OPTIMAL LIVESTOCK PRODUCTION OF REHABILITATED MINE LANDS

by

Fritz H. Brinck[1], Martin M. Fogel[2], Lucien Duckstein[3]

ABSTRACT

Strip mining leaves behind spoils to be recontoured to maximize the benefit of livestock production on the rehabilitated land. This paper designs watersheds to achieve a balance between two main range livestock requirements, forage and stock water by way of grading and furrowing man-made slopes.

The three design attributes, surface configuration, surface treatment, and range management policy are optimized with respect to maximal profit accounting for natural uncertainties in 3 variables, viz., time interval between storm arrivals, precipitation per storm event, and duration of the storm event. Runoff and sedimentation are modeled on an event basis as functions of said random variables. The stock water reservoir at the bottom of the watershed is dredged periodically. The stochastic model is applied to the Black Mesa in Northern Arizona which is in the process of being strip-mined for coal.

INTRODUCTION

In the Southwest, large scale surface mining is relatively new and there is much concern about rehabilitating the mine spoils to bring about a positive land use. In the Black Mesa region of northern Arizona, on the lands of the Navajo Nation, an area of 5700 ha eventually will have been turned upside-down when the surface mining for coal stops some 30 years from now. It has been and still is used as rangeland and has been heavily overgrazed (Verma and Thames, 1975). This semi-arid area lies at an elevation above 1800 m where the vegetation is classified as pinyon-juniper. Some climatological data recordings from Black Mesa starting in 1972 are published under Kayenta 21 SSW; Kayenta station has recorded precipitation data for many years. Average annual precipitation at Black Mesa is some 250 mm and more than 50% of the precipitation comes with the summer rainstorms during July through October. The distribution parameter estimates used in this paper are based partly on Kayenta data and partly on published analyses of data from other parts of Arizona.

PROBLEM DESCRIPTION

Once the situation described above has arisen and one is obliged to reclaim the land, it is clear that to landscape the area to make it look like it did before, not necessarily optimizes conditions for some planned land use. In general there are several uses that may come into consideration, either singly or in the form of multiple land use. As continued livestock production in the area probably is in harmony with the Navajo Nation's preferences for years ahead, it is natural to determine the surface configuration and surface treatment of the mine spoils that will benefit livestock production. This paper makes an analysis of how the economics of a single alternative, livestock production, is affected by surface geometry and surface treatment in order to find the economically optimal watershed design.

Forage yield obviously affects the efficiency of livestock production and May (1975, p. 334) states that "the biggest problem in reestablishing adequate stands of vegetation in these areas is the limited moisture available for plant growth." Accordingly it seems justified to analyze how surface configuration and surface treatment affect runoff and soil erosion, which in turn affect forage yield and volume of stock water available in the reservoir at the bottom of the slopes. May (1975) further writes that even in areas receiving less than 250 mm of annual precipitation, ecologically stable stands of vegetative cover can be established on strip mine overburden. Specifically, for Black Mesa, Verma and Thames (1975) have reported preliminary findings to the effect that reclaimed watersheds have great potential for use as rangeland. Three actions or decision variables are considered. 1. Average watershed slope steepness a_1. 2. Fraction a_2 of the watershed drainage area made subject to contour furrowing. 3. Range management policy a_3. The policy considered is either to maintain a <u>Good</u> range condition, or to let the range remain in <u>Poor</u> condition. The decision variables a_1 and a_2 are continuous on their intervals, whereas a_3 is discrete with two states, $a_3 = 1$ for Good range condition and $a_3 = \frac{1}{4}$ for Poor condition. The set (a_1,a_2,a_3) is denoted by $\underline{a}$.

The two variables a_1 and a_2 are assumed to be independent, i.e., within the limit of practically feasible grading any extent of contour furrowing is possible. There will be some overlap in effect as a gentle slope may have some of the runoff retarding and erosion reducing effect as furrows on a steeper slope. A level area, $a_1 = 0$, produces no stock water and no livestock, whereas the steepest slope gives

---

1. Graduate Research Assistant, Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ 85721.

2. Professor on joint appointment, School of Renewable Natural Resources and Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721.

3. Professor on joint appointment, Departments of Systems and Industrial Engineering and Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721.

many small watersheds with greater contouring costs. It also produces the highest peak flows and hence maximal sedimentation. Thus the steepest feasible slope probably is not optimal either. As regards a_2, no furrowing keeps forage production at a minimum. On the other hand a complete furrowing of the whole drainage area yields practically no stock water although most grass. Given that livestock production shall be maintained the optimum pair of a_1 and a_2 will lie in between these extremes.

THE STOCHASTIC MODEL

The model on which the cost-benefit analysis is based has a main body of relationships between precipitation, infiltration, runoff, and sedimentation describing discrete storm events and their effects. The storm events occur in a sequence throughout the years of project lifetime separated by random time intervals τ between storm arrivals. The time intervals are generated by random drawings from the proper probability distribution. For each storm event a pair of dependent drawings of rainfall depth $\underline{R}$ and event duration $\underline{D}$ are made from their joint distribution. The runoff and peak flow, if any, are computed with the Soil Conservation Service (SCS) formulas for each event for furrowed and for unfurrowed slopes separately. Also first year water storage capacity of the furrows is modeled as a random variable with a probability distribution. The year is divided into three seasons to allow for a dry spell with very few events. Distribution parameters and type of probability distribution may change from season to season.

The stochastic model is essentially that which is described above, but the term stochastic model will be used for the whole model as in stochastic livestock production model. In addition to the event based model the livestock production model includes computation of watershed geometry, average range carrying capacity over each year, feasible stocking level, and expected profit over the project lifetime. Figure 1 is an outline of the stochastic model.

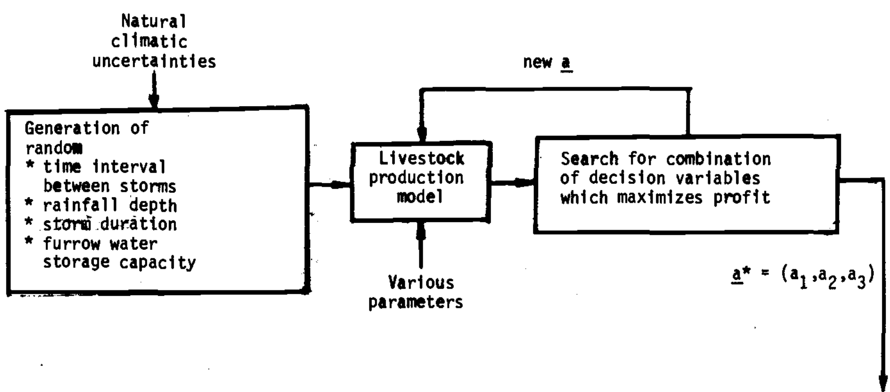

Fig. 1. Schematic diagram of the stochastic livestock production model.

The livestock production model is dynamic in the sense that it accounts for range carrying capacity fluctuations about a steady state condition, either Good or Poor. The model does not presume to describe transitions between the two states. The objective is to find the set of decision variables $\underline{a}^*$ which will maximize the mean profit of maintaining livestock production over a period of Y years. In the following sections, values for some of the many parameters are given; the reader is referred to BRINCK (1976) for complete details.

WATERSHED DESIGN

The total area leased for strip mining at Black Mesa is some 26,300 ha of which 5,700 ha will be stripped. The basal area or map area A_B of a watershed is supposed square, and assuming a reservoir surface area negligibly small in comparision with A_B, the drainage area consists of four equally large triangles. The drainage area is the grazing area for the livestock.

SURFACE CONFIGURATION

The stock water reservoir at the bottom of the watershed is the center of the livestock distribution on the watershed. The average maximal distance d upslope from the reservoir the cattle will travel is constrained by the steepness of the slope and this distance in turn defines the practical size of the watershed and its basal area A_B. Let the totally disturbed area be A_D. Then the ratio A_D/A_B gives the number of watersheds to be constructed. The unit watershed configuration is determined with the aid of Mueggler's (1965) relationship, based on a field study of cow chip distribution,

$$y = 107.06 + 100a_1 - 95.37 \exp\left(- \frac{1.094}{1000} d'\right) \quad \{\%\} \tag{1}$$

where: y = predicted accumulated land use (occupancy time) to d, in %, considering the total use on area as 100%,

a_1 = tan (average slope angle). $100a_1$ is slope steepness in %; a_1 is a decision variable,

d' = upslope distance from the water in m.

To find the drainage area A, eq. (1) is first solved for d with y = 100% and, after accounting for the fact that the watershed is square at its base, it is found that

$$A = 4d_0 \left(\frac{L_B}{2}\right) 10^{-4} \quad \{ha\} \tag{2}$$

$$\frac{L_B}{2} = d_0 \cos(\arctan(a_1)) = d_0(1 + a_1^2)^{-1/2} \quad \{m\} \tag{3}$$

and

$$A_B = 10^{-4} L_B^2 = A(1 + a_1^2)^{-1/a} \quad \{ha\} \tag{4}$$

L_B = length of one side of square watershed in m,

d_0 = shortest upslope distance up to the rim of the watershed.

SURFACE TREATMENT

The part of the watershed area to be contour-furrowed a_2 is a decision variable which is optimized together with slope steepness a_1. The kind of mechanical treatment referred to here as contour furrowing is characterized by parallel, horizontal furrows at 1 to 1.5 m distance between centerlines. Their depth would be around 15 to 25 cm, width some 150 cm with a trapezoidal intersection, and bottom width approximately 60 cm. This kind of furrow is described by Branson, Miller, and McQueen (1966). In order to model the storage capacity of the area a_2A the following exponential form is taken from Neff (1973),

$$F = voFo \exp(-(v+B)t_a) \quad \{mm\} \tag{5}$$

where: F = storage capacity of the contour furrowed area in mm,

t_a = time in years,

v_o = mean storage per effective furrow in mm,

F_o = ratio of number of effective furrows at time 0 to total number of furrows in the area,

ν = decay constant in yr^{-1},

β = probability of failure of any furrow.

In BRINCK (1976) a distribution for m with mean V.F. is derived; a value of 0.2 (yr^{-1}) for the decay time constant ($\nu+\beta$) was adopted.

POTENTIAL RUNOFF

In this paper three aspects of overland runoff are considered. First, runoff makes water available for harvesting, for example as here for the purpose of watering livestock. Secondly, decreased runoff means increased amount of water kept on the slopes and that in turn improves vegetation and range condition. Lastly, runoff from rangeland is the primary force in initiating soil movement and transporting sediments to reservoirs.

A modified version of the SCS rainfall-runoff formula was used for unfurrowed land,

$$Q = \frac{(R - I)^2}{R - I + S_L} \quad \{mm\} \tag{6}$$

where: Q = runoff depth per storm event in mm,

R = precipitation in mm,

I = initial abstraction including infiltration prior to runoff, in mm,

S_L = time varying maximal potential infiltration in mm.

The initial abstraction I is set equal to 1.0 for the summer and the dry season.

For the furrowed part of the slopes it must be taken into account that the soil moisture after a

For the furrowed part of the slopes it must be taken into account that the soil moisture after a potentially runoff-producing storm is higher than for the unfurrowed slopes. Hence the computation of possible runoff Q_F from furrowed slopes is a repetition of the procedure described above, accounting for the increased soil moisture,

$$Q_F = \frac{(R - I - F)^2}{R - I - F + S_{LF}}, \quad R > I + F \quad \{mm\} \tag{7}$$

where F is given by eq. (5) and S_{LF} is the time varying potential infiltration modified for furrowed land.

PEAK FLOW AND SEDIMENTATION

Sedimentation is estimated with the modified soil-loss equation (Smith, 1975).

$$z = 11.78(V_T q_p)^{0.56} K'CP(LS) \quad \{mt\} \tag{8}$$

where: z = sediment yield in metric tons per event,

q_p = peak flow in m^3/s,

K' = soil erodibility factor,

C = cropping management factor,

P = erosion control factor,

LS = slope length and gradient factor.

Values for four factors K', C, P, and LS can only be had through field studies. Here the product of the factors is approximated by

$K = K'CP(LS) = a_1$	if range condition	Good (a_3=1)
$K = K'CP(LS) = 3a_1$	is	Poor (a_3 = 1/4),

and

$$V_T = 10 A_B \left[(1-a_2)\, Q + A_2\, Q_F\right] \tag{9}$$

is the total runoff volume stored in the water reservoir during each rainfall event.

SEASONAL DISTRIBUTIONS

It was found by Fogel, Duckstein, and Sanders (1974) on the basis of Tucson Arroyo data that the distribution of the number of storm events k in the summer could be modeled by the Poisson distribution. It follows from accepting that distribution that the time interval t between storm arrivals is exponentially distributed. It is assumed that the Poisson distribution is also valid for the Black Mesa region. Winter storms are generally less intense and more widespread than summer storms and do not lend themselves so easily to the notion of a discrete event. Kao, Duckstein, and Fogel (1971) found that the number of storm groups occurring during the winter season also could be described by a Poisson distribution. Table 1 shows the time interval density distributions, and Table 2 contains the numerical values for the estimates of the distribution parameters.

Point rainfall R and duration D for each storm event are dependent random variables for which Crovelli in 1971 suggested a bivariate gamma distribution (Fogel, Duckstein, and Kisiel, 1974). Rao and Chenchayya (1974) presented this distribution in the following form

$$f_{R,D}(R,D) = \begin{cases} \kappa\eta e^{-\eta R}(1 - e^{-\kappa D}), & 0 \leq D \leq \frac{\eta}{\kappa} R \\ \kappa\eta e^{-\kappa D}(1 - e^{-\eta R}), & 0 \leq R \leq \frac{\kappa}{\eta} D \end{cases} \tag{10}$$

where: $f_{R,D}(R,D)$ = bivariate gamma probability density distribution,

R = rainfall per storm in mm,

D = storm duration in hr,

κ,η = distribution parameters > 0.

Table 1. Probability density distributions of time interval τ between storm arrivals.

Season	Distribution of time interval τ between storm arrivals
Summer	Exponential (Fogel, Duckstein, and Sanders, 1974)
	$f_\tau(\tau) = \lambda e^{-\lambda\tau} \quad 0 \leq \tau$
	$E(\tau) = \frac{1}{\lambda}$ (season), $\lambda = \bar{k}$
Winter	Exponential (Kao et al., 1971)
Dry	Gamma
	$f_\tau(\tau) = \lambda \frac{(\lambda\tau)^{\alpha-1}}{\Gamma(\alpha)} e^{-\lambda\tau} \quad 0 < \alpha$
	$E(\tau) = \frac{\alpha}{\lambda}$ (season)
	$\mathrm{var}(\tau) = \frac{\alpha}{\lambda^2}$

Table 2. Distribution parameter estimates -- Fogel, Duckstein, and Kisiel (1974); Kao et al. (1971); Climatological records for Kayenta 1953-1974.

	Seasons		
	Summer	Winter	Dry
τ (day)	123	151	91
Average seasonal rainfall (mm)	132	70	28
$\bar{k}$ (#/season)	7	7	3
$\bar{R}$ (mm)	13	10	10
$\bar{D}$ (hr)	2.5	34	34
α (1)	1	1	.2
λ (#/season)	10	7	.6
κ (hr^{-1})	.8	.06	.06
η (mm^{-1})	.19	.17	.14

RANGE CONDITION AND CARRYING CAPACITY

The following three factors are considered in the range model:

1. Present and preceding years' precipitation.
2. Contour furrowing.
3. Range management policy to obtain Good, $a_3 = 1$, or Poor range condition, $a_3 = ¼$.

The feasible herd in the jth year is

$$N_j = \min(N_h, N_w) \quad \text{(head)} \tag{11}$$

where: N_h = herd size matching annual grazing capacity in number of head,

N_w = herd size matching annual stock water supply in number of head,

At the end of one simulation run the efficient herd N_y which is 90% of the average herd (Martin, 1975a) is computed and the sequence of Y years is run through again to compute annual deviations in the form of stock water shortage or surplus, and over- or undergrazing.

THE OBJECTIVE FUNCTION

The objective function $L(\underline{a})$, to be maximized, is defined as the difference between the present value of the returns and the present value of the costs for the whole area to be reclaimed

$$L(\underline{a}) = P(\underline{a}) - K(\underline{a}) \quad (\$) \tag{12}$$

where: $L(\underline{a})$ = profit function in \$,

$\underline{a}$ = reclamation scheme, i.e., decision variable vector,

$P(\underline{a})$ = present value of returns over Y years, in \$,

$K(\underline{a})$ = present value of costs over Y years, in \$.

The costs considered as reclamation costs are grading costs, furrowing costs, and reseeding costs. Other costs include reservoir construction and periodic dredging, range management policy, and stock water supplement. Again, all these costs are discussed in detail in BRINCK et al. (1976).

DISCUSSION AND CONCLUSIONS

The annual return to management from cattle or sheep production in the southwest of the United States is about $10 per AU (Ogden, 1975). If the yearlong carrying capacity of the range averages 0.05 AU per ha of range in Good condition, the return from each ha is 50¢ per year. Furrowing costs about $50 per ha, and livestock production cannot carry such investments with a 30 year project lifetime and 5% discount rate. The optima were accordingly found on the basis of a reduced profit function G_{red} excluding reclamation and reservoir construction costs. That leaves the reduced profit function with the costs of reservoir dredging, the cost of range upkeep, and the cost of hauling water in case of occasional stock water shortages.

The Monte Carlo simulation covered 30 years project lifetime, and 35 runs were made for each reclamation scheme. Figures 2 and 3, and Tables 3 and 4 present results.

SUMMARY OF RESULTS

1. Cattle production on a Poor range has a smaller total loss than production on the same area in Good condition; in terms of profit -$716,128 versus -$832,546. The standard deviation is less than $7000. The model uncertainties, however, render this difference insignificant.

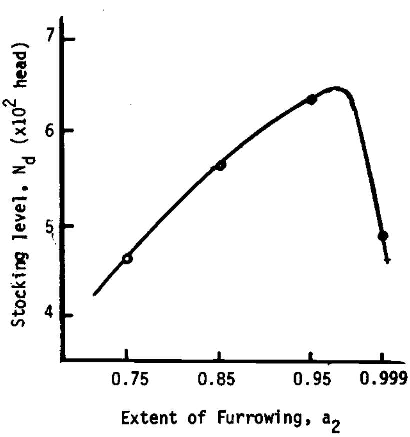

Fig. 2. Stocking level, for good range condition, as a function of furrowed area.

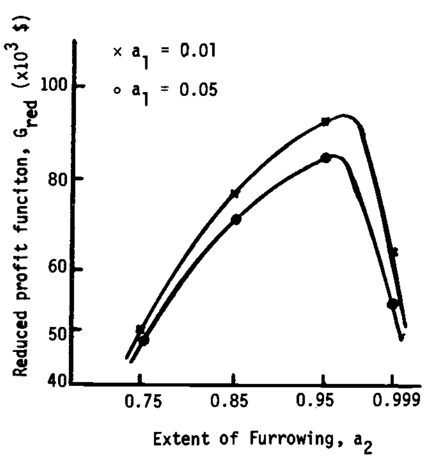

Fig. 3. Reduced profit function of cattle production, for good range condition, as a function of furrowed area.

2. Maximal profit of cattle production excluding costs of reclamation and reservoir construction is G^*_{red} = \$92,000 for the range in Poor condition. This maximum is reached for

$$\underline{a}^* = (0.01, 0.95, 0.25)$$

3. Maximal profit of cattle production excluding costs of reclamation and reservoir construction is G^*_{red} = \$87,000 for the range in Good condition. The optimal design is about the same as for the Poor condition.

4. Maximal cattle stocking level is about 650 head for the Good range.

5. Maximal cattle stocking level is about 200 head for the Poor range.

6. The average ratio of runoff to precipitation is about 3.5% over all storm events.

CATTLE GRAZING

The efficient stocking level goes up with increasing extent of furrowing up to a threshold. The Good condition implies that the furrows are maintained at their initial storage capacity, whereas in the Poor condition the furrows are modeled to decay. With an expected furrow longevity of some 10 years, furrowing has a smaller effect for the Poor range than for the Good, considering a project lifetime of 30 years.

Increased furrowing reduced the runoff available for stock water, and from a_2^* about 0.95 and on, the unfurrowed area which is the major runoff producer becomes too small and the herd is correspondingly reduced. For lower degrees of furrowing there will be surplus runoff which is not accounted for by the model, but which may represent a source of income from other uses. In a climate with even higher intensity summer rainstorms than in Arizona, the stock water-reducing effect of the furrows will be weaker because the furrows will then be overtopped more often and contribute to producing stock water. In these simulations the rainfall distribution parameters were set to simulate an average of 230 mm. Along with reduced runoff with increased furrowing, the soil transportation down the slope is also reduced, and a smaller reservoir dredging cost results. Also, when a_2 approaches 1 the carrying capacity with respect to forage is continuously increased to a maximum, and when this coincides with a reduced stocking level overgrazing will occur less often with the effect of making range upkeep cost smaller. But it is seen in Figure 3 that these reductions are not large enough to compensate for the reduced herd size as the reduced profit function follows the stocking level closely. Including the cost of building the reservoir would probably push a_2^* toward lower values. When the runoff producing area gets smaller the natural uncertainty present in the precipitation results in greater relative variability in the runoff. That in turn may lead to larger reservoir construction cost per livestock head in order to build into the reservoir reserve capacity in proportion to the variability.

Table 3. Simulation results for a_1 = 0.01 (n_D = 3.5).

a_2		0.75	0.85	0.95	0.999
N_D	(head)	480	570	636	490
σ	(head)	7.3	8.3	10.6	24.6
G_{red}	(\$)	49,435	74,898	88,613	59,011
σ	(\$)	7,513	3,037	2,825	4,840

Table 4. Simulation results for a_1 = 0.05 (n_D = 5).

a_2		0.75	0.85	0.95	0.999
G_{red}	(\$)	51,172	77,075	91,279	66,381
σ	(\$)	7,525	3,044	2,796	4,290

CONCLUSIONS

1. Livestock production alone cannot with its present (1975) level of returns carry the cost of land reclamation.

2. The profit of livestock production on a Good range is about the same as on a Poor range. The effort of maintaining the Good condition is not worth it in terms of economic efficiency.

3. In most years the constraint on herd size is the carrying capacity of the range.

4. A small reduction in the furrowed area as given by the optimum will release runoff for other uses. The marginal loss from a reduced herd shall have to be compared with the return from other water uses.

5. Possible other on-site water uses could be a runoff farm, or a fish pond.

ACKNOWLEDGEMENTS

The authors are grateful to Prof. John L. Thames for the support that made this study possible and for his interest and constant encouragement. We owe many thanks to Prof. Phil R. Ogden without whose insight in range management this work hardly could have found the form it has. He has served as catalyst for important model developments. Further, we would like to thank Prof. Don Davis and Visiting Prof. Ferenc Szidarovszky for listening and helping. The latter also supplied two computer subprograms.

REFERENCES CITED

Branson, F. A., Miller, R. F., and McQueen, I. S. 1966. Contour furrowing, pitting, and ripping on rangelands of the western United States. J. Range Mgmt. 19:182-190.

Brinck, F. H. 1976. A stochastic livestock model for cost-benefit analysis of reclamation of disturbed lands. Master's thesis, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona.

Fogel, M. M., Duckstein, L., and Kisiel, C. 1974. Modeling the hydrologic effects resulting from land modification. Trans. ASAE 17:1006-1010.

Fogel, M. M., Duckstein, L., and Sanders, J. L. 1974. An event-based stochastic model of areal rainfall and runoff. Proc. Symp. Statistical Hydrology. Misc. Publ. No. 1275, USDA.

Kao, S. E., Duckstein, L., and Fogel, M. M. 1971. A probabilistic model of winter rainfall. Proc. Fall National Meeting American Geophysical Union, San Francisco.

Martin, S. Clark. 1975a. Stocking strategies and net cattle sales on semidesert range. USDA For. Serv. Res. Pap. RM-146. Rocky Mt. For. and Range Exp. Stn. Fort Collins, Colorado.

May, M. 1975. Moisture relationships and treatments in revegetating stripmines in the arid West. J. Range Mgmt. 28:334-335.

Mueggler, W. F. 1965. Cattle distribution on steep slopes. J. Range Mgmt. 18:255-257.

Neff, E. L. 1973. Water storage capacity of contour furrows in Montana. J. Range Mgmt. 26:298-301.

Ogden, P. R. 1975. Personal communication. School of Renewable Resources. University of Arizona, Tucson.

Rao, R. A., and Chenchayya, B. T. 1974. Probabilistic analysis and simulation of the short time increment rainfall process. Tech. Rep. No. 55. Purdue University Water Resources Research Center.

Smith, G. H. 1975. A stochastic sediment yield model for Bayesian decision analysis applied to multipurpose reservoir design. M.S. Thesis, University of Arizona, Tucson.

Thames, J. L. 1975. Personal communication. School of Renewable Natural Resources, University of Arizona, Tucson.

Verma, T. R., and Thames, J. L. 1975. Rehabilitation of land disturbed by surface mining coal in Arizona. J. Soil and Water Cons. 30:129-131.