TURBULENCE, DIFFUSION AND SEDIMENTATION IN STREAM CHANNEL EXPANSIONS AND CONTRACTIONS

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Studies of the behavior of the suspended load of streams resolve themselves into an analysis of flow conditions. Since streams have non-uniform cross sections, the average velocity of a stream is constantly varying. It is in the abrupt channel expansions and contractions that flow conditions depart most widely from the less disturbed ones of other sections. Here, as in all parts of the stream, turbulence, diffusion and sedimentation are closely linked together.

The flow conditions at channel expansions and contractions were observed in a number of streams, and more especially on the Middle and Little Popo Agie rivers near Lander, Wyoming. A model stream constructed on the side of Table Mountain made it possible approximately to duplicate flow conditions found on these streams.

TURBULENT FLOW. All streams, with the exception of very small and slowly running ones, have turbulent flow. The flow pattern of a turbulent stream has a character similar to that of a laminar. In laminar flow the streamlines appear to divide the entire region of flow into an orderly series of fluid laminae conforming generally to the boundary configuration. In turbulent flow the laminar pattern is hidden behind an irregular one of flow fluctuations which is superimposed over the main flow. The streamlines are hopelessly entwined and change their shape from moment to moment. The rate of energy dissipation is greatly increased over that of laminar flow.

Turbulence includes all pulsating velocities in the water. It manifests itself in upward currents, and acts as a lifting agent. Bed material, though, cannot be lifted by vertical turbulence for it cannot act on or near the stream bed. Such heavier and larger material, which sometimes may be considered as bed load and at other times as suspended load, is entrained by horizontal turbulent currents or pulsating movements which are most noticeable along the sides and bottom of the channel.

Eddy diffusitivity or the dispersing tendency in the turbulent flow accounts for sediment suspension, mixing, and transportation. The water behaves as if it were composed of small temporarily indistinguishable masses that proceed in random jumps. The intensity of the turbulence is represented by the velocity of the jumps, and the mixing length by the length of the jumps. Since turbulence is a comparative phenomenon, some regions of the channel irregularities will have more turbulence than others, and in those regions of lesser turbulence there will be no sedimentation.

EDDY FORMATION. Eddies were epecially numerous on those streams which were cutting through a succession of sediments offering differing degrees of resistence to erosion. Cross sections of the streams often changed abruptly from one width to another so that pressure conditions within the flow were constantly changing with resulting eddy formation.

The boundary layer, that part of the flow field which is influenced by the friction along the channel walls, may have either laminar or turbulent flow. Between a turbulent boundary layer and the channel wall is a laminar sub-layer which is commonly about 1/10mm thick. The main flow follows the channel wall as long as this sub-layer remains stable. If the pressure increases in any part of the sub-layer in the direction of the flow, there is danger that the flow in the sub-layer may become unstable. Should the sub-layer become unstable, it usually causes an accumulation of still water in the region of the lowest pressure. The main flow is then pushed away from the channel wall and *separates*. When this occurs, the space between the wall and the main flow is filled with water which does not take part in the main flow pattern. It usually rotates slowly forming large stationary eddies.

FLOW AT CHANNEL EXPANSIONS. A. *Angle of flare*. It was noted that whenever the stream channel expanded abruptly there was a large stationary eddy on one or both sides of the main or live flow. On the other hand, if the angle of flare of the diverging channel walls was small, *i.e.* less than 10 degrees, there was little or no eddying. Gooseberry River, a stream which enters Lake Superior about 40 miles from Duluth, Minnesota, has such a gentle angle of flare in its downstream meander that the water in its eddy current is almost stagnant. This condition is in contrast to that found at many places in the Middle and Little Popo Agie Forks.

Eddying could be produced or prevented on the model stream by changing the angle of flare of its channel walls. It was also possible to change the flow pattern by putting a long narrow pebble or several small more rounded ones into the channel along a widely flaring wall. The stones acted as *guide vanes* or *guide surfaces* in preventing back flow and eddying.

It is presumed that channel islands may act likewise and prevent the main flow of the stream from breaking away from the channel walls and separating so as to form eddies. Such a case was believed to have been found on the Little Popo Agie in the Dallas Dome area for despite the abruptness of flare of the channel wall on one side of the stream, no eddy had formed in the expanded section. In another area, however, a channel bar, whose center had just been built up to the surface of the water, offered no hindrance to the formation of an eddy current. It was washed on three sides by one which was slowly enlarging it. The eddy current was about 200 feet long, and the bar about 25 feet in length.

B. *Change of kinetic to potential energy*. The speed at which an eddy current rotated was changed by modifying the angle of flare of the channel walls on the model stream. When the stream flowed from the relatively restricted area into the abruptly expanded one, because of its decreased velocity, it had some of its kinetic energy changed into potential energy. As a result of this increase in potential energy, a pressure gradient was established between some downstream locus in the expanded section and some locus upstream. Upstream flow took place down the pressure gradient. In those expansions where the angle of flare was more than 10 degrees with the channel wall in the restricted area, it was evident that the loss of velocity in the expanding section was due primarily to the shape and form of the channel. Frictional loss was of no importance. If the expansion took place very gradually, the pressure gradient was slight or might not exist at all, but if it was abrupt, the pressure gradient was steep enough to cause rapid upstream flow.

The eddy currents which form when the boundary layer breaks away from the channel walls cause water to pile up along the upstream end of the rotating mass of fluid. This water has more pressure than that which surrounds it, and consequently it breaks through the flow to join the live current.

C. *Sedimentation*. At one bend on the Middle Popo Agie where one channel wall flared out widely, there was a large and rapidly moving eddy current. The backflow had divided in such a way that it had scalloped the outer bank of the stream in five places. The scour hole at this end had a configuration like many another scour hole except for its division into segments and its deposits at the foot of each cusp of the channel wall. These deposits were moulded by the currents that flowed upstream against them, and consequently they were steep-faced buttress-like appendages to the channel wall. Their lower extremities had been built up to a height of two or three feet in water 12 to 15 feet deep. The strength of the current along the outer bank was sufficient

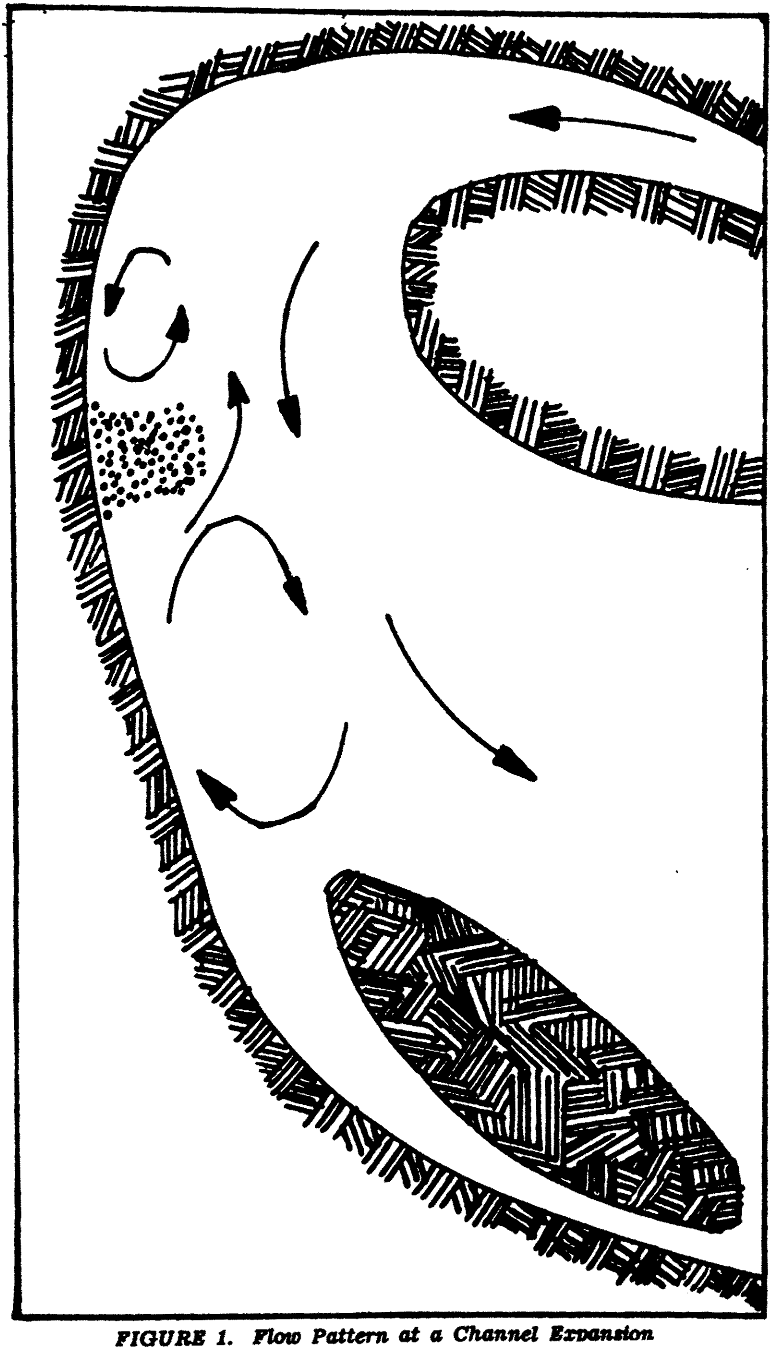

FIGURE 1. Flow Pattern at a Channel Expansion

to carry upstream for a short distance a cobblestone, four inches in diameter. The path of the cobblestone, which had been dropped into the stream next to the outer bank, made an angle of about 80 degrees with the vertical until it came to within a few feet of the stream bed. Then it struck a much faster-moving current which slowed up its rate of settling. It was carried rapidly upstream for about 3 feet and settled at the foot of one of the heaps of debris piled up along the steep outer bank between two eddy currents. The rapid shallowing of the scour hole at its extremities and the smaller amount of turbulence there, allowed gravel to be deposited at those two places.

In the Dallas Dome area the Little Popo Agie had built up a bar almost to water level at the foot of a steep concave bank. The bar supported a growth of willows several feet in height. An island in the channel separated the flow into two unequal divisions, the larger channel being near the convex bank, the smaller near the outer bank. (Fig. 1). This island is slightly downstream from the bar. Between the channel division and the bar was a strong eddy current, and upstream from the bar a small and weaker one. The eddies flowed in opposite directions. The large eddy moved upstream against the concave bank in a clockwise direction, and the smaller eddy moved in a counter-clockwise direction. Thus the bar was built up on both its downstream and its upstream sides by eddy-deposited material. A 12-foot log, which circled in these eddies for half an hour, finally came to rest on the upstream end of the bar. The larger eddy had been strong enough to dislodge the log every time one end of it came to rest among the willows growing on the bar. After it got into the circling waters of the small eddy it soon came to rest on the upstream end of the bar.

In another case observed, debris was not deposited in an area of slack water between two adjacent eddies. It was deposited in the center of one. A very small eddy on Tischer Creek, Duluth, Minnesota, deposited a small heap of material on the rock floor of the stream at the center of the eddy. As soon as surface debris became waterlogged, it was carried toward the stream bed in a downward swirling path. Pulsations in the water often changed the location of the apex of the debris mound, but on the whole it remained in approximately the same place. The material became rudely sorted, and some which was deposited on the periphery of the mound was carried downstream. This small eddy showed the manner in which bars may be built up in stream channels.

D. *Flow patterns.* The eddies that formed along the sides of the channel in the expanded cross sectional areas varied in size from very small ones to some that were 200 or more feet in length. Almost all the eddies were long and narrow. Most of them were comparatively small in width in comparison with that of the main flow, but a few had grown to such size that they either squeezed the live flow between them, providing one had formed on each side of the channel, or else they pushed it to one side. At one channel expansion the live flow moved from one side of the channel to the other so that it scoured first one bank and then the other. The channel at this place widened out rather uniformly, and pressure differences determined at which side of the stream the eddying began. When the flow was unstable, the live part of the flow was in the center of the channel, but when it became stable, the live flow swung from side to side. When the live flow swung from one side of the channel to the other, it moved with comparative rapidity. The surface of separation between the main and backflow seemed to rise slightly or at least was agitated enough so that it stood out plainly while the live flow swung to the opposite side of the channel.

E. *Mixing of the sedimentary load.* At one channel expansion a von Kármán vortex trail originated in the wake of a large boulder. This very regular pattern of alternating eddies caused a mixing of surface debris for some distance downstream. A disturbance in the flow had caused the streamlines alternately to diverge and converge. When they converged the velocity increased and the pressure decreased, and *vice versa*. The pressure differences tended to increase the displacement of the streamlines, and resulted in the growth of the vortices. The surface downstream from the wake swung back and forth as the vortices alternately formed along the centerline and detached themselves.

Other small vortices which resembled vortex trails were very numerous. Some of these formed where the channel wall had a sharp angle. Others came into being in the region of highly disturbed flow that demarcated the main flow from the back flow. Most of these vortices left this surface of discontinuity and entered the back flow, but some were carried downstream. Although none of these vortices persisted for any length of time, they rotated with such rapidity that they churned up the water violently and with it the suspended load. Debris carried on the surface of the water took intricate paths, and sometimes was carried several inches beneath the surface.

At very short intervals pulsating currents shot out a mass of very muddy water from the main flow. It immediately lost its identity as it was diffused into another part of the flow field.

CHANNEL CONTRACTIONS. Whereas a channel expansion may cause either an increase or a decrease in stream velocity, a contraction in cross sectional areas causes only an increase. Stated in another way, stream velocity is increased when the hydraulic radius is increased and the wetted perimeter is decreased. When the hydraulic radius is denoted by *R*, the area of the cross section by *A*, and the wetted perimeter, that part of the perimeter of the cross section wetted by the water, by *P*, then $R = A/P$. Reducing the cross sectional area of a stream is a far more efficient way of obtaining an increase in velocity than is expanding it. Even at a channel contraction debris may be deposited. Eddies may form at the downstream end of a wide channel just upstream from the contraction. They also form at the upstream end of the contracted section. When a stream flows into a contracted area it may contract so much that the live flow leaves the channel walls for a short distance, and then suddenly expands and fills the entire channel. The eddies which form because of the contraction are very small in comparison to those which form as a result of a channel expansion. Areas of deposition are likewise small.

CONCLUSION. Most of the flow patterns were comparatively simple. In general flow at a channel contraction was a stable process, whereas that at an expansion was unstable, inefficient, and accompanied by large losses and appreciable eddying regions.