THE SELECTION OF EXPERIMENTAL WATERSHEDS AND METHODS IN DISTURBED FOREST AREAS

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ABSTRACT

Mountain watersheds in many areas are undergoing severe mechanical disturbances such as intensive road construction and surface mining. Studies indicate the effects of such disturbances are directly related to the intensity or area of the disturbance. Maximum disturbances in small headwater watersheds have been found to be 7 % for truck roads, 12 % for truck and skid roads, and 40 % for surface mines. Traditional research methods and criteria for selecting experimental watersheds may not apply in these areas.

Research methods for evaluating watersheds have generally followed three basic approaches including runoff plots, paired watersheds, and single watershed methods. These methods can be used under certain circumstances to evaluate watershed disturbances. However, a relatively new approach, the multiple watershed method, offers many advantages over traditional methods. In this method, a large number of non-uniform watersheds are selected. The parameter to be evaluated, (streamflow, sediment, etc.) becomes the dependent variable which is statistically related to a number of independent variables such as watershed area, area of disturbance, etc. Advantages include (1) results are applicable over broader regions, (2) more flexibility in selecting experimental areas, (3) downstream effects of disturbance can be determined, and (4) method is applicable on a sampling basis.

RÉSUMÉ

Les bassins de réception des montagnes passent par des dérangements mécaniques et sévères à cause de la construction des chemins et des mines à ciel ouvert. Des études montrent que les résultats de tels dérangements sont en rapport direct avec l'intensité ou l'étendue du dérangement. La plupart des dérangements dans les bassins de réception des hauts bassins ont été trouvés être 7 % pour les routes de camions, 12 % pour les pistes, et 40 % pour les mines à ciel ouvert. Les méthodes traditionnelles de recherche et les critères de choix des bassins de réception expérimentaux ne s'appliquent peut-être pas dans ces régions.

Les méthodes de recherche pour évaluer les dérangements ont suivi généralement trois voies d'approche. Ce sont (1) la méthode du terrain d'écoulement, (2) la méthode des bassins en couple, et (3) la méthode d'un seul bassin. Ces méthodes peuvent s'employer dans certaines circonstances pour évaluer les dérangements des bassins de réception.

Toutefois, une approche relativement nouvelle — la méthode de multiples bassins de réception donne beaucoup d'avantages sur les méthodes traditionnelles. Dans cette méthode beaucoup de bassins dissemblables sont choisis. Le paramètre (l'écoulement, le sédiment, etc.) que l'on va évaluer devient la variable dépendante qui statistiquement se rapporte à plusieurs variables indépendantes comme le terrain ou le degré du dérangement, la superficie du bassin et d'autres paramètres hydrologiques.

Les avantages sont : (1) les résultats sont applicables aux régions plus larges (2) la sélection des bassins expérimentaux est plus flexible (3) les influences du dérangement aval peuvent se déterminer, et (4) la méthode est applicable sur une base de prise d'échantillons.

The forest watershed manager, traditionally, has had two things to work with : vegetation and soil. Disturbances on a watershed similarly have been classified as vegetative (denudation due to fire, grazing, and logging) or soil disturbances (erosion and compaction). A third kind of disturbance, which will be considered in this paper,

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is that kind involving the mechanical excavation of soil and rock over broad areas. Such disturbances, which might best be termed geologic disturbances, include road construction and surface mining. Both forms have important hydrologic implications and are occurring with increasing frequency on forested land in the United States and other countries.

Research methods and criteria for selecting experimental watersheds on undisturbed areas have been fairly well defined. Unfortunately, these traditional methods usually require complete administrative control of the watershed as well as a pre-disturbance calibration. Thus, they are not applicable in severely disturbed areas where ownership patterns preclude a closely controlled experimental method. It is the purpose of this paper to describe several research methods and their application to hydrologic studies on disturbed forest areas.

Research methods and watersheds

Three research methods for evaluating watershed disturbances have commonly been used : plot methods, paired watersheds, and single-watersheds method (Storey, 1957). The paired and single-watershed methods are used primarily to evaluate before-and-after effects of watershed treatments, while plots are used to determine the various processes at work within the watershed. A fourth approach, the multi-watershed method, enables the researcher to evaluate disturbances under a range of watershed conditions.

The selection of a research method depends primarily upon the research objectives. Each method can be used to provide answers to specific questions, yet each must satisfy certain requirements before it can be used effectively.

Plot methods

Plots can provide a great deal of specific information about hydrologic processes and the plots can have an infinite variety of shapes, depending on the process being studied. Runoff plots are one of the more common types used. These are generally rectangular, elongated, uniform in slope, and instrumented to measure runoff or erosion (Mutchler, 1963). Perhaps the greatest advantage of runoff plots is that they give the researcher control over some of the influencing variables. Site variables can be held constant for a number of plots so that different vegetative treatments can be evaluated under identical conditions. In addition, groups of plots are usually small enough so that rainfall and other climatic variables are uniform over the area.

The primary disadvantage, of course, is that results cannot be directly translated to a whole watershed. It is usually impractical to try to sample all conditions within a watershed.

The plot method can be used for a variety of purposes; for example, measuring erosion and runoff from road cuts (Diseker et al., 1963) or determining subsurface flow (Whipkey, 1965). Runoff plots need not be rectangular but are sometimes constructed to conform to natural drainage areas. However, when this is done, part of the control is lost since drainage areas may not be identical in all respects.

Paired Watersheds

The paired-watershed method requires the selection of two or more watersheds. The watersheds selected should be as similar as possible in size, shape, aspect, slope, elevation, soil type, climate, and vegetative cover. The general procedure is to gauge the watersheds long enough to find a statistical relation between them. The streamflow characteristics selected for correlation may include annual flows, monthly flows, daily

flows, and minimum and maximum flows. A pair of watersheds may be considered sufficiently calibrated when a streamflow characteristic of Watershed 1 can be used to predict the corresponding value for Watershed 2 within an acceptable margin of error. The time required for a satisfactory calibration will depend upon the characteristic being evaluated, the allowable error, and the size and frequency of runoff-producing events. Kovner and Evans (1954) outline a method for estimating the minimum duration of watershed experiments.

After calibration, one or more of the watersheds is treated and then compared with a controlled or untreated watershed. Treatments are evaluated by comparing the measured streamflow characteristic with that predicted on the basis of the previously established relations.

The major advantage of the paired-watershed method is that small differences due to treatment can be evaluated. However, there are many disadvantages. Pairs of watersheds that are sufficiently similar are difficult to find. The method is usually limited to small watersheds that are easier to work with, more likely to be uniform, and less costly to gauge. In addition, there is always the possibility that fire or some other agent will disturb the control watershed and destroy the calibration relations. It is also difficult to translate results from the experimental watershed to other watersheds with any degree of confidence.

Single-Watershed Method

A slightly newer approach is single-watershed calibration. In this method, a streamflow characteristic is statistically related to climatic variables on the same watershed rather than to streamflow on an adjacent watershed. Single-watershed calibration can take several forms and can include many climatic variables. The simplest form is a simple correlation between streamflow and precipitation; for example, monthly discharge vs. monthly rainfall. Other variables that help to explain the variation in the streamflow can be added if they improve the correlation. For example, Reigner (1964) predicted annual and monthly streamflow using precipitation, groundwater, and soil moisture data.

Disadvantages of the single-watershed method include less precision, a more complex analysis, and a longer calibration period. However, there are several advantages which may more than offset the disadvantages. Single-watershed calibration can be used on almost any watershed. It need not conform to the rigid requirements for pairing. The method can be adapted to evaluate treatment effects on a disturbed watershed. For example, the effects of reforestation and erosion control on the hydrology of Pine Tree Branch Watershed have been evaluated by the single-watershed method (TVA, 1962).

Multi-Watershed Method

The multi-watershed method is also a fairly new approach. The basic procedure is to select a number of watersheds representing different conditions with respect to the factors being evaluated (vegetative cover, size, or watershed disturbance). The hydrologic phenomenon to be analyzed (storm runoff, sediment yield, etc.) becomes the dependent variable which is statistically related to a number of independent variables such as watershed area, disturbed area, soil types, vegetative density, and rainfall. The multiple regression analysis, which weighs each of the independent variables according to its influence on the dependent variable, is most commonly used although more promising techniques are being developed.

In the past, this method, has largely been used to relate sediment yield to climate and land use. One of the earliest studies (Gottschalk, 1947) related sediment catch in stock ponds on small grazed watersheds to drainage area, drainage density, age of the

stock pond, and rainfall. Other studies have related sediment yield to various other land use, climatic, and watershed variables (Anderson, 1957). Other streamflow attributes can also be evaluated.

One of the major advantages of this method is that a range of conditions is being sampled and, as a result, conclusions can be drawn as to which factors are important and to what extent they influence the hydrology of the sample watersheds.

Another advantage is that greater flexibility is permitted in the selection of sample watersheds. They need not be uniform in size, shape, topography, or land use. However, in order to assure a successful analysis, the sample watersheds should meet a number of conditions. Watersheds selected should exhibit a broad range of values with respect to the factors being evaluated. For example, in evaluating the effects of a disturbance on sediment yield, the sample should include watersheds with little or no disturbance, the maximum expected disturbance, and intermediate degrees of disturbance. Watersheds selected should be free from any extraneous influence. Thus, if the relation between a land use and sediment yield is sought, the sample watersheds should be free from any other major sediment source unless that source is included as an independent variable.

The multi-watershed method can be applied in various ways depending on research objectives. Thus, to evaluate annual or periodic water yields, or sediment yields, a continuous measurement of streamflow is usually required. On the other hand, if storm peaks or sediment concentrations are to be evaluated, maximum stage measurements or a frequency sampling system can be used.

Evaluating disturbed watersheds

In any hydrologic analysis, the methods used and the basis for selectings experimental watersheds depend upon the objectives of the study. On disturbed areas we want to know what effect a disturbance has on the hydrology of a basin and how this effect can be modified or reduced.

Disturbances due to road construction and surface mining have long been recognized as contributing to erosion and runoff problems (Frank, 1941; Bullard, 1963).

Physically, the two forms of disturbance are very similar (Fig. 1). Both involve side hill cuts and fills, displacement of the natural soil and parent rock, and cause an interruption in the natural soil and surface drainage. The principal difference is the size of the excavation. The width of a road excavation is only a fraction of that of a strip-mine excavation. Another difference is that strip mines are horizontal while most roads have some gradient.

Although only a small proportion of a watershed is actually disturbed by roads and mines, the nature and extent of the disturbance is important in its evaluation. Past studies have shown that sediment yield and other streamflow characteristics are directly related to the area of roads within the watershed. For example Anderson (1954), in a study of suspended sediment yield from 29 watersheds found a direct relation between sediment yield and road areas. Road areas in this study ranged from .05 to .60 percent of the watershed areas. Other measurements of road areas indicate that small intensively logged watersheds can have as much as 7 percent of their area occupied by truck roads, while if skid roads are included as much as 12 percent of the area may be disturbed (table 1).

The effects of surface-mine disturbances will also be related to the proportion of disturbed area within the watershed. Although no studies have been completed to show this effect, measurements of minedarea disturbances indicate that small headwater watersheds can be as much as 60 percent distrubed by surface mining (table 2).

In evaluating disturbed watersheds, there are perhaps four important problem areas to be considered : (1) storm runoff, (2) erosion, (3) sedimentation, and

(4) geochemistry. The particular problem to be studied will influence the method to be used and the experimental area requirements. Representative data for each of these phenomena, as presented below, will indicate the general order of magnitude of hydro-

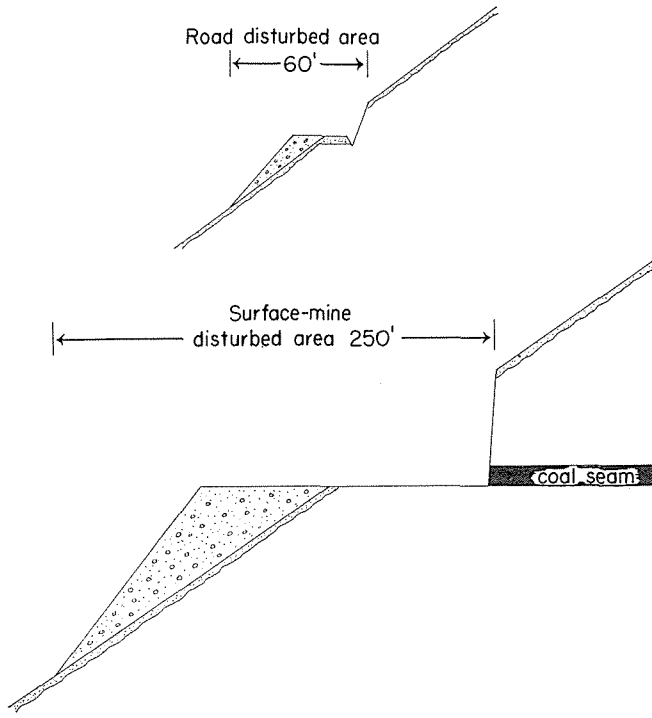

Fig. 1

TABLE 1

Typical amounts of watershed disturbance by roads

Watershed area (square kilometers)	Percent area occupied by roads			
	Skid roads	Truck roads	Total	Reference (1)
0.10-0.73	2.5-7.0	1.5	4.0- 8.5	(1)
.13- .46	2.5-5.2	.6-7.0	3.1-12.2	(2)
.16- .31	1.9-7.3	—	1.9- 7.3	(3)
1.01	—	6.2	6.2	(4)
2.85	—	5.0	5.0	(5)
10.4	1.5	—	1.5	(6)
145-18,880	—	.05- .60	.05- .60	(7)

(1) Mitchell and Trimble (1959); (2) Haupt (1960); (3) Reinhart et al. (1963); (4) Fredricksen (1963); (5) Goodell (1958); (6) Anderson (1962); (7) Anderson (1954).

logic values that can be expected from disturbed watersheds. This information can serve as a planning guide to the researcher, not only in the selection of adequate instrumentation, but also in the selection of research methods.

TABLE 2

Mined area disturbance in Eastern Kentucky watersheds

Watershed	Area (Hectares)	Mined area	
		(Hectares)	(Percent of total)
Watershed 1	10	6	60.0
Left Fork, Peters Branch	85	37	45.0
Long Fork, Peters Branch	119	27	22.3
Peters Branch	244	83	33.8
North Fork, Youngs Fork	215	72	33.4
Elk Lick Fork	263	63	24.0
Clear Fork	466	154	33.0
Youngs Fork	738	135	18.3
Stoney Fork	3,410	211	6.2
Clear Creek	7,460	671	.9
Pucketts Creek	8,140	3,175	3.9

Storm Runoff

Normally, rain falling on an undisturbed forest watershed soaks into the soil and flows through the shallow soil layers. In disturbed watersheds this subsurface stormflow, as well as natural ground-water flow may seep out along the cut bank, concentrate in the road ditch or surface-mine pit, and be discharged into the stream channel more quickly than otherwise. In addition, surface runoff from the disturbed area will help to swell the volume of storm runoff.

An evaluation of the effect of disturbances on storm runoff could take several approaches. One would be the direct measurement of stormflow from the various components of the disturbed area. On roads this would include road surface and ditch runoff measured at a culvert or other natural break, and runoff from the outer fill slope by runoff plots. On surface-mined areas, the logical components would be terrace areas with runoff measured at natural drainage ways, and spoil-bank outslopes with runoff again measured on a runoff plot system. Such measurements are being made in eastern Kentucky strip-mined areas.

The multi-watershed method could also be used to advantage. Although it would be impractical to instrument a large number of watersheds with stage recorders, a number of watersheds could be instrumented with crest recorders and a record of peak flows could be accumulated. In this type of study, a rating curve should be developed for each station so that stream stage can be translated into discharge.

Erosion

Recently disturbed soil is usually highly erosive. On highways most erosion occurs during construction. On temporary roads, however, erosion may be most severe after

the road is abandoned. The amount of soil loss from disturbed areas will undoubtedly vary according to many factors. Several recent studies provide information on erosion losses from typical disturbed areas. A survey of erosion from abandoned coal haul roads showed that erosion losses could amount to as much as 36 cubic meters per hectare of road surface per year. ([2]) Erosion from strip-mine areas can be equally as severe. Collier, et al. (1964) found that sheet erosion on a 17-hectare watershed 10 percent disturbed by mining averaged 14.8 metric tons per hectare per year. Ninety-six percent of the erosion occurred on the mined area. A similar unmined watershed averaged only 1.8 metric tons per hectare per year.

Erosion studies on disturbed areas are frequently conducted by plot or runoff plot methods. As in evaluating storm runoff, the various components of the disturbed area can be evaluated separately in order to obtain quantitative comparisons. These studies, while very difficult to relate to the entire watershed, do provide much information on basic erosion processes and sediment source areas.

Erosion plots have recently been installed on spoil bank outslopes in eastern Kentucky. Other techniques which are also being used include erosion stakes and surveying methods. Erosion estimates from abandoned haul roads were obtained by plotting cross sections at regular intervals, determining the original road surface, and computing the volume lost between original and present surfaces.

Sedimentation

Although closely related to erosion, the sediment yield from a watershed is a more meaningful measure of soil loss than erosion measurements. Sediment yield from a mechanically disturbed watershed is the combined result of erosion from the disturbed area and the transportation of the eroded material from the watershed. Therefore sediment yield varies, not only with the extent of disturbance within the watershed, but also with the proximity of the disturbed area to the natural stream channels. Thus, roads or surface mines where the outer fill slope approaches the stream channel will yield greater quantities of sediment than those separated from the channel by a forested zone. Similarly, roads and mined areas that intercept a stream and divert it across the disturbed area will also yield more sediment.

Much information is available on sediment yields as related to land use. However, little has been done to specifically evaluate sediment yield from roads or mined area disturbances (table 3). Anderson (1954) as previously indicated, did find a direct relation between road area and sediment yield. And Fredricksen (1963) observed an initial increase in sediment concentration up to 250 times the normal sediment loads during road construction on a small forested watershed. During the 2-month period following construction sediment loads decreased to near normal levels yet remained significantly higher than normal. In another study, Collier et al. (1964) recorded an average of 440 metric tons of sediment yield per square kilometer from a disturbed watershed for 3 years and only 27 metric tons from a similar but undisturbed watershed.

Several methods can be used to determine the effect of watershed disturbances on sediment yield. Paired- and single-watershed studies frequently include sediment yield as a part of the analysis. However, as previously mentioned, these controlled watershed methods are difficult to apply in disturbed areas and if used, result in little more than a case history of the particular watershed. The multi-watershed method, on the other hand, will yield much more information with respect to effects of varying proportions of disturbances, downstream effects, and in addition, give results which are applicable over broader regions.

([2]) WEIGLE, W.K., Road erosion survey. Unpublished file report. U.S. Dept. Agr., Forest Service, Cent. States Forest Expt. Sta., Berea, Ky., field office, 1965.

TABLE 3

Maximum observed sediment concentrations in disturbed watersheds

Watershed	Area (Hectares)	Disturbed area		Sediment (Parts per million)
		(Hectares)	(Percent of total)	
Anco 1	7.3	5.5	75.0	11,500
Watershed 3 (1)	102	61	6.0	1,780
Cane Branch (2)	174	17	10.0	112,000
North Fork, Youngs Fork	215	72	33.4	18,300
Elk Lick Fork	263	63	24.0	13,000
Youngs Fork	738	135	18.3	19,100
Lotts Creek	4,800	384	8.0	18,800

Geochemistry

Stream geochemistry is not a major consideration in road building. However, in surface-mining disturbances, and especially surface mining for coal, the freshly exposed spoils material rapidly weathers and releases large quantities of soluble salts. Many of these salts are toxic to plants and aquatic organisms and may do considerable damage to streams.

The type of salts released will depend primarily on the geologic material exposed. The quantity released will probably depend on the area disturbed and the most direct route to the stream.

Several studies have reported how surface mining affects water quality. In the Beaver Creek Study mining disturbances increased the total dissolved concentration by 14 times the first year and 7 times the second (Collier et al., 1964). Sulfate was the most prominent compound released. A total of 41 metric tons of acid (equivalent sulfuric acid) per square kilometer was discharged from the watershed between October 1956 and September 1958. Other elements which also increased include silicon dioxide, manganese plus aluminum, and calcium and magnesium. On the other hand, in the Wetmore Project (3), a small closely controlled mining operation showed only minor changes the first year of mining. Other data are included in Table 4.

Water quality values can be evaluated in the same manner as sediment, eithera controlled watershed method or a comparatively uncontrolled multi-watershed method. Here again, the multi-watershed approach offers many advantages. If a total measure of chemical yield is desired, continuous streamflow records are required. However, if representative concentrations are needed, a much broader sampling network can be installed.

Summary

This paper has presented various watershed research techniques and their application to specific problems on mechanically disturbed watersheds. The geologic disturbances as discussed can be evaluated with reasonable accuracy using the methods outlined.

(1) Fredricksen (1963).
(2) Collier et al. (1964).
(3) U.S. Forest Service, Region 7, Upper Darby, Pa., Unpublished Data. 1964.

TABLE 4

Maximum observed stream chemical measurements in representative surface-mined watersheds

Watershed	Area (Hectares)	Area disturbed (percent)	Chemicals (Parts per million)				Specific conductance (Micro-ohms *at* 25°C.)	pH
			Al	Fe	Mn	SO_4		
Anco 5 (1)	1.0	100	13.0	7.6	0.3	5,000	6,500	2.6
Anco 1	7.3	75	.5	.8	2.0	720	1,500	5.1
Cane Branch (1) (2)	174	10	85.0	48.0	28.0	1,050	2,101	2.5
Foresters Creek 3	101	15	.2	.4	—	41	173	6.6
Foresters Creek 1	286	13	.2	.3	—	41	206	7.0
Foresters Creek 11 (1)	921	12	.7	.4	—	116	596	7.6
Four Mile Run (3)	364	3	.1	.5	.8	45	—	6.0
Lotts Creek (1)	4,800	8	6.7	1.7	1.5	395	1,200	3.3

(1) Streamflow may contain small amounts of deep mine drainage.
(2) Collier et al. (1964).
(3) U.S. Forest Service, Upper Darby, Pa., unpublished data.

Many of these methods are being used by the Central States Forest Experiment Station, U.S. Forest Service, to evaluate the effects of surface mining on the hydrology of forested watersheds. Evaluation of these effects, not only in the United States but in other countries as well, is essential to the intelligent development and utilization of the world's soil and water resources.

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