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DINAMIKA PREMEŠČANJA LEBDEČIH PLAVIN V POREČJIH
SUSPENDED LOAD TRANSPORT DYNAMICS IN RIVER BASINS

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Članek podaja vpogled v dinamiko premeščanja lebdečih plavin na nivoju porečij. V uvodnem delu so predstavljeni osnovni vzroki za spremenjene količine lebdečih plavin v vodnem okolju ter problemi, ki so posledica teh sprememb. V nadaljevanju je podan opis elementov dinamike premeščanja suspendiranih plavin od procesov sproščanja do procesov premeščanja in odlaganja. Glede na prostorsko razsežnost so posebej obravnavani procesi erozije tal, procesi podpovršinskega spiranja in premeščanja, procesi erozije brežin vodotoka ter medsebojni vplivi med temi procesi. Predstavljeni so osnovni dejavniki, ki vplivajo na razvitost posameznega erozijskega procesa. V drugem delu so podrobneje opisane nekatere možnost matematičnih zapisov posameznih elementov dinamike premeščanja lebdečih plavin. Posebna pozornost je namenjena procesom sproščanja in premeščanja delcev zemljin pod vplivom udarcev dežnih kapljic, nadaljnjemu premeščanju mobiliziranih delcev s površinskim padavinskim odtokom ter premeščanju lebdečih plavin po strugi vodotoka.
Ključne besede: *hidrologija, erozija tal, sproščanje sedimentov, premeščanje plavin, lebdeče plavine, modeliranje, rečni procesi*

The article gives an insight into the dynamics of suspended load transport in river basins. In the introductory section, some basic causes for the changed quantity of suspended load in the aquatic environment are presented together with the problems that arise from these changes. In continuation a description of the elements of the suspended load transport dynamics is represented, ranging from the processes of sediment detachment to the processes of suspended load transport and deposition. As regards the spatial dimension, the processes of soil erosion, processes of subsurface flushing and transport, processes of bank erosion end interactions between these processes are discussed. Some basic factors influencing the development of erosion processes are introduced. In the second part some possible mathematical formulations of the suspended load transport dynamics are more precisely described. Special attention is given to the processes of detachment and transport of soil particles by raindrop impact, further transport of the mobilised soil particles with surface rainfall runoff and transport of suspended load in river channels.
Key words: *hydrology, soil erosion, sediment detachment, sediment transport, suspended load, modelling, fluvial processes*

1. UVOD

Negativne vplive visokih koncentracij lebdečih plavin na vlogo vodotokov kot kompleksnih ekosistemov opazujemo že dolgo časa. Spremenjena dinamika premeščanja lebdečih plavin v vodotoku je večinoma posledica spremenjene rabe prispevnih površin vodotoka. Kmetijske površine so ob neizvajanju ukrepov za zmanjšanje odplavljanja zemljine s površinskim odtokom, ukrepov za preprečevanje koncentriranja padavinskega odtoka in posledičnega razvoja

1. INTRODUCTION

The negative impacts of high concentrations of suspended load on the role of rivers as complex ecosystems have been observed for a long time. The changed dynamics of the suspended load in a river is frequently a consequence of the changed land use in the river basin. If anti-erosion measures in agricultural areas are not properly carried out, these areas are the largest source of suspended load in the river. These measures prevent the concentration of the surface runoff and the resulting development of different različnih oblik vodne erozije največji vir lebdečih plavin, ki se po vodotoku premeščajo (Woodward, 1995; Boardman, 1996). Po drugi strani predstavljajo poplavne ravnice, na katerih se lebdeče plavine odlagajo, zelo rodovitne kmetijske površine. Izdaten vir lebdečih plavin so tudi industrijska in urbana območja (Walling, 1995). Intenzivirana in pospešena koncentracija meteornega odtoka z neprepustnih (tlakovanih) urbanih površin privede do intenzivnega spiranja drobnih delcev (Lougran in Campbell, 1995; Walling, 2005).

Gledano z vidika vodotoka kot ekosistemske enote, se ti vplivi odražajo na spremenjenih samočistilnih procesih v vodotoku. Ocena skupnega letnega premeščanja lebdečih plavin s kopnega v oceane znaša približno 15 x 10^9 ton, maksimalni ekstremi letnih specifičnih dotokov lebdečih plavin pa dosežejo okoli 50.000 t/km^2 (Walling, 1995).

Prepoznavanje širšega okoljskega pomena lebdečih plavin je spodbudilo težnjo po prostorskem in časovnem kvantificiranju koncentracije ter količine plavin v vodotokih. Suspendirani sedimenti so tako v ZDA na seznamu glavnih onesnažil površinskih voda tako v smislu količine (ko govorimo o t. i. »čistem sedimentu«) kot tudi kvalitete sedimentov, pri čemer imamo v mislih onesnažila, ki so na sedimente adsorbirana (EPA, 1993).

V članku so podrobneje predstavljeni nekateri vidiki dinamike sproščanja, premeščanja in odlaganja lebdečih plavin ter možnosti modeliranja teh naravnih procesov.

2. DINAMIKA PREMEŠČANJA SUSPENDIRANIH SNOVI

2.1 PROCESI

S pojmom sediment imenujemo zemljine, ki so se zaradi določenega erozijskega procesa premestile (sprostile) iz lege svojega nastanka in odložile drugje. S pojmom plavine pa mislimo sedimente v rečni strugi, ki se pod vplivom vodnega toka vsaj občasno premeščajo (Petkovšek, 2002). Lebdeče

forms of water erosion (Woodward, 1995; Boardman, 1996). On the other hand, floodplains on which the deposition of the suspended sediments occurs make for very fertile agricultural land. Industrial and urban areas are another abundant source of suspended load (Walling, 1995). Intensified and accelerated concentration of rainfall runoff from impervious (paved) urban areas causes intensive flushing of fine particles (Lougran and Campbell, 1995; Walling, 2005).

Looking at the watercourse as an ecosystem unit, the influences of changed dynamics of the suspended sediment processes are also expressed through changed self-purification processes in the watercourse. On a global scale, the estimated quantity of transported suspended load from the land to the sea amounts approximately 15 x 10^9 tons, the maximum extremes of annual specific suspended load reach about 50,000 t/km^2 (Walling, 1995).

The recognition of a wider environmental importance of suspended load has stimulated the tendency for spatial and temporal quantification of the suspended load concentration in the rivers. In the USA, suspended sediments are recognized as one of the main pollutants of surface waters in the sense of quantity (when talking about the so called “pure sediment”) and in the sense of the quality of the sediment when we have in mind the pollutants which are adsorbed on the sediment particles, respectively (EPA, 1993).

In this paper, some aspects of the dynamics of detachment, transport and deposition of suspended load with the possibilities of modelling of these natural processes are presented in more detail.

2. SUSPENDED MATTER TRANSPORT DYNAMICS

2.1 PROCESSES

The term sediment is used for the soil which has been transported from the position of its origin and deposited elsewhere due to certain erosive processes. The term load represents sediments which are at least occasionally displaced by the water current inside the river channel (Petkovšek, 2002). Suspended load is a part of the total quantity (suspendirane) plavine so del skupne količine plavin, ki so ob premeščanju zelo redko v stiku z dnom vodotoka. Zaradi turbulence lebdijo v vodnem toku in se zadržujejo na določeni razdalji od dna vodotoka. Hitrost premeščanja lebdečih plavin je večinoma enaka hitrosti vodnega toka. Glede na zrnavostno sestavo lebdečih plavi so to predvsem drobni delci velikostnega razreda gline in melja.

Veliko naravnih in antropogenih dejavnikov vpliva na proces sproščanja, premeščanja in odlaganja lebdečih plavin. Med najpomembnejše dejavnike dinamike premeščanja plavin štejemo predvsem padavine kot gonilno silo, geomorfologijo, pedološke značilnosti tal ter vegetacijo (Wharton, 2000). Antropogeni dejavniki vplivajo na stopnjo povezljivosti virov plavin in vodotokov ter nadaljnje premeščanje lebdečih plavin po rečni mreži. Z izgradnjo drenažnih sistemov (dreniranje kmetijskih površin ali meteorna odvodnja z urbanih površin itd.) se te povezave okrepijo (Richards, 1993). Sproščanje je rezultat neravnotežja med silami, ki ohranjajo delce zemljine na mestu oz. vezane v strukturne agregate tal (te sile so kontrolirane predvsem z zrnavostno sestavo zemljine in stopnjo vlažnosti v tleh) ter strižnimi napetostmi, ki delce mobilizirajo. Sproščanje je predvsem posledica erozijske moči dežnih kapljic in strižnih napetosti površinskega odtoka padavinske vode. Glavni dejavnik premeščanja sedimentov po pobočju je torej vodni tok, premeščanje sedimentov pa je lahko spodbujeno tudi s pljuski dežnih kapljic. Večinoma se premeščanje pojavi šele z nastopom površinskega odtoka in se torej pojavi prej na podlagi, ki je manj prepustna in ima manjšo infiltracijsko sposobnost (Petkovšek, 2000).

2.2 ELEMENTI DINAMIKE TRANSPORTA LEBDEČIH PLAVIN NA NIVOJU ODSEKA VODOTOKA

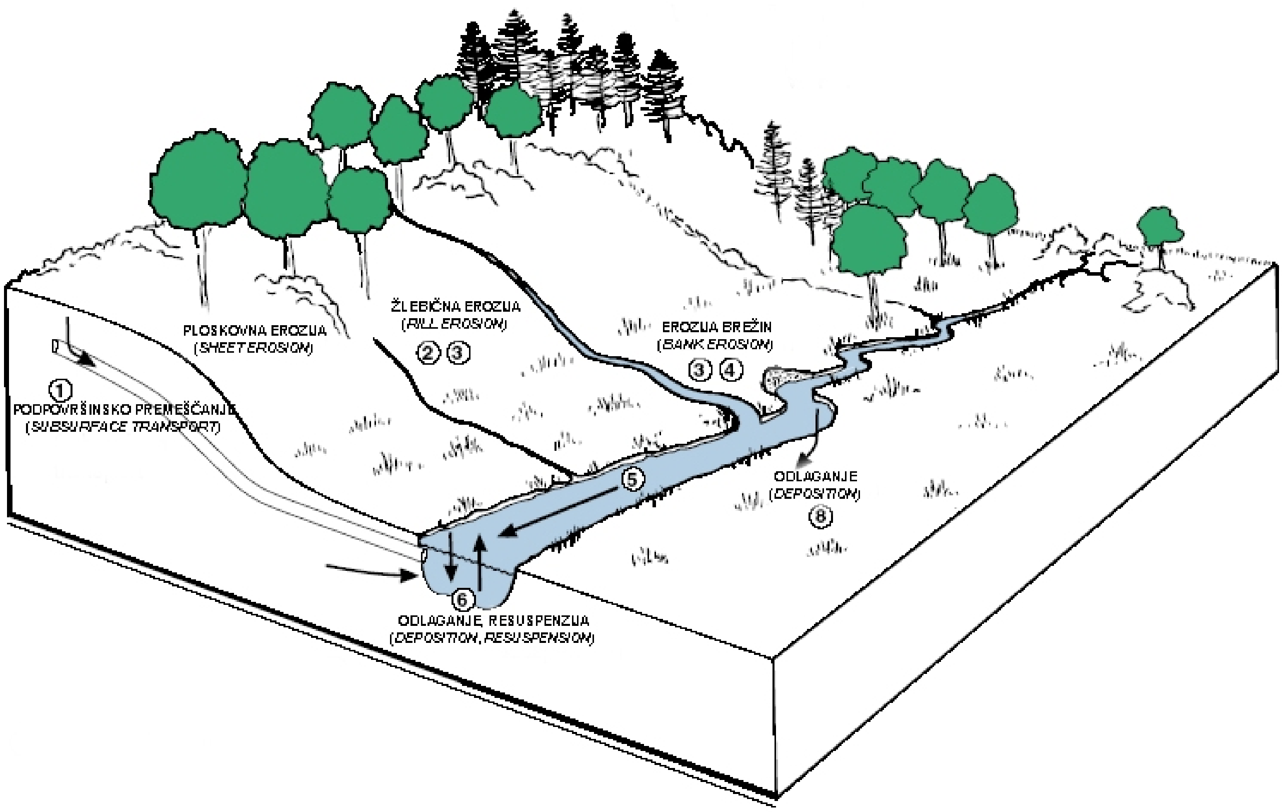
Poti sproščanja, premeščanja ter odlaganja lebdečih plavin na nivoju rečnega odseka so prikazane na sliki 1.

of load which is very rarely in contact with the river channel bottom during the transport. Owing to the turbulence, the suspended load particles float inside the water column on a certain distance from the channel bottom. The velocity of the transport of suspended load is mostly equal to the velocity of the water current. Regarding the particle size distribution of the suspended load, the particles are mainly in the class of silt and clay.

A great deal of natural and anthropogenic factors influences the process of detachment, transport and deposition of suspended sediments. Among the most important natural factors of the dynamics of suspended sediment transport are rainfall as the driving force, geomorphology, soil pedological characteristics and vegetation (Wharton, 2000). The anthropogenic factors influence the degree of the connectivity between suspended sediment source areas and rivers and their further transport along the river channel network. The construction of drainage systems (drainage of agricultural areas, urban drainage systems, etc.) strengthens these connections (Richards, 1993). The detachment is a result of imbalance between forces, which keep soil particles bound in structure aggregates of soil (these forces are controlled by soil texture and soil moisture) and shear forces which tend to mobilize these particles. Detachment is mainly the consequence of the erosive strength of raindrops and shear stress of the rainwater runoff. Therefore, the main factor of further sediment transport is water flow but the dislocation of the sediments can be also induced by the splash of raindrops. The sediment transport mostly occurs after the formation of the surface rainfall runoff, furthermore, the transport of the sediments occurs earlier on the surface which is less pervious and has small infiltration capacity (Petkovšek, 2000).

2.2 ELEMENTS OF THE DYNAMICS OF SUSPENDED LOAD TRANSPORT ON THE RIVER REACH LEVEL

Paths of detachment, transport and deposition of suspended load on the level of the river reach are shown in Figure 1.



Slika 1. Dinamika premeščanja lebdečih plavin na nivoju rečnega odseka.
Figure 1. Suspended sediment transport dynamics on the level of a river reach.

Vzdolž vseh poti je prisotna velika prostorska in časovna spremenljivost premeščanja. V nadaljevanju sledi opis posameznih elementov dinamike premeščanja sedimentov (erozijskega procesa) na nivoju odseka vodotoka.

2.2.1 Erozija tal

Gledano s hidrološkega vidika pojmujemo površinsko spiranje in odplavljanje zemljin zaradi delovanja tekoče vode erozija tal (Laubel, 2004). To lahko nadalje glede na razvoj erozijskega procesa delimo na ploskovno erozijo, žlebično, medžlebično ter jarkovno erozijo. Ploskovna erozija je bolj ali manj enakomerno razporejena na površju tal in povzroča spiranje (sproščanje in začetno premeščanje) delcev zemljin in zemljinskih agregatov po površju. Žlebična erozija se pojavi, ko pride do koncentriranja površinskega odtoka vode. Rezultat tega je tvorba žlebičev. Razvoj žlebičev je odvisen od potencialnega sproščanja, premestitvene

High spatial and temporal unsteadiness is present along all the paths of transport. In the continuation, a description of individual elements of the sediment transport (erosion process) on the level of a river reach is given.

2.2.1 Soil erosion

Looking from a hydrological point of view, surface flushing and washing of the soil due to runoff water is called soil erosion (Laubel, 2004). Regarding the evolution of the erosion process, soil erosion can be further divided into processes of sheet erosion, rill erosion, interrill erosion and gully erosion. Sheet erosion is more or less evenly distributed on the soil surface and causes washing (detachment and initial transport) of soil particles and soil aggregates. Rill erosion occurs when the surface rainfall runoff concentrates which results in the formation of rills. The development of rills depends on the potential detachment of soil particles, sediment zmogljivosti, dejanskega premeščanja, koncentriranosti površinskega odtoka in medsebojnega ravnotežja teh procesov (Hahn *et al.*, 1994). Večji del erozije v medžlebičnem prostoru (medžlebična erozija) je posledica pljuskov dežnih kapljic. Jarkovna erozija se pojavlja z nadaljnjim stekanjem površinskega odtoka vode. Pomembna razlika med jarkovno in žlebično erozijo je poleg samih dimenzij jarkov v primerjavi z žlebiči (morfoloških karakteristik) tudi različen vpliv erozijske moči dežnih kapljic. Pri jarkovni eroziji je vpliv pljuskov dežnih praktično zanemarljiv, pomemben element premeščanja pa postane sediment, ki se nahaja pod površjem tal odvisno od globine erozijskih jarkov (Collison, 1996). Količinska razmerja med sproščenimi in dejansko premeščenimi sedimenti z omenjenimi erozijskimi procesi so lahko zelo spremenljiva (Richards, 1993; Prossed in Dietrich, 1995).

Vse omenjene oblike erozije tal lahko zaradi površinskega odtoka vode nastopajo ločeno, v večini primerov pa gre za kombinacijo različnih oblik erozije tal. Pojav žlebične in jarkovne erozije je močno vezan na zadostno dolžino pobočja, ki vpliva na stopnjo koncentriranosti površinskega odtoka vode. Dominantno sosledje razvoja procesov erozije tal navzdol po pobočju je torej: ploskovna → žlebična + medžlebična → jarkovna erozija.

2.2.2 Podpovršinsko spiranje in premeščanje

Analiza premeščanja drobnih delcev zemljin skozi različne plasti talnih horizontov pod vplivom pronicajoče vode je bila tradicionalno deležna manjše pozornosti, saj so procesi površinskega spiranja veliko intenzivnejši. Nekatere študije kažejo, da je delež naravnega podpovršinskega spiranja in premeščanja delcev zemljin manj kot 1 % skupne količine premeščenega sedimenta (Grant *et al.*, 1996). Pri podpovršinskem premeščanju skozi talne horizonte se s pronicajočo vodo transportirajo najdrobnejši delci zemljin in razni raztopljeni minerali v ionski obliki, ki jih štejemo med skupne raztopljene snovi v vodi (TDS – Total Dissolved Solids).

carrying capacity, sediment load, concentration of the runoff and interacting equilibrium of the processes (Hahn *et al.*, 1994). The majority of the erosion in the interrill space (interrill erosion) is a consequence of raindrop impact upon the soil. Gully erosion appears due to further concourse of rainfall runoff. Besides the differences in the dimension of rills and gullies (morphological characteristics), an important distinction arises from the influence of raindrop impacts. The splashing of the raindrops can be neglected in the case of gully erosion. Depending on the depth of gullies, an important element of the erosion becomes sediment detachment in the soil subsurface layers (Collison, 1996). The variableness of quantity ratios between detached and transported sediments by these soil erosion processes can be substantial (Richards, 1993; Prossed & Dietrich, 1995).

The emergence of the soil erosion processes can appear separately but the combination and interactions of all these forms of soil erosion is more likely. The phenomenon of rill and gully erosion depends mainly on the sufficient length of the slope which influences the degree of the concentration of surface rainfall runoff. The dominant sequence of the processes further downslope is: sheet erosion → rill + interrill erosion → gully erosion.

2.2.2 Subsurface washing and transport

Analysis of transport of fine soil particles through different soil horizons due to percolation of water was traditionally not given much attention because surface soil erosion processes are much more intensive. Some studies show that the proportion of natural subsurface washing and transport through soil horizons reaches less than 1 % of total sediment load (Grant *et al.*, 1996). Subsurface transport causes the displacement of the finest soil particles and dissolved soil minerals in ionic form (these are referred to as TDS – Total Dissolved Solids) with percolating water.

When subsurface drainage systems are installed, which accelerate the detachment and mobilization of soil particles and dissolved

Pri vgradnji drenažnih sistemov lahko postane podpovršinsko premeščanje s pospešeno mobilizacijo delcev zemljin skozi horizonte tal nezanemarljiv element določanja bilance premeščenih plavin in identifikacije virov plavin v vodotoku. Drenažni sistem lahko predstavlja neposredno povezavo med viri plavin ter strugo vodotoka. Modifikacije v strukturiranosti tal (prisotnost makropor) izboljša mobilnost delcev, saj je v večjih medzrnskih prostorih sposobnost adsorbcije, sedimentacije in sejanja delcev, ki se premeščajo z izcejanjem vode, manjša (Armstrong in Harris, 1996). Makropore pripomorejo k hitrejši infiltraciji padavinske vode v tla ter premeščanju mobiliziranih finih delce skozi mikropore v globlje plasti tal. Ko govorimo o procesih premeščanja sedimentov skozi makropore se pogosto uporablja izraz »interna erozija«. Izraz identificira proces, ko se lahko znotraj makropor v talnih horizontih, ki segajo globje, pojavljajo procesi erodiranja tal (Grant *et al*., 1996).

2.2.3 Erozija brežin vodotoka

Erozija brežin vodotoka lahko v rečno mrežo prispeva izdatno količino lebdečih plavin. Suspendirane snovi, ki se sproščajo s spodjedanjem brežin strug z erozijskim delovanjem vodnega toka, lahko predstavljajo tudi 50 % vseh lebdečih plavin, ki se sproščajo na določenem prispevnem območju vodotoka (Hahn *et al*., 1994). Ocenjene stopnje (intenzivnosti) erodiranja brežin se tako gibljejo od 0.01 m/leto do 1000 m/leto (Dietrich *et al*., 1992). Ocena povprečne stopnje erozije brežin na izbranem odseku vodotoka je zaradi tega zahtevna. Bilanco lebdečih plavin znotraj odseka brežine lahko zapišemo kot (Laubel, 2004):

solids with draining water, the subsurface transport could become an unnegligible element of the determination of the sediment transport balance and identification of the sources of the suspended load in the watercourse channel. Drainage systems (i.e. from agricultural areas) can represent the direct link between the sediment source areas and watercourse channel. Modification of the soil structure (presence of macropores) improves the mobility of the particles transported by percolating water owing to the diminished adsorption, sedimentation and sowing capacity of the larger intergranular spaces (Armstrong & Harris, 1996). The macropores improve the rainfall infiltration capacity of the soil and transport of mobilized fine soil particles into deeper soil layers. When talking about the process of the transport of fine sediment particles through macropores, the term “internal erosion” is often used. The term identifies the process when soil erosion can occur inside the macropores in the deeper soil horizons (Grant *et al*., 1996).

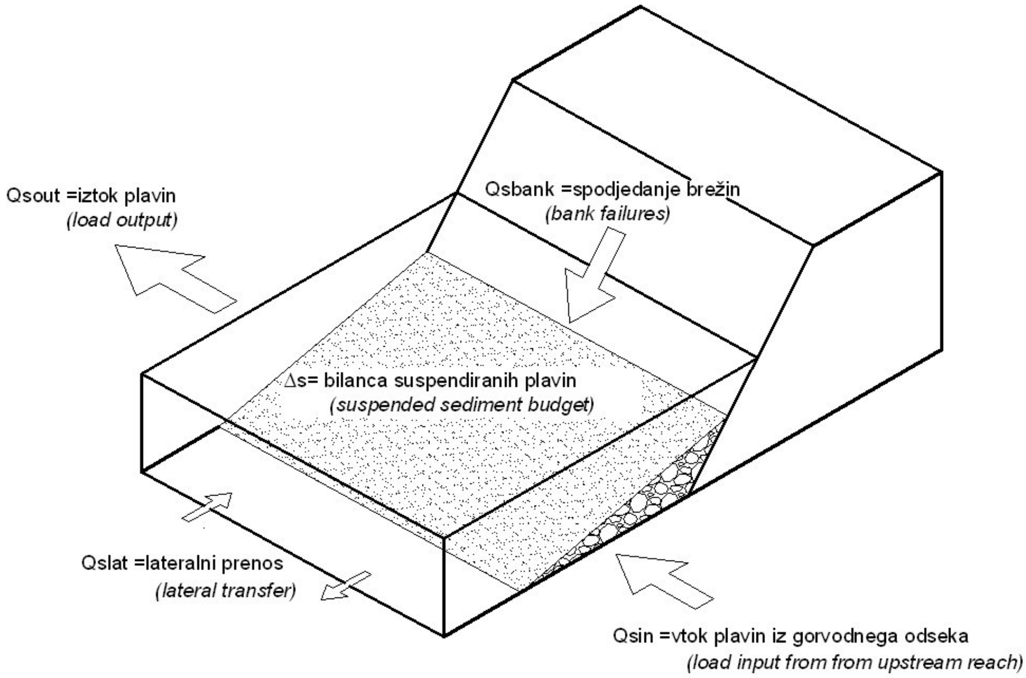
2.2.3 Bank erosion

Bank erosion can contribute a significant amount of suspended load to the fluvial system. Suspended load detached from the banks by water current undercutting can represent more than 50 % of all suspended load that is transported from certain river basin (Hahn *et al*., 1994). The evaluation of the degree (intensity) of the bank erosion varies from 0.01 m/year to 1000 m/year (Dietrich *et al*., 1992). Evaluating the average degree of the bank erosion is therefore difficult. The suspended sediment budget in the watercourse bank section can be expressed as (Laubel, 2004):

$$\Delta s = Qs_{in} - Qs_{out} \pm Qs_{lat} + Qs_{bank} \tag{1}$$

kjer je Δs bilanca lebdečih plavin, Qs_{in} je vtok lebdečih plavin, Qs_{out} je iztok lebdečih plavin, Qs_{bank} je sproščanje lebdečih plavin z brežin, Qs_{lat} pa lateralni prenos lebdečih plavin (slika 2).

where Δs is suspended load budget (sediment storage), Qs_{in} is load input from upstream reach, Qs_{out} is load output downstream, Qs_{bank} is wash of suspended load from the banks, and Qs_{lat} is lateral transfer of suspended load (Figure 2).



Slika 2: Bilanca lebdečih plavin znotraj odseka brežine vodotoka.
Figure 2: Suspended load budget inside the watercourse bank section.

Procese erodiranja brežin strug vodotokov lahko razdelimo v tri osnovne skupine (Lawler, 1992):

1. Procesi, katerih posledica je razrahljanje povezav med delci zemljine v brežini.
2. Neposredno erozivno delovanje vodnega toka.
3. Masna gibanja in masne izgube.

Procesi erozivnega delovanja vodnega toka in razrahljanja povezav med delci v zemljini so prevladujoči v vodotokih manjših velikostnih razredov oz. povirnih delih vodotokov, medtem ko se v dolvodnih odsekih vodotokov oz. večjih vodotokih pogosteje pojavljajo procesi večjih masnih gibanj in masnih izgub. Najpomembnejši dejavniki, ki vplivajo na intenzivnost erozijskih procesov na brežinah, so predvsem naslednji (Schiechtl in Stern, 1997):

1. Lastnosti vodnega toka (razporeditev pretočnih hitrosti v prečnem prerezu).
2. Sestava materiala v brežini (sosledje plasti materiala v talnem profilu).
3. Podnebne razmere (količina in razporeditev padavin).
4. Vlažnostne razmere v tleh.
5. Morfologija struge vodotoka (razmerje med širino in globino struge).

The processes of the watercourse bank erosion can be classified into tree basic groups (Lawler, 1992):

1. Weakening processes that cause the loosening of the connections between bank soils particles.
2. Direct fluid entrainment.
3. Mass failures.

The prevalence of the processes of the direct fluid entrainment and the weakening processes in the bank soil was observed in small streams, e.g. in the uppermost stream reaches. In larger rivers, e.g. in the downstream river sections, the processes of larger mass failures occur more often. The most important factors influencing the intensity of the bank erosion processes are (Schiechtl & Stern, 1997):

1. Properties of the water current (distribution of water velocity in the cross section).
2. Composition of the bank material (sequence of bank material layers).
3. Climate (quantity and distribution of precipitation).
4. Soil moisture.
5. Morphology of watercourse channel (width/depth ratio).
6. Vegetation cover of the watercourse bank.

6. Prisotnost vegetacije na brežini.
7. Antropogeni vplivi.

Hooke (1980) je analiziral prostorsko spremenljivost erozije brežin. Rezultati kažejo, da je prostorska spremenljivost erozijskih pojavov na brežinah strug v 73 % primerov odvisna od sedmih poglavitnih spremenljivk: velikosti prispevnega območja, razmerja med deležem glineni in meljastih delcev, prisotnosti prodnatega sloja, razmerja med širino in globino struge, polmera rečnega zavoja, padca dna struge in višine brežin.

Lawler (1995) izpostavlja vpliv magnitude, časovne in prostorske razporeditve pretokov v vodotoku na pojav erozijskih procesov na brežinah. Poudarjena je povezava med pojavnostjo treh osnovnih skupin procesov erodiranja brežin in spremenljivostjo moči vodnega toka, geometrijo ter sestavo materiala v brežinah.

Fluviomorfološki klasifikacijski sistem (Rosgen, 1996) v svojem t. i. tretjem nivoju ocene razmer znotraj rečnega odseka (the Level III stream reach condition assessment) predstavlja orodje za pridobitev kvantitativnih ocen erozije brežin za primerljive odseke (tipe) vodotokov. V sistem sta vključena faktor potencialne erozije brežin (BEP – Bank Erosion Potential ratings) in faktor za oceno strižne napetosti ob brežini (NBS – Near Bank Stress estimates). Rosgen (1996) podaja vrednost R^2 med 0,87 in 0,93, ko je primerjal dve vzorčni območji glede na pripadajoči vrednosti faktorjev BEP in NBS za oceno stopnje erozije brežin ter dejanskimi meritvami erozije brežin. Harmel *et al*. (1999) je po drugi strani ugotovil slabo ujemanje faktorjev BEP in NBS z dejanskimi stopnjami erozije brežin na 36 izbranih odsekih brežin.

3. MODELIRANJE DINAMIKE PREMEŠČANJA SUSPENDIRANIH SNOVI

Zaradi kompleksnosti dinamike transporta suspendiranih snovi se je procesno utemeljeno modeliranje, ki bi vključevalo procese sproščanja, premeščanja in odlaganja, pojavilo veliko kasneje kot empirični modeli za ocenjevanje skupnih količin sproščenih

7. Anthropogenic influences.

Hooke (1980) analyzed the spatial variability of the bank erosion. The results show that in 73 % of study cases, the spatial variability of the bank erosion depends on seven main variables: size of the catchment area, ratio between clayey and loamy particles in the bank material, presence of the gravel layer, radius of the watercourse bend, slope of the watercourse channel and height of the banks.

Lawler (1995) has stressed the influence of the magnitude, temporal and spatial distribution of discharges in the watercourse on the phenomenon of bank erosion processes. The stress is on the interconnectivity between the occurrence of three basic classes of bank erosion and the water flow strength variability, geometry and the structure of the bank material.

The fluviomorphological classification system (Rosgen, 1996) in the third level of stream reach condition assessment represents a tool for acquiring a quantitative assessment of bank erosion for comparable reaches (types) of rivers. The system includes the BEP factor (Bank Erosion Potential ratings) and factor for the assessment of the shear stress on the bank (NBS – Near Bank Stress estimates). Rosgen (1996) gives values of R^2 between 0.87 to 0.93 when comparing two sample study sites regarding their values of BEP and NBS factors for the assessment of the bank erosion rates and measured bank erosion. On the other hand, Harmel *et al*. (1999) discovered a much worse agreement between the BEP and NBS factors and the actual measured degree of bank erosion on 36 studied watercourse sections.

3. MODELLING TRANSPORT DYNAMICS OF SUSPENDED MATTER

Due to complexity of the suspended matter transport dynamics, the process based modeling, which would include the processes of detachment, transport and deposition, occurred much later than the empirical models for the assessment of total quantity of sedimentov z določenega območja. Procesno utemeljeni modeli se večinoma uporabljajo za oceno erozijskih procesov na mikro nivojih (območja velikosti od nekaj m^2 do nekaj 10 m^2) na posebej pripravljenih merilnih poljih, rezultate pa se ekstrapolira na večje površine.

Za potrebe modeliranja transporta lebdečih plavin na nivoju porečja se procese najpogosteje razdeli na tiste, ki se odvijajo na prispevnih površinah, ter procese, ki se odvijajo v rečni strugi. Nekateri pristopi k modeliranju posameznih elementov premeščanja lebdečih plavin so predstavljeni v nadaljevanju.

3.1 MODELIRANJE SPROŠČANJA SUSPENDIRANIH SEDIMENTOV ZARADI UDARCEV DEŽNIH KAPLJIC

Udarci dežnih kapljic razrahljajo in prekinejo kohezivne vezi med delci zemljine in jih na ta način naredijo mobilne. Osnovni dejavniki, ki vplivajo na efektivnost udarcev dežnih kapljic, so značilnosti dežja, značilnosti zemljine, pokrovnost tal ter globina vode na površju tal (Hairsine *et al*., 1999). Številne teoretične in empirične raziskave so prispevale k razvoju enačb, s katerimi skušamo opisati vpliv udarcev dežnih kapljic na sproščanje suspendiranih sedimentov. Elementi, ki se najpogosteje vključeni v enačbe, so intenziteta dežja, kinetična energija dežja ter gibalna količina dežnih kapljic. Teoretična raziskava, ki sta jo izvedla Styczen in Hogh-Schmidt (Wicks in Bathurst, 1996), je stopnjo sproščanja lebdečih plavin povezala z vsoto kvadratov gibalne količine dežja v času padavinskega pojava. Za izračun te vsote je treba poznati porazdelitev velikosti dežnih kapljic, intenziteto dežja ter hitrost, pri kateri dežne kapljice udarjajo ob tla. Zahtevani podatki, predvsem o porazdelitvi dežnih kapljic ter hitrosti, s katero dežne kaplje udarjajo ob tla, so le redko na voljo. Poenostavljeni zapis enačbe za izračun kvadrata gibalne količine dežja ima obliko (Wicks in Bathurst, 1996):

transported sediments from the catchment. Process based models are mainly used to assess the erosion processes on the micro-scale (areas of few m^2 to few 10 m^2) on specially prepared measuring fields; the results obtained on the measuring fields are then extrapolated to larger areas.

For the purpose of modeling the suspended load transport on the scale of the river basin, the processes are divided into processes which take place in the river basin and those inside the watercourse channel. Some of the approaches to the modeling of the elements of suspended load transport are discussed bellow.

3.1 MODELLING THE SUSPENDED SEDIMENT DETACHMENT BY RAINDROP IMPACT

Raindrop impacts loosen and break the cohesive bonds between soil particles. The soil particles become mobile. The main factors influencing the efficacy of the raindrop impacts are the characteristics of rain, soil characteristics, soil cover and thickness of water layer on the soil surface (Hairsine *et al*., 1999). Many theoretical and empirical researches contributed to the development of the equations which try to describe the raindrop impact on the suspended sediment detachment. The elements that are often included in the equations are rainfall intensity, kinetic energy and rainfall momentum. Theoretical research by Styczen and Hogh-Schmidt (Wicks & Bathurst, 1996) linked together the degree of the suspended sediment detachment and the sum of the total rainfall momentum squared through the rainfall event. For the computation of this sum, the distribution of the raindrop size through the rainfall event, rainfall intensity, and velocity at which raindrops hit the ground should be known. It is very unlikely that the distribution of the raindrops through the rainfall event and the velocity at which raindrops hit the ground is known. The simplified equation for the total rainfall momentum squared computation has a form (Wicks & Bathurst, 1996):

$$M_R = \alpha \cdot I^{\beta} \tag{2}$$

kjer je M_R kvadrirana gibalna količina dežja na enoto površine v [(kgm/s)^{2}m^{-2}s^{-1}], I je intenziteta dežja [mm/h], α in β sta brezdimenzijska koeficienta, ki sta podana tabelarično v odvisnosti od intenzitete dežja. Vpliv značilnosti zemljine na stopnjo sproščanja suspendiranih sedimentov zaradi udarcev dežnih kapljic se poizkuša ovrednotiti z zrnavostno sestavo zemljine, vsebnostjo glinenih delcev v zemljini, strižnimi značilnostmi zemljine ter koherentnost zemljinskih agregatov. Do sedaj ugotovljene povezave med stopnjo sproščanja suspendiranih sedimentov in značilnostmi zemljine ne omogočajo splošne kvantifikacije pojava (Hairsine *et al*., 1999).

Zelo pomembna je pravilna opredelitev vpliva pokrovnosti tal na sproščanje suspendiranih sedimentov. Ponavadi se pokrovnost tal pri modeliranju upošteva z raznimi empiričnimi redukcijskimi faktorji kinetične energije dežja. Z vidika modeliranja je posebej zanimiv vpliv višje vegetacije. Visoka vegetacija prestreza dežne kaplje, padavinska voda se koncentrira na listih ter v obliki večjih kapljic pada proti tlom (ang. »leaf drip«). Takšna kaplja pa ima poleg velikosti povsem spremenjeno kinetično energijo. Vpliv udarcev kapljic, ki padajo z listov dreves, na intenziteto sproščanja suspendiranih sedimentov je lahko celo večji, kot je sproščanje zaradi neposrednih udarcev dežnih kapljic. Dejavniki, s katerimi opredelimo vpliv kapljanja dežja z višje vegetacije, so (Dissmeyer in Foster, 1984): povprečna višina, s katere prestrežene dežne kaplje padajo proti tlom, delež pokritosti tal z visoko vegetacijo in stopnja dreniranja vegetacijskega pokrova, s katero opredelimo delež prestreženih padavin, ki dejansko dosežejo tla. Kvadrat gibalne količine dežnih kapljic, ki so rezultat prestrezanja, se določa z naslednjo enačbo (Wicks in Bathurst, 1996):

where M_R is the total rainfall momentum squared on the unit of surface in [(kgm/s)^{2}m^{-2}s^{-1}], I is rainfall intensity [mm/h], α in β are dimensionless coefficients which are defined in subordination to the rainfall intensity and are given in tables. The influence of the soil characteristics on the degree of the suspended sediment detachment owing to the raindrop impact is described by the soil texture, containment of clay particles in the soil, soil shear characteristics and coherence of soil aggregates. So far, however, the established relationships linking the degree of soil detachment by raindrop to soil properties have defied the general quantification of the phenomena (Hairsine *et al*., 1999).

Proper characterisation of the influence of ground cover on the suspended sediment detachment is very important. The ground cover is usually considered by different empirical reduction factors of the rainfall kinetic energy. From the perspective of the modelling, the influence of tall vegetation cover is of special interest. The tall vegetation intercepts the raindrops, the rainfall concentrates on leafs and falls on the ground in the form of larger drops. The process is called "leaf drip". Besides their modified size, these raindrops also have completely changed kinetic energy. The influence of the impact of these modified raindrops on the suspended sediment detachment can be even greater than the sediment detachment caused by direct raindrop impacts. The factors used to describe the leaf drip effect are (Dissmeyer & Foster, 1984): the average height from which the intercepted raindrops fall on the ground, portion of the soil covered by taller vegetation and the degree of the vegetation cover drainage which serves to define the proportion of the intercepted rainfall that actually reaches the ground. The rainfall momentum squared of the intercepted raindrops is described by equation (Wicks & Bathurst, 1996):

$$M_D = \frac{\left(\frac{V \cdot \rho \cdot \pi \cdot D^3}{6}\right)^2 \cdot DRIP\% \cdot DRAIN}{\left(\frac{\pi \cdot D^3}{6}\right)}, \quad (3)$$

kjer je M_D kvadrat gibalne količine dežnih kapljic, ki padajo proti tlom z višje vegetacije (dreves) v [(kgm/s)^{2}m^{-2}s^{-1}], V je hitrost dežnih kapljic, ki padajo z dreves v [m/s], ρ je gostota vode v [kg/m^3], D je premer dežnih kapljic, ki padajo proti tlom z višje vegetacije v [m], (tipično naj bi bil premer dežnih kapljic 5–6 mm), *DRIP%* je delež padavinskega odtoka, ki odteka z vegetacijskega pokrova kot kapljanje, *DRAIN* pa je hitrost odvajanja padavinske vode skozi vegetacijski pokrov v [m/s].

Debelina plasti površinskega padavinskega odtoka ima prav tako pomemben vpliv na stopnjo sproščanja suspendiranih sedimentov. Pogosto se opredeli t. i. kritična globina, ki izniči vplive udarcev dežnih kapljic ob tla. V modelih se opredeli redukcijski faktor vpliva udarcev dežnih kapljic ob tla, ki jih absorbira plast padavinskega odtoka. Opredelitev redukcijskega faktorja mora poleg globine (debeline) plasti površinskega odtoka vode upoštevati tudi velikost dežnih kapljic. Redukcijski faktor se določi na naslednji način (Knighton, 1998):

where M_D represents the rainfall momentum squared of the intercepted raindrops in [(kgm/s)^{2}m^{-2}s^{-1}], V is the velocity of the intercepted raindrops in [m/s], ρ is density of water in [kg/m^3], D is diameter of the intercepted raindrops in [m], (typically the raindrop diameter is 5 to 6 mm), *DRIP%* is the proportion of the rainfall which drains from the vegetation cover as leaf drip; *DRAIN* is the velocity of rainfall drainage through canopy [m/s].

The thickness of the surface rainfall runoff layer has also an important impact on the detachment rate of suspended sediments. The critical depth of the surface runoff that eliminates the influence of the raindrop impact is usually defined. In models, this is described by the reduction factor of the raindrop impact which is absorbed by surface layer of the rainfall runoff. Beside the thickness of the surface runoff layer, the definition of the reduction factor should also consider the size of the raindrops. The reduction factor is defined as (Knighton, 1998):

$$F_w = \exp((1 - h / D_m); \quad \mathrm{h} > \mathrm{D_m} \tag{4}$$

$$F_w = 1; \quad \mathrm{h} < \mathrm{D_m}, \tag{5}$$

kjer je F_w redukcijski faktor, h je globina oz. debelina plasti površinskega odtoka v [m] in D_m srednji premer dežnih kapljic v [m].

Izvedene so bile številne študije, katerih cilj je bil ugotoviti povezavo med velikostjo dežnih kapljic in intenziteto padavin. Ena od razvitih empiričnih povezav, ki sta jo razvila Laws in Parson (Wicks in Bathurst, 1996), ima obliko:

where F_w is water depth correction factor, h is depth or thickness of the surface rainfall runoff layer in [m], and D_m is median raindrop diameter in [m].

Numerous studies aimed to ascertain the connection between the size of the raindrops and the intensity of the rainfall. One of the empirical linkages was developed by Laws and Parson (Wicks in Bathurst, 1996). It has a form:

$$D_m = 0.00124 \cdot I^{0.182}, \tag{6}$$

kjer je D_m srednji premer dežnih kapljic v [mm] in I intenziteta padavin v [mm/h].

Kombinacijo vplivov opisanih procesov na stopnjo sproščanja sedimentov pod vplivom udarcev dežnih kapljic zapišemo z naslednjo enačbo (Wicks in Bathurst, 1996):

where D_m represents median diameter of the raindrops in [mm] and I is rainfall intensity in [mm/h].

A combination of described influences on the degree of the suspended sediment detachment can be described by the equation bellow (Wicks & Bathurst, 1996):

$$D_R = k_r \cdot F_w \cdot (1 - C_G) \cdot [(1 - C_C) \cdot M_R + M_D], \tag{7}$$

kjer je D_R sproščanje zemljine pod vplivom udarcev dežnih kapljic v [kg/m^{2}s], k_r je koeficient erodibilnosti zemljine zaradi udarcev dežnih kapljic v [J^{-1}], F_w redukcijski faktor zaradi površinskega padavinskega odtoka, C_G je delež površine tal pokrit z nizko vegetacijo (trave, zelišča, nizko grmičevje), C_C je delež površine tal pokrit z visoko vegetacijo (višje grmičevje, drevesa), M_R kvadrirana gibalna količina dežja v [(kgm/s)^{2}m^{-2}s^{-1}] in M_D kvadrat gibalne količine dežnih kapljic, ki padajo proti tlom z višje vegetacije (dreves) v [(kgm/s)^{2}m^{-2}s^{-1}].

where D_R is suspended sediment detachment by the raindrop impact in [kg/m^{2}s], k_r is coefficient of soil erodibility due to raindrop impact in [J^{-1}], F_w is correction factor for the surface rainfall runoff, C_G is portion of the land surface covered by low vegetation (grass, herbs, moderate bushes), C_C is portion of the land surface covered by tall vegetation (tall bushes, trees), M_R is total rainfall momentum squared in [(kgm/s)^{2}m^{-2}s^{-1}], and M_D represents the rainfall momentum squared of the intercepted raindrops which fall on the ground from higher vegetation in [(kgm/s)^{2}m^{-2}s^{-1}].

3.2 MODELIRANJE SPROŠČANJA SUSPENDIRANIH SEDIMENTOV ZARADI POVRŠINSKEGA ODTOKA

Površinski padavinski odtok razrahlja vezi med delci zemljine s strižnimi silami, ki delujejo na površino tal. Ključni element pri tem je prostorska variabilnost, ki je pogojena s stopnjo koncentriranja padavinskega odtoka ter pojavnostjo ploskovnega spiranja, žlebične, medžlebične ter jarkovne erozije. Poenostavljeno lahko procese sproščanja zemljine zaradi površinskega odtoka opišemo z naslednjo enačbo (Knighton, 1998):

3.2 MODELLING THE SUSPENDED SEDIMENT DETACHMENT BY SURFACE RAINFALL RUNOFF

Surface rainfall runoff (overland flow) weakens the bonds between soil particles by shear forces acting on the soil surface. The key element in this is spatial variability which depends on the degree of concentration of the rainfall runoff and related processes of sheet erosion, rill, interrill and gully erosion. The following simple description of the processes of the suspended sediment detachment due to surface rainfall runoff can be used (Knighton, 1998):

$$D_F = k_f \cdot \left(\frac{\tau}{\tau_c} - 1 \right); \ \tau > \tau_c \tag{8}$$

$$D_F = 0; \ \tau \le \tau_c, \tag{9}$$

kjer je D_F sproščanje zemljine zaradi površinskega padavinskega odtoka v [kg/m^{2}s], k_f je koeficient erodibilnosti zemljine zaradi površinskega padavinskega odtoka v [kg/m^{2}s], τ_c je kritična strižna napetost določena iz prirejenega Shieldsove krivulje v [N/m^2] in τ je strižna napetost, ki jo povzroči površinski padavinski odtok v [N/m^2]. Vrednost koeficienta erodibilnosti k_f je določena eksperimentalno za različne tipe zemljin.

where D_F is suspended sediment detachment by overland flow in [kg/m^{2}s], k_f is overland flow soil erodibility coefficient in [kg/m^{2}s], τ_c is critical shear stress defined from adapted Shields curve in [N/m^2] and τ is shear stress caused by surface rainfall runoff in [N/m^2]. The value of the overland flow soil erodibility coefficient k_f is defined experimentally for different soil types.

3.3 MODELIRANJE PREMEŠČANJA LEBDEČIH PLAVIN S PADAVINSKIM POVRŠINSKIM ODTOKOM

Modeliranje premeščanja lebdečih plavin po pobočju mora upoštevati prostorsko in časovno spremenljivost. V procesno utemeljenih modelih erozije tal se premeščanje plavin po pobočju simulira s primerjavo lokalne premestitvene zmogljivosti površinskega odtoka, količine sedimentov, ki so razpoložljivi oz. dotekajo z višjih območij pobočja, ter lokalne erozije. Za opis procesa se uporabljajo dvodimenzijske parcialne diferencialne enačbe, s katerimi upoštevamo zakon o ohranitvi mase sedimentov (Knighton, 1998):

3.3 MODELLING SUSPENDED LOAD TRANSPORT BY SURFACE RAINFALL RUNOFF

Modelling of the suspended load transport by surface rainfall runoff downslope must consider the spatial and temporal variability. Process based soil erosion models simulate the process through the comparison of local suspended load transport capacity of surface runoff, quantity of sediments available from upslope areas as upstream supply and local erosion. For the description of the process two dimensional partial differential equations for the conservation of suspended sediment mass are used (Knighton, 1998):

$$\frac{\partial(h \cdot c)}{\partial t} + (1-\lambda)\cdot\frac{\partial z}{\partial t} + \frac{\partial g_x}{\partial x} + \frac{\partial g_y}{\partial y} = 0\,, \qquad (10)$$

kjer je h globina površinskega padavinskega odtoka v [m], c je koncentracija sedimentov v [m^3/m^3], λ je poroznost površja tal, z je višinska razlika [m], t je časovni korak v [s], g_x je količina plavin premeščena v smeri x v [m^3/sm] in g_y je količina plavin premeščena v smeri y v [m^3/sm]. Enačbo se v modelih običajno aplicira na določene prostorske podenote. Prostorske razsežnosti teh podenot v x- in y-smeri so odvisne od morfoloških značilnosti površja.

Skupno premeščanje s skupka posameznih podenot površja tal se v nadaljnji fazi preračunava z uporabo različnih algoritmov, ki omogočajo opredeljevanje smeri premeščanja navzdol po pobočju na podlagi morfoloških značilnosti površja. Poglavitni problem pri tovrstnem pristopu k modeliranju premeščanja suspendiranih snovi predstavlja natančnost opisa morfoloških nepravilnosti (npr. lokalna depresijska območja), ki znatno vplivajo na dinamiko premeščanja. Opisani pristopi k modeliranju procesov sproščanja in premeščanja lebdečih plavin so vključeni v model SHESED, ki je eden od modulov SHE (System Hydrologique Europeen) hidrološkega modelnega sistema (Wicks in Bathurst, 1996; Weltje in Eynatten, 2004).

where h is depth of surface rainfall runoff layer in [m], c is sediment concentration in [m^3/m^3], λ is soil surface porosity, z is difference in height in [m], t is time step in [s], g_x is load transport rate in the x direction in [m^3/sm] and g_y is load transport rate in the y direction in [m^3/sm]. In models, the equation above is usually applied on pre-defined spatial sub-units. Spatial extensions of these sub-units in the x and y direction depend on the soil surface morphological characteristics.

In the next phase, total transport from the cluster of individual soil surface sub-unit is calculated by the use of different algorithms which enable definition of the direction of downslope sediment transport based on the morphological characteristics of the surface. The main problem of the described approach to downslope suspended matter transport is the accuracy of the description of morphological irregularities (for example local depression areas) which can substantially influence the transport dynamics. The described approaches to the modelling of the suspended load detachment and transport processes are included into the SHESED model, which is one of the modules of SHE (System Hydrologique Europeen) hydrological modeling system (Wicks & Bathurst, 1996; Weltje & Eynatten, 2004).

3.4 MODELIRANJE PREMEŠČANJA LEBDEČIH PLAVIN V STRUGI VODOTOKA

Količina premeščenih plavin po strugi vodotoka je rezultat dotoka plavin s prispevnih površin ter procesov sproščanja in odlaganja plavin znotraj struge. Podlaga modeliranja teh procesov so v večini primerov laboratorijske raziskave. V naravnih strugah se procesi premeščanja plavin močno zakomplicirajo, veliko modelov, razvitih v laboratorijskem okolju, pa pri dejanskih aplikacijah v naravi ne nudi uporabnih rezultatov. V nadaljevanju je na kratko predstavljen princip računanja premeščanja lebdečih plavin v vodotokih, kakršen je uporabljen v modelih HEC 6, GSTARS 2.0 in STAND. V modelih so med lebdeče plavine uvrščeni drobni peski, melji in gline. Transport posameznega zrnavostnega razreda lebdečih plavin opišemo z advekcijsko-disperzijsko enačbo (Zeng in Beck, 2003):

3.4 MODELLING SUSPENDED LOAD TRANSPORT IN A RIVER CHANNEL

Quantity of the transported suspended load in the river channel is the result of the suspended sediment inflow from the river basin and the processes of detachment and deposition of suspended load inside the channel. The modelling of these processes is mainly based on laboratory research. In natural channels the processes of suspended load transport become much more complex; many models developed in laboratory conditions do not offer applicable results when applied in natural rivers. In continuation, a short description of the suspended load transport principles as used in modelling systems HEC 6, GSTARS 2.0 and STAND is given. The suspended load in these models includes fine sand, silt and clay. The transport of individual suspended load grain class is described by advection-dispersion equation (Zeng & Beck, 2003):

$$\frac{\partial(AC_s)}{\partial t}+\frac{\partial(QC_s)}{\partial x}-\frac{\partial}{\partial x}\left(A\cdot E_s\cdot\frac{\partial C_s}{\partial x}\right)-A\cdot P_s=0\,, \tag{11}$$

kjer je C_s koncentracija suspendiranih snovi za posamezen zrnavostni razred v [kg/m^3], Q je pretok, E_s disperzijski koeficient za suspendirane snovi posameznega zrnavostnega razreda v [m^2/s], P_s izvor oz. ponor lebdečih plavin, ki ga določajo procesi sproščanja in odlaganje lebdečih plavin ter morfološke karakteristike struge katere upoštevamo z omočenim obodom struge A v [m]. Izvor ali ponor lebdečih plavin opredelimo na naslednji način (Zeng in Beck, 2003):

where C_s is suspended matter concentration for each class in [kg/m^3], Q is discharge in [m^3/s], E_s is suspended matter dispersion coefficient for each grain class in [m^2/s], P_s is a source or sink term of suspended load which is determined by the processes of sediment entrainment, deposition and morphological characteristics of the channel considered by the wetted perimeter A in [m]. The source or sink of suspended load is defined as (Zeng & Beck, 2003):

$$P_s=-k_{sed}\cdot\left(C_s-C_p\right), \tag{12}$$

kjer je k_{sed} koeficient, ki opisuje stopnjo oz. prirastek, s katerim se dejanska koncentracija lebdečih plavin približuje potencialni koncentraciji, C_p je premestitvena zmogljivost vodnega toka za posamezen zrnavostni razred, izražena kot koncentracija lebdečih plavin v [ppm]. Koeficient k_{sed} se nadalje opredeli kot (Zeng in Beck, 2003):

where k_{sed} is a coefficient describing the rate or increment at which the actual suspended load concentration reaches its potential concentration, C_p is transport potential of the water flow for each grain class expressed as concentration of suspended load in [ppm]. Coefficient k_{sed} is further defined as (Zeng & Beck, 2003):

$$k_{sed} = k_{sedDep}\left(\frac{l\cdot\varpi}{q}\right) \tag{13}$$

za odlaganje suspendiranih snovi in

for deposition of suspended matter, and

$$k_{sed} = k_{sedEnt}\left(\frac{q}{l\cdot\varpi}\right) \tag{14}$$

za sproščanje (vnos) suspendiranih snovi. Elementi zgornjih enačb so: k_{sedDep} je koeficient odlaganja lebdečih plavin; k_{sedEnt} je koeficient sproščanja (vnosa) lebdečih plavin; q je specifični pretok vode na širinski meter struge v [m^2/s], l je značilna dolžina med dvema zaporednima prečnima prerezoma struge v [m]; ϖ je hitrost usedanja delcev suspendirane snovi v [m/s]. Potencialno premestitveno zmogljivost vodnega toka C_p za posamezen zrnavostni razred lebdečih plavin, izraženo kot koncentracijo lebdečih plavin v [ppm], se določi po Yangovi enačbi (Yang *et al.*, 1998):

for entrainment (inflow) of suspended matter. Elements of the equation above are: k_{sedDep} is suspended load deposition coefficient, k_{sedEnt} is suspended load entrainment coefficient, q is specific discharge per unit width in [m^2/s], l is characteristic length between two consecutive channel cross sections in [m], ϖ is suspended load particle settling velocity in [m/s]. Water flow transport potential C_p for individual suspended load grain class expressed as concentration of suspended load concentration in [ppm] is determined by the Yang equation (Yang *et al.*, 1998):

$$C_p = 5.435 - 0.286\cdot\log\frac{\varpi\cdot d}{\nu} - 0.457\cdot\log\frac{U_*}{\varpi} + \left(1.799 - 0.409\cdot\log\frac{\varpi\cdot d}{\nu} - 0.314\cdot\log\frac{U_*}{\varpi}\right)\cdot\log\left(\frac{V\cdot s}{\varpi} - \frac{V_{cr}\cdot s}{\varpi}\right), \tag{15}$$

kjer je ϖ je hitrost usedanja delcev v [m/s]; d je srednja velikost posameznega zravostnega razreda v [m]; ν je kinematična viskoznost vode v [m^2/s]; U_* je strižna hitrost v [m/s]; V je hitrost vodnega toka v [m/s]; s je padec energijske črte in V_{cr} je kritična hitrost za začetek gibanja delcev lebdečih plavin v [m/s]. Enačba je primerna za račun premestitvenih zmogljivosti vodotokov, katerih pretežni del plavin (več kot 60 %) predstavljajo lebdeče snovi.

where ϖ is particle settling velocity in [m/s], d is median grain size of individual grain class in [m], ν is water kinematic viscosity in [m^2/s], V is flow velocity in [m/s], s is energy slope and V_{cr} is critical velocity for incipient motion of particles in [m/s]. The equation is useful especially for the computations of transport potential of rivers where the substantial portion of the total load (more than 60 %) represents the suspended load.

4. ZAKLJUČKI

Podrobnejša analiza dinamike premeščanja lebdečih plavin je možna le na podlagi kakovostnih podatkov, ki omogočajo vpogled v časovno in prostorsko spremenljivost koncentracije lebdečih plavin v vodotoku. Ugotavljanje poglavitnih virov ter spremljanje masne bilance lebdečih plavin na karakterističnem prispevnem območju zahteva vzpostavitev dodatnih meritev na prispevnih površinah vodotoka.

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4. CONCLUSIONS

A detailed analysis of the suspended load transport dynamics is feasible only on the basis of quality data which provide an insight into spatial and temporal suspended load concentration changeability in the rivers. The assessment of the principal sources of suspended load requires additional measurements in the river basins.

In Slovenia, the monitoring of the suspended load transport is performed by the Environmental Agency of the Republic of Slovenia (ARSO); in 2006, 13 rivers were lebdečih plavin izvaja Agencija Republike Slovenije za okolje (ARSO); v letu 2006 je bilo tako v mrežo monitoringa vključenih 13 rek (Ulaga, 2006). Dnevni odvzem vzorcev se izvaja na petih večjih rekah, na ostalih pa se odvzem opravlja v času izjemnih hidroloških dogodkov. Dosedanje analize rezultatov monitoringa premeščanja lebdečih plavin so pokazale, da se približno 70 % materiala premesti prav v obdobjih visokih voda (Ulaga, 2005). Podrobnejše študije sproščanja in premeščanja lebdečih plavin na nivoju prispevnih območij vodotokov so v Sloveniji redke. Analizo bilance lebdečih plavin vzdolž verige hidroelektrarn na reki Savi podaja Mikoš (2000). V povirnih predelih reke Soče so bili kot zelo pomemben lokalni vir suspendiranih sedimentov prepoznani pojavi masnega gibanja kot so zemeljski plazovi in drobirski tokovi, ki so se sprožili ob močnih padavinah ter podori, sproženi ob potresih (Mikoš *et al.*, 2006). Lebdeče plavine in premeščanje na njih vezanega partikularnega živega srebra po reki Idrijci in Soči do Tržaškega zaliva (Žagar *et al.*, 2004; 2006; Žibert in Gosar, 2006) je redek primer upoštevanja lebdečih plavin pri ocenjevanju ekološkega stanja vodnega okolja v Sloveniji.

Bodoče raziskave se bodo morale usmeriti v pridobivanje dolgotrajnejših nizov podatkov z večjo frekvenco vzorčevanja o dejavnikih, ki kontrolirajo procese sproščanja suspendiranih sedimentov in premeščanja lebdečih plavin vzdolž rečnega sistema (Boardman, 1996). Napredek v tej smeri predstavlja uvajanje novih merilnih naprav, ki omogočajo zvezni časovni zajem podatkov. Večina naprav za zvezno zajemanje podatkov temelji na različnih merilnih tehnikah, ki omogočajo posredno določevanje količine in zrnavosti suspendiranih sedimentov (Wren *et al.*, 2000).

Tako na primer laserski disdrometer omogoča pridobitev podatkov o velikosti in hitrosti dežnih kapljic, ključnih dveh parametrov za napovedovanje in modeliranje sproščanja suspendiranih sedimentov. Zvezne meritve koncentracij lebdečih plavin v vodotoku omogoča merilec motnosti OBS-3+ (podrobnejši opis merilne opreme na http://ksh.fgg.uni-lj.si/).

included in the monitoring network (Ulaga, 2006). Daily sampling of suspended load is carried out on 5 large rivers, other sampling is performed in the periods of extreme hydrological events. The analysis of the monitoring results of the suspended load transport accomplished so far showed that about 70 % of the material is transported during the periods of high water stages (Ulaga, 2005). In Slovenia, detailed studies of suspended load detachment and transport on the level of watersheds are rare. The analysis of the suspended load budget along the chain of hydropower plants on the Sava river is given by Mikoš (2000). In the headwater parts of the Soča river basin, mass movement processes such as rainfall-induced landslides and debris flows, as well as earthquake-induced rock falls, were identified as very important local suspended sediment sources (Mikoš *et al.*, 2006). Suspended load and transport of adsorbed particulate mercury along the Idrijca and Soča rivers into the Gulf of Trieste (Žagar *et al.*, 2004; 2006; Žibert & Gosar, 2006) is a rare example of taking into account suspended loads when estimating the ecological state of the water environment in Slovenia.

Future research should be orientated into the acquirement of longer series of data with increased frequency of data acquisition about the factors, which control the processes of suspended sediment detachment and suspended load transport along the stream network (Boardman, 1996). An advance in this direction is offered by the implementation of new measuring equipment which provides continuous data acquisition. The majority of equipment for continuous acquisition is based on different measuring techniques that enable indirect determination of quantity and granular composition of suspended sediments (Wren *et al.*, 2000).

For instance, laser disdrometer enables gathering of data on raindrop size and velocity that are the two key parameters for the prediction and modelling of suspended sediment detachment. Continuous measurements of suspended load concentrations in a stream are possible by OBS-3+ turbidimeter (detailed description of the equipment can be found at: http://ksh.fgg.uni-lj.si/).

Ob tem velja omeniti nekatere omejitve pri uporabi te merske opreme, predvsem veliko energijsko potratnost (zato akumulatorsko napajanje pogosto ne zadošča) v primeru laserskega disdrometra ter občutljivost na lokalne okoljske pogoje (svetloba, rast alg, plavje) v primeru merilca motnosti OBS-3+. Omenjeni faktorji lahko znatno omejuje avtonomnost te terenske opreme.

Na Katedri za splošno hidrotehniko UL FGG že več let uvajamo sodobne merilne tehnike na eksperimentalnih porečjih v Sloveniji. Esperimentalno porečje reke Reke ter njenega pritoka Padeža je opremljeno z laserskim disdrometrom ter dvema merilcema motnosti OBS-3+ (Brilly *et al.*, 2002; Rusjan *et al.*, 2006). Na prispevnem območju Padeža se na podlagi meritev potencialnega sproščanja suspendiranih sedimentov in njihovega premeščanja po vodotoku ocenjuje količina odloženih sedimentov v načrtovani akumulaciji, ki bo novi vir pitne vode za slovensko obalno območje.

Kakovostnejši podatki o koncentracijah lebdečih plavin v vodotokih, merjeni v posameznih hidroloških prerezih, bodo omogočili boljše razumevanje procesov v smislu kratkotrajne spremenljivosti kakovosti vode ter ekološkega stanja vodnega ekosistema.

Z vidika modeliranja dinamike premeščanja lebdečih plavin so zato gotovo najbolj zanimivi specifični “neobičajni” hidrometeorološki dogodki različnih povratnih dob.

Po drugi strani daljši časovni nizi podatkov o vsakdanjem, na prvi pogled nezanimivem dogajanju, omogočajo sledenje trendov dinamike premeščanja lebdečih plavin kot posledico človekovih aktivnosti ali širših (globalnih) okoljskih sprememb.

V večini terenskih primerov analize dinamike premeščanja lebdečih plavin na nivoju porečja ostaja skoraj nerešen problem opredelitve prostorskega merila, ki glede na značilne klimatske, hidrološke, geomorfološke razmere ali primerljivo rabo površin, še omogoča ekstrapolacijo lokalno izmerjenih podatkov.

However, this measuring equipment has some limitations, for example, the laser disdrometer has a very high energy demand (thus often battery energy is not enough); OBS-3+ turbidimeter is very sensitive to the local environmental conditions (light, algae growth, floating debris). Furthermore, suspended load concentrations are measured indirectly. All these factors can substantially diminish the autonomy of this field equipment.

At the Chair of Hydrology and Hydraulic Engineering UL FGG, we have been implementing the advanced measuring equipment for several years in the experimental watersheds in Slovenia. The experimental watershed of the Reka river and its tributary the Padež stream are equipped by a laser disdrometer and two OBS-3+ turbidimeters (Brilly *et al.*, 2002; Rusjan *et al.*, 2006). On the Padež watershed, the measurements of potential detachment of suspended sediment and its transport along the stream will be used to assess sediment deposition in the planned reservoir, foreseen as a new souce of water supply for the Slovenian coastal region.

The improved quality of the data about the suspended load concentration in streams, measured in single hydrologic cross sections, will enable a better understanding of the processes in the sense of short-term changeability of water quality and ecological state of the water ecosystem.

Thus, from the point of view of suspended sediment transport modelling, the specific “unusual” hydrometeorological events of different recurrence intervals are of special interest.

On the other hand, longer time series of data about everyday, seemingly uninteresting events, provide the tracing of the trends of suspended sediment transport dynamics as a consequence of anthropogenic activities or wider (global) environmental changes.

In the majority of field cases of analysis of the dynamics of suspended sediment transport, the problem of the definition of the spatial scale, which as to the climatic, hydrological, geomorphological conditions or land use, still enables upscaling of locally measured data, remains largely unsolved.

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