Predicting WEPP Effective Hydraulic Conductivity Values on Rangelands

Fred Pierson[1], Ken Spaeth[2], Mark Weltz[3], Steven Van Vactor[1], and Mary Kidwell[3]

Abstract

The Agricultural Research Service (ARS) and the Natural Resource Conservation Service (NRCS) cooperatively conducted rainfall simulation experiments at 26 sites in 10 western states for a total of 444 plot-runs. The data was combined with other similar rainfall simulation data from an additional 21 sites collected as part of the original ARS Water Erosion Prediction Project (WEPP) to create a database containing a total of 820 plot-runs. Subsets of this database were then used to estimate WEPP Green-Ampt effective hydraulic conductivity values for rangelands. This paper provides site-specific summaries of the soil, vegetation and hydrology data collected from all sites and presents regression equations for estimating time-invariant WEPP effective hydraulic conductivity values on rangelands.

Introduction

In 1990, the Agricultural Research Service (ARS) and the Natural Resource Conservation Service (NRCS) entered into a cooperative effort to specifically address the development of the Water Erosion Prediction Project (WEPP) model for use on rangelands. As a result of this cooperation, the National Range Study Team (NRST) and Interagency Rangeland Water Erosion Team (IRWET) were created. The NRST conducted rainfall simulation experiments at 26 sites in 10 western states for a total of 444 plot-runs. IRWET combined the NRST data with other similar rangeland rainfall simulation data from an additional 21 sites collected by the WEPP Team to create a database containing a total of 820 plot-runs. Subsets of this database were then used to develop, calibrate, and validate rangeland specific components of the WEPP model. This paper outlines the database and methodology IRWET used to estimate WEPP Green-Ampt effective hydraulic conductivity values for rangelands.

Rainfall Simulation Experiments

Rainfall Characteristics

A rotating boom simulator (Swanson, 1965; Swanson, 1979; Simanton et al., 1987, 1990) was used at all locations. It is trailer-mounted and has ten 7.6 m booms radiating from a central stem. The 30 nozzles on each boom spray continuously downward from an average height of 3 m. The boom movement is circular over the plots and applies rainfall intensities of approximately

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[1]USDA-ARS, NWRC, 800 Park Blvd, Plaza 4, Suite 105, Boise, ID 83712

[2]USDA-NRCS, NWRC, 800 Park Blvd, Plaza 4, Suite 105, Boise, ID 83712

[3]USDA-ARS, SWRC, 2000 East Allen Road, Tucson, AZ 85719

65 or 130 mm/hr with drop size distributions similar to natural rainfall. Simulation was done at 65 mm/hr on each plot for 60 minutes or until steady state runoff was achieved for a 'dry run' (initially dry), for 30 minutes or until steady state runoff occurred for the 'wet run' (initially at field capacity i.e. 24 hours after the 'dry run'), and finally 130 mm/hr of rainfall was applied until steady state runoff was achieved for the 'very wet run' (i.e. 30 minutes after the 'wet run').

Runoff Plots

Rainfall was simulated uniformly over three pairs of 3.05 by 10.67 m plots. Distribution of rainfall within each plot was determined by both non-recording and recording rain gauges. Runoff was determined by using pressure transducer bubble gauges calibrated to the flume positioned at the plot headwall (Simanton et al., 1987, 1990). Runoff samples were collected on timed intervals to measure sediment concentration and estimate total sediment yield. For the WEPP data, six plots were sampled at each site where paired plot treatments consisted of natural, clipped (vegetative material was clipped to a 20 mm height) and bare soil (all soil cover removed) treatments. Data from the natural plots were used to develop erosion, runoff, and infiltration relationships whereas data from the clipped plots were used to separate canopy cover effects on runoff and erosion. For the NRST data, all six plots sampled were undisturbed replicates of native vegetation where soil characteristics and slope were nearly constant.

Site Characteristics

Thirty-four of the 47 locations sampled were used in this analysis (sites and plots were removed from analysis due to missing data or runoff equilibrium problems). All sites were representative of common rangeland soils and plant cover types that contribute to variation in rangeland hydrology. Thirty unique combinations of rangeland cover type, range site, soil family, and soil surface texture were represented (Tables 1 and 2).

Soil Properties

Twenty-two pedons around each study site were examined, five representative pedons were selected and described, and a detailed profile description and characterization was done on one representative pedon. Soil descriptions and characterizations were performed by NRCS personnel and the NRCS National Soil Survey and Soil Mechanics Laboratories in Lincoln, Nebraska. Antecedent soil moisture condition of each plot and bulk density were determined using open-ended core and compliant cavity methods, respectively. Selected soil properties for each study site are shown in Table 1.

Vegetation Characteristics

Canopy and ground cover were determined by point-sampling (Mueller-Dombois and Ellenberg, 1974). The point center quarter method (Dix 1961) was used to determine plant parameters such as height, canopy cover, geometric shape, density, and mean distance of shrub,

bunchgrass, sod, and annual grasses. Estimates of standing biomass of current year's growth by species and previous year's growth plus decumbent litter were collected utilizing SCS double sampling techniques (SCS, 1976) and by clipping and separating all biomass within five sub-plots located in each runoff plot. Biomass was determined by oven-drying and weighing each sample. Plant composition was determined by the weight method (SCS, 1976). A general description of vegetation characteristics for each site is given in Table 2.

Table 1. Abiotic mean site characteristics and optimized effective hydraulic conductivity (K_e) (mm hr^{-1}) values from USDA-IRWET [1] rangeland rainfall simulation experiments used to develop the baseline effective hydraulic conductivity equations for the WEPP model.

Location	Soil family	Soil series	Surface texture	Slope (%)	Organic matter (%)	Bulk density (g cm^{-3}) [2]	Mean optimized K_e	Range in optimized K_e Min.	Max.
1) Prescott, Arizona	Aridic argiustoll	Lonti	Sandy loam	5	1.3	1.6	7.0	4.1	9.8
2) Prescott, Arizona	Aridic argiustoll	Lonti	Sandy loam	4	1.3	1.6	5.6	3.4	6.9
3) Tombstone, Arizona	Ustochreptic calciorthid	Stronghold	Sandy loam	10	1.8	9.8	28.7	24.5	32.9
4) Tombstone, Arizona	Ustollic haplargid	Forest	Sandy clay loam	4	1.5	6.9	8.7	3.6	13.8
5) Susanville, California	Typic argixeroll	Jauriga	Sandy loam	13	6.4	32.9	16.7	15.3	18.7
6) Susanville, California	Typic argixeroll	Jauriga	Sandy loam	13	6.4	1.2	17.2	13.9	20.3
7) Akron, Colorado	Ustollic haplargid	Stoneham	Loam	7	2.5	1.5	7.3	1.5	15.0
8) Akron, Colorado	Ustollic haplargid	Stoneham	Sandy loam	8	2.4	1.5	16.5	8.4	23.0
9) Akron, Colorado	Ustollic haplargid	Stoneham	Loam	7	2.2	1.5	8.8	4.8	14.0
10) Meeker, Colorado	Typic camborthid	Degater	Silty clay	10	2.4	1.5	8.0	5.2	10.8
11) Blackfoot, Idaho	Pachic cryoborall	Robin	Silt loam	7	7.5	1.3	7.0	4.7	9.7
12) Blackfoot, Idaho	Pachic cryoborall	Robin	Silt loam	9	9.9	1.2	7.8	6.6	9.7
13) Eureka, Kansas	Vertic argiudoll	Martin	Silty clay loam	3	6.0	1.4	2.9	1.1	4.6
14) Sidney, Montana	Typic argiboroll	Vida	Loam	10	5.2	1.2	22.5	18.4	26.5
15) Wahoo, Nebraska	Typic argiudoll	Burchard	Loam	10	5.1	1.3	3.3	2.0	4.4
16) Wahoo, Nebraska	Typic argiudoll	Burchard	Loam	11	4.8	1.3	15.3	13.1	17.5
17) Cuba, New Mexico	Ustollic camborthid	Querencia	Sandy loam	7	1.5	1.5	16.5	14.5	18.5
18) Los Alamos, New Mexico	Aridic haplustalf	Hackroy	Sandy loam	7	1.4	1.5	6.3	5.2	7.3
19) Killdeer, North Dakota	Pachic haploborall	Parshall	Sandy loam	11	3.6	1.3	23.2	21.2	25.4

Table 1. *Continued.*

Location	Soil family	Soil series	Surface texture	Slope (%)	Organic matter (%)	Bulk density (g cm^{-3}) [2]	Mean optimized K_e	Range in optimized K_e Min.	Max.
20) Killdeer, North Dakota	Pachic haploborall	Parshall	Sandy loam	11	3.5	1.3	22.4	17.9	26.9
21) Chickasha, Oklahoma	Udic argiustoll	Grant	Loam	5	4.0	1.3	17.8	9.4	27.7
22) Chickasha, Oklahoma	Udic argiustoll	Grant	Sandy loam[3]	5	2.3	1.5	13.6	8.8	18.8
23) Freedom, Oklahoma	Typic ustochrept	Woodward	Loam	6	3.1	1.4	14.9	13.0	16.8
24) Woodward, Oklahoma	Typic ustochrept	Quinlan	Loam	6	2.3	1.5	20.4	15.5	25.9
25) Cottonwood, South Dakota	Typic torrert	Pierre	Clay	8	3.2	1.5	9.3	8.6	10.0
26) Cottonwood, South Dakota	Typic torrert	Pierre	Clay	12	3.7	1.4	3.6	2.7	4.4
27) Amarillo, Texas	Aridic paleustoll	Olton	Loam	3	3.0	1.5	8.4	6.5	9.7
28) Amarillo, Texas	Aridic paleustoll	Olton	Loam	2	2.5	1.5	5.8	2.4	10.4
29) Sonora, Texas	Thermic calciustoll	Perves	Cobbly clay	8	8.9	1.2	2.2	0.8	3.7
30) Buffalo, Wyoming	Ustollic haplargid	Forkwood	Silt loam	10	2.8	1.5	5.9	4.2	8.8
31) Buffalo, Wyoming	Ustollic haplargid	Forkwood	Loam	7	2.4	1.5	4.6	1.7	11.5
32) Newcastle, Wyoming	Ustic torriothent	Kishona	Sandy loam	7	1.7	1.5	21.7	14.8	26.3
33) Newcastle, Wyoming	Ustic torriothent	Kishona	Loam	8	2.2	1.5	23.1	20.0	28.6
34) Newcastle, Wyoming	Ustic torriothent	Kishona	Sandy loam	9	1.4	1.5	9.0	6.3	12.4

[1] Interagency Rangeland Water Erosion Team is comprised of USDA-ARS staff from the Southwest and Northwest Watershed Research Centers in Tucson, AZ and Boise, ID, and USDA-NRCS staff members in Lincoln, NE and Boise, ID.

[2] Bulk density calculated by the WEPP model based on measured soil properties including percent sand, clay, organic matter and cation exchange capacity.

[3] Farm land abandoned during the 1930's that had returned to rangeland. The majority of the 'A' horizon had been previously eroded.

Table 2. Biotic mean site characteristics from USDA-IRWET [1] rangeland rainfall simulation experiments used to develop the baseline effective hydraulic conductivity equation for the WEPP model.

Location	MLRA[2]	Rangeland cover type[3]	Range site	Dominant species by weight (descending order)	Canopy Cover (%)	Ground Cover (%)	Standing Biomass (kg ha^{-1})
1) Prescott, Arizona	35	Grama-Galleta	Loamy upland	Blue grama Goldenweed Ring muhly	48	47	990
2) Prescott, Arizona	35	Grama-Galleta	Loamy upland	Rubber rabbitbrush Blue grama Threeawn	51	50	2,321
3) Tombstone, Arizona	41	Creosotebush-Tarbush	Limy upland	Tarbush Creosotebush	32	82	775
4) Tombstone, Arizona	41	Grama-Tobosa-Shrub	Loamy upland	Blue grama Tobosa Burro-weed	18	40	752
5) Susanville, California	21	Basin Big Brush	Loamy	Idaho fescue Squirreltail Wooly mulesears Green rabbitbrush Wyoming big sagebrush	29	84	5,743
6) Susanville, California	21	Basin Big Brush	Loamy	Idaho fescue Squirreltail Wooly mulesears Green rabbitbrush Wyoming big sagebrush	18	76	5,743
7) Akron, Colorado	67	Wheatgrass-Grama-Needlegrass	Loamy plains #2	Blue grama Western wheatgrass Buffalograss	54	96	1,262
8) Akron, Colorado	67	Wheatgrass-Grama-Needlegrass	Loamy plains #2	Blue grama Sun sedge Bottlebrush squirreltail	44	86	936
9) Akron, Colorado	67	Wheatgrass-Grama-Needlegrass	Loamy plains #2	Buffalograss Blue grama Prickly pear cactus	28	82	477
10) Meeker, Colorado	34	Wyoming big sagebrush	Clayey slopes	Salina wildrye Wyoming big sagebrush Western wheatgrass	11	42	1,583

Table 2. *Continued.*

Location	MLRA[2]	Rangeland cover type[3]	Range site	Dominant species by weight (descending order)	Canopy Cover (%)	Ground Cover (%)	Standing Biomass (kg ha^{-1})
11) Blackfoot, Idaho	13	Mountain big sagebrush	Loamy	Mountain big sagebrush Letterman needlegrass Sandberg bluegrass	71	90	1,587
12) Blackfoot, Idaho	13	Mountain big sagebrush	Loamy	Letterman needlegrass Sandberg bluegrass Prairie junegrass	87	92	1,595
13) Eureka, Kansas	76	Bluestem prairie	Loamy upland	Buffalograss Sideoats grama Little bluestem	38	58	526
14) Sidney, Montana	54	Wheatgrass-Grama-Needlegrass	Silty	Dense clubmoss Western wheatgrass Needle & thread grass Blue grama	12	81	2,141
15) Wahoo, Nebraska	106	Bluestem prairie	Silty	Kentucky bluegrass Dandelion Alsike clover	27	80	1,239
16) Wahoo, Nebraska	106	Bluestem prairie	Silty	Primrose Porcupinegrass Big bluestem	22	87	3,856
17) Cuba, New Mexico	36	Blue grama-Galleta	Loamy	Galleta Blue grama Broom snakeweed	13	62	817
18) Los Alamos, New Mexico	36	Juniper-Pinyon Woodland	Woodland community	Colorado rubberweed Sagebrush Broom snakeweed	16	72	1,382
19) Killdeer, North Dakota	54	Wheatgrass-Needlegrass	Sandy	Clubmoss Sedge Crocus	69	96	1,613
20) Killdeer, North Dakota	54	Wheatgrass-Needlegrass	Sandy	Sedge Blue grama Clubmoss	71	88	1,422
21) Chickasha, Oklahoma	80A	Bluestem prairie	Loamy prairie	Indiangrass Little bluestem Sideoats grama	60	46	2,010

Table 2. *Continued.*

Location	MLRA[2]	Rangeland cover type[3]	Range site	Dominant species by weight (descending order)	Canopy Cover (%)	Ground Cover (%)	Standing Biomass (kg ha^{-1})
22) Chickasha, Oklahoma	80A	Bluestem prairie	Eroded prairie	Oldfield threeawn Sand paspalum Scribners dichanthelium Little bluestem	14	70	396
23) Freedom, Oklahoma	78	Bluestem prairie	Loamy prairie	Hairy grama Silver bluestem Perennial forbs Sideoats grama	39	72	1,223
24) Woodward, Oklahoma	78	Bluestem-Grama	Shallow prairie	Sideoats grama Hairy grama Western ragweed Hairy goldaster	45	62	1,505
25) Cottonwood, South Dakota	63A	Wheatgrass-Needlegrass	Clayey west central	Green needle grass Scarlet globemallow Western wheatgrass	46	68	2,049
26) Cottonwood, South Dakota	63A	Blue grama-Buffalograss	Clayey west central	Blue grama Buffalograss	34	81	529
27) Amarillo, Texas	77	Blue grama-Buffalograss	Clay loam	Blue grama Buffalograss Prickly pear cactus	23	97	2,477
28) Amarillo, Texas	77	Blue grama-Buffalograss	Clay loam	Blue grama Buffalograss Prickly pear cactus	10	87	816
29) Sonora, Texas	81	Juniper-Oak	Shallow	Buffalograss Curly mesquite Prairie cone flower Hairy tridens	39	68	2,461
30) Buffalo, Wyoming	58B	Wyoming big sagebrush	Loamy	Wyoming big sagebrush Prairie junegrass Western wheatgrass	53	59	7,591
31) Buffalo, Wyoming	58B	Wyoming big sagebrush	Loamy	Western wheatgrass Bluebunch wheatgrass Green needlegrass	68	60	2,901

Table 2. *Continued.*

Location	MLRA[2]	Rangeland cover type[3]	Range site	Dominant species by weight (descending order)	Canopy Cover (%)	Ground Cover (%)	Standing Biomass (kg ha^{-1})
32) Newcastle, Wyoming	60A	Wheatgrass-Needlegrass	Loamy plains	Prickly pear cactus Needle-and-thread Threadleaf sedge	11	77	1,257
33) Newcastle, Wyoming	60A	Wheatgrass-Needlegrass	Loamy plains	Cheatgrass Needle-and-thread Blue grama	56	81	2,193
34) Newcastle, Wyoming	60A	Wheatgrass-Needlegrass	Loamy plains	Needle-and-thread Threadleaf sedge Blue grama	32	47	893

[1] Interagency Rangeland Water Erosion Team is comprised of USDA-ARS staff from the Southwest and Northwest Watershed Research Centers in Tucson, AZ and Boise, ID, and USDA-NRCS staff members in Lincoln, NE and Boise, ID.

[2] USDA - Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. Agricultural Handbook 296. USDA - SCS, Washington, D.C.

[3] Definition of Cover Types from: T.N. Shiflet, 1994. Rangeland cover types of the United States, Society for Range Management, Denver, CO.

WEPP Effective Hydraulic Conductivities for Rangelands

When using WEPP on rangelands, the user should only use the time-invariant effective hydraulic conductivity (K_e) by setting the flag in line 2 of the soil file to 0. No provisions have been put in the model for changing K_e over time on rangelands. Therefore, users are advised against setting the flag in line 2 of the soil file to 1 when simulating rangeland conditions. Using a flag equal to 1 will allow the model to alter K_e based on cropland conditions. The selected input value for time-invariant K_e on rangelands must represent both the soil type and the management practice. This method differs from the curve number method in that no soil moisture correction is necessary since WEPP accounts for moisture differences via internal adjustments to the wetting front matric potential term of the Green and Ampt equation.

Baseline default equations for predicting WEPP optimized K_e values on rangelands were developed using rainfall simulation data collected on 150 plot-runs from 34 locations across the western United States (Table 1). K_e for each of the 150 plot-runs was obtained by optimizing the WEPP model based on total runoff volume (mm). Multiple regression procedures were then used to develop predictive equations for optimized K_e based on both biotic and abiotic plot-specific properties (Table 3). The resulting equations are as follows:

If rill surface cover (cover outside the plant canopy) is less than 45%, K_e is predicted by:

$$K_e = 57.99 - 14.05(\ln CEC) + 6.21(\ln ROOT10) - 473.39(BASR)^2 + 4.78(RESI)^2 \quad (1)$$

where CEC is cation exchange capacity (meq/100 ml), ROOT10 is root biomass in top 10 cm of soil (kg m^{-2}), BASR is the fraction of basal surface cover in rill (outside the plant canopy) areas based on the entire overland flow element area (0-1), and RESI is the fraction of litter surface cover in interrill (under plant canopy) areas based on the entire overland flow element area (0-1). BASR is the product of the fraction of basal surface cover in rill areas (FBASR, expressed as a fraction of total basal surface cover) and total basal surface cover (BASCOV). RESI is the product of the fraction of litter surface cover in interrill areas (FRESI, expressed as a fraction of total litter surface cover) and total litter surface cover (RESCOV).

If rill surface cover is greater than or equal to 45%, K_e is predicted by:

$$K_e = -14.29 - 3.40(\ln ROOT10) + 37.83(SAND) + 208.86(ORGMAT) + 398.64(RROUGH) - 27.39(RESI) + 64.14(BASI) \quad (2)$$

where SAND is the fraction of sand in the soil (0-1), ORGMAT is the fraction of organic matter found in the soil (0-1), RROUGH is soil surface random roughness (m), and BASI is the fraction

of basal surface cover in interrill areas based on the entire overland flow element area (0-1). BASI is the product of the fraction of basal surface cover in interrill areas (FBASI, expressed as a fraction of total basal surface cover) and total basal surface cover (BASCOV).

The user is cautioned against using equations 1 and 2 with data falling outside the ranges of data values upon which the regression equations were developed. Ranges of values for each variable used in equations 1 and 2 are given in Table 3. Equations 1 and 2 have not been independently validated, however, they performed well at predicting K_e compared to the data set from which the equations were derived (Figure 1). The residuals plotted in Figure 2 show no bias and are similarly distributed between the two equations. Predictions of K_e were used in the model to predict runoff volume and peak runoff rate with the results shown in Figures 3 and 4.

Table 3. Ranges of values for variables used to develop equations 1 and 2.

Equation 1			
Variable	Mean	Minimum	Maximum
CEC (meq/100 ml)	20	7	45
ROOT10 (kg m^{-2})	0.45	0.09	0.99
BASR (0-1)	0.06	0.00	0.27
RESI (0-1)	0.34	0.05	0.84
Equation 2			
Variable	Mean	Minimum	Maximum
ROOT10 (kg m^{-2})	0.69	0.12	1.95
SAND (0-1)	0.43	0.02	0.71
ORGMAT (0-1)	0.04	0.02	0.10
RROUGH (m)	0.013	0.005	0.045
RESI (0-1)	0.16	0.02	0.41
BASI (0-1)	0.05	0.00	0.34

Future Research Needs

The assumption used in WEPP (95.7) that hydraulic conductivity is spatially uniform and temporally constant on rangelands is completely inadequate. However, the data does not currently exist to improve upon such an approach. If models of infiltration, such as the Green-Ampt model, are going to continue to be built on the concept of relating a driving force for flow with a resistance to flow, then methods of isolating each factor and accurately measuring soil and vegetation properties associated with each factor need to be drastically improved. Experimental procedures need to be developed which will quantify and explain the spatial and temporal variability in *in-situ* saturated and unsaturated hydraulic conductivity. Plot and watershed studies play an important role in this effort, but must be better designed to collect all necessary information and uniformly applied across time and space so data are consistent and additive. The ARS should consider defining and implementing an experimental procedure involving laboratory

studies, rainfall simulation plots, permanent plots and small watershed areas at several locations throughout the U.S. which would provide the data necessary to build, validate and parameterize an infiltration model useful across all ARS hydrology and erosion models.

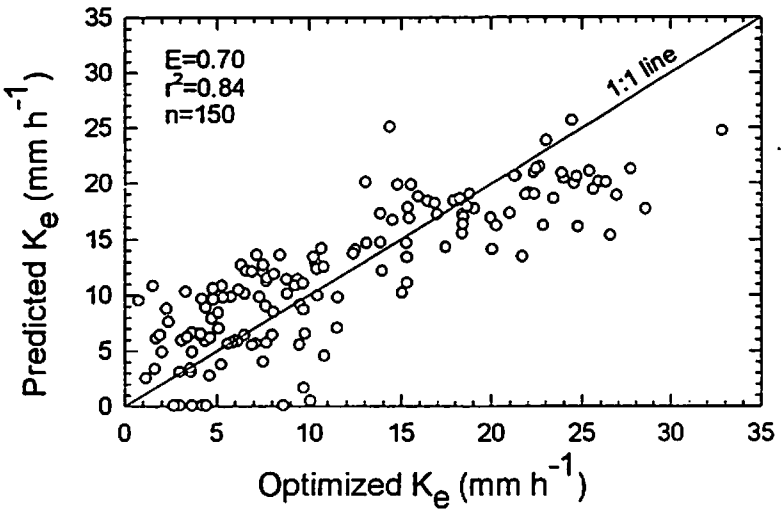

Fig. 1. Comparison of WEPP optimized and predicted effective hydraulic conductivity (K_e, mm h^{-1}) using equations 1 and 2. E is the coefficient of efficiency (Nash and Sutcliff, 1970), r^2 is the coefficient of determination and n is the number of data points.

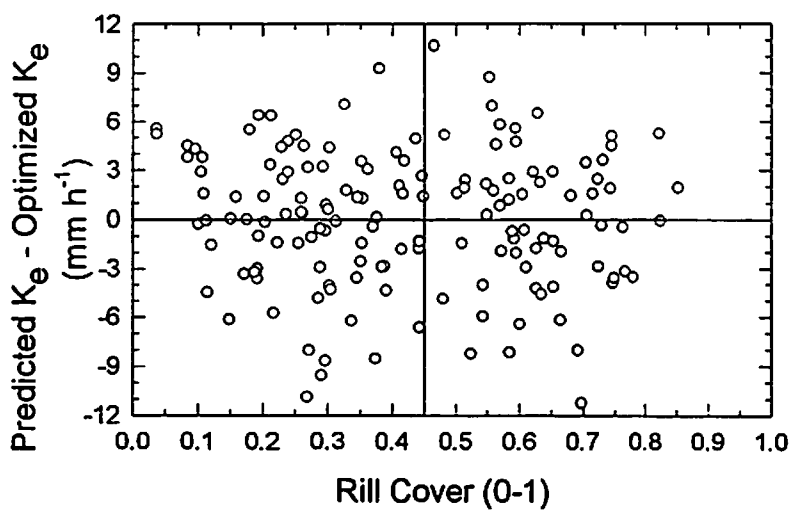

Fig. 2. Difference between WEPP optimized and predicted K_e using equations 1 and 2.

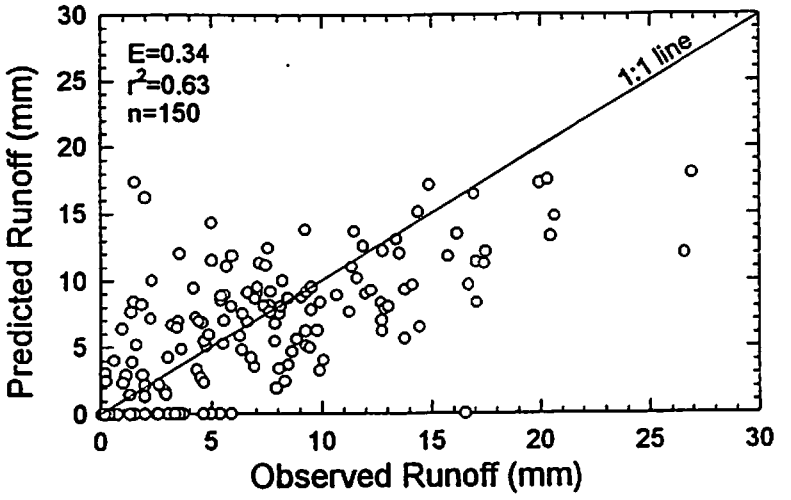

Fig. 3. Comparison of WEPP predicted runoff using K_e values estimated using equations 1 and 2 and observed runoff. The data set of observed runoff is from the same plots that equations 1 and 2 were developed from. E is the coefficient of efficiency (Nash and Sutcliff, 1970), r^2 is the coefficient of determination and n is the number of data points.

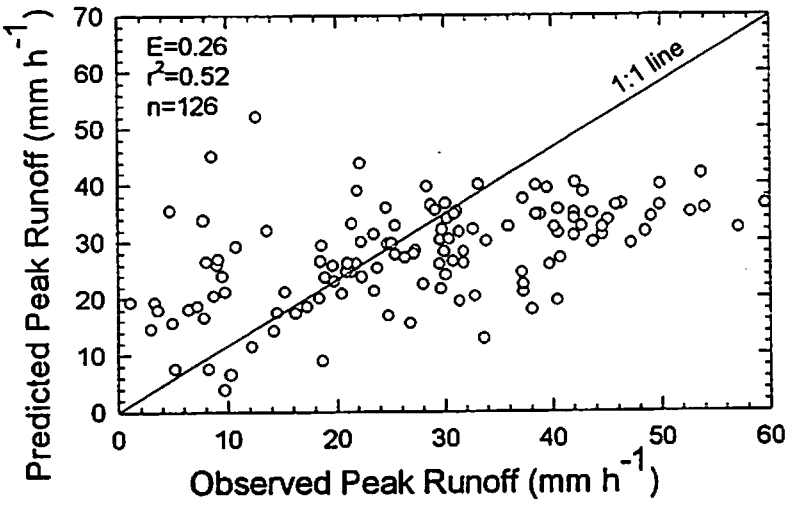

Fig. 4. Comparison of WEPP predicted peak runoff using K_e values estimated using equations 1 and 2 and observed runoff. The data set of observed peak runoff is from the same plots that equations 1 and 2 were developed from. E is the coefficient of efficiency (Nash and Sutcliff, 1970), r^2 is the coefficient of determination and n is the number of data points. The number of data points shown is 126 because 24 plots had zero predicted runoff.

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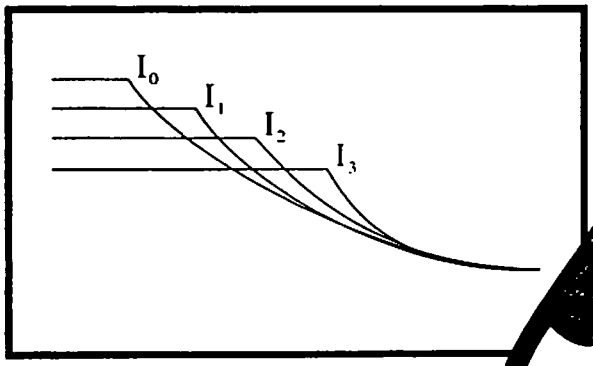

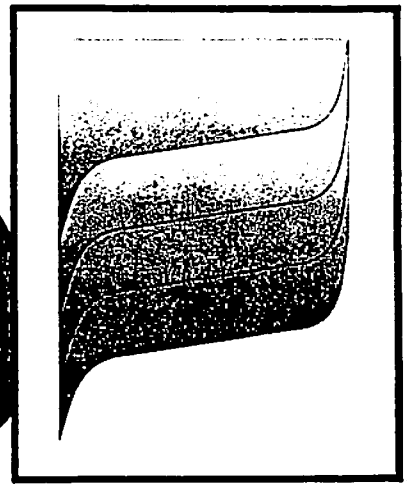

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