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TESTING THE APPLICABILITY OF THE CREAMS MODEL TO ESTIMATION OF AGRICULTURAL NUTRIENT LOSSES IN FINLAND

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CREAMS is a physically based simulation model that estimates runoff, erosion/sediment transport, plant nutrient and pesticide yield from field-sized areas. It was calibrated to Finnish conditions with data from the Hovi basin, situated in Vihti, about 30 kilometers west of Helsinki. The basin is totally agricultural and its area is 12 hectares. The calibration years were 1968 and 1969. Calculated and observed runoff values corresponded with each other quite well on a monthly and annual basis. In 1968 the total observed runoff + percolation was 267 mm and the corresponding value calculated by the model was 289 mm. In 1969 the values were 224 mm (observed) and 229 mm (calculated). The soil losses calculated by the model were small, but because there were no observations it was not possible to compare calculated and observed values. Nitrogen and phosphorus losses calculated by the model were sifnificantly greater than the observed losses. This may be due to incorrect parameter values, because the values had to be estimated from the literature. On the other hand, the observations on nutrient losses may have given misleading values because of insufficient sampling frequency.

Index words: Hydrology, erosion, sediment transport, plant nutrient transport, mathematical model, non-point source pollution, agriculture.

1. INTRODUCTION

Non-point source loading is becoming a more significant question in water protection because loading from point sources, especially sewage treatment plants, has become smaller due to better treatment methods. It is now therefore necessary to be able to estimate loads from non-point sources more accurately than earlier.

Estimation of non-point source loading has generally been based on observations of runoff and its water quality. However, it is not always possible to make observations, but loads have to be estimated in some other way. One possibility is to use estimates obtained from representative and experimental basins, but there is not always such a basin in the same climatic and soil conditions.

In the 1970's Clean Waters Act in the United States called for mathematical models to evaluate non-point source pollution and to consider management practices for reducing pollution. Many different models were developed, but most of them had the same basic structure: first a hydrological model was selected and the sediment and chemistry components were then added to it.

The CREAMS model considered here was developed by scientists in the Science and Education Administration - Agricultural Research (SEA - AR). In November 1980 the author had the possibility to test the model during her visit to the International Institute for Applied Systems Analysis (IIASA), where the model has been obtained from the U.S. Department of Agriculture.

2. DESCRIPTION OF THE MODEL

The following description is based on the model manual published by the U.S. Department of Agriculture (Knisel 1980).

2.1 General

CREAMS (A field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) is a physically based, daily simulation model that estimates runoff, erosion/sediment transport, plant nutrients, and pesticide yield from field-sized areas. A field is defined as a management unit having (1) a single land use, (2) relatively homogenous soil (3) spatially uniform rainfall, and (4) single management practices. Figure 1 shows a schematic representation of a field with natural and management input and the associated water, sediment, and chemical output.

The general logic of the model is that hydrological processes provide the transport medium for sediment and agricultural chemicals. Therefore, the hydrological component provides input to the other model components. The erosion/sediment yield component in turn provides estimates of sediment yield and silt/clay/organic matter enrichment to be used in the chemical transport components.

The hydrological component consists of two options. When only daily rainfall data are avail-

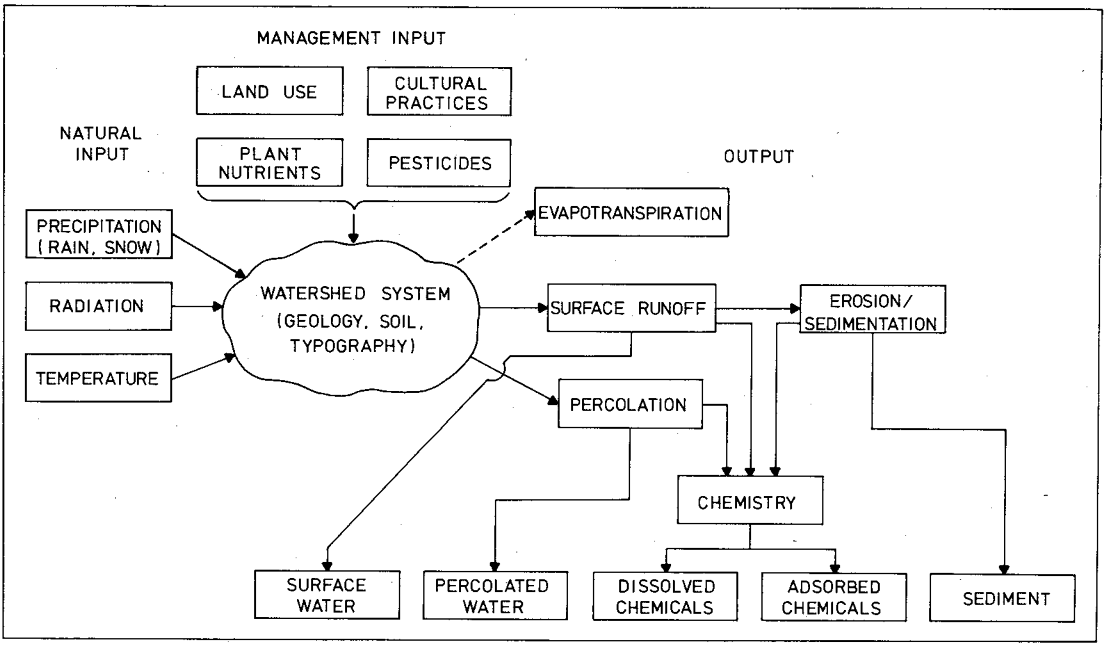

Fig. 1. Flow chart of system for evaluating nonpoint source pollution.

able to the user, the SCS curve number model (U.S. Soil Conservation Service 1972) is used to estimate surface runoff. If hourly or breakpoint rainfall data are available, an infiltration-based model is used to simulate runoff. Both methods estimate percolation through the root zone of the soil.

The erosion component is based on the Universal Soil Loss Equation, USLE (Wischmeier and Smith 1965), but includes sediment transport capacity for overland flow. A channel erosion/deposition feature of the model permits consideration of concentrated flow within a field. Impoundments are also treated in the erosion component.

The plant nutrient submodel has a nitrogen component that considers mineralization, nitrification, and denitrification processes. Plant uptake is estimated, and nitrate leached by percolation out of the root zone is calculated. Both the nitrogen and phosphorus parts of the nutrient submodel use enrichment ratios to estimate the portion of the two nutrients transported with sediment.

The pesticide component considers foliar interception, degradation, and washoff, as well as adsorption, desorption and degradation of pesticides in the soil. The submodel uses enrichment ratios and partitioning coefficients to calculate the separate sediment and water phases of pesticide loss.

2.2 Hydrology

The field-scale hydrological response simulation includes models for infiltration, soil water movement, and soil/plant evapotranspiration. The parameters required by the hydrology model are:

DACRE	Field area
RC	Saturated hydraulic conductivity
FUL	Portion of plant-available water storage filled at field capacity
BST	Portion of plant-available water storage filled when simulation begins
CONA	Soil evaporation parameter
POROS	Soil porosity
BRI5	Immobile soil water content
TEMP	Average monthly temperature (12 values)
RADI	Average monthly net radiation
GR	Winter cover factor (1 for crops, 0.5 for grass)
X(I)	Leaf area index, day I (must specify X (1) and X(366)
SIA	Initial abstraction coefficient (CN method)
CHS	Channel slope
CN2	SCS curve number for AMC condition II
WLW	Watershed length/width ratio
RD	Maximum rooting depth
UL(1-7)	Plant available water storage in 7 soil layers

Selection of parameter values is described in the manual. The rainfall data are on a separate file from the parameters.

The output includes calculated values of infiltration, soil water storage, evapotranspiration and runoff on storm, daily, monthly and annual level as selected.

2.3 Erosion/sediment yield

The model computes erosion, sediment yield and particle composition of the sediment on a storm-by-storm basis. It is based on the concept that if sediment available from detachment is less than transport capacity, detachment controls sediment yield and if sediment load exceeds transport capacity, transport capacity controls sediment yield. The model is structured around three basic elements: overland flow, concentrated (channel) flow, and an impoundment (pond). The study area is represented by a sequence of these elements. The overland flow element is called first, followed by a channel or pond element, or both, if these additional elements are required. In this presentation only the overland flow element is considered.

The model inputs are the hydrological variables rainfall, storm erosivity (EI), volume of runoff, and characteristic peak excess rainfall rate. They are generally obtained from the hydrology component of CREAMS or from observed data.

The model parameters characterize the erosion/sediment transport-deposition features of the area. The input parameters required by the erosion model (overland flow) are as follows:

KINVIS	Kinematic viscosity
NBAROV	Manning's N for overland flow over bare soil
WTDSOI	Weight density of soil
KR	Soil erodibility for erosion by concentrated flow

NBARCH	Manning's n for channel flow over bare soil
YALCON	Yalin constant for sediment transport
SOLCLY SOLSLT SOLSND SOLORG	Fraction of clay/silt/sand/organic matter in the original surface soil layer exposed to erosion
SSCLY SSSLT SSSND SSORG	Specific surface area of clay/silt/sand/organic matter particles

The particle distribution of sediment detached can be calculated from the particle distribution of the original surface soil layer or the particle specifications can be read in. In this presentation it is calculated.

DATOV	Area represented by overland flow profile
SLNGTH	Slope length of representative overland flow profile
AVGSLP	Average slope of representative overland flow profile
SB	Slope at the upper end of the profile
SM	Slope of mid-section
SE	Slope at the lower end of the profile
XIN(3)	Distance from top of slope where mid-uniform section begins
YIN(3)	Elevation above lowest point where mid-uniform section begins
XIN(4)	Distance from top of slope where mid-uniform section ends
YIN(4)	Elevation above lowest point where mid-uniform section ends

When simulating a uniform slope SB = SM = SE = AVGSLP; XIN(3) = XIN(4) = SLNGTH, YIN(3) = YIN(4) = 0.0

NK	Number of slope segments differentiated by changes in soil erodibility factor
XKIN(I)	Relative horizontal distance from the top of the slope to the bottom of segment I
KIN(I)	Soil erodibility factor for slope segment just above XKIN(I)

The field can be divided into segments differentiated by changes in cropping management factor, contouring factor and Manning's N. The parameters needed can be found in the manual and they are also updateable.

Many parameter values can be obtained from the model manual or from the map, but some need soil survey. The output can be taken on a storm, monthly and/or annual basis.

2.4 Nitrogen and phosphorus losses

The storm/hydrology/erosion input data file of the nutrient submodel is created in the hydrology and erosion components of the model passed from the erosion component. The initial parameter inputs are:

SOLPOR	Soil porosity
FC	Field capacity
OM	Organic matter available for denitrification (% of soil mass)
SOLN	Soluble nitrogen in surface centimeter of soil
SOLP	Soluble phosphorus in surface centimeter of soil
NO_3	Nitrate in the root zone
SOILN	Total nitrogen in the surface soil
SOILP	Total phosphorus in the surface soil
EXKN, EXKP	Extraction coefficients for nitrogen and phosphorus
AN, AP	Enrichment coefficients for calculating the degree of N and P enrichment in the sediment
BN, BP	Enrichment exponents for calculating the degree of N and P enrichment in the sediment
RCN	Concentration of nitrogen in rainfall

The updateable parameters permit specification of the information that changes with crop or for year-to-year changes for the same crop. They include data on nutrient additions (dates, amounts, type of application), plant emergence (date), harvest (date) and nitrogen uptake. There are two alternative options for calculating nitrogen uptake. In option 1 uptake is calculated by using the ratio of actual plant evaporation to potential plant evaporation and cubic coefficients to estimate the nitrogen content in the crop dry matter. This option requires the following parameters: maximum depth of the potential root zone (RZMAX), potential yield of grain for the crop grown under ideal conditions (YP), ratio ot total dry matter yield (grains + stover + roots) to the dry matter yield of grain (DMY), amount of potentially mineralizable nitrogen in the root zone (POTM), actual water used by the crop (AWU, obtained from the output of the hydrology model), potential water use by the crop (PWU) and coefficients relating the nitrogen content of the crop to its stage of growth. In option 2 nitrogen uptake calculations are based on the number of days to reach 50 % uptake (DOM), and the number of days between 50 % and 84 % uptake (SD), determined from the normal distribution curve. Other parameters needed are the previously mentioned RZMAX, YP, DMY and POTM and the new one PU, which is the potential uptake of nitrogen by the crop under ideal conditions.

The model prints out the plant nutrient losses on a storm, monthly or annual basis.

3. CALIBRATION OF THE MODEL

The CREAMS model was calibrated with data from the totally agricultural basin, Hovi, situated in Vihti, about 30 kilometers west of Helsinki. The data chosen for calibration were from the years 1968–1969, when a special investigation with frequent sampling was carried out.

3.1 Description of the case study basin

The area of the Hovi basin is 12.0 hectares and during the years 1968-1969 it was entirely open-ditched (Fig. 2). The mean slope of the basin is 2.8 % and the distribution of soil types is 55 % clay,43 % silt and 2 % sand.

In 1968 the crop consisted of wheat (2.3 hectares), oats (4.3 hectares) and barley (3.3 hectares) and fertilizers applied (date 5.5.1968) were 26 kg ha^{-1} nitrogen and 15 kg ha^{-1} phosphorus calculated per total area. In 1969 the crop consisted for the main part of oats (5.6 hectares) and the other plants were barley (2.7 hectares) and wheat (1.0 hectares). The amount of plant nutrients applied (date 19.5.1969) were 32 kg ha^{-1} nitrogen and 16 kg ha^{-1} phosphorus.

3.2 Selection of parameter values

3.21 Hydrology

Monthly mean temperatures were calculated from daily observations of the Vihti meteorological station and monthly mean radiation from daily observations of the same Vihti station in summer and of the Ilmala metorological station in winter. Daily precipitation values were from

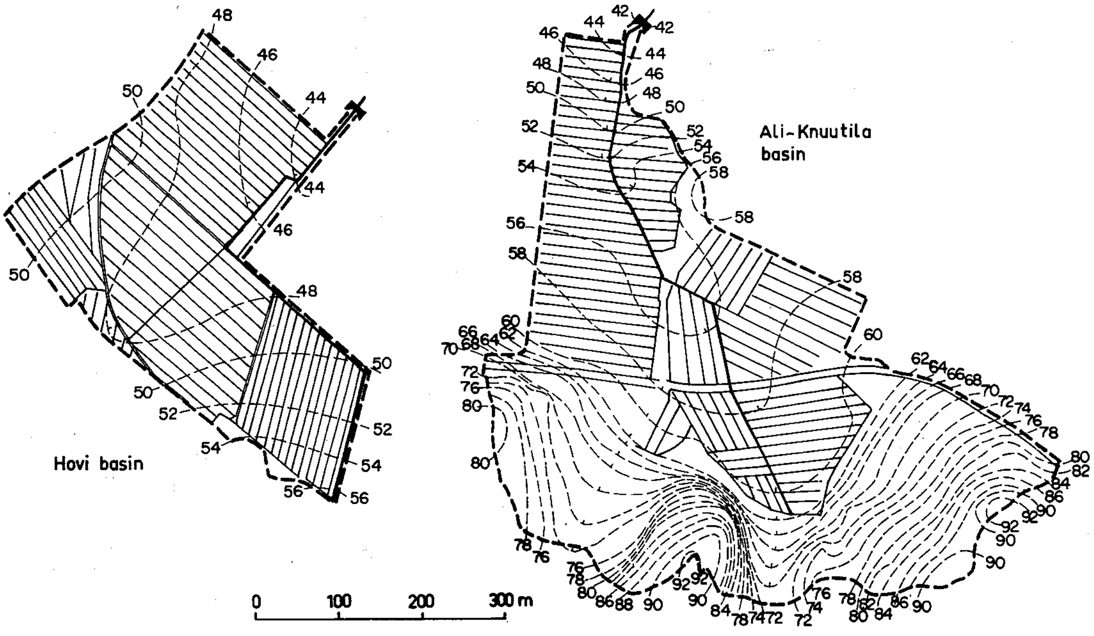

Fig. 2. Hovi and Ali-Knuutila research basins. Hovi = the treatment basin, Ali-Knuutila = the control basin.

the Vihti station. Because option 1 does not include snow accumulation and snowmelt the input precipitation data had to be modified. Precipitation between December 1, 1967 and March 20, 1968 as well as precipitation between December 1, 1968 and April 10, 1969 was summed. The rainfall so accumulated was then divided equally among the dates between March 21 and April 4, 1968 and April 11 and April 30, 1969 respectively. This selection of dates is based on daily temperature data available from Vihti. Although the method described above is very approximate; it was the only possibility of taking the winter conditions into account because of lack of time. In future one of the most important factors in adapting the CREAMS model more accurately to Finnish conditions will be to include a snow accumulation and melting model.

Direct measurements of many characteristics of the soil were missing. Parameter values were estimated on the basis of measurements made in experimental fields in Vihti near the Hovi basin (Seuna 1977) and on the basis of information given in the manual. The values of the parameters are given in Table 1.

Table 1. Parameter values used in the hydrology (option 1) model.

Parameter	Value			
DACRE	44.4	(acres)		
RC	0.10	(in hr^{-1})		
FUL	0.90			
BST	1.00			
CONA	3.3			
POROS	0.50			
BRI5	0.20	(in in^{-1})		
SIA	0.2			
CN2	90.0			
CHS	0.0027			
WLW	1.47			
RD	15.7	(in)		
UL (1-7)	0.13	0.65	0.78	0.78
	0.78	0.78	0.78	
GR	0.50			

Leaf area index:

DATE (julian day)	LAI
001	0.00
122	0.00
148	0.29
160	0.55
196	0.55
208	0.99
220	1.83
232	1.83
244	0.59
259	0.00
366	0.00

3.22 Erosion/sediment yield

The basin was regarded as a uniform flow element for simplicity, because information on parameter values needed by the other elements was almost totally lacking. Direct observations on erosion/sediment yields are also lacking, as only the concentrations of suspended solids in runoff water have been measured. In spite of these defects it was considered important to simulate the erosion/sediment yield, because without it simulation of phosphorus losses would have been impossible.

The parameter values were selected according to the manual, and default values were used for many parameters (Table 2).

The cropping management factor was the only updateable parameter used in the case of the Hovi basin.

3.23 Nutrient losses

General parameters which did not change during the simulation period were given values selected from the data of Seuna (1977).

Because measurements of the soluble and total nutrient contents of the soil in the basin were missing, these parameters had to be estimated. Estimation was carried out mainly on the basis of studies by Hartikainen (1978 and 1979). Option 2 was used for simulating nitrogen uptake.

The parameter values used are given in Table 3. The date of plant emergence was May 10 in 1968 and May 30 in 1969 and the date of harvesting September 15 in both years. Fertilizers were applied as described in Section 3.1. The application factor had a value of 0.1, which means that the

Table 2. Parameter values given the erosion/sediment model. For other parameters default values were used.

Parameter	Value
KINVIS	1.67 E - 05 (ft^2 sec^{-1})
SOLCLY	0.55
SOLSLT	0.43
SOLSND	0.02
SOLORG	0.01
DATOW	44.4
SLNGTH = XIN(3) = XIN(4)	557.0 (acres)
AVGSLP = SB = SM = SE	0.028
YIN(3) = YIN(4)	0.0
NK	1
XKIN(I) (I = 1 to NK)	1.0
KIN (I)	0.07

Table 3. Parameter values used in the nutrient model.

Parameter	Value
SOLPOR	0.50
FC	0.47
OM	0.50
SOLN	0.50 (kg ha^{-1})
SOLP	0.013 (kg ha^{-1})
NO_3	30.0 (kg ha^{-1})
SOILN	0.02 (kg kg^{-1})
SOILP	0.009 (kg kg^{-1})
EXKN = EXKP	0.07
AN = AP	7.4
BN = BP	-0.2
RCN	1.0 (mg l^{-1})
RZMAX	500.0 (mm)
YP	3500.0 (kg ha^{-1})
DMMY	1.00
POTM	50.0 (kg ha^{-1})
DOM	50.0 (days)
SD	8.0 (days)
PU	110.0 (kg ha^{-1})

application was mixed into the top 10 cm. In order to take into account the fertilization of the autumn of 1967 (before the first date of simulation) this parameter was put into the model on the first day of simulation.

4. RESULTS AND DISCUSSION

4.1 Hydrology

Observations on runoff measured in the Hovi basin represent both runoff and percolation. When comparing them with the calculated values, runoff and percolation calculated by the model had therefore to be summed up. Calculated and observed values corresponded quite well on a monthly and annual basis (Table 4). In 1968 the total runoff + percolation observed was 267 mm and the corresponding value calculated by the model was 289 mm. In 1969 the values were 224 mm (observed) and 229 mm (calculated). On a daily basis the timing of runoff was not successful, because according to the model the runoff response occurred on the same day as the rainfall, whereas in reality the response was observed on the day after the rainfall. This indicates a necessity for further calibration.

In summary, if winter conditions could be included in the model in a satisfactory manner, the hydrological part would operate quite well in Finnish conditions.

4.2 Erosion/sediment yield

Soil losses are not a common problem in Finland in contrast to many other countries, where prevention of erosion has been the most important criterion when seeking the best management practices. For this reason no direct observations on soil losses are available, but only estimates based on suspended solids concentrations in runoff.

The soil losses calculated by the model were small compared to the American values presented in the model manual. In 1968 the average

Table 4. Observed and calculated values of monthly runoff + percolation in 1968 and 1969 in the Hovi basin, southern Finland.

Month	Runoff + percolation (mm)			
	1968		1969	
	Observed	Calculated	Observed	Calculated
January	0	0	0	0
February	0	0	0	0
March	112	107	0	0
April	59.9	49.5	140	108
May	4.83	21.8	0.76	0.51
June	0.25	1.02	0	0
July	0.25	2.03	0	0.25
August	1.78	15.8	0	0
September	26.7	25.2	0.51	16.8
October	17.5	27.7	9.40	21.3
November	41.2	38.6	72.1	81.8
December	0	0	0	0

soil loss calculated by the model was 110 t $km^{-2} a^{-1}$ and in 1969 88 t $km^{-2} a^{-1}$. Calculated from the suspended solids concentrations in runoff, values of 14 t $km^{-2} a^{-1}$ for 1968 and 24 t $km^{-2} a^{-1}$ for 1969 were obtained. Direct observations on soil losses would reveal which set of results is of the right order of magnitude. On the other hand the model manual advises sparing use of calibration because of difficulties and sources of errors in making observations.

4.3 Nutrient losses

Nitrogen and phosphorus losses calculated by the model were significantly greater than those calculated from concentration observations and runoff (Table 5). Especially in autumn the model gave very high nutrient losses. It is difficult to say which values are correct because observations were not frequent enough. Parameter estimation would require data on nitrogen and phosphorus contents of the soil, which were not available at the time of calibration.

5. APPLICABILITY OF THE CREAMS MODEL TO FINNISH CONDITIONS

The hydrology part of the model has great defects when applied to Finnish conditions: option 1, which was used, does not include winter conditions, i.e. snow and frost. However, with a simple and crude modification of the input precipitation data, satisfactory results were obtained. This implies that after connection of a snow melting model to the CREAMS the hydrology part would work very well in Finnish conditions. This will be one of the most important tasks in the near future.

The calibration of the erosion/sediment model could not be effected because of lack of observations. The calculated values seem very small compared with the American values. This is in agreement with the fact that erosion is known to be small in Finland. Observations should be made to confirm the results.

In the case of nutrient losses the calibration was not very succesful. This may, however, be due to the selection of parameter values. In particular, the nutrient contents of the soil should be meas-

Table 5. Observed and calculated nitrogen and phosphorus losses in 1968 and 1969 in the Hovi basin, southern Finland.

Month		Loss of nitrogen ($kg\ km^{-2}\ month^{-1}$)		Loss of phosphorus ($kg\ km^{-2}\ month^{-1}$)	
		Observed	Calculated	Observed	Calculated
1968	January	0	0	0	0
	February	0.30	0	0	0
	March	150	130	14	1.8
	April	420	270	19	23
	May	7.4	410	0.38	37
	June	0.16	39	0.01	4.0
	July	0.20	41	0.03	4.2
	August	2.9	360	0.71	37
	September	29	420	6.4	48
	October	33	360	3.9	24
	November	100	22	10	0
	December	1.4	0	0.09	0
1969	January	0	0	0	0
	February	0	0	0	0
	March	0.07	0	0.01	0
	April	870	230	62	23
	May	0.84	0	0.06	0
	June	0.06	0	0.01	0
	July	0	0	0	0
	August	0	0	0	0
	September	0.41	600	0.05	61
	October	26	800	0.64	80
	November	390	1300	17	140
	December	2.3	0	0.14	0

ured in the basin, because these can vary very much even between basins situated near to each other. When these measurements are available the nutrient model could be tested more accurately.

In summary, the CREAMS model seemed to be potentially suitable as a model for estimation of agricultural pollution in Finnish conditions. Its use is, however, restricted to field scale. In water protection planning it is often more important to be able to estimate non-point source loads in a basin scale.

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TIIVISTELMÄ

CREAMS on Yhdysvalloissa kehitetty hajakuormituksen ja sen vähentämistoimenpiteiden arviointiin soveltuva malli. Sen avulla voidaan arvioida yhtenäiseltä peltoalueelta tuleva valuma, erodoituneen maa-aineksen määrä sekä typen, fosforin ja pestisidien häviöt. Mallin lähtökohtana on, että vesi toimii maa-aineksen ja kemikaalien kuljettajana. Näin ollen mallin hydrologinen osa tuottaa inputin mallin muille osille, ja eroosio-osa puolestaan kemialliselle osalle.

Mallin soveltuvuutta hajakuormituksen arviointiin Suomessa testattiin kalibroimalla sitä Hovin valuma-alueen aineistolla vuosilta 1968 ja 1969. Valuma-alue on kooltaan 12 hehtaaria ja se on kokonaan viljelty. Vuosina 1968 ja 1969 valumaveden laatua tarkkailtiin normaalia tiheämmin, mistä syystä nämä vuodet valittiin kalibrointivuosiksi.

Malliin ei sisälly talviolosuhteita: maan jäätymistä ja sateen tuloa lumena. Tämä ratkaistiin muokkaamalla sisäänsyötettäviä sadetietoja niin, että talvikauden aikana kertynyt sademäärä syötettiin malliin vasta kevään sulamiskauden aikana. Havaitut ja lasketut valumat vastasivat hyvin toisiaan kuukausi- ja vuositasolla. Vuonna 1968 havaittu vuosivaluma oli 267 mm ja vastaava laskettu arvo 289 mm. Vuonna 1969 havaittu valuma oli 224 mm ja mallin laskema 229 mm. Vuorokausitasolla vastaavuus ei ollut yhtä hyvä, sillä tietystä sadetapahtumasta aiheutunut valumahuippu ajoittui mallin mukaan samalle päivälle kuin sade, kun todellisuudessa se havaittiin vasta sadetapahtumaa seuraavana päivänä.

Eroosion aiheuttamia maa-aineksen häviöitä ei Suomessa juurikaan ole tutkittu. Hovin alueeltakaan ei ollut käytettävissä muita havaintoja kuin valumaveden kiintoainepitoisuudet. jotka edustavat vain osaa eroosiosta. Mallin laskemat häviöt olivat pieniä verrattuna amerikkalaisiin havaintoihin, mutta moninkertaisia verrattuna kiintoainepitoisuuksista laskettuihin arvoihin.

Mallin laskemat typpi- ja fosforihäviöt olivat huomattavasti suurempia kuin valumaveden pitoisuuksista lasketut. Erityisesti syksyllä malli antoi korkeita ravinnehäviöitä. Saattaa olla, että havaitut arvot ovat liian pieniä johtuen havainnoinnin puutteellisuudesta. Toisaalta myös eräiden maaperää koskevien parametrien arviointi oli hyvin epävarmaa, koska mittauksia ei ollut.

Mallin käyttö hajakuormituksen arviointiin Suomessa edellyttäisi sulantamallin liittämistä siihen. Muilta osin malli saattaisi hyvinkin soveltua meidän oloihimme. Sen käyttö nykyisessä muodossaan vesiensuojelun suunnittelussa on kuitenkin melko rajoitettua, koska sen avulla ei voida arvioida hajakuormitusta maankäytöltään vaihtelevilla valuma-alueilla.

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