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PREDICTING STREAMFLOW CHANGES CAUSED BY FOREST PRACTICES USING THE EQUIVALENT CLEARCUT AREA MODEL

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TABLE OF CONTENTS

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George H. Belt

A PROBLEM AND A SOLUTION

The Equivalent Clearcut Area (ECA) Model evolved through the collective efforts of hydrologists with the USDA Forest Service, Northern Region (R-1). The equivalent clearcut concept was first conceived and applied by H. Lee Silvey, who described a "water yield increase analysis procedure" for the Nezperce National Forest. Silvey's procedure and subsequent modifications and extensions by his co-workers are described in the USDA Forest Service publication, Forest Hydrology, Part II, (USDA 1974). This document describes applications of the method on National Forests in Idaho, Washington, and Montana, where spring snowmelt is the dominant hydrographic event. For this reason, the model is designed to describe changes in mean annual streamflow and does not model individual storm events. The purpose of the following discussion is to generalize these various applications into a single framework, hereafter referred to as the ECA model, and to evaluate the model as a predictive tool.

Initially, the ECA model was conceived as a means of estimating the hydrologic impact of additional timber sales in a drainage where previous harvesting or other land use activities had already occurred. The objective was not a highly accurate annual forecast of streamflow, but a projection of streamflow change over time, assuming average climatological conditions and the current hydrologic condition of the watershed.

Forest management normally dictates multiple harvests of timber at different locations and times within a drainage. The times, places, and volumes of timber harvested are guided by the appropriate silvicultural practices, but determined by many additional considerations in the context of multiple-use management. The ECA model is the expression of future aggregate increases in water yield expected as a result of both past and proposed timber harvests. Predictions of water yield increase thus obtained are evaluated using predetermined criteria and standards developed for each National Forest.

At the initial stage of development, the model was used primarily as a tool for project level, e.g., timber sale, planning. A typical problem is illustrated by the following example:

> Given a timbered drainage of 2500 acres with average annual precipitation of 60 inches and streamflow of 22 inches, determine the potential impact on water yield and channel stability of two 80-acre timber sales planned for 1978 and 1980. Consider in the evaluation the effects of previous treatments, i.e., a 200-acre commercial thinning and 65-acre clearcut block harvested in 1964, a 230-acre fire which denuded the site and was replanted in 1965, and a 120-acre powerline right-of-way cleared in 1972 and maintained in brush.

More recently the model has been coded for the computer and used in formulating environmental impact statements under the requirements of the National Environmental Policy Act (Rosgen 1974). The equivalent clearcut area concept, as will be illustrated later, facilitates consideration of the hydrologic impacts of different forest practices in both time and space. Hence, the model lends itself to either project level planning or the broader unit planning level necessary for land use allocation and environmental impact assessment.

The following presentation describes the basic form of the model. Some of the refinements incorporated in

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specific applications and described in Forest Hydrology, Part II, have been omitted for clarity of presentation. The author gratefully acknowledges the cooperation of Forest Service colleagues in the conduct of this review, but assumes full responsibility for its contents.

THE ECA MODEL

The ECA Model in Concept

The basic concept devised by Silvey (1970) which subsequently evolved into the R-1 ECA Model can be summarized procedurally:

1. Determine water yield for each elevation zone assuming no management activity using local precipitation or other available data.

2. Establish the water yield increase which would occur within each zone if harvested by clearcutting.

3. Determine the water yield increase from other silvicultural or related activities and express this as a percent of the increase resulting from clearcutting.

4. Project changes in long-term water yield increase as vegetation is reestablished, and express this as a percent of the original increase by habitat types.

5. Using selected criteria, compare the projected change to management standards as indicated below in Table 1.

General Form of the ECA Model

The model is designed to estimate changes in mean annual streamflow resulting from forest practices or treatments which remove or reduce vegetative cover. Treatments here refers to harvest systems, e.g., thinnings, partial cuts and clearcuts, but also includes road constructions, power line and ski-slope clearings, and natural occurrences which alter the hydrologic character of the land–fire, avalanche, and insect infestations. The watershed is described in the model as a distributed system where differences in hydrology are stratified by habitat type, elevation, and time. The driving variable is the treatment, i.e., the acreage altered by nature or man through application of a forest practice. The watershed is modeled as a system in equilibrium; when forest practices are applied to the land, the equilibrium is interrupted, and the effects of the practices are described over time. Information derived from the model consists of estimates of mean annual streamflow and changes in equivalent clearcut area over time. The major feature of the model is the aggregation of the effects of such treatments over space (by drainage system) and time, in terms of a single parameter, equivalent clearcut area.

Equivalent clearcut area is a normalizing concept relating the hydrologic effects of any treatment (T) at any time (t) to the hydrologic changes produced by clearcutting, a particular treatment, during the first year after its occurrence. Equivalent clearcut area was defined by Silvey (1970) as the "total area within a drainage that exists in an (equivalent) clearcut condition" in any given year (t); thus ECA is a means of lumping the hydrological effects of treatment. The ECA concept is incorporated in the model by use of three dimensionless factors, τ, ω, and ρ defined below.

Treatment Factor (τ)

The fraction of treated area (A) which can be considered as clearcut area is expressed as the treatment factor (τ). Below, τ is defined in terms of vegetation density (D) and treatment (T). Various measures of vegetation density, e.g., board foot or crown cover or percent crown removal, may be used. However, the relationship must be defined from site specific observational data for *each* treatment (T) as shown below.

$$\tau\,(D,T) = f(t = 1, T,D) \tag{1}$$

Table 1. Criteria and standards for evaluating streamflow changes.

CRITERIA	STANDARDS: Nominal values	Data source
Average annual runoff	110% norm	Discharge records
Peak flow or average monthly runoff	115-120% norm	Discharge records
Channel impact period	120% norm	Discharge records
Channel stability	Subjective rating	Field data
Drainage order	3rd - 4th - 5th	Map

The notion $t = 1$ indicates the relationship is defined for the first year after treatment and remains constant thereafter.

Water Yield Increase Factor (ω)

The change in water yield attributable to treated acres in elevation zone (E), $t = 1$, referred to as the on-site water yield increase factor (ω), is defined as:

$$\omega(E) = f(t = 1, E) \qquad (2)$$

Note that $\omega(t = 1,E)$ refers to that fractional component of on-site water yield attributable to the treated acreage in an elevation zone (E), which appears as streamflow. Thus, ω implicitly expresses the routing of subsurface flow from each elevation zone to the channel.

Recovery Factor (ρ)

The recovery factor introduces into the model differences in vegetative regrowth rates subsequent to harvest. For each habitat type, ρ expresses net changes in the rates of interception, evapotranspiration, soil water storage and redistribution of snow, which over time alter water yield. The factor (ρ) can be considered a means of modifying the water yield increase factor (ω) to reflect differences in time and habitat type. The recovery factor (ρ) is defined as:

$$\rho(t,H) = f(t,H) \qquad (3)$$

Computationally, ρ is calculated to express the water yield increase following regrowth of vegetation as a fraction of the initial condition, i.e., the increase obtained during the first year after treatment.

In practice, ρ, τ, and ω were determined for average climatological conditions and based on local data where available. Illustrative relationships are shown in Figure 1. These examples are derived from relationships which appear in Forest Hydrology, Part II.

A fourth relationship necessary in the model development is the water yield of undisturbed land expressed as a function of elevation:

$$\bar{q}(E) = f(t = 0,E) \qquad (4)$$

Use of the bar above a symbol, e.g., $\bar{q}$, denotes an average value obtained over several years of record. The notation $t = 0$ refers to the time prior to treatment, the reference condition. Treated areas (A) within the watershed are stratified by elevation zone (E), habitat type (H), vegetation density (D) and type of land use treatment (T). Equivalent clearcut area for each elevation zone and time (t) can then be expressed as:

$$ECA(t,E) = \sum\sum\sum A(t = 1,E,T,H,D) \cdot \tau(T,D) \cdot \rho(t,H)$$
$$\text{where } T = 1,M \quad H = 1,N \quad D = 1,K \qquad (5)$$

for any time (t) the total ECA within a drainage is then:

$$ECA(t) = \sum_{E = 1,L} ECA(t,E) \qquad (6)$$

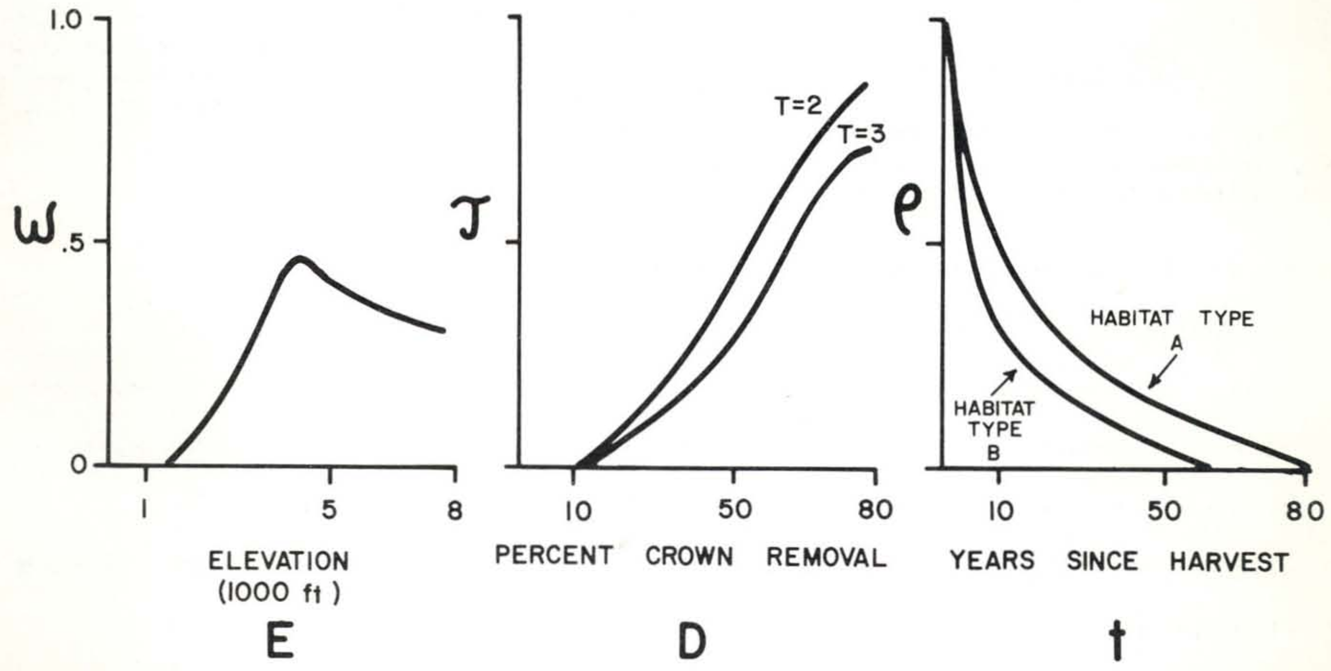

Figure 1. Dimensionless factors used to determine ECA. The functional relationships shown are illustrative; they are not appropriate for general application.

and streamflow increase, ΔQ at time (t), is given by:

$$\Delta Q(t) = \sum_{E=1,L} ECA(t,E) \cdot \bar{q}(E) \cdot \omega(E) \qquad (7)$$

Model Summary

The General Model is then summarized as:

Treatment Factor

$$\tau(D,T) = f(t = 1,T,D) \qquad (8)$$

Water Yield Increase Factor

$$\omega(E) = f(t = 1,E) \qquad (9)$$

Recovery Factor

$$\rho(H,t) = f(t,H) \qquad (10)$$

Water Yield, Undisturbed Land

$$\bar{q}(E) = f(t = 0,E) \qquad (11)$$

Equivalent Clearcut Area

$$ECA(t) = \sum_{E = 1,L} ECA(t,E) \qquad (12)$$

Annual Streamflow Increase

$$\Delta Q(t) = \sum_{E=1,L} ECA(t,E) \cdot \bar{q}(E) \cdot \omega(E) \qquad (13)$$

Symbols used above are defined in Table 3 of the Appendix.

Equations 12 and 13 represent the basic outputs of the model. Through use of the appropriate summations, these equations can be used to provide various projections of allowable ECA or streamflow increase in time and space which are useful in planning. Operational forms of the model documented by Rosgen (1974), Galbraith (1975), and Isaacson (1977) incorporate the necessary bookkeeping procedures for such planning, along with the model.

Use of local data to define the relationships shown in Figure 1 is the basic means of refining the general model to specific applications. Local data for ρ, ω, and $\bar{q}$ account for geographical variation in climate, soil, and related ecological conditions. Similarly, differences in management standards or silvicultural practice are incorporated in the model through the treatment factor (τ).

Note that equations 8-13, which constitute the general model, do not explicitly contain the processes (terms) in the annual water balance equation expressed below in equation 14. It is the change in streamflow (ΔQ) which is predicted, not $\bar{Q}$. Precipitation (PPT) and evapotranspiration (ET) are implicitly contained in equations 11 and 10, respectively. Hence, an independent algebraic check of the water balance is not possible unless independent estimates of ET and PPT are made.

Model Verification

Verification of a model is the process of checking the internal logic of the modeled relationships. Internal logic for the ECA model is based on the normal annual water balance equation, which can be expressed as:

$$\bar{Q}(t = 0) = \overline{PPT}(t = 0) - \overline{ET}(t = 0) \pm \bar{S}(t = 0) \qquad (14)$$

Here S refers to soil water, ground water, and snow storage as influenced by interception and redistribution of precipitation at the surface. As indicated previously, knowledge of the above relationships is assumed for land in an undisturbed or "natural" condition. The natural or reference condition is indicated by $t = 0$, and the bar denotes a statistical norm.

Within a given ecosystem and climatic regime, variation in the annual runoff, $Q(t) - \bar{Q}(t = 0)$, is the result of (1) climate fluctuations and (2) the effects of forest practices. This is expressed as:

$$Q(t) = \bar{Q}(t = 0) \pm \Delta Q_*(t) \pm \Delta Q(t) \qquad (15)$$

Here $\Delta Q_*(t)$ is annual variation in streamflow caused by climate, as indicated by the asterisk.

$$\Delta Q_*(t) = \pm \Delta PPT(t) \pm \Delta ET_*(t) \pm \Delta S_*(t) \qquad (16)$$

Assuming land use does not alter precipitation, i.e., $\Delta PPT(t)$ is due solely to climate, the change in the normal water balance equation (14) due to treatment, $\Delta Q(t)$, is given by:

$$\Delta Q(t) = \pm \Delta ET \pm \Delta S \qquad (17)$$

Systematic differences in ΔET and ΔS due to elevation (E), treatment (T), vegetation density (D) and habitat type (H) are expressed as additional arguments and incorporated in equation 17 as:

$$\Delta Q(t,E,T,H,D) = \pm \Delta ET(t,E,T,H,D) \pm \Delta S(t,E,T,H,D) \qquad (18)$$

Recall that:

- $T = 1$ indicates a clearcut condition;
- $t = 1$ indicates the first year after treatment; and
- $t = 0$ indicates the natural or reference land condition;

then the factors τ, ω, and ρ defined implicitly in equations 8-10 can be defined explicitly in terms of the water balance using equation 18. Thus we have:

$$\rho(t,E,T,H) = \frac{\Delta ET(t,E,T=1,H,D) + \Delta S(t,E,T=1,H,D)}{\Delta ET(t=1,E,T=1,H,D) + \Delta S(t=1,E,T=1,H,D)} \quad (19)$$

$$= \frac{\Delta Q(t,E,T=1,H,D)}{\Delta Q(t=1,E,T=1,H,D)} \quad (19a)$$

$$\omega(t,E,T=1,H) = \frac{\Delta Q(t=1,E,T=1,H,D)}{\bar{Q}(E,T=0)} \quad (20)$$

$$\tau(t,E,T,H) = \frac{\omega(t,E,T,H,D)}{\omega(t,E,T=1,H,D)} \quad (21)$$

$$= \frac{\Delta Q(t,E,T,H,D)}{\Delta Q(t,E,T=1,H,D)} \quad (21a)$$

The dimensionless ratios defined by equations 8-10 of the ECA model do not incorporate all of the arguments shown in equations 19-21. In the model, omission of an argument indicates that, for computational purposes, the ratio is considered independent of the argument. Omission of arguments is due primarily to lack of information.

Using the above definitions for ρ, τ, and ω, and substituting these into equation 13, the streamflow increase is given by:

(Note that: $\bar{Q}(E,T = 0) = A(t = 0,E,T,H,D)\ \bar{q}(E)$)

$$\Delta Q(t,E,T,H,D) = \bar{Q}(E,T=0) \cdot \frac{\Delta Q(t=1,E,T=1,H,D)}{\bar{Q}(E,T=0)} \cdot \frac{\Delta Q(t,E,T=1,H,D)}{\Delta Q(t=1,E,T=1,H,D)} \cdot \frac{\Delta Q(t,E,T,H,D)}{\Delta Q(t,E,T=1,H,D)} \quad (22)$$

Canceling, this reduces to:

$$\Delta Q(t,E,T,H,D) = \Delta Q(t,E,T,H,D)$$

Thus for a given year (t) and land use treatment (T), the change in streamflow, $\Delta Q(t)$ (as estimated by the ECA model), reflects the variation in streamflow due to the cumulative effects of treatment, but not annual fluctuation in climate. Finally, it should be noted that equations 19a, 20, and 21a, although used to define the dimensionless ratios, ρ, ω, and τ, are also state equations relating ΔQ to time ($\rho(t)$), space ($\omega(E)$), or treatment ($\tau(T)$).

Model Validation

The accuracy of the model in predicting streamflow changes was examined using data from the Benton Creek drainage on the Priest River Experimental Forest, Priest River, Idaho. Benton Creek is a second order stream supplied by an area of 950 acres, and has a well documented hydrologic record and management history (A.R. Stage 1957; C.A. Wellner 1976). The watershed is situated in a cedar-hemlock forest type where precipitation averages 39.4 inches annually. During the 25 years prior to the harvest treatment, streamflow averaged 17.04 inches (1349 acre feet). Variation in streamflow was appreciable, having a standard deviation of 4.3 inches (341 acre feet) or 27 percent.

In 1968 at an average elevation of 4500 feet, 98 acres were harvested by clearcutting. Road surface area in the drainage totaled 19.2 acres. Thus, the total treated area in the drainage was 117.2 acres. During the 5 years subsequent to harvest, 1969-1973, annual streamflow averaged 17.32 inches (1371.2 acre feet) with a standard deviation of 5.6 (440 acre feet). For the same 5-year period, precipitation was 38.2 inches or 1.2 inches below normal.

Existence of a Treatment Effect

Because of the difference in mean precipitation between the pretreatment and posttreatment periods, and the comparatively few years (5) of posttreatment data, the treatment effect was first examined independently of the ECA model. Independent estimates of posttreatment streamflow were obtained using a regression equation developed by Harold Haupt of the USDA Forest Service Intermountain Forest and Range Experiment Station. This equation, derived from 25 years of pretreatment precipitation and streamflow records, utilizes posttreatment measurements of winter streamflow, snow storage, and fall-winter precipitation to predict annual streamflow. This relationship, defined in Table 1 of the Appendix, was used to estimate "natural" (unaltered by treatment) streamflow for each year during the posttreatment period. The average increase thus obtained was 84.5 acre feet for the 5-year period. To test the statistical significance of the treatment effect, differences between actual measured streamflow and the posttreatment predicted, "natural" streamflow were compared using a paired *t*-test. The null hypothesis, that there was no difference between these paired values (measured and predicted streamflow), was rejected at the 95 percent confidence level, indicating that there was a treatment effect. This test and streamflow differences are shown in Table 2 of the Appendix.

A second estimate of the treatment effect was obtained by subtracting pretreatment and posttreatment flows. Based on differences between average streamflow data for the 25-year pretreatment and the 5-year posttreatment periods, the streamflow increase is 0.28 inches (17.32-17.04) or 22.17 acre feet. However, since precipitation was below normal during the 5-year posttreatment period, a further adjustment was made. Using the mean precipitation, 39.4 inches, and average runoff, 17.04 inches for the pretreatment period, the delivery rate (17.04/39.4) was estimated to be 43 percent for the posttreatment period. Thus, to adjust the posttreatment runoff for below normal precipitation, 43 percent of 1.2 inches (0.52 inches), or 40.85 acre feet, was added to the previously computed 22.17 acre feet. Thus, for the 5-year period, the estimated streamflow increase averages 63.0 acre feet per year. Since the delivery-rate adjustment did not consider ΔQ resulting from treatment, 63 acre feet per year is a conservative estimate.

The magnitude of the above estimates is further supported by data supplied by Haupt (personal communication) describing increases in water yield measured directly on the 98 acre clearcut. Measuring snowmelt with lysimeters, and soil water storage changes with a neutron probe, Haupt found the water yield to be 12.1 inches greater on the clearcut acres than on adjacent undisturbed forest. If the total on-site increase was delivered to the stream channel, this would correspond to an annual increase of 1.25 inches or 99 acre feet for the entire watershed area. Since it is unlikely that the total on-site yield was delivered to the channel, the actual yield would be less than 99 acre feet. Variability in potential water yield gains due to treatment is further documented by Cline et al. (1977).

In summary, clearcutting 98 acres of the 950 acre watershed (10.3%) resulted in a statistically significant average water yield increase for the 5-year posttreatment period. Estimates of the magnitude of the increase range from 63 to less than 99 acre feet. The best estimate of yield increase is taken to be 83 acre feet based upon the regression relationship obtained from 25 years of data.

Estimating the Treatment Effect With the ECA Model

Using the ECA model, annual streamflow increases were calculated as shown in Table 2. The largest increase in 1969 was 63.8 acre feet; during the fifth year the increase diminished to 42.8 acre feet. The average increase over the 5 years as predicted by the model is 51.3 acre feet. Thus, the 5-year average streamflow increase of 51.3 acre feet obtained using the ECA model provides a conservative estimate in comparison to the preceding values of 63 and 85 acre feet.

Testing the Predicted Treatment Effect

Annual streamflow increases due to treatment predicted by the ECA model (and listed in Table 2) were added to the "natural" streamflow calculated using the previously described regression equation. These estimated annual posttreatment flows were then compared with measured posttreatment flows using a paired *t*-test. The null hypothesis was that no difference existed between measured streamflow and estimated streamflow. The hypothesis was accepted at the 95 percent confidence level. This is reasonable in that the average difference between estimated and measured streamflow was 0.42 inches or 2.4 percent of the average measured posttreatment flow. (Data and statistics appear in Table 3 of the Appendix.)

However, despite the fact that total streamflow was estimated to within 2.4 percent using the ECA model, it must also be recognized that the water yield increase due to treatment was underestimated by 40 percent (85-51/85). In the following section, potential sources of error in water yield increase prediction which could have resulted in the underestimate are discussed.

Table 2. Computation of water yield increases for Benton Creek drainage using the ECA model.

I. Water Yield Increase for 1969

ΔQ (t=1) ac-ft	A (ac)	τ	ρ	$\bar{q}$(E) (ft)	ω	Source
53.57	98	1	1	1.33	.41	Clearcut (4500 ft)
.39	1.2	1	1	1.17	.28	Road
2.25	4	1	1	1.25	.45	Road
3.3	6	1	1	1.25	.44	Road
2.19	4	1	1	1.33	.41	Road
2.2	4	1	1	1.42	.39	Road
63.90	Total Q for clearcut and roads					

II. Mean Water Yield Increase 1969-1973

Year	n	ΔQ (t=n) ac-ft	ΔQ (Roads) ac-ft	ρ	Total ac-ft
1969	1	53.57	10.33	1.0	63.9
1970	2	44.50	10.33	0.83	54.8
1971	3	39.11	10.33	0.73	49.4
1972	4	35.43	10.33	0.66	45.8
1973	5	32.51	10.33	0.61	42.8

Sum. 256.7 ac-ft
5 year Ave. 51.3 ac-ft

Error Propagation in the ECA Model

As can be seen in equations 8-13, the basic model has a multiplicative form where the dependent variable is computed as the product of several independent variables. The question then is: given a value for each independent variable and an estimate of the error in this value, what is the magnitude of the error expected in the dependent variable. In other words, how sensitive would estimates of ECA or Q(t) be to errors in measurement or errors in the relationships shown in Figure 1?

Multiplicative error propagation can be expressed as follows. Let θ_x, θ_y, and θ_z be errors in the independent variables x, y, z, respectively. The error in the product xyz can then be written:

$$\theta_{xyz} = (x \pm \theta_x) \cdot (y \pm \theta_y) \cdot (z \pm \theta_z) - xyz \qquad (23)$$

ECA is calculated as the product of A, ρ and τ as shown in equation 5. To illustrate error propagation in ECA estimates, the error in ECA (for 1976) will be calculated for a 100-acre clearcut harvested in 1970. In the example, the clearcut is assumed to be located within a single habitat type and elevation zone. The errors are assumed to be:

θ_A = 1 acre (1 percent)

θ_ρ = 0.1 (10 percent of the first year on-site water yield)

θ_τ = 0 (the treatment is a clearcut; no error is involved by definition)

Rewriting equation 23 using a value for ρ of 0.6, obtained from Figure 1, gives:

$$\theta_{ECA}(1976) = [(100 \pm 1)(0.6 \pm 0.1)(1.0 \pm 0)] - 60$$

Taking the worst case, the larger error, $\theta_{ECA}(1976)$, is found to be:

$$\theta_{ECA}(1976) = [(101)(.70)(1)] - 60 = 10.7 \text{ acres} \quad (24)$$

Since the ECA estimate (100 ac)(0.6)(1.0) is 60 acres, the relative error is 17.8 percent (10.7/60). Continuing this example, since only one treatment (clearcut) occurs, $\Delta Q(t)$ can be calculated by:

$$\Delta Q(t) = ECA(t) \cdot \bar{q}(E) \cdot \omega(E) \quad (25)$$

Rewriting equation 23, the error in $\Delta Q(t)$ is:

$$\theta_{\Delta Q(t)} = [(ECA \pm \theta_{ECA}) \cdot (\bar{q} \pm \theta_{\bar{q}}) \cdot (\omega \pm \theta_\omega)] - \Delta Q(t) \quad (26)$$

If it is assumed that both q(E) and ω(E) can be determined within 10 percent, i.e., had an error of 10 percent, then these errors are:

$$\theta_q = \pm 0.1 (\bar{q}(E)) = \pm .13 \text{ ft} \quad (27)$$

$$\theta_\omega = \pm .1 (\omega(E)) = \pm .04 \quad (28)$$

(10 percent of the normal on-site water yield)

Using the value previously estimated for θ_{ECA} of 10.7 acres, the error in water yield increase in acre feet is computed as:

$$\theta_{\Delta Q(t)} = [(100 \pm 10.7) \cdot (1.3 \pm .13) \cdot (.4 \pm .04)] - \Delta Q(t)$$

where $\Delta Q(t) = (100) \cdot (1.3) \cdot (.4) = 52$

Again taking the worst case:

$$\theta_{\Delta Q}(1976) = [(110.7) \cdot (1.43) \cdot (.44)] - 52 = 17.65$$

The relative error is (17.65/52) or 34 percent. This example illustrates how errors in the independent variables can accumulate in the dependent variables, ECA(t) and $\Delta Q(t)$. However, in practice it is reasonable to assume that some of the error will be compensating, and hence the relative error of the dependent variables would be reduced.

Improving Model Sensitivity

While formulated as a distributed parameter system, the model does not explicitly consider: 1) aspect, which is an important index to energy availability for evapotranspiration and snowmelt, 2) routing procedures to express differences in water yield due to topographic position (within an elevation zone) or previous treatment.

Aspect is in part expressed by habitat type and therefore implicitly considered in the recovery factor (ρ). Since the recovery function is by definition determined in part by the vegetative regrowth on the site, and rate of regrowth is known to differ with aspect, a more explicit expression of aspect would seem appropriate. Redefinition of the recovery factor (ρ) as a function of habitat type (H), aspect and time, would permit the inclusion of aspect as a distributed variable and should increase the model's sensitivity to treatment effects.

Routing of subsurface flow is achieved in the model through stratification of ω and Q(t=0) by elevation. This procedure does not consider differences in delivery efficiency which could occur *within* the same elevation zone due to soil differences or topographic location and their interaction. For example, clearcuts separated from stream channels only by a buffer strip, would normally have a relatively high delivery efficiency. In contrast, upslope clearcuts not immediately adjacent to a channel where subsurface flow must move an appreciable distance downslope would normally have a reduced delivery efficiency, due to additional ET and soil water storage losses. Still additional losses (and reduction in delivery efficiency) could occur if the subsurface water from such upslope clearcuts passed through a previously clearcut area. Here fast growing reproduction could further reduce the subsurface flow in contrast to passage through a more mature stand. Both the effects of topographic location and previous treatment should be incorporated in the water yield increase factor (ω). This modification should enhance the ability of the model to discriminate between the cumulative effects of alternate harvesting proposals.

Summary and Conclusions

The general ECA model provides a relatively simple framework for evaluation of the hydrologic impacts of forest practices. The primary feature of the model is the use of the ECA concept to indicate the current status of the watershed and to predict the net combined impact of current and proposed forest practices. The model is not designed for determination of extreme hydrographic events or individual storm hydrographs. The model does estimate annual streamflow increases under average climatic conditions and is most appropriate for areas where the snowmelt hydrograph is the dominant hydrographic event.

Accuracy of model predictions depends primarily on the availability of local hydrologic data (ω and $\bar{q}$) and the ability of the user to define local treatment effects, (ρ, τ). Because of the multiplicative form of the model, accumulated error could be significant, as previously illustrated.

Viewed in an operational context and employed by experienced professionals, the model provides a rational tool with relatively modest data requirements. With refinement it has the potential of becoming an even more effective and sensitive means of predicting the hydrologic effects of forest practices.

LITERATURE CITED

Cline, R.G., H.F. Haupt and G.S. Campbell. 1977. Potential water yield response following clearcut harvesting on north and south slopes in northern Idaho. Res. pap. Int-191. Intermountain Forest and Range Experiment Station. Ogden, Utah. 16 pp.

Galbraith, A.F. 1975. Method for predicting increases in water yield related to timber harvesting and site conditions. Pages 169-184 *in* Watershed Management Symposium, ASCE. Logan, Utah. Aug 11-13, 1975.

Isaacson, J.A. 1977. A computer model for determining water yield from forest activities. USDA Forest Service. Idaho Panhandle N.F. (mimeo) 36 pp.

Rosgen, D. 1974. Water yield computer model I. Pages 44-49 *in* Forest Hydrology, part II, section 2D (1974). USDA Forest Service. Missoula, Montana. 229 pp.

Silvey, H.L. 1970. Interim procedures for estimating average annual water yields and increases in water yields due to timber harvesting on the St. Joe National Forest. USDA Forest Service. St. Joe N. F. (mimeo). 35 pp.

Stage, A.R. 1957. Some runoff characteristics of a small forested watershed in Idaho. Northwest Sci. 31(1):14-24.

U.S. Department of Agriculture, Forest Service. 1974. Forest hydrology part II–hydrologic effects of vegetation manipulation. Missoula, Montana. 229 pp.

Wellner, C.A. 1976. Frontiers of forestry research–Priest River experimental forest, 1911-1976. USDA Forest Service. Intermountain Forest and Range Experiment Station. Ogden, Utah. 148 pp.

APPENDIX

Table 1. Prediction equation for Benton Creek annual streamflow obtained by stepwise regression[1]

$$Y = -5.84 + 0.279(X_1) + 0.212(X_2) + 0.038\,(X_3) + 0.435(X_4) + 1.197\,(X_5)$$

Y = predicted annual streamflow

X_1 = net fall-winter precipitation

X_2 = antecedent precipitation, June-September

X_3 = weighted spring precipitation

X_4 = snow storage, April 1

X_5 = winter runoff (December -March)

Units for above data are in inches. The standard error of estimate is 1.47 inches; the multiple correlation coefficient is 0.92. The regression is based on 25 years (1941-1965) of record prior to treatment.

[1] The regression equation was developed by H.F. Haupt, Intermountain Forest and Range Experiment Station, USDA Forest Service, Moscow, Idaho.

Table 2. Comparison of "natural" (assuming no treatment) streamflow estimated by regression and measured streamflow for the posttreatment period.

Data Summary

Yr	(1) q (in) Regression estimate	(2) q (in) measured	(3) Y Δq (in) (2 - 1)
1969	21.43	23.73	2.30
1970	13.73	15.04	1.31
1971	17.38	18.36	.98
1972	19.36	20.04	.68
1973	9.42	9.49	.07

Paired *t*-test

$H_o = 0$ $\quad (\Sigma Y)^2 = 28.52$ $\quad S^2 = \frac{S.S.}{n-1} = .68$

$n = 5$ $\quad (\Sigma Y)^2/n = 5.71$

$\Sigma Y = 5.34$ $\quad (\Sigma Y^2) = 8.43$ $\quad S^2/n = .136$

$\bar{Y} = 1.07$ $\quad S.S. = 2.72$ $\quad (S^2/n)^{1/2} = .369$

$$t = \frac{1.07 - 0}{.369} = 2.90 \text{ @ 4 d.f.}$$

t_{05} @ 4 d.f. = 2.776 (table)

∴ Reject null hypothesis; there is a difference @ 95 percent confidence.

Table 3. Comparison of measured streamflow and total predicted streamflow for the posttreatment period. (Total predicted flow was computed as the sum of "natural" flow and the increase predicted by the ECA model.)

Data Summary

Yr	(1) q (in) Haupt regression	(2) q (in) ECA model	(3) Total q (1 + 2)	(4) q (in) measured	(5) Y Δq (in) (4 - 3)
1969	21.43	0.81	22.24	23.73	1.49
1970	13.73	0.69	14.42	15.04	.62
1971	17.38	0.623	18.00	18.36	.36
1972	19.36	0.577	19.94	20.04	.10
1973	9.42	0.540	9.96	9.49	- .47

Paired *t*-test

$H_o = 0$

$n = 5$

$\Sigma Y = 2.10$

$\overline{Y} = .42$

$(\Sigma Y)^2 = 4.41$

$(\Sigma Y)^2/n = .882$

$\Sigma Y^2 = 2.96$

$S.S. = 2.08$

$S^2 = \frac{S.S.}{n-1} = .519$

$(S^2/n)^{1/2} = .36$

$$S.S. = \Sigma Y^2 - (\Sigma Y^2/n) = 2.08$$

$$t_{05} \text{ @ 4 d.f.} = 2.776 \text{ (table)}$$

$$t = \frac{\overline{Y} - Ho}{(S^2/n)^{1/2}} \quad \frac{.42}{.36} = 1.16$$

∴ Accept the null hypothesis; there is no difference between measured and predicted at 95 percent confidence.

SYMBOLS

A	area treated (acres)
ECA	equivalent clearcut area (acres)
E	elevation zone (number)
T	treatment (numerical index, T = 0 is no treatment, T = 1 is clearcut)
H	habitat type (number index)
t	time, years 0 = pretreatment, 1 = 1st year after treatment
D	density of vegetation, e.g., basal area (ft^2)
q	streamflow (ft)
Q	streamflow (acre-ft)
ΔQ	change in streamflow (acre-feet)
Q_*	streamflow estimated using PE (acre-feet)
τ	treatment factor, dimensionless
ρ	recovery factor, dimensionless
ω	streamflow increase factor, dimensionless
L	total number of elevation zones
M	total number of land use treatments
N	total number of habitat types
K	total number of vegetation densities
ET	evapotranspiration (ft)
PPT	precipitation (ft)
PE	potential ET (ft)
θ_X	error in X