© *Acta hydrotechnica* **18/28 (2000)**, Ljubljana
ISSN 1581-0267

UDK: 551.311.2
Pregledni znanstveni prispevek

UDC: 551.311.2
Scientific paper

PROCESNO UTEMELJENO MODELIRANJE EROZIJE TAL
PROCESS BASED SOIL EROSION MODELLING

Gregor Petkovšek

Članek podaja pregled procesno utemeljenih metod za modeliranje erozije tal. V uvodu so podani zgodovina in razlogi za modeliranje erozije tal na področjih kmetijstva in gradbeništva. Nato sledi pregled procesov erozije, konceptov modeliranja in enačb. Opisani so procesi žlebične in medžlebične erozije, pljuskovna erozija, sproščanje in premeščanje površinskega toka in toka v žlebičih ter nastanek kanalskega toka. Razloženi so medsebojni vplivi med posameznimi procesi in matematična formulacija teh vplivov. V nadaljevanju so predstavljene in komentirane tradicionalne metode napovedovanja sproščanja zemljin, kot sta USLE in Gavrilovićeva enačba. V poglavju o modernih metodah pa so predstavljeni trije novejši procesno utemeljeni modeli: ameriški WEPP, nizozemski LISEM in avstralski model TOPOG. Pri vsakem je poudrajena struktura modela ter procesi, vključeni v model. Opisan je tudi namen in možnosti uporabe.

Ključne besede: *erozija tal, odplavljanje, procesno utemeljeno modeliranje, modeli s porazdeljenimi spremenljivkami.*

The paper presents an overview of process based methods for soil erosion modelling. In the introduction, the history and the reasons for soil erosion modelling in the fields of agriculture and civil engineering are given. Then an overview of erosion processes, modelling concepts and equations follow. The processes of rill and interrill erosion, splash erosion, detachment and transport capacity of overland and rill flow, and channel initiation are described. The interrelations between the processes and the corresponding mathematical formulations are explained. Further, the paper presents and comments on the traditional methods used for soil erosion prediction, such as USLE and the Gavrilović equation. Also, three recently developed process based models are presented: the American WEPP, the Hollandese LISEM and the Australian TOPOG model. The structure of the models is emphasized, as well as the processes incorporated. The aims and possible applications are described.

Key words: *soil erosion, sediment yield, process based modelling, distributed models*

1. UVOD

Zemeljsko površje je med drugim rezultat spiranja in odlaganja zemljin. V večini primerov je ta proces rezultat naravnih dejavnikov. V nekaterih primerih pa erozijo tal povzroča tudi človekova dejavnost. Najbolj značilni primeri so kmetijstvo, rudarstvo in gradbeništvo. Preučevanje erozije tal in razvoj zaščitnih ukrepov ima na področju kmetijstva že kar dolgo zgodovino. Prve empirične modele so že pred več kot 50 leti predlagali Cook (1936), Zingg (1940) in Smith (1941). Po drugi strani pa se je na področjih gradbeništva in rudarstva zanimanje za to problematiko pokazalo razmeroma pozno.

1. INTRODUCTION

The earth’s surface is greatly influenced by soil erosion and deposition. In most cases, this process is caused by natural forces. However, some human activities also contribute notably to soil erosion, namely agriculture, mining and construction. In agriculture, erosion has been studied for a relatively long time, different prediction methods have been developed and control measures proposed. The first empirical soil erosion models were proposed more than 50 years ago by Cook (1936), Zingg (1940) and Smith (1941). On the other hand, in the fields of mining and construction, this topic emerged much later.

Razlogi za to so gospodarske narave. Za lastnika kmetijskega zemljišča izguba tal pomeni izgubo hranil in produktivne zmožnosti tal, kar ga spodbuja k preprečevanju oziroma omejevanju erozijskih pojavov. V rudarstvu in pri gradbenih delih pa ni takih gospodarskih spodbud, zato je bilo treba uvesti ustrezno regulativo za preprečitev nezaželenih vplivov na okolje (Hahn et al., 1994).

Pri omenjenih dejavnostih je torej pomembno sproščanje zemljin. Za urejanje vodotokov in načrtovanje vodogradbenih ukrepov pa je pomembno odplavljanje. Iz prakse so znani zlasti primeri zaplavljanja akumulacij in posledičnega načrtovanja prodnih usedalnikov, pa tudi problem transporta polutantov, ki se premeščajo, vezani na plavine.

V tem članku s pojmom erozija tal označujem površinsko spiranje in odplavljanje tal (prsti) zaradi delovanja tekoče vode. To je običaj tudi v strokovnih (iz področja hidrologije) virih iz angleškega govornega področja, medtem ko je v slovenski literaturi ta izraz običajno rabljen širše, tako da označuje vse oblike erozije površja, kot so poleg vodne še plazna idr.

2. PROCESI SPROŠČANJA, PREMEŠČANJA IN ODPLAVLJANJA PLAVIN

2.1 DINAMIKA PROCESOV IN DEFINICIJA POJMOV

Dinamiko erodiranja zemljin na pobočjih povodja sestavljajo procesi sproščanja, premeščanja in odlaganja (Meyer & Wischmeier, 1969). Sproščanje je proces, pri katerem se delci (zrna ali agregati) ločijo od matičnih tal. Sproščanje je predvsem posledica erozijske moči dežnih kapelj in vodnega toka. Vodni tok je tudi glavni vir premeščanja zemljin po pobočju, čeprav je premeščanje deloma mogoče tudi zaradi vpliva pljuska dežnih kapelj. Zato se premeščanje pojavi šele z nastopom površinskega odtoka in se torej prej pojavi na manj prepustni podlagi z manjšo infiltracijo. Premestitvena zmogljivost vodnega toka narašča s hitrostjo. Ko se hitrost

The reasons for that are economical. In an agricultural land, soil loss represents a loss in nutrients and productive capability, which stimulates the landowner to undertake certain measures to prevent or reduce soil erosion. In mining and construction, no such economic incentive is present, and to eliminate undesirable environmental impacts, regulations had to be imposed (Hahn et al., 1994).

For the mentioned activities, soil erosion is important. For the design of hydraulic structures and river training, it is sediment delivery that matters. Reservoir sedimentation and the design of sediment retention basins are known practical problems where sediment yield, as well as the transport of pollutants attached to sediments, must be taken into account.

In this paper, the term *soil erosion* refers to the superficial soil detachment and transport caused by running water. This kind of terminology is also used in English-speaking references, while in Slovene literature, it is usually used as a generic term that also covers processes such as landslides, etc.

2. PROCESSES OF EROSION, TRANSPORT AND SEDIMENT YIELD

2.1 PROCESS DYNAMICS AND RELATED TERMINOLOGY

The soil erosion process consists of soil detachment, transport and deposition (Meyer & Wischmeier, 1969). Detachment is a process of separating the soil particles (grains or aggregates) from the ground. Detachment is caused by raindrop impact force and the shearing force of flowing water. Flowing water is also responsible for transporting soil down slope, although down slope transport can also be partially due to raindrop splash. Therefore, the transport only begins when surface runoff occurs. Consequently, transport capacity and soil erosion decrease with the infiltration rate. The transport capacity increases with the flow velocity. Moving down slope, the slope tends to decrease, flow zmanjša, običajno zaradi zmanjšanja naklona pobočja, nastopi odlaganje (Hahn et al., 1994).

Glede na to, ali se erozija pojavlja v žlebičih, ki jih izdolbe vodni tok, ali na površinah med njimi, delimo erozijski proces na žlebično in medžlebično erozijo. Značilnosti in načini posameznih procesov so opisani v naslednjih točkah.

2.2 MEDŽLEBIČNA EROZIJA

Večina erozije v medžlebičnem prostoru je pljuskovna erozija, ki se pojavlja ob pljuskih dežnih kapelj ob tla in je posledica erozijske moči dežnih kapelj. Odvisna je od intenzitete dežja *i*, kinetične energije dežnih kapelj k_e in deleža glin p_c. Nekateri avtorji upoštevajo tudi vpliv naklona pobočja *S* (npr. Hirschi & Barfield, 1988a;b). Hahn et al. (1994) navaja študije, ki kažejo odvisnost pljuskovne erozije od globine površinskega toka. Te so pokazale, da se erozija povečuje do globine vode, ki je enaka 1/6 do 1 premera dežne kaplje, nato pa se zmanjšuje. Voda na površini namreč deluje kot razprševalec kinetične energije dežnih kapelj.

Enačbe za izračun stopnje sproščanja D_i zaradi pljuskovne erozije so običajno oblike:

velocity also decreases and deposition takes place (Hahn et al., 1994).

Erosion in the catchment can be rill erosion, which occurs in the small channels, or rills, incised by the water, or interrill erosion, which occurs in the zone between the rills. The description of the different soil erosion processes is given in the next sections.

2.2 INTERRIL EROSION

In interrill areas, most of the erosion is caused by splash erosion, which is the result of raindrop impact upon the soil. The quantity of detached soil depends on the rainfall intensity *i*, the kinetic energy of the raindrops k_e and the soil clay percentage p_c. Sometimes, slope *S* is also taken into account (e.g. Hirschi & Barfield, 1988a;b). Hahn et al. (1994) gives examples of studies showing the dependence of splash erosion on ponded depth. These studies showed that splash increased up to a ponded depth of 1/6 to 1 raindrop diameter, and decreased with deeper depths. The reason for this is that the water on the surface dissipates the kinetic energy of the raindrops.

The splash erosion detachment rate D_i is usually expressed as:

$$D_i = k_r \cdot i^p \tag{1}$$

Koeficeint k_r predstavlja erodibilnost tal in je odvisen od lastnosti zemljine, pokrovnosti oziroma rabe tal in topografskih lastnosti. *i* je intenziteta dežja, *p* pa empirični koeficient, katerega vrednost je običajno približno 1 (Jayawardena & Bhuiyan, 1999). Če pa želimo s to enačbo oceniti celotno medžlebično erozijo, torej tudi del zaradi površinskega odtoka in vpliv premestitvene zmogljivosti, je vrednost *p* približno 2; primere različnih modelov navaja Hahn et al. (1994). Kinetična energija dežnih kapelj k_e v teh enačbah ne nastopa, ker jo je moč empirično izraziti iz intenzitete dežja (npr Brown & Foster, 1987).

Pljuski dežnih kapelj deloma prispevajo tudi k premeščanju delcev zemljin, kar pa seveda velja le na nagnjenem terenu. Večina premeščanja pa poteka pod vplivom

Coefficient k_r is the soil erodibility factor, which depends on the soil and cover properties, respectively, land use and topography. The symbol *i* is rainfall intensity, and *p*, the empirical coefficient whose value is usually close to 1 (Jayawardena & Bhuiyan, 1999). If this equation is used for estimating the net interrill erosion, meaning that overland flow detachment and transport capacity are also taken into account, the value of *p* is around 2; examples of different models are given by Hahn et al. (1994). The kinetic energy of raindrops does not occur in these equations, since it can be empirically expressed from rainfall intensity (e.g. Brown & Foster, 1987).

Raindrop splash also contributes to the transport of soil, which is obviously true for a sloping surface only. However, the majority of površinskega toka. Sloj površinsko odtekajoče vode je običajno tanek in rezultirajoče strižne sile ne zadoščajo za dodatno spiranje zemljin. Vendar pa je zlasti zaradi dežnih kapelj, ki povzročajo dodatno turbulenco, ta tok zmožen premeščanja.

O premestitveni zmogljivosti površinskega toka danes še ne vemo prav mnogo. Kot poudarjata Jayawardena & Bhuiyan (1999), premeščanje ni veljalo za omejitveni dejavnik medžlebične erozije, vendar navajata tudi nekatera opazovanja, ki kažejo nasprotno. Modeli za račun premestitvene zmogljivosti površinskega toka T_c so bili večinoma prevzeti iz področja premeščanja plavin v strugah. Pri teh modelih je premestitvena zmogljivost odvisna ali od pretoka vode Q, ali od strižne napetosti τ oziroma od efektivne moči toka Ω. Pomanjkljivost takega prevzemanja modelov iz drugega področja je, da so količine vode pri površinskem toku mnogo manjše kot pri toku v strugi. Poleg tega ti modeli ne upoštevajo vpliva dežja, katerega energija ima pri plitvem površinskem toku mnogo večji vpliv kot pri globljem toku v strugi.

Jayawardena & Bhuiyan (1999) sta izvedla vrsto poskusov, pri katerih sta merila tako sproščanje kot premestitveno zmogljivost. Sproščanje sta merila v skodelicah, ki sta jih vgradila v eksperimantalno pobočje, premestitveno zmogljivost pa sta preračunala z modelom iz količin erodirane zemljine, zbrane ob dnu eksperimentalnega pobočja. Ugotovila sta, da so vsi trije omenjeni načini modeliranja premestitvene zmogljivosti T_c zadovoljivi. To pomeni, da je mogoče najti zvezo T_c s katerimkoli parametrom Q, τ ali Ω ob zadovoljivem koeficientu korelacije ($R^2 > 0.90$). Vendar je pogoj za to ločitev primerov z dežjem in brez dežja; razlika v premestitveni zmogljivosti med tema dvema primeroma je reda velikosti (10x), se pa zmanjšuje s količino odtekajoče vode in s tem z globino.

transport is a result of overland flow. The film of runoff water is usually thin, and the corresponding shear stresses do not suffice for additional soil detachment. But the raindrop impact increases the turbulence in this film, which makes the overland flow capacity high enough for transport.

At present, not much is known about the transport capacity of overland flow. As stated by Jayawardena & Bhuiyan (1999), the transport was generally not considered a limiting factor for interrill erosion. They, on the other hand, cite observations showing this is not always the case. Models for the transport capacity of the overland flow T_c were usually from the field of stream flow sediment transport. These models relate the transport capacity to either water discharge Q, shear stress τ or effective unit stream power Ω. The disadvantage of simply using models developed for stream flow conditions is that discharges of flowing water can be much lower in the case of overland flow. Further, the impact of rainfall energy is much higher in a shallow overland flow than it is in a deeper stream flow.

Jayawardena & Bhuiyan (1999) carried out a set of experiments where both detachment and transport were measured. The detachment was measured by the splash cup technique. The cups were placed in the experimental tray. The transport capacity was calculated using a model from the collected samples at the lower end of experimental tray. They found that all the mentioned transport capacity T_c relationships performed well; i.e., it was possible to find a relationship between T_c and any of the three parameters Q, τ or Ω with a correlation coefficient $R^2 > 0.90$. However, the data for the case with rain and without rain was split, and the difference in the transport capacity of the two sets was in order of magnitude (10x). The difference was reduced with larger quantities of water (and, hence, depth).

2.3 ŽLEBIČNA EROZIJA

Žlebiči so pomemben element v procesu odtoka vode in plavin iz povodja. Njihova gostota, to je število žlebičev na enoto širine, je odvisna od strmine in dolžine pobočja, površinskega odtoka, teksture in erodibilnosti tal in prisotnosti oziroma odsotnosti deževij (Meyer & Monke, 1965). Na zelo erodibilnih tleh erozijo omejuje premestitvena zmogljivost, žlebiči so enake velikosti vzdolž pobočja in njihova gostota je velika (Ellison & Ellison, 1947). Na manj erodibilnih tleh pa je omejitev sproščanje, širina žlebičev se spreminja in njihova gostota je manjša.

Hahn et al. (1994) povzema, da sta Hirschi & Barfeld (1988b) izvedla analizo občutljivosti erozije glede na gostoto žlebičev z uporabo modela KYERMO. Pri njunem specifičnem testnem primeru sta ugotovila, da je sproščanje največje pri približno 6 žlebičih na širini 4.5 metrov. Zmanjšanje pri večji gostoti sta pripisala manjši količini vode v posameznem žlebiču. Hkrati sta poudarila, da so rezultati odvisni tudi od izbire uporabljenih enačb za sproščanje in strižno silo.

Razvoj žlebičev je odvisen od potencialnega sproščanja, premestitvene zmogljivosti, dejanskega premeščanja in medsebojnega ravnotežja teh procesov (Hahn et al., 1994). Podrobnosti so podane v naslednjih poglavjih.

2.3 RILL EROSION

Rills are an important element of surface runoff and the sediment delivery processes. Their density, i.e. the number of rills per unit width, depends on slope steepness and length, runoff rate, soil texture and erodibility, and the presence, or absence, of rainfall (Meyer & Monke, 1965). On highly erodible soil, the limiting factor for erosion is transport capacity; the rills have the same size along the slope and their density is high (Elison & Elison, 1947). On less erodible soil, erosion is detachment-limited, the width of rills varies along the slope, and their density is lower.

Hahn et al. (1994) cites an example of sensitivity analysis on the rill density. It was performed by Hirschi & Barfeld (1988b) using the KYERMO model. For their specific test condition, they found the maximum sediment yield at about 6 rills in 4.5 meters. They proposed that the decline in sediment yield at the higher rill density was due to a lower flow rate per rill. They also demonstrated that the results varied, depending on the rill detachment and the boundary shear stress equations used.

The development and growth of rills is governed by the rill detachment potential, transport capacity, sediment load and their interactions (Hahn et al., 1994). Details are given in the following sections.

2.4 MOŽNO SPROŠČANJE

Sproščanje zemljin v žlebičih povzroča turbulenca. Obstajata dve skupini enačb za modeliranje možne stopnje sproščanja e. V prvo skupino sodijo enačbe, ki temeljijo na povprečnih parametrih toka, kot sta strižna napetost τ_0 ali specifična moč toka ω. Primer enačbe s strižno napetostjo je (Foster, 1982):

2.4 DETACHMENT POTENTIAL

Soil detachment in rills is caused by turbulence. There are two groups of equations used for modelling the potential detachment rate e. In the first group are equations based on average flow parameters such as shear stress τ_0 or unit stream power ω. An example of such an equation is given by Foster (1982):

$$e = a \cdot (\tau_0 - \tau_{cr})^b \tag{2}$$

kjer sta a in b empirična koeficienta. Podobne so tudi enačbe, ki upoštevajo specifično moč toka ω. Ta je definirana kot (q je specifični pretok, S je padec, ρ gostota tekočine, g pa težnostni pospešek):

where a and b are empirical coefficients. Equations that contain unit stream power are of similar form. Unit stream power ω is defined as (q is unit discharge, S is slope, ρ fluid density and g gravitational acceleration):

$$\omega = \rho \cdot g \cdot q \cdot S \tag{3}$$

Drug pristop temelji na parametrih, ki opisujejo turbulentna nihanja napetosti. Primer take enačbe je (Nearing, 1991):

The second approach is based on the characteristics of intermittent turbulent flow. A relationship by Nearing (1991) is:

$$e = F \cdot P \cdot M \tag{4}$$

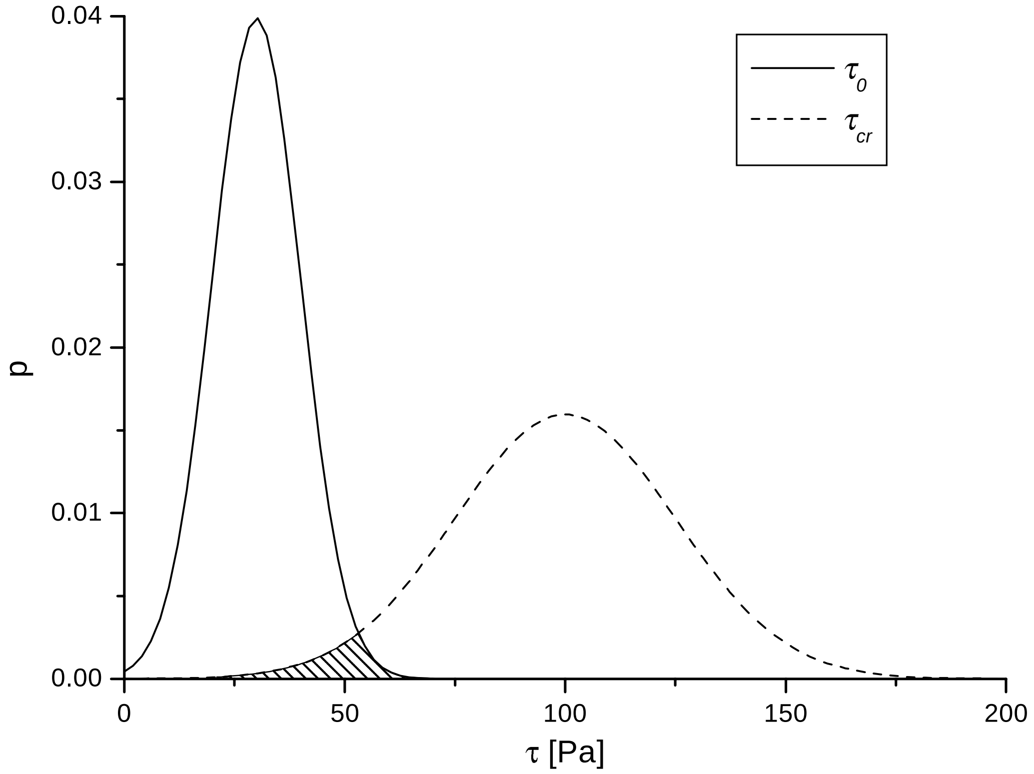
kjer je F prostorska in časovna frekvenca turbulentnih motenj, P je verjetnost, da bo izbruh motnje povzročil sprostitev delcev dna, M pa je povprečna masa zemljine, ki se ob izbruhu motnje sprosti. Enačbo lahko preoblikujemo (Nearing, 1991):

where F is the spatial and temporal frequency of turbulent bursts, P is the probability that the burst will cause a failure event and thus detachment and M is the average mass detached, per event. This equation can also be written in the following form (Nearing, 1991):

$$e = K \cdot C \cdot P \cdot h^{1/2} \cdot S^{3/2} \tag{5}$$

kjer je K empirični koeficient in C Chezyjev koeficient hrapavosti. Na sliki 1 je prikazana verjetnost sproščanja P kot presek porazdelitvenih funkcij za strižno napetost τ_o in odpornost tal τ_{cr}.

where K is the empirical coefficient and C is the Chezy roughness coefficient. Figure 1 shows the probability of detachment P as the overlapped area of soil tensile strength τ_{cr} and shear stress τ_o distribution functions.



Slika 1. Gostota verjetnostne porazdelitve za strižno napetost τ_0 in odpornost tal τ_{cr} (po Lei et al., 1998).

Figure 1. Probability density function for shear stress τ_0 *and soil tensile strength* τ_{cr} *(after Lei et al., 1998).*

2.5 PREMESTITVENA ZMOGLJIVOST

Modeliranje premestitvene zmogljivosti tudi temelji na različnih parametrih vodnega toka, kot so strižna napetost, efektivna strižna napetost, specifična moč vodnega toka in efektivna moč vodnega toka. Efektivna strižna napetost je tisti del strižne napetosti, ki je posledica hrapavosti dna (npr. Einstein & Barbarossa, 1951). Efektivna moč vodnega toka pa je definirana kot (Govers, 1990):

2.5 TRANSPORT CAPACITY

Transport capacity modelling can also be based on different flow parameters, e.g. shear stress, effective shear stress, unit stream power and effective stream power. Effective shear stress is obtained by dividing the total shear stress into an "effective" (bed roughness) and form roughness component (Einstein & Barbarossa, 1951). Effective stream power is defined as (Govers, 1990):

$$\Omega = (\omega - \omega_{cr})^{1.5} / R^{2/3} \qquad (6)$$

kjer je ω_{cr} kritična moč vodnega toka za začetek premeščanja, R pa hidravlični polmer. Nearing et al. (1997) so izvedli šest serij poskusov toka v žlebičih na dveh kmetijskih zemljiščih. Poskusi so bili izvedeni tako v laboratoriju kot na terenu, pri različnih pretokih in padcih. Merjen je bil pretok plavin q_S, a je bilo ugotovljeno, da je ta v danih razmerah blizu premestitveni zmogljivosti. Kot najustreznejši parameter za oceno premestitvene zmogljivosti T_C se je pokazala specifična moč vodnega toka ω. Koeficient korelacije med izračunanimi in merjenimi vrednostmi je bil $r^2 = 0.93$. Drugi parametri so dali slabše rezultate. Končna enačba, kjer so A, B, C in D konstante, je naslednja:

where ω_{cr} is the critical stream power (for the beginning of the transport) and R is the hydraulic radius. Nearing et al. (1997) conducted six series of rill experiments on two agricultural soils. Experiments were carried out both in laboratory and field, with quite a range of discharges and slopes. The sediment load q_S was measured, but for the given conditions it was close to the transport capacity. It was found that the best parameter for transport capacity T_C evaluation was stream power. The coefficient of determination between the predicted and measured values was $r^2 = 0.93$. Other parameters gave lower coefficients of determination. Their equation, where A, B, C and D are constants, is as follows:

$$\log(T_C) = A + B \cdot e^{C+D\cdot\log(\omega)} / (1 + e^{C+D\cdot\log(\omega)}) \qquad (7)$$

Govers (1990) pa kot najustreznejšo zvezo med premestitveno zmogljivostjo in hidravličnimi parametri predlaga:

On the other hand, Govers (1990) suggests the following relationship between transport capacity and hydraulic parameters as the best:

$$T_C = a \cdot q^b \cdot S^c \qquad (8)$$

kjer so a, b in c empirične konstante. Tudi ta enačba daje precej dobro korelacijo za T_C. Vendar Nearing et al. (1997) opozarjajo, da se vrednosti konstant v tej enačbi precej razlikujejo za posamezne tipe zemljine in vrsto poskusa, medtem ko je njihova enačba (7) bolj splošna.

where a, b and c represent empirical constants. This equation also gives good predictions for T_C. However, Nearing et al. (1997) showed that the values of the constants varied significantly among different soil materials and experiments, while their equation (7) was more universal.

2.6 DEJANSKA STOPNJA SPROŠČANJA IN ODLAGANJA

Dejansko sproščanje D_r v žlebičih je odvisno od dejanskega pretoka plavin q_S. Večji kot je pretok plavin, manj energije je na voljo za dodatno sproščanje. Poleg tega prisotnost plavin v toku zmanjšuje turbulenta nihanja hitrosti, plavine v premeščanju pa tudi ščitijo dno pred nadaljnjo erozijo. Lei et al. (1998) v svojem modelu uporablja naslednjo zvezo med možno in dejansko stopnjo sproščanja v žlebičih:

2.6 DETACHMENT AND DEPOSITION RATE

The detachment rate D_r in rills depends on the sediment load q_S. The higher the sediment load, the less energy is available for additional detachment. Furthermore, the presence of sediments in the flow reduces the turbulent velocity fluctuations. Also, the bed is protected by the sediments already being transported. Lei et al. (1998) used the following relationship between the potential detachment rate and the detachment rate in the rills:

$$D_r = e \cdot \left(1 - \frac{q_S}{T_C}\right) \tag{9}$$

Kadar je pretok plavin večji od premestitvene zmogljivosti, nastopi odlaganje. Odlaganje se modelira, podobno kot erozija, na podlagi razlike pretoka plavin in premestitvene zmogljivosti:

When the sediment load is higher than the transport capacity, deposition occurs. Similarly to erosion, deposition is calculated on the basis of the difference between sediment load and transport capacity:

$$A_r = -\alpha \cdot (q_S - T_C) \tag{10}$$

kjer je α empirični linearni koeficient odlaganja [m^{-1}].

where α is an empirical first-order deposition coefficient [m^{-1}].

2.7 NASTANEK KANALSKEGA TOKA

Prosser & Dietrich (1995) obravnavata dve procesno utemeljeni teoriji o prehodu površinskega v kanalski tok. Po prvi nastane prehod iz površinskega v kanalski tok zaradi nestabilnosti prečnih perturbacij površine pod vplivom površinskega toka. Ta teorija je primerna za napovedovanje gostote žlebičev na slabo vezljivih tleh. Po drugi teoriji pa je nastanek kanalskega toka posledica prekoračitve erozijske odpornosti tal, ki je rezultat kohezijskih sil in vegetacijske pokrovnosti tal. Tipičen primer je nastanek novega žlebiča s splazitvijo tal.

Prehod iz površinskega v kanalski tok lahko povzročijo naslednje vrste erozije (Dietrich & Dunne, 1993):

- erozija Hortonovega površinskega toka

2.7 CHANNEL INITIATION

To predict the location of the channel head, two process based theories have been proposed (Prosser & Dietrich, 1995). The first suggests that the transition from overland to channel sediment transport occurs because of the lateral instability of perturbation on the surface in the presence of overland flow. This theory may be appropriate to predict rill density on poorly cohesive surfaces. The second theory relates channel initiation to the resistance to erosion, which results form soil cohesion and vegetation cover. An example of a process threshold is channel initiation by land slide.

The transition from overland to channelised flow occurs by one of the following processes (Dietrich & Dunne, 1993):

- erosion by Horton overland flow

- erozija zasičenega površinskega toka
- erozija zaradi pronicanja
- zdrs zemljine
- notranja erozija.

- erosion by saturation overland flow
- seepage erosion
- mass failure
- tunnel scour

V primeru stalnega zasičenega površinskega toka lahko razvijemo enačbo za kritične razmere za nastanek kanalskega toka na naslednji način (Prosser & Dietrich, 1995). Površinski odtok *Q* je enak

In the case of steady state saturation overland flow, the equation for critical conditions for the channel initiation can be derived the following way (Prosser & Dietrich, 1995). Discharge of overland flow *Q* equals

$$Q = i \cdot A - T \cdot S \cdot b \tag{11}$$

kjer je *i* intenziteta padavin, *A* prispevna površina, *b* pripadajoča širina konture, *T* hidravlična prevodnost tal in *S* lokalni padec. Strižno napetost na dno τ_0 izračunamo kot

where *i* is rainfall intensity, *A* is source area, *b* is the corresponding contour width, *T* is the soil transmissivity and *S* is the local gradient. Boundary shear stress τ_0 can be calculated as

$$\tau_0 = \rho \cdot g \cdot R \cdot S \tag{12}$$

kjer je *R* hidravlični polmer oziroma globina toka. Pretok *Q* in strižno napetost τ_o povežemo preko srednje hitrosti *U*:

where *R* is the hydraulic radius or flow depth. The discharge *Q* and the shear stress τ_o can be related via the mean velocity *U*:

$$Q = U \cdot R \cdot b \tag{13}$$

$$U^2 = \frac{8}{f} \cdot g \cdot R \cdot S \tag{14}$$

f je Darcy-Weissbachov koeficient trenja, ki ga v ozkem območju lahko izrazimo z Reynoldsovim številom Re in empiričnima koeficientoma *K* in *c*, ν je kinematična viskoznost tekočine:

f is the Darcy-Weissbach friction coefficient, which can be, in a certain interval, calculated from the Reynolds number Re, and the empirical coefficients *K* and *c*, ν is kinematic viscosity, such that:

$$f = K \cdot \mathrm{Re}^c \tag{15}$$

$$\mathrm{Re} = UR/\nu \tag{16}$$

Iz zvez (11) - (16) lahko ob nadomestitvi τ_0 s kritično vrednostjo τ_{cr} dobimo pogoj za nastanek kanalskega toka:

Replacing τ_0 by the critical value τ_{cr} and combining (11) - (16) yields the condition for channelised flow:

$$\frac{A}{b} \ge \left(\frac{8 \cdot \nu^c \cdot \tau_{cr}^3}{g^2 \cdot \rho^3 \cdot K}\right)^{1/(2+c)} \cdot \frac{1}{i \cdot S^{2/(2+c)}} + \frac{T}{i} S \tag{17}$$

S pomočjo enačbe (17) in empirično določenih vrednosti K, c, T/i in τ_{cr}, ta zadnja je znašala 16 Pa, so Dietrich et al. (1992; 1993) na podlagi digitalnega modela terena (DTM) pravilno napovedali elemente s kanalskim tokom v 92 odstotkih in elemente s samo površinskim tokom v 77 odstotkih primerov. Prosser & Dietrich (1995) pa sta ugotavljala vpliv zatravljenosti na erozijsko odpornost tal. Terenske poskuse sta izvedla v povodju reke Tennessee. Poskusno območje sta ogradila in vanj dovajala takšno količino vode, da so pretoki ustrezali že izmerjenim dogodkom. Pri gosti travi se spiranje in premeščanje ni pojavilo pri strižnih napetostih, manjših od 104 do 108 Pa. Ko so travo porezali, so ugotovili 3- do 9-kratno zmanjšanje tega praga (20 do 40 Pa). Tudi upor toku vode se je zmanjšal za najmanj red velikosti. Kljub temu pa se še vedno ni pojavil kanalski tok. Avtorja tudi opozarjata, da je kritična strižna napetost precej občutljiv parameter, saj njeno dvojno povečanje pomeni 4- do 8-kratno povečanje prispevne površine, potrebne za nastanek kanalskega toka. Kljub temu pa so njuni poskusi potrdili uporabnost hipoteze o pragu erozijske odpornosti tal za zatravljene površine.

3. TRADICIONALNO NAPOVEDOVANJE EROZIJE TAL

3.1 ENAČBA USLE

Tradicionalne metode za napovedovanje erozije tal izhajajo s področja kmetijstva. To so empirični modeli, namenjeni napovedovanju sproščanja, to je količini zemljine, ki jo voda izloči iz matičnih tal. Značilen primer takega modela je Univerzalna enačba izgub zemljine (USLE, "Universal Soil Loss Equation"). Model je sestavljen iz glavne enačbe in pomožnih enačb oziroma preglednic in grafikonov za določanje posameznih vrednosti glavne enačbe. Enačba je bila uporabljena pri načrtovanju za napovedovanje vpliva rabe tal na erozijo (Hahn et al., 1994). Prvotno je bila razvita za napovedovanje srednje letne izgube tal, kasneje pa

Dietrich et al. (1992; 1993) applied this equation to a digital terrain model (DTM). The values of the parameters K, c, T/i and τ_{cr}, the former's value being 16 Pa, were empirically determined. Thus, 92% of channeled elements and 77% of the unchanneled elements were correctly attributed. Prosser & Dietrich (1995) demonstrated the effect of vegetation cover on erosion resistance. Their experiments were conducted in a field site in the Tennessee Valley catchment. Flume walls were constructed and water was supplied to the flume such that discharges were comparable to previously measured events. Under dense grass cover, sediment transport didn't occur at shear stresses lower than 104÷108 Pa. When the grass was clipped, the threshold was reduced by 3÷9 times (20-40 Pa). Also, flow resistance was reduced by at least an order of magnitude. But still, no channelised flow occurred. Furthermore, the authors found that critical shear stress is quite a delicate parameter, since its 2-fold variation results in 4÷8-fold variation in the source area required to support a channel. But, in spite of that, the experiments provided support for the assumption that channel initiation in grassland is threshold dependent.

3. TRADITIONAL SOIL EROSION PREDICTION

3.1 THE USLE EQUATION

Traditional methods for soil erosion prediction were developed for agricultural land. These are empirical models. Their purpose is to predict soil loss, i.e. the amount of soil lost from the surface by water impact. The most known example of such a model is the Universal Soil Loss Equation (USLE). The model consists of one main relationship and a set of equations, tables and figures for the determination of the parameters of the main relationship. This equation has been widely used for planning purposes to predict the impact of land use on soil erosion (Hahn et al., 1994). Originally, it was developed for the prediction of the average annual soil loss, but spremenjena tako, da je bilo z njo mogoče napovedovati erozijo tudi mesečno in celo ob posameznem dogodku, t.j. nalivu. V novejšem času je bil model izboljšan z novimi spoznanji in je zdaj znan pod imenom RUSLE ("Revised USLE", t.j. popravljena USLE). Glavna enačba RUSLE/USLE je v obliki zmnožka:

$$A = RKLSCP \tag{18}$$

A [kg/ha·leto] je povprečna izguba tal na enoto površine, ki je odvisna od aktivnih hidroloških in topografskih dejavnikov (*R*, *L*, *S*) in reaktivnih dejavnikov (*K*, *C*, *P*), ki opisujejo erodibilnost, pokrovnost in rabo tal. Posamezni dejavniki so (Hahn et al., 1994):

R	dejavnik padavin in odtoka, to je število enot dežja za energijo padavin in odtok, in vode iz taljenja snega za odtok [MJ·mm/ha·h·leto],
K	dejavnik erodibilnost zemljine glede na standardne razmere (raba tal, padec, in dolžina pobočja),
L	dejavnik dolžine pobočja, to je razmerje med izgubo tal pri podani dolžini in standardni dolžini 22.1 m,
S	dejavnik naklona pobočja, to je razmerje med izgubo tal pri podanem padcu in standardnem padcu 9 odstotkov,
C	dejavnik pokrovnosti in obdelave tal, to je razmerje med izgubo tal pri podani pokrovnosti in izgubo tal z neobdelanega polja,
P	dejavnik kmetijskih zaščitnih ukrepov, to je razmerje med izgubo tal s polja, ki se obdeluje s podanimi ukrepi in izgubo tal s polja, ki se obdeluje z oranjem navzgor in navzdol.

Enačba se največ uporablja v ZDA. Tam so za določevanje vsakega od omenjenih dejavnikov izdelane enačbe, grafikoni oziroma karte. Primer uporabe v Evropi za Bavarsko podaja Lang (1997), za Južni Limburg na Nizozemskem pa De Roo (1998). Kasneje je bila na temelju USLE razvita spremenjena USLE oziroma MUSLE (Modified USLE). Razlika je v nadomestitvi dejavnika R z dejavnikom energije odtoka.

later it was modified to estimate monthly and even single event (i.e. single storm) erosion. In recent times, the model has been improved with the new data available. The modification is named RUSLE (Revised USLE). The main relationship of RUSLE/USLE is a multiplicative one:

A [kg/ha·year] is the average soil loss per unit area, which depends on active hydrological and topographic factors (*R*, *L*, *S*) and reactive factors (*K*, *C*, *P*), such as soil erodibility, cover and land use. The factors are (Hahn et al., 1994):

R	rainfall-runoff factor, i.e. the number of rainfall units for rainfall energy and runoff, and runoff from snowmelt [MJ·mm/ha·h·year],
K	erodibility factor in comparison to standard conditions (land use, slope, slope length),
L	slope length factor, which is the ratio of soil loss from a given slope to that of the standard slope length of 22.1 m,
S	slope steepness factor, which is a ratio of the soil loss from a given slope relative to that of the standard slope of 9%,
C	cover and management factor, which is a ratio of the soil loss from a field of a given cover, and management relative to that in continuous fallow,
P	is the supporting conservation practise, which is a ratio of the soil loss from a field, of a given conservation support practise relative to that with straight row farming up and downhill.

The method is mostly used in the USA, where equations, charts and maps were defined for the determination of these factors. In Europe, it has been used in Bavaria (Lang 1997) and in South Limburg, in the Netherlands (De Roo, 1998). Later, on the basis of the USLE equation, the modified USLE, or MUSLE, was developed. The difference is in replacing the R factor with the runoff energy factor.

3.2 GAVRILOVIĆEVA ENAČBA

Za območje Sredozemlja je Gavrilović (1970) predlagal naslednjo enačbo za izračun srednjega letnega sproščanja zemljin *W* [m^3/leto] zaradi vodne erozije:

3.2 THE GAVRILOVIĆ EQUATION

For the Mediterranean region, Gavrilović (1970) proposed the following equation to predict average annual sediment production *W* [m^3/year] due to water erosion:

$$W = 3.14 \cdot H_Y \cdot K_T \cdot K_Z^{1.5} \cdot F_W \tag{19}$$

kjer je F_W površina povodja [km^2], H_Y so srednje letne padavine [mm], K_T je temperaturni koeficient območja, ki je funkcija srednje letne temperature, K_Z pa je erozijski koeficient območja, ki se oceni na podlagi ustreznih preglednic ali pa izračuna kot:

where F_W is the catchment area [km^2], H_Y is the average annual rainfall [mm], K_T is the coefficient of temperature, which is a function of mean annual temperature, and K_Z is the coefficient of erosion, which can be estimated using corresponding tables or calculated from:

$$K_Z = K_X \cdot K_Y \cdot (K_0 + \sqrt{S}) \tag{20}$$

V tej enačbi je K_Y koeficient erodibilnosti tal, K_X je koeficient zaščitenosti tal zaradi rastlin ipd., K_0 je koeficient razvitosti erozijskih procesov, *S* pa srednji nagib v povodju. Kadar je povodje oziroma izbrana površina heterogena glede na erozijski koeficient K_Z, Gavrilović (1970) predlaga, da se skupni K_Z izračuna kot povprečje, uteženo s pripadajočimi površinami. To sicer z matematičnega vidika ni povsem jasno, saj sproščanje *W* ni linearna funkcija K_Z, torej:

In this equation, K_Y is the soil erodibility coefficient, K_X is the soil protection coefficient due to vegetation etc., K_0 is the coefficient of the development of the erosional process and *S* is the average slope. When the catchment or the concerned area is not uniform with respect to the coefficient of erosion K_Z, Gavrilović (1970) suggested calculating the mean K_Z as the sub-area weighted average. From a mathematical point of view, this is not very clear, since *W* is not a linear function of K_Z, therefore:

$$\sum_i F_{W,i} \cdot K_{Z,i}^{1.5} \neq F_W \cdot \left(\sum_i \frac{F_{W,i}}{F_W} \cdot K_{Z,i} \right)^{1.5} \tag{21}$$

Vendar ta razlika v primerjavi s točnostjo metode ni bistvena. Vzemimo sproščanje zemljin z dveh enako velikih površin in razmerjem v erozijskem koeficientu 1:5. Če ju obravnavamo kot enotno površino po enačbi (21), dobimo za 15 odstotkov nižjo vrednost za sproščanje, kot če ju obravnavamo kot dve ločeni površini. Kljub temu se matematično pravilen račun povprečnega erozijskega koeficienta K_Z glasi:

However, this difference is not significant compared to the accuracy of the method. Let us calculate the sediment production form two equally large areas with an erosion coefficient ratio of 1:5. If calculated as one area using equation (21), the obtained sediment production is 15 percent lower than if calculated as two separate units. Nevertheless, the mathematically correct expression for average erosion coefficient K_Z is:

$$K_Z = \left(\sum_i \frac{F_{w.i}}{F_W} \cdot K_{Z,i}^{1.5} \right)^{0.67} \tag{22}$$

Za posamezne koeficiente iz enačb (19) in (20) obstajajo preglednice vrednosti za vsako opisano stanje. Enačba je bila preverjena na podatkih z območja nekdanje Jugoslavije in Severne Afrike (Gavrilović, 1970).

Pintar et al. (1986) so ugotovili, da so za vrednotenje erozije v Sloveniji največje dnevne padavine $H_{D,max}$ ustreznejši parameter od srednjih letnih padavin H_Y. Nadalje poročajo, da srednja letna temperatura ni pomemben parameter. Tako so za napovedovanje sproščanja plavin predlagali spremenjeno enačbo:

Tables giving a description for the different values exist for each of the coefficients of the equations (19) and (20). The equation was validated on the data from former Yugoslavia and North Africa (Gavrilović, 1970).

Pintar et al. (1986) found that, for erosion prediction in Slovenia, the maximum daily precipitation $H_{D,max}$ is more appropriate than the average annual precipitation H_Y. Furthermore, they report that the mean annual temperature is not significant. To predict sediment production, they proposed a modified equation:

$$W = 20 \cdot H_{D,\max} \cdot K_Z^{1.5} \cdot F_W \qquad (22)$$

4. MODERNE METODE

4.1 TEMELJI IN RAZVOJ MODELOV

Rezultat v prejšnji točki opisanih modelov je količina sproščanja zemljin. Ta pa pogosto ni enaka odplavljanju, t.j. količini zemljine, ki je bila dejansko odstranjena s pobočja. Prej ko slej se na pobočju namreč pojavijo razmere, ko voda ni več sposobna odnašati vsega erodiranega materiala in zato nastopi odlaganje.

Sodobne metode za napovedovanje odplavljanja zemljin zato temeljijo na modelih, ki upoštevajo celoten cikel erozijskega procesa: sproščanje, premeščanje in odlaganje, kakor tudi njihove medsebojne vplive. Diagram poteka računa je razviden iz slike 2.

Hahn et al. (1994) podaja zgodovinski pregled razvoja erozijskih modelov. Prvi fizikalno utemeljen model se je pojavil konec šestdesetih let (Meyer & Wischmeier, 1969). Polteoretična FMO enačba (Foster et al., 1977) je bila kasneje uporabljena v računalniškem modelu CREAMS ("Chemicals-Runoff-Erosion in Agricultural Management Systems", Kemikalije-odtok-erozija za upravljalske sisteme v kmetijstvu). Ta model je namenjen napovedovanju erozije na enoto kmetijske površine pri stalnih razmerah. Hirschi & Barfield (1988a;b) sta za raziskave erozije razvila procesno utemeljen model KYERMO. Ta model je namenjen simulaciji

4. MODERN METHODS

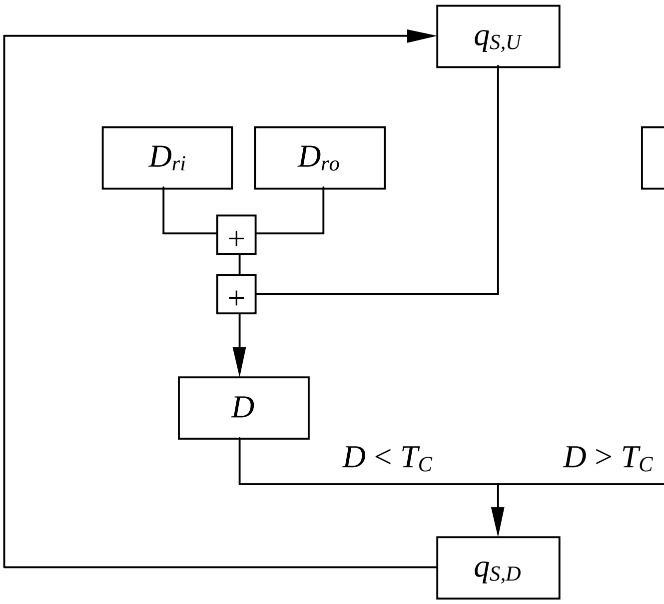
4.1 THE BASIS AND DEVELOPMENT OF THE MODELS

The models described in the previous section can be used to predict soil erosion. This is, however, often different from sediment yield, which is the amount of sediment that is actually removed from the slope. The reason for that is that sooner or later, the sediment load exceeds the transport capacity, and deposition of the eroded material occurs.

Modern methods for sediment yield prediction are, therefore, based on the models, which take into account the entire erosion process: detachment and transport and deposition, as well as their interactions. These interrelationships are shown in Figure 2.

Hahn et al. (1994) gives the historical overview of erosion modelling. The first physically based model was developed in the late sixties (Meyer & Wischmeier, 1969). The semitheoretical FMO equation (Foster et al., 1977) was later used in a computer model called CREAMS (Chemicals-Runoff-Erosion in Agricultural Management Systems). This model was intended for use on a field-sized area under steady-state conditions. Hirschi & Barfield (1988a;b) developed a research-oriented process-based model KYERMO. This posameznega dogodka in napoveduje sproščanje in erozijo v posameznih žlebičih na podlagi pretoka vode v njem. Med vrsto procesno utemeljenih modelov, razvitih v zadnjih letih (npr. EUROSEM, 2D in 3D EROSION ...), so v nadaljnjem besedilu opisani trije: WEPP, LISEM in TOPOG.

model is intended for the simulation of single events. It predicts sediment detachment and transport in individual rills as a function of flow rates. Among many process based models developed in recent years (e.g. EUROSEM, 2D & 3D EROSION ...), three are described in the next section: WEPP, LISEM and TOPOG.



Slika 2. Procesno utemeljeno modeliranje erozije (po Meyer & Wischmeier, 1969) Simboli: $q_{S,U}$ - dotok plavin od zgoraj, $q_{S,D}$ - odtok plavin navzdol, D_{ri} - sproščanje zaradi dežja, D_{ro} - sproščanje zaradi odtoka, D - skupno sproščanje, T_{Cri} - premestitvena zmogljivost dežja, T_{Cro} - premestitvena zmogljivost odtoka, T_C - skupna premestitvena zmogljivost.

Figure 2. Process based erosion modelling (after Meyer & Wischmeier, 1969). Symbols: $q_{S,U}$ *- soil from upslope,* $q_{S,D}$ *- soil carried downslope,* D_{ri} *- detachment by rainfall,* D_{ro} *- detachment by runoff,* D *- total detached,* T_{Cri} *- rainfall transport capacity,* T_{Cro} *- runoff transport capacity,* T_C *- total transport capacity.*

4.2 MODEL WEPP

Model WEPP ("Water Erosion Prediction Project", Projekt napovedovanja vodne erozije) je zasnovan na podlagi obširne baze podatkov, zbranih v ta namen. Ta procesno utemeljeni model je namenjen napovedovanju erozijskih procesov na enotnem pobočju ali pa v manjših povodjih (Flanagan et al., 1995). Različica za povodja povezuje pobočja z rečnimi strugami in zajezitvami (slika 3a). S tem se je WEPP že približal dvodimenzionalnemu modeliranju erozijskih procesov. Ciljni namen modela je načrtovanje projektov in zaščitnih ukrepov ter pregled in

4.2 THE WEPP MODEL

The WEPP model (Water Erosion Prediction Model) was developed on the basis of field data. A large database was collected with this purpose in mind. This process based model can be used for the prediction of erosion processes on hillslopes or small catchments (Flanagan et al., 1995). In the catchment version, the model links hillslope profiles to channels and impoundments (Figure 3a). By this feature, WEEP approaches two dimensional erosion modelling. Anticipated applications of the model include project planning, conservation planning, inventory and ocena stanja. Največja prednost pred tradicionalnimi modeli je možnost časovne in prostorske simulacije procesov.

Model obravnava naslednje procese: žlebično in medžlebično erozijo, premeščanje in odlaganje, infiltracijo, konsolidacijo zemljin, vpliv tal in pokrovnosti na sproščanje in infiltracijo, zablatenje površine, žlebično hidravliko, površinski odtok, rast rastlin, razgradnjo organskih ostankov, perkolacijo, izhlapevanje, transpiracijo, taljenje snega, vpliv zmrzovanja na infiltracijo in erodibilnost, podnebje, vpliv obdelovanja na lastnosti tal, naključno hrapavost površine in vpliv kontur. Model upošteva prostorsko in časovno spreminjanje površja, hrapavosti površine, lastnosti tal in rastlinskega pokrova ter rabo tal (Flanagan et al., 1995). Model ima tudi modul za generacijo vremenskih podatkov.

Model WEPP ne upošteva jarkovne erozije. Prav tako je uporaba modela omejena na površine, kjer prevladuje Hortonov površinski odtok in je infiltracija zanemarljiva. Različica za pobočja je primerna za dolžine pobočij nekaj deset metrov, za večja območja pa je treba uporabiti različico za povodja (Flanagan et al., 1995).

4.3 MODEL LISEM

Med leti 1991 in 1994 se je v pokrajini Južni Limburg na Nizozemskem izvajal projekt na temo erozije tal. Poleg terenskih meritev in laboratorijskih raziskav je bilo del projekta tudi modeliranje procesa (De Roo, 1996a). Za razvoj lastnega modela, ki temelji na okolju GIS, so se odločili zaradi naslednjih razlogov (De Roo, 1996b):

- izboljšanje opisa procesov, na primer infiltracije in sproščanja,
- vgraditev v okolje GIS, na primer zaradi boljšega opisa površja,
- razvoj modela, ki omogoča uporabo podatkov daljinskega zaznavanja; dostopnost primernih podatkov je težava pri vseh procesno utemeljenih modelih.

assessment. The most important advantage over the traditional models is the capability of temporal and spatial simulation of the processes.

The model considers the following processes: rill and interrill erosion; sediment transport and deposition; infiltration; soil consolidation; the residue and canopy effect on soil detachment and infiltration; surface sealing; rill hydraulics; surface runoff; plant growth; residue decomposition; percolation; evaporation; transpiration; snow melt; the frozen soil effects on infiltration and erodibility; climate; the tillage effects on soil properties and the random roughness and conture effects. The model takes into account the spatial and temporal changes in the topography, surface roughness, soil properties, crops and the conditions of land use (Flanagan et al., 1995). A component for weather generation is also included in the model.

The WEPP model does not consider gully erosion. Furthermore, the model can only be used for the hydrology dominated Hortonian overland flow with negligible infiltration. The hillslope version can be used for slope lengths of tens of meters. For larger areas, the catchment representation is necessary (Flanagan et al., 1995).

4.3 THE LISEM MODEL

Between 1991 and 1994, a soil erosion project was carried out in the South Limburg region in the Netherlands. In addition to field measurement and laboratory investigations, modelling was also a part of the project (De Roo, 1996a). They decided to develop a new GIS based model for the following reasons (De Roo, 1996b):

- improvement of process descriptions, infiltration and detachment, for example,
- implementation in GIS, e.g. to prevent the unnecessary lumping of topography,
- development of a model that allows input from remotely sensed data; the data availability is a major problem in physically based modelling

Model je zapisan v jeziku dinamičnega rastrskega GIS okolja PCRaster (Wesseling et al., 1996), ki so ga razvili na univerzi v Utrechtu. Ta omogoča zelo učinkovito kodiranje, saj je imela različica iz leta 1996 manj kot 200 vrstic. S tem je zagotovljeno preprosto spreminjanje, vzdrževanje in uporaba delov kode za druge namene (De Roo, 1996b).

V modelu obravnavani procesi so naslednji (De Roo, 1996b): prestrezanje padavin, površinsko zadrževanje v mikrodepresijah, infiltracija, navpični tok vode v tleh, površinski tok, tok v strugi, sproščanje zaradi dežja neposredno ali kapljanje s površine rastlin, sproščanje in premestitvena zmogljivost površinskega toka ter žlebična in medžlebična erozija. Vpliv traktorskih kolesnic in majhnih utrjenih poti, ki so manjše od velikosti ene celice, je tudi upoštevan v modelu.

4.4 MODEL TOPOG

TOPOG sta skupaj razvili CSIRO Land and Water in Cooperative Research Centre for Catchment Hydrology iz Avstralije. Ta model je determinističen hidrološki paket s porazdeljenimi parametri (CSIRO, 1999). Temelji na natančni analizi površja, kar pa zahteva tudi kakovostne podatke. Namenjen je predvsem za raziskovalne namene in ga lahko uporabljamo za opis topografskih atributov, prostorsko napovedovanje vodne bilance ter nevarnosti površinske erozije in plazenja, za simulacijo nestalnih hidroloških pojavov v povodju, modeliranje rasti in spreminjanja rastja in posledični vpliv na odtok vode iz povodja, modeliranje širjenja polutantov in dinamike plavin na površini povodja.

Paket sestavlja več kot 30 programov, ki so računski, pomožni, kontrolni ali pa namenjeni grafični predstavitvi. Računske celice so prilagojene površju. Primer delitve povodja na celice lahko vidimo na sliki 3b. Avtorji priporočajo uporabo modela za manjša povodja, do velikosti 10 km^2.

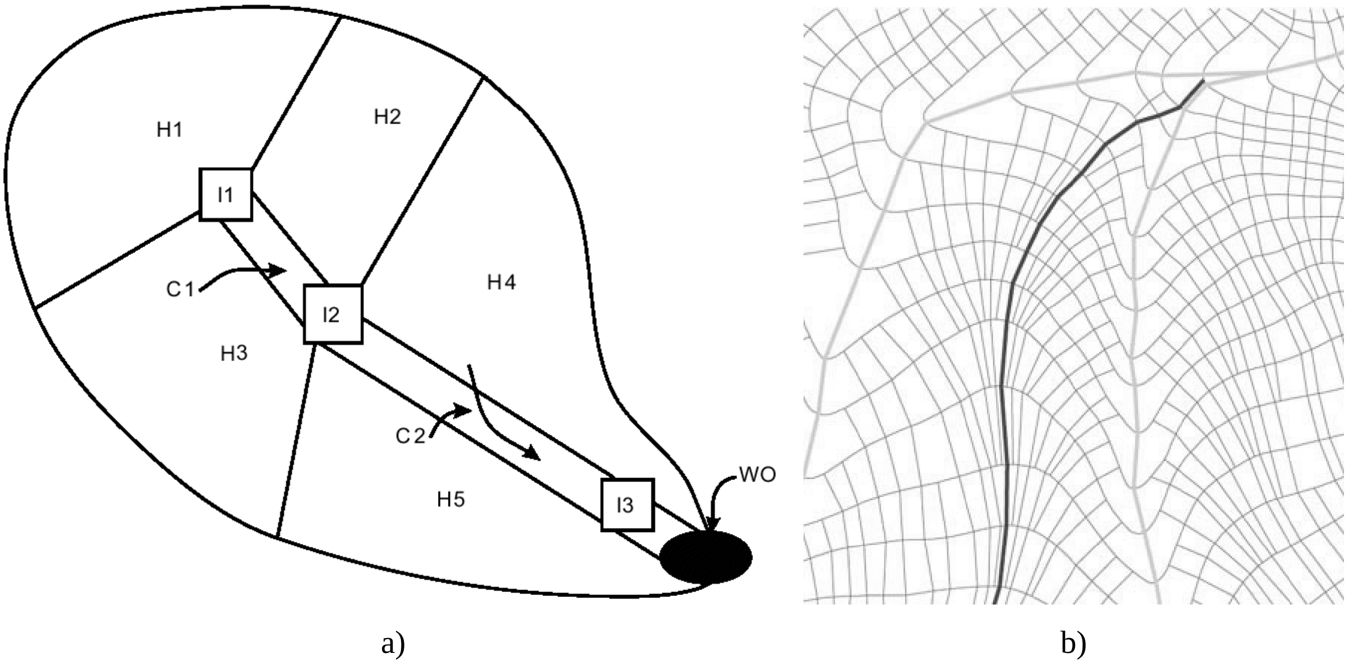
The model is written in a dynamic modelling language of PCRaster GIS environment (Wesseling et al., 1996), developed at the University of Utrecht. It allows very efficient coding; the version of 1996 had fewer than 200 lines. This simplifies model modification, and maintenance and reusability of parts of the code for use for other purposes (De Roo, 1996b).

The model incorporates the following processes (De Roo, 1996b): rainfall interception; surface storage in micro-depressions; infiltration; vertical water movement; overland flow; channel flow; the detachment by rainfall by throughfall or drainage from leaves; the overland flow detachment and transport capacity and rill and interrill erosion. The influence of tractor wheelings and small paved roads that are less than the cell size are also taken into account in the model.

4.4 THE TOPOG MODEL

TOPOG has been developed jointly by the CSIRO Land and Water and the Cooperative Research Centre for Catchment Hydrology from Australia. It is a deterministic distributed-parameter hydrological model (CSIRO, 1999) based on a sophisticated terrain analysis, which also requires appropriate input data. It is intended as a research tool, and can be used to describe the topographic attributes, to predict the spatial distribution of waterlogging, erosion hazard and landslide risk, to simulate the unsteady hydrological behaviour of catchments, to model the growth of vegetation and its influence on water balance, and to model solute movement and sediment dynamics over the soil surface.

The package consists of over 30 programs, which are either computational, utility, control or graphical routines. The computational cells are topography fitted. An example of catchment division into cells can be seen in Figure 3b. The model is intended for application to small catchments up to 10 km^2.



a) b)

Slika 3. a) Združevanje elementov v modelu WEPP (Flanagan et al., 1995): H- pobočje, I- zajezitev, C- struga, WO- iztok iz povodja. b) Delitev površja na celice v modelu TOPOG (CSIRO, 1999). Temna debela črta je vrh grebena, svetla pa dno doline. Celice so prilagojene površini.
Figure 3. a) The linkage of the elements in WEPP (Flanagan et al., 1995): H- *hillslope,* I- *impoundment,* C- *channel, WO- catchment outlet. b) Dividing the landscape into cells in TOPOG (CSIRO, 1999). The dark line is the top of a ridge; the bright bold lines, the bottom of a valley. Cells are topography fitted.*

5. ZAKLJUČKI

V novejšem času so razne raziskovalne ustanove razvile več procesno utemeljenih modelov za napovedovanje erozije tal. Ti modeli omogočajo časovno in prostorsko modeliranje celotnega kroga erozijskih procesov, od sproščanja, premeščanja do odlaganja. Uporabljati jih je mogoče za posamezna pobočja ali pa na manjših povodjih. Njihova slabost je veliko število vhodnih parametrov (topografija, lastnosti tal, podatki o rastju itd.). Te parametre je pogosto težko dovolj zanesljivo oceniti oziroma izmeriti, kar lahko vodi do napačnih napovedi modela (De Roo, 1998). Tradicionalni modeli so primerni za napovedovanje srednjega letnega sproščanja s pobočij s preprosto geometrijo, kar je tudi njihov edini namen. V teh primerih so ravno tako uspešni kot bolj kompleksni procesno utemeljeni modeli, kar kaže primerjava med enačbami USLE/RUSLE

5. CONCLUSION

In recent years, different research organisations have developed several process based models for erosion prediction. These models are capable of temporal and spatial modelling of the entire erosion process, including detachment, transport and deposition. They can be used either for individual hillslopes or smaller catchments. However, their disadvantage is the large number of input parameters needed (topography, soil properties, vegetation data, etc.). Estimating and measuring these parameters is often associated with a high degree of uncertainty, which can lead to poor model prediction (De Roo, 1998). Traditional models can be used to predict average annual soil loss from hillslopes of simple geometry, which is also their only purpose. But, in these cases, they can be just as successful as the more complex process based models, as shown by comparing the USLE/RUSLE equations in modelom WEPP (Neraing & Nicks, 1998). Za modeliranje erozije tal v povodjih, in predvsem dotoka plavin v vodotoke, ter za časovne in prostorske napovedi, pa je nujna uporaba modernejših metod.

V Sloveniji se je do zdaj za ocenjevanje sproščanja zemljin uporabljala Gavrilovićeva metoda. Primer so ocene za povodja Soče in primorsko-istrskih vodotokov (BF, 1970). Danes pa lahko storimo korak naprej. Geodetska uprava RS je pripravila digitalne modele reliefa v mreži 100x100 m ali manj (GURS, 2000), ki so podlaga za natančnejšo obravnavo procesa. Tako bi bilo na primer v povodju Idrijce, kjer je znan problem spiranja živega srebra, treba uporabiti katerega od omenjenih modelov (npr. WEPP ali LISEM). Opozoriti pa je treba, da so za uporabo modernih simulacijskih orodij potrebni tudi zanesljivi podatki.

with the WEPP model (Nearing & Nicks, 1998). However, to predict soil erosion in catchments, and especially sediment yield, as well as for temporal and spatial predictions, the modern methods must be used.

Up to now, the Gavrilović method has been used to estimate sediment yield from catchments in Slovenia. An example is an assessment of sediment production in the Soča basin and the coastal region (BF, 1970). But today, we can move further. The Surveying and Mapping Authority of the Republic of Slovenia has prepared the Digital Relief Model for the whole territory in a grid of 100x100 m or less (GURS, 2000). This is the basis for more accurate process modelling. A well known problem that could be handled with one of the mentioned models (e.g. WEPP, LISEM) is the erosion of the mercury-contaminated sites near Idrija. However, to use the process based models, accurate data is also needed.

DODATEK: SLOVENSKO-ANGLEŠKI SLOVARČEK POJMOV S PODROČJA MODELIRANJA EROZIJE TAL

APPENDIX: SLOVENE-ENGLISH DICTIONARY OF SOIL EROSION MODELLING TERMINOLOGY

Modeliranje	Modelling
model za simulacijo posameznega dogodka	single event based model
procesno utemeljeno modeliranje	process based modelling
Vodni tok	Water flow
izbruh turbulentne motnje	turbulent burst
moč vodnega toka	stream power
specifična moč vodnega toka	unit stream power
Erozija tal	Soil erosion
pljuskovna erozija*	splash erosion
žlebič*	rill
sproščanje	detachment
potencialno sproščanje	detachment potential
premeščanje	transport
premestitvena zmogljivost	transport capacity
odplavljanje	sediment yield
dotok plavin	sediment delivery
pretok plavin	sediment load

* povzeto po Mikoš & Zupanc (2000)

* after Mikoš & Zupanc (2000)

VIRI - REFERENCES

BF (1970). Erozija in plavine v območju povodji Soče in primorsko-istrskih vodotokov v SR Sloveniji (Erosion and sediment yield in the catchments of the river Soča and the coastal region of Slovenia). University of Ljubljana, Biotechnical Faculty, Department of Forestry, (in Slovenian).

Brown, L.C., Foster, G.R. (1987). Storm erosivity using idealised intensity distributions. *Trans. ASAE* **30**, 293-307.

Cook, H.L. (1936). The nature and controlling variables of the water erosion process. *Soil Sci. Soc. Am. Proc.* **1**, 60-64.

CSIRO (1999). TOPOG Online. http://www.clw.csiro.au/topog.

De Roo, A.P.J. (1996a). The LISEM project: An Introduction. *Hydrol. Process.* **10**, 1021-1025.

De Roo, A.P.J. (1996b). LISEM: A single-event, phisically based hydrological and soil erosion model for drainage basins. I: Theory, input and output. *Hydrol. Process.* **10**, 1107-1117.

De Roo, A.P.J. (1998). Modelling runoff and sediment transport in catchments using GIS. *Hydrol. Process.* **12**, 905-922.

Dietrich, W.E., Dunne, T. (1993). The Channel head. In: Beven K., Kirkby M.J., *Channel Network Hydrology*, 175-219. John Wiley & Sons, Chichester, UK.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., Bauer, R. (1992). Erosion thresholds and landscape morphology. *J. Geology* **20**, 675-679.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J. (1993). Analysis of erosion thresholds, channel networks and landscape morphology using a digital terrain model. *J. Geology* **101**, 259-278.

Einstein, H.A., Barbarossa, N.L. (1951). River channel roughness. *Trans. ASCE* **117**, 1121-1132.

Ellison, W.D., Allison, O.T. (1947). Soil erosion studies. IV. Soil detachment by surface flow. *Agric. Eng.* **26**(6), 1766-1777.

Flanagan, D.C., Ascough, J.C., Nicks, A.D., Nearing, M.A., Laflen, J.M. (1995). USDA-WEPP: Hillslope profile and watershed documentation. Chapter I. Overview of the WEPP erosion prediction model, 12 pp, http://topsoil.nserl.purdue.edu/NSERLWeb/weppmain/weppdocs.html.

Foster, G.R., Meyer, L.D., Onstad, C.A. (1977). An erosion equation derivetd from basic erosion principles. *Trans. ASAE* **20**(4), 678-682.

Gavrilović, S. (1970). Savremeni načini proračunavanja bujičnih nanosa i izrada karata erozije (Contemporary methods of predicting torrent deposits and erosion mapping). Proc. of Erozija, bujični tokovi i rečni nanos. Jaroslav Černi Institute, Beograd, 85-100. (in Serbian).

Govers, G. (1990). Empirical relationship for the transport capacity of overland flow: Erosion, transport and deposition process. *IAHS Publ.* **189**, pp.45-63.

GURS (2000). http://www.sigov.si/gu/.

Hahn, C.T., Barfield, B.J., Hayes, J.C. (1994). *Design hydrology and sedimentology for small catchments*. Academic Press Inc., San Diego, USA. 588 p.

Hirschi, M.C., Barfield, B.J. (1988a). KYERMO - A physically based research erosion model. I Model development. *Trans. ASAE* **31**(3), 804-813.

Hirschi, M.C., Barfield, B.J. (1988b). KYERMO - A physically based research erosion model. II Model sensitivity analysis and testing. *Trans. ASAE* **31**(3), 814-820.

Jayawardena, A.W., Bhuiyan, R.R. (1999). Evaluation of an interrill erosion model using laboratory catchment data. *Hydrol. Process.* **13**, 89-100.

Lang, R. (1997). Modellierung von Erosion und Nitratustrag in Agrarlanschaften. FAM-Bericht 19. Shaker, Aachen, 177 p. (in German).

Lei, T., Nearing, M.A., Haghighi, K., Bralts, V.B. (1998). Rill erosion and morphological evolution: A simulation model. *Water Resources Research* **34**(11), 3157-3168.

Meyer, L.D., Monke, E.D. (1965). Mechanics of soil erosion by rainfall and overland flow. *Trans. ASAE* **8**(4), 572-580.

Meyer, L.D., Wischmeier, W.H. (1969). Mathematical simulation of the process of soil erosion by water. *Trans. ASAE* **12**(6), 754-758.

Mikoš, M., Zupanc, V. (2000). Erozija tal na kmetijskih površinah (Soil erosion on agricultural land). Sodobno kmetijstvo, 6 p. (in Slovenian).

Nearing, M.A. (1991). A probabilistic model of soil detachment by shallow turbulent flow. *Trans. ASAE* **34**, 81-85.

Nearing, M.A., Nicks, A.D. (1998). Evaluation of the Water Erosion Prediction Project (WEPP) model for hillslopes. In: Boardman J., Favis-Mortlock D.: *Modelling soil erosion by water*. Springer, Berlin, 43-53.

Pintar, J., Mikoš, M., Verbovšek, V. (1986). Elementi okolju prilagojenega urejanja vodotokov (Elements of environment-friendly watercourse management). Proc. of *Drugi kongres o vodama Jugoslavije*, Ljubljana. Book II, 800-814. (in Slovenian).

Prosser, I.P., Dietrich, W.E. (1995). Field experiments on erosion by overland flow and their implication for a digital terrain model of channel initiation. *Water Resources Research* **31**(11), 2867-2876.

Smith, D.D. (1941). Interpretation of soil conservation data for field use. *Agric. Eng.* **22**, 173-175.

Wesseling, C.G., Karssenberg, D., Burrough, P.A., Van Deursen, W.P.A (1996). Integrating dynamic environmental models in GIS: The development of a Dynamic Modelling Language. *Trans. in GIS* **1**, 40-48.

Zingg, A.W. (1940). Degree and length of land slope as it affects soil loss and runoff. *Agric. Eng.* **21**, 59-64.

Naslov avtorja - Author's Address

Gregor PETKOVŠEK
Univerza v Ljubljani - University of Ljubljana
Fakulteta za gradbeništvo in geodezijo - Faculty of Civil and Geodetic Engineering
Katedra za splošno hidrotehniko - Chair of Hydrology and Hydraulic Engineering
Jamova 2, 1000 Ljubljana, Slovenia