EMERGENCY RESCUES AT LOW-HEAD DAMS

Kenneth R. Wright, P.E.[1]
Jonathan M. Kelly[2]
Robert J. Houghtalen, Ph.D., P.E.[3]
Mark R. Bonner[4]

ABSTRACT

Emergency rescues at low-head dams can be hazardous to rescue personnel because of the reverse roller phenomenon (hydraulic) common below many hydraulic structures. Characteristics of hydraulic jumps are discussed along with various tailwater conditions. Rescue methods are described using both non-motorized and motorized boats. Emergency rescue personnel should never cross the "boil" area, otherwise they, too, may become victims. Retrofitting dangerous low-head dams is recommended so as to reduce the hazard. "Safe low-head dams" refers to those structures which are not characterized as being "drowning machines" where the task of extraditing one's self from the "hydraulic" ranges from very difficult to near impossible.

INTRODUCTION

Low-head dams for power production or water diversion are hazardous to recreational boaters and swimmers because of a unique hydraulic phenomenon known to the engineering profession as a "roller." (Peterka, 1978) Boaters term this characteristic a "hydraulic." Grade control structures to protect stream beds against erosion can have similar characteristics. Even as low-head dams and grade control structures are hazardous to the general public, similarly they are hazardous to rescue personnel and have resulted in drownings among their ranks. (USBR, 1989) (Borland-Coogan, 1980)

Low-head dams are characterized for this paper as having a vertical drop of less than three meters. It is this modest drop in elevation that creates an appearance of little or no danger to the layman and rescuer. The surface appearance of the "hydraulic" immediately downstream of the dam is oftentimes tranquil which is most deceiving to the observer. (Wheat, 1989)

The energy of the falling water is dissipated near the toe of the dam and, with certain flow conditions, the hydraulic forms, which represents a reversal in the flow direction back towards the falling water jet. (McLaughlin, 1986) (City of Tempe, video, undated) Even a good swimmer would find it almost impossible to swim out of the hydraulic. Rescue personnel can be caught in the hydraulic in the same way as the unwary boater or swimmer. A

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1 Wright Water Engineers, Chief Engineer; former American Ski Patrol "Avalanche" Instructor; Fellow, American Society of Civil Engineers.

2 Wright Water Engineers, Project Engineer, Denver, Colorado.

3 Wright Water Engineers, Senior Hydraulic Consultant; "Visiting Professor" from Rose-Hulman Institute of Technology, Terre Haute, Indiana. Member, American Society of Civil Engineers.

4 Wright Water Engineers, Project Engineer, Denver, Colorado.

rescue boat carried into the path of the falling water jet by the reverse current can easily capsize, throwing the rescue personnel into the hydraulic. (Borland-Coogan, 1980)

Emergency rescue agencies must have standard operating procedures for rescues at the toe of low-head dams. Agencies with low-head dams in their jurisdictions would be well advised to have practice sessions at those locations. Of importance in rescues is that the lives of rescue personnel should not be risked to recover a body or to retrieve an overturned boat.

Low-head dams and grade control structures which exhibit these types of reverse rollers or "hydraulics" have been termed "drowning machines." (Leutheusser, 1991) (Borland-Coogan, 1980) Drowning machines can be retrofitted to reduce the hazard by reshaping the downstream face or by providing a boat chute. (Wright, 1995) (USBR, 1989) However, it is best to incorporate protective features into the design of new facilities. (USBR, 1974)

Experienced rafters and kayakers believe that one can dive to the bottom of the flowing water to escape a reverse roller or a deep hole in order to be carried free by the submerged jet.

HYDRAULICS OF LOW-HEAD DAMS

Significant energy exists in the flowing body of water at the crest of a low-head dam as a result of its elevation. This potential (positional) energy transforms into kinetic (velocity) energy as the water passes over the crest of the structure and as it gains velocity when it falls. A hydraulic jump typically forms at the structure base to dissipate the excess kinetic energy and to return the flow to normal downstream subcritical conditions. (Hwang & Houghtalen, 1995)

Various types of hydraulic jumps occur depending on the character and height of the structure, the depth of the tailwater, and the magnitude of the flow. (USBR, 1987) The four common types of hydraulic jump conditions that form below low-head dams are depicted in Figure 1.

Case I represents a fairly well defined hydraulic jump with a low tailwater depth. The flow immediately upstream of the jump is characterized by low depths and high velocities (supercritical flow). The flow downstream of the jump is characterized by high depths and low velocities (subcritical flow). The jump itself is relatively unstable, turbulent, and short in length. No unusual hazard exists in this scenario; swimmers and boaters tend to be swept downstream by the high velocity waters preceding the jump. The jump is known to rafters as a standing wave.

As the tailwater depth rises, a Case II scenario occurs. The jump moves upstream towards the downstream face of the dam. In this case, the hydraulic jump is more well defined and stable, though the turbulence in the jump increases. Small floating debris can get trapped between the jump and the nappe; however, the danger is modest to swimmers and boaters as the strong current tends to sweep them downstream. Boaters and rafters are likely to bounce over the hydraulic jump. The abrupt bounce may cause rafters to be thrown into the water.

Case III occurs with an additional increase in tailwater depth. The jump is now submerged and not apparent. Therein lies the danger! Velocities are still high, much energy is still being dissipated, and significant amounts of air entrainment occurs. Even a strong swimmer would find it difficult to get out of the reverse roller. A detailed discussion of the dangers associated with this case follows in the next section.

Finally, Case IV represents the hydraulic conditions associated with high tailwater depths. The drop structure is inundated and no hydraulic jump occurs. Standing surface waves are present. Because energy loss and velocities are modest (i.e., very little elevation difference between headwater and tailwater), little unusual hazard exists to swimmers and boaters.

DROWNING HAZARDS

Although the hazards to boaters at low-head dams are understood (Smalley, 1987), the potential danger to volunteer rescue personnel is not widely recognized. This may stem from a misconception of where the hazard occurs within the drop structure. Intuition may say that going over the crest of the dam would cause the greatest concern for safety. However, the real danger exists immediately downstream of the structure when there is a moderately high tailwater created by downstream river characteristics and the shape of structure (Case III, Figure 1).

As the water travels over the crest of the dam, the flow becomes a supercritical jet as shown in Figure 2. The supercritical flow transitions itself into subcritical flow downstream. This transition usually occurs in the form of a hydraulic jump, where the energy is dissipated through turbulence and an increase in depth resulting from the lower velocity.

In a given range of flows, the hydraulic jump will become submerged. The submerged jump results in a reverse rolling current in the direction toward the face of the dam. As Figure 2 shows, the point where the flow separates into a downstream component and an upstream reverse current is often called the boil. Between the face of the dam and the boil, the direction of the surface flow is upstream, into the plunging jet. It is this phenomenon that creates the hazard to boaters and rescue personnel.

Boaters typically experience problems when their downstream momentum is not enough to escape the reverse current or if the boat capsizes. Once the boat is trapped in the hydraulic, the reverse current carries the boat back into the plunging jet. The force of the jet is sufficient to capsize a boat, especially once the boat gets turned sideways. As the boaters are thrown from the boat, they too become trapped in the reverse roller. The velocity of the upstream current is in excess of the swimming ability of most persons. Hence, a rescue situation arises.

If the structure is located in an urbanized area, there is a chance that rescue personnel will arrive at the site before the victims have drowned. However, in their zeal to rescue the trapped boaters, the rescue personnel often put themselves in extreme danger. The hazard potential is often less apparent since the rescue boat approaches the drop structure from downstream and, thus, never travels over the crest of the dam. As discussed above, danger exists if the rescue boat travels too far upstream and crosses the boil.

With the rescue personnel traveling in a motorized boat upstream toward the dam, they are initially fighting the current of the stream as they approach the boil. As they pass over the boil, the boat surges forward due to both the force of the motor and the upstream current. Because of extreme turbulence within the submerged jump, the water is highly aerated. The aerated water provides less resistance to the propellers, making the motor less efficient. So, when the boat operator reverses the propeller direction, the motor no longer has sufficient thrust to allow the boat to escape the hydraulic. The current then continues to move the boat into the plunging jet, where the boat will likely be capsized, increasing the number of potential victims.

EMERGENCY RESCUE PRECAUTIONS

There are two basic scenarios at low-head dams that would necessitate action by emergency rescue personnel. The first is when an accident occurs and a victim is caught in the hydraulic who is thought to still be alive. The other occurs after a drowning has occurred and the body has to be recovered. The primary difference between the two scenarios is the sense of urgency inherent in a rescue attempt. Both operations should take full precautions to ensure that emergency rescue personnel are not endangered. **The fundamental rule in rescues is that the rescuers must not be exposed to unusual danger.**

Approach From Downstream. All boat-based rescue attempts at low-head dams should approach the drop structure from the downstream side. The victim is often trapped near the face of the dam. Approaching from the downstream side allows the boat operator to better control the velocity and positioning towards the dam, since the boat is working against the stream's normal current.

Don't Cross Boil. Although approaching the dam from the downstream side is critical, this is not where most emergency rescue attempts fail. Most emergency rescue personnel recognize the need for an upstream approach to the victim. However, many are not aware of the hazard of the boil area. The boil is the location (downstream of the dam) where the surface direction of the water separates into a downstream component and an upstream component. The location of the boil dictates where the reverse, upstream current begins. Don't cross the boil!

Power Boats. Even during the excitement of a rescue, emergency rescue personnel must never allow their boat to cross over the boil. Seeing a person drowning in the hydraulic, the inclination of rescue personnel may be to get as close to the victim as possible. Once a boat crosses the boil, rescue personnel face the same danger as the original boaters. The boat will surge forward as it moves into the upstream current. The ability to escape from the hydraulic is hampered by the effect of the highly-aerated water on the boat's propeller. The entrained air reduces the efficiency of the propeller and may not allow the boat's power to overcome the reverse current of the hydraulic.

Rescue Boat Capsizing. As the boat continues to be forced upstream, the plunging wall of water over the crest of the dam becomes a factor. As the boat approaches the face of the dam, the plunging jet hits the bow, often causing the boat to capsize. Even if the initial force of the failing water does not result in the boat capsizing, the boat may be turned sideways by the upstream current and begin to fill with water. The end result is usually the same; that is, by crossing the boil, the emergency rescue personnel have become victims of the hydraulic. Too many rescue personnel have become victims.

Provide Anchoring. Even if a boat stays downstream of the boil on approach, it still must be able to hold its position during the rescue attempt. A method of anchoring the boat should be employed so that the boat does not cross the boil or, if it does, it may be retrieved.

A line should be carried across the stream and anchored on both banks. A rescue may be attempted without using a boat if a rope is stretched across the stream. This method entails attaching a floatation device to the rope and dragging it across the lower face of the dam. Another method is to use an air-inflated fire hose pushed out from shore. (City of Tempe, 1993) The hose will ride at the base of the falling jet. In many cases, the victim is disoriented and weakened from being submerged and from the tumbling effect of the reverse roller. In such cases, the victim is likely to be unable to grab or hold onto the floatation device or fire hose.

A boat must be used if the victim is unable to significantly assist in the rescue. The boat should be anchored by a rope secured on both banks. From downstream of the boil, a flotation device is thrown to the drowning victim until the victim is able to grab the device. As the rescue personnel begin to pull the victim from the hydraulic, it is important that the safety lines keep the boat a safe distance from the boil. If the victim is unconscious or too weak to hold onto a floatation device, a hooked device (grappling hook) can be used.

Use of Two Boats. Emergency rescue personnel attempting rescues on large rivers may not be able to reasonably span the river with safety lines. On wide rivers, a second boat may need to be used to anchor the first. As Figure 3 shows, the second boat is located further downstream from the first and is not directly involved in the rescue attempt. The sole purpose of the second boat is to keep the rescue boat from crossing the boil. The rescue proceeds from the first boat in the same manner as described above.

Shore Rigged Non-motorized Boat. Highly-experienced emergency rescue teams may opt for use of rigging to shore-based personnel so as to provide better control over the boat location as shown in Figure 4. A general rule of such teams is not to cross the boil. (Denver Fire Department, 1995)

Use of Helicopter. Some rescue organizations have helicopters available from the sheriff or police department. If weather conditions are satisfactory, the helicopter can hover over the "hydraulic," a life preserver can be lowered, and the victim can be extricated by pulling the victim downstream out of the hazard zone. Under no conditions should a frogman jump into the hydraulic for the rescue.

Adverse Time Element. Unfortunately, in most low-head dam accidents involving the reverse rollers, a normal victim's chances of surviving more than ten minutes is low because of hypothermia, excitement, thrashing about and because becoming submerged each minute or so quickly drains energy.

Training. Since low-head dam rescues are not easily performed, emergency rescue personnel with such dams in their jurisdiction should be specially trained. Simulated rescues should be practiced on a periodic basis at the local hazardous dams. Education of both the public and the emergency rescue personnel as to the dangers associated with low-head dams is key. Persons unfamiliar with the proper techniques should not attempt to rescue victims as they may become victims themselves.

Alternatives. The retrofit of hazardous low-head dams and check structures is recommended whenever recreational boating may exist and where members of the public may reasonably become involved. (USBR Center Line, 1992) Retrofits generally require changing the downstream shape and character of the low-head dam or grade control structure or constructing a user-friendly boat chute with adequate upstream signing and carefully-placed pilot rocks.

While no retrofitted low-head dam or grade control structure can be declared strictly "safe" and "non-hazardous" because of inherent dangers around flowing water bodies, the objective is to eliminate the "drowning machines" where unsuspecting individuals and rescue personnel are caught unaware in a hydraulic trap from which self-extrication is unlikely.

Diving Down. A victim may be able to escape by diving down so as to be carried downstream by the submerged jet. This technique is used by experienced boaters in "deep holes" formed in river rapids.

CONCLUSIONS

When tailwater depth at low-head dams or drop structures reaches certain levels, a reverse roller can be created which can trap swimmers and boaters and potentially drown them. The danger of this situation is compounded by the fact that unwary rescue workers can fall victim to the same phenomenon. Rescue personnel who may be involved in rescues at low-head dams need to be properly trained to execute emergency rescues without endangering themselves.

Dangerous reverse rollers (hydraulics) do not always occur at a given dangerous low-head dam. The reverse roller phenomenon is a result of a combination of flow rate and tailwater depth--the problem being that, when the conditions are most dangerous, the hydraulic may appear tranquil.

Rescue operations are best carried out with maximum control of the rescue boat. This may entail four shoreline stationed personnel with four ropes to the boat which is non-motorized. Care is needed when using motorized boats.

Retrofitting dangerous structures is recommended using either a reshaped downstream dam face condition, a stair-stepped series of dams or a suitable boat chute with adequate upstream signing and a good portage. (Leutheusser, 1991) (Wright, 1994)

Existing dams should be reanalyzed periodically to insure that they meet the test of safety by current standards. (Jansen, 1980)

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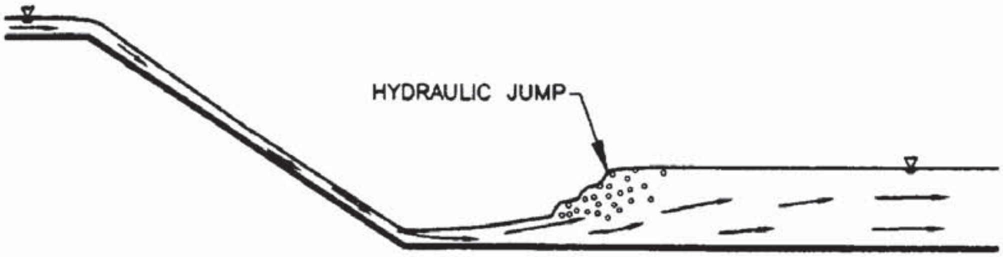
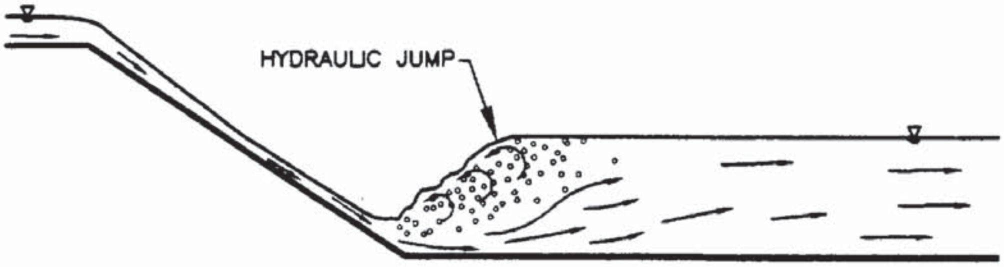


LITTLE ENTRAPMENT POTENTIAL

CASE I

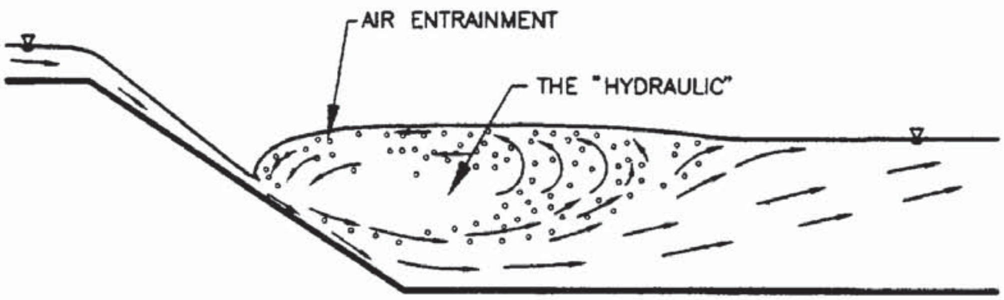
- LOW TAILWATER WITH SWEPT-OUT JUMP
- PERSONS WILL USUALLY BE SWEPT DOWNSTREAM



MODEST ENTRAPMENT POTENTIAL

CASE II

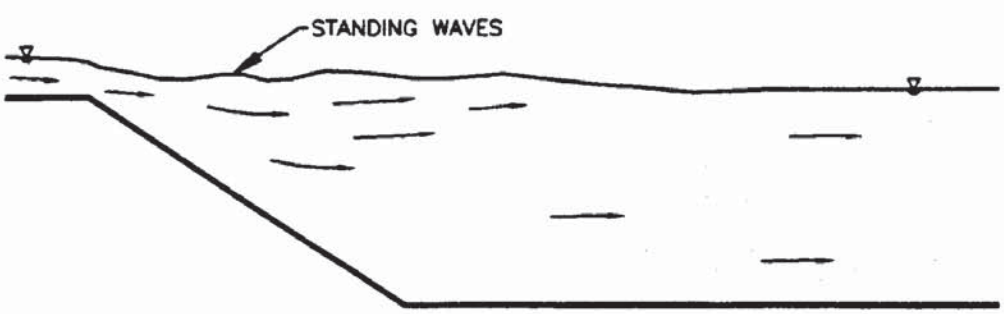
- NORMAL TAILWATER WITH OPTIMUM JUMP.
- MODEST ENTRAPMENT FOR PERSONS, ALTHOUGH LOGS AND SIDEWAYS CANOES CAN GET TRAPPED IN SMALL "HOLE".



HIGH ENTRAPMENT POTENTIAL
EXTREME HAZARD WITH TRANQUIL APPEARENCE

CASE III

- HIGH TAILWATER WITH SUBMERGED HYDRAULIC JUMP
- THE RESULTING "HYDRAULIC" WILL TRAP A PERSON IN THE REVERSE ROLLING CURRENT
- RESCUE BOATS WILL BE "SUCKED" TOWARDS FALLING JET
- DIVING TO THE BOTTOM MAY CAUSE THE PERSON TO BE CARRIED DOWNSTREAM



NO UNUSUAL HAZARD

CASE IV

- VERY HIGH TAILWATER ASSOCIATED WITH HIGH FLOWS INUNDATES THE DROP STRUCTURE
- NO HYDRAULIC JUMP OCCURS
- NO UNUSUAL HAZARD TO PERSONS OR BOATS

FIGURE 1

TYPICAL TAILWATER EFFECTS ON THE HYDRAULIC JUMP AT LOW-HEAD DAMS OR DROP STRUCTURES.

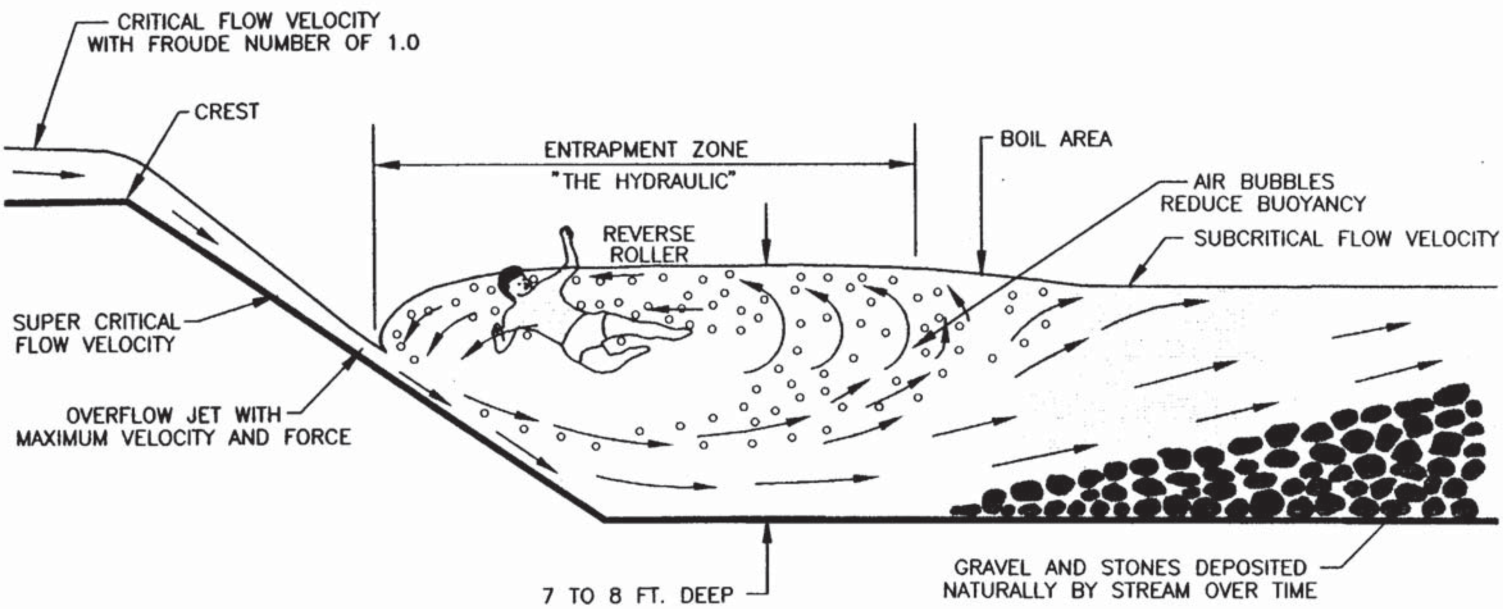


FIGURE 2

LOW-HEAD DAM OR DROP STRUCTURE WITH HIGH TAILWATER WHICH SUBMERGES THE HYDRAULIC JUMP. VICTIM MAY ESCAPE BY DIVING DOWN TO NEAR BOTTOM IN HOPE OF BEING CARRIED DOWNSTREAM BY LOWER REMNANTS OF JET.

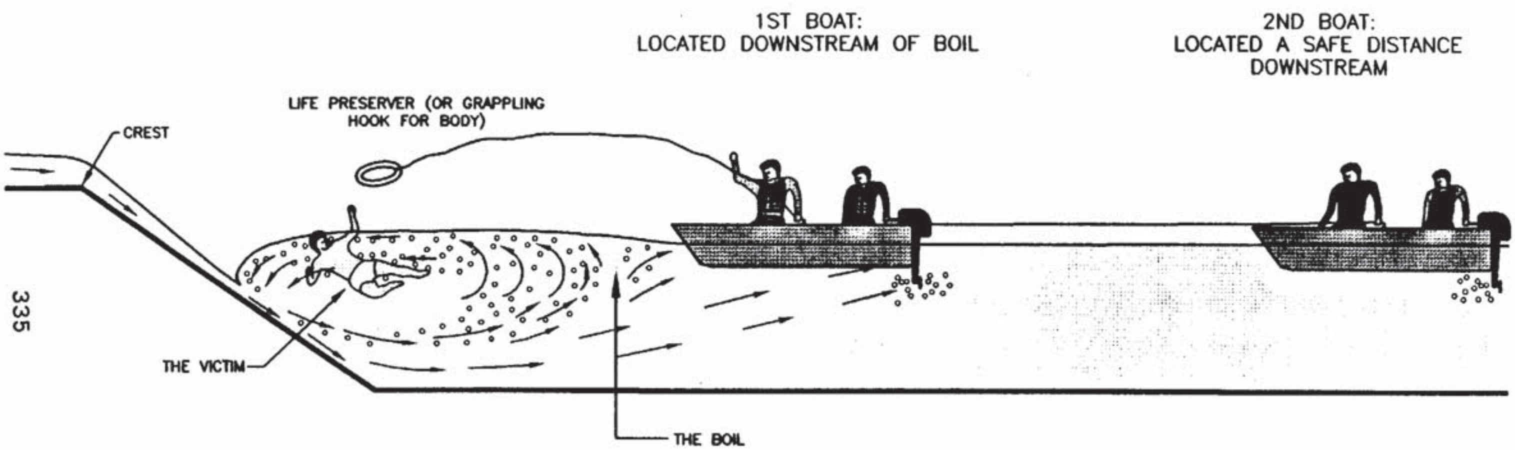


FIGURE 3

POSITIONING OF BOATS FOR A RESCUE ATTEMPT
AT A LOW-HEAD DAM

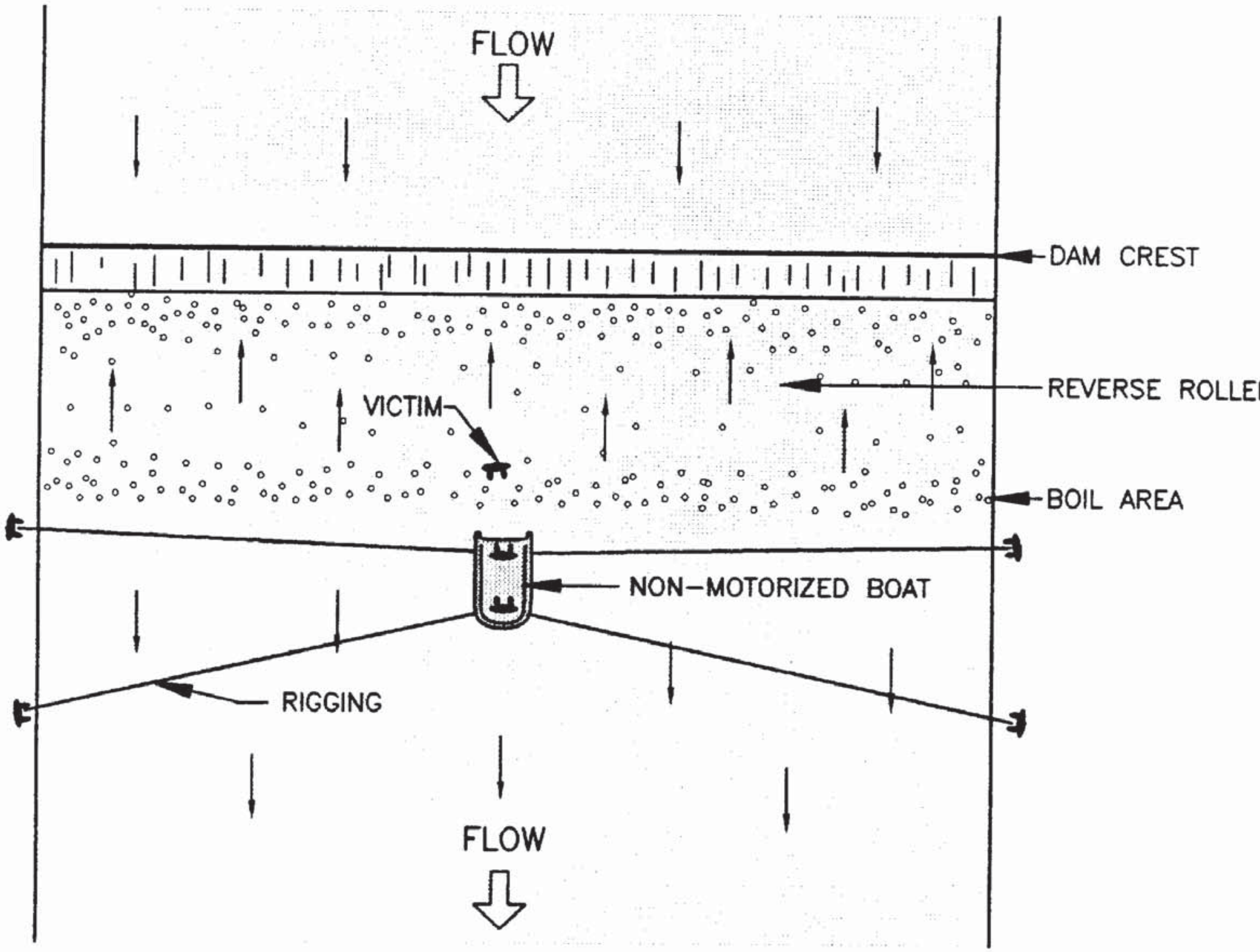


FIGURE 4

RESCUE WITH SHORE RIGGED, NON-MOTORIZED BOAT FOR MAXIMUM STABILITY. BOAT MUST NOT CROSS BOIL. VICTIM EXTRICATED AS HE RISES TO SURFACE AT BOIL.