can be classified as sub-Mediterranean; Köppen-type C_f. The average annual temperature is 14°C at the coast and 10°C at the eastern part of the catchment. The absolute temperature varies from -10°C to 35°C (HMZ, 2003; Ogrin, 1995). The yearly precipitation varies from 700 mm to 1400 mm and increases with distance from the coast. The maximum-recorded daily precipitation is 133 mm. From 1950 till 2000 the precipitation has decreased, the trend shows a decrease of 19%. The average discharge at the outlet over the period 1960 till 1998 is 1.19 m^{3}s^{-1}. However the hydrological record shows a decrease in mean discharge of 79 % from 1960 to 2002 (HMZ, 2003). There is an increase in dry flow events and a decrease of high flow events (Fig. 4.2). The precipitation discharged by the river decreased from 67% (average over the period 1961-1971) to 34% (1991-2002). The reservoir constant, k, indicating the resistance of the catchment against outflow, is estimated to be 40 days for the upper Dragonja catchment. The quick flow had an average duration of 15 hours. At Pod Kaštel the hydrological record from 1960 to 2002 places the 1, 10 and 50-year recurrence interval floods at 30 m s^{-3}, 70 m s^{-3} and 105 m s^{-3} respectively.

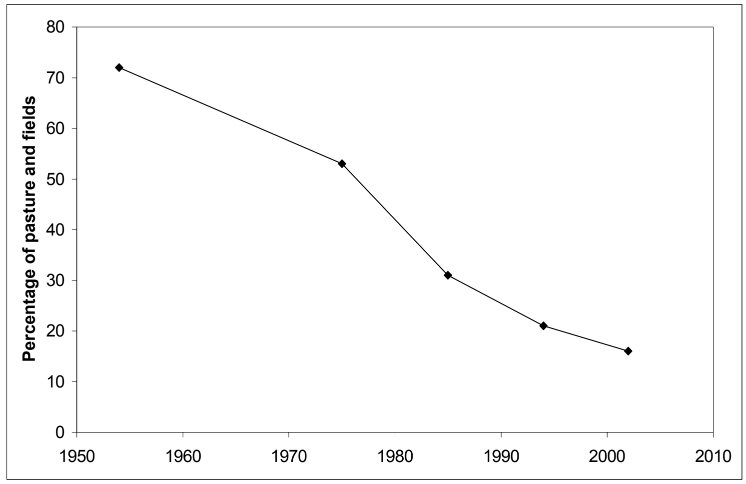

Figure 4.3: Decrease in percentage of agricultural land in the Dragonja catchment since 1950 (Keesstra and van Dam,2002).

Over the last 55 years important changes in land use have occurred. After the Second World War socio-economic changes in the region caused depopulation resulting in large scale abandonment of agricultural fields, which slowly changed into a mature forest (Fig. 4.3, Keesstra and van Dam, 2002). Due to the natural reforestation the river has narrowed and incised into its former bed. From 1950 till 1975 the river incised and thus formed a terrace, which now stands 1.5 m above the current river. After 1975 the process of narrowing and incision intensified due to an increase of mature forest, forming a terrace that stands 0.5 to 1.0 m above the current river (Keesstra et al., 2005 = Chapter 7).

4.3 Methods

4.3.1 WaTEM/SEDEM model

The change in erosion as a result and hill slope sediment delivery of the land use changes in the catchment was estimated with the model WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al, 2001; Verstraeten et al., 2002). WaTEM/SEDEM is a spatially distributed model to simulate erosion and deposition by water and tillage processes in a two-dimensional landscape. Unlike more sophisticated dynamic models, WaTEM/SEDEM focuses on the spatial, and less the temporal, variability of relevant parameters. As such, WaTEM/SEDEM allows the incorporation of landscape structure or the spatial organisation of different land units and the connectivity between them. In order to avoid major problems with respect to the spatial variability of parameter values and uncertainty of parameter estimates, WaTEM/SEDEM is a simple topography-driven model. WaTEM/SEDEM first calculates mean annual hillslope erosion rates using an adapted version of the Revised Universal Soil loss equation or RUSLE (Renard et al., 1997) for 2D-landscapes. Therefore it needs the same input parameters, R- rainfall-runoff factor, K- soil erodibility factor, C- cropping factor and P-conservation practices factor. The slope-length factor LS is calculated from a DEM using a multiple flow algorithm to assess the unit contributing area according to Desmet and Govers (1996). Next, the eroded sediment is routed along the runoff pattern towards the river, taking into account the local transport capacity (TC) of each pixel. Transport capacity is proportional to the potential of concentrated flow erosion by a transport capacity coefficient (ktc). If the local TC is smaller than the sediment flux, sediment deposition is modelled. When the sediment reaches the river, it is directly delivered to the most downstream end of the river link. No bank erosion or floodplain deposition is modelled with WaTEM/SEDEM. The transport capacity coefficient (ktc) needs to be calibrated for various land use categories by comparing predicted with observed values of sediment yield for various combinations of ktc.
The WaTEM/SEDEM model was tested widely for NW- and Central Europe (van Rompaey et al., 2001; van Rompaey et al., 2003) and SW-Australia (Verstraeten et al. submitted). For Mediterranean climate the model was tested in Italy (Van Rompaey et al., 2005). But the

information on the studied catchments studied by Van Rompaey et al. (2005) is much coarser than the detailed information available for the Dragonja drainage basin.

4.3.1.1 R; Rainfall-runoff factor

The rainfall-runoff factor is calculated from precipitation data. Both the amount and intensity of the precipitation are important factors. The precipitation was measured just outside the catchment on the coast in Portorož since 1961. This station recorded daily total amounts of precipitation. Since October 2000 the precipitation was measured on 7 locations in the catchment with tipping bucket systems (Fig. 4.1), which gives in addition the intensity of the precipitation.

For the erosion model input parameter R, the rainfall-runoff parameter was calculated. For the model run of 2002 the factor was derived from the tipping bucket data of the years 2000 to 2003, using the procedure described in the RUSLE handbook (Renard et al., 1997):

$$R = \frac{1}{n}\sum_{j=n}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_k\right] \quad (2)$$

with E total kinetic energy of the rain event (MJ/m²), I_{30} maximal rain intensity during 30 minutes (mm/h), n the number of years for which data are available, m the number of rain events in each year.

For every rain event, EI_{30} is calculated by:

$$EI_{30} = \left(\sum_{k=1}^{m}\sum_{r=1}^{o} e_r \Delta V_r\right) I_{30} \qquad (3)$$

with e_r the rain kinetic energy per unit of rain amount and surface (MJ/m².mm) for pluviophase r and ΔV_r: the total rain amount for pluviophase r (mm). Every rain event is subdivided in o-pluviophases of equal duration (10-minutes). The rain kinetic energy per unit of rain amount is calculated by:

$$e_r = 0.29\left(1 - 0.72e^{(-0.05 * i_r)}\right)$$

with i_r the rain intensity for the 10-min interval. Even though we know the precipitation has decreases over the period 1961-2004 we have no information on the intensity of the precipitation prior to October 2000. Therefore we assume that the intensity did not change over time.

4.3.1.2 K; Soil erodibility factor

This factor is dependent on the texture and organic matter content of the soil. The soil structure and permeability play a minor role in determining this factor. Parameter K (kg m² hr m^{-2} $MJ^{-1}mm^{-1}$) is calculated with the following formula:

$K = [2.1*10^{-4} (12\text{-}OM) M^{1.14} + 3.25 (s-2) + 2.5 (p-3] / 759$

Where OM = organic matter content (%)

M = texture product: % silt * (%silt + % sand)

s = structure class

p = permeability class

The required input parameters were collected during field and laboratory research (cf. Chapter 2) and partly derived form the Slovene soil map (Fig. 4.4)(Geološki zavod Slovenije, 2003).

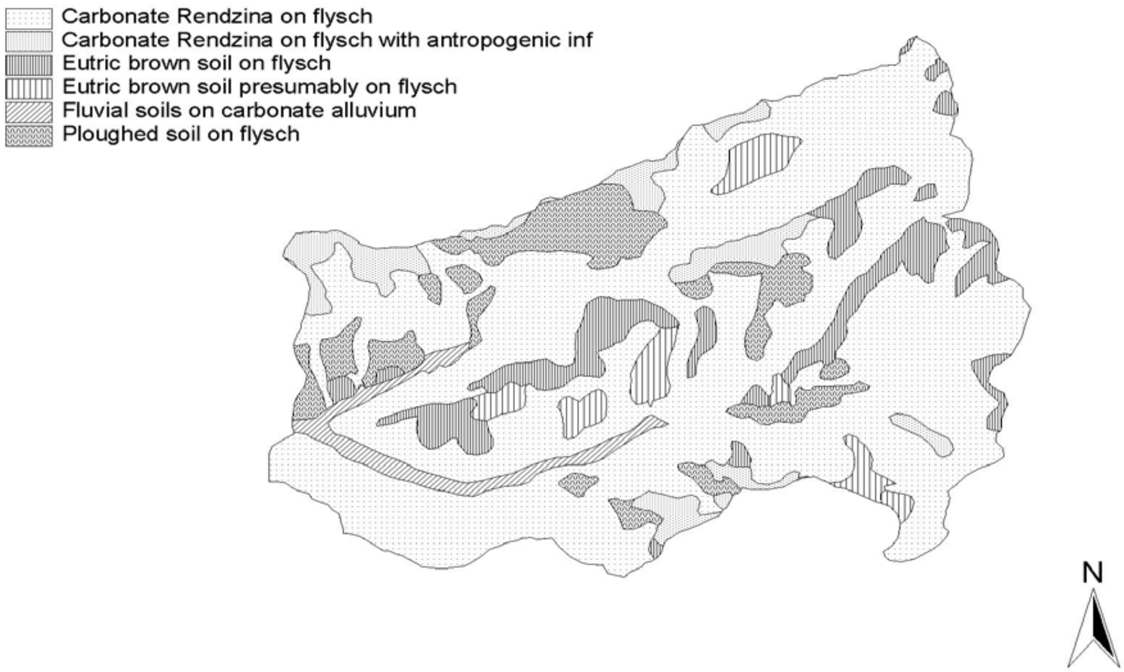

Figure 4.4: Soil map of the Rokava and Upper-Dragonja catchment (Geološki zavod Slovenije, 2003).

For each land use type (fields, pasture, abandoned fields, young forest and mature forest) in three landscape settings (valley floor, hill slope, plateau) fixed volume samples (100 cm^3) were taken from the top soil (0-5 cm) and the sub surface (5-10 cm). A total of 105 samples were taken. On small trails though forest and in between fields an additional 14 samples were taken. On each site the soil profile and the structure of the soil was described. These point data were extrapolated to the entire catchment with the use of the Slovene Soil map. Texture analysis was done with a Laser Particle Sizer (A22, Fristch). The samples were prepared according to the methods by Konert and Vandenberghe (1997). The usual HCl was not added to the sediment, since that would dissolve parts of the sediment itself. The organic matter content was analysed by loss on ignition at 500ºC.

The $CaCO_3$ content was analysed by dissolving the $CaCO_3$ with an excess of HCl (25 % solution) and measuring the CO_2 gas that forms during the reaction. The saturated permeability was measured both in the field (double ring-infiltrometer) and in the laboratory the saturated conductivity was measured on fixed volume samples with both constant and falling head methods (ANSI/ASTM, 1974).

Table 4.1: Cropping factor per land use (after Wischmeier and Smith, 1978; Renard et al., 1997; Dissmeyer and Foster, 1980)

Land use	*C-factor*
Fields and pasture	0.271
Abandoned fields	0.015
Young forest	0.02
Mature forest	0.05
Bad lands	0.9
River bed	0.95

4.3.1.3 LS; Length and steepness of slope factor

The LS factor is derived from a Digital elevation model (DEM) in

WaTEM/SEDEM. Within IDRISI, a raster DEM with a 20m resolution was obtained after interpolation between contour lines that were digitised from scanned topographical maps using spatial data builder Cartalinx.

4.3.1.4 C; Cropping factor

The cropping factor is directly derived from the land use. The change in land use is the main input for the model runs. The land use change was derived from aerial photographs taken in 1954, 1975, 1985 and 1994. The present situation was mapped during a field survey in 2002. The aerial photographs were digitised in Cartalinx. The land use was simplified into 6 categories, riverbed, erosional cliff and badlands, fields, abandoned fields, young forest and mature forest (Figs. 4.5 and 4.6). During the field survey a further distinction was made between fields and pasture. Since it is not possible to distinguish between these two land cover types on the aerial photographs and the fact that pastures are regularly ploughed in this area, the area of pasture and fields mapped in 2002 was grouped.

The quality of the aerial photographs taken in 1954 was poor. Therefore the only reliable distinction that could be made was forest versus non-forest. Since the abandonment of the agricultural lands only started around 1950, it is assumed that in 1954 the land uses could be divided into fields and mature forest. The riverbed and badlands were not considered in the analysis of 1954. The analysis was only done for the Upper-Dragonja and Rokava catchments, because in the Lower Dragonja catchment the reforestation succession is not as evident. The value of the cropping factors was derived from other work (Table 4.1, Wischmeier and Smith, 1978; Renard et al., 1997; Dissmeyer and Foster, 1980).

4.3.1.5 P; Conservation practices factor

Although localized terraces are present on some of the steep slopes of the catchment, these conservation practices were not accounted for as these terraces are usually very narrow and fall within the scope of the cell size used in the modelling. Furthermore a large part of these terraces are not well maintained and thus lost most of their conservation value.

4.3.2 Suspended sediment concentration:

The suspended sediment was sampled regularly intensively on three locations; at the outlet of the study area and on both branches, upstream from the confluence of the Rokava and the Upper Dragonja River. At the latter two sites, an ISCO-sampler was installed, which automatically took samples during floods. At the outlet of the study area samples were taken manually, during 3 floods. On other locations, such as small tributaries and gullies, samples were taken occasionally. The samples were evaporated to determine the suspended sediment concentration and this sediment was analysed on texture.

4.4 INPUT FOR WATEM/SEDEM

4.4.1 R; Rainfall factor

The rainfall factor R is determined by the intensity and volume of the precipitation over a year. It is important to use continuous data to determine this factor. Since we only have continuous data (tipping bucket) of the last 4 years, these data were used to extrapolate the continuous precipitation from earlier years for which only daily precipitation was available. The calculated R factor for the year 2002 was extremely high (0.538 MJ.mm/m^2.h.j) for the other available years the R-factor was around 0.3. As this is a more realistic number we used 0.3 for all other WaTEM/SEDEM runs. Rainfall records measured in the nearby city of Trieste saw no change in precipitation over the period 1950 to 2002. However, the record measured within the catchment from 1961 to 2000 shows a 19% decrease in precipitation.

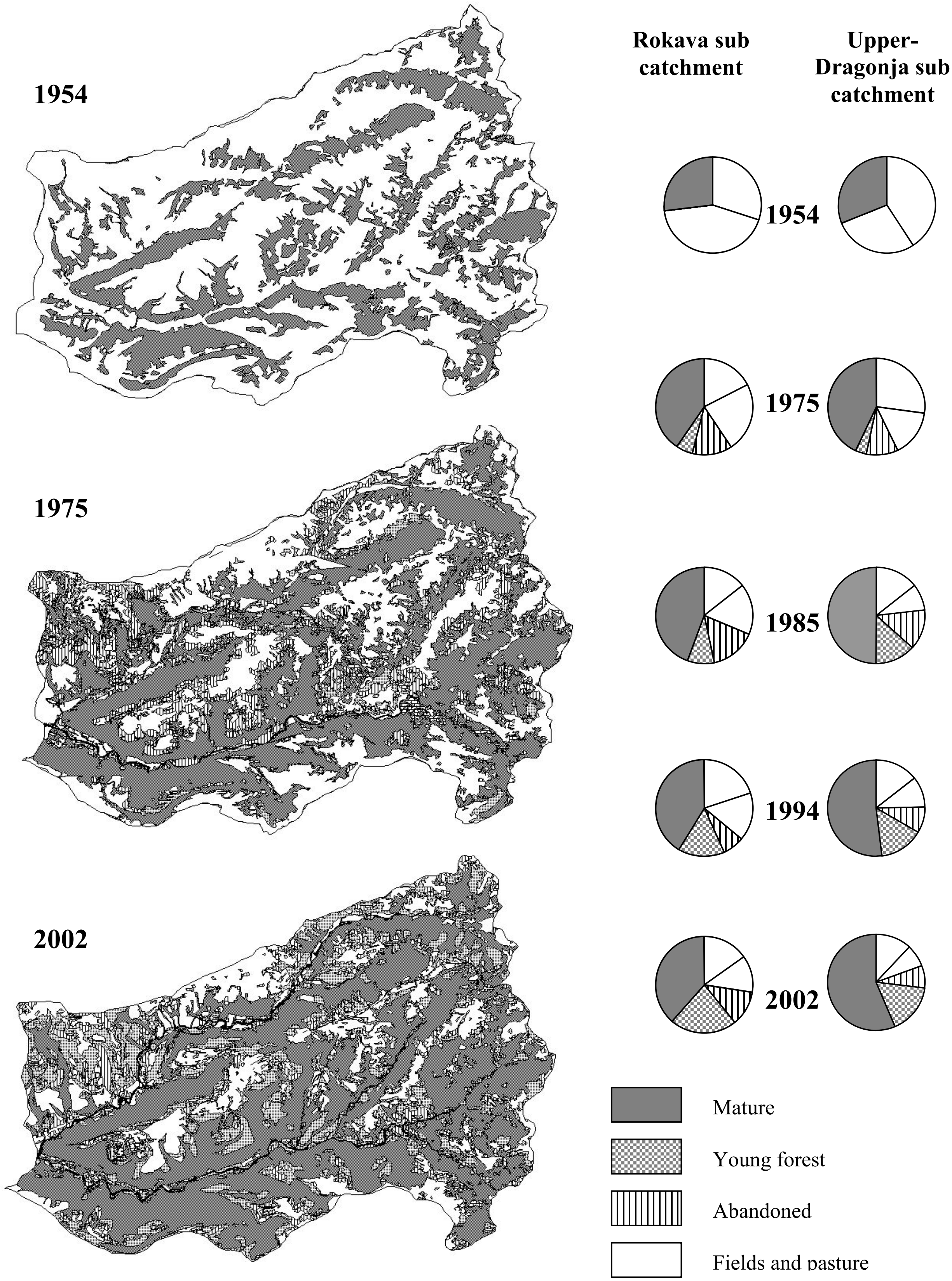

Figure 4.5: Land-use maps of the Upper-Dragonja and Rokava sub-catchments in 1954, 1975 and 2002 as derived from aerial photographs. The pie charts reflect the land use distribution over the catchment in all studies years, 1 1954, 1975, 1985, 1994 and 2002 for the Rokava and Upper-Dragonja sub-catchments.

Despite this observation, we do not have sufficient information that indicates that this trend is significant and therefore we assumed a constant R-factor because a minor change in the R-factor has a considerable impact on the model output of total sediment production. Nevertheless it is possible that the R-factor was significantly higher in 1954, which means the erosion could be underestimated in the model runs. It will therefore be tested what the influence of land use changes is on the sediment dynamics of the Dragonja catchment according to the model experiments, irrespective of climate impacts.

4.4.2 K; Soil erodibility factor

The 119 samples were divided into 17 units. These units consist of the five land use classes (pasture, fields, abandoned fields, young forest and mature forest) on three landscape units (valley floor, slope and plateau) and small trails in forest and between fields. The samples were tested on texture, structure, organic matter, $CaCO_3$ and saturated conductivity. Furthermore 40 of the collected suspended sediment samples were measured on texture.

4.4.3 Texture and structure

The texture analysis of the soil samples shows that texture is only weakly related with the geomorphological position (Fig. 4.7, left), except for the field trails, which have a more silty texture compared to the other samples. A few samples from the fields on the slope show a sandy texture, implying more erosional activity on the surface. However most samples from the slope show a more clayey texture. The texture range is the largest on the slopes compared to plateau and valley soils. On average the texture of the soil in the valley is slightly coarser, which is probably caused by mixture of the sediment with erosion debris coming from bad lands and large erosional cliffs. Furthermore, sorting may have taken place during deposition of the floodplain sediment. The coarsest sediment settles out of the water column first and the finest sediment fraction is transported away to sea.
The suspended sediment texture was compared with the texture of the soil samples taken

Figure 4.6: Examples of the mapped land uses, Fields (A), abandoned fields (B), young forest (C) and mature forest (D).

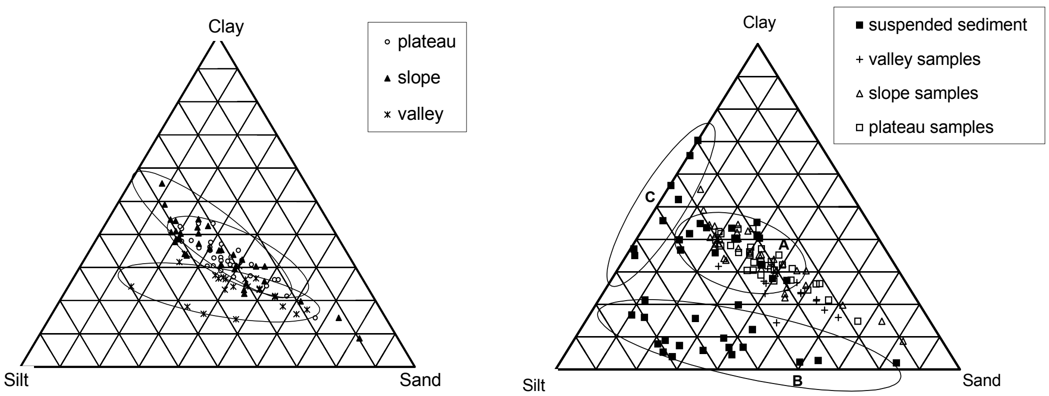

Figure 4.7: Tri-plots of the texture of soil samples taken throughout the valley (left). Circles indicate rough groups of the same texture. In the right-hand tri-plot the texture of the suspended sediment load is plotted as well. Group A represents samples taken during high flow, group B during falling stage intermediate flow and group C during low flow.

throughout the catchment. The samples of the suspended sediment are much more variable than the soil samples and can be divided into 3 groups. One with similar texture as the slope samples (Fig. 4.7 right, A), one similar to slope texture but depleted from sand (Fig.4.7, B) and one relative coarse group with dominantly fine sands (Fig. 4.7, C). The explanation for these differences is explained in the section 'origin of the suspended sediment' (§ 4.6). The structure of the soil was highly dependent on the land use. The structure in a forest is always very loose and on fields there is no structure at all.

4.4.4 $CaCO_3$ and organic matter

The $CaCO_3$-content of the samples varies between almost zero to 40 % (Fig. 4.8, right). On average the $CaCO_3$ content on the hill slopes is relatively low compared to the plateau and the valley. This is probably caused by relative high amount of colluvial material on the hill slopes that consist of the residue of carbonate weathering and is generally low in $CaCO_3$ content. Soils on the plateau tend to have a lower organic matter content than in the valley and on the slopes. Furthermore the soil type influences the $CaCO_3$ and organic matter content as well, which is sometimes superimposed on the land use and landscape unit.

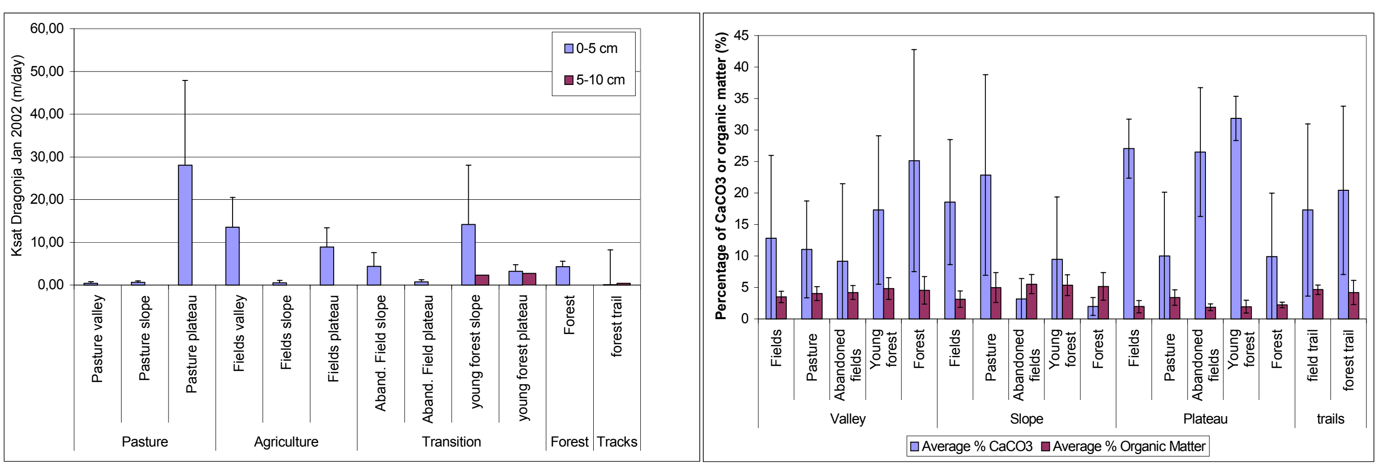

Figure 4.8: Average saturated conductivity (left) and average organic matter and $CaCO_3$ content (right) for all land-use types (pasture, fields, abandoned fields, young forest, forest and trails) in each landscape unit (valley, slope and plateau).

4.4.5 Saturated conductivity

The saturated conductivity of the soil samples measured with the double ring infiltrometer was very variable and not connected to the land use or landscape setting. In most cases the conductivity was either very high or very low, dependent only on macro-pores.
In the laboratory the fixed volume samples gave better results (Fig. 4.8, left). No significant differences were found in the conductivity of the surface samples (0-5 cm). However, some variance in the data may be linked to differences in the landscape or land use. The saturated conductivity is weakly related to the soil type, with the exception of soils under forest, where the conductivity is always rather high, due to abundant bio pores. Almost all samples taken at 5-10 cm below the surface give an extremely low conductivity.

4.4.6 Combination of the parameters

Table 4.2: K-factor for soil types in Dragonja catchment

Soil type	*K-factor**
Carbonate rendzina on flysch (with/without anthropogenic influence)	0.0206
Eutric brown soil (presumably) on Flysch	0.0258
Fluvial soil on carbonate alluvium	0.0354
Ploughed soil on flysch	0.0232

*kg.h/Mj.mm

All the soil parameters were used to derive the K-factor, the soil erosivity factor, for the erosion model input. As there is a weak relation between the saturated conductivity and the soil type, the soil type distribution was used to make the K-factor map. The samples were classified and divided over the soil classes on the soil map (Geološki zavod Slovenije, 2003). The results were averaged and this resulted in values for the K-factor for each soil class (Table 4.2).

The land use is the only factor that has changed significantly. This is reflected in different C-value maps for the various time periods. To model the effect on erosion of the changed land use, all other factors were kept stable in all runs.

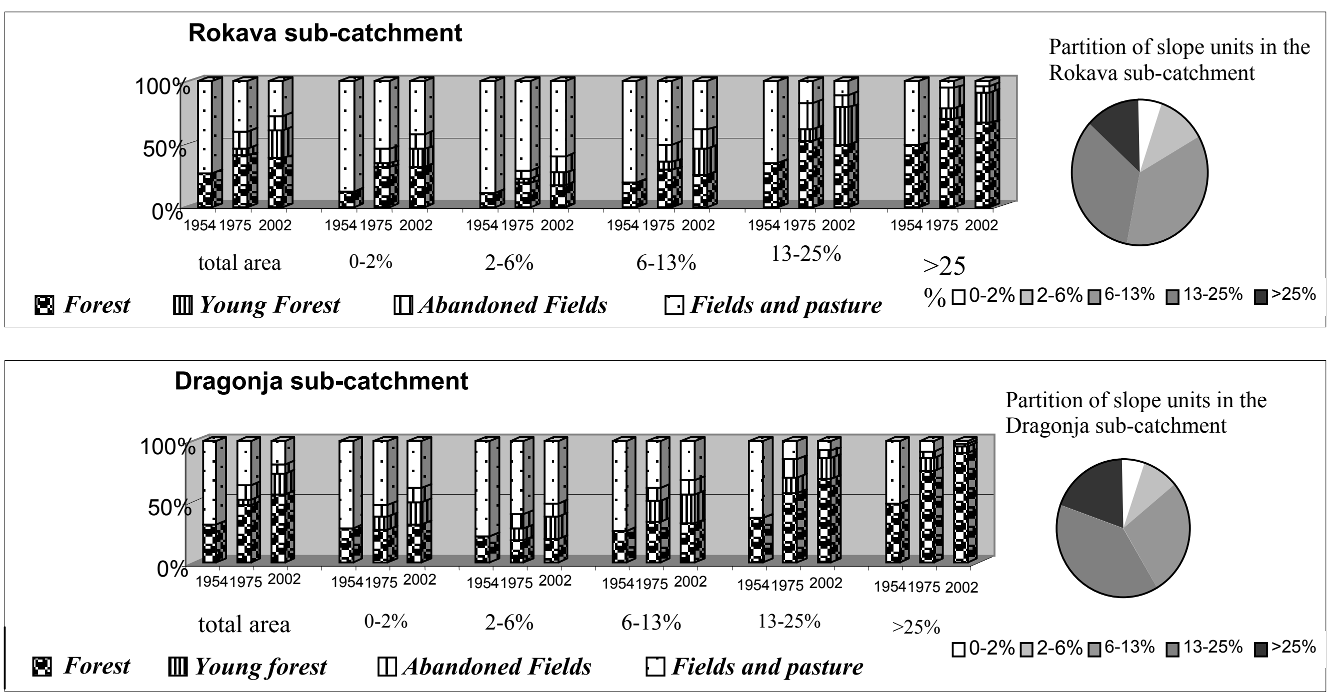

Figure 4.9: Land use distributions for 1954, 1975 and 2002, divided in slope classes as derived from aerial photographs. Pie diagrams show the distribution of the slope classes.

4.4.6.1 C; Cropping factor (Figs. 4.5 and 4.6)

In 1954 the majority of the two sub-catchments, Upper Dragonja and Rokava catchment, was used for agriculture. In the Upper-Dragonja catchment only 29% of the area was forested, of which a large part was located on the steepest slopes. In general the largest change in land use occurred between 1954 and 1975. Also in the period 1975 to 1985 a distinct decrease of agricultural land occurred. However, after 1985 land use did not change much. During the field survey in 2002 we observed that some of the abandoned fields were taken back into use. This suggests that at present the reforestation has come to a halt. Furthermore, important differences exist between the Upper-Dragonja and the Rokava catchment. A large part of the Rokava catchment is still under agriculture. Only 61% of the area was forested (young and mature forest) in 2002 as opposed to 73% in the upper Dragonja catchment. The reason for this difference is the more favourable geographical position of the Rokava catchment to the coastal cities and the gentler slope (Fig. 4.9). The Upper-Dragonja catchment was always less intensely used for agriculture than the Rokava catchment, even on the flatter parts of the catchment. For instance on the unfavourable slope class of 13-25%, 6 % of the Rokava catchment is used for agriculture, while this is only 3 % in the Upper-Dragonja catchment in 2002 (Fig. 4.9).

Associated to these changes is the significant relation between the percentage of fields in the catchment and the discharge at the outlet of the catchment, discharge station Pod Kaštel (Figs. 4.1 and 4.10). The discharge decreases with less agriculture, indicating the effect of increased evapotranspiration due to more trees and shrubs. Similar results of the relation between forest density and discharge were involved to explain changes in river activity and morphology during the Late Glacial times (Vandenberghe, 1995).

4.4.6.2 Calibration of the model output

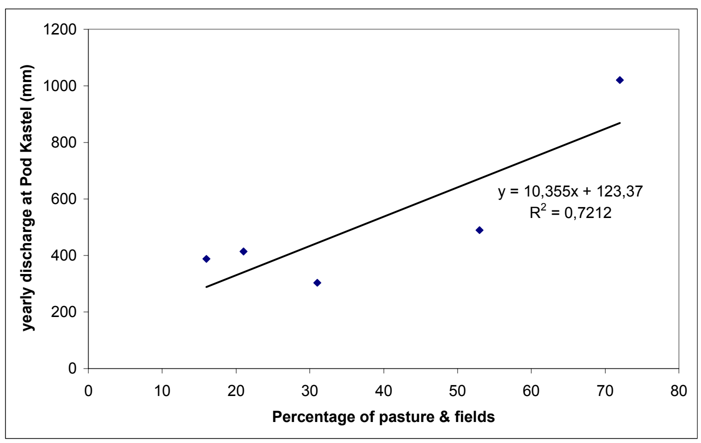

Figure 4.10: Relation between the percentage of fields (Keesstra and van Dam, 2002) and the yearly discharge from the years 1954, 1975, 1985, 1994 and 2002 (HMZ, 2003).

WaTEM/SEDEM requires a transport capacity coefficient (ktc) that varies between different land use categories. However, this value needs to be calibrated first. Land use was subdivided into 6 categories, whereby it is assumed that the first category (forest, beginning forest and abandoned fields) has a low, and the second category (fields, badlands and river bed) has a high ktc-value. There are not sufficient data available to calibrate the high and low transport capacity coefficient separately. Therefore, only one ktc-value was changed and the other was calculated using a fixed ratio of both ktc-values. For central Belgium, the ratio between the ktc for cropland and the ktc for non-eroding surfaces equals 3.3. The same ratio was applied in this study.

To calibrate ktc, the results obtained with model runs using the land use map of 2002 were compared with the estimated total sediment outflow from the catchment in 2002. Regularly, the suspended sediment load was measured in the period October 2000 to April 2004. These measurements give an average suspended sediment load of 0.05 g l^{-1} for low flow (< 0.6 m^3s^{-1}), and 1.2 g l^{-1} for high flow (> 0.6 m^3s^{-1}). The value of 0.6 m^3s^{-1} discharge was determined

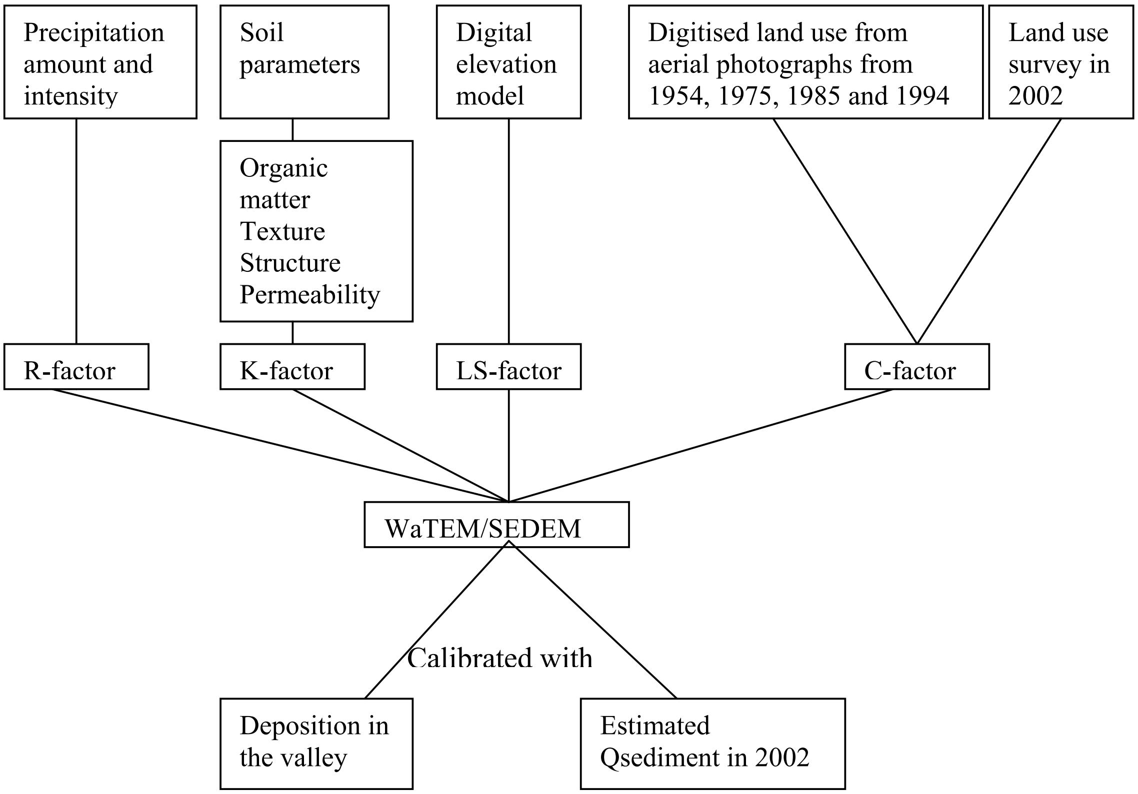

Figure 4.11: Schematic diagram of the used model procedure.

on the basis of the average value of the flex points of the discharge waves in 2002. When these concentrations are used to calculate the total sediment discharge at the outlet in 2002, the latter value equals 4.5 t ha^{-1}. This gives us an idea of the order of magnitude of the current sediment yield.

A second independent calibration was performed with the sedimentation rates on the lowest terrace (0.5 m above the current river). With corings in the overbank deposits on this terrace an average sedimentation rate of 0.75 cm y^{-1} from 1975 till 2002 was estimated (Keesstra, accepted = Chapter 8). The total area of this terrace in the Rokava catchment is 9 ha, which

Table 4.3: Results of the WaTEM/SEDEM model runs with several calibrations and for the separate sub-catchments.

Year	1954	1975	1985	1994	2002	Reduction in sediment outflow from 1954 to 2002
Trimble's 10%/30% of outflow is deposited in river plain (ton ha^{-1})	10%:43.7 30%: 21.2	10%:21.8 30%: 7.7	10%:16.5 30%:6.1	10%:18.2 30%: 7.0	10%:14.8 30%: 5.8	10%: 66 % reduction 30%: 72 % reduction
Calibrated with sediment discharge (Qsed) (ton ha^{-1})	13.9	5.9	4.8	5.5	4.5	67 %
Rokava (calibrated with Qsed) (ton ha^{-1})	12.6	6.9	6.4	7.1	5.9	53 %
Dragonja (calibrated with Qsed) (ton ha^{-1})	14.6	5.3	3.6	4.3	3.5	76 %

corresponds to 450 ton y^{-1} of sediment deposited on this terrace since 1975. The river in the model is one pixel wide (20 m), whereas the actual river is between 5 and 10 m wide.

All sedimentation in this area is not modelled and is part of the outflow in the model results. Trimble (1999) states that 10 to 30% of the river outflow is deposited in the valley. We know the amount of sediment deposited in the valley, and can therefore use this to calibrate the modelled outflow by changing the transport capacity coefficient. The calibrated factors were fixed for all other runs of the model that calculated the erosion response in 1954, 1975, 1985 and 1994. The deposition on higher floodplain lies outside the 20 m zone and is therefore modelled and not used for calibration.
Because Trimble (1999) gives a wide range of 10 to 30 % of total outflow deposited in the lowest floodplain, the results of the model are given for the two extremes (Table 4.3). Furthermore it needs to be taken into account that the results of the study of Trimble in the USA are possibly not entirely suitable for the Dragonja catchment.

6.5 MODEL RESULTS

Even though WaTEM/SEDEM was initially made to model sediment yield in Belgium (Van Oost et al., 2000; Verstraeten et al, 2002), it also proofed to be fairly accurate in Mediterranean climate (Van Rompaey et al., 2005). The model seems to be unfit for mountainous areas. However, for catchments with steeps slopes but relative little height differences, such as the tested Italian catchments and the Dragonja catchment, the model worked well. Figure 4.11 gives a schematic overview of the used model procedure.

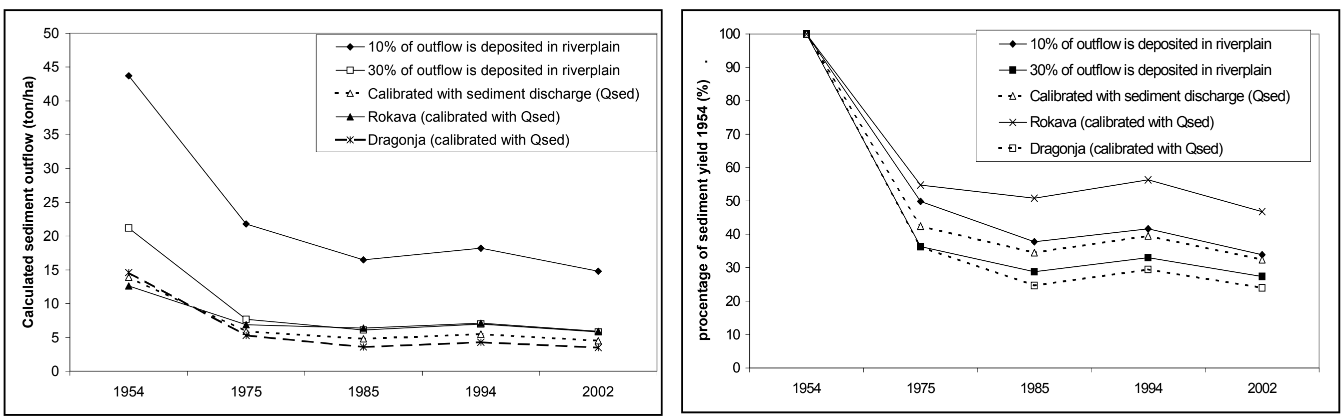

Figure 4.12: Modelled absolute (left) and relative (right) decrease in sediment outflow for the different calibration methods: with 10 or 30% of the sediment outflow deposited in the river plain or with estimated sediment discharge at the river outlet (Qsed)) and for the separate sub-catchments Rokava and Upper-Dragonja.

In the Mediterranean the sediment yields of catchments are very diverse. For catchments similar to the Dragonja catchment, yields range from very minor yields of 0.2 (Italy, Van Rompaey et al., 2005) to extremely high sediment yields of 1750 ton/ha (Amore et al., 2004). With the calibration of Trimble (30% of the sediment is deposited in the valley), the sediment yield in the Dragonja catchment in 2002 is 14.8 ton ha^{-1}. With the same input parameters the sediment yield modelled for 1954 is 43.7 ton ha^{-1}, 72 % reduction, which means a reduction of 72 % in sediment yield in the period 1954 and 2002. When the calibration is done with the calculated annual sediment discharge in 2002, 4.5 ton ha^{-1}, the sediment yield modelled for 1954 is 13.9 ton/ha, a reduction of 67% when the yields of 1954 is compared to 2002 (Table 4.3, Figs. 4.12 left, 4.13).
The sediment outflow calculated with the calibration of Trimble (1999) is always higher than the calculations with the sediment discharge in 2002. Probably more than 30% of the rivers

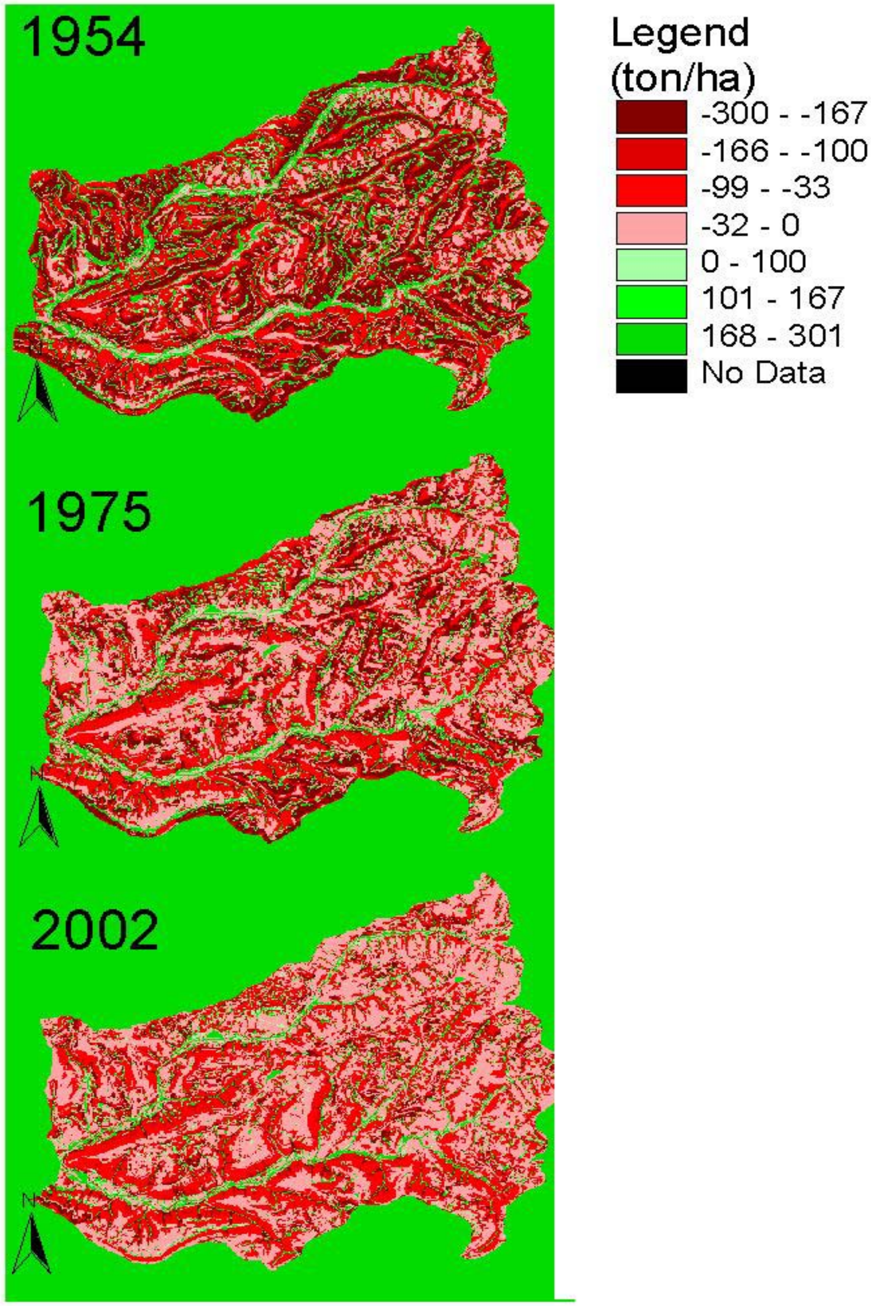

Figure 4.13: Output of WaTEM/SEDEM of the calibration run with the amount suspended sediment discharged in 2002.

sediment load is deposited in the floodplain, which indicates that Trimble's model is not entirely usable for this catchment. As a result of the used calibrations, the range in sediment yields is large. Nevertheless the total sediment yield reduction is consistent to be 69 % +/- 3% for all calibrations.

Separate calculations for the sub-catchments Rokava and Upper-Dragonja show a reduction of 45 % in the sediment yield in the period 1954 to 1975 for the Rokava catchment (Table 4.3). After 1975 the sediment yield stayed more or less stable. In the Upper-Dragonja the largest change occurred also in the period 1954 to 1975. But in this catchment the decrease in sediment outflow continued, making the total reduction 76 % of the sediment outflow in 1954 (Fig. 4.12 right). It can be concluded that the model calculates the relative decrease of erosion. Unfortunately the absolute figures (e.g. for 1954 ranging from 43.7 to 13.9 ton ha^{-1}, Table 4.3) of the erosion are very variable as a result of uncertainties in the input parameters and the used method of calibration.

4.6 Origin of the suspended sediment

The sediment that leaves the catchment originates from three sources, the hill slopes, the erosional cliffs and the channel with its banks.
The sources can be determined by analysing the dynamics of the discharge wave, the hysteresis of the discharge wave, and the suspended sediment texture.

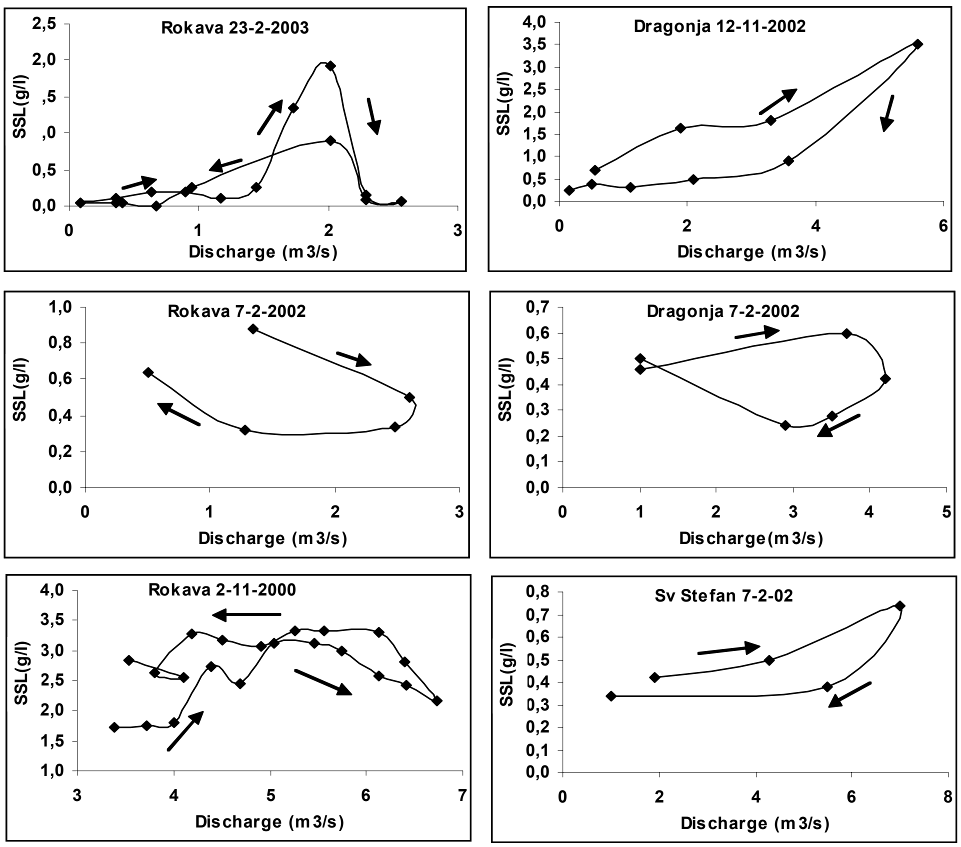

Figure 4.14: Examples of hysteresis diagrams for several floods at the discharge and suspended sediment load (SSL) measuring stations of the outlet of the Rokava, the Upper-Dragonja and the Dragonja River as a whole (Sv Stefan) in 2000 to 2003. Diagrams indicate clockwise hysteresis for most discharge waves, except for the 2-11-2000 flood where anti-clockwise hysteresis was measured at the Rokava measuring station.

4.6.1 Sediment dynamics in the discharge wave

Analysis of the hysteresis effects of the discharge waves gives mixed information.
In most floods a clockwise hysteresis was observed. As described by Seeger et al. (2004) (Central Pyrenees) and Lenzi and Marchi (2000) (Italy), this clockwise hysteresis occurs during 'normal' storm flow conditions, when the catchment soils are moist and runoff generation and sediment supply is limited to areas next to the channel. Counter-clockwise hysteresis occurs during very moist conditions and very high antecedent rainfall conditions. The sediment sources of the whole catchment are incorporated.

As the sub-catchments Rokava and Upper-Dragonja did not reforest in the same way and extent, the sediment yield response is different as well. The Dragonja suspended sediment response is always a clockwise hysteresis response (some examples are given in Fig. 4.14). This means little direct sediment from the hill slopes. The mechanism after the peak discharge is supply limited, whereas before the peak of the discharge wave the sediment supply is transport limited (Nistor and Church, 2005).
In the Rokava sub-catchment most of the discharge waves show the same pattern as the ones from the Upper-Dragonja sub-catchment. But during discharge waves with high antecedent rainfall, especially in autumn, when the fields are bare and the catchment is very moist and susceptible to erosion, the input of sediment from the hill-slopes is sufficient to allow a counter-clockwise hysteresis. It can be argued that this is the result of the more extensive fields in this area. The sediment from the hill slopes can therefore enter the river more quickly than in the Upper-Dragonja, where the hill slopes are more forested. Next to that, the Rokava catchment has more fields next or close to the river that have no retarding elements, such as dense riparian vegetation, in between the sediment producing plots and the river. Another difference between the Rokava and the Upper-Dragonja catchment is the shape of the catchment. The drainage pattern of the Upper Dragonja is mostly denditric, whereas that of the Rokava is more trellis-like. The travel distance for a given detached sediment particle in the Rokava catchment is shorter than in the Upper Dragonja. This may also cause a higher frequency of counter-clockwise hysteresis.
As the sediment source from the hill slopes has reduced since the beginning of the reforestation and this source causes counter-clockwise hysteresis, it is likely that this kind of hysteresis was more common before the widespread reforestation.

4.6.2 Analysis of the suspended sediment texture

The suspended sediment has two sources, the hill slopes and the river banks. The largest contributor are the hill slopes, which provide sediment due to rainfall-induced erosion. The sedimentary riverbanks also contribute their sediment to the river during high stage river flow, because the predominant erosion process is undercutting by river flow. The supply of sediment to the river from large erosional cliffs along the river is largely independent from rainfall, as rock falls and frost and thaw processes are more important.

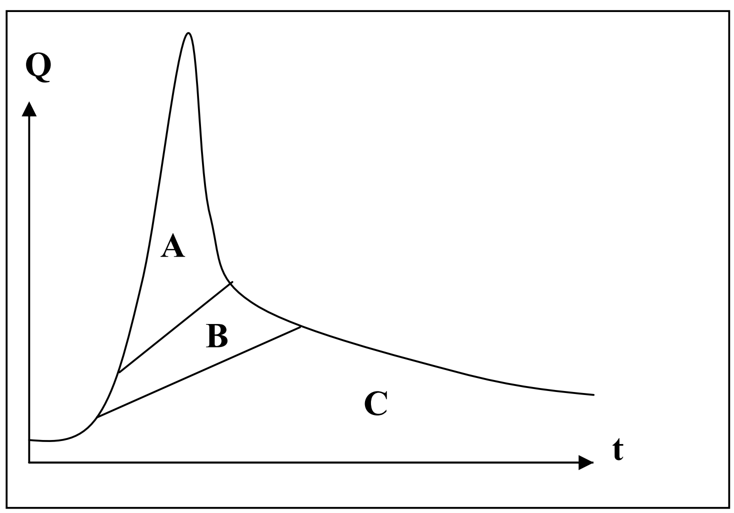

Figure 4.15: Idealised discharge wave with sediment groups indicated by A: undiluted sediment from the hill slopes, with high concentrations of suspended sediment load (SSL). B: sorted (finer) sediment from the hill slopes due to incapable transport, with intermediate concentrations of SSL. C: Sediment from bedrock banks, with very low concentrations of SSL.

When the texture results of the suspended sediment samples (Figs. 4.7, right, 4.15) are compared to the discharge height during sampling, the low stage samples predominantly show a fine-grained texture (group B), the high stage samples have a texture similar to the texture of the slopes (group A) and the middle stage samples predominantly have a relative coarse texture (group C) (Figs. 4.7 right, 4.15). During a flood wave, large amounts of sediment are detached by rainfall from the slopes. At the beginning of the flow wave, slightly sorted, finer, sediment is discharged together with the accumulated sediment at the base of the erosional cliffs (group B, Figs. 4.7 right, 4.15). At peak discharge the hillslope sediments enter the river without sorting (group A). When rainfall stops and discharge starts to drop, the sediment flow retards and larger particles deposit in the channels. Sediment discharged during this part of the discharge wave will therefore be relative fine (group B, Figs. 4.7 right, 4.15). During low stage all available fine material has already flushed through system. The sediment still available to the river is the sediment from the erosional cliffs, which consist of sand, silt and clay stone. The sediment delivered by the cliffs has therefore a wide range in texture. This sediment is transported in very low concentrations during base flow and also during the beginning of the next flood wave (group C, Figs 4.7 right, 4.15). Some samples of intermediate flow are relatively coarse (Fig. 4.7 right). These samples were taken during the rising limb of the discharge wave and therefore partly consist of the material delivered by the erosional cliffs.

The total amount of sediment supplied by the erosional cliffs is of minor importance, compared to the amount of sediment coming from the hill slopes (Keesstra et al, submitted = Chapter 5). However at low flow, when the input from the hill slopes is diminished, this source is percentage wise of importance. This is also evident when the colour of the suspended sediment is evaluated. The low flow samples tend to be greyer, the colour of the bedrock, where the high flow samples are brownish, similar to the soil on the slopes. The bedrock debris consists of coarser material, which is reflected in group C (Fig. 4.7, right). From the field observations and the literature (Russell et al., 2001; Rijsdijk and Bruijnzeel, 1990) it is known that agricultural land (mostly vineyards) provide more sediment (fines) to the river than forested areas. Surface erosion on the forested slopes in the area is considered minimal. Suspended sediment samples taken during the 3-year field survey period from small tributaries with high a percentage of fields in their catchments show an average suspended sediment load of 2.7 g l^{-1}. This concentration is used as the average suspended sediment

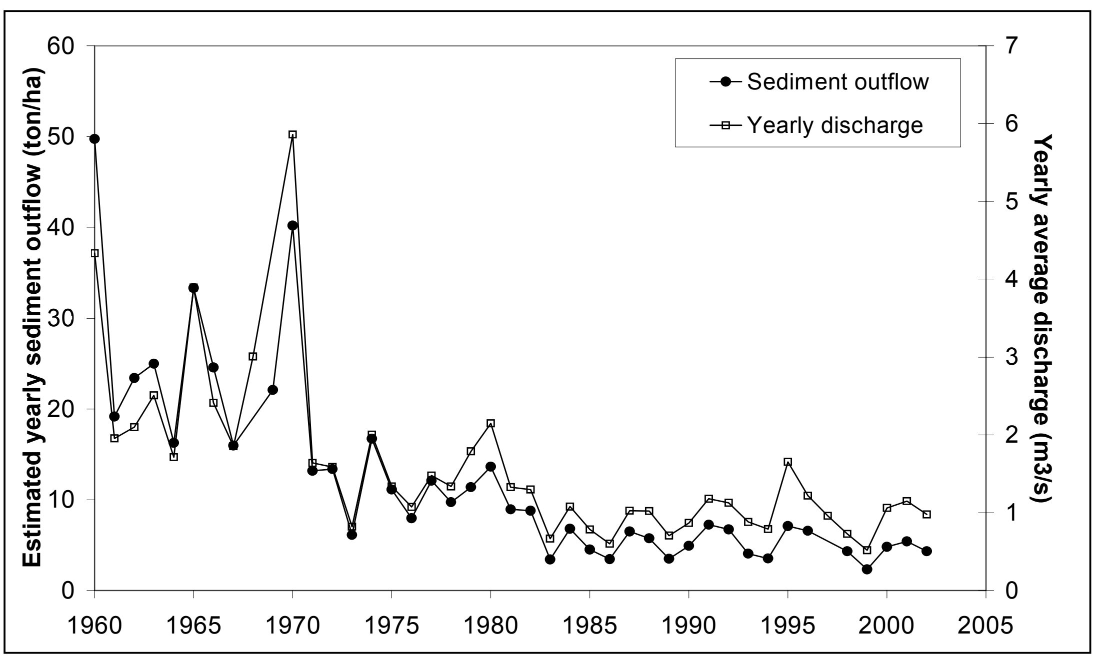

Figure 4.16: Comparison of the estimated yearly sediment outflow and yearly average discharge from 1960 to 2002.

concentration during peak flows in 1960. The average suspended sediment concentration during peak flows in 2002 was 1.2 g l^{-1}. The concentration for the years in between 1960 and 2002 were interpolated. The average suspended sediment concentration during base flow was 0.05 g l^{-1} in 2002. As the small tributaries are ephemeral, we assumed the base flow concentration to have stayed the same. For each year in the period 1960 to 2002 the average flex point of the discharge waves in that year (HMZ, 2003) was calculated. All discharge above this averaged flex point discharge rate was multiplied with the suspended sediment concentration calculated for that specific year. All discharge below the averaged flex point discharge rate was multiplied with the base flow suspended sediment concentration of 0.05 g/l. When the decrease in discharge is compared to the decrease in suspended sediment load, the diagrams show a significantly larger decrease in sediment load (85%) than in discharge (75%; Fig. 4.16). Especially after 1975 the difference in decrease is evident, which coincides with a new incision phase in the morphology of the channel (Keesstra et al, 2005= Chapter 7).

4.7 CONCLUSIONS

The change in land use over the period 1954 to 2002 has had a significant impact on the erosion of the hill slopes in the Dragonja catchment. In 1954 the majority of the catchment was used for agriculture. In general, the most important land-use changes occurred between 1954 and 1975. Also in the period 1975 to 1985 a significant decrease of agricultural land occurred. However, after 1985 the land use did not change much. In the Rokava catchment a larger part of the catchment is still in agricultural use because of its more favourable geographical position to the coastal cities and the gentler slope. Only 61% of the area is forested (young and mature forest) in 2002 as opposed to 73% in the upper Dragonja catchment.

For several calibration runs WaTEM/SEDEM modelled a decline of approximately 69 % +/- 3% in sediment delivery to the river over the period 1954 - 2002. There was insufficient information on sediment yield data available to calibrate WaTEM/SEDEM such that it models the correct levels of sediment yield. Yet, the relative changes in sediment yield due to land use change can be predicted well.

Separate calculations for sub-catchments Rokava and Upper-Dragonja show a reduction of 45 % in the sediment yield in the period 1954 to 1975 for the Rokava catchment. After 1975 the sediment yield stayed more or less stable. In the Upper-Dragonja the largest change occurred in the period 1954 to 1975 also. But in this catchment the decrease in sediment outflow continued, making the total reduction 76 % of the sediment outflow in 1954.

The sediment that leaves the catchment originates from three sources, the hill slopes, the erosional cliffs and the channel with its banks. Hysteresis of the discharge waves and analysis of the suspended sediment texture show the major input source.

As the sub-catchments Rokava and Upper-Dragonja did not reforest in the same way and extent, the suspended sediment response is different as well. The Upper-Dragonja's response is always a clockwise hysteresis response. This means little direct sediment from the hill slopes, but from the vicinity of the river channel. In the Rokava sub-catchment most of the discharge waves also show clockwise hysteresis, but during discharge waves with high antecedent rainfall, the input of sediment from the hill-slopes is sufficient to allow a counter-clockwise hysteresis. As the sediment source from the hill slopes has reduced since the beginning of the reforestation and this source causes counter-clockwise hysteresis, it is likely that this kind of hysteresis was more common before the widespread reforestation.

In contrast, the analysis of the suspended sediment texture suggests that during a discharge wave the suspended sediment originates predominantly from the hill slopes. The sedimentary banks have only a minor input during discharge waves. During low stage, when little sediment is discharged, the sediment in the water column largely originates from the large bedrock banks.

Despite the discrepancy between the two methods it can be concluded that most suspended sediment originates from the hill slopes but is not transported to the river channel at the beginning of a storm. The sediment is first transported to the base of the valley, and during a later stage in the same storm or a next one is transported to the river channel.

PART III: CHANGING RIVER BEHAVIOUR


Chapter 5: Sediment budget, channel-sediment transport and riverine habitats of the Dragonja River, SW Slovenia


Chapter 5: Sediment budget, channel-sediment transport and riverine habitats of the Dragonja River, SW Slovenia

Abstract

As a result of regional depopulation since 1950 the 90 km^2 Dragonja catchment in Southwestern Slovenia gradually became reforested by natural re-growth. As a result, the number of sediment-transporting storm flow events has diminished accordingly. To determine the impact of reforestation on the catchment sediment budget and in-channel sediment transport, the sediment budgets for 1954 (30 % forest) and 2002 (76 % forest) were compared based on monitored or modelled supply and transport of both bed load and suspended sediment. Fine, suspendable, sediment originated from three sources: hillslopes, bedrock banks and older fluvial sediment in stream banks. The coarse, bed load, sediment originated from large bedrock banks, as well as from sedimentary banks and bed erosion.
For in-channel sediment transport, suspended sediment sampling and stone tracing were used. Sedimentary riverbank retreat rates were monitored using erosion pins and bedrock outcrops with erodible banks using photogrammetric techniques. Sediment inputs from the hillslopes were modelled using WaTEM/SEDEM. Stone tracing measurements and suspended sediment sampling indicated that the majority of sediment was transported during large events.
In 2002 erosion on the hillslopes and subsequent outflow of the eroded material from the catchment together made up 90% of the current sediment budget of the Dragonja valley. Riverbed degradation, erosion of sedimentary banks and bedrock banks, accounted for approximately 10 %.
As a result of the reforestation the erosion on the hillslopes over the period 1954-2002 showed a decline of 70%. Inputs of bed load material from bedrock and sedimentary banks decreased by more than 50 %, but this was partly compensated by channel incision. The total reduction in transported bed load over the period 1954-2002 was estimated at 30%. The reforestation has increased the occurrence and duration of low flows, thereby influencing the riverine habitat, fewer pools stay filled during the entire summer which diminishes refuges for aquatic fauna.

Key words: Sediment budget, bed load, suspended sediment, bank erosion, reforestation, hillslope erosion

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5.1 Introduction

For catchment management purposes, it is important to know the basins sediment budget, as well as the river's hydraulic properties (Salo and Cundy, 1987). The amount and kind of sediment transported by a river is largely responsible for the shape and pattern of the riverbed and the associated floodplain (Ashmore and Church, 1998). The channel of the Dragonja River in SW Slovenia (Fig. 5.1) consists partly of bedrock and partly of cobble bed. In summer, parts of the channel usually run dry while in some pools the water remains stagnant. These pools are refuges for the aquatic life in the river. If the riffles confining the pools disappear, or if too much fine sediment is deposited in the pools, their importance as habitats for aquatic fauna diminishes (Milhous, 1998; Rathburn and Wohl, 2003). Due to depopulation, the Dragonja catchment became largely naturally reforested since 1950, which has profoundly changed the fluvial morphology as well as the water and sediment supply to the river. The channel has narrowed by 60 to 70 % in the upper and middle reaches of the river (Globevnik, 1998; Keesstra et al., 2005 = Chapter 7). In addition, daily peak- and mean discharges have dropped by 53 % and 79 % respectively, as a result of the increased evapotranspiration of the growing forest (Globevnik and Sovinc, 1998). Finally, sediment delivery from the slopes to the river decreased by approximately 70 % (Keesstra et al., submitted a = Chapter 4). However, the impact of reforestation on in-channel processes, such as bed load transport, the production of bed load material and suspended sediment (other than from the hillslopes, Fig. 5.2) is largely unknown. To study the effect of reforestation on the sediment budget of the river, the supply and transport of both bed load and suspended sediment material were monitored and modelled for two contrasting situations, viz. 1954 (30% forest) and 2002 (76% forest, cf. Fig. 5.3 below).

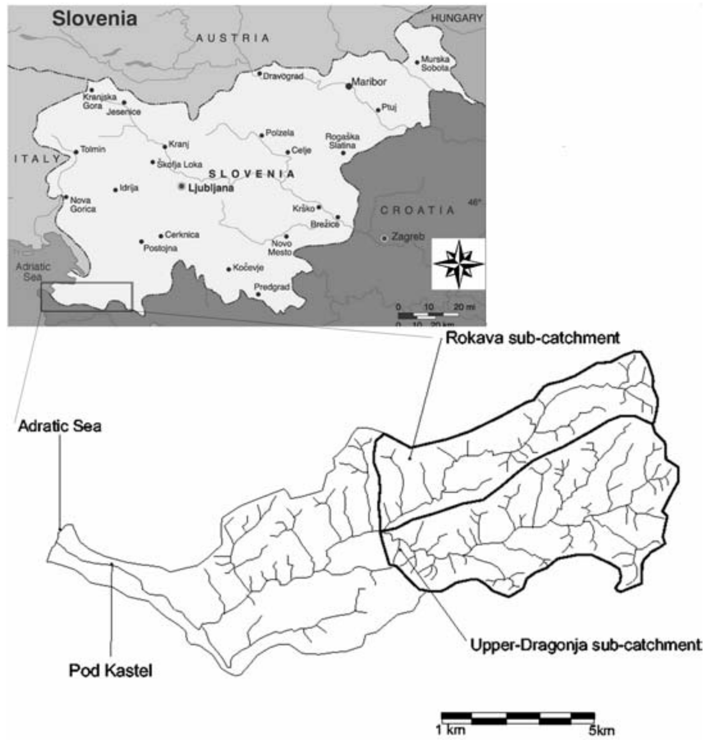


Figure 5.1: Location of the Dragonja catchment, southwestern Slovenia (45°28'N, 13°35'E).

5.2 STUDY AREA

The ca. 90 km^2 Dragonja catchment is situated in the southwestern part of Slovenia at the border with Croatia. The river is ca. 30 km long and elevation ranges from 485m to sea level (Fig.1). The Upper part of the catchment consists of two sub-catchments, the Rokava and Upper-Dragonja sub-catchments (20 and 32 km^2 respectively). The geology is quite uniform and composed of sub-horizontal to gently north-dipping Eocene flysch deposits consisting of highly calcareous and erodible silt and clay stones, with intermittent sandstone layers up to 1.5 m thick (Melik, 1960; Orehek, 1972). The soils are mostly rendzinas or, locally, brown eutric cambisols, with the exception of the valley floors where fluvisols have developed (FAO, 1990; Geološki zavod Slovenije, 2003). The climate of Slovene Istria can be classified as sub-Mediterranean, Köppen-type C_f. The average annual temperature is 14°C at the coast vs. 10°C in the higher, eastern part of the catchment. Absolute daily temperature varies from -10°C to 35°C (HMZ, 2003; Ogrin, 1995). Annual precipitation varies from 700 mm to 1400 mm and increases somewhat with elevation and distance to the coast. The maximum-recorded daily precipitation total is 133 mm. The average discharge at the catchments outlet (Pod Kaštel) over the period 1960-1998 is 1.19 m^{3}s^{-1}. However, the hydrological record shows decreases in peak and mean discharges of 53 % and 79 %, respectively, since 1961(HMZ, 2003). Also there is an increase in the number of days without flow and a decrease in high flow events (Globevnik and Sovinc, 1998, HZM, 2003). The change in the behaviour of the river is caused by the extensive natural reforestation that took place over the period 1950 until present (Fig. 5.3) (Globevnik and Sovinc, 1998; Keesstra et al., submitted a = Chapter 4).

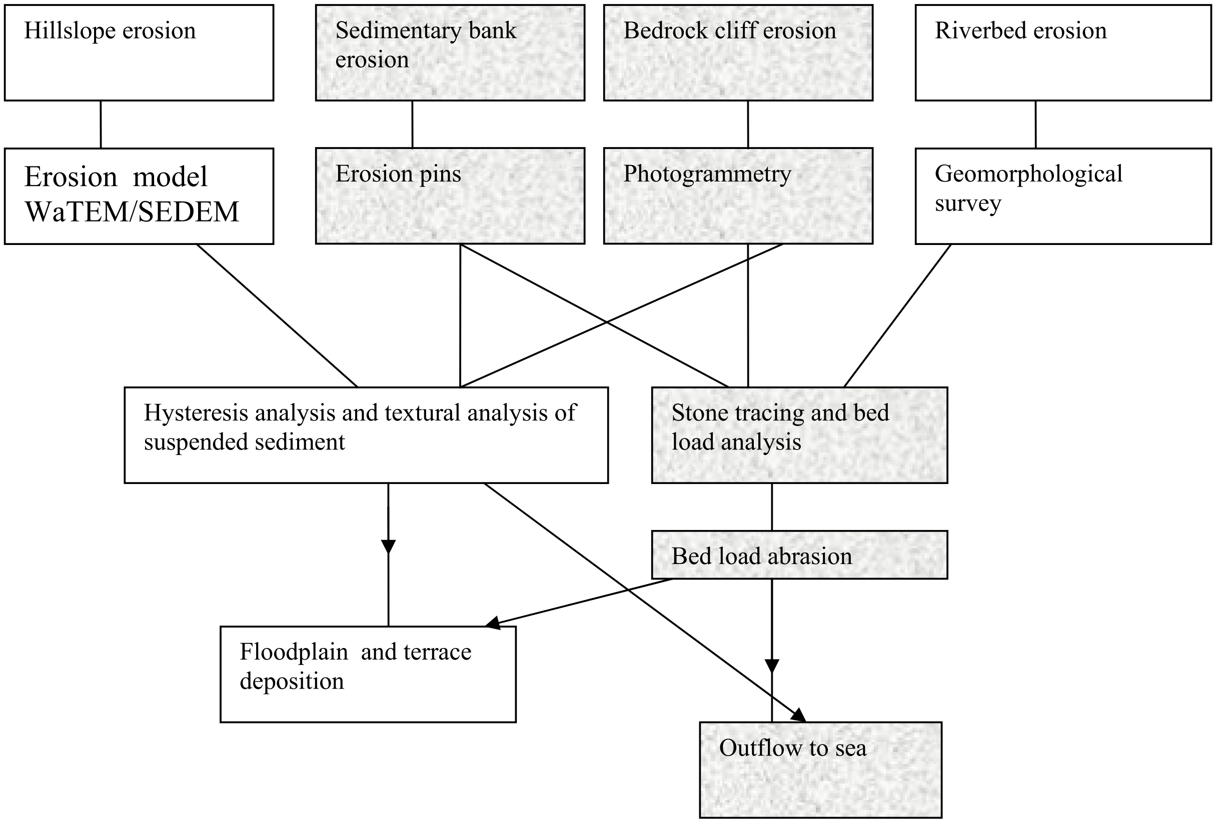


Figure 5.2: Schematic diagram of sediment production and transport in the Dragonja catchment. Grey boxes indicate processes covered by the present investigation.

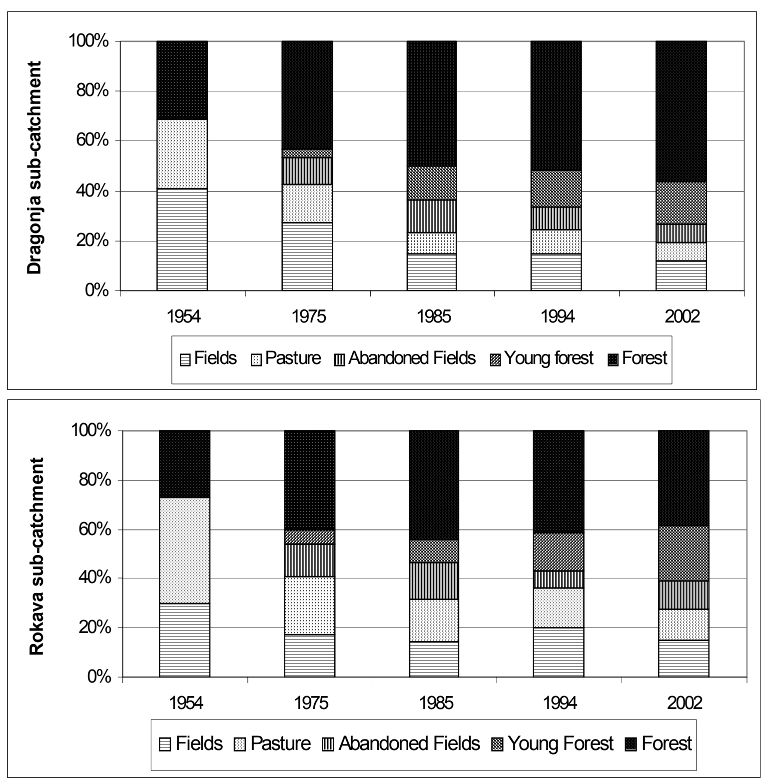


Figure 5.3: Land use (% area) in the Dragonja catchment due to natural reforestation over the period 1954 to 2002 derived from aerial photographs (1954, 1975, 1985, 1994) and a field survey (2002).

The overall morphology of the catchment is characterised by long flat ridges and plateaux with steep slopes at the margins of the valleys. The river has a single channel with low sinuosity. In the upper and middle reaches the river has formed several terraces that are absent in the lower reaches. The youngest two terraces, situated at 1.5 and 0.5 m above the river, were formed very recently, ca. 60 and 30 years ago, in response to the changed hydrology and sediment delivery resulting from the reforestation (Keesstra et al., 2005 = Chapter 7). The banks along the Dragonja and Rokava Rivers consist mostly of overbank sediments and old channel deposits. The upper parts of these banks are made up of silty material, whereas the lower parts of cobbles similar to the ones found presently in the riverbed. However, at several locations the riverbanks consist of bedrock cliffs, which can be up to 50 m high. Total length of these bedrock banks is approximately 1000 m, which is less than 1% of the total length of the riverbanks.

Pool-riffle sequences are typical for all reaches of the Dragonja River (gradient 0.0136 to 0.0032), with the exception of the upper reaches where the morphology can be described as step-pool sequences. Riffles dominate over pools in the upper reaches, whereas in the lower reaches the opposite occurs (Keesstra et al., 2005 = Chapter 7). The bed load has an average size of ca. 6 cm (D_{50}) and a D_{90} of 9.7 cm (Table 5.1). The material typically forms a censored gravel bed, having coarse armour at the top above a finer sub-layer, as described by Church (1996).

The channel in pool sections consists largely of bedrock in the upper reaches. Outcrops of the underlying sub-horizontal sandstone beds determine the position and size of the riffles, which occur downstream of steps created by these beds (Keesstra et al., 2005 = Chapter 7). However, where such steps in the bedrock are far apart, riffles form without being influenced by bedrock structure around so-called key-stones (Zimmerman and Church, 2001).

Site 1: Sv Stefan, ST; stone tracing, ersion pins, cross-section; discharge and suspended sediment measurements
Site 2: Jamnek, JM; bedrock bank stone tracing, pin measurements
Site 3: Čupinje, CU; a: bedrock bank, pin measurements b: stone tracing
Site 4: Mlin, ML; pin measurements
Site 5: Rokava, RK; a: discharge and suspended sediment measurements; b: bedrock bank, pin measurements, 3D photogrammetry
Site 6: Zupančičci, ZP, stone tracing, pin measurements
Site 7: Mrtveč, MR; a: pin measurements, b: discharge, suspended sediment and pin measurements
Site 8: Kost Koper, KK; bedrock bank, pin measurements, 3D-photogrammetry
Site 9: LN; bedrock bank
Site 10: PK; a: bedrock bank, pin measurements, b: stone tracing
A-H indicate river sections where eroding banks were surveyed

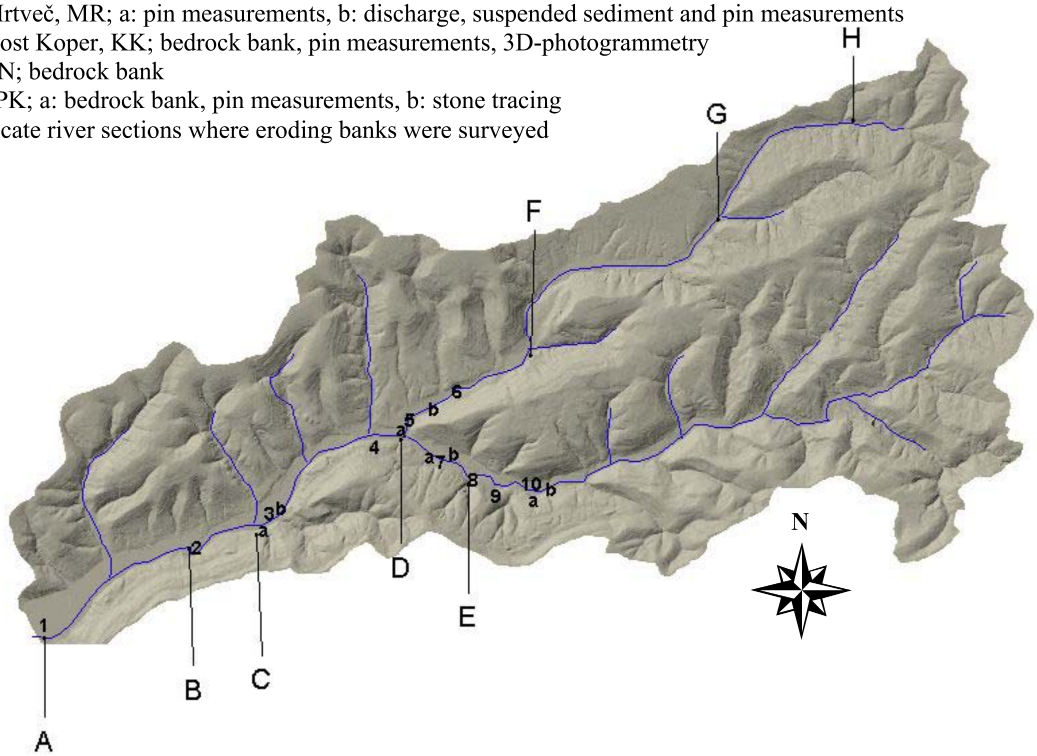


Figure 5.4: Locations of all measurement sites in the catchment. Letters indicate reaches of the river as used for calculation of sediment production by sedimentary riverbanks.

5.3 METHODS

5.3.1 Riverbank erosion measurements

Erosion of the banks along the river was monitored using a total of 128 erosion pins of 30 cm length and 92 pins of 50 cm long distributed among 10 locations (Fig. 5.4). The pins were remeasured 11 times during the period July 2000-June 2003 from which approximate erosion or deposition rates were calculated. As recommended by Cooper et al. (2002) and Lawler (2005) the pins were only remeasured at low water and during dry weather to minimize errors in the

Table 5.1: Morphological and sedimentary characteristics of bed load material at sites ST, JM, CU, PK, and ZP (see Fig. 5.4 for locations).

	ST	JM	CU	PK	RK
Width	20m	25m	12m	6m	5m
Height of banks	5m	1.5-50m	1.5-2.5m	2.5m	1.5-2.5m
Lithology	20% cobbles 90% silt	100%cobbles	100% cobbles	50% bedrock 50% cobbles	20%bedrock 80%cobble
Bedload structure	Isolated riffles	No structure to pool-riffle	Pool-riffle, large pools	Step-pool	Pool-riffle Pool and riffles same size
Bedload size (surface)	D_{50} = 3.9 cm D_{90} = 7.3 cm	D_{50}=5.6 cm D_{90}=9.3 cm	D_{50} = 4.9 cm D_{90} = 8.5 cm	D_{50} = 7.1 cm D_{90} = 10.2 cm	D_{50} = 8.4 cm D_{90} = 13.4 cm
Gradient	0.0032	0.0088	0.0064	0.0139	0.0136

measurements, and negative recordings (indicating deposition) were included in the calculations of the average (net) erosion rates. Five of the locations had sedimentary banks formed in eroding overbank deposits (Fig. 5.4, sites 1, 4, 6 and 7a and b). At each location two or three rows of eight pins were driven into the banks, the exposed part of the pins was measured with 0.1 cm accuracy at each visit. At sites ST and ZP (Fig. 5.4, sites 1 and 6) an additional four sets of two pins were monitored. All sedimentary banks consisted of silty overbank deposits with a cobble stone base. The total surface area of all eroding banks was determined by field mapping. Length and height of the eroding banks were measured and a description of the sediment composition was made (percentage silt, cobbles and/or bedrock). The remaining five sites had their banks formed in bedrock material. These often highly active bedrock banks, which were up to 50 m high, formed debris cones and debris toes at the bottom (Fig. 5.5). An attempt was made to monitor erosional and depositional activity at rill, interrill and debris cone sites using 50 cm long metal pins. At sites JM, CU, RK and KK (Fig. 5.4, sites 2, 3, 5b and 8) numerous (a total of 92) pins were driven into debris cones, but they were frequently buried or even washed away. At sites RK and CU an additional five sets of five pins were monitored for rill-interrill activity. At site PK (Fig. 5.4, site 10a) six sets of four pins were monitored in the accumulating and stabilising debris cone. However, as erosion and deposition were very variable and sometimes very rapid, the results were insufficient. Therefore (3-D) photogrammetric techniques were used as well. The eroding surface area of the large riverbanks was mapped during a field survey. The largest bedrock bank in the catchment, RK (Fig. 5.4, site 5), situated along the Rokava River (the major tributary of the Dragonja), was monitored with 3-D photogrammetry during the period September 2001-August 2002 (Petkovšek, 2002). Part of the second largest bedrock bank, KK (Fig. 5.4, site 8), was monitored in this way on three occasions (July 2001, February and November 2002). During the remaining monitoring time, from July 2000 to June 2003, the RK and KK sites (Fig. 5.4, sites 5b and 8) and the other four major bedrock banks (CU, JM, LN and PK; Fig. 5.4, sites 2, 3, 9 and 10) were monitored using ordinary photography during each of the 11 visits to obtain a first assessment of the magnitude of erosion and deposition.

5.3.2 Stone tracing

Bed load transport rates of medium to coarse-sized particles (> 4 cm) were estimated using magnetically tagged and coloured particles, which were produced and detected using standard methods (Hassan et al., 1984). The sediment transport was calculated as described by Wathen et al. (1997). The bed load transport was measured at five locations (Fig. 5.4). A limited number of stones (ranging from 9 to 165 per site) was used per site to maximise spatial coverage in this very variable within-stream environment. During the measuring period, July 2001-June 2003, three large events occurred. The monitored particles represented the coarse (< 4 cm) to medium (4 - 10 cm) particles of the armour layer.
At two sites, ST and PK (sites 1 and 10b, Fig. 5.4) the traced stones (9 and 13 particles respectively) that were used for tracing represented only the coarse fraction (>10 cm) of the sediment in the channel. At the three additional sites, CU, JM and RK (sites 2, 3 and 6, Fig. 5.4) a larger number of stones (55, 49 and 165 respectively) was used, which included the medium-sized fraction (4-10 cm) of the armour layer. The thickness of the active layer of bed load material was measured at each of the stone tracing sites.

In the middle section of the river (next to site 5a, Fig. 5.4), the bed load was trapped behind a 30 cm high stone weir. The amount of bed load accumulated behind the weir from October 2000 to April 2001 was estimated by volumetric measurements.

The present measurements of stone tracing were limited in terms of duration and number of tracers used. Therefore, the inferred amount of bed load transport is possibly overestimated as both Cudden and Hoey (2003) and Wathen et al. (1997) found that the longer the stone tracing study, the lower the resulting estimated transport rates. Lindsay and Ashmore (2002) reported that, higher amounts of bed load are calculated for higher measurement frequencies. On the other hand, underestimation is also possible as Ferguson (2003) found that simple calculations of averaged transport rates usually give underestimation of overall bed load transport. Furthermore, it is known from field observations that, generally, the stones tend to move quickly through a pool section and more slowly over a riffle. Because most of the present measuring sites were situated on a riffle, the transport rate may have been underestimated. Another important aspect relates to the fact that measured floods are usually of average size, while the impact of a truly large (e.g. the 100-year flood) is generally unknown (Ham and Church, 2000). Because of these opposing considerations, no corrections were applied to the raw data.

Figure 5.5: Bedrock bank along the Dragonja River at site 8 (Fig. 5.4) with (a) large debris cones following a long period of sediment accumulation (15 July 2001) and (b) debris cones removed after a large flood (22 March 2002).

5.3.3 Suspended sediment transport

Suspended sediment was sampled at three locations: at the outlet of the study area (site ST, Fig. 5.4) and the two tributaries, just upstream from the confluence of the Rokava and the Upper Dragonja River (sites RK and MR, Fig. 5.4, sites 5a and 7b). At the latter two sites an ISCO water-sampler (Elscolab 6712 portable sampler) was installed, which was programmed to take samples during storm events at every 5 cm rise or fall in stream water level. However, due to frequent malfunctioning of the instruments only 13 events were sampled, resulting in a total of 178 and 167 processed samples for the Rokava and Upper-Dragonja branches, respectively. At the outlet of the study area a total of 18 samples were manually taken during 3 peak events. At other locations, such as small tributaries and gullies, suspended sediment was sampled occasionally during high stages.

Suspended sediment concentrations were obtained by evaporating the sample on a stove, weighing the residue and dividing the result by the original sample volume (usually 0.5 L). Suspended sediment transport was computed by combining the information on sediment concentrations and discharge (continuous measurements of water level using a Diver pressure gauge [Van Essen Diver] and pressure transducer gauges [Druck Ltd. PDCR-830]). To estimate the annual suspended sediment discharge over the period 1960-2002, the current suspended sediment concentrations were used, together with the discharge data measured at the river outlet, at Pod Kaštel (Fig. 5.1; HZM, 2003). The river samples taken in the period 2000-2004 gave an average suspended sediment concentration of 0.05 g L^{-1} for low flow and 1.2 g L^{-1} for high flows. For earlier years the value of suspended sediment concentrations were assumed to be similar for low flow conditions and somewhat higher for flood discharges, based on measurements of suspended sediment concentrations in gully tributaries draining agricultural fields (ranging from 2.7 g L^{-1} in 1960 down to 1.2 g L^{-1} in 2004). The discharge threshold value for the discrimination between low and high flows was determined per year on the basis of the average value of the inflexion points in the discharge record (HZM, 2003) of each individual year for which the sediment budget was constructed. For the year 2002 a threshold value of 0.6 m^3s^{-1} was used.

5.3.4 Hillslope erosion estimates

The sediment delivery from the hillslopes was calculated using the RUSLE-based erosion model WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al., 2001). The required soil and precipitation parameters plus a Digital Elevation Model were measured in 2002 and partly derived from land cover maps that were based, in turn, on aerial photographs taken in 1954, 1975, 1985 and 1994 (scales 1:5,000 (1954, 1994), 1:10,000 (1985) and 1:17,500 (1975)) and a field survey conducted in 2002 (see Keesstra et al., submitted a = Chapter 4 for details).

5.4 RESULTS

In the following sections the results obtained for the chief components of the present-day catchment sediment budget (cf. Fig. 5.2) are presented. This is followed by the impact of the gradual reforestation on the sediment budget.

Table 5.2: Average bank erosion rates (cm y^{-1}) derived from erosion pin measurements at sites ST, ML, MR1, MR2 and ZP (see Fig. 5.4 for locations).

Location	*Average bank erosion rate (cm y^{-1})*
ST	0.9
ML	7.5
MR1	6.4
MR2	6.8
ZP	6.2

5.4.1 Bank erosion

5.4.1.1 Sedimentary banks

The dimensions of eroding sedimentary banks were surveyed along several sections of the river channel (sections C-D-E, D-F and upstream of H, Fig. 5.4)

Table 5.3: Total volume of sediment eroded (m^3) from sedimentary riverbanks in 2002. The area of erodable banks was multiplied by an average of the measured erosion rates.

River reach (Fig. 5.4 for location)	*Reach length (m)*	*Erodible bank area ($m^2\ m^{-1}$)*		*Erodible bank (m^2)*		*Total area of erodible bank (m^2)*	*Erosion rate ($cm\ y^{-1}$)*	*Total volume of eroded sediment (m^3) (silt/cobbles)*
		Silt	Cobbles	Silt (m^2)	Cobbles (m^2)			
A-B** (ST-SV)	2,440	0.4	0.01	976	24.4	1,000	0.9	9 (9/0)
B-C** (SV-CU)	3,100	0.33	0.5	1023	1,550	2,573	6.7	172 (69/103)
C-D-E* (CU-KK)	2,850	0.33	0.74	940.5	2,109	3,050	6.7	204 (63/141)
Upstream of E** (>KK)	6,760	0.2	0.4	1352	2,704	4,056	6.7	272 (91/181)
D-F*	2,300	0.18	0.07	414	161	575	6.7	39 (28/11)
F-G**	4,350	0.18	0.07	783	304.5	1,088	6.7	73 (53/20)
G-H**	2,920	0.05	0.07	146	204.4	350	6.7	24 (10/14)
Upstream of H*	1,423	0.05	0.07	71.15	99.61	171	6.7	11 (4/7)
Small tributaries	9,300	0.01	0	186	0	186	6.7	12 (0/12)
Total	26,143			5,892	7,157	13,049		816 (338/478)

* measured during field survey

** extrapolation

over a total length of 11.5 km. Together, the sections represent 1425 m^2 of silty erodible bank material, and 2370 m^2 of cobbled banks. For extrapolation purposes, the length of the remaining, unsurveyed, channel parts were determined using a GIS and categorised in sections that were comparable to the measured reaches. The bank area of the lowest reach (A-B, Fig. 5.4) was estimated separately, as this part of the river was morphologically different. The area of erodible bank area in the lower reach was estimated from a cross section measured at site ST (site 1, Fig. 5.4) and the length of the reach. For the entire river reach a total of 5700 m^2 of silty and 7160 m^2 of cobbled banks was obtained. The pin-based bank erosion rates measured in the middle and upper parts of the river were remarkably similar (Table 5.2). Therefore, the average erosion rate of 6.7 cm y^{-1} was used for the calculation of the total amount of eroded bank material for all sedimentary sections, except for section A-B where the average erosion rate as measured at location ST was much lower, 0.9 cm y^{-1}(Table 5.2). The total amount of sediment eroded from the sedimentary banks was estimated at 816 m^3y^{-1}, of which 478 m^3y^{-1} consisted of cobbles and 338 m^3y^{-1} of silt (Table 5.3).

Table 5.4: Sediment supply from bedrock banks along the Dragonja and Rokava Rivers in 1954 and 2002. The area of cliffs in 1954 (before reforestation, estimated from aerial photographs) and 2002 (after reforestation, measured in the field) are multiplied with the measured erosion rate.

Cliffs (Fig. 5.3 for location)	*Estimated area of cliff in 1954 (m^2)*	*Measured* erosion in 1954(m^3y^{-1})*	*Current area of cliff (m^2)*	*Estimated erosion in 2002 (m^3y^{-1})*	*Change in sediment supply to river (m^3)*
CU	950	67	600	46	20
JM	1900	133	1400	98	35
RK	5000	352	3200	224	126
KK	2200	154	1300	91	63
LN	800	56	320	23	34
PK	1600	115	820	57	55
currently vegetated cliffs Rokava	3000	210	0	0	210
currently vegetated cliffs Dragonja	4000	280	0	0	280
Total	19,450	1,365	7,700	540	825

* Erosion rates measured, area of bedrock banks estimated during field survey

5.4.1.2 Bedrock banks

The sediment-generating processes on the debris toes and cones accumulating below the bedrock cliffs (Fig. 5.5) were generally too rapid and irregular to be measurable with erosion pins. Based on 3-D photogrammetry and photo repeat-interpretation an average of 315 m^3y^{-1} of eroded material was estimated to have been generated by bedrock banks RK (224 m^3y^{-1}, site 5 in Fig. 5.4) and KK (91 m^3y^{-1}, site 8 in Fig. 5.4) during the period July 2000 to June 2003 (Table 5.4). For the other bedrock banks a total of 225 m^3y^{-1} was estimated, bringing the overall volume of sediment generated by bedrock cliffs and banks to 540 m^3y^{-1} (Table 5.4). Petkovšek (2002), also using 3-D photogrammetry, reported that from the large bedrock bank at site RK (site 5b in Fig. 5.4) along the Rokava River, about 500 tonnes (190 m^3) of sediment was eroded during the period September 2001 to August 2002. The data collected by Petkovšek (2002) might be an underestimation of the actual erosion, as the measurements at the beginning and end of the survey period, were not made on a representative moment. Even though the associated amount of precipitation was about average (1032 mm), a large proportion fell in summer, which did not result in major discharge events. Therefore, a relatively large volume of sediment had accumulated at the base of the bedrock bank by the end of the measuring period. Furthermore, one month prior to the start of the measurements of Petkovsek (2002), an exceptionally large flood event had removed all loose material lying at the base of the cliff.

One bedrock bank was found to be stabilizing (site 9 (LN), Fig. 5.4). As a result of the narrowing river channel the debris cone at the base of this cliff had become less exposed to erosion by peak flow events. An average deposition rate of 17 cm y^{-1} was obtained for this site with pin measurements at the middle and lower parts of the debris cone. Possibly large volumes of the currently deposited sediment will be transported downstream during a large flood.

5.4.2 Bed erosion

Due to the reforestation the river incised into its older bed (Keesstra et al., 2005 = Chapter 7). As a result a large volume of predominantly coarse sediment has come available for transport. From GIS analysis a total of ca. 46,000 m^3 sediment was estimated to have been eroded from the channel bed since 1975, which is equivalent to 1700 m^3y^{-1}.

5.4.3 Hillslope erosion

The sediment delivered to the river by the hillslopes only consists of fine material and is carried in suspension by the Dragonja River. In 2002 was the amount of suspended sediment transported by the river was estimated at 4.5 ton ha^{-1} (or 25,300 m^3y^{-1}; Keesstra et al., submitted a = Chapter 4) from which the majority originates from the eroding hillslopes.

Table 5.5: Bed load transport rates at sites ST, JM, CU, RK and PK as calculated from stone tracing measurements. Average particle movement multiplied with the active layer depth, the average particle size and the river width. The recovery rate is indicated together with the number stones of used per site (n).

Stone tracing line	Depth active layer (m)	D_{50}/D_{90} of measured stones (cm)		Recovery rate (%) (number of used stones (large/s\mall)	Average width of river section (m)	Average stone movement (m y^{-1}) and standard deviation		Derived sediment transport rate (m^3y^{-1})
		Large	Small			Average	SD	
ST	0.2	2.7/	-	89 (n=9)	8.9	1.8	1.3	3
JM	0.4	12.0/17.0	7.1/9.7	81/86 (n=21/34)	25	4.3 10.7	5.7 14.9	75
CU	0.3	12.5/16.8	7.1/9.5	88/85 (n=16/33)	12	32.7 27.0	31.7 25.1	108
ZP	0.10	12/15	7/10	40/70 (n=12/153)	4	21* 9.8**	17.4 14.6	24* 7**
PK	0.15	9.2/12.5	-	100 (n=13)	6.8	16.2	8.6	17

*unreliable
** only minor flood

5.4.4 Sediment transport

5.4.4.1 Bed load

At site ST (site 1 in Fig. 5.4), which represents the lowermost reach of the Dragonja River, a bed load transport rate of 3 m^3y^{-1} was found as calculated from tracer stone movement during major flow events occurring between July 2001 and June 2003 (Fig. 5.6a).

Stone tracing sites CU and JM (sites 2 and 3 in Fig. 5.4) represented the middle part of the river. For site CU an average bedload transport rate of 108 m^3y^{-1} was calculated over the period July 2001 to June 2003 vs. 75 m^3y^{-1} at site JM (Table 5.5). Two clusters of stones could be distinguished at site CU that coincided morphologically with the location of two riffles (Fig. 5.6c). After transportation during floods the stones were deposited preferably on the riffles, even though the bed in the pool between the two riffles also consisted of cobbles. At site JM, where the morphological structure is poorly developed, no preferential deposition of particles was observed (Fig. 5.6b).

The upper part of the Dragonja River (i.e. upstream of section E) was represented by stone tracing site PK (site 10b in Fig. 5.4). The inferred bed load transport rate at PK was low (17 m^3y^{-1}, Table 5.5) due to the relatively small amount of bed load material present. The bulk of bed load material was supplied to the river downstream of this site, where the river passes the large bedrock banks at sites LN, KK, CU and JM (Fig. 5.4). Furthermore, little additional sediment was provided by bed incision in the upper stretches because large parts of the channel consisted of solid bedrock. The step-pool structure found in this reach may also have influenced the transport rate. A step-pool structure can be very stable due to the key-stones forming the step, thereby ensuring the stability of smaller stones even under flow conditions

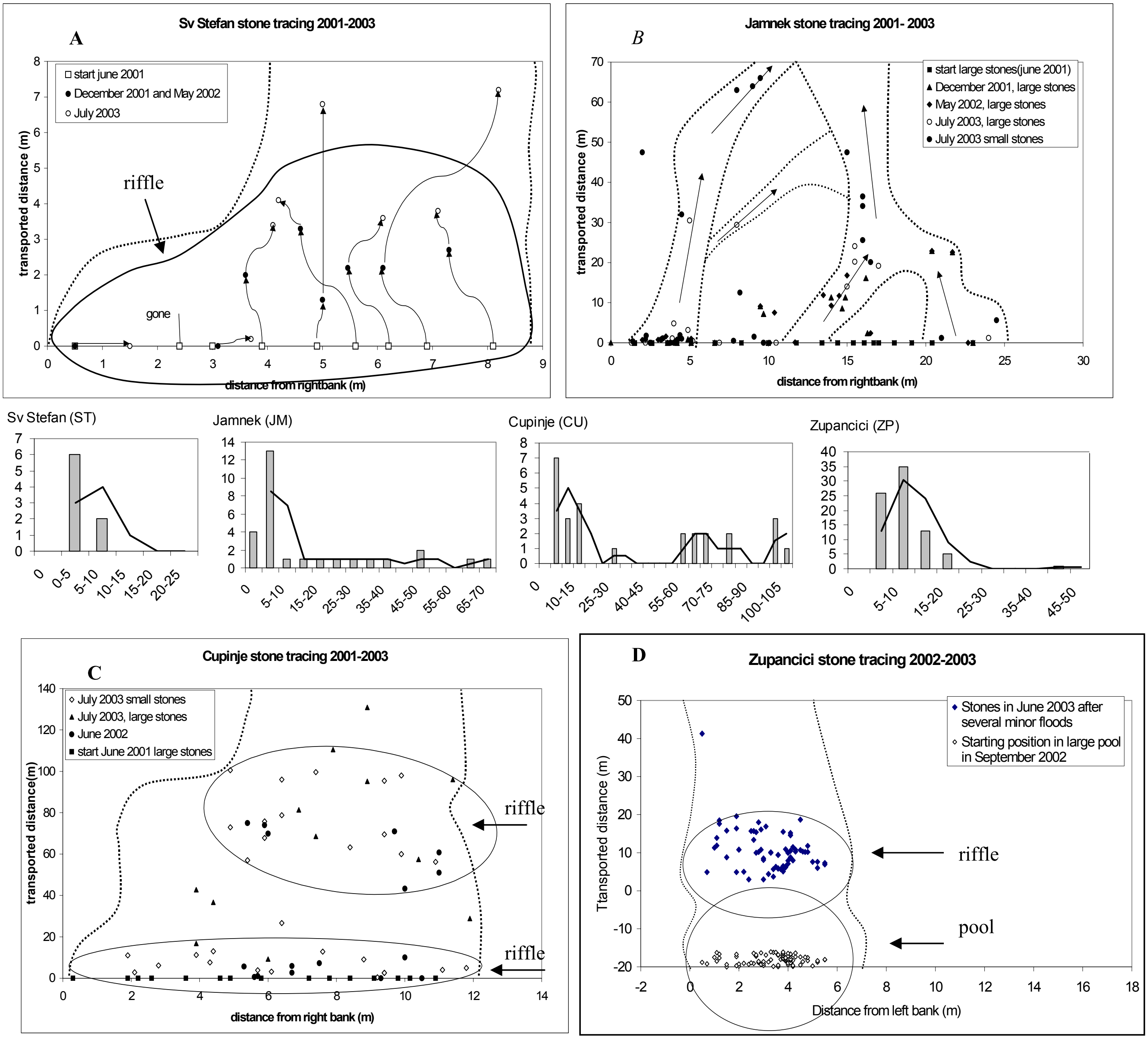


Figure 5.6: Bed load transport at sites ST (a), CU (b), JM (c) and ZP (d). Dotted lines indicate riverbanks. Ellipses roughly indicate morphological features such as pools and riffles. Histograms of travelled distances indicate size-selective transport at sites ST, JM, and ZP. At site CU (b) no such size selective transport occurred (see text for explanation). The histograms in the middle section of the figure show the frequency of occurrence of transported tracers (y-axis) in a section of the river that is a specific distance (m) from the starting line (x-axis).

that would normally have been able to move these smaller stones (Zimmerman and Church, 2001).

At site ZP on the Rokava tributary (site 6 in Fig. 5.4), two sets of stones were used. The proportion of recovery for the first set, which was exposed to all three major floods occurring between July 2001 and June 2003), was very low (Table 5.5), rendering the derived transport estimate (24 m^3y^{-1}) potentially doubtful. Nevertheless, the rate is similar to that observed at site PK on the Dragonja branch (17 m^3y^{-1}). The other set of stones at site ZP only experienced

only small peak events; hence the inferred transport rate measured was rather low at 7 m^3y^{-1} (Table 5.5).
A second, independent estimate of bed load transport at site RK on the Rokava branch (site 5a in Fig. 5.4) was made over the period October 2000- April 2001, during which five major peak events (Q > 15 m^3s^{-1} for the Dragonja branch and Q > 4 m^3s^{-1} for the Rokava branch) occurred. During this period ca. 25 m^3 of coarse sediment accumulated behind the weir at site RK, which is very similar to the estimate for the nearby site ZP.

5.4.4.2 Suspended sediment transport
The majority of sediment input to the channel consists of fine material (96%). The rest of the sediment enters the river in the form of larger sized particles. The suspended sediment transported by the Dragonja has two main sources: hillslopes and river banks. The largest contributors were non-forested hillslopes, which supplied sediment via rainfall-induced erosion (91% of the total input in 2002). Sedimentary banks also contributed fine sediment to the channel during high stages of river flow, but the amounts involved were considerably lower (3% in 2002). The supply of fine sediment to the channel from large bedrock cliffs (2% of the total input in 2002) occurs continuously during the long periods in between floods. Sediment falling off the bedrock banks is partly discharged directly in suspension. But the majority is stored in debris cones at the base of the bedrock banks. During times of floods these debris cones are flushed away (Fig. 5.5). However, compared to the amount of sediment coming from the non-forested hillslopes during major storms, this source is of minor importance. At low flow stages, when there is little sediment in the water column and no input from the hillslopes, the bedrock banks are, relatively speaking, an important source of suspended sediment (Keesstra et al., submitted a = Chapter 4).
The total suspended sediment outflow from the catchment in 2002 as estimated from measured suspended sediment concentrations amounted to 4.5 ton ha^{-1}.

5.4.5 Catchment sediment budget
The input sources are the hillslopes (contributing approximately 90.7 % of the total sediment input in 2002), the riverbanks (5% in 2002) and bed degradation (4.3 % in 2002). The majority of the sediment is transported out of the catchment (90%); the rest is (temporary) stored on floodplains and terraces (10%) (Keesstra et al., submitted a = Chapter 4).
The approximate sediment budget constructed for the year 2002 of the total sediment leaving the catchment 4.5 ton ha^{-1} was carried in suspension. As all sediment breaks down before leaving the catchment there is no bedload leaving the catchment. Contributions to the total output of the 4.5 ton ha^{-1} were as follows: (i) erosion from the hillslopes 4.5 ton ha^{-1}; 90.7%); (ii) erosion of sedimentary banks (0.15 ton ha^{-1}; 3%); (iii) erosion from bedrock banks (0.1 ton ha^{-1}; 2%) and (iv) bed incision (0.2 ton ha^{-1}; 4.3%). Together these sources make up 4.9 ton ha^{-1}, the excess input (10%) was stored in depositions within the catchment.

5.5. DISCUSSION
5.5.1 Sediment supply
Sediment generated on the hillslopes is mostly the result of overland flow induced erosion. All sediment from this source is produced during flood events. Furthermore, the sedimentary banks are undercut during flood events and then provide sediment to the channel. During low flows this source was negligible. During the long periods in between floods sediment continues to be delivered by the bedrock banks and cliffs. The supply of sediment to the channel from the bedrock banks was largely independent from rainfall, because slope processes proved more important according to field surveys carried out between October 2000 and July 2003. Rock fall is demonstrated in two ways: continuous rock fall of small particles

that break off the cliffs as a result of weathering, and large rock falls, where larger blocks of bedrock break off and fall into the river channel. During the long periods between peak flow events, debris toes were observed to accumulate at the feet of the bedrock banks as a result of continuous rock fall (Fig.5a). During frost periods the accumulation rate became particularly high, as a result of freeze-thaw processes to which the flysch bedrock is very susceptible. During flood events the accumulated sediment is carried away (Fig. 5.5b). Therefore, the size of the debris toes is largely dependent on the time elapsed since the last major discharge event. In contrast, rock fall events appeared to occur independently from individual floods. Although the river undercuts the bedrock banks, this had no immediate effect on the stream sediment load.

In the Mediterranean the sediment yields of catchments are very diverse. For catchments similar in geology and land use to the Dragonja catchment, yields range from very minor values of 0.2 ton ha^{-1} (Van Rompaey et al., 2005), to intermediate values of 10-20 ton ha^{-1} (Fouache, et al., 2001), to extremely high sediment yield of 1750 ton ha^{-1} (Amore et al., 2004).

5.5.2 Sediment transport

The bed load transport inferred from the stone tracing measurements in the lower reaches of the Dragonja (site 1, ST in Fig. 5.4) must be considered an underestimation, because the measurements were performed on a riffle and no stones were found in pools. This suggests that in the lower reaches transport in the pools is very rapid. Secondly, the total amount of movable bed load is limited, because most of the bed load has disintegrated before reaching this part of the river (cf. Chapter 6).

The two sites, JM and CU, in the middle reach of the Dragonja (sites 2 and 3 in Fig. 5.4) were situated relatively closely together, but the transport rates differed considerably (Table 5.5, Fig. 5.7). There are two possible reasons for the low transport rate at JM compared to CU. Firstly, a few large rocks at site JM did not move at all which lowered the average transport rate. Secondly, JM was situated below a large bedrock bank where the channel received fresh bed load material, both coarse (> 4 cm) and small-sized (< 4 cm) material. The latter used part of the transport capacity of the river, thereby lowering the transport rate of the measured larger stones (cf. Carbonneau and Bergeron, 2000; Batalla and Martín-Vide, 2001).

The bed load transport rates were temporally and spatially very variable. The majority of transport took place during major flow events. Bed load material moved through the valley from riffle to riffle. The material moved slowly from one end of a riffle to the other and was then transported rapidly through the pool to the next riffle. The rapid sediment movement in pools was facilitated by the low friction afforded by the flat, even bedrock surfaces in the (mostly upstream) channel. This theory is supported by the presence of few stones in the pools as well as by the bed load measurements (Fig. 5.6 and Table 5.5).

Sediment transport activity within poorly sorted gravel beds is partly dependent on grain size. If movement is size-selective, finer fractions will be transported further and more frequently than coarser material. If all size fractions are equally mobile once a threshold flow is exceeded then fractional contrasts would not be so obvious (e.g. Ashworth and Ferguson, 1989). Both processes are reflected by the present measurements. Size-selective transport is shown by the results of the stone tracing in reaches PK (Upper Dragonja), JM (Middle Dragonja) and ST (Lower Dragonja) which all show a typical, positively skewed path length distribution (middle section of Fig. 5.6). This implies that the discharge responsible for transport in these reaches took the form of low-intensity (or short) events (Hassan and Church, 1992; Schmidt and Ergenzinger, 1992). Only in the lower middle reach (at site CU, middle section of Fig. 5.6) the discharge exceeded the threshold associated with the transport of all particles. These then become influenced by, and contribute to, the development of a distinct morphological

Figure 5.7: Photograph of a piece of representative bedrock bank. The white blocks indicate the sandstone layers that typically deliver bed load to the channel and which make up ca. 30 % of the total volume of bedrock. The rest of the bedrock consists of clay and silt stones which contribute to the suspended load of the river.

character of the channel, such as riffles (Pyrce and Ashmore, 2003). This is shown by the clustered deposition of stones at site CU (Fig. 5.6c).

The large differences in bed load transport rate inferred for the different river reaches (Table 5.5) were party influenced by the different pulses of sediment going through the river system and reflecting different processes. Firstly, bed load transport itself is not a steady-state process and natural bed load pulses are evident in every river system (Taconi and Billi, 1987). Secondly, the bedrock banks produced more sediment during the winter period, especially during frost periods, which tend to vary in intensity from year to year. Thirdly, the river system may be adjusting itself as a result of the changing inputs of water and sediment supply as the vegetation biomass continues to increase (Globevnik, 1998; Keesstra et al., submitted a = Chapter 4; cf. Church, et al., 1998).

5.5.3 Sediment output

Most of the generated sediment is transported out of the catchment (90% in 2002). The rest of the sediment is (temporarily) stored on floodplains and terraces. The amount of sediment stored on the floodplain and terraces was estimated using ^{137}Cs measurements and GIS analysis of the valley (Keesstra, accepted = Chapter 8). Over the period 1986 to 2001 an average of 3,600 m^3y^{-1} (or 0.64 ton ha^{-1}) was deposited on the terraces and floodplains.

5.5.4 Effects of reforestation on catchment sediment budget and riverine habitats

5.5.4.1 Introduction

The gradual reforestation of the slopes of the Dragonja catchment since 1945 affected the magnitude of all components of the catchment sediment budget. By 2002 flood frequency had decreased by 60% (Keesstra, accepted = Chapter 8) and flood magnitude by 50% compared to the values for the years 1960-1970 (Globevnik et al., 1998; HZM, 2003). As such, both the

river's transport capacity as well as its ability to erode its banks and bed greatly diminished over the years. In addition, the improved vegetation cover of the hillslopes greatly reduced the generation of overland flow and thus surface erosion and sediment supply to the streams.
In the following paragraphs the present-day catchment sediment budget is compared with that for the year 1954 when forest cover was only 30% and hillslope erosion still widespread (Globevnik et al., 1998), in an attempt to assess the overall effect of the natural regrowth of the vegetation.

5.5.4.2 Effects on bank erosion

Due to the decreased flood height and frequency the erosion of sedimentary banks in the period before reforestation was assumed to be at least twice the rate measured in the period 2001 to 2003. This resulted in a rough estimated erosion rate of 15 cm y^{-1} for the sedimentary banks using calculations along the line of Table 5.3, which gave a total amount of eroded sediment of 1800 m^3y^{-1} (750 m^3y^{-1} silt, 1050 m^3y^{-1} cobbles; Table 5.6) compared with 825 m^3y^{-1} (390 m^3y^{-1} silt, 472 m^3y^{-1} cobbles) in 2002 (Table 5.3).

As for the erosion of bedrock banks, aerial photographs show that before reforestation the number of actively eroding banks was greater while currently active banks were larger (Table 5.4). Trees were planted in the 1950s as anti-erosion measures on some of the bedrock banks (Globevnik, 1998). Moreover, due to the decreased flood height and frequency the bedrock banks are currently less susceptible to undercutting because of the smaller erosive force of the river. In addition, as the channel narrows, debris cones at the base of the bedrock banks are increasingly stabilised and protected by vegetation. As such, the erosion intensity on active bedrock cliffs is largely independent of the discharge characteristics of the river. Consequently, the erosion rate per area of bedrock cliff was assumed to have remained the same. From aerial photographs an estimate of the total area of bedrock cliffs in 1954 was made and multiplied times the erosion rate measured in 2002 (0.03 m y^{-1}), giving an estimate of the total volume of eroded sediment in 1954 (Table 5.4). The amount of sediment delivered to the stream by the bedrock banks was estimated to be reduced from 1365 m^3y^{-1} in 1954 to 540 m^3y^{-1} in 2002, a reduction of 60%. The fraction of sandstone in the bedrock, which provides the bulk of the bed load material, is approximately 30% (Fig. 5.7). The remaining 70 % of the bedrock consists of silt- and clay stones which immediately break down into fine sediment that is transported in suspension and accumulated temporarily in the debris cones at the base of the bedrock banks (cf. Fig. 5.5).

Table 5.6: Changed bed load production due to reforestation. 1954: sedimentary banks produced more cobbles than in 2002: total of 1900 m^3 y^{-1} eroded material, 1050 m^3 y^{-1} cobbles. Bedrock banks produced more material than in 2002: 410 m^3 y^{-1} for 1954, 162 m^3 y^{-1} for 2002. The reduction in bed load is partly compensated by incision of the riverbed, in 1954 no incision, in 2002 162 m^3y^{-1}.

Bedload source	1954 (m^3y^{-1})	2002 (m^3y^{-1})
Sedimentary banks	1050	478
Bed incision	0	515
Bedrock banks	410	162
Total	1460	1155

5.5.4.3 Effects on the supply of bed load material and its subsequent transport

As a result of the reforestation the bed load material supply by sedimentary and bedrock bank erosion has decreased (Tables 4 and 6). However, a decrease in the supply of bed load material can induce a river to incise into its own bed (Rinaldi, 2003; Liébault and Piégay, 2001), thereby introducing a third source of bed load. Information on timing and dimensions

of recently formed terraces in the area (Keesstra et al., 2005 = Chapter 7) was used to estimate the total area affected by channel incision since the beginning of the reforestation. The depth of incision was determined during a field survey. A total of 515 m^3y^{-1} of material was estimated to have become available for bed load transport as a result of channel incision since 1975.
With the information on coarse sediment production through bed incision, bedrock and sedimentary bank erosion, calculations of the amounts of sediment available to the river before and after reforestation were made (Table 5.6). Because of less and smaller bedrock banks, a reduction of 60% in sediment production was calculated over the period 1954-2002. Some 30% of the bedrock contributes bed load material, resulting in 1365*0.3 = 410 $m^3\,y^{-1}$ in 1954 vs. 540*0.3 = 162 $m^3\,y^{-1}$ in 2002 (cf. Fig. 5.6). The sedimentary banks delivered 54 % less cobbles (from 1050 to 485 m^3y^{-1}) because of decreased bank erosion rates. The reduction in bed load supply is partly compensated by incision of the riverbed. In 1954 no incision occurred, vs. 515 m^3y^{-1} in 2002. All this leads to the conclusion that 21% less sediment was available for bed load transport in 2002 compared to 1954.

Not only the supply of bed load material was reduced by the reforestation, the river's transport capacity as well. As there are no measurements available for the situation before reforestation, past bed load transport rates were calculated with transport formulas using the available discharge data from 1960 to 2003.
Instead of the classic formula of Meyer-Peter Müller (1948), which was used in an earlier study in the Dragonja catchment (Globevnik, 2001b), two revised versions of this formula were used to estimate the bed load transport over the period 1960 to 2002. However widely used, the Meyer-Peter-Müller formula is not particularly well-suited for this type of river, as it was derived for finer-grained and low-gradient rivers and does not take into account bed structures such as riffles and steps (Church et al., 1998; Hassan and Church, 2000). Pools and riffles are known to consume a relatively large part of the available transport energy (Petit et al., 2005). Therefore, the Meyer-Peter-Müller formula can severely overestimate the actual bed load transport. Fernandez Luque and van Beek (1976) and Wong and Parker (submitted) modified the Meyer-Peter and Müller formula to make it more suitable for use in steep-gradient rivers with large particle diameters. Their adjusted formulas were used here to provide an alternative and more realistic estimate of the bed load transport in the Dragonja River before and after reforestation.
An overall reduction of 60 to 70 % in bed load transport capacity was derived with starting values of an average 3500 m^3y^{-1} in the early 1960s and final average values of 1200 m^3y^{-1} for the period 1995-2002.

The values calculated for the period in which the stone tracing experiments were done (July 2001 to June 2003) ranged from 370 m^3y^{-1} (Wong and Parker formula) to 530 m^3y^{-1} (Fernandez-Luque van Beek formula), compared with 1080 m^3y^{-1} as derived with the classic Meyer-Peter Muller formula for the same period. However, comparison of measured bed load transport at site 5 in the Rokava branch (cf. Fig. 5.4) between October 2000 and April 2001 with the values predicted by the two modifications of the Meyer-Peter Müller formula, suggested that even the revised formulas overestimated actual transport by a factor of two to three.
Therefore, even though these formulas do take bed structure and other factors limiting transport into account, measured transport rates were still much lower. This may be caused by the presence of stronger, more stable armour than was assumed in the calculations. A strong armour increases the critical shear stress needed to initiate bed load movement. To reduce the predicted bed load transport to measured values required adjustment of the critical shear stress

value (a dimensionless parameter) to 0.07, instead of the 0.06 recommended by Wong and Parker. Another possible reason for the lower observed rates, especially in the lower reaches (Section A-B, Fig. 5.4), could be the fast degradation of the bed load material during transport, which may have caused a supply-limited transport regime.

5.5.5 Effects on suspended sediment supply and transport

From field observations and the literature (e.g. Russell et al., 2001) it is well established that agricultural land (in this case mostly vineyards) supplies more fine sediment to the streams than do forested areas. Surface erosion on the densely forested slopes in the area is considered minimal. Suspended sediment sampling in gully tributaries with a high proportion of (newly created) agricultural fields on steep slopes gave an estimate (2-4 g L^{-1}) of the high amounts of sediment that were possibly produced before the reforestation of the catchment. Together with measurements of current suspended sediment concentrations and known daily discharge data (HZM, 2003) a rough calculation was made of the annual suspended sediment discharge over the period 1960–2002. The amount of sediment generated in the early 1960s was estimated at ca. 27 $t^{-1}y^{-1}ha^{-1}$ versus 4.5 $t^{-1}y^{-1}ha^{-1}$ for 2002, a reduction of some 80 % (Keesstra et al., submitted a = Chapter 4). The model WaTEM/SEDEM predicted a slightly less severe decrease of 70% in sediment input from the hillslopes for the period 1954 to 2002 (Keesstra et al., submitted a = Chapter 4) for two independent calibrations. One calibration was based on the discharge data (as described above), the other was based on measured sedimentation rates in the valley (Keesstra, accepted = Chapter 8) and the assumption of Trimble (1999) that an average of 10 to 30% of sediment delivered to a stream is deposited on the valley floodplains in catchment areas of this size.

5.5.6 Effects on catchment sediment budget

The sediment budget of the Dragonja catchment for 1954 and 2002 are summarised in Fig. 5.8. In 2002 the total inputs of sediment to the river amounted to ca. 60,000 m^3y^{-1}, of which 91% was supplied by surface erosion on the hillslopes, and 9% by bank erosion (5%) and bed incision (4%, Fig. 5.8).

The average sediment input and output differed by about 6,000 m^3y^{-1} (10%), the difference being accounted for by material that went into (long-term) storage in the form of river terraces and floodplains. In the sediment budget calculations the inputs of coarse and fine sediment can be added up, because at the outlet of the river all coarse material has disintegrated and is transported to the sea as suspended load (cf. Chapter 6). Before the reforestation (represented by 1954) the hillslopes were even more important as a sediment source (95%), as fine sediment delivered by the sedimentary and bedrock banks decreased by 54% compared to a 70% decrease in sediment input from the hillslopes. The sediment deposition on the floodplains and terraces before reforestation was considerable, as shown by sedimentation rates inferred from Cs-137 cores (average of 1 cm y^{-1} , Keesstra, accepted = Chapter 8). This suggests that a similar percentage as derived for 2002 (9%) of the produced sediment was (temporarily) stored on the floodplains and terraces in 1954 as well.

5.5.7 Effects on aquatic habitat

The bed of the Dragonja River partly consists of bedrock and partly of cobble stones. In summer the channel usually falls dry over most part of the rivers length, although in some pools large volumes of stagnant water remain. These pools act as an important refuge for aquatic life such as fish (*Rutilus alba, Barbus plebejus;* IUCN Red List of Threatened Animals (1994*)*, crayfish *(Orconectus limosus*) and toads (*Bombina variegata;* also on the IUCN Red List). Due to the gradual regrowth of the forest on the slopes the riverbed has become narrower over time, although its morphology and sediments have more or less stayed

the same. The narrowing causes a decrease in the net surface area available for different types of riverine faunal habitats (Walters et al., 2003), rendering these more vulnerable. Due to the increase in the number of days without stream flow in summer (Globevnik and Sovinc, 1998); the number of pools that stay filled during the entire summer has become fewer, smaller and more vulnerable to droughts.
Moreover, changes in the Mediterranean climate implying more extreme weather conditions (e.g. Stone and Allen, 2004) will further increase the pressure on the riverine ecosystem.
Apart from the riverine habitat in the Dragonja River, the wetland at the outlet is influenced by the changes in water and sediment discharge of the river. The wetland, which has a national park status, gives shelter to numerous species of bird, including some Red List species (e.g. *Larus cachinnans*, *Larus melanocephalus* (Vahtar, 2003)).

5.6 Conclusions

Fine sediment inputs to the Dragonja River in southwestern Slovenia (Fig. 5.8) include suspendable sediment originating from hillslopes, bedrock banks and older fluvial bank sediment. From an analysis of the hysteretic patterns in stream suspended sediment concentrations during stormflows and the texture of the suspended sediment it may be concluded that most sediment originated on the hillslopes. Contributions of suspended sediment from bank and bed erosion were only minor.
Coarse bed load material is provided by large bedrock banks and cliffs along the channel, by older bed material that the river is currently eroding through incision and by lateral erosion of sedimentary banks that consist partly of cobbles. The supply of sediment to the channel from bedrock banks is largely independent from rainfall, as rock falls and frost-and-thaw processes are more important. The size of the debris toes at the feet of the bedrock banks is therefore largely dependent on the time elapsed since the last major discharge wave.

In the present-day sediment budget (2002) the total input of sediment to the river is dominated by the supply from surface erosion on the hillslopes (91%). The remaining sediment is generated by bank erosion (both sedimentary and bedrock banks). Most of the sediment supplied to the streams is transported to sea (91%); whereas approximately 9% is (temporarily) stored in floodplains and terraces.

The natural reforestation of the catchment since 1945 caused a major decrease in sediment input from the hillsides. The model WaTEM/SEDEM simulated a drop in sediment delivery to the channel via surface erosion of ca. 70 % over the period 1954 until 2002.
Furthermore, before the reforestation the number of actively eroding bedrock banks was greater and currently active bedrock banks were larger. In 1954 the size of the bed load was completely dependent on the amount of sediment supplied by the bedrock banks and cliffs along the channel. Reforestation and additional anti-erosion measures resulted in a decrease in the supply of bed load material from bedrock banks to the stream ca. 50 %. The decrease in bed load supply induced incision of the river bed, which partly compensated the loss of bed load material inputs. The total reduction in bed load supply over the period 1954 to 2002 is estimated at 21%.
Bed load was predominantly transported during large peak events. Measured transport rates were temporally and spatially very variable, ranging from 10 to 100 m^3y^{-1}. Part of this variability must be considered inherent to the processes at work, but in addition, the Dragonja River is not in equilibrium due to the changes in sediment supply and transport capacity as a result of the regrowth of the forest. A computational effort to estimate the reduction in bed load transport capacity of the river suggested a reduction of 60 to 70% due to the severely decreased flood height and frequency associated with the progressive natural reforestation.

Before the reforestation the hillslopes were an even more important source of sediment (95% of the total sediment input to the streams) as the decrease in sediment supply from banks (54%) was less than the drop in sediment supply from the hillslopes (70%). Furthermore, a new source of sediment came available as the river began to incise its own bed.
The sedimentation rate on the floodplains and river terraces before reforestation was high, and our data suggest that a similar percentage of the produced sediment was (temporarily) stored on the floodplains and terraces as in 2002 (ca. 9%). Although the catchment is also under influence of tectonic uplift, the changes in the sediment budget discussed in this paper occurred on a time-scale of decades, and therefore tectonics cannot be the main driving factor.

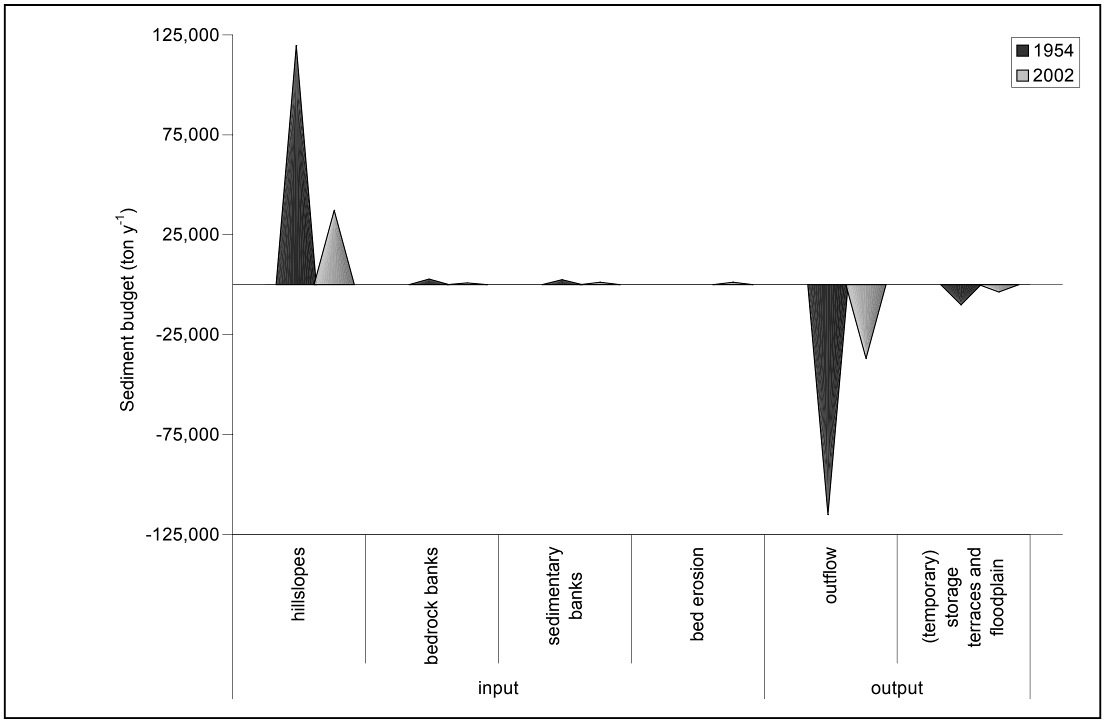


Figure 5.8: Simplified annual sediment budget of the Dragonja catchment for the years 1954 and 2002. Erosion rates of bedrock banks, riverbanks and bed erosion are explained in the results section of this paper. Erosion rates on the hillslopes and outflow to sea were modelled with WaTEM/SEDEM (Keesstra et al., submitted). Sedimentation rates on terraces and floodplains were derived from ^{137}Cs cores (Keesstra et al., 2005).

Chapter 6: Downstream fining and rounding of bedload material in the Dragonja River, SW Slovenia

CHAPTER 6: DOWNSTREAM FINING AND ROUNDING OF BEDLOAD MATERIAL OF THE DRAGONJA RIVER, SW SLOVENIA

6.1 INTRODUCTION

From field visits it was noticed that large differences exist in the amount and size of bedload between the upstream and downstream part of the Dragonja River. In fact, at the river mouth no bedload was found. To explain this phenomenon, the size, amount and angularity of the bedload material was studied at several sites along the river. Although the obtained observations are interesting to show here, the research was not conducted in a sound systematical or statistical way. The gathered data were limited in number and not evenly distributed over the studied sites. Therefore the results of this chapter are only an indication of the processes that occur in the Dragonja River channel. For sound conclusions on the downstream fining processes in this river more research should be done.

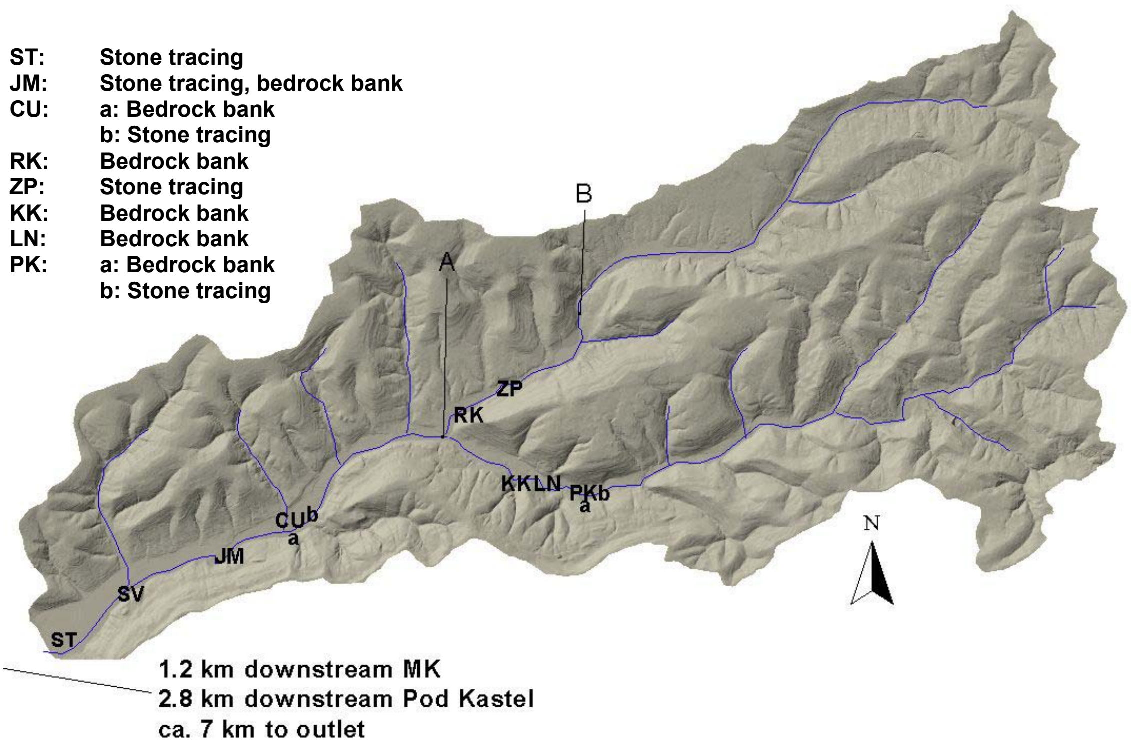


Figure 6.1: Locations of the bedrock banks and stone tracing measurements sites in the catchment. Stone tracing monitored with magnetic tracers. Bedrock banks (erosional cliffs) were monitored with erosion/deposition pins, 3-D photogrammetry (only RK and KK) and regular photographs. Bedload analysis was carried out between A and B and on all stone tracing sites.

6.2 METHODS

The most extensive analysis was carried out at the Rokava River, where on average every 100 m a site was selected (in the section from A to B, Fig. 6.1). Furthermore, the bedload was analysed at each stone-tracing site (Fig. 6.1, sites ST, JM, CU, ZP and PK, see chapter 5 for further explanation on bedload transport). A total of 29 plots of 1 m^2 were selected, where the three axes of 50 surface particles were measured and the particles were weighed with a 1 gram precision (after Gomez, 1979 and Church et al., 1987).

To investigate whether stones fine in the downstream direction, the D_{50} at all measured sites was calculated. The amount of bedload in a specific section of the river was calculated from estimated percentages of channel bed with bedrock (upstream and middle reaches) or silty clays (in the downstream reaches) and percentages of channel bed covered with movable bedload material. The width of the channel and thickness of the active layer were estimated in the field.

To investigate whether stones get more rounded with greater distance from their main source, the bedrock banks, bedload was measured downstream of the last large bedrock bank (JM, Fig. 6.1). Here every 50 m a site was selected were 50 stones were measured and weighed. To estimate the roundness of the stones without subjectivity, the maximum possible weight of a block of the size of the measured axes was calculated. The measured weight was divided by the calculated maximum weight, giving the roundness coefficient, RC.

6.3 Results

The average size (D_{50}) of the bedload in the Dragonja River varies from an average 8.4 cm in the Rokava River (Fig. 6.1, in between A and B) to 3.9 cm at the most downstream measuring site (Fig. 6.1, Site ST; Fig. 6.2). Because the bedload material in the Rokava River was measured in most detail, these measurements were statistically analysed. The average size and weight of the stones in the Rokava channel bed was 8.4 cm and 970 gr. Frequency analysis (Fig. 6.3) of the bedload material shows a positively skewed size distribution and mostly has disc or tabular shaped particles (Zingg, 1935).

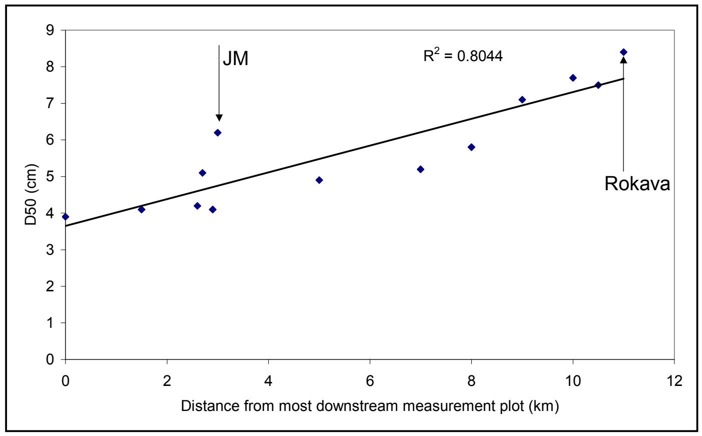


Figure 6.2: Relation between the average grain size of the bedload material measured in 1 m^2 plots versus the distance from the measurement plot to the most downstream measurement plot. The dot indicated with JM was measured at bedrock bank JM (Fig. 6.1, site 2). The dot indicated with Rokava shows an average of all measurements done in the Rokava River bed.

The bedload has three important sources, the large bedrock banks (PK, LN, RK, CU and JM in Fig. 6.1), the degrading riverbed itself and the sedimentary banks, which partly consist of former bedload material. The bedrock banks are composed of flysch. 70 % of the bedrock is composed of clay- and siltstones; the remaining 30 % are sandstones. As a result of weathering and undercutting by the river these bedrock banks retreat slowly, delivering sediment to the river. The silt- and claystones break down shortly after they fall into the river. The sandstones, which are not all equally resistant to weathering, form the majority of the bedload of the river. The second source is the retreating sedimentary banks. These banks consist of fine overbank deposits and coarse, former bedload,

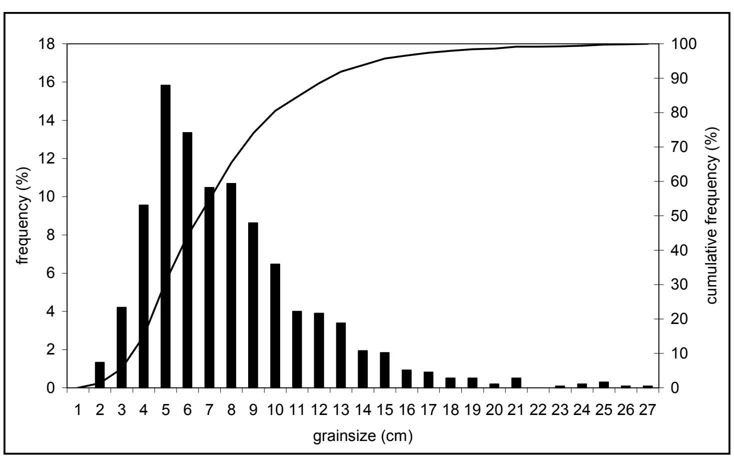


Figure 6.3: Histogram and cumulative frequency diagram of bedload material in the Rokava River.

material. The third source, the degrading riverbed, partly consists of bedrock and partly of older bedload material. Due to the reforestation the river has incised, especially on locations where the riverbed consists of cobbles.
Both the coarse material in the sedimentary banks and the coarse material in the riverbed originate from the bedrock banks also, but have temporally been stored in the sedimentary banks (41%) or the riverbed (46%) itself. In 2002 most bedload material is delivered to the stream by bed incision and sedimentary bank erosion (Table 6.1), while in 1954 the main sources were the sedimentary banks (72%) and the bedrock banks (28%).
The amount of bedload per meter of riverbed increases downstream until the last bedrock bank is passed (JM, Fig. 6.1). After site JM (Fig.6.1) less coarse sediment is delivered to the stream. Table 6.2 shows the rapid diminishing of the amount of bedload in the Lower reaches of the Dragonja River.

Table 6.1: Sources and amount (percentages) of bedload in 1954 and 2002 (derivation explained in Chapter 5).

Bedload source	1954 (m^3y^{-1})	2002 (m^3y^{-1})
Sedimentary banks	1050 (72%)	478 (41 %)
Bed incision	0	515 (46 %)
Bedrock banks	410 (28 %)	162 (14 %)

Table 6.2: Decreasing amount of bedload transported in different sections of the river.

River reach (Fig. 6.1)	*Cobbles (% of total bed area)*	*No bedload (% of total bed area)*	*Average width river (m)*	*Average thickness active layer (m)*	*Volume of stones per m river length (m^3)*	*Remarks*
<PK	80	20	6	0.2	1.0	
PK-ML	80	20	8	0.4	2.6	
ML-JM	100	0	12	0.4	4.8	Last large bedrock bank
JM-SV	50	50	12	0.3	1.8	River banks and channel bed consist largely of clay
SV-ST	35	65	14	0.2	1.0	
ST-MK	20	80	15	0.2	0.6	
MK-Pod Kaštel	10	90	15	0.2	0.3	

When rock fragments fall from a bedrock bank into the channel, the stones are very angular, but after a relative short distance (several hundred meters) the stones are sub-rounded to rounded. To prove the stones get more rounded with a greater distance from a bedrock bank, bedload was measured as indicated in the method section.
On average the fresh rocks have a RC (rounding coefficient) of 0.66 (Fig. 6.4), this relative low number is due to the fact that the stones are not square blocks but can be trapezoidal or even triangular. After approximately 250 m downstream of large bedrock cliffs, the RC has decreased to an average of 0.55. After this point the RC-coefficient remains stable.

6.4 Discussion

6.4.1 Downstream fining

As shown in Fig. 6.2 the bedload material fines going downstream. As causes of downstream fining two main phenomena have been described in literature, which are considered to explain downstream grain-size fining in gravel-bed rivers: (1) abrasion or breaking up of single particles that reduce their size and (2) hydraulic sorting or selective transport due to differential transport (Parker, 1991a; Parker, 1991b; Hoey and Bluck, 1999; Rice, 1999, Surian, 2002 and Moussavi-Harami, 2004). Most studies conclude that a mixture of the two processes is responsible for the downstream fining observed in the studied river systems.

However, in the Dragonja River the bedload material is not very resistant to abrasion, as it easily breaks on pre-existing sedimentary weaknesses and rounds easily also. Therefore the differences in lithology as described by e.g. Werrity (1992), are not of crucial importance as all rocks easily abrade. As a result the downstream fining is so severe that not only the size of the coarse sediment decreases but also the actual amount of transported coarse sediment decreases. This happens in such a way that by the time the river reaches the sea; all coarse sediment has fallen apart and is transported to the sea in the form of suspended sediment. Morphological mapping also shows this decrease in the amount of transported coarse sediment (Table 6.2). The amount of coarse sediment diminishes within a few kilometres, because of the absence of new bedload sources after site JM (Fig. 6.1), and the rapid abrasion processes.
In chapter 5 some evidence of selective transport was found with the stone tracing measurements, but the majority of bedload transport takes place during major flood events, when all sediment is transported equally, regardless of the sediment size. Furthermore, the weakness of the bedload material facilitates such quick abrasion that this process is by far the main process of downstream fining and not selective transport. Hence, the gradient, which decreases gradually downstream (Fig. 7.5A), is of little influence on the downstream fining, as it only affects the transport capacity of the river, and thus also on the selective transport of bedload material.

Even though the primary sources of bedload, the bedrock banks, are spread through the catchment, a linear trend was found in the Dragonja River for the decrease in particle size versus the distance from the most downstream measurement plot (Fig. 6.2). This is probably the result of the large input of bedload from the secondary sources, bed incision and bank erosion, in comparison to the input from the bedrock banks. The dot indicated with JM (Fig. 6.2) represents the material at the base of a large bedrock bank. Fresh material is provided to the river at this point. But measurements downstream of this location indicate that the effect of such a point on grain size is restricted to a short distance only.

6.4.2 Downstream rounding

Before any analysis on the relation between the roundness of the particles and the position of these particles in the river can be made, it needs to be tested if the roundness is independent of the grain size. The D_{50} of all measured stones was plotted against the calculated rounding coefficient (Fig. 6.5 left) and the measured and calculated weight (multiplying the three measured axis's with the assumed density of the stones of 2.6 gr cm^{-3}, Fig. 6.5 right). No relation was found between the size and the RC of the stones (Fig. 6.5 left) and a strong correlation was found between the measured and calculated weight over the whole weight spectrum. Therefore, the RC is not size or weight dependant and can be used as an indication of the roundness of the stones. The rounding is significant up to 200

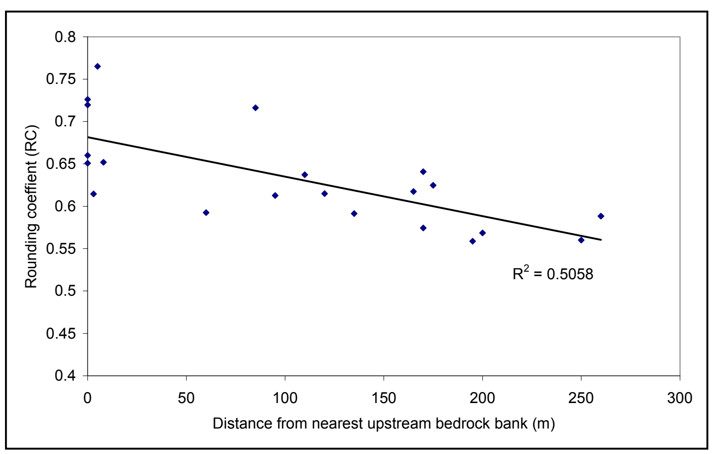
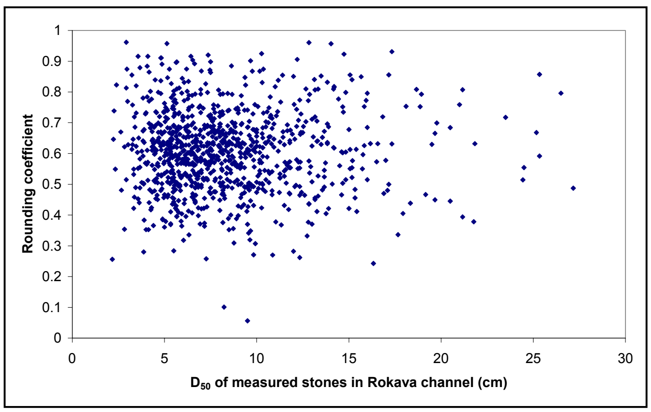


Figure 6.4: Rounding coefficient (RC) versus distance from the nearest upstream bedrock bank (the nearest large source of bedload material).

m meters downstream from a bedrock bank (Fig. 6.4), after this point, the rounding number does not decrease with distance. Possible reasons for this are: the breaking up of rocks, making them angular again. Secondly, the softest rocks have fallen apart by this distance, and the more cohesive stones are still intact and these rocks abrade slower than the softer ones. Thirdly, mixing with the eroded bed and bank material will be of greater importance with greater distance from the last bedrock bank as the newly delivered sediment from the bedrock banks provides a relatively small part of the total bedload (14 % in 2002, Table 1). Therefore, the direct effect of a bedrock bank on the roundness of the bedload material is limited to approximately 200 m downstream of the bedrock banks (Fig. 6.4).

No measurements on bedload material were available from before the reforestation. However it is probable that downstream fining is currently more intense than before reforestation as the particles take longer to travel to the outlet as a result of decreased flood height and flood frequency (cf. Chapter 3). Consequently rocks are longer exposed to elements such as freeze and thaw processes and possibly more dissolving of $CaCO_3$ takes place, inducing more weathering. In addition, the source of bedload has changed, as nowadays a much smaller part of the transported material directly originates from the bedrock banks compared to the situation before the reforestation (Table 6.1). The stones from the bed incision and banks



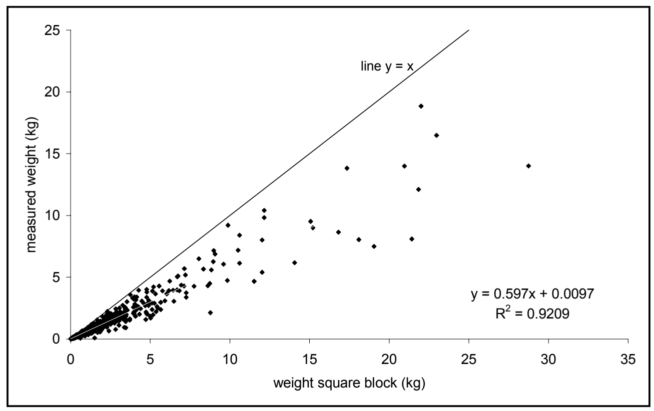


Figure 6.5: Left: Measured weight of bedload particles versus the D_{50} of the measured stones in the Rokava channel. Right: Dots represent the rounding coefficient (RC), (=measured weight of each particle (y-axis) divided by the largest possible weight of a block with the same axis's as the measured stones axis's (x-axis)).

have had more time to weather while stored in the bed or banks. This might cause these stones to be more fragile and more susceptible to downstream fining.

6.5 Conclusions

The downstream evolution of the coarse material is evident in the amount (Table 6.2; cf. Chapter 7), size (§ 6.4.1) and angularity (§ 6.4.2) of bedload. This is mainly caused by the softness of the bedrock material, which produces the bedload. The downstream fining in respect to size and amount of particles is most evident in the fact that over the whole river stretch the sediment fines down from boulders and cobbles in the upper reaches to silt and clay when the river reaches the outlet. All rocks wear down before reaching the outlet. Therefore the suspended sediment load at the outlet of the river contains the total sediment load for the catchment. The main process of downstream fining is comminution of coarse sediment particles and not selective transport. The downstream rounding of the particles is significant up to 200 m meters from the bedload producing bedrock banks. After this point breaking down of particles (making them angular again), and mixing with sediment already present in the channel prevents further downstream rounding.

Chapter 7: Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes

CHAPTER 7: EVOLUTION OF THE MORPHOLOGY OF THE RIVER DRAGONJA (SW SLOVENIA) DUE TO LAND-USE CHANGES

ABSTRACT

The effects of increasing agricultural land use on fluvial morphology have received much attention in fluvial research. However, in several regions in Europe a reversing trend of decreasing agricultural activity and land abandonment, followed by reforestation, is observed. The response of fluvial morphology deserves attention because of its large impacts on landscape and riverine habitats. With the help of geomorphological mapping, multi-date aerial photography and a range of dating techniques, we reconstructed the evolution of the morphology of the riverbed and the floodplain of the Dragonja River in southwestern Slovenia. The results of this study show that the fluvial morphology in this Mediterranean catchment has changed considerably as a result of shifts in agricultural land use, in particular large-scale land abandonment in the second half of the 20th century. Until the first half of the 19th century, floodplain aggradation prevailed. Probably around 1870, a large erosion event occurred from which the floodplain did not fully recover. A terrace standing 2.5 m above the present floodplain was formed. Natural reforestation, due to depopulation since World War II, caused a reduction in discharge and sediment supply to the river. The decreased intensity and frequency of floods allowed invasion of the riverbed by vegetation, causing narrowing and incision of the riverbed. This resulted in the formation of a terrace, which now stands 1.5 m above the present-day river. This terrace is about 60 years old. However, the largest increase in forest area occurred since 1975, which intensified this process of riverbed narrowing and incision, creating a local terrace at 0.5 m at 0.5 m above the presently meandering river.

Keywords: channel narrowing, land-use change, reforestation, terrace formation, Dragonja, Slovenia

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7.1 INTRODUCTION

Changes in floodplain sediment dynamics and the shape of the riverbanks have profound effects on riverine habitats and on the biodiversity of the riparian zone. In the past, rivers have changed considerably under the influence of increasing agricultural activity. These morphological changes have attracted considerable scientific attention (e.g. Rogersa and Schumm, 1991; Orbock Miller et al., 1993; Kazanca et al., 2003). However, under the influence of socio-economic changes in many regions in Europe a reversed trend of decreasing agricultural activity is seen. This trend includes either planned reforestation and nature development in catchments, or unplanned land abandonment and natural reforestation. This reforestation profoundly changes water and sediment supply to the rivers, and is likely to cause major fluvial morphology changes. We studied the morphological changes that are purely due to natural reforestation in the Dragonja River in southwestern Slovenia. The Dragonja catchment is a medium-scale, geologically homogeneous catchment, for which a well-documented record of land-use change and discharge measurements is available. Anthropogenic environmental change is restricted to agricultural land-use change, no other human disturbance (e.g. gravel extraction, river engineering, road construction) obscures the effects of land abandonment (Globevnik et al., 1998; Keesstra and van Dam, 2002). In

previous studies on the effect of reforestation, the study sites were either larger and less homogeneous (Liébault and Piégay, 2001, 2002) or much smaller and not at a catchment scale (García-Ruiz et al., 1995, 1997) or the study was carried out in a different climatic zone (e.g. Lach and Wyzga, 2002). Furthermore, other catchment-wide studies have mixed signals of both natural reforestation and gravel mining in the channel (Surian and Rinaldi, 2003).
Recently, plans for establishing a natural park in the Dragonja valley have been approved. The management of this park requires sound information on the hydrological, geomorphological and ecological functioning of the area. This area has been under cultivation for a long period of time, probably already since Roman time. The deforestation caused, as in many other regions (e.g. González-Sampériz and Vicién, 2002; Oldfield et al., 2003), large-scale erosion on the hillslopes and deposition of large volumes of fine sediment in the valley. In recent times, the morphology of the riverbed of the river Dragonja and its largest tributary the Rokava underwent a distinct transformation due to a change in sediment load and river discharge. The forest cover went from ca. 30% in 1954 to ca. 70% in 2003. These changes were caused by the depopulation of the region after the Second World War and the resulting abandonment of agricultural fields and broad scale reforestation.
In this paper the impact of human interference and especially the effects of reforestation on the river morphology of the Dragonja river is studied. Furthermore the spatial variability of river response to land-use change in the catchment is presented.

Figure 7.1: The study area: the Dragonja catchment, southwestern Slovenia. (45º28'N, 13º35'E).

7.2 Study area

The Dragonja catchment is situated in the southwestern part of Slovenia. The river is 30 km long and the catchment area is approximately 90 km^2 (Fig.1). The elevation of the catchment ranges from sea level to about 400 m. The Dragonja debouches into the Adriatic Sea. The geology of the catchment is largely uniform. The substratum of the catchment is composed of sub-horizontal to gently north-dipping Eocene flysch beds, consisting of highly calcareous, soft silt and claystone, with sandstone layers up to 1.5 m thickness (Melik, 1960; Orehek, 1972). The overall morphology of the catchment is characterized by long flat ridges and plateaus with steep slopes at the margins of the valleys. The soil is mostly a carbonate rendzina, with the exception of the valley floors, where a fluvisol has developed. On places where a sandstone layer is very close to the surface, a brown eutric soil developed.

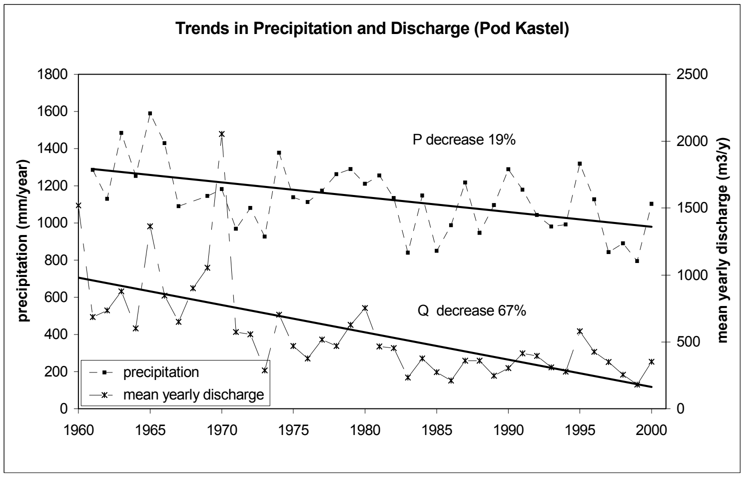


Figure 7.2: Trend of the annual precipitation and discharge of the Dragonja catchment from 1960 to 2000. Straight lines are fitted trends (HMZ, 2003).

All soils are highly calcareous (Zupancic and Pric, 1999). The thickness of the soils can vary from more than 1 meter on the plateau to being completely absent on the slopes, partly as a result of erosion associated with former agricultural activities. The climate of Slovene Istria can be classified as sub-Mediterranean, Köppen-type C_W. The average annual temperature is 14ºC at the coast and 10□C at the eastern part of the catchment. The absolute temperature varies from -10□C to 35°C (Ogrin, 1995; HMZ, 2003). The yearly precipitation varies from 700 mm to 1400 mm and increases with distance from the coast. The maximum-recorded daily precipitation is 133 mm. From 1950 to 2000 the precipitation has decreased, the trend shows a decrease of 19% (Fig. 7.2). The average discharge at the outlet over the period 1960 to 1998 is 1.19 m^3s^{-1}. However the hydrological record shows a decrease in peak and mean discharge of 80 % and 67 % respectively since 1961 (Fig. 7.2)(HMZ, 2003). There is an increase in low flow events and a decrease of high flow events (Fig. 7.3). The average percentage of the precipitation discharged by the river was 22 % for the Upper-Dragonja sub-catchment and 26% for the Rokava sub-catchment.

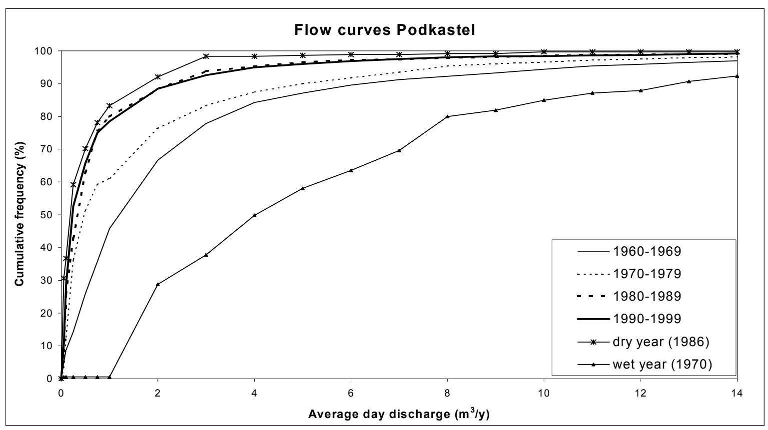


Figure 7.3: Cumulative frequency curves of the daily discharges at Pod Kaštel, near the outlet of the Dragonja river (HMZ, 2003).

The reservoir constant, 1/k, indicating the resistance of the catchment against outflow, is estimated to be 16 days for the upper Dragonja sub-catchment and 12 days for the Rokava sub-catchment. The quick flow had an average duration of 25 hours for the Upper-Dragonja River and 58h for the Rokava River.

7.3 Methods

7.3.1 Dating of river incision by tree ring analysis and lichenometry

River incision phases were dated by determining the age of trees growing on the stream terraces. Mainly *Juniper sp.* trees were used for that purpose, as they are known to be a pioneer species (VGI, 1992; Globevnik et al., 1998). 15 trees were sampled with a tree auger and the growth rings of the trees were counted, from which the age of the terraces was derived. This was complemented by lichenometric dating, used to determine the age of one species of lichen – in our case the species *Verrucaria nigrescens* – growing on rocks that

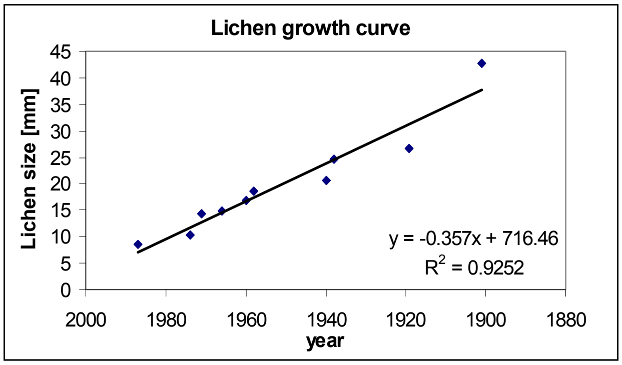


Figure 7.4: Diameter-age curve for lichen, species ***Verrucaria nigrens****, from the Dragonja region to validate the lichen found on the terraces along the river (van Duinen and Vork, 2002).*

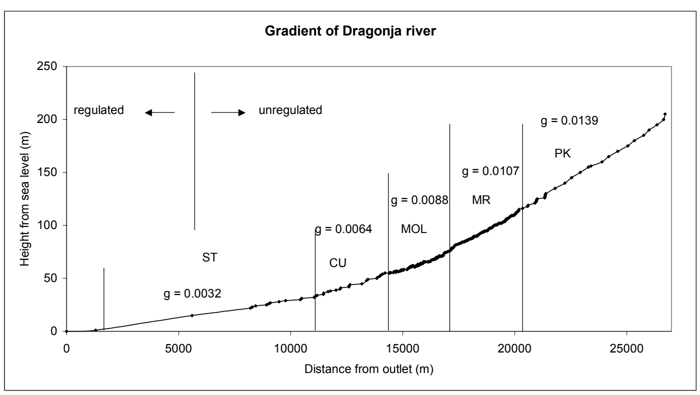
were no longer transported or submerged for long periods of time (Lock et al., 1979; van Duinen and Vork, 2002). A diameter-age curve was derived from lichen growing on sites with a known age, such as old buildings and gravestones (Fig.4). 18 of the largest lichens on the terraces were measured. The calculated age of lichens on the surface of a terrace is assumed to correspond with the beginning of the incision of the river.

7.3.2 Reconstruction of floodplain sedimentation rates using ^{137}Cs and ^{14}C

Caesium-137 is an isotope in radioactive fallout form nuclear bomb testing and nuclear accidents. It may provide a valuable tracer of sediment movement (Walling et al., 2000; Panin et al., 2001). The method used to interpret the ^{137}Cs profiles of the cores in this study is based on the ‘principle of stretching’. The position of the deepest peak in the profile is considered to correspond with the depth of the surface in 1960 (related to nuclear bomb testing) and the upper peak with the surface of 1986 (the Chernobyl reactor accident) (Walling and He, 1992).

Samples for ^{14}C dating were collected from terrace sediment exposures along the river to reconstruct the sedimentation and erosion history of the terraces. The samples consisted of woody debris, charcoal and snail shells. In the lower reaches of the river the overbank material was dated with ^{14}C analysis of woody debris found in boreholes.

A



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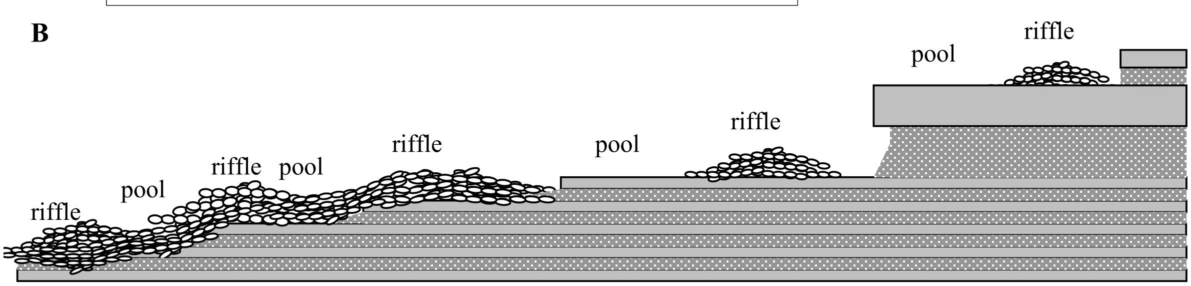

Figure 7.5: A: Measured gradient of the Dragonja river in its different reaches.
B: schematic representation of the way the pools and riffles are connected to the layering of the underlying flysch bedrock.

7.3.3 Geomorphological and land use mapping

The morphology of the riverbed and the floodplain were reconstructed using morphological mapping and aerial photograph interpretation. Geomorphological mapping was carried out in the summers of 2000 and 2001, and included construction of a longitudinal gradient profile, precise leveling of cross sections (Thorne, 1998; Gordon et al., 1993) and detailed mapping of the riverbed and associated floodplains and terraces. The remaining part up to the outlet was derived from digital elevation model (DEM). Manning's n was estimated in each section of the river according to Cowan (1956) and Gordon et al.(1993).
The land-use change was investigated for the upper part of the Dragonja catchment, upstream of the confluence with the Rokava, Dragonjas largest tributary. The historical land use was derived from aerial photographs taken in 1954, 1975, 1985 and 1994. In 2002 a field survey was conducted to map the land use. In these surveys the land uses were divided into five mapping units; forest, young forest, recently abandoned fields (less than 5 years ago), grassland and fields. The aerial photographs were also used to estimate the change in the width of the riverbed. Manning's n was estimated for the year 1960, to compare it with the current situation.

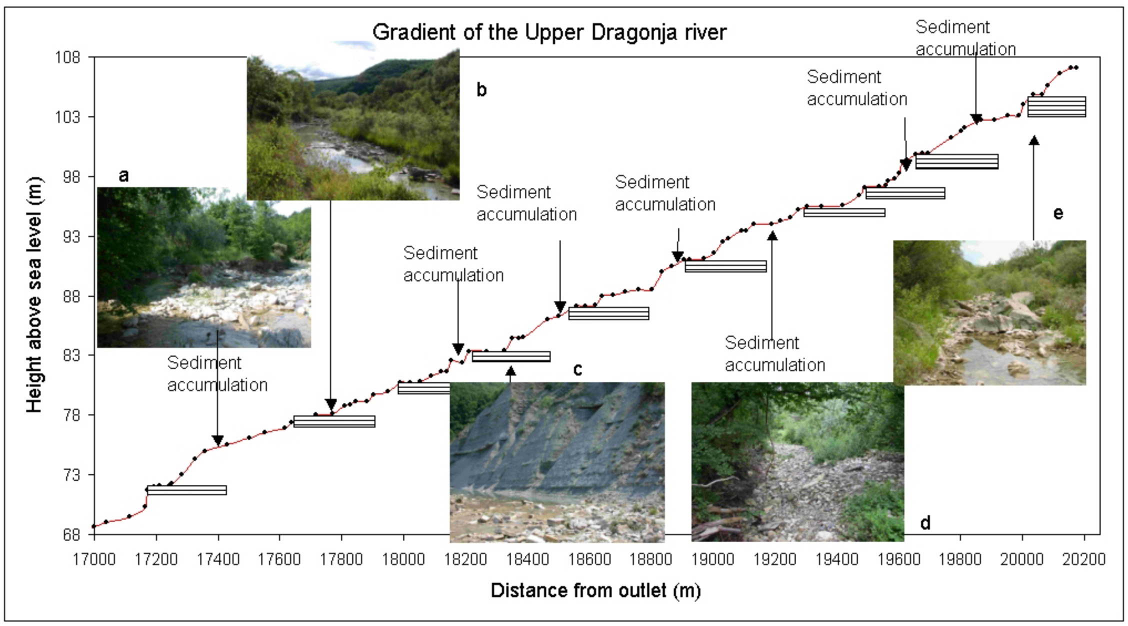

Figure 7.6: Longitudinal profile of the upper part of the Dragonja river, with photographs to illustrate the different aspects of the riverbed. a&d: an example of a sediment accumulation. b: bedrock riverbed. c: Erosional cliff, producer of most of the bedload sediment. e: Step-pool morphology in the upper part of the river (section PK). Striped blocks indicate the location of bedrock in the river bed.

7.4 GENERAL GEOMORPHOLOGY

7.4.1 Pool-riffle sequences

Pool-riffle sequences are typical for all reaches of the Dragonja river, with the exception of the upper reaches where the morphology can be described as step-pool sequences. Bedload transport measurements show that the bedload material moves through the channel from riffle to riffle. The material moves slowly from one end of the riffle to the other end and than moves rapidly through the pool to the next riffle. The rapid sediment movement in pools is facilitated by low friction at flat, even bedrock surfaces in the channel. The riffles themselves seem to stay in the same place.

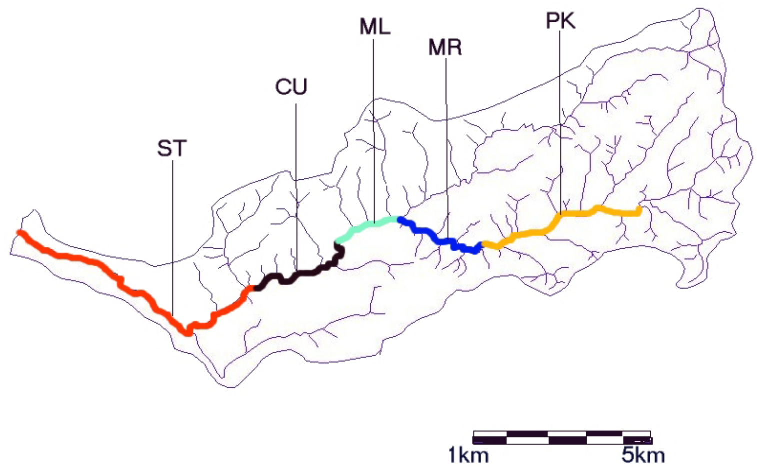

Figure 7.7: Location of river reaches ST (Sv Stefan), CU (Čupinje), ML (Mlin), MR (Mrtveč) and PK (Perosa) within the study area (45º28'N, 13º35'E).

The position and the size of the pools and riffles is related to the position of changes in the lithology of the underlying bedrock. The base of the riverbed is determined by the sub-horizontal sandstone layers. The successive river sections are separated by small steps and waterfalls along the river. After passing a step the river loses energy and drops its heaviest load, which subsequently forms a riffle. Figure 5b shows a schematic, typical section along the river indicating the way the pools and riffles are connected to the structure of the underlying bedrock. The longitudinal profile (Fig. 7.6) shows the flat parts where the bedrock forms the riverbed and the steeper parts where the river has cut through the sandstone layers; sedimentation zones are present just downstream of the bedrock steps.

The distinctive features of the upper reaches are the steep gradient –0.0128–with subsequently a step-pool to plunge bed morphology (Church, 1996). A large part of the riverbed consists of bedrock. The middle reaches show more variation. The gradient gradually decreases from 0.0107 to 0.0064 (Fig. 7.5). The lower reach has a gradient of 0.0032 and the floodplain relief of this part of the river is purely depositional. In the upper reaches of the catchment, the riffles dominate over the pools, while in the lower reaches this is reversed. The riffle cobbles largely originate from the upper part of the valley where the river undercuts the valley sides and has created up to 50 m high, erosional cliffs. During transport the bedload material rapidly abrades, and may ultimately break down into fine-grained material that is moved in saltation or suspension. Therefore the amount of coarse, cobble and stone-size bedload decreases along the river, implicating a decrease in the number of riffles to store the sediment. The bedload material typically forms a censored gravel bed as described by Church (1996).

7.4.2 Downstream evolution of the riverbed morphology

Five sections have been investigated in detail (locations in Fig. 7.7) and are represented at scale in 3D-sketches in Figure 8. The upper reaches of the river, represented by section PK (Perosa, Fig. 7.8a) show a step-pool morphology or even a plunge-pool morphology (Fig. 7.6, photo e). 20% of the riverbed consists of bedrock, the rest consists of cobbles with D_{50} of 7.1 cm and D_{90} of 10.2 cm. This part of the river has a low sinuosity as a result of the high gradient.

The middle reach includes three sections, MR (Mrtveč), ML (Mlin) and CU (Čupinje). In the most upstream section, MR (Fig. 7.8b), pools generally consist of bedrock while the cobble size is $D_{50} = 4.5$ cm and $D_{90} = 8.4$ cm in the riffles. The banks consist of bedrock, silt and cobbles. The riffles have irregular spacing, related to the underlying bedrock, as is illustrated in Figure 6. In between the bedrock pools (e.g. Fig. 7.6, photo b; Fig. 7.8b), occurring at the

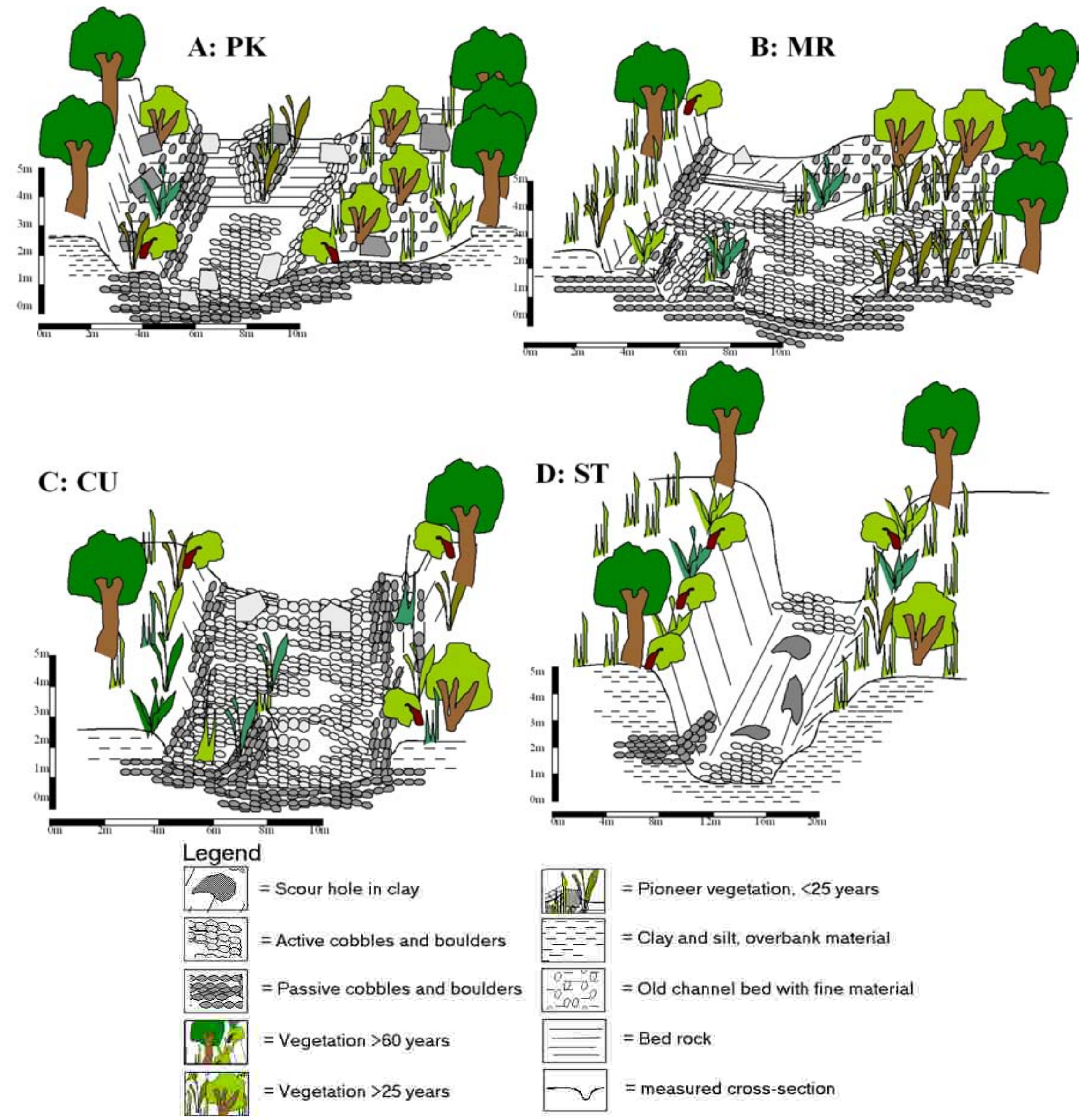

Figure 7.8: Block diagrams of typical sections along the Dragonja River. A: Section Perosa, PK, upper reach. B: Mrtveč, MR, upper middle reach. C: Čupinje, CU, lower middle reach D: Sv Stefan, ST, lower reach.

outcropping sandstone layers, the profile shows humps, which represent the sediment accumulations of the riffles (e.g. Fig. 7.6, photos a and d). Where the sandstone layers in the bedrock are absent over a long distance, the pool-riffle sequence is formed in the gravelly bed sediment. The sinuosity is relatively high –1.23–, as a result of the large bends in the upstream part of this section. In the large bends the river undercuts the valley sides, resulting in the aforementioned erosional cliffs (example in Fig. 7.6, photo c). The large amount of coarse sediment that is supplied from these cliffs, results in a braiding pattern downstream. In section ML the sediment is slightly coarser (D_{50} = 5.6 cm and D_{90} = 9.3 cm) due to a contribution from the Rokava tributary. The heavy sediment load from that tributary causes the river to create multiple channels and the sinuosity to decrease.

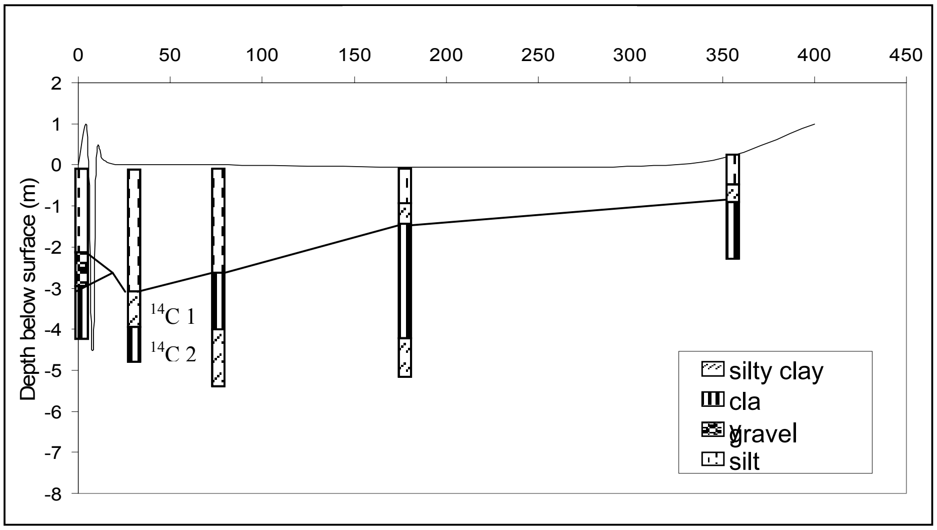

Figure 7.9: Floodplain cross-section with borehole data at section Sv Stefan (ST, Fig. 7.7). Numbers 1 and 2 indicate ^{14}C samples.

Table 7.1: Overview of the average properties of the river Dragonja's reaches: the, terraces that are present, and their width, height and material of the banks, bedload structure and size sinuosity, gradient and estimated Manning's n. The river is divided in a lower, middle and upper reach represented by typical sections ST(Sv Stefan), CU (Cupinje), ML (Molina), MR(Mrtveč) and PK(Perosa).

	Lower reaches		*Middle reaches*		*Upper reach*
	ST	*CU*	*ML*	*MR upstream Rokava*	*PK*
Terraces	-	0.5m, 1.5m	0.5m, 1.5m, 2.5m	0.5m,1.5m, 2.5m	1m, 1.5m, 2.5m
Width	20m	12m	9m	9m	6m
Height banks	5m	1.5-2.5m	1.5-2.5m	1.5-2.5m	2.5m
Material banks	10% cobbles 90% silt	30% cobbles 70% silt	5%bedrock 30%cobbles 65%silt	5% bedrock 40%cobbles 55% silt	10% bedrock 50% cobbles 40% silt
Bedload structure	Isolated riffles	Pool-riffle, large pools	Pool-riffle Pool and riffles same size	Pool-riffle, large riffles	Step-pool
Bedload size (surface)	D_{50} = 3.9 cm D_{90} = 7.3 cm	D_{50} = 4.9 cm D_{90} = 8.5 cm	D_{50}=5.6 cm D_{90}=9.3 cm	D_{50} = 4.5 cm D_{90} = 8.4 cm	D_{50} = 7.1 cm D_{90} = 10.2 cm
Sinuosity	1.31	1.78	1.09	1.23	1.15
Gradient	0.0032	0.0064	0.0088	0.0107	0.0139
Manning's n (Cowan, 1956)	0.05	0.08	0.08	0.10	0.12

Approximately 2 km downstream of the confluence with the Rokava, the bedrock disappears into the subsoil and the river becomes a gravel river. This change is characteristic for the next river section, CU (Fig. 7.8c). The river has an average width of 12 m with cobbles of D_{50} of 4.9 cm and D_{90} of 8.5 cm. The valley starts to widen in this section and the sinuosity of the river increases significantly to 1.78, which classifies this part of the river as meandering. In this section is the most downstream cliff that supplies large amounts of bedload. Because the bedload material is soft and rapidly abrades during transport, the riffles gradually become smaller in favor of the pools downstream from this section. In the lowest reach of the catchment (type section ST (Sv Stefan)) the river has a very different character. In this part of the valley, the river has a single channel without terraces. The river has a wide bed, which is approximately 20 m wide with steep, erosional banks of 5 m high (Fig. 7.8d). Lateral erosion rates measured using erosion pins ranged from 0.2 to 10 cm/yr. The river is scouring older clayey overbank material (Fig. 7.8d) in which the river has cut its channel. Every approximately 50 m a riffle with cobbles of D_{50} = 8 cm, D_{90}= 15 cm is present. The banks consist of cobbles and clayey overbank material. The bank material consists of cobbles (fossilized riffles) and clayey silts. The percentage of cobbles varies from 30% in the upper part of the reach down to 10% near the outlet. Even though the river is currently scouring its channel, floodplain build up has been continuous over the last few centuries. Therefore there are no terraces in this river reach. ^{14}C samples from depths between 6 and 2 m below the surface indicate a sedimentation rate of 1 cm per year (Fig. 7.9). In this reach the recent reforestation has caused this sedimentation rate to decrease. Several ^{137}Cs cores taken in this area show a decreasing sedimentation rate since 1960 (Keesstra, 2002). This accords with the fact that this part of the valley used to be flooded several times a year, while it presently floods only every 2 to 3 years (oral information from local farmers).

7.5 VALLEY EVOLUTION

The river has made several terraces along its course. This study has focused on the three lowest terraces, which are the terraces that date from the times of strongest human influence in the drainage basin. Formerly the Dragonja River was a cobble-bed river with few fine-grained sediments in the valley as suggested by the sedimentology of the exposed deposits of older Quaternary terraces (Fig. 7.10A). The first large-scale deforestation probably took place during Roman times (Zagar,

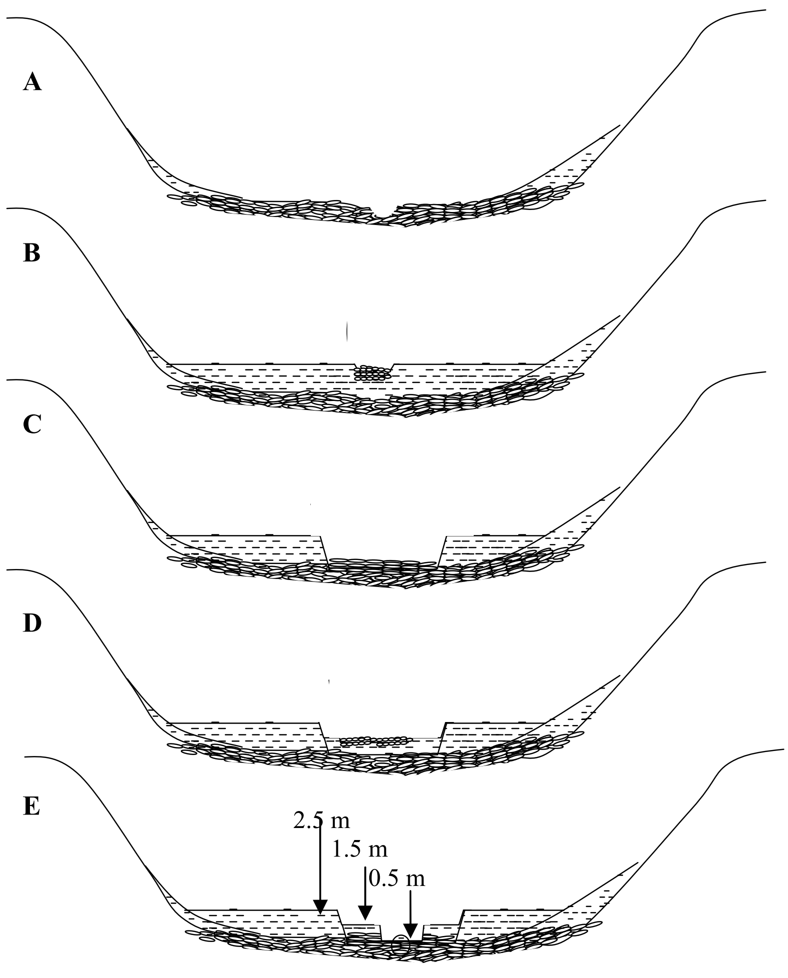

Figure 7.10: Schematic diagram of the cross-section of the middle reach of the Dragonja valley. A: Before Roman deforestation, B: After Roman deforestation, C: After large flood around 1890, D: After abandonment of fields after WWII, E: After increased area of mature forest around 1975, current terraces indicated with their height.

1991). As in many other areas (González-Sampériz and Vicién, 2002; Oldfield et al., 2003) the deforestation of the hillslopes caused large volumes of fine sediment to fill the valley. In the lower reaches this is confirmed by an archaeological find, where a Roman structure was unearthed at a depth of 6 m below the surface (Zagar, 1991). Furthermore ^{14}C samples of wood taken in the lower reaches showed dates of 330 y BP at a depth of 420 cm and 420y BP at a depth of 520 cm (Table 7.2; Fig. 7.9)). Although the exact relation of these wood fragments to the

sedimentation surface is not known, this suggest rapid sedimentation of at least a few metres in 330 - 420 years. Cores taken near the river mouth suggest a rapid onlap of fluvial sediments in Piran Bay (Fig. 7.1; Ogorelec et al., 1981). During large floods, part of this fine sediment was occasionally eroded, but subsequently the ongoing sedimentation covered the resulting scars again. These scars are preserved in the sediment sequences as erosional levels. ^{14}C analysis has confirmed large age differences above and below such erosional levels (Fig.11; Table 7.2). It is unlikely that these age differences have been caused by contamination of the younger samples, since the samples are situated closely above each other. Such large-scale erosion in the floodplain that is caused by floods are also described by e.g. Sloan et al. (2001), Meyer (2001) and Liébault and Piégay (2002) as well.

According to the latter dates, large floods made a considerable incision around 120 years ago, creating a terrace at 2.5 m (Fig 10C). Two historical floods could be the cause of this, one flood in 1852 or one in 1896. Liébault and Piégay (2002) quoted the same period as a channel

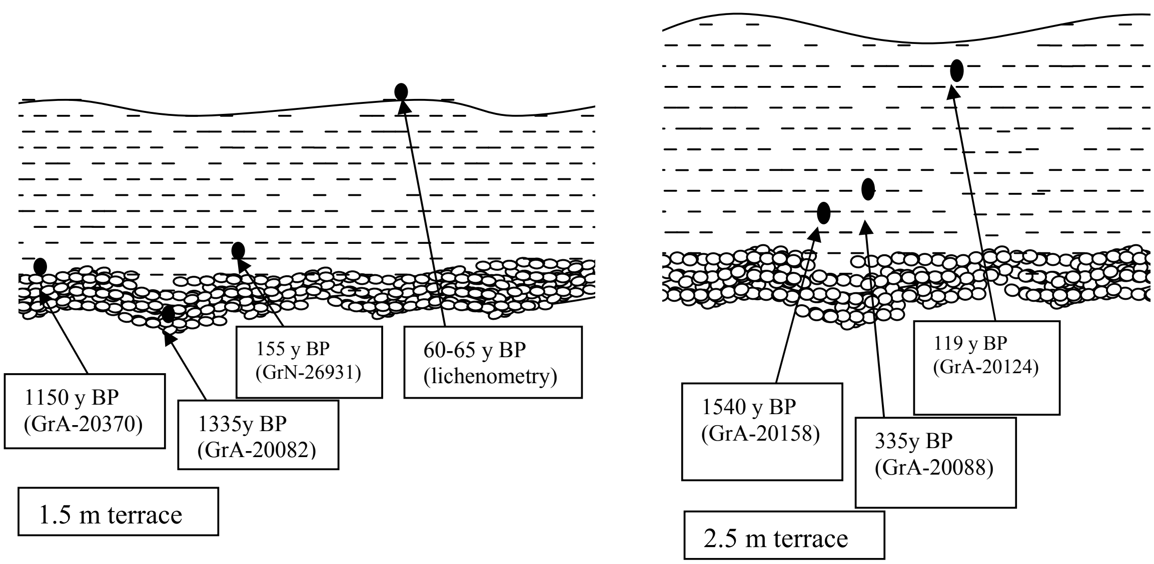

Figure 7.11: Composite view of bank faces in the 1.5 m and 2.5 m terrace with the locations of the ^{14}C samples (Table 7.2) and lichenometry samples (at the surface).

destabilization period due to major floods. According to historical sources, both floods of the Dragonja were responsible for demolishing of the saltpans, located in the delta (Zagar, 1991). In the precipitation record for Triest, approximately 40 km to the north of the study site, large quantities of precipitation were measured in the autumns of 1851, 1872 and 1896, which supports the theory of a major flood (Brunetti et al., 2004).

Table 7.2: ^{14}C sample results from the terraces.

Location	*Laboratory number*	*^{14}C age (y BP)*	*Calibrated date* CalAD (probability)*	*Comments*
Coring at ST, 408-420cm	GrN-26200	330 ± 25	1480-1640 (95.4%)	Wood
Coring at ST, 515-525cm	GrN-26201	420 ± 50	1410-1530 (71.3%)	Wood
Terrace 1.5m (section MR)	GrN-26931	155.7 ± 0.5%	1730-1770 (54.8%)	Wood, 1.10m-surface
Terrace 1.2m (Rokava)	GrA-20383	180 ± 45	160-1890 (79.9%)	Terrace of tributary
Terrace 1.5m (section ML)	GrA-20370	1150 ± 50	770-1000 (95.4%)	Wood, Below erosion surface, coring, 1.9m-surface
Terrace 1.5m (section ML)	GrA-20082	1335 ± 45	620-780 (95.4%)	Wood, Below erosion surface, Coring, 1.95m-surface
Terrace 2.5m (section ML)	GrA-20124	119 ± 0.5%	1830-1880 (71.6%)	Wood
Terrace 2.5m (section ML)	GrA-20088	335 ± 40	1460-1650 (95.4%)	Carbon
Terrace 2.5m (section MR)	GrA-20158	1540 ± 50	420-640 (95.4%)	Snail-shells
Terrace 2.5m (section MR)	GrA-20363	12.860 ± 160	14100BC-12400BC (95.4%)	Unreliable

*Radiocarbon dates were calibrated with the program OxCal (Bronk Ramsey, 2001)

After the flood of the second half of the 19th century and the simultaneous incision, the aggradation in the valley continued until appoximately 1945, when the abandonment of the agricultural fields started (Fig.10D). The sedimentation of the new floodplain did not reach its former height, but remained c.1m lower. As a result of the natural reforestation after 1945 the two lowest terraces, at 1.5 m and 0.5 m were formed (Fig 10E). These terraces have been studied in more detail. Figure 12A shows the section of the river where the terraces have been mapped in detail. Because of the natural reforestation the river started to incise again, creating a new terrace, which stands 1.5 m above the present-day river. According to the lichenometric dates and tree ring counting, channel activity on top of this terrace became inactive approximately 60 years ago, thus since 1945. Aerial photographs show that the riverbed is narrowing and the large erosional cliffs have decreased in size, indicating that the bedload has decreased. Since the erosional cliffs are the main source of coarse debris, the amount of coarse bedload should have diminished considerably. We suppose that this decrease of discharge and bedload are the main causes for the river incision. Vegetation that invades the riverbed also plays a role in these changes, by trapping sediment and concentrating river flow, inducing further vertical erosion of the remaining channel floor. Even though the abandonment of the fields had started around 1945, aerial photos show that the largest change in forest area has taken place since 1975. The flooding frequency and intensity decreased even more after 1975, enhancing the channel narrowing and down-cutting. The formerly active bars were stabilized by vegetation and now form the lowest ‘terrace’, 0.5 m to 1 m above the current riverbed (Fig.10E). Lichenometry and tree ring analysis give an age of approximately 30 years for this level.

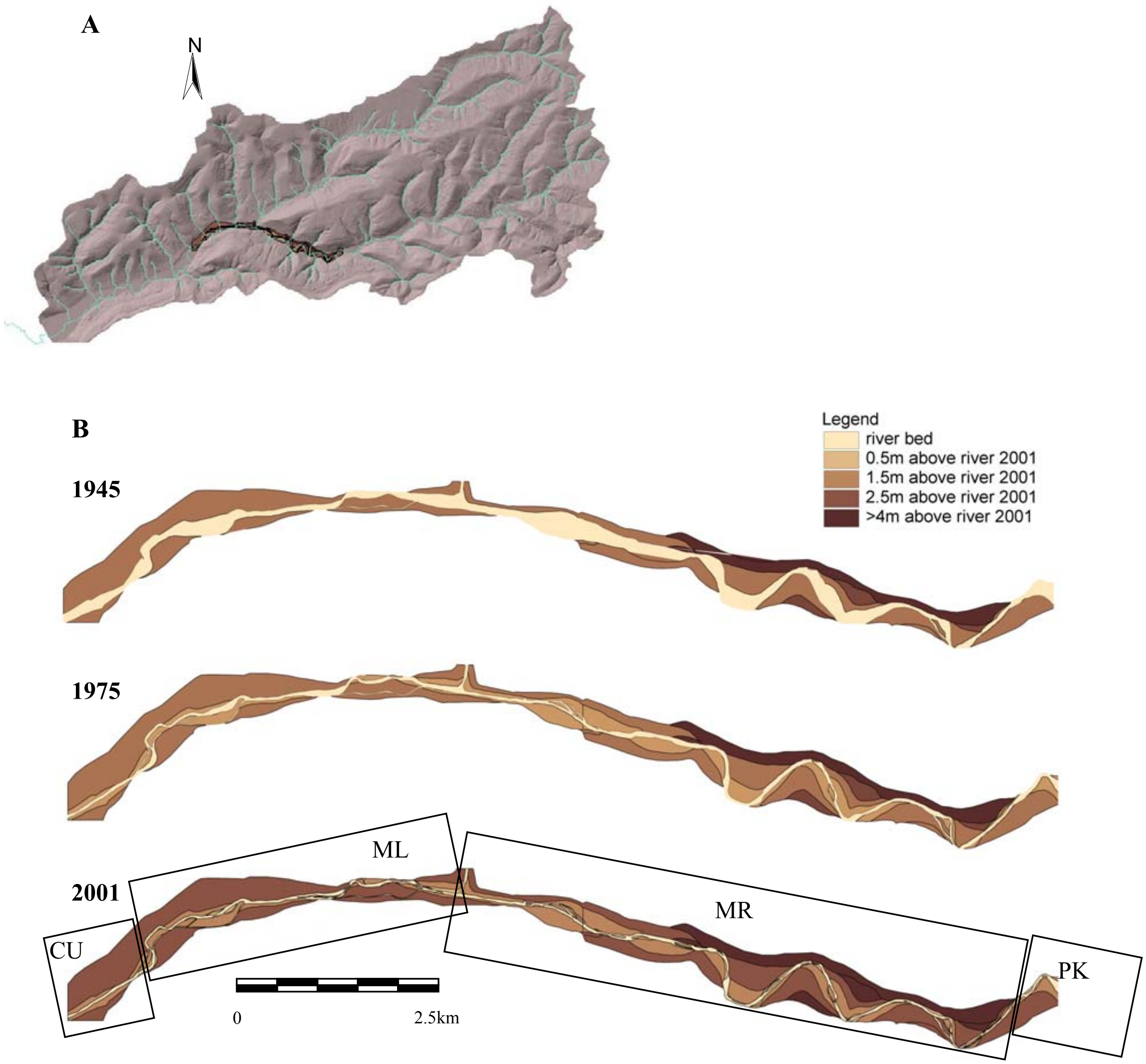

Figure 7.12: A: Location of the terrace field survey displayed on the 5 m DEM of the catchment (45º28'N, 13º35'E). B: Terrace maps: the 2001 map was mapped during a field survey, the 1945 and 1975 maps are constructed from the mapped terraces. Boxes indicate location of described sections.

7.6 Spatial variability in the response of the valley morphology to human impact

The response of the river to the discharge and sediment load changes is not uniform in the different reaches of the catchment.

7.6.1 Upper reaches (section PK (Perosa))

Before the extensive natural reforestation from 1945 onwards the upper reaches –section PK – had a wider, braided riverbed. Presently, the river has cut into its own riverbed material and formed a channel half the width of the former channel. The former riverbed, which now stands 1.5 m above the current riverbed, has been invaded with young trees and bushes. The 0.5 m terrace is relatively narrow in this section of the river (Fig. 7.8a). The largest change has occurred since 1975, when the river has started to meander within its old riverbed. Although the river morphology changed significantly, Manning's roughness factor (n) increased only slightly, from 1.14 before 1960 to 1.15 in 2001. This is the result of conflicting factors. For example, the river currently has a single channel, instead of braiding channel of 1960, which decreases Manning's n. But there is more vegetation growing in the channel in 2001, which increases Manning's n.

7.6.2 Middle reaches (section MR (Mrtveč), ML (Mlin) and CU (Čupinje))

In the upper middle reach, section MR, the changes due to the natural reforestation since 1945 are most evident. The river transformed from a braided cobble-bed river into a narrower, more sinuous channel (Figs. 12; 8b). Both the 1.5 m terrace and the 0.5 m terrace are well developed. Figure 11B shows the morphology of this section (MR and ML and a small part of PK and CU) derived from the geomorphological mapping of the terraces. In 1975 the river had abandoned 65% of the riverbed of 1954. This part of the riverbed is now the 1.5 m terrace. Between 1975 and 2001 the surface of the riverbed reduced a further 7%, this part of the river is now the 0.5 m terrace. The sediment accumulations as shown in Figure 6 are most vulnerable to erosion. On these locations the incision of the river is most evident and vigorous (example site in Fig. 7.8b). A mid-channel erosional bar of 8 m length and 2 m width developed within 2 years (from 2000 to 2002). Figure 13 shows the change in river morphology in section MR as observed on the aerial photographs from 1954, 1975, 1985 and 1994. The lines in the 1945 and 1975 pictures indicate the narrowing of the riverbed in this period. The section of the 1945 riverbed that is no longer in use in 1975 has transformed into the 1.5 m terrace. After 1975 terraces within the channel were formed. The mid-channel-bar visible on the aerial photograph of 1985 and 1994 (indicated with arrows) is an exceptionally large example of this new level, 0.5 m to 1.0 m above the current river. The vegetation on the mid-channel bar was still small in 1985, probably just weeds and small bushes. On the photograph of 1994, the mid-channel bars are overgrown with larger (darker) vegetation. The smaller terraces that were formed after 1975, are not visible on these aerial photographs.
In the more downstream section ML, the changes are similar to the changes in section MR. In

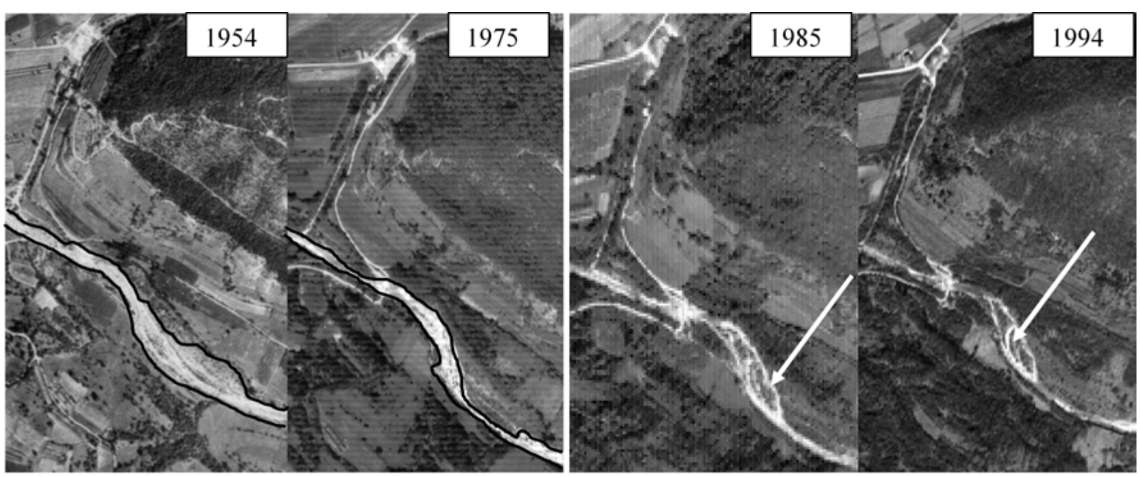

Figure 7.13: The narrowing and incising of the river is clearly visible on aerial photographs taken from the area just upstream from the confluence of the Dragonja and its major tributary, the Rokava, section MR. From left to right the photographs were taken in 1954, 1975, 1985 and 1994.

1975 the riverbed occupied 55% of the bed of 1945 (Fig. 7.11B). In 2001 63% of the 1945 bed was vegetated (Fig. 7.11B). In the lower middle reach, section CU, the change in bed form due to the natural reforestation is similar to the changes in the upper middle reaches, however changes in riverbed surface are not as severe (Fig. 7.8c). The river has formed the same terraces but is usually not as wide as in the upper middle reaches. The lowest terrace especially, has a much smaller surface.
Manning's n has changed most profoundly in the middle section of the river. It was estimated to have been 1.06 before 1960 (Gordon et al., 1993) and was measured in 2001 to be 1.10.

7.6.3 Lower reaches, (section ST (Sv Stefan))

The morphology of the lowest reaches shows only modest changes. In between the riffles, scour holes suggest the riverbed is currently eroding, creating a deeper channel (Fig. 7.8d). However it is not certain that this has been a trend over the last decades. The usual steep banks of 5 m high are occasionally smoother and the riverbed is wider then the typical 10 m. On these locations the 0.5 m and even sometimes the 1.5 m terrace are present.

7.7 Discussion and Conclusions

Table 7.3: Summary of ages of the terrace levels

Terrace level	*Formation*
2.5 m terrace	around 1870
1.5m terrace	1945-1975
0.5m terrace	1975-2001

The general morphology of the Dragonja River is similar to other Mediterranean rivers in a flysch basin (e.g. Cambi et al., 2003). Generally the river has a pool-riffle morphology with exception of the most upper reaches of the river, which can be described as step-pool sequences (Fig.8).
Morphologically the river can be divided in three reaches. The distinctive features of the upper reach are the steep gradient with step-pool morphology and predominantly a bedrock channel. The middle reach has large riffles with bedrock pools, which gradually change into a cobble bed river. In the upper and middle reaches the river has formed several terraces, but in the lower reach these terraces are absent. This part of the river valley is depositional. The Dragonja morphology has changed considerably under the influence of human interference. The first large scale deforestation, which probably took place during the Roman age, caused erosion of large volumes of fine sediment from the hillslopes and subsequent deposition in the valley. During large floods, part of this fine-grained sediment was occasionally eroded, but subsequently sedimentation covered these scars again. In the sediment record these scars are preserved as erosional surfaces. In the second half of the 19th century large floods caused strong incision that created a terrace scarp and a widespread terrace 2.5 m above the current river. In other Mediterranean-climate studies (e.g.Sloan et al.,2001; Liébault and Piegay, 2001) large scale widening of the channel has also been attributed to large floods.
As a result of the reforestation of the catchment, two terraces were formed in the middle and upper reaches of the Dragonja since 1945 (Fig. 7.14). The reforestation caused a decrease in discharge and sediment supply. The decreased intensity and frequency of floods allowed vegetation to invade the riverbed. This resulted in the formation of a new floodplain level that now stands 1.5 m above the current river. This terrace was dated with lichenometry to be 60 years old. The remaining channel started to erode its bed. The largest increase in forest area has taken place since 1975, which intensified the process of channel incision and narrowing. The present riverbed shows characteristics of an underfit river, meandering in its former wider bed. The remaining part of the riverbed has been vegetated since this time and stands 0.5 m above the current river. This terrace was dated at approximately 30 years BP. Figure 12

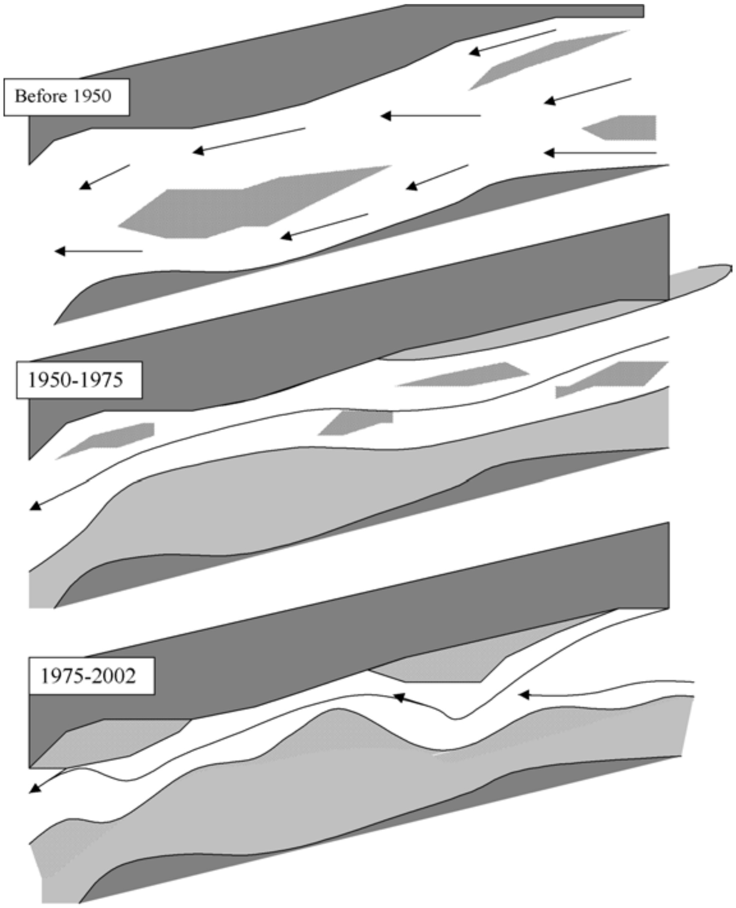

Figure 7.14: The evolution of the morphology of the channel from 1945 to 2001 as derived from geomorphological mapping. Before the reforestation (before 1945) the riverbed was at some places braiding. From 1945 to 1975 the river incised, forming a terrace at 1.5 m above the current river. From 1975 to 2001 incision continued, while the river started to meander within the old riverbed.

shows schematical planviews of the evolution of the river morphology from 1945 to 2001. Table 7.3 gives a summary of the terrace ages. These processes have occurred in most parts of the river. The upper and middle reaches have reacted in more or less the same way. The 2.5 m terrace extends over a large area, especially after the confluence with the Rokava, where the valley becomes much wider. The 1.5 m terrace has its largest area in the middle reaches, where the river lost 55% to 65% of its bed area between 1945 and 1975. The 0.5 m terrace has a much smaller area. This terrace was formed by river meandering through its 30-year-old riverbed and the newly formed terrace consists of fixed, mostly alternate bars at 0.5 m above the current river.
Incision and narrowing of the channel is often attributed to gravel mining (e.g. Rinaldi, 2003; Marston et al., 2003) or a combination of gravel mining and land-use change (e.g. Liébault and Piegay, 2001; Kondolf et al, 2002). Besides agriculture, no other significant human activity modifies the river discharge and geomorphology in the Dragonja catchment. Therefore the recent morphological changes of the channel in the Dragonja River are purely the result of the natural reforestation.

Summarizing, two major phases of morphological change have occurred in the Dragonja valley due to land abandonment: formation of a river terrace with braided channels around the mid 20th century, and further incision accompanied by channel narrowing and transition to a meandering pattern since 1975. For the latter period, processes occurring during the transition are well documented. These comprise in the middle reaches of the river: 1) decrease in reworking of the bars; 2) encroachment of vegetation on inactive bar surfaces; and 3) channel narrowing and incision, resulting in an underfit channel meandering in its former braided-river bed.

PART IV: RECONSTRUCTION OF OVERBANK SEDIMENTATION

Chapter 8: Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia.

CHAPTER 8: IMPACT OF NATURAL REFORESTATION ON FLOODPLAIN SEDIMENTATION IN THE DRAGONJA BASIN, SW SLOVENIA

ABSTRACT

Changes in floodplain sediment dynamics have profound effects on riverine habitats and riparian biodiversity. Depopulation due to socio-economic changes in the Dragonja catchment (91 km^2) in southwestern Slovenia resulted in the abandonment of agricultural fields, followed by natural reforestation since 1945. This profoundly changed the water and sediment supply to the streams, as well as floodplain sediment deposition.

This paper presents a reconstruction of the development of the Dragonja floodplain due to these land use changes during the last 60 years. The reconstruction is based on dating of floodplain sediments using ^{137}Cs-profiles, measurement of actual sedimentation rates using artificial grass sedimentation mats, and linking this information to the present-day hydrological behaviour of the river. The sedimentation mats showed that floodplain sedimentation was restricted to peak flows of considerable magnitude. Due to the reforestation, the return period of such high flows increased from 0.31 year in the period 1960 – 1985, to 0.81 year between 1986 and 2003, with commensurate changes in sedimentation rates. At the 1.5 m river terrace (formed about 60 years ago), ^{137}Cs-based sedimentation rates (1960-1986) were roughly twice the rates inferred from the artificial grass mats (2001-2003). This finding matches the increase in the return period for larger peak events during the 1986-2003 period that caused fewer major inundations at this level. Conversely, sedimentation rates determined for the lowest terrace at 0.5 m were similar for both techniques (and periods) because the return periods of the peak events responsible for sediment deposition at this lower level did not change much over the period 1986 to 2003.

Keywords: natural reforestation, floodplain sedimentation, Dragonja, sedimentation mats, ^{137}Cs dating

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8.1 INTRODUCTION

Changes in floodplain sediment dynamics can have profound effects on riverine habitats and biodiversity in the riparian zone. In many regions of the world increased agricultural activity and gravel mining have a considerable impact on the river hydrological behaviour and channel morphology. The impact of these changes on erosion and sedimentation dynamics has attracted considerable scientific attention (e.g. Trimble, 1976, 1981; Ehui and Hertel, 1992; McDonald et al., 2002). However, due to socio-economic changes in several regions in southern Europe a reverse trend of decreasing agricultural activity in recent decades can be observed. This trend is either followed by planned reforestation or nature development, or takes the form of unplanned land abandonment followed by natural forest regeneration (Globevnik et al., 1998; Liébault and Piégay, 2002). Reforestation may profoundly change the water and sediment supply to the rivers, and, ultimately, floodplain sediment deposition rates (Tennessee Valley Authority, 1961; Trimble, 1976; Globevnik et al., 1998; Lach and Wyzga, 2002). Previous studies of the effects of reforestation on stream sediment dynamics sometimes pertained to large catchments with rather heterogeneous land cover (e.g. Liébault and Piégay, 2001; Marston et al., 2003) or relatively small hillslope plots rather than catchments with uniform vegetation (García-Ruiz et al., 1995, 1997). In some cases, where hillslope sediment supply is dominated by surface erosion, catchment water and sediment yields are reduced considerably following reforestation (Globevnik and Sovinc, 1998; Zhou et al., 2002; Scott et al., 2005). In others, where mass wasting and bank erosion constitute dominant sources of sediment, the presence or absence of forest has little effect on stream sediment load (Ramsay, 1987ab).

The Dragonja River in southwestern Slovenia represents one of the few remaining streams draining into the Adriatic Sea whose channel has not been regulated by man (Globevnik and Sovinc, 1998). As such, any changes in channel morphology will reflect changes in the flow regime and sediment dynamics as caused by changes in climate or land cover. As a result of several decades of depopulation, this previously severely eroding 91 km^2 catchment (Fig. 8.1) has seen a steady increase in the proportion of mostly broad-leaved secondary forest from ca. 30% in 1954 to 70% in 2002 (Keesstra and van Dam, 2002). With the return of the forest, profound changes in the flow regime and the morphology of the main river have taken place. Notably, a gradual reduction in average annual and dry-weather flows (3.5% and 10% per year, respectively; cf. Globevnik and Sovinc, 1998), and a 68% decrease in channel width in the middle reaches between 1954 and 2001 have occurred (Keesstra et al., 2005).

Figure 8.1: The study area: the Dragonja catchment, Southwestern Slovenia (45°28'N, 13°35'E).

This paper presents a reconstruction of the development of the Dragonja floodplain over the last 60 years in relation to the cited land use changes. The approach involved dating of floodplain sediments using ^{137}Cs-profiles, measurement of actual sedimentation rates using artificial grass sedimentation mats, and linking this information to the present-day behaviour of the river.

8.2 STUDY AREA

The Dragonja catchment is situated in the southwestern part of Slovenia at the border with Croatia. The river is ca. 30 km long and the catchment is approximately 91 km^2 (Fig. 8.1). Elevations range from 485 m to sea level. The upstream part of the catchment consists of two sub-catchments, the Upper Dragonja sub-catchment (32 km^2) and the Rokava sub-catchment (20 km^2). The geology is quite uniform and composed of sub-horizontal to gently north-dipping Eocene flysch deposits, consisting of highly calcareous and erodible silt- and clay

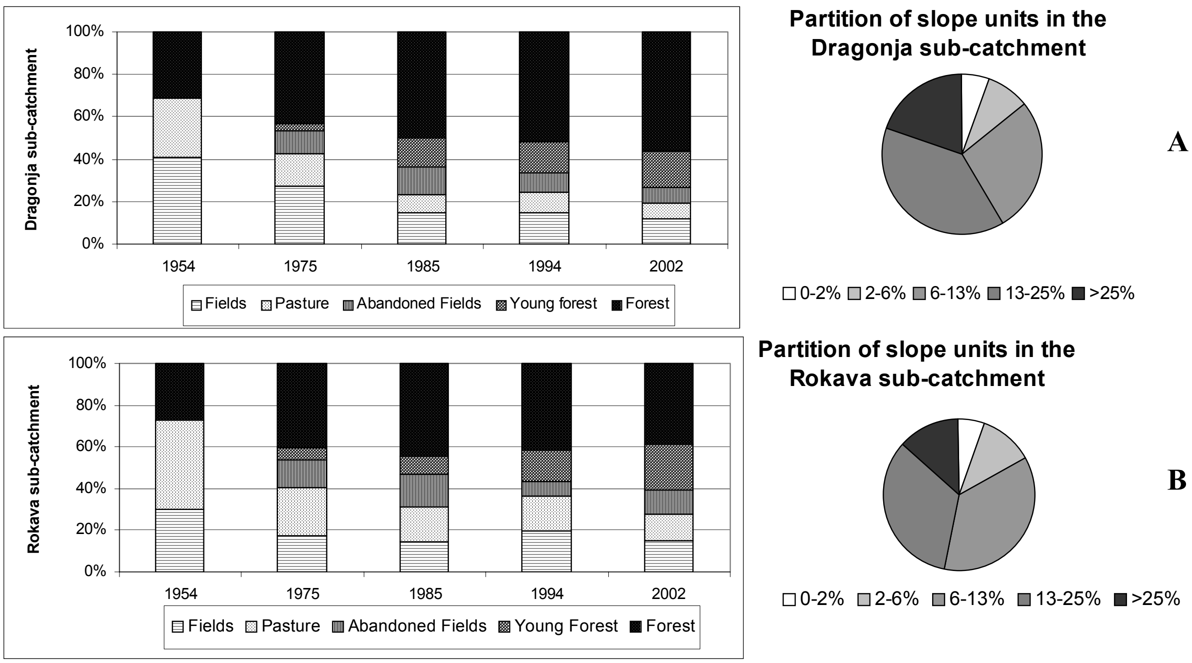


Figure 8.3: Land use change in the upper Dragonja and Rokava sub-catchments from 1954 until 2002 as derived from aerial photographs and field surveys. Pie diagrams indicates partition of the slope units in the Upper-Dragonja and Rokava sub-catchments.

stones with intermittent sandstone layers up to 1.5 m thick (Melik, 1960; Orehek, 1972). Overall morphology is characterized by long, flat ridges and plateaux that are separated from the valleys by relatively short, steep slopes, with slopes in the Upper Dragonja sub-catchment typically being steeper (Fig. 8.2a) than those in the Rokava sub-catchment (Fig. 8.2b) as a result of differences in the exposure of the more resistant strata. Soils are all highly calcareous and consist mostly of rendzinas (FAO, 1990)/ rendolls (USDA, 2003), with the exception of the valley floors, where fluvisols (FAO, 1990) / ustifluvents (USDA, 2003) have developed (Zupancic and Pric, 1999). The climate of Slovene Istria has been classified as sub-Mediterranean (Köppen-type C_w). The average annual temperature is 14^{o}C at the coast and 10^{o}C at the eastern upper end of the catchment. Absolute daily temperatures vary from -10^{o}C to 35^{o}C (HMZ, 2003; Ogrin, 1995). Annual precipitation varies from 700 mm to 1400 mm and increases somewhat with distance from the coast. The maximum-recorded daily precipitation total is 133 mm whereas events in excess of 50 and 75 mm d^{-1} occur on average 3 and 1 times per year (calculated on the basis of precipitation measured from October 2000 to July 2004). Between 1950 and 2002 annual precipitation has decreased by 19% whereas the hydrological record at the outlet of the entire basin (Pod Kaštel station, Fig. 8.1) shows a decrease in mean discharge of 79 % over the period 1960 - 2002 (HMZ, 2003). During this period there has been a steady increase in the number of days without flow and a decrease in the number of high flow events (Globevnik and Sovinc, 1998; HMZ, 2003; Fig. 8.3).

The long-term hydrological record at Pod Kaštel (1960 - 2002) suggests 1-, 10- and 50-year recurrence interval floods to have a magnitude of 28, 65, and 105 m^3 s^{-1} respectively. Yearly precipitation and discharge data show that the average percentage of precipitation that is discharged by the river decreased from 64% (1960-1970) to 33% (1990-2000). Quick flow events (sensu Hewlett and Doss, 1984) had an average duration of ca. 15 h measured over the period autumn 2000 to autumn 2004.

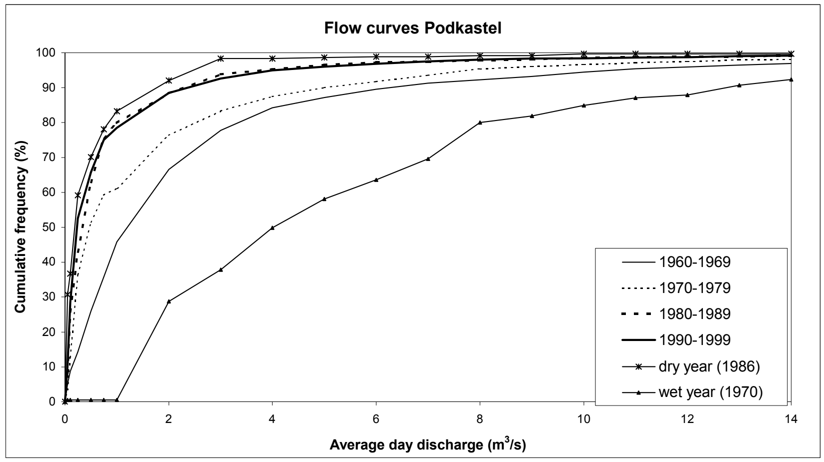


Figure 8.3: Flow curves of daily discharges at Pod Kaštel, at the outlet of the Dragonja catchment (HMZ, 2003).

Major changes in land use have occurred in the catchment over the last 55 years. After the Second World War socio-economic changes in the region caused considerable depopulation resulting in large-scale abandonment of agricultural fields and pastures. After abandonment, these fields gradually reverted to mixed deciduous forest dominated by oak (*Quercus pubescentis*), hornbeam (*Carpinus orientalis croaticus*) and ash trees (*Fraxinus ornus*)(te Linde, 2001). Figure 8. 2 shows the changes in land cover as derived from aerial photographs taken in 1954, 1975, 1985 and 1994. The data for 2002 were derived from a field survey by the author and co-worker (Keesstra and Van Dam, 2002). The changes in land cover are not uniformly distributed over the catchment. The greater accessibility and gentler slopes of the Rokava sub-catchment caused the depopulation to be less extensive in this part of the catchment. Therefore, a larger percentage of the land is still in agricultural use there today (Fig. 8.2).

Due to the natural reforestation of the slopes and the associated reductions in flows, the river has narrowed (Keesstra et al., 2005) and incised itself into its own bed, thereby creating a terrace between 1945 and 1975 about 1.5 m above the current river bed. After 1975 the process of narrowing and incision intensified as the forest matured, forming an additional terrace 0.5 - 1.0 m above the riverbed (Keesstra et al., 2005).

8.3 Methods

8.3.1 Reconstruction of overbank deposition using Caesium-137 profiles

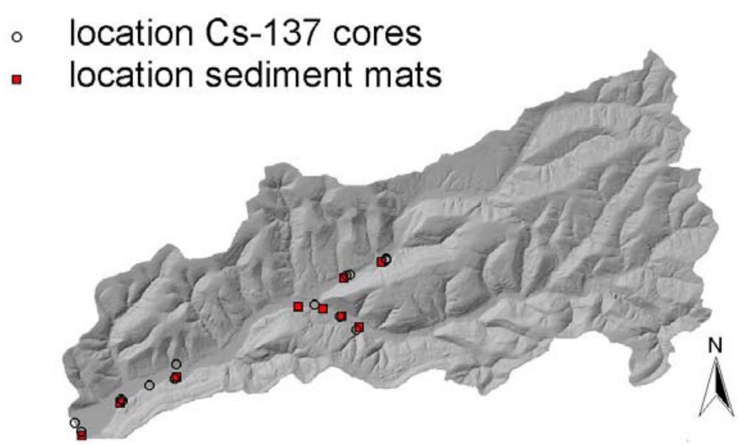


Figure 8.4: Locations of the ^{137}Cs cores and the artificial grass mats used as sediment traps.

Caesium-137 is widely used as a tracer of sediment movement (Panin et al., 2001; Walling et al., 2000). To estimate floodplain sedimentation rates from ^{137}Cs profiles the 'principle of stretching' was applied, in which the position of the deepest peak in the profile is considered to correspond with the position of the surface in 1960, when nuclear tests were at a maximum. Similarly, the uppermost peak is assumed to represent the surface in

1986 (the Chernobyl reactor accident) (Walling and He, 1992). Caesium is immobilized rapidly in soils that have a high proportion of micaceous minerals, and contain free carbonates and small amounts of organic matter (Livens and Loveland, 1988). The soils of the study area are clayey and have a high calcium content and may thus have immobilised the ^{137}Cs quickly in the top 5 cm (Barišic et al., 1999; Szerbin et al., 1999).

To correct for vertical transport of the deposited ^{137}Cs, reference cores were taken at locations where no deposition or erosion of sediment has taken place. The sample sites (Fig. 8.4) were selected in such a way as to represent a larger area that underwent the same sedimentation rate over the last 50 years. Because tillage disturbs the ^{137}Cs profile, aerial photographs taken in 1954, 1975, 1985 and 1994 were used to select undisturbed sites. Twenty samples of 0.5 m long and a diameter of 9 cm were taken with a hand auger. Fifteen of these cores were analysed on ^{137}Cs content using the PHAROS device that analyses sets of standard spectra including an aluminium background (Rigollet and Meijer, 2002). Geomorphological mapping was used to extrapolate the point measurements to larger areas. In the middle part of the river profile three terrace levels were found at 2.5 m, 1.5 m and 0.5 m above the current riverbed (Keesstra et al., 2005). The distribution of the terraces in the parts of the valley that were not mapped during the field survey were estimated with a GIS from the digital elevation model (DEM, 5m pixels), which was digitised from a 1:5000 map, with isoheights with an interval of 5m. Since the DEM was not accurate enough to digitally

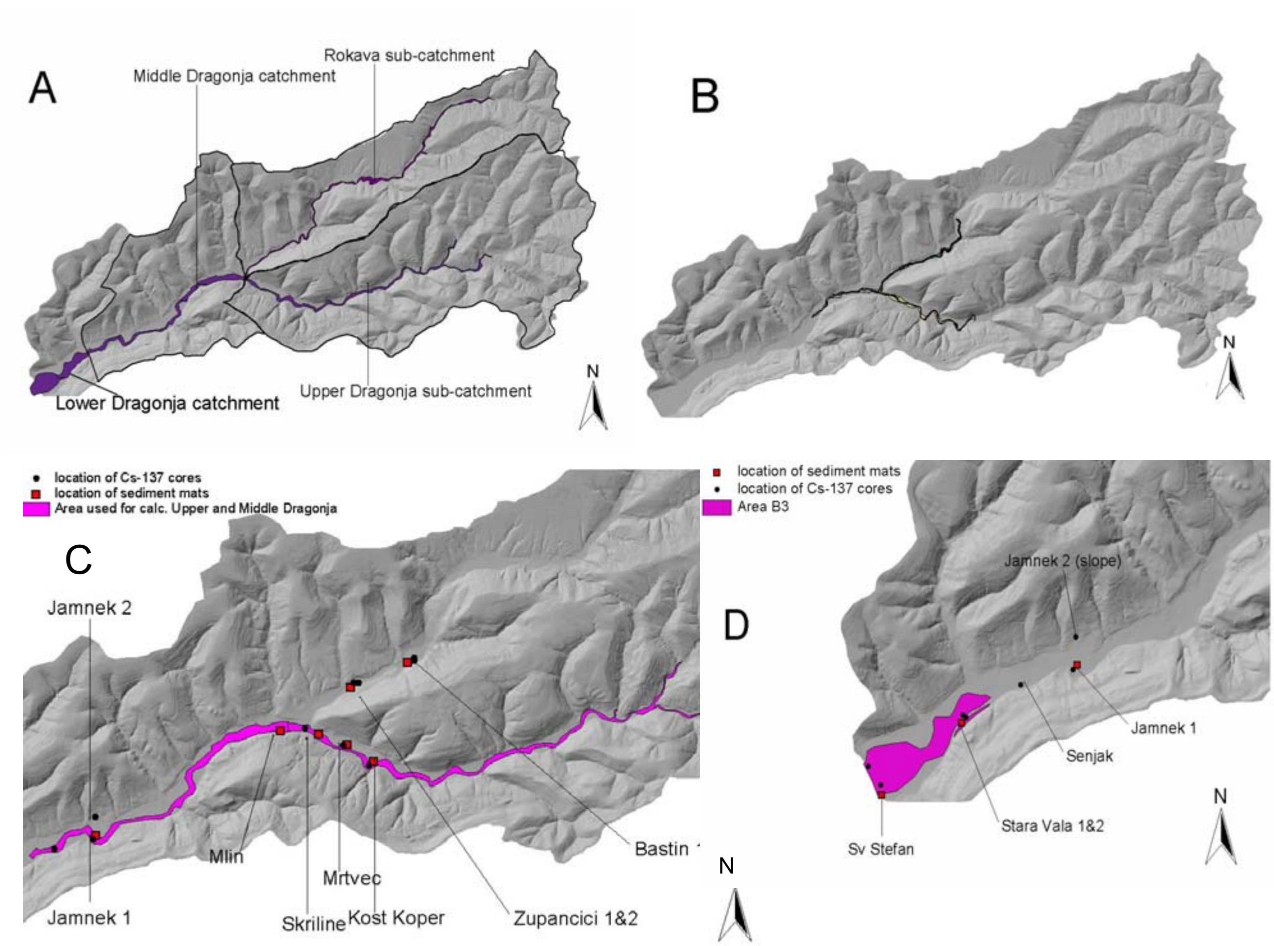


Figure 8.5: A: The interpreted extent of the floodplain as displayed on the DEM and the location of the sub-catchments. B: the extent of the geomorphologically mapped section of the floodplain. C: Area of floodplain used for calculations of the Upper and Middle Dragonja sub-catchments. D: Area used for calculations for the Lower Dragonja sub-catchment.

map the lowest terrace levels (0.5 m and 1.5 m), the latter were mapped during a detailed geomorphological field survey (Fig. 8.5B) and their areal percentages calculated subsequently. The surface area of the terraces in the remaining floodplain area (black area in Fig. 8.5A) was inferred from the field-based calculations. The 2.5 m terrace was not included in these calculations since it was not mapped completely during the field survey. The areas of the respective terraces were multiplied times the sedimentation rates derived from the ^{137}Cs analysis, to give the total amount of sediment deposited on the floodplain from 1960 to 1986 and from 1986 to 2001.

8.3.2 Measuring overbank sedimentation using artificial grass mats

To estimate the amount of sediment deposited on the floodplain, artificial grass mats of 0.5 m x 0.5 m (Middelkoop, 1997; Asselman and Middelkoop, 1995) were placed on point bars, as well as on the 0.5 m, 1.5 m and 2.5 m terraces (Fig. 8.4; Table 8.1). These terraces are usually narrow and therefore have little topographic variation within the terrace boundaries. The mats were pinned to the ground with four 10cm long pins and one 15 cm long pin. To compare present-day overbank deposition rates with historical deposition, 28 mats were divided over nine locations where ^{137}Cs-cores had been taken (Fig. 8.4). At each location several mats were distributed to cover all levels surrounding the river (Table 8.1). Vegetation cover and type influence the amount of sedimentation on the mats (Abt et al., 1994; Tsujimoto, 1999) and these parameters were therefore estimated within an area of 2 m^2 around each mat.
The mats were in place between June 2001 and June 2003. In February 2002 and July 2002

Table 8.1: Number of artificial grass mats installed at nine sites along the Dragonja and Rokava rivers.

Location	*Valley position (Units)*	*Overbank*	*In channel/ point bar*	*0.5 m terrace*	*1-1.5 m terrace*	*2.5 m terrace*
ST Sv Stefan	Down stream (A, B3)	3	2	-	-	-
SV Stara Vala	Middle section (A, B2)		1		1	1
JM Jamnek	Middle section (A, C)		1	1		1
ML Mlin	Middle section (A, B2)		1	1	1	
ZP Zupančiči	Rokava (A)			1		
BS Baštin	Rokava (A, B1)				4*	
SK Skrline	Middle section (A, B2)			2	2	
MR Mrtveč	Upper-Dragonja (A,B2)	1	1		2	
KK Kost Koper	Upper-Dragonja (C)					1

* 2 mats in gullies on floodplain, 2 mats on floodplain

Unit A: the 0.5 m terrace at 0.5 m and the low point bars in the whole catchment.
Unit B1: the terraces at 1 - 1.5 m above the river in the Rokava sub-catchment
Unit B2: the terraces at 1 - 1.5 m above the river in the Upper and Middle Dragonja sub-catchments
Unit B3: for the floodplain of the Lower Dragonja sub-catchment
Unit C: the higher terraces, situated above 1.5 m above the river in the entire catchment.

all mats were checked. Mats that had been inundated in the meantime were collected for analysis and replaced. In June 2003 all mats were collected. The sediment deposited on the mats was washed off, dried at 105°C and weighed. A sub-sample of the sediment was analysed for texture (see also below). It was assumed that no significant amount of sediment was removed from the mat by rainfall or splashed on the mat, because most mats were on horizontal sites with dense vegetation cover.

8.3.3 Discharge measurements

Daily Stream discharge was measured at the outlet of the catchment at Pod Kaštel by the Slovene Government since 1961 (Fig. 8.1). Return periods of peak events were calculated using HYMOS (WLDelft, 2003). The number of events responsible for the sediment deposited on the respective clusters of artificial grass mats was derived manually from the water level data. On several locations cross sections were made with a water leveller, from which the heights corresponding with the measured discharges were derived.

8.3.4 Textural analysis

Textural analysis was performed on 17 sediment samples from the artificial grass mats and on 91 soil samples taken throughout the catchment on different land use types and different landscape setting (Keesstra et al, submitted a). The analysis was done with a Type A22 Fritsch Laser Particle Sizer. The samples were prepared by boiling with H_2O_2 (30%) to remove organic matter and treated with $NaPO_4$ to peptisize the sediment (Konert and Vandenberghe, 1997). The usually employed HCl was not added in this case to avoid partial dissolution of the sediment.

Table 8.2: Depth of the peaks in the ^{137}Cs profiles, calculated sedimentation rates and average sedimentation rates for units A, B and C for the periods 1960 -1986 and 1986- 2001 as calculated from ^{137}Cs data (see Fig. 8.5 for explanation of units).

	Height above current river (m)	Peak depth 1960 corrected for infiltration (cm)	Peak depth 1986 corrected for infiltration (cm)	Sedimentation rate (cm year^{-1}) 1960-1986	Sedimentation rate (cm year^{-1}) 1986-2001	Unit	Mean sedimentation rate (cm y^{-1}) 1960-1986	Mean sedimentation rate (cm y^{-1}) 1986-2001
Zupancici 2	0.5	(*)	27.5	(*)	1.96	A	(*)	1.96
Bastin 1	1	17	5.5	0.65	0.39	B1	0.69	0.65
Bastin 2	1.2	16	13.5	0.62	0.96	B1	±	±
Zupancici 1	1.2	21	8.5	0.81	0.61	B1	0.10	0.29
Senjak	1	16	3.5	0.62	0.25	B2	0.66	0.46
Stara Vala 1	1.4	28	9.5	1.08	0.68	B2	±	±
Skriline	1	7	6.5	0.27	0.46	B2	0.41	0.22
Sv Stefan	4	12	0.5	0.46	0.04	B3	0.46	0.04
Stara Vala 2	2.5	9.5	(**)	0.37(***)	-	C	0.41	
Jamnek	1.5	9	2.5	0.35	0.18	C	±	<0.06
Kost Koper	2.5	13	(**)	0.50(***)	-	C	0.13	

(*) Before formation of the low terrace level
(**) Possibly erosion
(***) Highly uncertain value as a result of possible erosion

8.4 Results

8.4.1 Sedimentation rates derived from Caesium-137 profiles

Floodplain sedimentation rates were calculated from the measured ^{137}Cs profiles. The profiles of the reference cores (cores 1 and 2) exhibited a typical peak at 5.5 cm depth, as indicated by the box in Fig. 8.6 This is thought to reflect transport of ^{137}Cs shortly after deposition as well

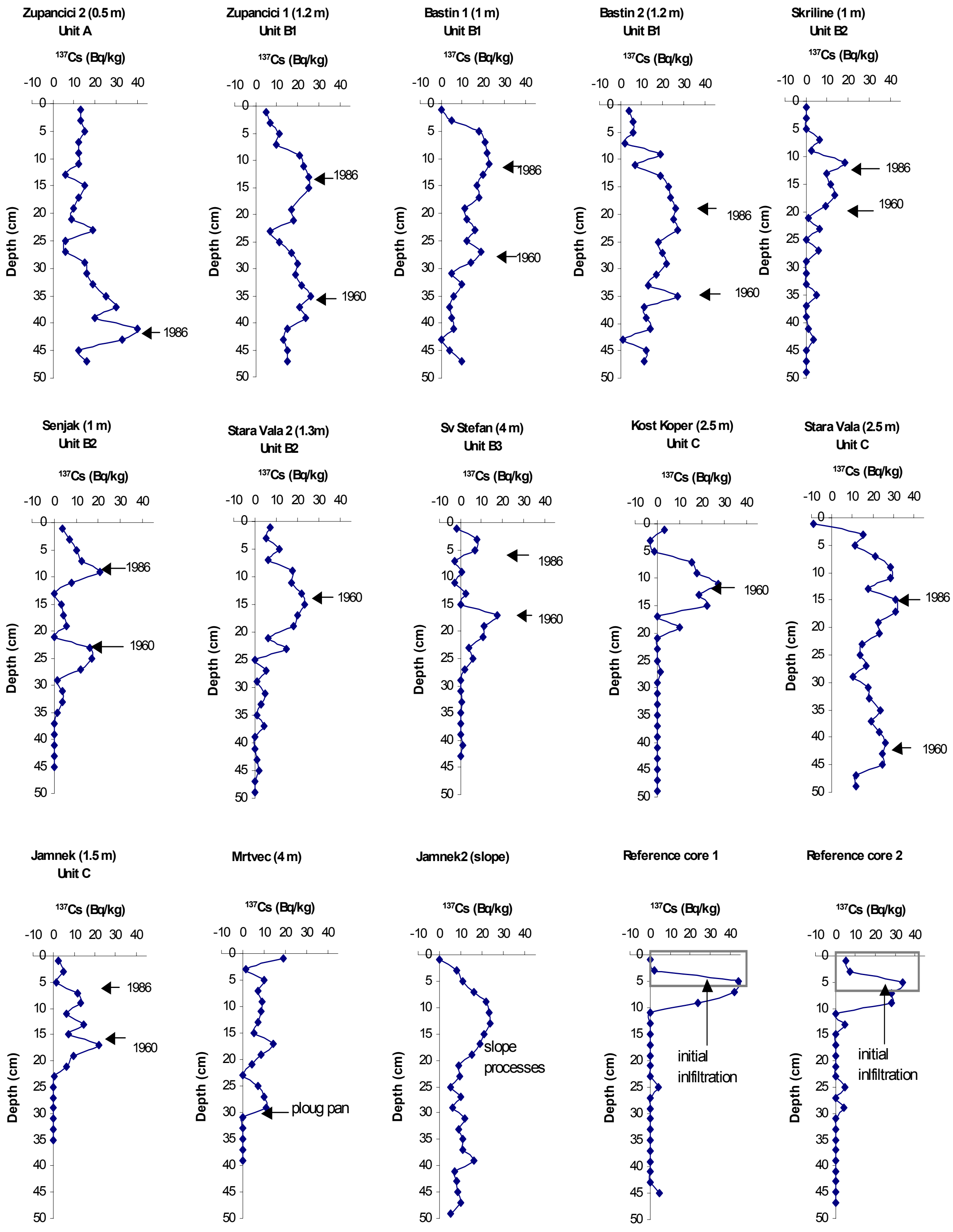


Figure 8.6: ^{137}Cs profiles at 15 locations in the Dragonja catchment. Arrows indicate interpreted land surfaces on the indicated date. Reference cores 1 and 2 were taken in erosionally and depositionally stable areas, representing the initial infiltration of ^{137}Cs for which the other profiles were adjusted.

as bioturbation. The ^{137}Cs profiles in the sedimentation areas were corrected accordingly (Table 8.2). Almost all profiles showed two peaks, representing the soil surface in 1960 and 1986, respectively (Fig. 8.6). Thus, sedimentation rates were calculated for the periods 1960-1986 and 1986-2001 (Table 8.2).

To analyse the spatial distribution of floodplain sedimentation rates the catchment was divided into three parts: the Upper and Middle Dragonja, the Lower Dragonja and the Rokava sub-catchments (Fig. 8.5A). The depositional area was divided into the following units: Unit A (core Zupančiči 2) represents the lowest terrace at 0.5 m above the river bed and the low point bars in the whole catchment. Unit B represents the terrace at 1 - 1.5 m above the river and is subdivided into three parts: B1 for the Rokava sub-catchment (cores Baštin 1, Baštin 2 and Zupančiči 1); B2 for the Upper and Middle Dragonja sub-catchments (Fig. 8.5C)(cores Senjak, Stara Vala 1 and Skriline); and Unit B3 (core Sv Stefan) for the floodplain of the Lower Dragonja sub-catchment (Fig. 8.5D). Finally, Unit C (cores Jamnek and Kost Koper) represents the higher terraces, situated above 1.5 m above the river in the entire catchment. In the following sections the results for the respective depositional units are presented and interpreted.

8.4.1.1 Unit A: 0.5 m terrace

Only one core could be taken from the lowermost terrace level that consisted of fixed mid-channel bars and sidebars made up largely of gravel material and boulders. This level was formed after 1975 when the river incised into its bed after a phase of intensified natural reforestation (Keesstra et al., 2005; cf. Fig. 8.2). A very high sedimentation rate of 1.96 cm y^{-1} between 1986 and 2001 was derived from this single core, which probably represents an infilled depression and thus cannot be considered representative for this level. However, from a detailed field survey it is known that the fixed bars had an average of about 20 cm of fine sediment on top of the coarse material of the original bar surface (Keesstra et. al., 2005). From this a more plausible sedimentation rate since 1975 of 0.75 cm y^{-1} is obtained.

8.4.1.2 Unit B1: 1-1.2 m terrace in the Rokava sub-catchment

The Zupančiči 1 and Baštin 1 & 2 cores representing the 1-1.2 m terrace level in the Rokava sub-catchment (Fig. 8.5C) gave very similar sedimentation rates, viz. 0.69 ± 0.10 cm y^{-1} for the period 1960 – 1986, and 0.65 ± 0.29 cm y^{-1} for 1986 - 2001 (Table 8.2).

8.4.1.3 Unit B2: 1- 1.4 m terrace in the Upper and Middle Dragonja sub-catchments

The Skriline, Stara Vala 1 and Senjak cores representing the 1-1.4 m terrace level in the Upper and Middle Dragonja sub-catchments (Figs. 5C and 5D) gave a wide range in floodplain sedimentation rates. On average, the sedimentation rate for the period 1960 - 1986 was 0.66 ± 0.41 cm y^{-1} vs. a much lower sedimentation rate of 0.46 ± 0.22 cm y^{-1} for 1986-2001 (Table 8.2). The difference in sedimentation rate is not significant due to a too limited population of samples.

The sedimentation rates derived from the Senjak core were close to the average rates derived for this Unit whereas the rates derived from the Skriline core were distinctly lower (Table 8.2). This might be connected to the low bulk density of the sediment, as well as the low amount of clay present in the upper part of this particular core, which may have led to reduced adsorption of Cs (cf. Livens and Loveland, 1988). The sedimentation rates derived from core Stara Vala 1 were remarkably high (Table 8.2) in view of its relatively high topographic position (1.4 m above the river). This place marks the most downstream site of the middle section of the river (Fig. 8.5C) which is inundated frequently during peak flows as a result the propelling force of the water in a narrower channel with higher banks.

8.4.1.4 Unit B3: The Lower Dragonja

No terraces are found in the Lower Dragonja valley (Keesstra et. al., 2005) and the Sv Stefan core is believed to represent the entire section (Table 8.2). A distinct decrease in floodplain sedimentation rate was found, from 0.46 cm y^{-1} between 1960 and 1986, to 0.04 cm y^{-1} between 1986 and 2001 (Fig. 8.7).

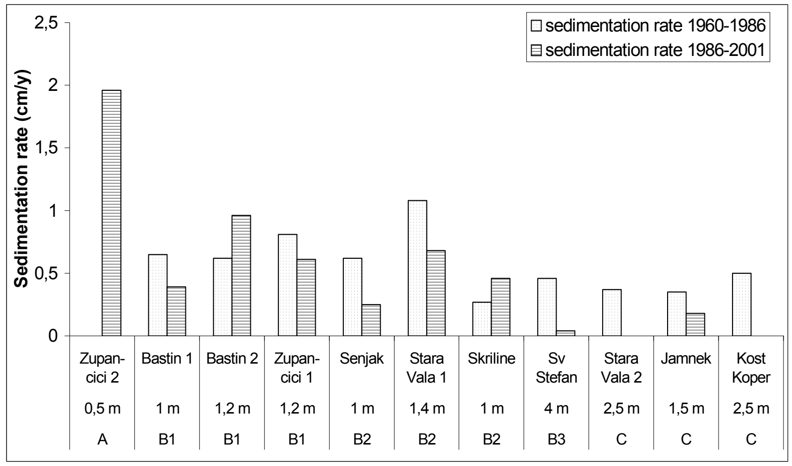


Figure 8.7: Sedimentation rates as derived from ^{137}Cs analysis. Each core shows the sedimentation rates for the periods 1960-1986 and 1986-2001.

8.4.1.5 Unit C:2.5 m terrace

This Unit represents all depositional areas situated at more than 1.5 m above the river (cf. Fig. 8.5C). All Cs co res were taken on a high terrace (2.5 m). Based on the Kost Koper (Upper Dragonja) and Stara Vala 2 (middle reach of catchment) cores an average sedimentation rate of 0.41 cm y^{-1} was derived for the period 1960-1986 (Table 8.2). During the following period, both sites seem to have experienced erosion and no deposition rate could be derived. Because it is unknown when the erosion started, the erosion rate derived for the period 1960-1986 is a minimum value. The Jamnek core (middle reach of the river),

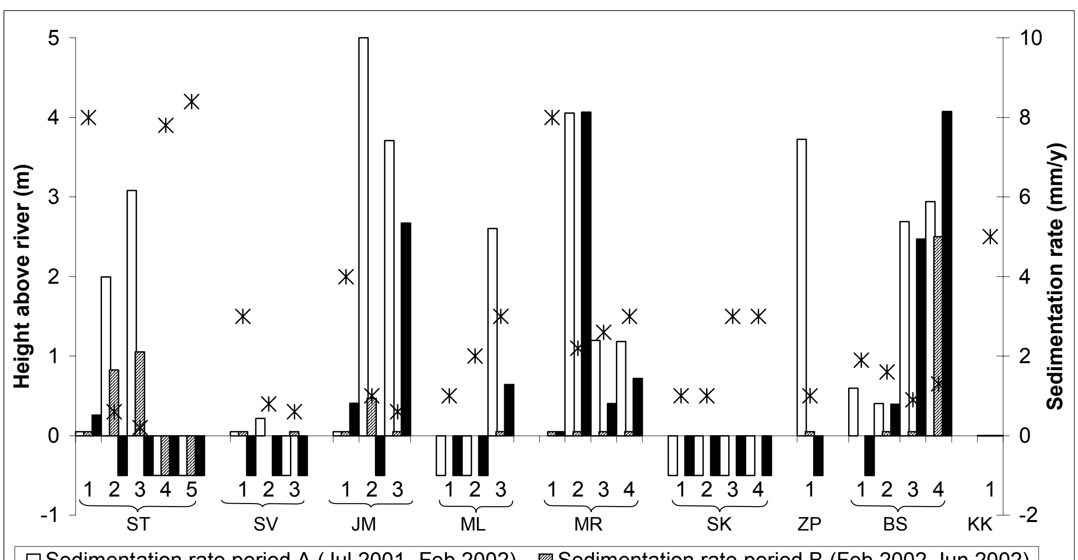


Figure 8.8: Sedimentation rates on artificial grass mats (e.g. bars ST1, ST2 etc.) throughout the Dragonja valley during three distinguished periods. The mats were nested on nine locations, near the locations of some of the ^{137}Cs cores, Location Sv Stefan (ST), Stara Vala (SV), Jamnek (JM), Mlin (ML), Skriline (SK), Mrtveč (MR), Zupančiči (ZP), Baštin (BS) and Kost Koper (KK). Asterix indicate the height of terrace where the mats were located. A removed or eroded mat is indicated with a column below the x-axis.

which indicated a very similar deposition rate to that found at Stara Vala 2 during the 1960-1986 period, suggested a strongly decreased sedimentation rate during the 1986-2001 period (0.18 cm y^{-1}; Table 8.2). The Mrtvec core from the same Unit showed no distinct peaks in ^{137}Cs due to ploughing (Fig. 8.6). The Jamnek 2 core was taken on a slope. The deposition recorded for this location (Fig. 8.6) most probably reflects hillslope contributions.

Table 8.3: Calculated areas of floodplain extent and terrace for the Upstream Dragonja and Rokava sub-catchments, and for the entire Dragonja catchment.

	Downstream Dragonja, (fig.8.5D) (km^2)	*Dragonja catchment from DEM (fig. 8.5C) (km^2)*	*Rokava sub-catchment from DEM (km^2)*	*Total catchment from DEM (fig.8.5A) (km^2)*
River	0.08	0.29	0.10	0.50
0.5 m terrace	0.03 (A)	0.15 (A)	0.09 (A)	0.24
1.5 m terrace	-	0.64 (B2)	0.22 (B1)	0.86
Flood-plain	0.35 (B3)*	-	-	0.35
Total	0.46	1.08	0.41	1.95

* Only one data point available
Remark: Unit C was not accurately morphologically mapped.

Table 8.4: Amounts of sediment accumulation (m^3) as derived from the ^{137}Cs cores in the various floodplain zones.

	Downstream Dragonja (m^3)		*Upper & Middle Dragonja from DEM (m^3)*		*Rokava from DEM (m^3)*		*Total catchment from DEM (m^3)*	
Period	1960-1986	1986-2001	1960-1986	1986-2001	1960-1986	1986-2001	1960-1986	1986-2001
0.5 m terrace (Unit A)	-	-	-	16,900	-	10,100	-	27,000
1.5 m terrace (Unit B1+ B2)	-	-	109,800	44,200	39,500	21,400	149,800	71,600
Floodplain (unit B3)	41,700	2,100	-	-	-	-	41,700	2,100
Total floodplain	41,700	2,100	109,800	61,100	39,500	31,500	149,800	98,600

Remark: Unit C has not enough data points for the sedimentation rate and was not accurately morphologically mapped to allow an estimation of the total accumulated sediment.

8.4.2 Sediment distribution and accumulation

The average sedimentation rates for each floodplain unit as derived from the ^{137}Cs cores were multiplied with the surface area of the respective units (Table 8.3) to give sediment accumulation totals for the two periods, 1960-1986 and 1986-2001 (Table 8.4). Sediment deposition in the lower part of the catchment (Unit B3) was 95% less during 1986-2001 compared to the 1960-1986 period. Sedimentation on the terraces of the Rokava sub-catchment (Unit B1) was 20% less whereas in the Upper and Middle Dragonja sub-catchment (Unit B2) 45% less sediment was deposited during the second period. Overall catchment-wide reduction in sediment deposition was 34% (Table 8.4).

8.4.3 Sedimentation rates measured with artificial grass mats

A total of 28 sedimentation mats were in use from June 2001 until June 2003, distributed over 9 locations (Figs. 8.4 and 8.8). Seven mats were stolen whereas another two were washed away. During the first observation period (P1, June 2001 until February 2002), one large flood event in September 2001 and several minor peak events deposited sediment on 17

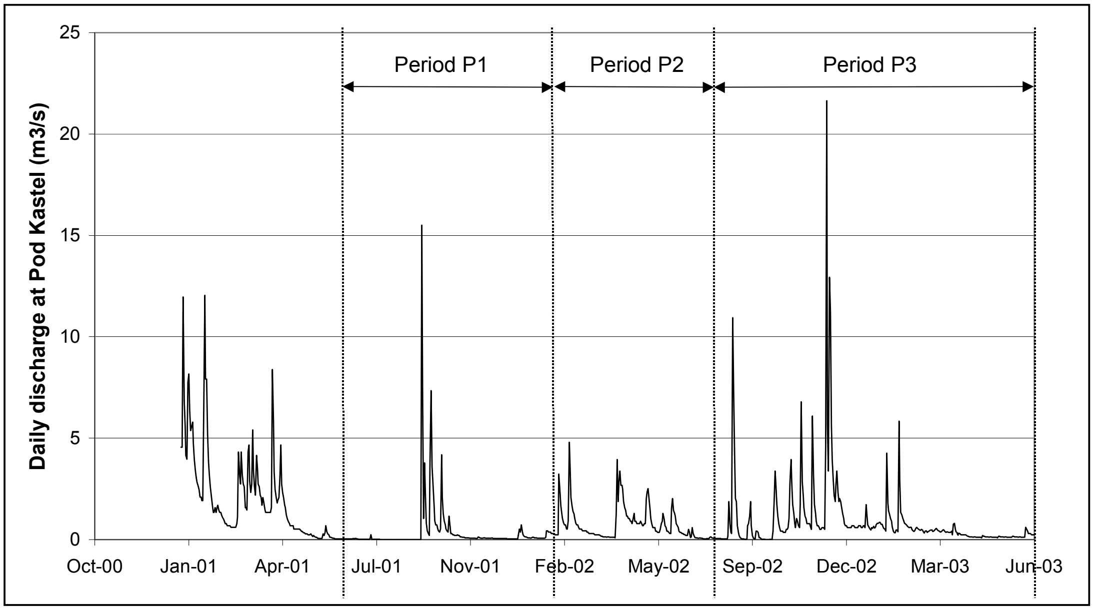


Figure 8.9: Daily discharge measured at Pod Kaštel from January 2001 until December 2002. Periods represent the times the sediment mats were out on the floodplain. Period A: June 2001-February 2002, Period B: February 2002-July 2002; Period C: July 2002-June 2003. Discharge measurements in 2000-2002 were done by Slovene Government (HMZ, 2003), measurements in 2003 were taken by the author just upstream from the Pod Kaštel gauging station.

of the mats (Fig. 8.9). These mats were replaced together with the 9 mats that had been washed away or stolen (mats indicated by –1 in Fig. 8.8 and Table 8.5). During the second period (P2, February 2002 until July 2002), no large discharges were recorded (Fig. 8.9). The inundated (4 mats) or removed (3 mats) mats were replaced. During the third period (P3, July 2002 until June 2003), a large event on the 19th of November 2002 and a few smaller peak events occurred (Fig. 8.9) which deposited sediment on the mats, but also washed away one-third of the mats, reducing the amount of measuring points. On average, large amounts of sediment were deposited during periods A and C whereas during the drier period B little or no sediment was deposited (Fig. 8.8, Table 8.5). The sites of the mats were located at different heights above the river to represent different parts of the respective depositional areas. To

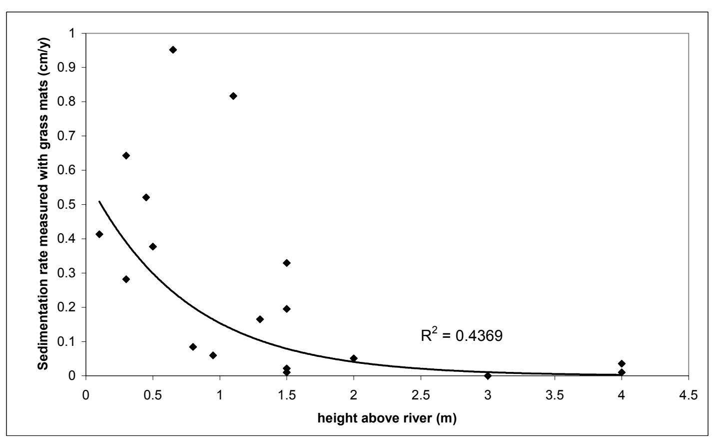


Figure 8.10: Average sedimentation rate as measured with artificial grass mats over the period 2001-2003 versus the height of the location of the mat above the river.

average the measurements, the sum of all three periods was dived by 2 (years). For data points obtained with mats that were recorded for a shorter period, the measured sediment accumulation was divided by the actual measurement period of that specific site. For Unit A (point bars and lowest terrace), the average sedimentation rate was 0.69 cm y^{-1}. For Unit B1 (1.0-1.5 m terrace in Rokava sub-catchment), the average rate was 0.37 cm y^{-1} vs. 0. 26 cm y^{-1} for Unit B2 (1.5 m terrace in the Upper and Middle Dragonja sub-catchment), and only 0.04 cm y^{-1} for Unit B3 (floodplain in Lower Dragonja sub-catchment). The mats representing Unit C (highest terraces) were not inundated during the measurement period. As expected, the amount of sediment deposited at a specific site was inversely related to the height above the river (Fig. 8.10; significant at $p<0.01\%$; r^2: 0.44).

Table 8.5: Average sedimentation rate per sample site and depositional unit as derived from the sediment mats, over the total measuring period June 2001 until June 2003.

Location	*Number of mats*	*Average sedimentation rate of unit A (cm y^{-1})*	*Average sedimentation rate of unit B1 (cm y^{-1})*	*Average sedimentation rate of unit B2 (cm y^{-1})*	*Average sedimentation rate of unit B3 (cm y^{-1})*	*Average sedimentation rate of unit C (cm y^{-1})*
ST	5	0.35 (3)	-	-	0.04 (1)	-
SV	3	-1	-	0.08* (2)	-	0.01 (1)
JM	3	1.6 ** (1)	-	0.05 (1)	-	0.05 (1)
ML	3	-1	-	0.33 (1)	-	-
MR	4		-	0.40 (2)	-	-
SK	4	-1	-	-1	-	-
ZP	1	-	0.38 (1)	-	-	-
BS	4	0.52 (2)	0.35 (2)	-	-	-
KK	1	-	-	-	-	0 (1)

-1 mat washed away during first large flood.
(n) number of mats used at the specific site.
* calculated over part of measuring period (from July 2001 to July 2002).
** pointbar sedimentation, including coarse bed sediment.

8.5 Discussion

8.5.1 The influence of reforestation on floodplain sedimentation

During the 1960-1986 period there was no real difference in sedimentation rate between the Rokava and Dragonja sub-catchments (Table 8.2). However, for the 1986-2001 period the average sedimentation rate in the Rokava sub-catchment was much higher than that in the Dragonja sub-catchment (0.65 vs. 0.46 cm y^{-1}; Table 8.2), mostly because of differences in the degree of land use change over the years (Fig. 8.2). The Dragonja sub-catchment became largely reforested (from 31% forest (young and mature forest) in 1954 to 63% in 1985 and 73% in 2002), which resulted in a major reduction in the erodibility of the hillsides. The

Rokava sub-catchment on the other hand retained a reasonable amount of agricultural activity (31% forest in 1954 vs. 51% in 1985 and 60% in 2002; Keesstra and Van Dam, 2002).

8.5.2 The influence of vegetation on overbank deposition

During peak flows, clumps of vegetation on the inundated terraces and floodplain tend to slow down the flow of the water, thereby inducing sediment to settle in between the vegetation (e.g. van Dijk et al., 1996; Rey, 2003). To determine to what extent the amount of sediment deposited at specific sedimentation mat was dependent on the density of the vegetation, the percentage of vegetation and number of species were mapped for each location. Several studies have found a relationship between vegetation type and flood frequency (e.g. Bren, 1993; Teversham and Slaymaker, 1976), others have reported a relationship between the number of vegetation species and sedimentation rates on the floodplain (Hupp, 1987; 1988). Gregory and Gurnell (1988) state that riparian and within-channel vegetation has a large effect on the erodibility of the channel and its banks, deeper roots inducing greater resistance to erosion. The present measurements show no relation between the amount of sediment deposited and the percentage of vegetation cover or vegetation type (Fig. 8.11). Several physical (Abt et al., 1994) and mathematical studies (Tsuijimoto, 1999) show that such a relation does exist, but because sedimentation rate is also dependent on the height above the river (Fig. 8.10; cf. Howard, 1992; Marriott, 1992; Walling, 1996), the height factor should be eliminated first. The small size of the current dataset precluded this, however.

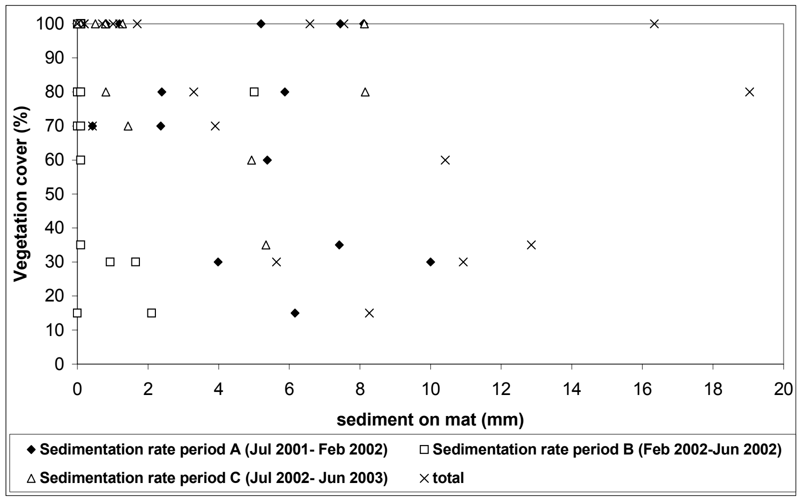


Figure 8.11: The percentage of vegetation cover at sedimentation mat locations versus the sedimentation rate on each artificial grass mat.

Sediment deposited on the artificial grass mats was analysed for texture. The mean grain size of all overbank deposit samples (*n* = 91) varied between 25 and 120 μm, with an average of 72 μm (Fig. 8.12). The percentage of sand-sized grains was inversely related to the height of the location above the river (Fig. 8.13; 2.5% significance level, $R^2 = 0.30$). The texture of the sediment deposited on the mats was classified as sandy loam to loam. Surface and subsurface soil samples from the hillslopes and valley floors mostly classified as clay loams and loams (Keesstra and Van Dam, 2002). No significant difference was found between top and sub soils. The soils in the valley were on average slightly coarser than the soils on the slopes and plateaus. The coarser texture of the trapped sediment compared to the hillside material can be explained by two processes. Firstly, the sediment on the mats, originates mostly from the hillslopes, but may also be mixed with sediment from other contributing sources including erosional cliffs and gullies supplying rather coarser material (Keesstra et al, submitted b). A second explanation is the process of size selective transport. The finest fractions are transported out of the catchment during peak events as suspended wash load, leaving the deposited sediment coarser than the originally transported sediment.

Field measurements suggested that suspended sediment concentrations were no longer decreasing over the period 2000 to 2004, presumably because in several places land is being taken into agriculture again.

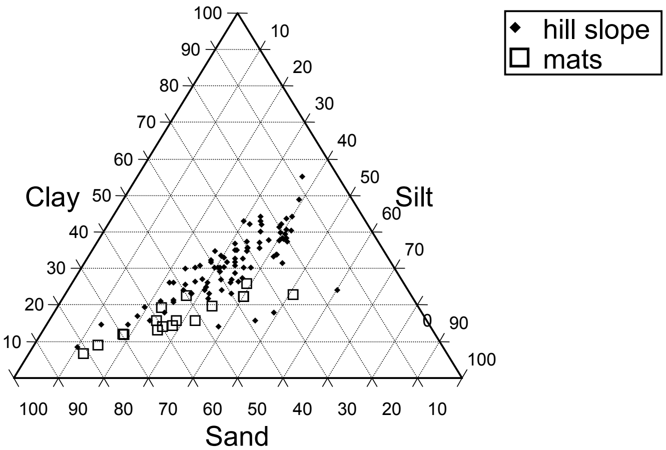


Figure 8.12: Triangular plot of sediment samples taken on the hillslopes and from the overbank deposits collected on the artificial grass mats.

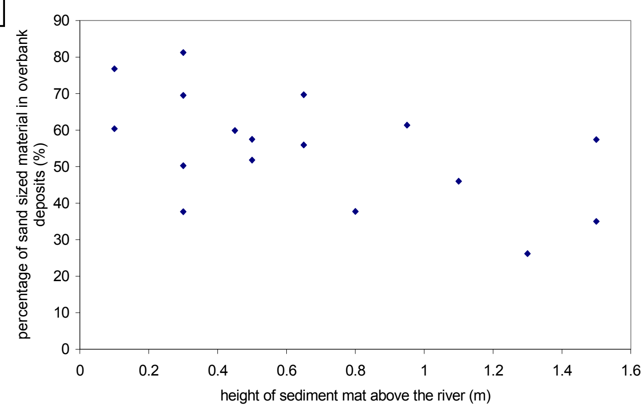


Figure 8.13: Relationship between height of the location of the sediment mat above the river and the percentage of sand-sized material in the overbank deposits.

8.5.3 Flood frequency and overbank sediment deposition estimates

As indicated previously, the extensive reforestation of the Dragonja catchment (Fig. 8.2) has reduced the discharge of the river across the entire spectrum of the flow (Fig. 8.3), although the situation seems to have stabilised more or less from the mid-1980s onwards, especially in terms of annual average daily flows (Fig. 8.14). During the period 1960 - 2003, the average annual discharge decreased by 81% whereas the maximum annual flood discharge decreased by 42%. However, reduction of the average annual discharge after 1985 was marginal at 5% (Fig. 8.14).

During the 1986-2003 period the maximum yearly flood height varied considerably but values were especially low during the period the sediment mats were in use (2001-2003; Fig. 8.14). On the basis of the 1986-2003 flood record 6.8 floods with a peak discharge of more than 15 m^3s^{-1} are expected to occur in 2 years. In the measuring period only 3 floods occurred. As such, the average rate of deposition derived with the sedimentation mats would be expected to be (much) lower than the average rate derived for the post-1986 period from the Cs-cores.

Table 8.6 compares the average floodplain sedimentation rates obtained with the two approaches for geomorphological units A-C distinguished earlier (cf. Figs. 7 and 8). Post-1986 ^{137}Cs-based sedimentation rates for the intermediate terrace levels (1-1.5 m; Units B1 and B2) were indeed about twice the rates derived with the sedimentation mats, reflecting the difference in flood return periods. The sedimentation rate derived for Unit A for the post 1986 period was derived from corings and geomorphological mapping. Between the calculated average sedimentation rate from these measurements and rate derived from the artificial grass mats no significant differences were obtained. Therefore, it would seem that the amount of sediment deposited on the lower parts of the floodplain (Unit A) during larger floods is not significantly higher than that during floods of lower magnitude. The number of observations available for the rarely inundated 2.5 m terrace (Unit C) is too small to draw firm conclusions

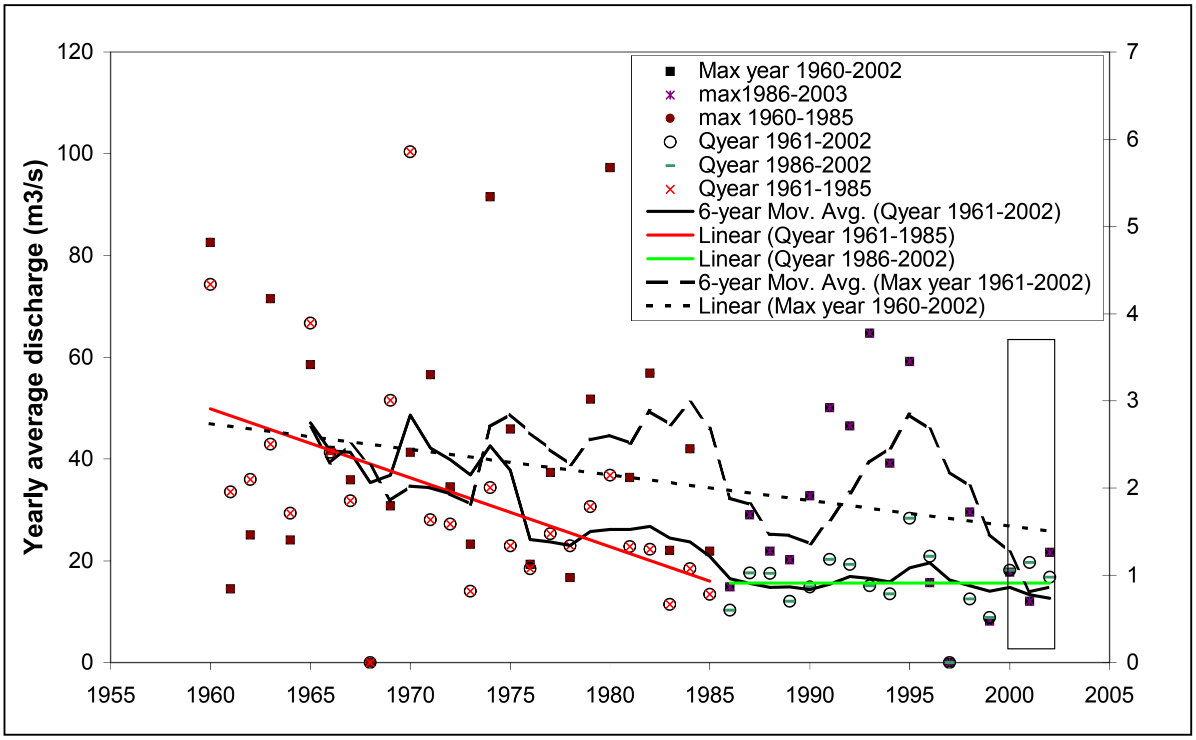


Figure 8.14: Annual average (Qyear) and maximum discharges (Max year) over the period 1960-2002, with corresponding trend lines. Box indicates measuring period of sedimentation mats.

and longer term observations would be needed. All in all, sediment transport by the Dragonja seems to be supply-limited rather than transport-limited. This contention is further supported by the clockwise hysteretic sediment-discharge loops determined during most peak events (Nistor and Church, 2005; Keesstra et al., submitted a).

During the period 1960 to 1985, both the yearly average daily discharge and the maximum daily discharge decreased strongly (Fig. 8.14). The associated increase in flood return periods caused the sedimentation rate to drop (cf. pre- and post-1986 Cs-based estimates of deposition in Table 8.2).

8.6 CONCLUSIONS

The average sedimentation rates for each floodplain unit as derived from the ^{137}Cs cores were multiplied times the surface area of the respective units to give sediment accumulation totals for the two periods, 1960-1986 and 1986-2001, of $1.5*10^5$ m^3 and $0.99*10^5$ m^3 respectively. Sediment deposition in the lower part of the catchment was 95% less during 1986-2001 compared to the 1960-1986 period. Sedimentation on the terraces of the Rokava sub-catchment was 20% less whereas in the Upper and Middle Dragonja sub-catchment 45% less sediment was deposited during the second period. Overall catchment-wide reduction in sediment deposition was 34%.

The decrease in sedimentation rate in the Rokava sub-catchment is relatively small. This is due to the greater accessibility and gentler slopes of the Rokava sub-catchment caused by of less extensive depopulation and more land is still in agricultural use there today.
The percentage of sand-sized grains in the overbank deposits was inversely related to the height of the location above the river. Although other researchers have found a relationship between the amount of sediment deposited and the percentage of vegetation cover or

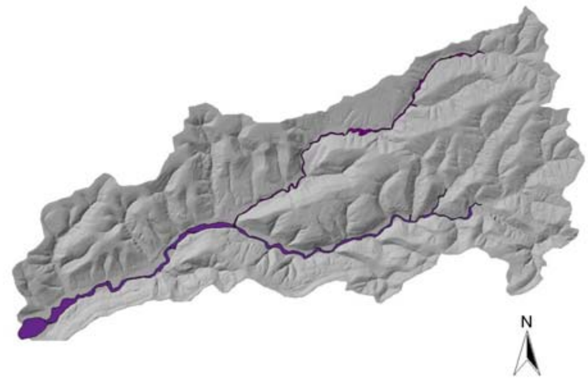
vegetation type, the present measurements show no such relation. The texture of the sediment caught on the sedimentation mats, is slightly coarser than the sediment sampled on the hillslopes, which can be explained by two processes. Firstly, the sediment originating from the hillslopes may be mixed with sediment from other contributing sources including erosional cliffs and gullies supplying coarser material. Secondly, the process of size selective transport may cause preferential transportation of suspended wash load out of the catchment, leaving the deposited sediment coarser than the originally transported sediment.
Since inundation of the terraces only takes place during floods of considerable magnitude, sedimentation rates have decreased significantly as a result of increased return periods of large floods due to the natural reforestation.
The floodplain sedimentation rates obtained with the two approaches, ^{137}Cs and the artificial grass mats, were compared. For the post-1986 ^{137}Cs-based sedimentation rates for the intermediate terrace levels (1-1.5 m) were about twice the rates derived with the sedimentation mats, reflecting the increase in flood return periods.
The sedimentation rate derived for Unit A for the post 1986 period was derived from corings and geomorphological mapping. Between the calculated average sedimentation rate from these measurements and rate derived from the artificial grass mats no significant differences were obtained. Therefore, it would seem that the amount of sediment deposited on the lower parts of the floodplain (Unit A) during larger floods is not significantly higher than that during floods of lower magnitude. Furthermore the return periods of the floods capable of depositing sediment on this terrace did not decrease much since the start of the formation of this terrace in 1975. The number of observations available for the rarely inundated 2.5 m terrace is too small to draw firm conclusions and longer-term observations are needed.
The ^{137}Cs technique and the artificial grass mats technique can complement each other in depositional studies.

Table 8.6: Comparison of average rates of sedimentation as measured with artificial grass mats, n indicates the number of mats, and from ^{137}Cs profiles.

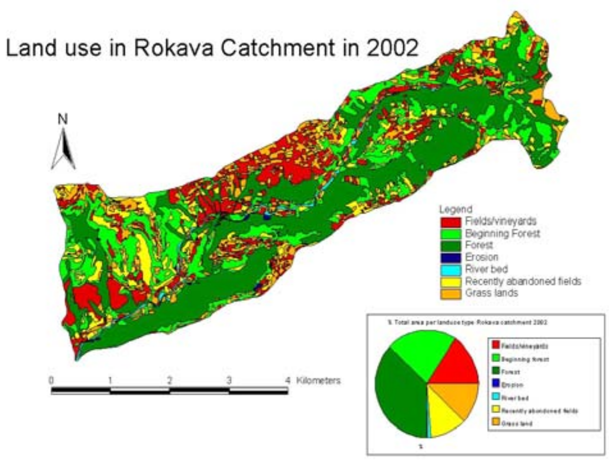
Unit	*Average sedimentation rate measured with ^{137}Cs 1986-2001 (cm y^{-1})*	*n*	*Average Sedimentation rate measured with mats (cm y^{-1})*	*n*
A	0.75*	Not applicable	0.69 ± 0.61	6
B1	0.65 ± 0.29	3	0.37 ± 0.51	3
B2	0.46 ± 0.22	3	0.26 ± 0.29	6
B3	0.04	1	0.04	1
C	<0.06	3	0.02 ± 0.02	3

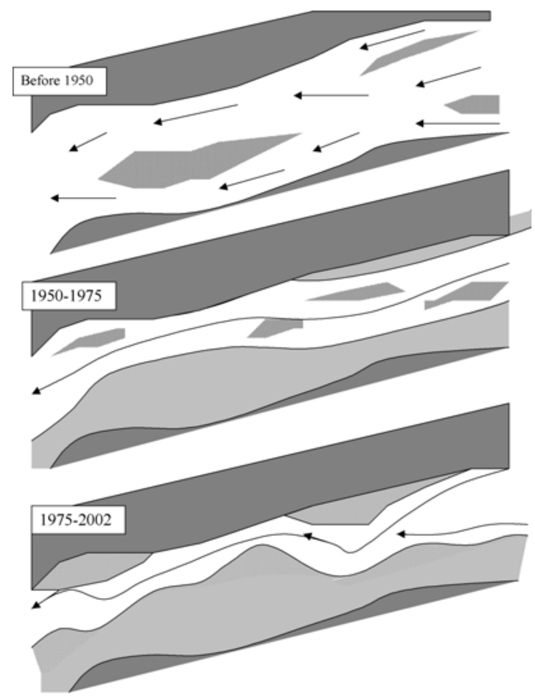
* sedimentation rate derived from geomorphological mapping and corings

PART V: SYNTHESIS



Chapter 9: Synthesis, conclusions and recommendations





CHAPTER 9: SYNTHESIS, CONCLUSIONS AND RECOMMENDATIONS

9.1 SYNTHESIS

9.1.1 Background

Scientific attention to changes in hydrology and sediment budget after reforestation under Mediterranean climatic conditions has been limited to a few studies in France, Spain, Italy and the USA (Chapter 1). The Mediterranean region constitutes a particularly interesting study object in this respect because it is highly sensitive to changes in climate or vegetation cover due to the fact that the prevailing hydrological and geomorphological balances are especially delicate (Brookes et al., 2000). Because most recent studies of the effects of reforestation in the Mediterranean either comprise only part of a catchment, or deal with diverse geological conditions and additional human influences besides reforestation (such as gravel-mining, dam construction or river regulation), their results (§ 1.3) are not always easy to interpret.
The Dragonja catchment in Southwestern Slovenia is especially suitable for investigating the effects of reforestation on hydrology, geomorphology and sediment dynamics, as it is relatively small (91 km^2) and geologically uniform. Moreover, no human interference in the catchment sediment budget, such as gravel mining, has occurred, while the reforestation (which started after the Second World War) also took place in a rather uniform fashion. The present study complements the results of earlier work conducted in this catchment (Globevnik and Sovinc, 1998; Globevnik, 2001b by providing in-depth information on the geomorphological dynamics and sediment budget of the main valley throughout the period of reforestation (1954 to 2002).

9.1.2 Land use change and reforestation succession (chapter 2)

Due to major changes in the economic and social situation in former Yugoslavia after the Second World War, including the development of heavy industry and tourism in coastal areas, the farmlands in the hinterlands of Slovenia and other areas were gradually abandoned. In the Dragonja area the abandoned fields were rapidly taken over by natural vegetation. Within 5 years after abandonment grasses, herbs, juniper trees and blackberry bushes had invaded the fields. After 15 years, broad-leaved trees such as oak and hornbeam started to overtake the junipers whereas at present, i.e. after a period of ca. 50 years, a full-grown forest has developed.
A comparison of aerial photographs taken in 1954, 1975, 1985 and 1994, plus a field survey conducted in 2002, show that: (i) in 1954 approximately 70% of the catchment was still used for agriculture; (ii) the most important land-use changes occurred between 1954 and 1985, with a reduction in the area under fields and pastures from 70% to 30%; and (iii) after 1985, land use did not change much anymore (24% fields and pastures in 2002). The differences in forest cover and land use between the Rokava and Upper-Dragonja sub-catchments within the study catchment can be used for a sensitivity analysis of the effects of reforestation, as the results show that a relatively small contrast in land use (forest area) can cause distinct differences in hydrologic response and the sediment budget (see below).

9.1.3 Hydrological changes (chapter 3)

The hydrological regime of the Dragonja River has changed markedly over the period 1960-2003. Peak-, mean and minimum discharges have all dropped to less than half of their values prior to the reforestation. Especially the low discharges have changed dramatically: mean maximum flow, mean annual flow and mean minimum flow decreased by 53%, 79% and 85%, respectively (HMZ, 2003, cf. Fig. 3.1). It is important to separate the impacts of climate and land use on the hydrological changes. Whilst annual precipitation decreased by 19% over the period 1960-2003, from an average of 1275 mm y^{-1} over the period 1961-1970 to 1025 mm y^{-1} over the period 1991-2000, the percentage of precipitation discharged by the river dropped even more: from 67% (1961-1969) to 34% (1991-2000). This indicates that the drop in precipitation is only a partial cause of the diminished discharge. Rather, the main cause for the observed decrease in discharge is the increase in evapotranspiration associated with the reforestation.

9.1.4 Fluvial geomorphology (Chapter 7)

The Dragonja River is a typical Mediterranean, cobble-bed river with pool-riffle and step-pool sequences, dependent on the local channel gradient. In the upper reaches the channel bed consists of bedrock (sandstones), the middle reaches have a cobble base of older channel deposits alternating with bedrock, while in the lower reaches, where a long-term depositional regime has formed a thick layer of fine sediments, the channel bed consists of these fine river deposits (Chapters 2 and 7). During detailed geomorphological mapping three terraces were distinguished, which stand 2.5 m, 1.5 m and 0.5 m above the present-day riverbed.

Due to the gradually lower intensities and frequency of flood events and a proportionally even larger decrease in sediment delivery to the channel due to the progressive reforestation, the river has started to incise into its former bed whereas vegetation has invaded the formerly braiding river-bed. A narrower, incised river-bed with actively moving channel bars has formed, with a lower floodplain terrace at ca. 1.5 m above the current river-bed that, according to lichenometric dating, is about 60 years old. After 1975, the narrowing of the river-bed intensified as a result of further reductions in annual discharge. River flows reached a level where channel bars were no longer mobile and rapidly invaded and further stabilized by riparian vegetation. The present riverbed shows characteristics of an underfit river that is meandering within its former wider braiding bed. The most recently formed terrace, dated at approximately 30 years BP, consists of fixed, mostly alternate channel bars at ca. 0.5 m above the current river-bed.

The above processes have occurred in most parts of the river and the upper and middle reaches have behaved in more or less the same way. The 1.5 m terrace has its largest extent in the middle reaches, where the river lost 55-65% of its bed area to this terrace between 1945 and 1975. The 0.5 m terrace occupies a much smaller area; the river lost an additional 7% to this terrace after 1975 (cf. Fig. 7.14). In the lower reaches of the catchment no terraces have been formed, but deposition rates on the corresponding floodplain section dropped by as much as 95% since reforestation began.

Besides changes in land use and vegetation cover, no other significant human activity has modified river discharges and geomorphology in the Dragonja catchment since the beginning of the reforestation. Therefore, the recent morphological changes of the channel of the Dragonja River must primarily reflect the progressive natural reforestation. In other studies of the effects of reforestation around the Mediterranean, such a one-to-one relationship between cause and effect has not been obtained generally due to complications introduced by additional human interference (gravel mining, dams, river regulation) or natural phenomena (diverse geology). Nevertheless, the same kind of geomorphological changes have been observed in these areas as described above for the Dragonja.

9.1.5 Sediment production (Chapter 4)

The suspended sediment carried by the Dragonja River is fine-grained, consisting mostly of clay- and silt-sized particles, while the bedload material is coarse-grained (ranging from fine gravel to boulders, with a D_{50}-value of 6-8 cm). Fine, suspendable sediment originates from three sources: hillslopes, flysch bedrock banks, and older fluvial bank sediment. Hysteretic analysis of discharge flood events, and the texture of the suspended sediment indicate that most suspended sediment originates on the hillslopes.

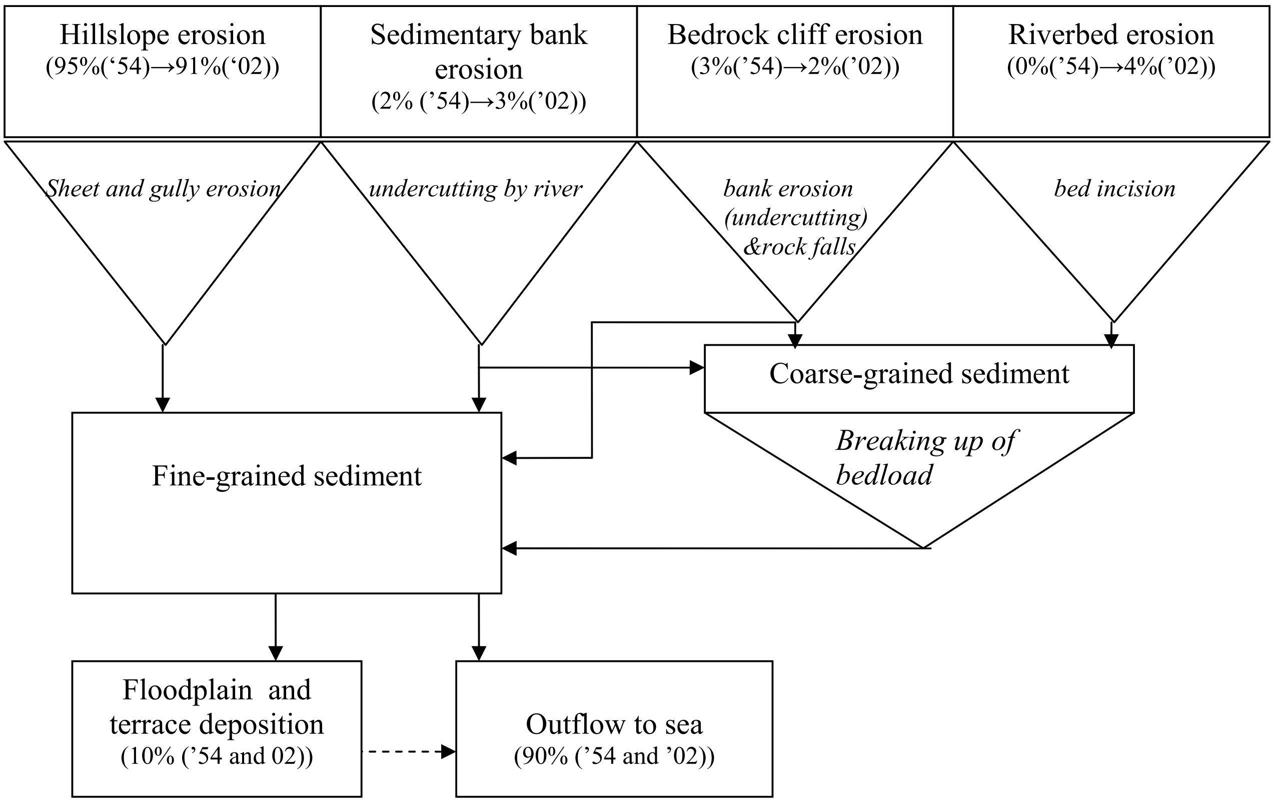


Figure 9.1: Sediment budget of the Dragonja catchment (1954/2002)

The change in land use and forest cover over the period 1954-2002 has had a significant impact on the erosion of the hillslopes. The decline in sediment delivery from the hillslopes was modelled with WaTEM/SEDEM, which uses the same input parameters as the well-known RUSLE model, but simulates hillslope sedimentation also. Measured precipitation and soil data were used to derive the rainfall erosivity (R-factor) and soil erodibility (K-factor) values, respectively; slope lengths and gradients (LS-factor) were taken from a Digital Elevation Model, whereas corresponding values for the land cover factor (C-factor) were derived from aerial photographs taken in 1954, 1975, 1985 and 1994, and a land use survey conducted in 2002. The model was calibrated with two independent sets of measurements: (i) the total deposition of sediment in the valley between 1975 and 2002 (Chapter 8), and (ii) the volume of discharged sediment in 2002. Both calibrations gave a similarly sharp decline by approximately 70% in sediment delivery to the river over the period 1954-2002 (Chapter 4). Both sedimentary and bedrock banks were shown to be relatively minor contributors of fine sediment (4-5% of the total sediment budget) compared with the amount delivered by the hillslopes (91-95%; Fig. 9.1).

Coarse, bedload material has three sources: (i) extensive bedrock banks along the river channel, (ii) lateral erosion of sedimentary banks that partly consist of cobbles, and (iii) older bed material being eroded by river incision. The supply of sediment from bedrock banks proved to be largely independent of rainfall, as rock fall processes were more important than undercutting by the river. The size of the debris toes in front of the bedrock banks therefore largely reflect the time elapsed since the last major discharge wave. Based on aerial photographs and field surveys, the total area of actively eroding bedrock banks was larger before the reforestation. Reforestation resulted in a decrease in bedload input from bedrock banks by more than 50%. In 1954 the bedload supply was completely dependent on the amount of sediment coming from the bedrock banks and the reworking of cobbles from sedimentary banks. However, in response to the changes in sediment and water dynamics the river has incised into its own bed material, thereby generating extra bedload and partly compensating the decrease in supply. The net reduction in transported bedload over the period 1954-2002 was ca. 30%.

In 2002 surface erosion on the hillslopes dominated (91%; Fig. 9.1) the sediment budget of the Dragonja valley. Other sediment contributors, such as degrading river beds (4%), eroding sedimentary banks (3%) and bedrock banks (2%), account for approximately 5% of the sediment budget. This dominance of the hillslopes as the main sediment supplier was even more pronounced before the reforestation (1954), when the hillslopes supplied as much as 95% of total sediment delivery to the channel. Back then, sedimentary banks delivered ca. 2% of the total sediment production, vs. bedrock cliffs 3% (Fig. 9.1).

9.1.6 Sediment transport (Chapter 5)

The majority of the transport of fine sediment as suspended sediment is discharged during flood events. As stated earlier, most of this sediment is generated on the hillslopes, whereas the sedimentary and bedrock banks deliver only modest amounts. During low river stages, when little sediment is discharged, virtually all of the sediment comes from the large bedrock banks (Chapter 8).

Naturally, bedload is also transported mostly during larger floods events. Measured transport rates were temporally and spatially very variable for several reasons. Firstly, sediment transport in rivers is generally not a steady-state process, but occurs in pulses. Secondly, the Dragonja River is not in equilibrium due to the changing input parameters (discharge, sediment production) as a result of the reforestation (Chapter 5). Tectonic uplift can be ruled out as a significant factor in the study area (Chapter 2).

Downstream fining of coarse bed material is evident in terms of amount, roundness and size. The relative softness of the prevailing bedrock causes the material to break and abrade rapidly during transport. The main process of downstream fining is sediment weathering and not selective transport (Chapter 6). All bedrock is worn down completely before reaching the catchment outlet, as can be deduced from the gradually decreasing size of riffles when going downstream, and from the absence of cobbles in the lowermost section of the river. Therefore, the suspended sediment load at the outlet represents the total sediment output from the catchment (estimated at 4.5 t ha^{-1} y^{-1} in 2002; Chapters 4 and 6).

9.1.7 Sediment deposition (Chapter 8)

Past and current floodplain sedimentation rates were obtained using ^{137}Cs dating (1960-2001) and deposition on artificial grass mats (2001-2003). The ^{137}Cs core sampling allowed the

computation of two separate, averaged sedimentation rates for the periods 1960-1986 and 1986-2001. The flooded area was divided into five sections which were all represented by one or more ^{137}Cs cores and artificial grass mats, viz.: (i) the 0.5 m terrace in all sections of the river channel, (ii) the 1.5 m terrace in the Rokava tributary, (iii) the 1.5 m terrace in the Upper and Middle sections of the Dragonja River, (iv) the floodplain of the Lower Dragonja river, where no terraces were formed, and (v) the 2.5 m terrace (Chapter 7).
The ^{137}Cs dating showed that in all river sections sedimentation rates decreased significantly from the first period to the second; total sediment accumulation on the entire floodplain area was $1.5*10^5$ m^3 in 1960-1986 vs. $0.99*10^5$ m^3 in 1986-2001. The reduction in sedimentation rate increased in a downstream direction. Overall catchment-wide reduction in sediment deposition between the two periods was 34%.
The results obtained with the artificial grass mats indicated that all floodplain sedimentation takes place during flood events of considerable magnitude. Due to the progressive reforestation, the return period of large floods increased until ca. 1985 after which the frequency (like the area under forest cover) more or less stabilised (Chapter 3), which explains the lower sedimentation rates. However, the sedimentation rates derived from the artificial grass mats on the 1.5 m terrace were roughly half that estimated from the ^{137}Cs cores due to the relatively dry period in which the mats were in operation. Only half the expected number of floods actually occurred during this period. For the lowest terrace (0.5-1.0 m above the river-bed) the sedimentation rates obtained with the two measurement techniques were similar. Therefore, it would seem that the amount of sediment deposited on the lower parts of the floodplain during large flood events was not significantly higher than that during floods of lower magnitude. For the rarely inundated 2.5 m terrace the number of observations available is too small to draw firm conclusions and longer-term observations are needed.

In summary, the floodplain sedimentation measurements indicate that (Fig. 9.1) only 10% of the total volume of generated sediment is deposited on the floodplains and adjacent river terraces. The remaining 90% is transported to the sea (Fig. 9.1).

9.1.8 Differences between the Rokava and Upper Dragonja sub-catchments

In the upstream part of the Dragonja catchment, the Rokava (20 km^2) and Upper Dragonja (32 km^2) sub-catchments were reforested in a different manner. In the Rokava sub-catchment a larger area has remained under agricultural use because of its greater accessibility from the coastal cities and its gentler topography. Only 61% of the Rokava area was forested in 2002 as opposed to 73% in the Upper Dragonja sub-catchment. A more detailed description of the reforestation sequence in the two areas has been given in §2.4. Because of the contrast in vegetation cover, the hydrological and erosion response of the two sub-catchments differ to some extent.

Hydrologically, the two areas behave quite differently. Measurements of rainfall and streamflow carried out between October 2000 and September 2001 show that the Upper Dragonja sub-catchment always discharges less water at the same antecedent wetness level than the Rokava sub-catchment. The contrasts relate to runoff response to rainfall: in the Rokava sub-catchment 26% of the precipitation is converted into discharge, versus 22% for Upper-Dragonja. Furthermore, the Rokava sub-catchment discharges about 58% of the total flow as quickflow, vs. 45% for the Upper Dragonja sub-catchment. Also the slope of the separation line between quick and delayed flow shows a generally steeper slope for the Upper-Dragonja, indicating a relatively shorter period of quick flow, an average 58h and 25h for the Rokava and Upper-Dragonja respectively.

Thus, all hydrological parameters indicate a slower and less intensive hydrological response for the more forested Upper Dragonja area. Such contrasts are thought to reflect the better infiltration capacity, higher rainfall interception, and higher water use commonly associated with forest. A more detailed discussion of the differences in hydrological functioning of the Rokava and Upper Dragonja sub-catchments may be found in Chapter 3.

Marked differences between the two sub-catchments were also found in terms of their hillslope sediment delivery. Model calculations for the Rokava and Upper Dragonja areas showed a similar reduction in sediment delivery during the period 1954 - 1975 of 45%. Whilst sediment delivery remained more or less stable after 1975 in the Rokava area, the decrease continued in the Upper Dragonja area after 1975, rendering the total reduction in sediment production in 2002 76% less than that in 1954 (Chapter 4).

In terms of floodplain sediment deposition, the total volume of deposited sediment on the 1.5 m river terrace in the Middle and Upper-Dragonja and Rokava sub-catchments decreased by 45% and 20%, respectively, during the period 1960-2001. These reductions are in line with the decreases in flood height and frequency discussed earlier (Chapter 8). The smaller decrease in sedimentation in the Rokava sub-catchment is due to the fact that more land is still in agricultural use there today. For coarse sediment dynamics no differences between the two sub-catchments were demonstrated in this research. The observations and measurements indicated the same sediment sources, and the same transport and downstream fining processes. Any possible differences in bedload transport were not detected due to insufficient measurements (Chapter 5).

9.2 Conclusions

The present research has demonstrated the unambiguous effects of progressive natural reforestation in this Mediterranean catchment on:

- *Hydrology*: The balance between the positive (improved infiltration rates) and negative (extra water use by trees) effects of reforestation on stream discharge is clearly dominated by the high water use of the vigorously growing trees of the aggrading forest. Not only did the number of large runoff events decrease but a large increase in the periods with very low to zero flows during the summer period was recorded. There exists a close relationship between river discharge and percentage of forest cover (Chapter 3). When the forest regrowth stabilizes around 1986, the discharge curve measured at the outlet of the Dragonja River (HZM, 2003) shows a stabilization of the flood frequency from 1986 to 2003 also.

- *Fluvial geomorphology*: Considerable narrowing and some incision of the main river channel have been observed. Two incision phases can be distinguished each represented by a river terrace. The first terrace was formed after the initial abandonment of agricultural fields, shortly after the Second World War. This abandonment caused a major reduction in sediment delivery from the hillslopes to the drainage network, but because the trees replacing the crops were small and their water use correspondingly limited, the reduction in streamflow was modest at the time. This caused narrowing and incision of the channel, forming the terrace, which stands 1.5 m above the present riverbed. A second, smaller incision occurred around 1975. By then, the forest had begun to mature and the transpiration and interception components of the water balance were considerable. This resulted in a substantial reduction in annual runoff by then, which induced additional narrowing of the channel. Also, the formerly active channel bars became fixed by vegetation, causing the river to meander through its former bed. The small additional incision since 1975 resulted in the formation of a second terrace, consisting of the fixed channel bars, and standing about 0.5 m above the active channel (Chapter 8).

- *Sediment budget:* Another major change resulting from the reforestation concerns the reduction in erosion of the hillslopes. The transformation from a catchment under active agriculture (ca. 30% forest, 1954) to a predominantly reforested one (ca. 70% forest, 2002) resulted in a modelled reduction in hillslope sediment delivery to the drainage network of as much as 70%. Amounts of sediment delivered by other sources, such as bedrock banks and sedimentary banks, decreased also by about 50%. However, as a result of incision of the river channel, a new sediment source has become available which generates about 4% of the total sediment production. Because of the reduced river discharge after reforestation the transport of bedload material must have dropped as well. Field measurements show that all current bedload transport occurs during large flood events only. Because no bedload measurements of the situation prior to the reforestation are available, an estimate of the reduction was made using bedload transport formulas (Chapter 5). A reduction of 90% in bedload transport capacity was predicted by the latter. The total amount of sediment carried out of the catchment and deposited on the floodplain and adjacent lowest terraces was reduced in similar amounts (70%) as the sediment production. However, the distribution of the sediment seems to have stayed stable.

- An analysis of the bedload material shows considerable downstream fining due to abrasion, resulting in the total absence of coarse material in the lowermost reaches of the river.

9.3 RECOMMENDATIONS FOR CATCHMENT MANAGEMENT

To bring the deterioration of biodiversity in Europe to a halt by 2010, the European Union founded the Natura 2000 network. All participating countries agreed to take all measures needed to realise the required habitat zones essential for maintaining biodiversity, taking into account economic, social and cultural requirements. The Dragonja catchment has enjoyed a Natura 2000 status since 2004.

The reduced water and sediment flow rates currently coming from the catchment (Chapters 4 and 5) both pose a potential threat to the continued functioning of wetland reserve near the outlet of the drainage basin and limit the possibilities for renewed agricultural development in the area. In addition, the observed change in river channel morphology (Chapter 7) profoundly influences the aquatic habitat of the Dragonja River. Under the prevailing Mediterranean climatic conditions the supply of water in the generally dry summer is of vital importance to the aquatic fauna.

After decades of depopulation and subsequent natural reforestation, the Dragonja area is beginning to be developed again in various ways. As a result, several conflict situations have arisen recently among the different stakeholders in the catchment. Examples of conflicting interests include: (i) the development of the area as both a drinking water supply and food production resource, both on the Slovenian and Croatian sides; (ii) the touristic development of the valley (e.g. a golf resort); and (iii) the maintenance of nature conservation under the Natura 2000 directives, and the ecological functioning of the saline wetland nature reserve at the outlet of the Dragonja catchment.

Sustainable water management in the area must consider the interests of all stakeholders concerned. Thus, apart from preserving the area's natural (floral and faunal) and cultural heritage and protecting the quality of its water resources, the water and agricultural demands of the more development orientated stakeholders will need to be addressed as well.

To come to a workable solution for all parties the following considerations and recommendations are offered:

- The reforestation has had a positive effect in terms of flood height and flood frequency reduction. However, summer baseflows have decreased drastically and there are currently long periods without flow; this has had a negative effect on agriculture and eco-tourism in the catchment and is disastrous for the aquatic fauna as well. Possibly the natural state of the Dragonja River is to run dry completely in summer, but this is an unfavourable situation for all parties. The aquatic fauna and the riparian flora and fauna will be negatively influenced by longer periods without flow. Neither will farmers, water supply authorities and tourism benefit from further decreases in discharge as a result of continued reforestation of the region.

- In terms of hydrological and biological stability it is important to sustain the water quality and quantity, especially during the summer months. One possibility would be to not allow farmers to extract water from the river once a predefined minimum water level is reached. As this is both difficult to control and unreasonable to local farmers, it might be advisable to retain more grassland instead of planting vineyards and other crops that need irrigation in summer. However, the economical feasibility of such a proposal remains to be evaluated. To sustain a higher level of streamflow in summer it might even be necessary to clear some of the newly developed forests. However, only areas with low erosion potential (such as plateaux and slopes of low gradient) should be considered. In practice, it would seem that only well-managed grassland would qualify as a suitable substitute for the forest.

- In terms of erosion, the conversion of forest to grassland should not be a problem as well-managed grassland has a low erosion risk (e.g. Renard et al., 1997; Ritchie et al., 2005, provided the locations are well chosen and no regular ploughing of the pasture is undertaken.

- In terms of water yield, grassland is also a good choice because in general, for a given annual rainfall, grassland catchments yield more discharge than forested catchments (Hibbert, 1967; Bosch and Hewlett, 1982; Holmes and Sinclair; 1986; le Maitre et al., 1999; Zhangg et al, 1999). This can be attributed to higher annual evapotranspiration from forest compared to grassland.

- The development of more grassland is also advisable for ornithonological reasons as Globevnik and Sovinc (1998) reported that the reforestation has led to a loss of habitat for several endangered bird species in the area. These small-scale grassland areas, with bushes and trees acting as hedges represent a more diverse habitat than pure forest, thus creating a potential for larger overall biodiversity.

- Small-scale grassland areas would also be suitable in terms of maintaining the cultural heritage of the area, by preserving and restoring the original, marginal, agricultural landscape character.

- These grasslands should ideally be managed at a low intensity with mowing and removal of grasses and herbs only once a year in autumn, when the impact of mowing is low (e.g. no nesting of birds). No fertilisation of the soil would also improve the biodiversity of the flora (Girardin et al., 2000). To compensate the associated economic losses the costs associated with the specific management and maintenance of the grasslands might be funded by the Natura-2000 project.

9.4 Recommendations for further research

The progressive natural reforestation occurring in the Dragonja catchment presents a unique case that allows the study of a multitude of environmental impacts of reforestation, several of which are listed below.

- To complement the present catchment sediment budget, a study of the sedimentation record of the Bay of Piran could be undertaken. Possibly the same changes in sedimentation rate can be observed there as found for the Dragonja floodplain and terraces, whereas the modelled change in sediment generation on the hillslopes might be evident in this record as well. Moreover, the sedimentation record in the Bay of Piran is likely to be more continuous than the records studied in the present research, and will therefore be a good reference for the results presented here.

- The sediments in the Bay of Piran could also be analysed for their organic matter content. In order to assess the carbon cycle of the catchment, and of any long-term changes therein induced by land cover changes, the export of carbon to the long-term sink of the delta area of the Dragonja River needs to be studied.

- Another interesting topic is the sedimentation history in the downstream section of the valley. The area of transition between marine and fluvial environments has shifted over time. It would be of great interest to study the interactions between sea level change, sedimentation rates and human impact. For this purpose, corings in the lower reach of the valley could be studied for texture, pollen and geochemical signature of the sediments. Some information on the textural and geochemical composition of offshore sediment in the area is already available in literature (Orgorelec et al., 1981, 1997) but much more remains to be done if a complete picture is to be obtained.

- The sedimentation history and terrace evolution in the period prior to the current research window would be interesting to study in terms of the Quaternary history of the region. On several locations on the slopes pre-Holocene terraces were found. However, their age and correlations are unknown. Also, the relation between the formation of these terraces and climate and sea-level changes needs to be established.

- The terrace and colluvial deposits in the Dragonja area are also interesting in terms of their archaeology. As stated by Van Andel and Davis (2003) the Mediterranean area is of great interest for the study of early human development. Charcoal finds on two of terrace locations on 4.5 and 6 m above the current river were dated at 12,000 and 22,000 years BP (uncorrected). Two other terraces were also dated with Optically Stimulated Luminescence (OSL) dating; one was dated to be of Late Weichselian to Early Holocene age, the other early Holocene.

- Bedload transport in the Dragonja area requires more attention, as the present measurements did not have sufficient spatial and temporal coverage. The bedload transport is highly variable as a result of spatial and temporal differences in stone size and amount of bed material, and future measurements should therefore be conducted more extensively and more systematically over a larger part of the river system. Last but not least, the fact that during the present measurement period no extreme events occurred underlines the need for further measurements.

- Other important research topics related to the reforestation include:

  - Soil ecology: changes in numbers and diversity of soil fauna and microflora as a function of time since agricultural abandonment. Such changes can be expected to affect the hydrological functioning of the soil (rainfall infiltration, water retention, hydraulic conductivity) as well as its fertility.

  - Impact of reforestation on decomposition of organic material and associated possible storage of organic matter and thus of carbon and nitrogen in the soil.

Chapter 10: Abstract and/en Nederlandse samenvatting

CHAPTER 10: ABSTRACT AND/EN NEDERLANDSE SAMENVATTING

ABSTRACT OF THE PHD-THESIS:
THE EFFECTS OF NATURAL REFORESTATION ON HYDROLOGY, RIVER MORPHOLOGY AND SEDIMENT BUDGET OF THE DRAGONJA CATCHMENT, SW SLOVENIA

BACKGROUND
Scientific attention to changes in hydrology and sediment budget after reforestation under Mediterranean climatic conditions has been limited to a few studies in France, Spain, Italy and the USA. The Mediterranean region constitutes a particularly interesting study object in this respect because it is highly sensitive to changes in climate or vegetation cover due to the fact that the prevailing hydrological and geomorphological balances are especially delicate (Brookes et al., 2000). Because most recent studies on the effects of reforestation in the Mediterranean either comprise only part of a catchment, or deal with diverse geological conditions and additional human influences besides reforestation (such as gravel-mining, dam construction or river regulation), their results are not always easy to interpret.
The Dragonja catchment in Southwestern Slovenia is especially suitable for investigating the effects of reforestation on hydrology, geomorphology and sediment dynamics, as it is relatively small (91 km^2) and geologically uniform. Moreover, no human interference in the catchment sediment budget, such as gravel mining, has occurred, while the reforestation (which started after the Second World War) also took place in a rather uniform fashion. The present study complements the results of earlier work conducted in this catchment (Globevnik and Sovinc, 1998; Globevnik, 2001b by providing in-depth information on the geomorphological dynamics and sediment budget of the main valley throughout the period of reforestation (1954 to 2002).

LAND USE CHANGE AND REFORESTATION SUCCESSION
Due to major changes in the economic and social situation in former Yugoslavia after the Second World War, including the development of heavy industry and tourism in coastal areas, the farmlands in the hinterlands of Slovenia and other areas were gradually abandoned. In the Dragonja area the abandoned fields were rapidly taken over by natural vegetation. After a period of ca. 50 years, a full-grown forest has developed on the former fields and pastures.
In 1954 approximately 70% of the catchment was still used for agriculture. The most important land-use changes occurred between 1954 and 1985, with a reduction in the area under fields and pastures from 70% to 30%. After 1985, land use did not change much anymore (24% fields and pastures in 2002).

RESEARCH METHODOLOGY
The research methodology comprises a combination of techniques.

- Channel, terrace and floodplain morphology was geomorphologically mapped, and channel incision and terraces were dated with lichenometry and tree ring analysis. Morphological changes were also determined with aerial photographs and GIS analysis.
- The floodplain sedimentation rate was measured with two techniques: current present-day sedimentation rates were obtained from artificial grass mats and rates from 1960 to 2002 were obtained from Cs^{137} and ^{14}C-analysis.
- Riverbank erosion was monitored with erosion-deposition pins, 3-D photogrammetry and series of regular photographs. Historic riverbank erosion was estimated with the help of a GIS analysis.

- In-channel sediment transport was measured with stone tracing (coarse-grained material) and an automatic water (and suspended sediment) ISCO-sampler.
- The erosion rates on the hillslopes and the amounts of sediment being delivered to the rivers were calculated using a spatially distributed soil erosion and sediment delivery model WaTEMSEDEM (Van Oost et al., 2000; Van Rompaey et al, 2001; Verstraeten et al., 2002), which uses the same input parameters as the well-known RUSLE model, but simulates hillslope sedimentation also. The model was calibrated with two independent sets of measurements: (i) the total deposition of sediment in the valley between 1975 and 2002, and (ii) the volume of discharged sediment in 2002.
- Soil characteristics were measured by laboratory and field analyses of soil structure, hydraulic conductivity, texture, organic matter and $CaCO_3$.
- Discharge was measured with pressure transducers at three sites in the catchment. Precipitation was measured at 8 locations with tipping bucket systems. Historic discharge and precipitation data were obtained from the Slovene counterparts (HZM, 2003, Globevnik, 2001b). Other meteorological parameters were measured at a fully equipped meteorological tower (van der Tol, in prep).

HYDROLOGICAL CHANGES

The hydrological regime of the Dragonja River has changed markedly over the period 1960-2003. Peak-, mean and minimum discharges have all dropped to less than half of their values prior to the reforestation. Especially the low discharges have changed dramatically: mean maximum flow, mean annual flow and mean minimum flow decreased by 53%, 79% and 85%, respectively (HMZ, 2003, cf. Fig. 3.1). The percentage of precipitation discharged by the river dropped even more: from 67% (1961-1969) to 34% (1991-2000), while the number of days without flow increased. This indicates that the balance between the positive (improved infiltration rates) and negative (extra water use by trees) effects of reforestation on stream discharge is clearly dominated by this high water use of the vigorously growing trees of the aggrading forest. A close relationship between river discharge and the percentage of forest cover was found.

FLUVIAL GEOMORPHOLOGY

The Dragonja River is a typical Mediterranean, cobble-bed river with pool-riffle and step-pool sequences, dependent on the local channel gradient. In the upper reaches the channel bed consists of bedrock (sandstones), the middle reaches have a cobble base of older channel deposits alternating with bedrock, while in the lower reaches, where a long-term depositional regime has formed a thick layer of fine sediments, the channel bed consists of these fine river deposits. During detailed geomorphological mapping three terraces were distinguished, which stand 2.5 m, 1.5 m and 0.5 m above the present-day riverbed.

Due to the gradually lower intensities and frequency of flood events and a proportionally even larger decrease in sediment delivery to the channel due to the progressive reforestation, the river has started to incise into its former bed whereas vegetation has invaded the formerly braiding river-bed. A narrower, incised river-bed with actively moving channel bars has formed, with a lower floodplain terrace at ca. 1.5 m above the current river-bed that, according to lichenometric dating, is about 60 years old. After 1975, the narrowing of the river-bed intensified as a result of further reductions in annual discharge. River flows reached a level where channel bars were no longer mobile and rapidly invaded and further stabilized by riparian vegetation. The present riverbed shows characteristics of an underfit river that is meandering within its former wider braiding bed. The most recently formed terrace, dated at approximately 30 years BP, consists of fixed, mostly alternate channel bars at ca. 0.5 m above the current river-bed.

The above processes have occurred in most parts of the river and the upper and middle reaches have behaved in more or less the same way. The 1.5 m terrace has its largest extent in the middle reaches, where the river lost 55-65% of its bed area to this terrace between 1945 and 1975. The 0.5 m terrace occupies a much smaller area; the river lost an additional 7% to this terrace after 1975. In the lower reaches of the catchment no terraces have been formed, but deposition rates on the corresponding floodplain section dropped by as much as 95% since reforestation began.
Besides changes in land use and vegetation cover, no other significant human activity has modified river discharges and geomorphology in the Dragonja catchment since the beginning of the reforestation. Therefore, the recent morphological changes of the channel of the Dragonja River must primarily reflect the progressive natural reforestation. In other studies of the effects of reforestation around the Mediterranean, such a one-to-one relationship between cause and effect has not been obtained generally due to complications introduced by additional human interference (gravel mining, dams, river regulation) or natural phenomena (diverse geology). Nevertheless, the same kind of geomorphological changes have been observed in these areas as described above for the Dragonja.

SEDIMENT PRODUCTION
Fine, suspendable sediment that is transported by the Dragonja River consists largely of clay- and silt sized particles originates from three sources: hillslopes, flysch bedrock banks, and older fluvial bank sediment. Hysteretic analysis of discharge flood events, and the texture of the suspended sediment indicate that most suspended sediment originates on the hillslopes. The change in land use and forest cover over the period 1954-2002, from ca. 30% forest in 1954 to ca. 70% forest in 2002) has had a significant impact on the erosion of the hillslopes. The sediment delivery from the hillslopes declined with approximately 70% (modelled with WaTEM/SEDEM) over the period 1954-2002. Both sedimentary and bedrock banks were shown to be relatively minor contributors of fine sediment (4-5% of the total sediment budget) compared with the amount delivered by the hillslopes (91-95%; Fig. 9.1).

Coarse, bedload material has three sources:

(i) extensive bedrock banks along the river channel. The supply of sediment from bedrock banks proved to be largely independent of rainfall, as rock fall processes were more important than undercutting by the river. The size of the debris toes in front of the bedrock banks therefore largely reflect the time elapsed since the last major discharge wave. Based on aerial photographs and field surveys, the total area of actively eroding bedrock banks was larger before the reforestation. Reforestation resulted in a decrease in bedload input from bedrock banks by more than 50%.

(ii) lateral erosion of sedimentary banks that partly consist of cobbles. This source decreased by 50% as a result of the lower erosion rates of the riverbanks.

(iii) older bed material being eroded by river incision. In response to the changes in sediment and water dynamics the river has incised into its own bed material, thereby generating extra bedload and partly compensating the decrease in supply.

The net reduction in transported bedload over the period 1954-2002 was ca. 21%.
In 2002 surface erosion on the hillslopes dominated (91%; Fig. 9.1) the sediment budget of the Dragonja valley. Other sediment contributors, such as degrading river beds (4%), eroding sedimentary banks (3%) and bedrock banks (2%), account for approximately 5% of the

sediment budget. This dominance of the hillslopes as the main sediment supplier was even more pronounced before the reforestation (1954), when the hillslopes supplied as much as 95% of total sediment delivery to the channel. Back then, sedimentary banks delivered ca. 2% of the total sediment production, vs. bedrock cliffs 3% (Fig. 9.1).

SEDIMENT TRANSPORT

The majority of the transport of fine sediment as suspended sediment is discharged during flood events. During low river stages, when little sediment is discharged, virtually all of the sediment comes from the large bedrock banks.
Measured bedload transport rates in the measurement period (2001-2003) were temporally and spatially very variable for several reasons. Firstly, sediment transport in rivers is generally not a steady-state process, but occurs in pulses. Secondly, the Dragonja River is not in equilibrium due to the changing input parameters (discharge, sediment production) as a result of the reforestation.

Downstream fining of coarse bed material is evident in terms of amount, roundness and size. The relative softness of the prevailing bedrock causes the material to break and abrade rapidly during transport. The main process of downstream fining is sediment weathering and not selective transport. All bedrock is worn down completely before reaching the catchment outlet, as can be deduced from the gradually decreasing size of riffles when going downstream, and from the absence of cobbles in the lowermost section of the river. Therefore, the suspended sediment load at the outlet represents the total sediment output from the catchment (estimated at 4.5 t ha^{-1} y^{-1} in 2002)

As a result of the reforestation and the associated decrease in flood height and flood frequency, the transport capacity of the river dropped also. Field measurements show that transport of coarse sediment takes place during large floods. Because there are no measurements of the bed load transport rates before the reforestation, these values were calculated with several existing formulas. These formulas showed a reduction in transport capacity of ca. 90%.

SEDIMENT DEPOSITION

Past and current floodplain sedimentation rates were obtained using ^{137}Cs dating (1960-2001) and deposition on artificial grass mats (2001-2003). The ^{137}Cs core sampling allowed the computation of two separate, averaged sedimentation rates for the periods 1960-1986 and 1986-2001. The flooded area was divided into five sections which were all represented by one or more ^{137}Cs cores and artificial grass mats, viz.: (i) the 0.5 m terrace in all sections of the river channel, (ii) the 1.5 m terrace in the Rokava tributary, (iii) the 1.5 m terrace in the Upper and Middle sections of the Dragonja River, (iv) the floodplain of the Lower Dragonja river, where no terraces were formed, and (v) the 2.5 m terrace.
The ^{137}Cs dating showed that in all river sections sedimentation rates decreased significantly from the first period to the second; total sediment accumulation on the entire floodplain area was $1.5*10^5$ m^3 in 1960-1986 vs. $0.99*10^5$ m^3 in 1986-2001. The reduction in sedimentation rate increased in a downstream direction. Overall catchment-wide reduction in sediment deposition between the two periods was 34%.

The results obtained with the artificial grass mats indicated that all floodplain sedimentation takes place during flood events of considerable magnitude. Due to the progressive reforestation, the return period of large floods increased until ca. 1985 after which the frequency (like the area under forest cover) more or less stabilised, which explains the lower sedimentation rates. However, the sedimentation rates derived from the artificial grass mats on the 1.5 m terrace were roughly half that estimated from the ^{137}Cs cores due to the relatively dry period in which the mats were in operation. Only half the expected number of floods actually occurred during this period. For the lowest terrace (0.5-1.0 m above the river-bed) the sedimentation rates obtained with the two measurement techniques were similar. Therefore, it would seem that the amount of sediment deposited on the lower parts of the floodplain during large flood events was not significantly higher than that during floods of lower magnitude. For the rarely inundated 2.5 m terrace the number of observations available is too small to draw firm conclusions and longer-term observations are needed.

In summary, the floodplain sedimentation measurements indicate that (Fig. 9.1) only 10% of the total volume of generated sediment is deposited on the floodplains and adjacent river terraces. The remaining 90% is transported to the sea (Fig. 9.1). As a result of the reforestation the total volume of sediment deposited on the floodplain and adjacent lowest terraces decreased by approximately 70%. However the distribution of the sediment seems to have stayed stable.

DIFFERENCES BETWEEN THE ROKAVA AND UPPER DRAGONJA SUB-CATCHMENTS

In the upstream part of the Dragonja catchment, the Rokava (20 km^2) and Upper Dragonja (32 km^2) sub-catchments were reforested in a different manner. In the Rokava sub-catchment a larger area has remained under agricultural use because of its greater accessibility from the coastal cities and its gentler topography. Only 61% of the Rokava area was forested in 2002 as opposed to 73% in the Upper Dragonja sub-catchment. Because of the contrast in vegetation cover, the hydrological and erosion response of the two sub-catchments differ to some extent.

Hydrologically, the two areas behave quite differently. Measurements of rainfall and streamflow carried out between October 2000 and September 2001 show that the Upper Dragonja sub-catchment always discharges less water at the same antecedent wetness level than the Rokava sub-catchment. The contrasts relate to runoff response to rainfall: in the Rokava sub-catchment 26% of the precipitation is converted into discharge, versus 22% for Upper-Dragonja. Furthermore, the Rokava sub-catchment discharges about 58% of the total flow as quickflow, vs. 45% for the Upper Dragonja sub-catchment. Also the slope of the separation line between quick and delayed flow shows a generally steeper slope for the Upper-Dragonja, indicating a relatively shorter period of quick flow, an average 58h and 25h for the Rokava and Upper-Dragonja respectively.
Thus, all hydrological parameters indicate a slower and less intensive hydrological response for the more forested Upper Dragonja area. Such contrasts are thought to reflect the better infiltration capacity, higher rainfall interception, and higher water use commonly associated with forest.

Marked differences between the two sub-catchments were also found in terms of their hillslope sediment delivery. Model calculations for the Rokava and Upper Dragonja areas showed a similar reduction in sediment delivery during the period 1954 - 1975 of 45%. Whilst sediment delivery remained more or less stable after 1975 in the Rokava area, the decrease continued in the Upper Dragonja area after 1975, rendering the total reduction in sediment production in 2002 76% less than that in 1954.

In terms of floodplain sediment deposition, the total volume of deposited sediment on the 1.5 m river terrace in the Middle and Upper-Dragonja and Rokava sub-catchments decreased by 45% and 20%, respectively, during the period 1960-2001.

NEDERLANDSE SAMENVATTING VAN HET PROEFSCHRIFT: *INVLOED VAN NATUURLIJKE HERBEBOSSING OP DE HYDROLOGIE, RIVIER GEOMORFOLOGIE EN HET SEDIMENT BUDGET VAN DE DRAGONJA RIVIER IN ZUIDWEST SLOVENIË.*

ACHTERGROND

Als gevolg van herbebossing in het mediterraan klimaat vinden er veranderingen in de hydrologie en het sediment budget van een stroomgebied plaats. De wetenschappelijke aandacht hiervoor heeft zich tot nu toe beperkt tot enkele studies in Frankrijk, Spanje, Italië en de USA. Onder Mediterrane condities zijn deze effecten zeer interessant omdat deze klimaatzone extra gevoelig is voor veranderingen in klimaat of vegetatie, omdat de hydrologische en geomorfologische evenwichten bijzonder gevoelig zijn voor invloeden van buitenaf (Brookes et al., 2000). De meeste recente studies naar de effecten van herbebossing in het mediterraan gebied, omvatten dan wel alleen maar een onderdeel van een stroomgebied, of hebben een diverse geologie, of kennen buiten herbebossing ook andere menselijke factoren die de hydrologie, geomorfologie en het sediment budget beïnvloeden (zoals grindwinning, dammen of rivierregulatie). Hierdoor zijn de resultaten moeilijker te interpreteren.

Het stroomgebied van de Dragonja in Zuidwest Slovenië is zeer geschikt voor een studie naar de invloed van herbebossing op de hydrologie, geomorfologie en het sedimentbudget van het stroomgebied omdat het een relatief klein (91 km^2) en geologisch uniform gebied is. Buiten de relatief gelijkmatige herbebossing, die na de tweede wereldoorlog begon, zijn er in het gebied geen andere menselijke invloeden op het sedimentbudget geweest. De huidige studieresultaten vullen eerder onderzoek in dit gebied aan (Globevnik and Sovinc, 1998; Globevnik, 2001), met het doel uitgebreider in te gaan op de geomorfologische ontwikkelingen van de riviergeul en de aangrenzende overstromingsvlakte. Tevens worden de veranderingen van het sedimentbudget van het totale stroomgebied over de herbebossingperiode van 1945 tot heden geanalyseerd.

LANDGEBRUIKVERANDERINGEN EN HERBEBOSSINGSSUCCESSIE

Na de tweede wereldoorlog veranderde de economische en sociale situatie in voormalig Joegoslavië (waar Slovenië toen onderdeel van uitmaakte). In het kustgebied ontwikkelde zich de zware industrie en het toerisme. Dientengevolge ontvolkte het agrarische achterland. Het stroomgebied van de Dragonja is één van deze marginale landbouwgebieden. De verlaten akkertjes werden snel overwoekerd en in ca. 50 jaar ontwikkelde zich een volgroeid bos. De belangrijkste landgebruiksveranderingen zijn opgetreden tussen 1954 en 1985, toen het areaal landbouwgrond afnam van 70% in 1954 tot 30% in 1985. Na 1985 hebben geen grote veranderingen in landgebruik meer plaatsgevonden (24% landbouwgrond in 2002).

ONDERZOEKSMETHODES

De onderzoeksmethodes omvatten een combinatie van verschillende technieken:

- De geomorfologie van de riviergeul, terrassen en overstromingsvlakte was gedetailleerd gekarteerd. De rivierinsnijding en bijbehorende terrassen zijn gedateerd met lichenometrie en boomringanalyse en ^{14}C-analyses. Voor de geomorfologische veranderingen is ook gebruik gemaakt van luchtfoto-interpretatie en GIS-analyse.
- De sedimentatiesnelheid op de overstromingsvlakte is met twee technieken gemeten: de huidige sedimentatiesnelheid is gemeten met kunstgrasmatjes en de sedimentatiesnelheid in de periode 1960 tot 2002 is afgeleid van Cs^{137}- en ^{14}C-analyses.

- Stootoevererosie is gemeten met erosie-depositie pinnen, analyse van 3-D foto's en series normale foto's. Historische bankerosie is met behulp van GIS-analyse bepaald.
- Transport van grof sediment in de riviergeul is gemeten met behulp van 'stone-tracing'. Het fijne materiaal in suspensie is bemonsterd met een automatisch watermonstername-apparaat, een ISCO.
- De afname van de sedimenttoevoer vanaf de hellingen is gemodelleerd met het model WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al, 2001; Verstraeten et al., 2002), dat dezelfde invoerparameters gebruikt als het bekende RUSLE-model, maar tevens de sedimentatie op de hellingen modelleert. Het model is gekalibreerd met twee onafhankelijke reeksen metingen: (i) het totale volume sediment afgezet in de vallei in de periode 1975 tot 2002, en (ii) het volume sediment dat door de rivier is afgevoerd in 2002.
- Bodemkarakteristieken zoals bodemstructuur, hydraulische conductiviteit, textuur, organische stofgehalte en kalkgehalte zijn gemeten met behulp van veld- en laboratoriumtechnieken.
- Afvoer is op drie plaatsen in het stroomgebied met drukopnemers gemeten. Neerslag is op 8 locaties in het stroomgebied gemeten met zgn. tipping-bucket systems. De afvoer- en neerslag data van 1960 tot 2002 zijn gemeten nabij de monding van de rivier door de Sloveense overheid (HZM, 2003, Globevnik, 2001b). Andere meteorologische parameters zijn gemeten met een meteorologische toren in het stroomgebied in de periode oktober 2000 tot september 2004 (van der Tol, in prep).

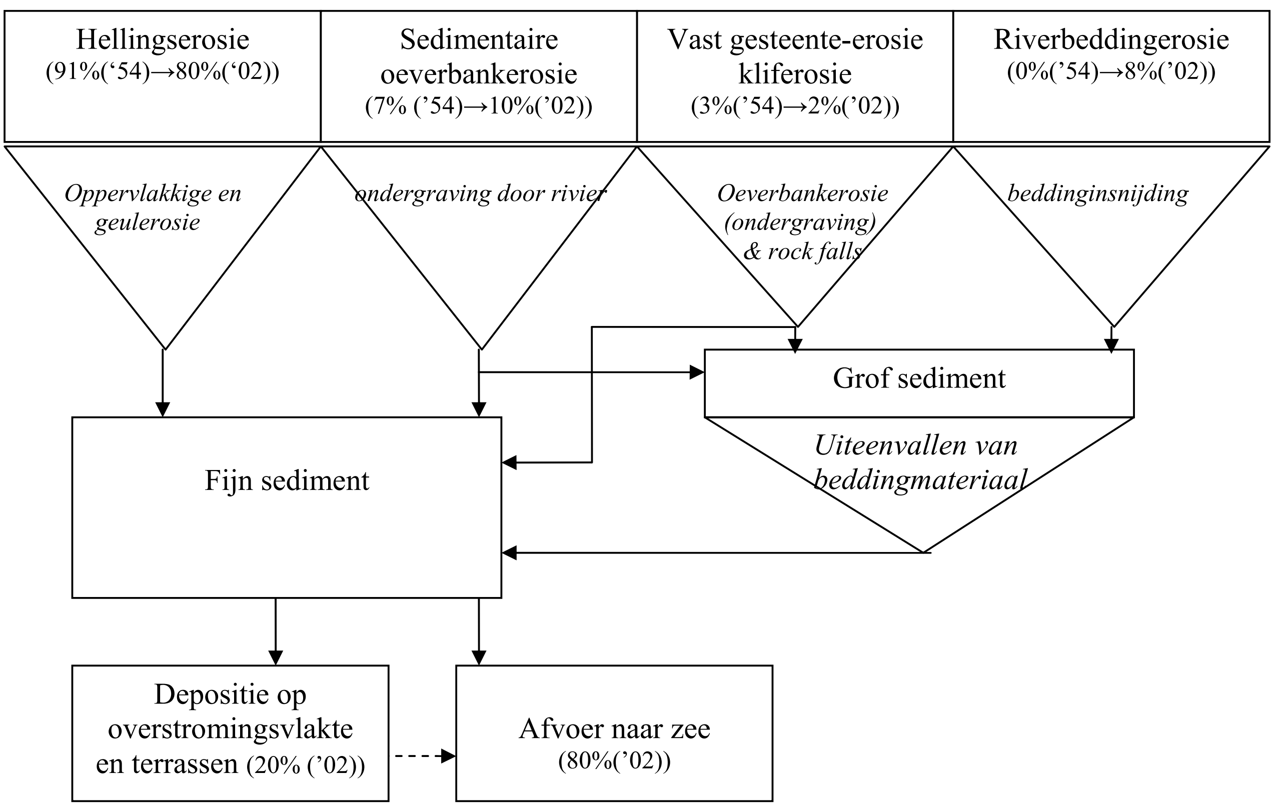
HYDROLOGISCHE VERANDERINGEN

Het hydrologisch gedrag van de Dragonja is in de periode 1960-2003 duidelijk veranderd. Maximale, gemiddelde en minimale afvoeren zijn allemaal tot minder dan de helft van de waarde van voor de herbebossing afgenomen. Met name de lage afvoeren zijn zeer sterk gedaald. De gemiddelde maximale, jaarlijkse en lage afvoer zijn respectievelijk met 53%, 79% en 85% afgenomen (HMZ, 2003) en het percentage van de neerslag dat door de rivier wordt afgevoerd is gedaald van 67% (1961-1969) tot 34% (1991-2000). Tevens zijn de frequentie en hoogte van de overstromingen sterk afgenomen terwijl het aantal dagen dat de rivier droogvalt is toegenomen. Dit geeft aan dat de balans tussen de positieve effecten (verbeterde infiltratiecapaciteit) en de negatieve effecten (extra watergebruik door de bomen) van herbebossing op de afvoer van een rivier in dit stroomgebied duidelijk gedomineerd wordt door het hoge waterverbruik van de snelgroeiende bomen. Er is een goede correlatie gevonden tussen de jaarlijkse afvoer en het percentage bosareaal.

GEOMORFOLOGIE VAN DE RIVERGEUL

De Dragonja is een typische mediterrane rivier en bestaat uit een grind bedding met zgn. pool-riffle en step-pool sequenties, afhankelijk van de lokale gradiënt van de riviergeul. In de bovenste secties van de rivier bestaat de bedding uit vast gesteente (flysch, met name zandsteen), in het middelste gedeelte van de rivier bestaat de bedding uit grove grinden afgewisseld met vast gesteente. In het meest benedenstroomse gedeelte van de rivier bestaat de riviergeul uit fijn sediment dat is afgezet als overstromingsafzettingen. Tijdens de veldkartering zijn drie recente terrassen onderscheiden, 0.5m 1.5m en 2.5m boven de huidige rivierbedding.
Als gevolg van de geleidelijke afname van de intensiteit en frequentie van overstromingen, en de afname van sedimentaanvoer naar de rivier (beide het gevolg van de herbebossing), heeft de rivier zich ingesneden in zijn voormalige bedding. Ook heeft vegetatie zich in de voorheen vlechtende rivierbedding gevestigd, waardoor de riviergeul veel smaller is geworden. Deze insnijding en versmalling van de riviergeul is in twee fases gebeurd. Een eerste terras,

bestaande uit 55-65% van de voormalige rivierbedding, ligt nu ca 1.5 m hoger dan de huidige rivierbedding. Dit terras is zo'n 60 jaar geleden gevormd. De overgebleven rivier bestond rond 1975 uit een smallere, ingesneden geul met zich verplaatsende grindbanken. Na 1975 veroorzaakte de doorgaande afname van de afvoer een versterkte versmalling van de geul. De afvoer bereikte een niveau waarmee de grindbanken niet meer verplaatst konden worden, en zich op de banken kon vestigen en daarmee stabiliseerde. De huidige rivier lijkt te klein voor zijn geul te zijn, en meandert door zijn voormalige bedding heen.
Door deze vastlegging van de grindbanken is een tweede 'terras' (bestaande uit ca 7% van de voormalige rivierbedding) gevormd dat ca. 0.5 m boven de huidige riviergeul ligt.
Het hierboven beschreven proces heeft zich op de meeste plaatsen in het bovenstroomse en middelste gedeelte van de rivier voorgedaan. Alleen in het meest benedenstroomse gedeelte van de rivier zijn geen terrassen gevormd omdat er een continue sedimentatie heeft plaatsgevonden, maar de depositiesnelheid op de overstromingsvlakte is in de zelfde periode wel sterk afgenomen (95 %).
Afgezien van de veranderingen in landgebruik, zijn er geen significante menselijke activiteiten in het gebied die de riviermorfologie hebben beïnvloed. Derhalve kunnen de recente morfologische veranderingen van de Dragonja aan de herbebossing worden toegeschreven.



Figuur 10.1: Sedimentbudget van het Dragonja stoomgebied (1954/2002)

SEDIMENT PRODUCTIE

Het fijne suspensiesediment dat door de Dragonja wordt afgevoerd bestaat voornamelijk uit klei- en siltdeeltjes. Het grove materiaal dat over de bedding van de rivier wordt verplaatst varieert in grootte van fijn grind tot blokken, met een D_{50}-waarde van 6-8 cm. Het fijne materiaal is afkomstig van drie bronnen: de hellingen, de oeverbanken in vast gesteente en de

oeverbanken waarin zich grof alluviaal materiaal bevindt. Hysterese en textuur analyse laten zien dat het grootste gedeelte van het sediment in suspensie afkomstig is van de hellingen. Als gevolg van de herbebossing is er een sterke afname van de erosie op de hellingen. De verandering van een actief landbouwgebied (ca. 30% bos in 1954) naar een hoofdzakelijk bebost gebied (ca. 70% bos in 2002) heeft er voor gezorgd dat de sedimenttoevoer vanaf de hellingen zo'n 70 % is afgenomen (gemodelleerd met WaTEM/SEDEM).
Het grove materiaal dat door de rivier wordt vervoerd heeft drie bronnen:

(i) erosieve kliffen langs de rivier in vast gesteente. De aanvoer van sediment van de kliffen is onafhankelijk van de neerslag omdat hellingsprocessen een groter effect op de erosiesnelheid van de kliffen hebben dan ondergraving door de rivier. De grootte van de puinwaaiers aan de voet van de kliffen wordt derhalve grotendeels bepaald door de lengte van de periode tussen twee grote afvoergolven. De aanvoer van sediment van deze bron is als gevolg van de herbebossing met 50% afgenomen.

(ii) laterale erosie van sedimentaire oeverbanken die gedeeltelijk uit fijn materiaal en gedeeltelijk uit grof materiaal bestaan. Ook deze bron is ca. 50% afgenomen als gevolg van een verlaagde erosiesnelheid van de stootoevers.

(iii) voormalig bedding materiaal dat weer beschikbaar is voor transport doordat de rivier zich insnijdt als gevolg van veranderde dynamiek tussen het afgevoerde water en sediment. Deze bron is pas beschikbaar sinds de insnijding van de rivier.

De netto afname van getransporteerd grof materiaal in de periode 1954-2002 is ca. 21%. In 2002 domineert de oppervlakkige erosie op de hellingen het sedimentbudget in de Dragonja vallei (91%; Fig. 10.1). De andere sedimentbronnen, de eroderende rivierbedding (4%), de sedimentaire oeverbanken (3%) en de kliffen (2%), dragen slechts 9% van het totale sedimentbudget bij. De dominerende rol van de dalhellingen als sedimentaanvoerder was voor de herbebossing nog uitgesprokener. Destijds droegen de hellingen wel 95% van het totale naar de rivier aangevoerde sediment bij. De sedimentaire oeverbanken droegen slechts 2% en de kliffen 3% bij.

SEDIMENTTRANSPORT

Het merendeel van het fijne sediment wordt tijdens grote afvoeren getransporteerd. Gedurende de lage afvoeren van de rivier is het weinige sediment dat zich in de waterkolom bevindt grotendeels afkomstig van de kliffen. Gedurende de meetperiode (2001-2003) waren de transportsnelheden van het grove beddingmateriaal in tijd en ruimte zeer variabel. Dit heeft verschillende oorzaken. Allereerst is sedimenttransport in een rivier geen ´steady-state´ proces. Ten tweede is de Dragonja momenteel niet in evenwicht als gevolg van de veranderende afvoer en sedimenttoevoer, als gevolg van de herbebossing.
Analyse van het grove materiaal in de riviergeul laat een zeer duidelijke afname in grootte en hoeveelheid grof materiaal zien. De afslijting van het materiaal is zodanig ernstig, dat de rivier bij de monding geen grof materiaal meer vervoert. Derhalve is het materiaal in suspensie bij de monding van de rivier (geschat op 4.5 t ha^{-1} y^{-1} in 2002) gelijk aan de totale hoeveelheid sediment die het stroomgebied verlaat.
Als gevolg van de herbebossing is ook de afvoer en daarmee de transportcapaciteit van de rivier afgenomen. Veldmetingen laten zien dat al het grove sediment wordt afgevoerd gedurende een aantal grote afvoerpieken per jaar. Omdat er geen metingen van het grove sediment transport van voor de herbebossing beschikbaar zijn, zijn deze waarden berekend met behulp van een aantal bestaande formules. Deze formules geven een reductie in transportcapaciteit aan van circa 90%.

SEDIMENTDEPOSITIE

Met behulp van ^{137}Cs ouderdomsbepalingen zijn twee afzonderlijke sedimentatiesnelheiden afgeleid voor de perioden 1960-1986 en 1986-2001 op de overstromingsvlaktes en terrassen. Het sedimentatiegebied is opgedeeld in vijf delen. In ieder sedimentatiegebied waren één of meerdere ^{137}Cs kernen en kunstgrasmatjes gelokaliseerd:

(i) het 0.5 m terras in de gehele rivierloop,
(ii) het 1.5m terras in de Rokava,
(iii) het 1.5 m terras in de midden en bovenloop van de Dragonja,
(iv) de overstromingsvlakte in de benedenloop van de rivier, waar geen terrassen zijn gevormd,
(v) het 2.5 m terras.

De ^{137}Cs dateringen laten in alle gebieden een sterke daling zien in de sedimentatiesnelheid wanneer de twee perioden (1960-1986 en 1986-2001) met elkaar worden vergeleken. De totale hoeveelheid afgezet materiaal daalde van $1.5*10^5$ m^3 in 1960-1986 tot $0.99*10^5$ m^3 in 1986-2001 (een totale afname van 34%). De afname in sedimentatiesnelheden neemt toe in stroomafwaartse richting.
Als gevolg van de voortgaande herbebossing, zijn de ´return periods´ van grote overstromingen sterk toegenomen tot ca. 1985. Daarna is het bosareaal evenals de frequentie van de overstromingen min of meer gestabiliseerd. De afname van de overstromingsfrequentie verklaart de lagere sedimentatiesnelheid gemeten met de matjes t.o.v. de snelheden afgeleid uit van de ^{137}Cs kernen voor de periode 1960-1986. Maar voor de periode 1986-2001 zou de sedimentatiesnelheid gemeten met de matjes op het 1.5 m terras gelijk moeten zijn aan die afgeleid van de cesiumdateringen. Echter de sedimentatiesnelheid gemeten op de matjes was maar half zo hoog als verwacht aan de hand van de metingen van de cesiumkernen. Dit is het gevolg van een lagere overstromingsfrequentie in de meetperiode van de matjes dan verwacht op basis van de berekende ´return periods´. Op het laagste terras (0.5 m boven de huidige rivierbedding) zijn de gemeten sedimentatiesnelheden voor beide technieken vergelijkbaar. Dit zou kunnen inhouden dat de hoeveelheid sediment die wordt afgezet in een overstroming niet afhankelijk is van de grootte van de overstroming. Voor het 2.5 m terras, dat slechts zeer zelden overstroomt, is het aantal metingen te klein om conclusies te kunnen trekken.
Samenvattend kan worden gezegd dat ongeveer 10% van het gegenereerde sediment op de overstromingsvlaktes en terrassen wordt afgezet. Het overige sediment (ca. 90%) wordt afgevoerd naar zee (Fig. 10.1).
Als gevolg van de herbebossing is de totale hoeveelheid afgezet sediment op de overstromingsvlakte en de terrassen met ca. 70% afgenomen. Maar de proportionele distributie van het sediment is ongeveer gelijk gebleven.

VERSCHILLEN TUSSEN HET ROKAVA EN BOVEN DRAGONJA SUBSTROOMGEBIED

Het bovenstroomse gedeelte van het stroomgebied van de Dragonja is opgedeeld in het Rokava (20 km^2) en Boven Dragonja (32 km^2) sub-stroomgebied. De twee sub-stroomgebieden zijn op een verschillende manier herbebost. Het areaal aan landbouwgrond is in het Rokava sub-stroomgebied groter dan in het Boven Dragonja sub-stroomgebied als gevolg van een betere bereikbaarheid en een iets vlakkere topografie. Als gevolg van deze verschillen in landgebruik zijn de veranderingen in de hydrologie en erosie ook verschillend.

Hydrologie: In de periode oktober 2000 tot september 2002 laten neerslag en afvoermetingen in beide sub-stroomgebieden zien dat de Rokava altijd meer water afvoert dan de Boven Dragonja bij een vergelijkbare initiële natheid van de stroomgebieden. Gemiddeld voert de Rokava 26% van de neerslag af als afvoer, terwijl de Boven-Dragonja maar 22% afvoert. Ook het percentage directe afvoer (‘quickflow’) van de totale afvoer is hoger in het Rokava sub-

stroomgebied (58% versus 45% voor het Boven-Dragonja sub-catchment). Tevens is de duur van de directe afvoer ook aanzienlijk langer in de Rokava (gemiddeld 58 uur) ten opzichte van de Boven-Dragonja (gemiddeld 25 uur).
Al met al laten de hydrologische parameters van het meer beboste Boven Dragonja sub-stroomgebied een langzamere of lagere respons zien. Deze verschillen zijn mogelijk het gevolg van een betere infiltratiecapaciteit, hogere neerslag interceptie en hoger waterverbruik, dat allemaal kan worden geassocieerd met de sterkere herbebossing van het Boven Dragonja sub-stroomgebied t.o.v. het Rokava sub-stroomgebied.

<u>Sedimenttoevoer vanaf de hellingen</u>: Aparte model berekeningen voor de sedimenttoevoer voor beide sub-stroomgebieden geven een vergelijkbaar beeld voor de periode van 1954 tot 1975, namelijk een reductie van ca. 45%. Na 1975 blijft de hoeveelheid sediment die uit het Rokava sub-stroomgebied komt min of meer stabiel, maar in de Boven Dragonja neemt de sediment toevoer verder af tot een reductie van 76% in 2002.

<u>Sedimentdepositie</u>: De gemiddelde jaarlijkse sedimentatiesnelheid op het 1.5 m terras in de Boven Dragonja is ca. 45% afgenomen in de periode 1960 tot 2001. In de zelfde periode is de sedimentatiesnelheid op hetzelfde terras in de Rokava maar 20% afgenomen.

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