Journal of Hydrology, 111 (1989) 89–106
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

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SEDIMENT CONCENTRATION VERSUS WATER DISCHARGE DURING SINGLE HYDROLOGIC EVENTS IN RIVERS

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(Received January 18, 1989; accepted February 8, 1989)

ABSTRACT

Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. J. Hydrol., 111: 89–106.

Relations between sediment concentration (C) and water discharge (Q) for a hydrologic event, such as a flood, are studied qualitatively by analyzing "smoothed" temporal graphs (discharge and concentration vs. time) in terms of mode, spread, and skewness. Comparing C/Q ratios at a given discharge on the rising and falling limbs of the discharge hydrograph provides a consistent, reliable method for categorizing C–Q relations. Five common classes of such relations are single-valued (straight or curved), clockwise loop, counterclockwise loop, single-valued plus a loop, and figure eight. Temporal-graph mode and skewness influence the type of relation, whereas temporal-graph spread affects the details of the particular C–Q relation (its graphical breadth, shape, orientation, and plotted location). Field examples of the various types of relations are given, including varieties that heretofore have received little attention, such as the figure eight. Explanations for each type of C–Q relation are discussed.

INTRODUCTION

The transport of sediment in rivers is important with respect to pollution, channel navigability, reservoir filling, hydroelectric-equipment longevity, fish habitat, river aesthetics, and scientific interests. A basic relation in dealing with all of these topics is that between concentration of suspended sediment (C) and water discharge (Q). A few types of C–Q relations, such as the hysteresis loop, are well known. However, no systematic exploration and classification of all types of C–Q relations seems to have been undertaken and published. Wood (1977) showed models for two such relations (including the clockwise hysteresis loop), based on his study of a single drainage basin in England.

The purposes of this paper are to: (1) identify and classify the major types of single-event C–Q relations, using models and field examples; (2) provide a simple graphical explanation for each type; and (3) summarize physiographic or hydrological reasons for each type. The single hydrologic event can be brief,

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such as a flood lasting hours or days, or it can be relatively lengthy, such as snowmelt runoff lasting weeks or months.

PROCEDURE

Although the results of this study will be presented in terms of classes of C–Q relations, the procedure in arriving at those classes was a graphical one. As a preliminary step, temporal graphs were plotted on semilog paper with time as the independent variable on the arithmetic scale and either C or Q on the ordinate. The concentration time graph hereafter is called a C-graph, and the discharge time graph is called a hydrograph or Q-graph. Plots of C versus Q are on log paper with C on the Y-axis.

The procedure consisted of: (1) drawing model or idealized temporal graphs by systematically varying the mode, spread, or skewness (i.e. varying one of these features while holding the other two approximately constant); (2) plotting the associated idealized C–Q relation; and (3) verifying and demonstrating these features with field examples. Varying of mode, spread, and skewness on the graphs was done in a nondimensional and qualitative way, rather than by detailed computations. Only the more common or likely combinations of mode, spread, and skewness (or those combinations needed to establish initial principles) were examined.

CLASSES OF C–Q RELATIONS

The various effects of different temporal-graph modes, spreads, and skewnesses revealed five classes of C–Q relations (Table 1). Other classes are conceivable, but Table 1 probably includes the major types. Each class is characterized by a simple, objective and reliable mathematical criterion, once the two temporal graphs are available. This criterion is the ratio C/Q at a few arbitrarily selected times during the temporal increase and decrease of C and Q. The rising and falling limbs of the Q-graph represent the two basic time zones. The first step in the analysis consisted of choosing a time during the rising limb of the Q-graph, reading the corresponding values Q_1 and C_1, and computing their ratio, C_1/Q_1. The second step was locating that same discharge value on the Q-graph's falling limb, reading the concentration associated with the discharge at that time, and determining this new ratio, C_2/Q_1. The two C/Q ratios — one on the Q-graph's rising limb and the other on its falling limb, for the same common value of Q — then were compared qualitatively to see which is larger. Finally, this type of comparison was repeated for several other selected values of Q.

Ideally, the values of both C and Q in the C/Q ratios should be within the rise and fall of these variables, rather than before or after the hydrologic event. If both the increase and decrease of C are completed during just the increase (or decrease) of Q, one of the C/Q ratios unavoidably must be determined before or after the increase and decrease of C. Some C–Q plots of field data have enough scatter that C/Q ratios are difficult to evaluate.

TABLE 1

Classes of C–Q relations

Class	Relation	C/Q criteria	Sample reference
I	Single-valued line	$(C/Q)_r \cong (C/Q)_f$	
	A. Straight line	A. Slopes of two subsections of the overall relation are equal	Wood (1977)
	B. Curve, slope of which increases with increasing values of Q	B. Slopes of two subsections of the overall relation are unequal — steeper for larger values of Q	Wood (1977)
	C. Curve, slope of which decreases with increasing values of Q	C. Slopes of two subsections of the overall relation are unequal — flatter for larger values of Q	–
II	Clockwise loop	$(C/Q)_r > (C/Q)_f$ for all values of Q	Paustian and Beschta (1979)
III	Counterclockwise loop	$(C/Q)_r < (C/Q)_f$ for all values of Q	Axelsson (1967)
IV	Single line plus a loop	$(C/Q)_r \cong (C/Q)_f$ for one range of Q values $(C/Q)_r \lessgtr (C/Q)_f$ for other range of Q values	–
V	Figure eight	$(C/Q)_r > (C/Q)_f$ for one range of Q values $(C/Q)_r < (C/Q)_f$ for other range of Q values	Arnborg et al. (1967)

$(C/Q)_r$ = (C/Q) on Q-graph's rising-limb, for a selected discharge; $(C/Q)_f$ = (C/Q) on Q-graph's falling limb, paired to a particular $(C/Q)_r$ by being calculated at same value of Q. Dashes mean no reference available.

Class I — Single-valued line

The simplest type of C–Q relation is the single-valued line. Its unique characteristic is that any C/Q ratio on the hydrograph's rising limb equals the C/Q ratio on the falling limb, for the same value of Q. Three subgroups of this single-valued-line class are the straight line, the curve bending upward, and the curve bending downward. In all three subgroups, C increases as Q increases (Figs. 1, 2).

The first subgroup, a straight line, occurs when the C-graph and Q-graph have simultaneous peaks and identical spreads and skewnesses, though not necessarily identical relative height of peaks (Fig. 1). Spread here is relative or nondimensional in that two bell-shaped distribution curves (temporal graphs) of identical form have the same spread, even though one curve might be many times bigger than the other (Figs. 1b, 1c).

The trend (if any) in C/Q ratios proceeding from the beginning of the Q-graph's rising limb to its peak indicates whether the slope of the straight-line C–Q relation is 1, > 1, or < 1. If all C/Q ratios are equal for all values of Q, the straight-line C–Q relation has a slope of 1. This occurs only when the two graphs have simultaneous peaks, the same shape, and the same size (i.e., plot as coincident increases and decreases when normalized and drawn on the same graph (Fig. 1a).

If the C-graph is relatively taller than the Q-graph, the two C/Q ratios for any given value of Q still are equal on the rising vs. falling limbs, but the C–Q ratios for various values of Q do not all have the same value; instead, the numerical value of these C/Q ratios increases systematically as we move along the rising limb of the Q-graph toward the peak. The straight line on the C–Q plot in this case has a slope greater than 1 (Fig. 1b).

If, instead, the C-graph is relatively shorter than the Q-graph (simultaneous peaks and same spread and skewness for both graphs), the numerical value of these C/Q ratios decreases systematically as we move along the rising limb of the Q-graph toward the peak. The straight line on the C–Q plot then has a slope less than 1 (Fig. 1c).

A curved, single-valued C–Q relation (Classes IB, IC) obtains when both temporal graphs have simultaneous peaks, identical skewnesses and heights, but different amounts of spread (Fig. 2). Results are generally the same even if the two peaks on the temporal graphs do not have the same relative height, when symmetrical curves are used. Where the spread of the C-graph (S_C) is less than that of the Q-graph (S_Q), the associated C–Q curve generally plots in the lower right region of the plottable zone, and it bends upward, such that its slope increases with increasing Q. This is the second subgroup of the single-valued line class and is shown in Fig. 2a. (Strictly, spread can be varied while keeping skewness constant only when both temporal graphs are symmetrical. The temporal graphs of most field data are not symmetric, usually being skewed to the right. The examples shown here, therefore, have different spreads but only approximately constant skewnesses. Also, for Fig. 2 and several other figures,

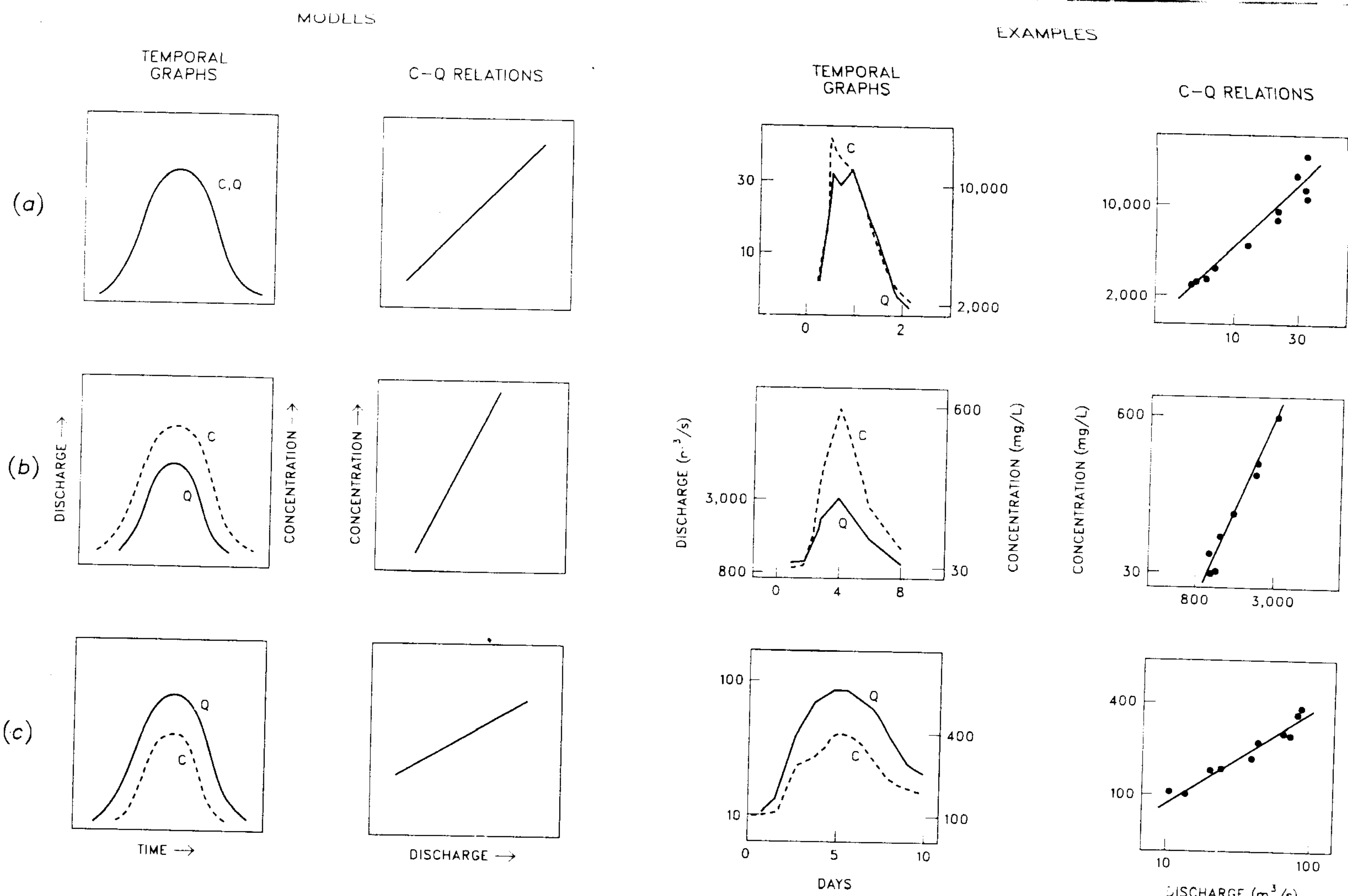

Fig. 1. Types of straight-line C–Q relations (Class IA): (a) 45° straight line, exemplified by Cottonwood Creek near Ewan, Wash., Jan. 28–29, 1965; (b) straight line with slope > 1, exemplified by Potomac River at Point of Rocks, Md., March 20–27, 1962; and (c) straight line with slope < 1, exemplified by Iroquois River near Chebanse, Ill., July 24–Aug. 2, 1979. Data from U.S. Geological Survey files.

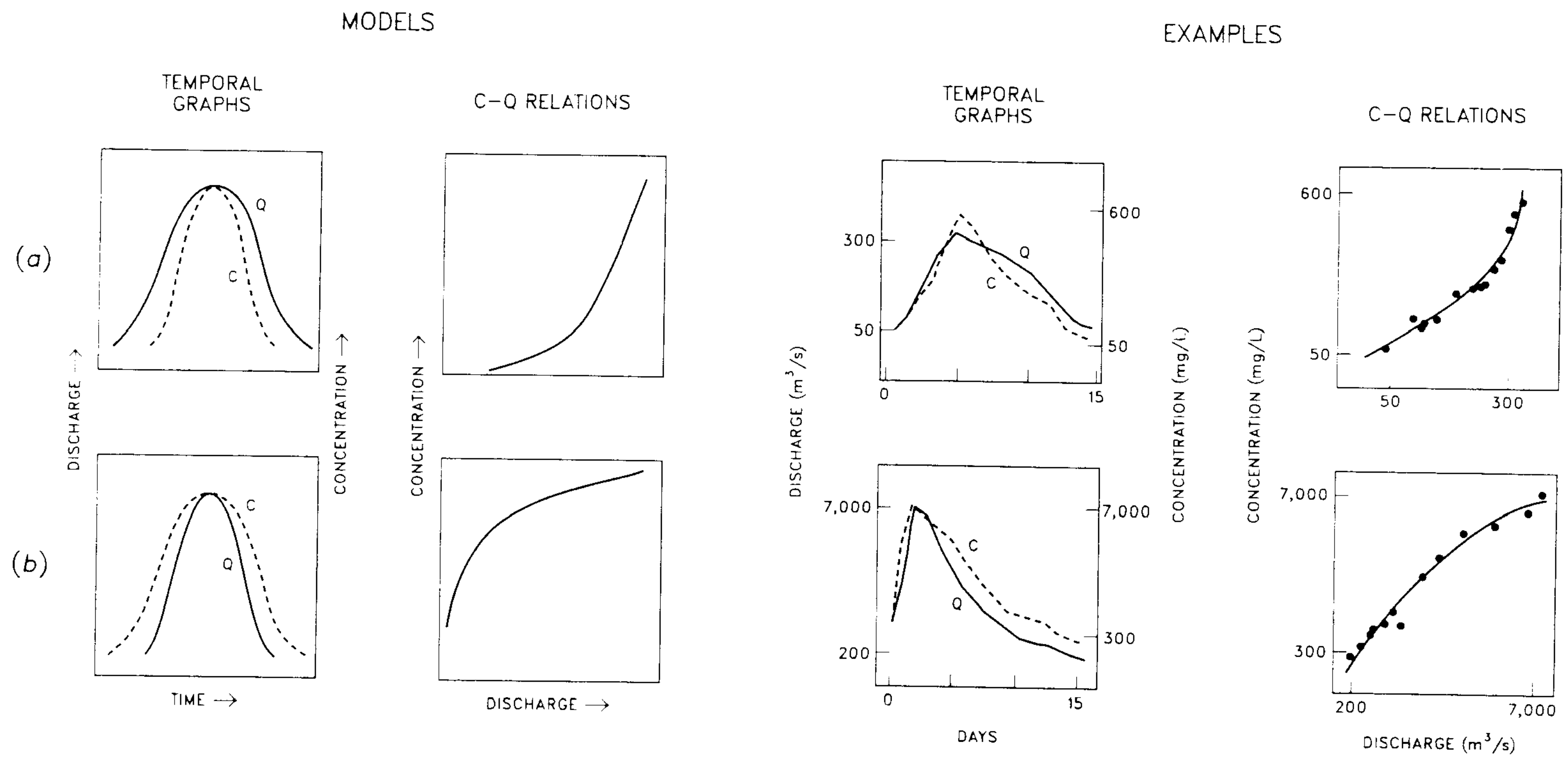

Fig. 2. Single-valued C–Q curves (Class IB, IC) showing effect of temporal-graph spread: (a) bending upward (Class IB), exemplified by Kankakee River near Wilmington, Ill., Aug. 18–31, 1979; and (b) bending downward (Class IC), exemplified by Eel River at Scotia, Calif., Feb. 6–22, 1960. Data from U.S. Geological Survey files.

models that convey the desired principles but that differ from the models shown in the figure, especially with regard to peak heights, are conceivable.)

The degree of curvature is least, i.e., the C–Q relation is nearly straight, when the spreads of the two temporal graphs are almost identical (S_C only slightly less than S_Q). Curvature becomes more pronounced as S_C becomes smaller relative to S_Q. Also, as these differences in spread become greater, the curve becomes asymmetric and shifts in location in that much of it tends to plot toward the vertical asymptote on the right side of the graph (the vertical line drawn at the maximum discharge, Q_{max}).

If, in contrast, the spread of the C-graph is greater than that of the Q-graph, the C–Q curve plots in the upper left region of the plottable zone and its slope, though still positive, decreases with increasing Q (subgroup three; Fig. 2b). The line is nearly straight when S_C is only slightly greater than S_Q; it becomes more and more curved, asymmetric, and relocated into the upper part of the plot (towards the horizontal line drawn at the maximum concentration, C_{max}) as S_C becomes larger relative to S_Q.

As far as I know, the only author to have published a single-valued C-curve for a hydrologic event is Wood (1977, fig. 4), whose examples bend upward. That is, the downward-bending relation (Fig. 2b) may not have been reported heretofore. There doesn't seem to be any published information as to how common such relations are.

Single-valued C–Q relations also occur (though rarely) under conditions other than the idealized ones described here. For instance, as long as the temporal graphs have simultaneous peaks, the differences in spread and skewness may offset one another such that the C/Q requirements for a single-valued C–Q relation are satisfied.

Class II — Clockwise loop

If the sediment peak arrives at the stream cross section before the water-discharge peak and both graphs have about the same skewness, a C-value on the rising limb of the Q-graph is greater than that for the same discharge on the falling limb (Fig. 3a). That is, the ratio C_1/Q_1 at any chosen time on the rising limb of the Q-graph is greater than that for the same discharge on the falling limb. On the C–Q graph, the data for the rising limb plot relatively high, and the data for the falling limb plot low. Considered sequentially, the points describe a clockwise loop. Clockwise loops are common and well known; published examples (couched in some cases in terms of suspended load, which decreases the scatter of points somewhat) may be found in Leopold and Maddock (1953), Sundborg (1956), Walling and Teed (1971), Wood (1977), and Paustian and Beschta (1979).

When the two temporal graphs have the same spread, skewness (symmetrical curves), and relative peak heights, the C–Q loop is symmetrical, with its long axis oriented at 45° to the horizontal. For a given length, the C–Q loop is widest when there is a large time gap between the arrivals of the two peaks. As the

Fig. 2. Single-valued C–Q curves (Class IB, IC) showing effect of temporal-graph spread: (a) bending upward (Class IB), exemplified by Kankakee River near Wilmington, Ill., Aug. 18–31, 1979; and (b) bending downward (Class IC), exemplified by Eel River at Scotia, Calif., Feb. 6–22, 1960. Data from U.S. Geological Survey files.

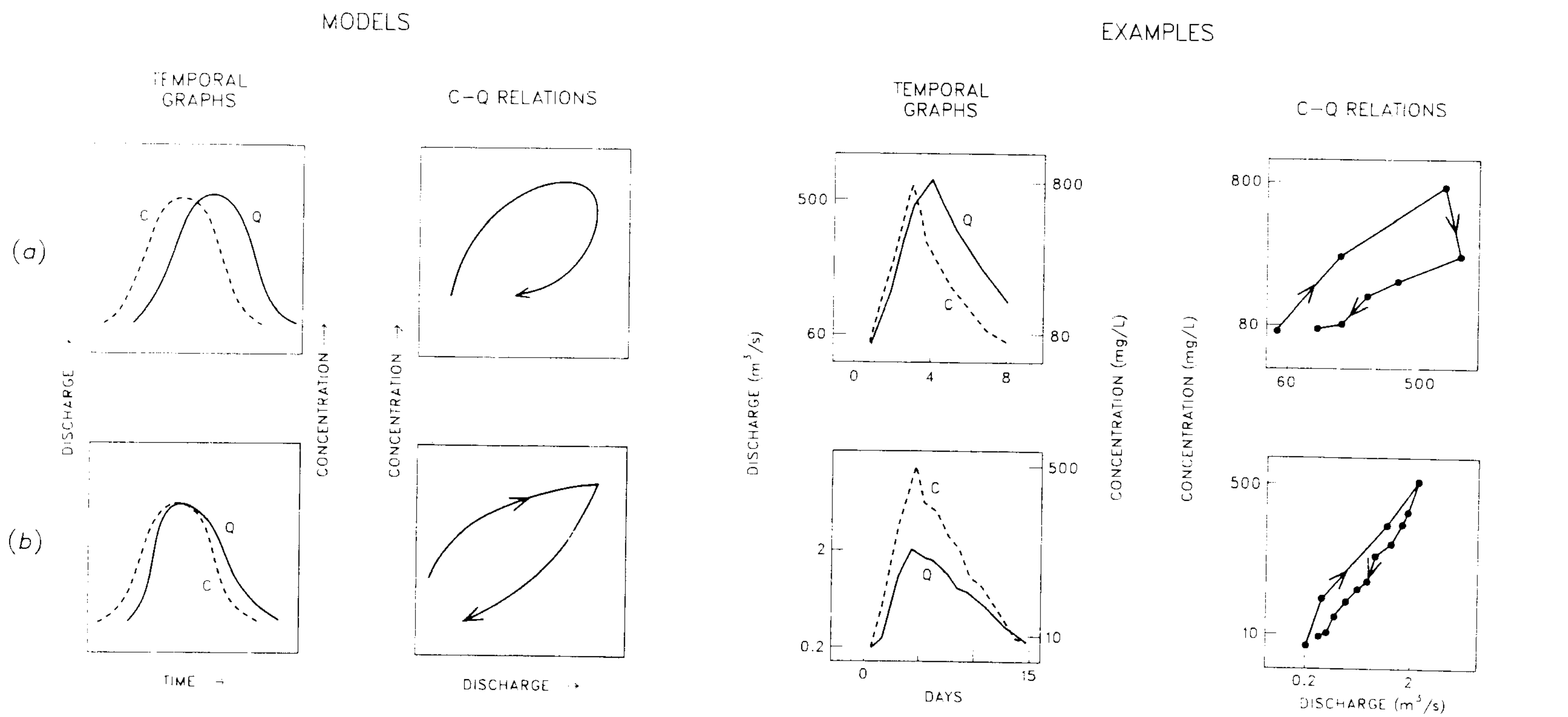

Fig. 3. Clockwise-loop C–Q relations (Class II): (a) concentration peaking before water discharge, exemplified by Yadkin River at Yadkin College, N.C., Oct. 15–22, 1964; (b) simultaneous peaks of water and sediment, exemplified by Flynn Creek near Salado, Ore., Dec. 19, 1964–Jan. 1, 1965. Data from U.S. Geological Survey files.

time between the arrivals of the two peaks decreases, the width of the C–Q loop also decreases (and eventually collapses to a single line when the two peaks occur simultaneously).

The C–Q loop also is narrow relative to its length when one temporal graph is considerably higher than the other or when both temporal graphs have large spread. Conversely, small spread ("flashy" behavior) on the temporal graphs results in a relatively broad C–Q loop.

When the relative spreads of the two graphs differ, changes occur in the size (relative breadth), shape, orientation, and sometimes in the location of the C–Q loop. Qualitatively, the changes seem to be consistent regardless of (a) relative height of the peaks in the temporal graphs or (b) which graph (C or Q) has the larger spread. These changes are as follows:

The length of the C–Q loop's long axis remains the same as long as temporal-graph peak heights remain the same. The breadth of the C–Q loop, however, decreases as the relative spreads of the two temporal graphs become more different.

Increased differences in relative spread affect the shape of the C–Q loop in that the loop becomes somewhat asymmetric (Fig. 4). (Symmetrical C–Q loops seem to result when the two temporal graphs have approximately the same spread, though not necessarily the same shapes or peak heights.)

The orientation of the C–Q loop's long axis is about at 45° to the horizontal when $S_C \approx S_Q$. If $S_C \ll S_Q$, the loop has an essentially vertical orientation (Fig. 4a). In contrast, when $S_C \gg S_Q$, the loop's long axis becomes approximately horizontal (Fig. 4b). With $S_C < S_Q$, most of the increase and decrease of C occurs during high Q-values, and the vertically oriented C–Q loop plots toward the right side of the plottable zone, in the region of high discharges (Fig. 4a). If, instead, $S_C > S_Q$ and most of the increase and decrease of Q occurs when concentrations are high, the horizontally oriented C–Q loop plots in the upper part of the plottable zone, in the region of high concentrations (Fig. 4b). Directions or amounts of skew on the temporal graphs do not affect the direction of the C–Q loop, its shape, or the region in which it plots.

Conventional thinking has held that, when sediment concentration peaks before water discharge, a clockwise hysteresis loop forms. The study procedure of systematically varying only one of mode, spread, or skewness, while adopting the C/Q criterion as diagnostic, revealed two interesting features about this belief. First, as shown below in the discussion of Class V relations, the overall C–Q relation will not necessarily be a clockwise hysteresis loop just because sediment concentration peaks first. Second, and apparently unknown heretofore, a clockwise C–Q loop can result even when the two temporal graphs peak simultaneously (Fig. 3b). That is, concentration need not peak before water discharge in order for a clockwise C–Q loop to form.

The reason that a clockwise sequential loop can occur even when the temporal graphs peak at the same time is found in the C/Q rationale described earlier. When the two graphs have simultaneous peaks but skewness for water discharge is greater than that for sediment concentration, the C/Q ratio on the

Fig. 3. Clockwise-loop C–Q relations (Class II): (a) concentration peaking before water discharge, exemplified by Yadkin River at Yadkin College, N.C., Oct. 15–22, 1964; (b) simultaneous peaks of water and sediment, exemplified by Flynn Creek near Salado, Ore., Dec. 19, 1964–Jan. 1, 1965. Data from U.S. Geological Survey files.

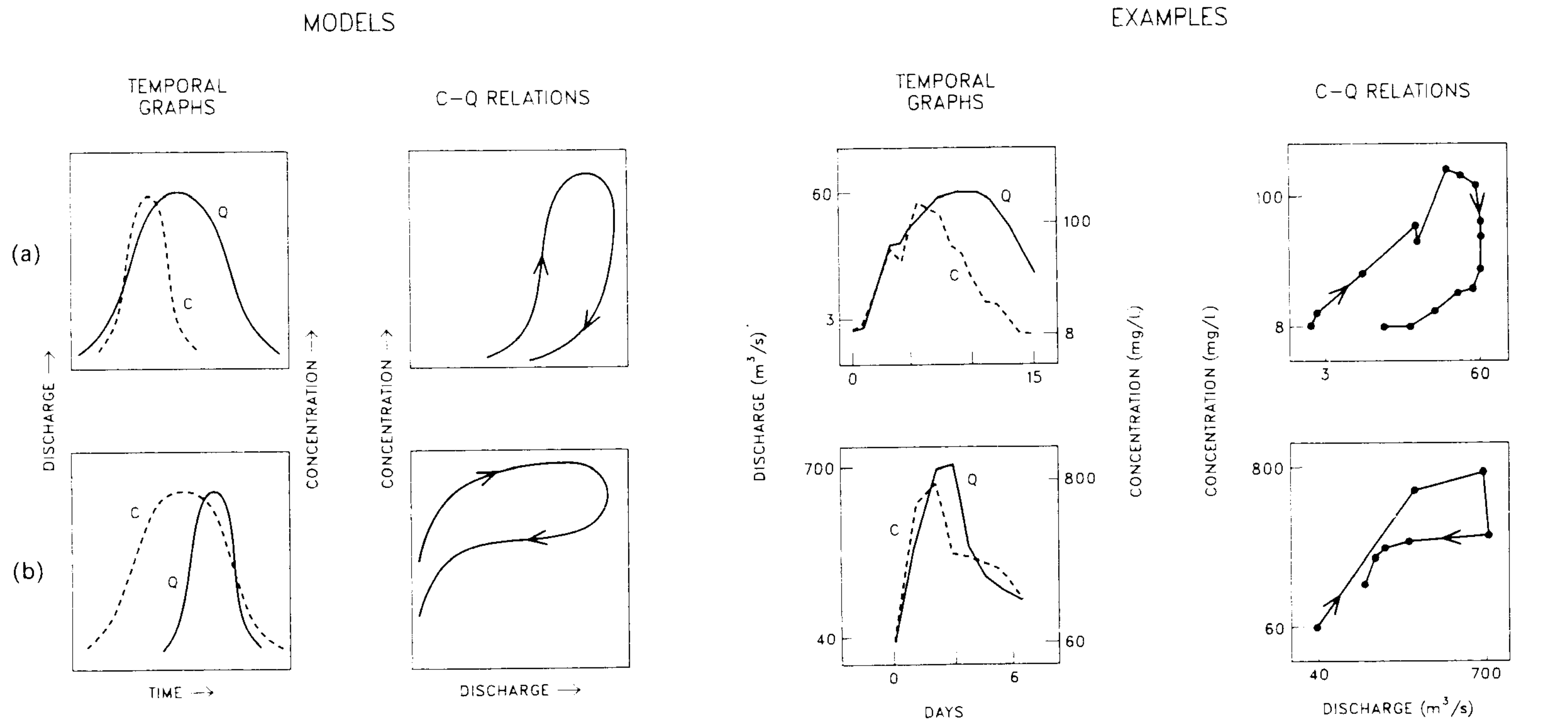

Fig. 4. Asymmetric C–Q loops showing effect of temporal-graph spread (Classes II or III; II shown here): (a) spread of C-graph less than that of Q-graph, with C peaking first, as exemplified by Tradewater River at Olney, Ky., Feb. 5–20, 1965; and (b) spread of C-graph greater than that of Q-graph, with C peaking first, as exemplified by Yadkin River at Yadkin College, N.C., Sept. 29–Oct. 6, 1959. Data from U.S. Geological Survey files.

rising limb of the Q-graph is consistently greater than the C/Q ratio on the falling limb, for each of various values of Q. If C/Q ratios are greater on the rising limb, C-values are relatively high on the rising limb and low on the recessional limb, producing a clockwise C–Q loop. Sequential loops due to a temporal-graph combination of simultaneous peaks and different skewnesses seem to be quite common.

Class III — Counterclockwise loop

If the C peak arrives later than the Q peak (skewness the same for both graphs), C-values on the rising limb of the Q-graph plot lower than those on the falling limb, for given values of Q. This means that, for a given discharge, the C/Q ratio on the rising limb of the Q-graph is less than the ratio at the same discharge on the falling limb. The chronologically arranged data plot as a counterclockwise loop (Fig. 5a). Counterclockwise loops apparently are well known, stemming from the paper by Heidel (1956); however, few examples seem to have been published for single hydrologic events. Even Heidel's (1956) graph does not actually show a counterclockwise loop, as he plotted water discharge on the Y-axis instead of on the X-axis, thus obtaining a clockwise loop.

All of the comments made earlier regarding the influence of temporal-graph characteristics on a clockwise C–Q loop's size, shape, orientation, and plotting position also apply to the counterclockwise C–Q loop. Also as with clockwise C–Q loops, a counterclockwise loop can form even when the C-graph and Q-graph peak at the same time (Fig. 5b). Again, this does not seem to have been reported in previous work; the impression heretofore apparently has been that the Q-graph must peak first in order for a counterclockwise loop to obtain. In general, the distinguishing criterion and sole requirement for hysteresis loops to form is that, for each and any value of Q, C/Q ratios on the rising limb of the Q-graph be consistently greater than (for clockwise loops) or less than (for counterclockwise loops) those on the falling limb.

Class IV — Single line plus loop

The C–Q relation for a single hydrologic event also can plot as a single-valued relation in one range of water discharges and a sequential loop in the adjoining range of discharges (Fig. 6). The type of relation within each range follows from the C/Q criteria outlined earlier. I have not found any published examples of this type of relation.

Class V — Figure eight

With spread held approximately constant, variable-skewness experiments revealed that, with C peaking first, a clockwise loop can form but does not always form. Similarly, with Q peaking first, a counterclockwise loop often but not always occurs. Instead, under certain conditions, a figure-eight C–Q loop

Fig. 4. Asymmetric C–Q loops showing effect of temporal-graph spread (Classes II or III; II shown here): (a) spread of C-graph less than that of Q-graph, with C peaking first, as exemplified by Tradewater River at Olney, Ky., Feb. 5–20, 1965; and (b) spread of C-graph greater than that of Q-graph, with C peaking first, as exemplified by Yadkin River at Yadkin College, N.C., Sept. 29–Oct. 6, 1959. Data from U.S. Geological Survey files.

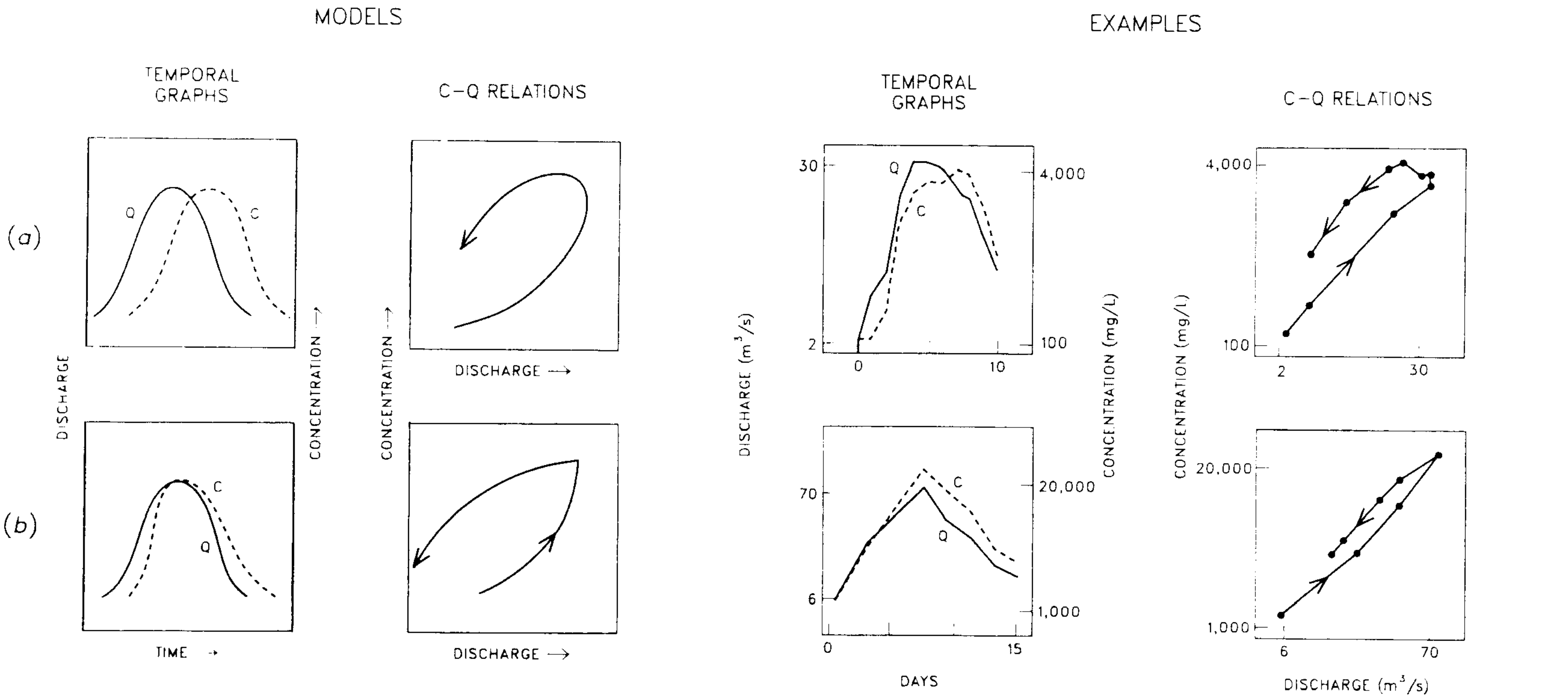

Fig. 5. Counterclockwise-loop *C–Q* relations (Class III): (a) water discharge peaking before sediment concentration, exemplified by Muddy Creek near Vaughn, Mont., March 15–24, 1969; (b) simultaneous peaks of water and sediment, exemplified by Animas River at Farmington, N.M., May 24–31, 1975. Data from U.S. Geological Survey files.

Fig. 5. Counterclockwise-loop C–Q relations (Class III): (a) water discharge peaking before sediment concentration, exemplified by Muddy Creek near Vaughn, Mont., March 15–24, 1969; (b) simultaneous peaks of water and sediment, exemplified by Animas River at Farmington, N.M., May 24–31, 1975. Data from U.S. Geological Survey files.

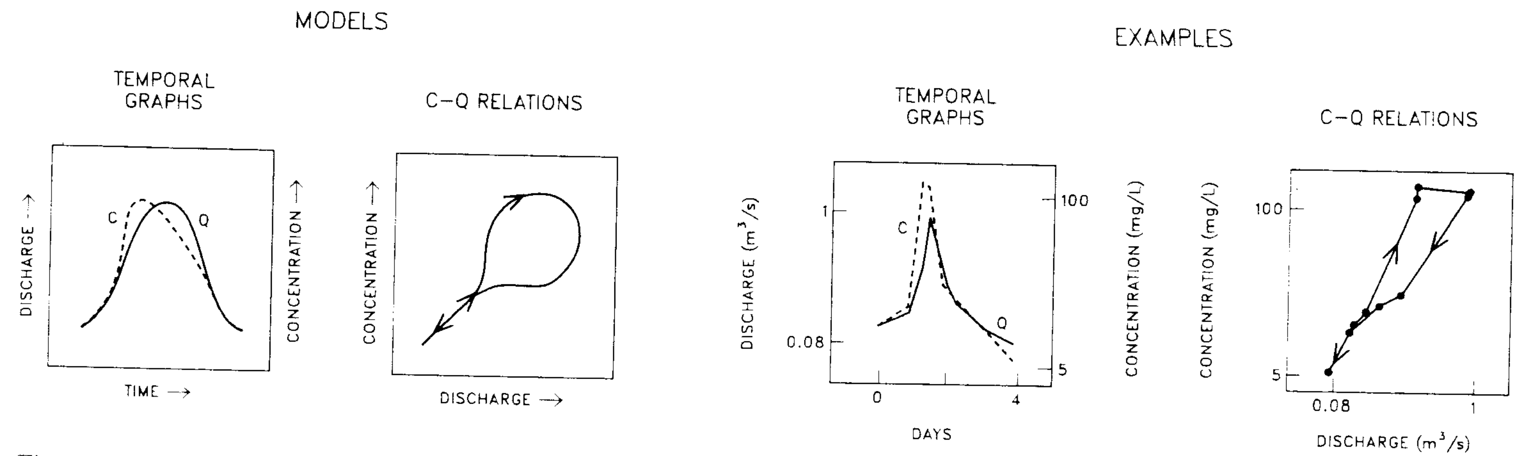

Fig. 6. Single-line-plus-loop C–Q relation (Class IV), exemplified by Oak Creek near Corvallis, Oreg., Nov. 12–16, 1971. Data from Milhous (1973).

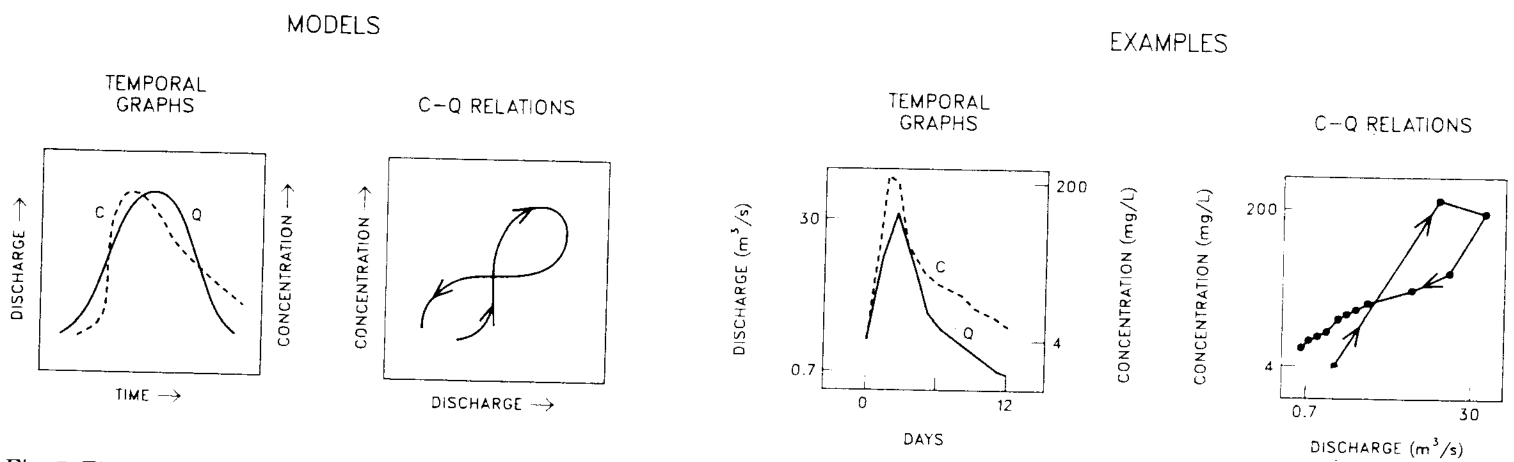

Fig. 7. Figure-eight C–Q relation (Class V), exemplified by Tradewater River at Olney, Ky., Aug. 8–20, 1970. Data from U.S. Geological Survey files.

develops, regardless of which variable peaks first. The two parts or subloops of the figure eight sequentially go in opposite directions.

C/Q ratios at various values of Q explain why some temporal graphs yield figure-eight C–Q relations. Certain combinations of temporal-graph skewness, time between peaks, and relative heights of peaks are such that C/Q ratios are larger for one range of Q on the rising limb of the Q-graph and smaller for another range of Q on that limb, compared to the same values of Q on the falling limb.

For example, in the temporal graphs of the model shown in Fig. 7, C/Q ratios in the lower part of the Q-graph's rising limb are smaller than those for the same values of Q on the falling limb. C–Q data for these smaller values of Q therefore describe a counterclockwise loop on the plot of C vs. Q. Conversely, for most of the upper part of the Q-graph's rising limb, a C/Q ratio at any value of Q is larger than that for the same value of Q on the Q-graph's falling limb. C–Q data for these larger values of Q therefore plot sequentially in a clockwise loop. Typically, the two loops of a figure eight are not of the same size.

For single hydrologic events, figure-eight C–Q relations have received little attention. Examples of such relations have been published by Bobrovitskaya (1967, fig. 1), though with no discussion, and by Arnborg, et al. (1967, fig. 6c). The commonness of such relations is unknown.

EXPLANATIONS OF C–Q RELATIONS

Many factors, summarized below, affect C–Q relations. Water-related considerations include precipitation intensity and areal distribution, runoff amount and rate, and travel rates and distances of floodwaters in the main channel. Sediment concentrations at a cross section reflect upstream spatial and temporal mobilization, storage, and depletion of available sediment. Within-channel sediment sources are the bed, banks (by erosion or slumping), and tributaries. Bed material transported in suspension to the measuring site can be influenced by amounts and sizes left by preceding floods and lesser streamflows, by the ability of the flood's rising limb to break up any armor layer, and by within-channel organic debris if such debris traps or releases sediment.

Sediment from beyond the channel banks can arrive by streamside landsliding, overland flow, and the return of overbank floodwaters to the channel. In some areas, man plays an important role in providing sediment through land-use practices, such as timber-harvesting and agriculture (Porterfield, 1972, p. 20).

The observed C-graph and hence C–Q relation also depend in part on: (a) the timing and amount of sediment (from whatever sources) that arrives at the measuring site, and (b) the proximity of the sources to the measuring site. Among other considerations, this involves the travel time or travel rate of the suspended sediment relative to the travel rate of the water wave.

Single-valued line

Single-valued-line C–Q relations (Class I) in specific instances have been associated wtih an uninterrupted sediment supply throughout the flood (Wood, 1977). The model curves of Figs. 1 and 2 indicate also that the suspended-sediment concentration must increase and decrease in direct synchronization with water discharge. That is, the two temporal graphs must have simultaneous peaks and comparable spreads and skewnesses. The continuous sediment supply might range from plentiful (Figs. 1b, 2b) to rather inhibited or less abundant (Figs. 1c, 2a), relative to the Q-graph. The same effect conceivably could result from factors that influence sediment transportability (e.g. particle size), even if the supply or availability of sediment is unlimited. From the viewpoint of a given C-graph, single-valued line relations might result from hydrographs that are either much more pronounced (Figs. 1c, 2a) or much less pronounced (Figs. 1b, 2b) than the C-graph.

Clockwise loop

The clockwise loop (Class II) has been attributed to either of two causes. The first is a depletion of available sediment before the water discharge has peaked (e.g. Arnborg et al., 1967; Walling, 1974; Wood, 1977; VanSickle and Beschta, 1983). Depletion or flushing out of sediment relatively early in the flood could occur either by: (a) a small supply being available, or (b) a long-lasting and/or very intense flood. The second postulated cause of a clockwise loop is the formation of an armoured layer prior to the occurrence of the discharge peak (e.g. Arnborg et al., 1967).

Clockwise loops in some instances tend to be more common during the early part of a storm- or runoff season than during the later part (e.g. Sidle and Campbell, 1985). This could be due to early-period sediment availability from preceding flows, compared to a relative lack or lesser quantity of stored sediment later in the season.

Heidel (1956, p. 56) stated that the maximum sediment concentration usually occurs prior to the peak water discharge if the stream is small. A wide-ranging study involving a great deal of data probably would be needed to verify this assertion.

Counterclockwise loop

Counterclockwise loops (Class III) result from any of at least three causes. One possible cause is the relative travel times of the flood wave and the sediment flux, especially in view of the downstream distance between the flood source and the measuring station (Heidel, 1956). Changes in water discharge tend to travel with wave velocity. This velocity generally is somewhat faster than the mean flow velocity, for many streams. Since suspended sediment tends to travel at a velocity closer to the mean flow velocity, the sediment flux tends to lag behind the flood wave. The lag time increases with distance downstream.

The delay in the sediment-peak's arrival at a downstream station is magnified on streams where the channel contains irregularities that inhibit sediment movement more than they do water movement. One example seems to be lakes. Axelsson (1967, p. 93) reported a lag of several days in the concentration peak on the river Rapaälven in northern Sweden, due to the influence of Lake Laitaure.

The second reported cause of counterclockwise loops is high soil erodibility in conjunction with prolonged erosion during the flood. Kung and Chiang (1977) studied small streams (5–40 km long) in the rolling loess area along the middle reaches of China's Yellow River. Where rainfall caused severe and protracted sediment erosion, the C-peak tended to occur later than the Q-peak. Also, the C-graph tended to taper off relatively slowly after its peak.

A third cause of counterclockwise loops is seasonal variability of rainfall distribution and of sediment production within the drainage basin. The annual rise and fall of water and sediment at downstream sites along the Yangtze River (Changjiang) in China create such C–Q loops (Shi et al., 1985). The reason is that early-season input, coming from a particular region within the drainage basin, has large water discharges and small sediment concentrations, whereas late-season input from another region has small discharges and high concentrations. The sediment peak therefore occurs later than the water peak.

Single-valued line plus loop

The single line plus loop relation (Class IV) combines Class I with Class II or III. The possible causes therefore are similar to the causes of those classes. The single line at lower discharges means that at the beginning and end of the hydrograph the sediment concentration varies directly with water discharge. The C–Q loop at higher discharges indicates that during the middle of the hydrograph concentration is not in synchronization with discharge, peaking instead either before or after the discharge. Sediment storage, availability, transportability and other factors as discussed above influence the relative timing of the two peaks.

Figure eight

The figure-eight relation (Class V) combines parts of Classes II (clockwise loop) and III (counterclockwise loop). Arnborg et al. (1967) describe an example that occurred during the 1962 ice breakup and post-breakup high flow on the Colville River, Alaska. Both rising limbs (sediment and water) began at about the same time. The rate of increase of concentration was greater than that of water, and concentration peaked first. This produced the expected clockwise C–Q loop, but only at high water discharges. Post-peak sediment availability and transport were high enough that concentrations decreased slowly with time, relative to water discharge. At low discharges, C/Q ratios for a given Q were greater on the hydrograph's falling limb than on the rising limb. This means that C-values at low discharges plot higher on the falling limb than on the rising limb, producing a counterclockwise C–Q loop. The C–Q pattern for the entire flood therefore is a figure eight, consisting of a clockwise loop at high flows and a counterclockwise loop at low flows.

CONCLUSIONS

The relation between sediment concentration and water discharge for a single hydrologic event follows automatically from the characteristics of the C-graph and the Q-graph. One useful way to describe and analyze those characteristics is in terms of temporal-graph mode, spread, and skewness.

The various effects of different temporal-graph modes, spreads, and skewnesses reveal five major classes of C–Q relations. These classes, in no particular order of importance are the single-valued relation (straight or curved), clockwise loop, counterclockwise loop, single-valued relation plus a loop, and figure eight. Graphical analysis enables each class to be characterized by distinctive relative values of C/Q ratios at various times along the rising limb of the Q graph, compared to those C/Q ratios for the same values of Q on the falling limb.

Earlier studies involving single hydrologic events have dwelt largely on the straight line, clockwise loop and, to a lesser extent, counterclockwise loop. Features brought out in this study which heretofore have received little or no attention include: (a) the upward- and downward-bending C–Q curves (single-valued lines); (b) the clockwise-loop C–Q relation when sediment and water peak simultaneously; (c) the counterclockwise loop when sediment and water peak simultaneously; (d) the single-line-plus-loop relation; (e) the figure-eight relation; (f) the overall classification of C–Q relations; and (g) the graphical explanations (C/Q ratios) for each relation.

C–Q relations are influenced by precipitation intensity and areal distribution, runoff amount and rate, floodwater travel rates and travel distances, spacial and temporal storage–mobilization–depletion processes of available sediment, and sediment travel rates and distances. The potential mix and interrelations of these and other variables present a formidable challenge to predicting the type and magnitude of C–Q relation for a particular site and occasion.

ACKNOWLEDGMENTS

The original manuscript was improved considerably by helpful comments from Robert L. Beschta, William P. Carey and Robert H. Meade.

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