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TABLE OF CONTENTS

ARTICLES

Concentration and Sources of Fecal and Organic Pollution in an Agricultural Watershed
– *Daniel R. Dudley and James R. Karr* 911
Deterministic Hydrologic Modeling of Grazing System Impacts on Infiltration Rates
– *G. F. Gifford and R. H. Hawkins* 924
Comparative Evaluation of Statistical Methods for Water Supply Forecasting
– *Richard H. McCuen, Walter J. Rawls, and Bob L. Whaley* 935
Urbanization and Stream Quality Impairment
– *Richard D. Klein* 948
Optimal Water Use and Salinity Control for Energy – Upper Colorado River Basin
– *Marshall Flug, Wynn R. Walker, and Gaylord V. Skogerboe* 964
Phytoplankton in the Fox Chain of Lakes
– *S. D. Lin, R. L. Evans, and D. B. Beuscher* 974
Preliminary Identification of Price River Basin Salt Pick-up and Transport Processes
– *J. Paul Riley, David S. Bowles, D. George Chadwick, and William J. Grenney*. . 984
Elements of a Water Quality Information System for the State of Illinois
– *Ronald C. Flemal, Donovan C. Wilkin, and Ben B. Ewing* 996
Casing and Leak Depths, and Solute Travel Times to Wells
– *Anwar Battikhi and Don Kirkham* 1004
Ground Water Replenishment From Riverflow
– *Bessel D. van't Woudt, Jeffrey Whittaker, and Kelvin Nicolle* 1016
A Multiobjective Model for Regional Water Quality Management
– *B. N. Lohani and Pakorn Adulbhan* 1028
An Economic and Environmental Evaluation of Alternative Land Development Around Lakes
– *Judith A. Pickering and Richard A. Andrews* 1039
Procedure for the Economical Evaluation of Water Networks' Parameters
– *Gideon Oron and David Karmeli* 1050
Temporal Variation in the Nutrient Export of Rivers Draining into the Bay of Quinte, Ontario, Canada
– *C. K. Minns and M. G. Johnson* 1061
Factors for Predicting Commercial Water Use
– *Jae R. Kim and Richard H. McCuen* 1073
Extension of River Flow Records in Argentina From Long Tree-Ring Chronologies
– *R. L. Holmes, C. W. Stockton, and V. C. LaMarche, Jr.* 1081
Income Distribution Impacts of a Water Development Project – Boise Project, Idaho, 1950-1970
– *E. Susan Boydstun, Terry Nelson, and Roger B. Long* 1086
Petroleum Hydrocarbons in Urban Runoff
– *William Whipple, Jr. and Joseph V. Hunter* 1096
Statistical Terminology: Definitions and Interpretation for Flood Peak Estimation
– *Richard H. McCuen* 1106

WATER RESOURCES BULLETIN
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DETERMINISTIC HYDROLOGIC MODELING OF GRAZING SYSTEM IMPACTS ON INFILTRATION RATES[1]

G. F. Gifford and R. H. Hawkins[2]

ABSTRACT: Techniques for predicting the hydrologic effects of grazing schemes have heretofore been unavailable. The available literature on grazing intensity influences on infiltration rates is used as a basis for a model of infiltration behavior in response to grazing systems. Background, development, cautions, and an example are given.

(KEY TERMS: grazing; infiltration; models; hydrologic; environmental impact.)

INTRODUCTION

Grazing is a widely applied use of the vast wildland resources in the western United States. Although both cattle and sheep have been grazed since the first settlements, appreciation for the hydrologic impacts did not begin until about 1930, and despite the long period of use, little is specifically known regarding the hydrologic impacts of grazing. The applied hydrology techniques for dealing with the question are both primitive and poorly founded.

Grazing systems are in current widespread vogue for their anticipated benefits in both animal production and long-term forage production and condition. These systems are specialized plans of grazing management defined on recurring periods of grazing and deferment for two or more land units. There is essentially no coherent body of literature on the hydrologic impacts of these grazing systems, although Gifford and Hawkins (1976) have recently completed a critical review of some of the component problems. A detailed review of the management systems themselves is given by Hickey (1977).

This paper presents and examines a model synthesized around grazing intensity as a key input to impacting infiltration rates on grazing system pastures. These rates may be compared on a "before and after" basis to evaluate proposed grazing schemes, and with design rainfalls, converted to runoff volumes and rates for hydrologic comparisons.

BACKGROUND

A widely used descriptor of grazing activity is *grazing intensity*. As shown in Figure 1, it may be envisioned as a treatment, or rate of utilization of range forage. In the short

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run, grazing intensity is a description of the fraction of the current years' forage production utilized, as defined by selected key plant species. Over a longer time perspective, it is related to the general health or vigor of the same key species. Intensity is commonly reduced to four categories: ungrazed (rest), light, moderate, or heavy. It is locally defined and usually subjectively evaluated. As shall be seen, hydrologic identification has been linked to grazing intensity classifications.

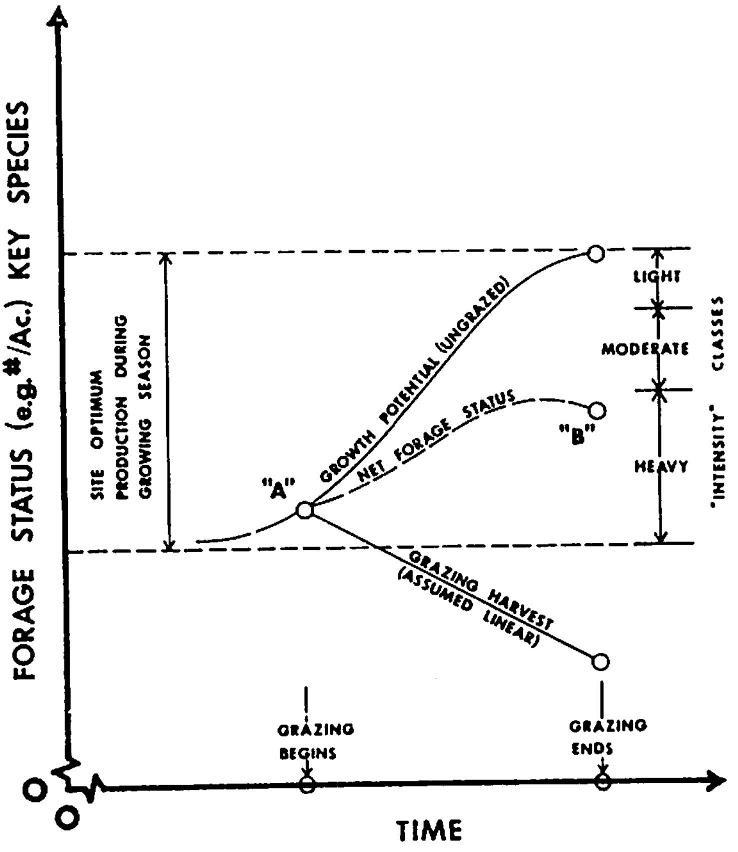


Figure 1. A Diagrammatic Representation of the Concept of Grazing Intensity. (Note that intensity is defined on the fraction of key species forage growth consumed over the duration of the activity, regardless of the input status or the interim rate of forage consumption. The path taken from "A" to "B" is unimportant. The boundary locations between the intensity classes are chosen locally, as are the key species, utilizing professional judgment of local ecology.)

The literature on grazing intensity influences on infiltration has been reviewed by Gifford and Hawkins (1978). Results from numerous studies have been evaluated, and only those data which were drawn from either actual rainfall or rainfall simulator experiments were used (this excluded flooding and soaking type experiments), and further winnowed to include only estimates of final near stable or long term constant rates. It is important to realize that the total infiltration volumes and the constant (end-of-run) rates provide different results for the evaluation of grazing, with the latter being the least sensitive, and perhaps even a poor evaluator of grazing impact in many instances. These data were studied for general relationships, and the following findings are relevant to this paper:

1. There is no statistical distinction between light and moderate grazing intensities as observed in the associated infiltration rates. They may be combined.
2. There is a distinct influence of grazing intensity on infiltration. Heavier grazing results in lower infiltration rates. As a general statement, moderate or light grazing reduces infiltration capacity to about 3/4 of the ungrazed condition; heavy grazing reduces it further, to about 1/2 of ungrazed.
3. Definite correlative relationships exist between infiltration rates under different grazing intensities. These are:

$$f_u = 0.281 + 1.025\, f_{m/l} \tag{1}$$

$$f_h = 0.405 + 0.374\, f_{m/l} \tag{2}$$

with all dimensions in in/hr, and symbols as defined in the Table of Symbols.

Statistical information on items 1 and 2 above are given in Table 1. Figure 2 shows the least squares fits relating infiltration rates under different grazing intensities as referenced to a combined light moderate intensity. As shall be seen, these form a basis for a grazing systems impact model.

TABLE 1. Results of Paired Data Analysis: Infiltration Rates (in/hr) Associated with Grazing Intensities.

Grazing Intensities						
Ungrazed	**Light**	**Moderate**	**Heavy**	**N**	**"t"**	**P (%)**
1.60 (1.00)	1.06 (0.60)			13	2.64	97.9
1.79 (0.73)		1.48 (0.50)		25	2.79	99.0
1.47 (1.01)			0.79 (0.43)	15	3.06	99.1
	1.43 (0.32)	1.56 (0.44)		10	-1.32	78.0
	1.10 (0.61)		0.82 (0.42)	17	2.16	95.3
		1.45 (0.44)	1.12 (0.29)	10	2.32	95.5
1.62 (0.82)	1.30 (0.61)*			31	3.21	99.7
	1.13 (0.64)*		0.82 (0.42)	17	2.28	96.1

NOTES: Table shows the mean infiltration rate in inches per hour with the standard deviation in parentheses. "t" statistic calculated by paired difference test. P is the probability in % associated with the "t" statistic (two tailed test). Starred (*) items are for light and moderate combined data. Source: Gifford and Hawkins, 1978.

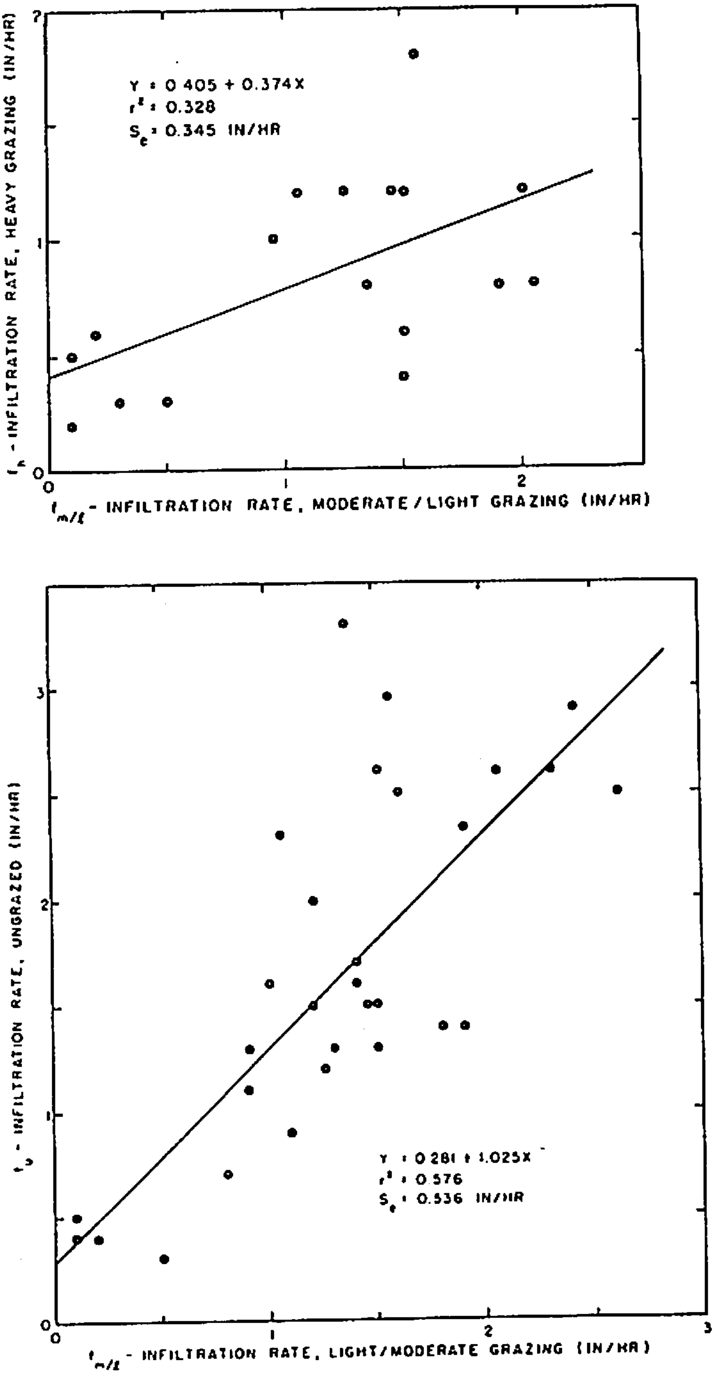


Figure 2. Relationships Between Infiltration Rates Under Different Grazing Intensities.

MODEL FORMULATION

The model is a march of infiltration capacity with time for a representative pasture in a grazing system. The synthesis of the grazing intensity impacts proceeds from the statistical relationships revealed in Equations (1) and (2), combined with assumptions of linear impact and recovery.

First, the specific infiltration rates identified by design grazing intensities provide boundaries between which all occasions must fall, and targets towards which rates will respond according to applied grazing intensities. These rates are defined by Equations (1) and (2), and on the basis of current infiltration status and grazing intensity (both user supplied).

Secondly, response to impacts (a targeted reduction in infiltration) is assumed to occur linearly and in entirety over the grazing episode duration. Although this does not violate the literature findings, it arises largely by default, and by a deficit of countrary information. Virtually all studies on the topic have ignored the time dimensions of grazing intensity impacts.

Third, recovery (a targeted increase in infiltration) is assumed to occur linearly over a characteristic recovery time, T. Literature reference to this is not common, but where available, has been found to be from 2 years to more than 13 years. Some data shows essentially no recovery with time, suggesting either that the recovery coefficient should be even larger or that in some instances grazing may have no measurable impact on infiltration rates. The recovery time can be easily visualized as a function of the land type, range condition, intensity of use, and climate. The algebraic expression of the recovery is given as

$$f = f_p + (f_t - f_p)(t/T) \qquad (3)$$

with symbols as defined in the Table of Symbols. Note that in some grazing schemes, a period of rest less than the recovery would not allow restoration to an ungrazed status. For example, a rest (no grazing) period of 1/2 year on a site with a recovery time T of 4 years would recover only 1/8 of the loss. Also, after the target rate is attained, no further recovery (past the target) is possible.

The model proceeds sequentially, impacting and recovering according to the above rules, and as outlined in the following steps:

1. The grazing system to be evaluated is defined in terms of grazing intensities and accompanying durations. As most systems currently popular prescribe discontinuous and sudden short term harvests of a high fraction of accumulated forage, such grazing periods may be validly classed as "heavy" intensity.

2. Given an initial infiltration rate and grazing intensity, target rates are established directly, or calculated. For example, under moderate/light grazing, the target rates for both ungrazed and heavy situations are calculated from Equations (1) and (2).

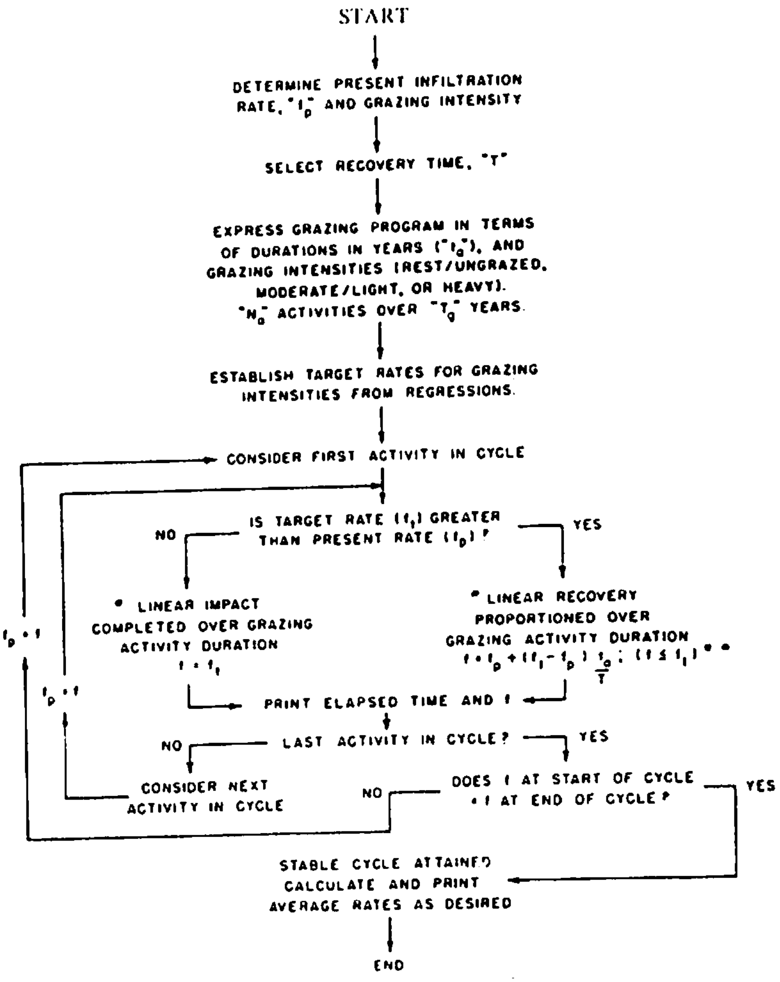
3. The impact or recovery from the first time element is then calculated. For example, with an initial moderate/light infiltration rate, if the first period is of heavy grazing, the impact occurs linearly over its duration. If the first period is a rest period, recovery occurs over its duration in accordance with Equation (3): If the first period represents moderate/light grazing, no change occurs.

4. The output from the above is used as the input for the next grazing period, again following the same rules. This is repeated for all periods throughout the cycle. The output is a matrix of times and infiltration rates.

5. The procedure is repeated over several cycles, until an equilibrium status results, in which the initial rate at the beginning of the cycle equals the final rate at the end of the cycle. This usually occurs after two cycles.

6. As desired, either average overall infiltration rates or average seasonal (summer rainstorm) rates may be calculated and used in evaluating hydrologic response.

The general procedure is given in flow chart form in Figure 3, and an example with notes is given in the following section.



* INDICATES PROCESS MAY BE MODIFIED AT USER OPTION

* * WHEN $t_g > T$, SPECIAL STEPS ARE REQUIRED TO AVOID RECOVERY PAST TARGET RATE.

Figure 3. Flow Chart of the Grazing Impact Model.

EXAMPLE

Given a range site under current moderate or light grazing, its current representative infiltration rate is judged to be 1.00 in/hr. A grazing system of the following structure is proposed (see Table 2):

1. From Equations (1) and (2), and knowing $f_{m/l}$ = 1.00 in/hr, the following rates for ungrazed (rest) and heavy situations are calculated:

$$f_u = 1.31 \text{ in/hr}$$

$$f_h = 0.78 \text{ in/hr.}$$

2. For the initial rest period, infiltration recovers toward an ungrazed target of 1.31 in/hr. The recovery time T is taken as 4.0 years. The infiltration at the end of the period is calculated as:

$$f = 1.00 + (0.25/4)(1.31 - 1.00) = 1.02 \text{ in/hr.}$$

3. For the heavy grazing period, the infiltration is reduced to the target value of 0.78 in/hr linearly over the duration of the activity.

4. The 2.00 year rest produces recovery towards the ungrazed target of 1.31 in/hr. Over the two year rest, this recovery is:

$$f = 0.78 + (2.00/4.00)(1.31 - 0.78) = 1.04 \text{ in/hr.}$$

5. The 0.25 year of heavy grazing causes infiltration reduction to the heavy grazing target of 0.78 in/hr, linearly over the 0.25 year duration.

6. The 1.25 year of moderate grazing causes infiltration to move towards the moderate/light target value of 1.00 in/hr, linearly for 1.25 year proportioned over a 4-year recovery time:

$$f = 0.78 + (1.25/4.00)(1.00 - 0.78) = 0.85 \text{ in/hr.}$$

TABLE 2. Example Grazing System.

Date		Duration	
From	To	(yr.)	Activity
1 April	1 July	0.25	Rest
1 July	1 October	0.25	Graze Heavy
1 October	1 October	2.00	Rest
1 October	1 January	0.25	Graze Heavy
1 January	1 April	1.25	Graze Moderate

One complete grazing cycle has been simulated. A second is computed using the last period output (0.85 in/hr) as input to the first period of the second cycle. The second cycle is stable: the final rate is equal to the initial rate. The results are summarized in Table 3, and shown graphically in Figure 4.

TABLE 3. Summary of Model Output for Example.

Date	Time (year) Cum.	Time (year) Inc.	Activity	Inf. Rate (in/hr) I	Inf. Rate (in/hr) II
1 April	0.00			1.00	0.85
		0.25	Rest		
1 July	0.25			1.02	0.88
		0.25	Graze Heavy		
1 October	0.50			0.78	0.78
		2.00	Rest		
1 October	2.50			1.04	1.04
		0.25	Graze Heavy		
1 January	2.75			0.78	0.78
		1.25	Graze Moderate		
1 April	4.00			0.85	0.85

Infiltration Rates: Annual: 0.87 in/hr
Summer Only: 0.90 in/hr

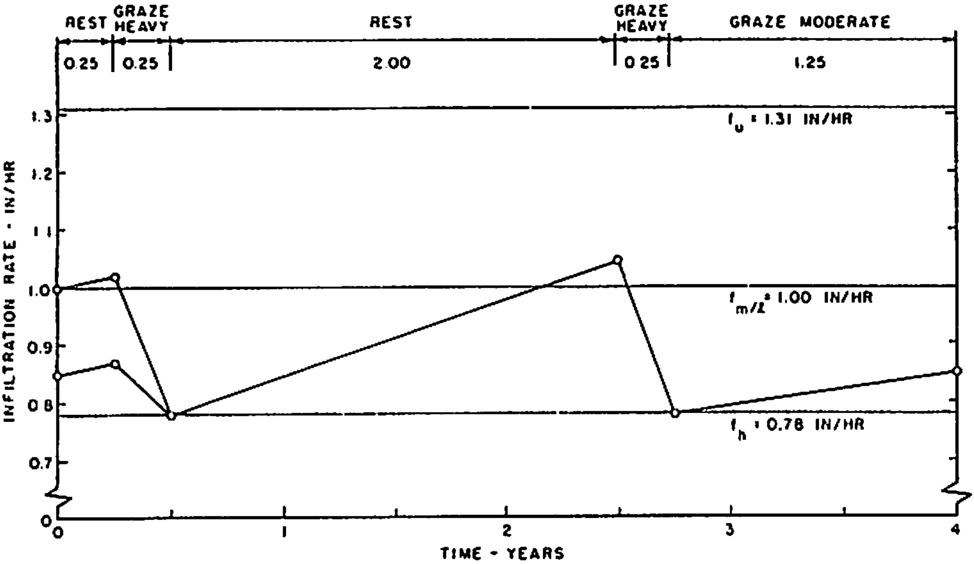


Figure 4. Graphical Representation of the March of Infiltration Rate with Time for Example Situation.

From the stable cycle, average rates for either the entire cycle or specific season (such as summer rainstorm periods) may be calculated. As shown in Table 3, this amounts to

0.87 and 0.90 in/hr, respectively, for the example. These rates, compared to an assumed alternate management of continuous moderate grazing, suggest a net overall reduction in hydrologic condition.

These rates might also be used as a basis for calculation of runoff volumes and peaks by conventional applied hydrology methods. They might be taken as ϕ indexes or as a basis for estimating runoff curve numbers. Some equations for making this latter conversion are given in Chapter 11 of Branson, Gifford, Renard, and Hadley (1979); and in Gifford, Hawkins, and Williams (1975), but are not presented here.

DISCUSSION

Usage

The model uses a direct field measurement (or estimate) of the initial infiltration rate, an estimate of grazing intensity, and a judged recovery time, T. However, the user should be fully aware of the psuedo-subjective nature of the intensity judgments that form the basis for the infiltration equations and the designation of the pasture grazing episodes in the systems as "heavy" intensity. Also, the intensity classifications have no necessary relationships with plant cover density. The model represents a state-of-the-art and should be applied with caution, and the user's judgment playing an overriding role.

As an example of the above caution, note in Figure 2 and Equation (2) that heavy intensity grazing apparently *improves* infiltration rates for inputs below about 0.65 in/hr. Such is certainly possible; the regressions make no inferences about the mechanics of the observed associations. However, because of the least squares linear fit and contradictions to popular understanding, usage of the equations at this level should be undertaken with caution and full awareness.

Alternate Impact Paths

In a similar vein, Figure 3 suggests possible user modification of the routine impact logic used thus far in the model. The assumption of linear impact over the grazing period duration is used as the simplest alternate in the face of no better or contradictory evidence. However, it might also be reasonable to assume that the *rate* of impacting is linear with time, or

$$\frac{d(f - f_t)}{dt} = \text{constant}. \qquad (4)$$

There are analagous reactions widespread throughout the physical and earth sciences; for example, Darcy's law, erosion equilibrium on disturbed sites (Megahan, 1974), or fuel moisture dynamics. Solution of (4) with appropriate boundary considerations leads to:

$$f = f_p + (f_t - f_p)(1 - \exp(-t/\tau)) \qquad (5)$$

where the symbols are as previously defined, and τ is a characteristic time constant, the time required for the infiltration to move $(1 - 1/e)$ or approximately 63 percent towards the final equilibrium status. The infiltration f approaches the target rate asymptotically with this arrangement, and thus short duration grazing produces less damage than longer episodes. This situation, while more in keeping with both reason and intuition, is completely unsupported by any known field data. Also, usage would require estimates of τ.

Other options which might be exercised upon the user's judgment for specific situations might be (1) to effect no change with moderate grazing in recognition of a commonly held (but unsupported) belief that a moderate land use is neither destructive nor beneficial to the environment, or (2) to program recovery in an exponential fashion as the above discussed impact modeling. Stochastic effects might be achieved by casting seasonal or long term recovery as a function of interim precipitation, which is also a generally unsupported idea.

SUMMARY

The hydrologic effects of grazing systems has been largely ignored in previous research, and thus their environmental impacts cannot be safely predicted from a basis of experience. There is, however, a limited information resource on the association between grazing intensity and infiltration. Utilizing these data, and making several necessary linking assumptions, a model of infiltration rate with time is synthesized, thus approximating the hydrologic influences of any proposed grazing system. Alternate assumptions of impact and recovery may be utilized in the model to meet user judgment or special needs.

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TABLE OF SYMBOLS

The following symbols are used (1 in = 2.54 cm):

f = final or long term infiltration rate (in/hr)

As subscripts on f:

p = at the beginning of a period ("present")
e = at the end of a period
t = target
h = under heavy grazing intensity
m = under moderate grazing intensity
l = under light grazing intensity
u = under rest conditions ("ungrazed")
m/l = under moderate or light grazing intensity; combined because the two intensities are hydrologically indistinguishable based on constant or near-constant infiltration rates.

T = linear recovery time, years

t = activity period duration, years; also shown as t_a

τ = (tau) exponential recovery time constant, years