A TAXONOMY OF SMALL WATERSHED RAINFALL-RUNOFF

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ABSTRACT

A study of over 11,000 event rainfall and associated direct runoff events from 100 small watersheds was done, in a search for distinct patterns of runoff response and/or association with land type. The results show unexpected variety in the geometry and scale of the rainfall-runoff response. Groupings of similar response type and magnitude were made, and the associations with vegetative cover were tested. Five separate response groups were identified as follows: 1) **Inactive**, characterized by no recorded responses to any rainstorm in an extended period of record; 2) **Complacent**, characterized by a very small part of the rainfall (ca 0.1 to 3 percent) being converted to direct runoff, often as a linear response; 3) **Standard** behavior, the expected "textbook" response common to agricultural lands and humid sites, and in which the runoff slope increases with increasing rainfall, and the scale of runoff far exceeds the complacent response; 4) **Violent** behavior, in which an abstraction threshold of 2-6 cm clearly precedes a sudden high response; and 5) **Abrupt** response in which a very high portion of the rainfall is converted to event runoff without appreciable abstraction, as typified by extensively urbanized drainages. The responses and the group identifications were parameterized by a simple broken-line linear rainfall-runoff equation, and a dichotomous key based on coefficient values is proposed. Only mild associations between response type or coefficient values and the four vegetative covers (Forest, Range, Agriculture, and Urban) were found. The variety of hydrologic behavior on forested watersheds encompassed that of the other three land types.

INTRODUCTION

A watershed's response to a rain event is an expression of its hydrologic characteristics. These events are major sources of floods and erosion, and in some situations, the sole source of water supply. Though other flow sources (baseflow and snowmelt) may dominate locally, the rainstorm and its accompanying runoff are conspicuous manifestations of hydrologic response. They usually form the basis for flood design and environmental impact analysis. Furthermore, the current interest in chemical ecology places value on a contributing watershed's ability to store and transform (buffer) a rainstorm's chemical load. With this in mind, the identification of regional or land-linked watershed characteristics could lead to generalized environmental strategies and management applications for ungaged basins or for hydrologic regions.

Purpose: The purpose of this work is to 1) demonstrate and document the observed spectrum of hydrologic response in scale and structure, 2) identify the clustering and/or classification of these responses, and 3) test their associations with land type.

Data: Data from a large number of rainstorm events on 100 different small watersheds were used. The data sets were taken from a variety of opportunistic sources: theses, agency reports, journal articles, progress reports, data summaries, publications, data files from other research organizations, etc., utilizing considerable personal contact and follow-up. Twenty-two (22) US states and two (2) foreign countries are represented. The data set contains 10,910 events, an average of about 109 events for 100 watersheds. Though a complete tabulation of watershed and data details is too bulky to be given here, copies are available in limited supply upon request to the author.

The drainage areas were from 0.30 to 11,200 hectares (0.74 to 27,675 acres), with a mean 394 hectares (974 acres), and a median was 60.9 hectares (150.5 acres). Thus there was a strong positive skew. The event rainfalls varied from 0.025 cm to 25.92 cm (mean 3.00 cm), and runoffs from 0.0003 cm to 23.10 cm (mean 0.6952 cm). Events which had rainfall but no runoff were not included, even though this information was available for some data sets.

Data Quality: It should be stressed that these event rainfall (P) and direct runoff (Q) depths were taken as given in the source publications. These in turn were extracted from basic rainfall and streamflow records by the original investigators. The fundamental integrity of the research installations, the rainfall sampling and data reduction, etc., was accepted "as-is" with the data sets. Only when aberrations or errors were obvious or well-known were any data rejected outright. Given the aim to gather the large data set from diverse locations, no other option was realistically possible.

ANALYSIS

Expression: For orderly description and analysis of the rainfall-runoff response patterns, the following was used:

$$Q = b_1*P \qquad P<a \qquad [1.1]$$
$$Q = b_1*a + b_2*(P-a) \qquad P>a \qquad [1.2]$$

where b_1 and b_2 are coefficients with the constraints of $0<=b_1<=b_2<=1.0$, and $0<a$, and "a" is a threshold rainfall depth, as implied by the equations, and P and Q are the rainfall and direct runoff depths in cm, as previously described.

The condition that $b_1<b_2$ assures that the slope dQ/dP is monotonically increasing, which serves as an approximation of the curvature seen in large data sets. Further conditions are that b_1 must be significantly different than b_2, and b_2 must be equal to or less than 1.0. It bears repeating that Equations 1.1 and 1.2 are empirical, and somewhat arbitrary, selected for simplicity and ease of fitting. However, while "a", b_1, and b_2 are merely coefficients found by statistical fitting, the constraints on them keep the function within hydrologically realistic limits, allowing some limited physical interpretation.

Note that Equation 1 consists of two distinct limbs, one for $P<a$, and the other for $P>a$, and that the two limbs of equation 1 meet at $P=a$ at the value of $Q=b_1*a$. Also, it should be noted that when $b_1=0$, and $a>0$, the equation reduces to $Q=b_2*(P-a)$ [for $P>a$], a form sometimes used in semi-arid areas (Fogel and Duckstein, 1970).

An even simpler form was also used, i.e.,

$$Q = b*P \qquad [2]$$

with the only constraint being that $0<b<1$, where "b" is the simple runoff ratio. It proved useful in isolating the cases in which meager runoff (in relation to rainfall) was the overpowering characteristic. Equation 2 can be seen as a reduced case of Equation 1, i.e, when $b_1=0$ and $a=0$, or when $b_1=b_2$, or when a is greater than the largest rainfall.

Analysis: All data sets were fitted by a least squares procedure to equations 1 and 2, and the general results are given in Table 1, and a sampling for selected watersheds is given in Table 2. The data was also plotted for all cases, giving a visual impression of the response pattern.

Table 1. Statistical Characteristics
of Fitted Coefficients and Goodness-of-Fit

Item	Mean	StDev	CV(%)	Skew	N
b	0.2379	0.1916	80.53	0.6243	100
r^2	0.5292	0.1967	37.16	-0.4812	100
a(cm)	3.7730	3.5566	94.26	1.3636	100
b_1	0.1311	0.1443	111.07	1.3546	100
b_2	0.4336	0.3377	77.80	0.2510	100
r^2	0.6521	0.2325	35.65	-0.9458	100
n	109.1	146.7	134.5	3.5116	100

Note: n=number of events per watershed. N=number of watersheds.

Table 2. Fitted coefficients for selected watersheds.

Watershed name and state	b	a (cm)	b_1	b_2	n	r^2 (%)
Missouri Gulch, CO	0.0030	0.00	0.0000	0.0030	14	42.34
Cabin Creek, ID	0.0046	1.01	0.0013	0.0066	43	48.77
W Donald Cr, OR	0.0034	1.11	0.0016	0.0054	48	76.51
3Bar D, AZ	0.0594	17.04	0.0356	0.1991	93	88.93
Klingerstown, PA	0.0909	1.91	0.0368	0.1820	144	48.53
Coweeta 2, NC	0.0936	5.25	0.0276	0.2142	799	69.72
Coweeta 8, NC	0.1303	8.92	0.0779	0.2955	202	80.34
Coweeta 37, NC	0.3627	4.59	0.2465	0.5807	89	80.00
Treynor 1, IA	0.2572	6.17	0.1855	0.9336	324	69.95
Badger Wash 2A, CO	0.3169	1.67	0.2183	0.6557	66	72.64
Ava 3, MO	0.4840	5.24	0.2732	1.0000	118	88.50
Beaver17, AZ	0.6689	4.47	0.0734	1.0000	22	96.46
Berea 6, KY	0.5514	4.10	0.2964	0.9838	84	79.38
Commerce, FL	0.8991	1.16	0.6743	1.0000	78	97.89

Note: The coefficients b_1, b_2, and b are dimensionless.

The goodness of fit statistics (r^2) varied from -1.90% to 97.89% with a mean of 65.21%. Thus, as an average value, the broken-line model (Equation 1) accounted for about 2/3 of the variance in direct runoff.

CLASSIFICATION

General: In most scientific endeavors classification is an early step in development. In biology, for example, classification is a major component on the path to objective description, the recognition of order, and to shedding light on such as origins, evolution, purpose, and processes. Similar classifications can be found in almost every well-developed scientific field, including the social sciences. In hydrology, classification might eventfully lead to similar benefits: perspective, understanding, and the ability to reference behavior on standard previously described examples. Classification and naming gives a common basis for labelling, or an instant identification for a mutually understood more complex identity or idea.

The classification here is done on an empirical or output-based foundation. That is, on the response patterns observed in the data sets, without conscious regard to the more fundamental underlying processes. This coincides with an unstated aim of maintaining minimum data requirements (simple storm and runoff depths). As shown previously in Table 2, these two event descriptors are in relatively high association (average r^2 is about 65%), thus suggesting a successful choice. To dwell deeper into process inference on a watershed basis would require more data (storm and runoff durations, hydrograph peaks, rainfall intensity patterns, etc.). This approach this treats the watershed as a fundamental unit of natural organization. For this study at least, inferences about the underlying on-land processes are not pursued.

Groupings: Drawing from the previously-described variety observations, and from the familiarity that comes with experience, the categories of rainfall-runoff response were formed, as outlined in Table 3. Knowledge of the watersheds themselves, the individual characteristics of the data sets, and the necessity for crisp clusters played a role in forming the groups.

Table 3. Categories of Rainfall-Runoff Response (Tentative)

COMPLACENT

1. **Defining Concept:** The main attribute is consistently low event runoff with respect to rainfall. Runoff ratios in the 0.5 to 2 percent range typify this behavior.
2. **Data Behavior:** $Q/P <$ ca 0.05. The relationship between P and Q may be either linear or non-linear. There seems to be no or little rainfall threshold.
3. **Possible Mechanisms:** Either channel or near-channel sources. Variable source areas are possible, but total source is a small part of the watershed area under most experienced conditions. This can be overland flow (from a road, for example), quick flow from selected wet spots, or direct channel interception.
4. **Type Examples:** Missouri Gulch, Colorado, Cabin Cr., Idaho, W. Donald Creek, Oregon, 3Bar D, Arizona.
5. **Attributes:** Mostly flowing streams and forest cover.

VIOLENT

1. **Defining Concept:** Substantial rainfall needed to cause a distinct sudden increase in runoff. A threshold precedes a high fraction response. A "two-phase" system.
2. **Data Behavior:** A "high" runoff threshold (with respect to the experienced storm depths), with or without a complacent lead-in. High runoff fractions for the rainfall increments above the threshold.
3. **Possible Mechanisms:** Shallow porous soils overlying impervious strata, or vertisols sealing with extended event rainfall. Overland flow or quickflows.
4. **Type Examples:** Beaver Creek #17, Arizona, Berea #6, Kentucky.
5. **Attributes:** Big storms (compared to threshold) in data set. Complacent examples may behave violently under extreme events.

STANDARD

1. **Defining Concept:** Traditional response expected between complacent and violent, with indications of effects of watershed wetness and/or storm intensity. P-Q appears to approach a maximum asymptotically given sufficient rainfall and in a distinct curvelinear fashion. $0<(dQ/dP)=f(P)<1$
2. **Data Behavior:** Fits equations meeting above definition. Initial rainfall threshold is usually absent or small.
3. **Possible Mechanisms:** Most overland flow situations show this behavior, but also many apparent quick flow and channel contributions. There is a strong suggestion of variable source areas with increasing storm depth.
4. **Type Examples:** Treynor, Iowa watersheds (USDA,ARS), Badger Wash Colorado (USGS), Coweeta, North Carolina watersheds (USFS), Edwardsville 4 ,Illinois (USDA,ARS) watershed.
5. **Attributes:** Variety of covers: forest, rangelands, and agricultural. Most bare-soil, rain-fed agricultural watersheds exhibit a standard response. Asymptotically consistent with the Curve Number runoff equation. The most common pattern encountered.

ABRUPT

1. **Defining Concept:** Near-impervious behavior, with most events having high fractional runoff, P-Q is nearly constant for most events.
2. **Data Behavior:** Q/P ca 0.7 to 0.95. Threshold is low, absent, or undetectable. P-Q approaches a constant for most events.
3. **Possible Mechanisms:** Impervious areas and overland flow.
4. **Type Examples:** Commercial watershed, Miami Florida (USGS)
5. **Attributes:** Typical of highly urbanized watersheds.

INACTIVE

1. **Defining Concept:** Inactive. No flow of any sort experienced in period of record, and scant evidence of anything except catastrophic happenings.
2. **Data Behavior:** All Q=0.
3. **Possible Mechanisms:** High infiltration capacities and soil storage, low rainfall intensities. Snowmelt situations.
4. **Type Examples:** Anecdotal only: Records of no flow not published for small watersheds.
5. **Attributes:** Rounded swales for channels. Forest and/or range cover. Semi-arid, low intensity situations. When provoked thru extreme events of rainfall and/or watershed wetness, these situations can provoke geomorphic events. No base flows because of inopportune geologic plumbing.

The above concepts can be related to Equation 1, using the equation coefficients a, b_1, and b_2 to express the nature of the hydrologic responses groupings. For example, a low values of b, b_1, and b_2 would be consistent with the "Complacent" category. Low or absent values of "a" combined with a high value of b_2 would be consistent with "Abrupt" behavior. High values of "a" with a major change from b_1 to b_2 would support the "Violent" category. Roughly, then, the following may be seen as the relative coefficient attributes of the runoff response groups already described:

Complacent: low b, low a, low b_1 and low b_2
Violent : medium to high b, high a, and high to very high b_2
Abrupt : high b, low a, and very high b_2
Standard : medium values of all coefficients.
Inactive : b_1=0, a exceeds highest rainfall, b_2 undefined.

Note that the coefficient b_1 plays little role, except in describing the change of runoff at the threshold for the Violent case. From this approach, the classifications have been assigned trial values of coefficients. As before, these are subjectively defined, and draw from the knowledge of the watersheds and the data's observed tendencies to cluster into reasonable groups. This information fits easily into a dichotomous key, given below in Table 4.

Table 4. Proposed Dichotomous Key for the Classification of Watershed Rainfall-Runoff Response Groups

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Definitions: 1. $Q=b*P$
2. $Q=b_1*P$ $P<a$
$Q=ab_1+b_2*(P-a)$ $P>a$

where $0<b<1.00$, and $0<=b_1<b_2<=1.00$, and $0<=a$

1. b=0	**INACTIVE** category 1.
Not as above, b>0	
2. b<0.06	**COMPLACENT** category
2. Not as above, b<0.06	
3. a<= 1.25 cm	
4. b_2 =>0.8	**ABRUPT** category
4. Not as above, b_2<0.8	**STANDARD** category
3. Not as above, a>1.25 cm	
5. a>2 cm	
6. (b_2-b_1)=>0.6	**VIOLENT** category
6. Not as above, (b_2-b_1)<0.6	**STANDARD** category
5. Not as above, a<2cm	**STANDARD** category

Note that there are three routes to getting to the "Standard" category. An earlier version of this Table (Hawkins, 1989) broke the major categories down further into subsets of "low" and "high". For simplicity, these are not given here.

Using these criteria (based on a, b, b_1, and b_2) the entire 100 watersheds were placed into the categories as given in Appendix III. The frequency count of the classes in the data set are as follows: Inactive, none; Complacent, 25; Standard, 57; Violent, 17; Abrupt, 1. Note that most of the most of the watersheds (57%) fell into the "Standard" category, and there were no representatives of the "Inactive" category in the sample.

ASSOCIATION

There exists a widely held notion that hydrologic behaviors are closely linked to surface vegetation. This would justifiably proceed from a philosophy of a grand scale cause-and-effect ecology, whereby specific soils are formed from specific geologic and climatic sources, and vegetation exists in response to these same items. Since hydrology is an expression of these same natural inputs, it then should be associated with the vegetation. Furthermore, intuitive arguments are often made. For example, the observed processes of ideal forests such as canopy and litter interception, soil biologic activity, and the condensation of fog, are often extolled, and by extension, their moderating effects on hydrology stressed. These are contrasted to other land types - such as rangelands, agricultural fields, and urban lands - with accompanying extension to their hydrologies. The work here will compare the land "types" with the response hydrology already described.

Land Types: The basic data sources almost always included some description of the watershed lands. In fact, in several cases, the data were drawn from reports in which the influence of land was a major study objective. However, there is no standard or uniform protocol for describing land use and condition: the land use/type is qualitative rather than quantitative, and uses adjectives rather than classes or numbers. Thus, only broad categories can be made: the lands were classed as either "Forest", "Range", "Urban", or Agricultural". Mixed types were classified according to the major cover/use component, and a sub-category allowed further descriptive detail. The descriptive judgements or the adjectives of the original source author were used whenever possible, and dominated the choices.

The term "Forest" included a wide variety of covers: hardwoods in the midwest, pinyon-juniper in the southwest, "...dry broad sclerophyll open forests..." in Australia, and old growth conifers in central Idaho. "Agriculture" generally was assigned to lands known to be under active cultivation in the traditional cropping sense, but also included some pasture lands. "Range" was mainly an arid land default category, as is the range (or grazing) land use, and included near-bare lands in western Colorado and Wyoming, mixed grassland-forest lands in eastern Oregon, and desert shrub lands in Arizona. Clearly, the lack of resolution here is a major problem.

The associations are made quite simply: by statistical comparison of the land type and the previously-derived response categories and/or coefficients. Table 4 following shows the array of coefficients for the land types.

Table 4. Means and standard deviations of Fitted Coefficients for Land Classes

Category	b	a(cm)	b_1	b_2	r^2(%)	N
MEANS						
Forest	0.2114	4.22	0.0966	0.3951	68.17	54
Range	0.2421	2.19	0.1226	0.4223	59.87	28
Agriculture	0.2742	5.32	0.1923	0.5812	56.27	13
Urban	0.4052	2.20	0.2965	0.5283	86.55	5
All(means)	0.2379	3.77	0.1311	0.4336	65.21	100
STANDARD DEVIATIONS						
Forest	0.1941	3.64	0.1135	0.3570	21.87	54
Range	0.1461	3.19	0.1036	0.2636	25.05	28
Agriculture	0.1772	3.05	0.1776	0.3326	19.80	13
Urban	0.2939	1.71	0.2551	0.3807	13.91	5

Comparison with "t" Tests: The above findings were analyzed with series of "t" tests. Considering just the coefficient "b" showed no significant differences between the hydrology of the land classes, in spite of the apparent trend in the means from Forest to Urban types. The highest associated probabilities were about 84%, between Forest and both Urban and Agriculture.

Differences in runoff response between land types as indicated by the coefficients "a", "b_1, and "b_2 are spotty. Probabilities in excess of 90% were for the following cases:

For "a"	: Between	Forest	and	Range(>99.5%)
		Forest	and	Urban(96%)
		Range	and	Agric(>99.5%)
		Agric	and	Urban(98%)
For "b_1"	: Between	Forest	and	Agric(92%)
For "b_2"	: Between	Forest	and	Urban(94%)
		Range	and	Urban(91%)

Although there was no pair of land types which displayed profound differences in all three coefficients, there were significant difference between the coefficients of some land classes, when taken as a vector. The "t" tests were combined using the Bonferroni inequality, as discussed previously. The results are given in Table 5.

Table 5. Probability of "t" (in %) for Coefficient Vector Land Type Classifications

	Forest	Range	Agric	Urban
Forest	------	98.5	76	88
Range		-----	98.5	73
Agriculture			----	94
Urban				------

These suggest that there are significant differences in the mean coefficient vectors between Forest and Range, and between Range and Agriculture. The difference between Urban and Agriculture is close to being significant, and the conservative nature of the Bonferroni inequality should be kept in mind when considering this comparison. (See Mendenhall et al, 1981). Furthermore, it should be stressed that the differences implied are in the <u>means</u> of the data, and not in all points. There is enormous overlap for individual group members. That is to say, although they are differences on the average, a high fraction of forested watersheds act (empirically, to be sure) like range and agricultural watersheds, and vice versa.

Hydrologic Domains: Additional insight to the behavior of the land types and their hydrologies is given in Figure 1. Here the difference in their runoff slopes (b_2-b_1) is plotted against the threshold coefficient "a" with the land type identified. Note the broad spread of data for the forested situations, encompassing nearly all the domain of the other three land types. The "forest" description thus says very little about the associated hydrology: it is not a distinctive association. The only apparent uniqueness is a shell of watershed experience surrounding the other three land types. Urban watersheds, on the other hand, show an tightly clustered behavior group.

SUMMARY/CONCLUSIONS

Diversity: There is a large diversity in the rainfall-runoff behavior of small watersheds. The differences are both in scale (i.e., the size of the coefficients) and in the structure of the response. Much of this is unanticipated and/or unappreciated.

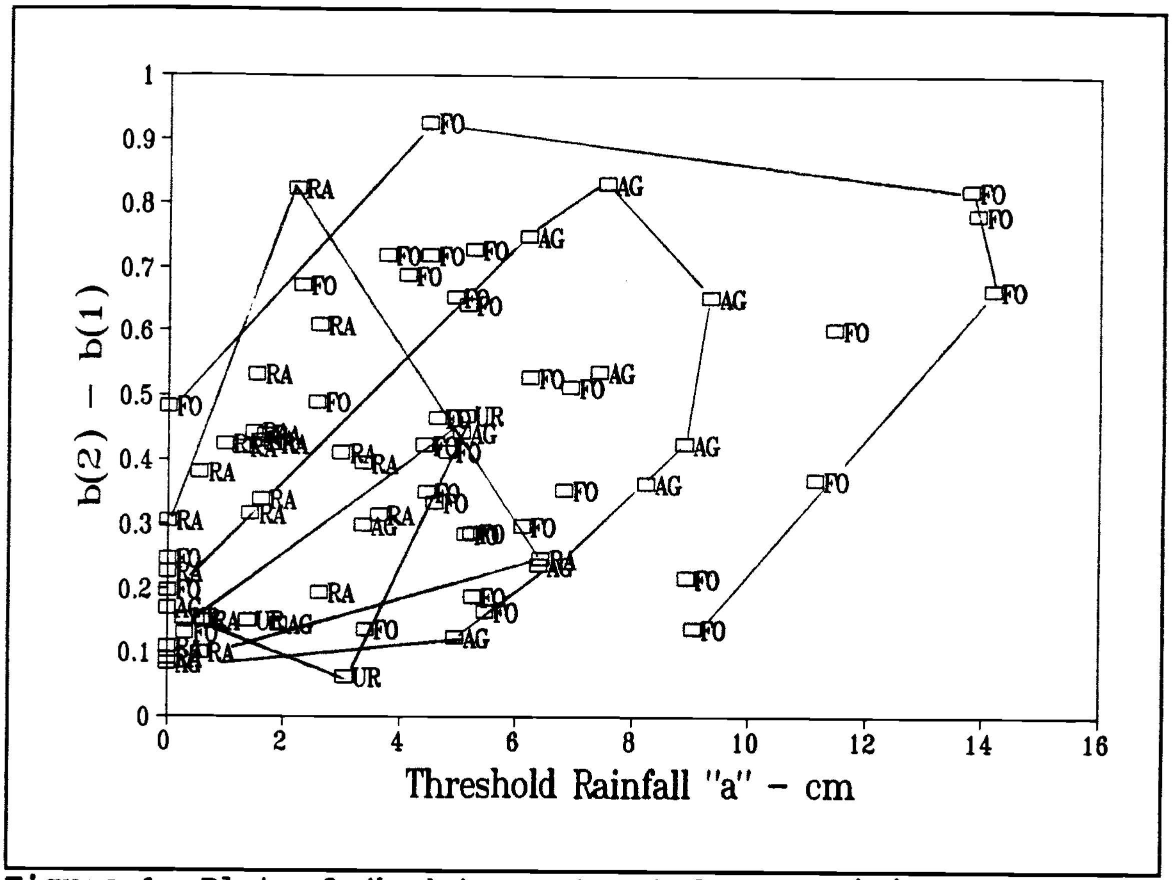

Figure 1. Plot of (b_2-b_1) vs threshold coefficient "a", with the land types identified, and the Complacent and Abrupt watersheds omitted. Note that the "FOrest" type encompasses almost all experience in the other types.

Classification: Based on the observed properties, a convention for orderly description of watershed event response has been worked out. Watershed response is placed into five groups: Inactive, Complacent, Standard, Abrupt, and Violent. Coefficient arrays for group membership have been provided.

Association: There is substantial overlap in individual watershed hydrologic performance between the land types. However, the mean values of coefficients and membership tables suggest strongest hydrologic contrasts between range and forest lands, range and agricultural lands, and urban and agriculture lands. All other comparisons are inconclusive. Forested watersheds cover all hydrologic categories (except Abrupt), while range and agriculture covers tend to be of Standard response. There were no agricultural watersheds with Complacent response. The behavior domain of forested watersheds included those of range, urban and agricultural watersheds.

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