David R. Dilen,[1] *M.S.*

The Motion of Floating and Submerged Objects in the Chattahoochee River, Atlanta, GA

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ABSTRACT: Two mannikins, one designed to float and one designed to sink, were used to examine the ways in which human bodies move in a river. The floating mannikin was used to examine the movement of a body floating downstream on the surface and to determine the flow patterns of surface currents through bends in the Chattahoochee River in Atlanta, GA. The submerged mannikin was constructed to have a specific gravity of a deceased person (over a range of specific gravities) and was used to examine the motion of a body immediately upon entering the water. The submerged mannikin also was used to examaine motion along the bottom of the river. Floating objects near each bank of the Chattahoochee River were found to remain along their respective banks as they moved downstream through the bends in the river. No mechanisms of transport from one bank to the other in the bends was found. The movement of a submerged dummy only occurred at very high river flows. The dummy remained stationary at the place where it reached the bottom for tests over a wide range of specific gravities and a moderate range of flow levels. A discussion of the river conditions (for example, bottom topography, bottom composition, flow rates, and hydraulics) is included. The results of the experiments offer initial guidelines and principles that can be used by officials and agencies involved in the search, rescue, and recovery of bodies in most rivers.

KEYWORDS: forensic science, drowning, rivers, humans, drowning victims, search and rescue, lift coefficient, drag coefficient

The purpose of this project is to identify the behavior of an object similar to that of a human body in the Chattahoochee River in Atlanta, GA. Details of the lift, drag, and friction forces acting on a body in a river, and the manner in which the body would move, are undefined at the present time. General hydraulic theory offers some initial, tentative suggestions towards identifying such movement, but in situ field experiments are paramount to be able to describe more specifically (or even begin to predict) any motion or behavior. Thus this project examines the hydraulic theory and in situ field conditions of one reach of the Chattahoochee River and the manner in which a body may move in this reach.

The study area of the Chattahoochee River extends from the State Route 280 (Jackson Parkway) bridge to an area 90 m (~ 300 yd) downstream of the Interstate 285 bridge, a distance of 1.9 km (1.2 miles) (Fig. 1). The Chattahoochee River is a river of moderate width with low, but steep, banks. The banks are covered with trees, shrubs, and brush (Fig. 2). Trees frequently fall into the water and disrupt the flow of water along the bank creating what are commonly called "strainers" or "snags." The Chattahoochee has a gentle slope through the study reach, and the bottom of the river is composed principally of sand and silt. The bottom has occasional snags of its own, however. Stumps and limbs break off from the banks, become water-logged,

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[1]President, HERC, Atlanta, GA.

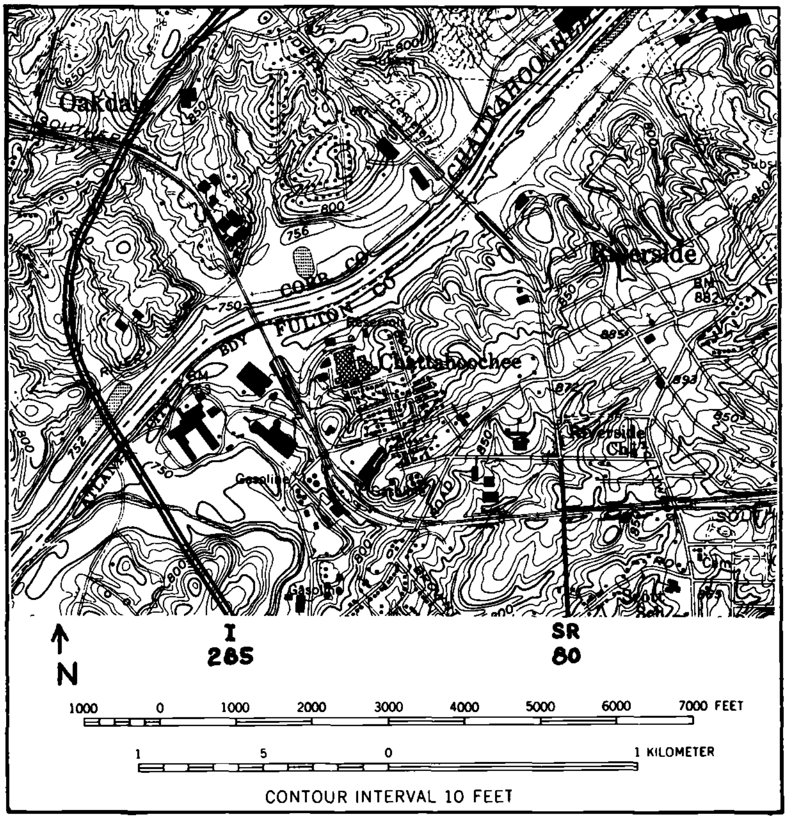

FIG. 1—*Study area of the Chattahoochee River in Atlanta, GA. Map drawn from a U.S. Geological Survey quadrangle map, scale 1:24 000.*

and sink. Numerous rocks and other miscellaneous debris are also present, protruding from the bottom.

The bends of the river in the study area are very mild. Two slight bends occur in this section. A 30° angle bend to the west occurs 656 m (2000 ft) downstream from the Jackson Parkway bridge, and another 30° angle bend back to the southeast occurs 1050 m (3200 ft) downstream from the bridge. The bend to the west has a radius of curvature of approximately 1000 m (3000 ft); the bend to the southeast a radius of approximately 656 m (2000 ft). The width of the river is a constant 56 m (170 ft) throughout the study area.

While the research was directed at one particular reach of the Chattahoochee River in Atlanta, the morphology and hydraulics of this reach are by no means unique. Nearly identical reaches may be found not only in the Southeast, but around the entire United States as well.

Theory

The behavior of any object in a river is governed by the way in which it responds to the forces of the flow of water in the river and the characteristics of the object itself. Thus, to understand the how and the why of the ways objects respond in rivers we must first understand the way a river actually flows, and then the conditions of the transported objects in question.

As water in a river moves downstream, the flow is affected by the size and shape of the channel, the slope (or steepness) of the riverbed, the smoothness (or roughness) of the banks and

FIG. 2—*Photograph of the Chattahoochee River in the vicinity of the State Route 280 (Jackson Parkway) bridge.*

river bottom, and sometimes by bends in the river's channel. Flow of a river through channels and bends may be depicted by streamlines, or lines that follow and represent the average motion of the water. Flow in a long, straight channel is three-dimensional, and the streamlines of the flow typically form two lateral patterns. These patterns are characterized by two spirals, side by side in the river channel as shown in Fig. 3. The spiral patterns are caused by the friction of the rough banks, and the double spiral permits the equalization of shear stresses on both sides of the channel [*1*]. Surface flow streamlines thus move downstream through the center of the channel, and toward each bank along that respective bank (Fig. 4).

Most of the research on flow and streamlines in channels in the past has been conducted in

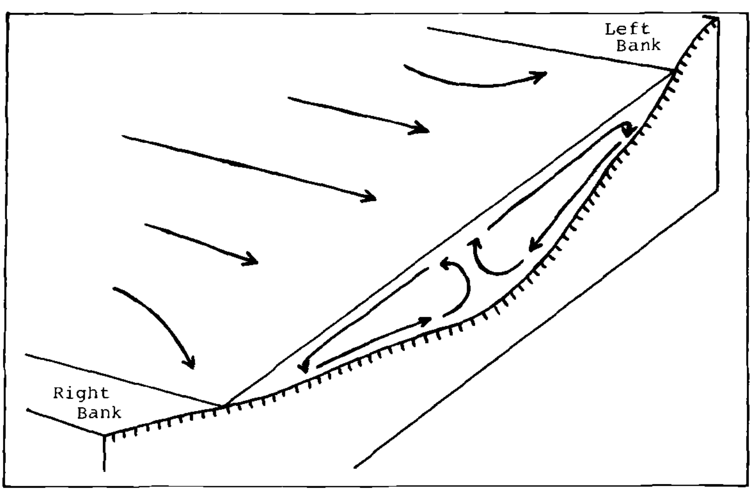

FIG. 3—*Three-dimensional flow in a river channel with double-spiral flow.*

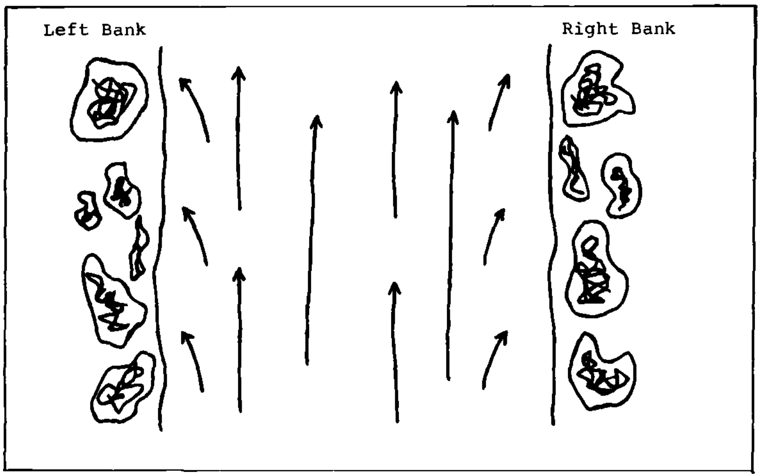

FIG. 4—*Surface flow in a river showing the effect of friction along the banks.*

the laboratory using flumes. Flow in both straight flumes and flumes with bends has been studied. The bends that have been examined have had very sharp angles of curvature, generally 90 or 180°. The research from these experiments does point to the existence of a double-spiral flow in the channel even through the bends [*2,3*]. In spite of the different width-to-depth ratios and other factors between laboratory flumes and natural channels, the research endorses the causes and the existence of double-spiral flow in bends in natural channels.

The effect of a bend in a river on the streamlines of flow, and thus on the river's currents, depends on a number of factors: velocity of flow, channel roughness, degree of sharpness of the bend (angle of curvature), and width of the river [*4*]. In laboratory channels where a bend is sharp, a large oversized spiral flow pattern has been observed from centrifugal force along the outside of the bend [*2,3*]. This dominant spiral may also be observed in natural channels with sharp bends. The spiral along the inside of the bend in both experimental and natural cases must correspondingly shrink to a very small size to preserve the conservation of momentum in the bend. This pattern has been found to be true [*4*] for bends where the channel radius of curvature to channel width ratio is greater than 3.0:

$$R_c/b > 3.0$$

where R_c is the radius of curvature and b is the width of the channel. Radius of curvature is measured by determining the length from the center of the channel to the point that represents the pivot point of the arc. In mild bends in a river, where the channel curvature to width ratio is less than 3.0, double spirals of streamlines (and thus currents) of nearly equal size will exist.

The behavior of an object in a river depends not only on the basic mechanics of flow, but also on the forces of drag, lift, friction, and gravity on the subject in question. These forces are the determinants of the motion of any object in a fluid flow. In this project the determination of any of these four forces on either a model or a person is not addressed. Rather the interest is in the similarity of form and structure between a model and a person.

The concerns in the design of the model are principally a consideration of the geometry of the model. Since the model and a person are identical in form and shape, the coefficients of the forces of drag, lift, and friction are also equal. Thus size and weight of the model and a person become the final factors in the design. Through similitude, these characteristics of the model are constructed to describe accurately the characteristics of an actual person. A relationship is derived that expresses the design in terms of the specific gravity of each subject and the length of the subjects. The equation for this relation is:

$$SG_m = 1.0 + (l_p/l_m)(SG_p - 1.0)$$

where

SG = specific gravity,
m = model (dummy),
l = length, and
p = prototype (person).

Phases of Movement

The movement of a body from the time it enters a river until the time it is discovered and removed can be described in four phases. In each phase of movement different forces act to govern the path taken by the body and thus its final location. The four phases of motion are:

1—settling to the bottom,
2—motion along the bottom,
3—ascent to the surface, and
4—drift along the surface.

A brief discussion of the forces that govern motion in each phase is presented below. This project specifically deals with observations of the behavior of a model in the second and fourth phase of motion, and not the entire sequence.

Phase 1—Settling to the Bottom

Most human bodies that enter water will sink to the bottom. Donoghue and Minnigerode [5] found that 93 to 95% of people at death have sufficient density to cause them to sink. The settling of a body is determined by a force balance between the submerged weight of the body and the fluid drag on the body. At the present time no experimental studies are known that estimate the vertical drag coefficient of a body. Thus in any attempt at calculating this settling motion the fluid drag force must be either neglected or have a rough estimate assigned arbitrarily.

A secondary force acting on a body as it sinks is the horizontal velocity of the water. In rivers or other locations where horizontal currents exist, the body will be moved downstream as it settles. The distance that the body moves is a function of the magnitude of the velocity of the water (the faster the water, the further downstream from the entrance location will the body reach the bottom).

The third component of the settling phase is governed by the principles of Boyle's law during the body's settling period. Boyle's law states that the product of the pressure P exerted on a gas times the volume V of the gas is equal to the product of two constants (n and R) times the ambient temperature T ($PV = nRT$). Dissolved gases in the tissues and air in the lungs will thus compress as the pressure of the water increases during settling, assuming the temperature of the water remains constant. (If the temperature also decreases, the volume of the gases must decrease even further.)

The effect of the compression of the gases is to decrease buoyancy of the body. Pressure is increased from the sinking and the gases compress again which causes another decrease in buoyancy and further sinking. This cycle will continue to repeat in incremental steps until the body reaches the bottom.

Phase 2—Motion Along the Bottom

Once on the bottom the body is governed by a number of factors, including the force balance on the body, the type of substrate, and the presence of any snags or debris on the bottom. The force balance on a body resting on the bottom is composed of four components: lift, gravity, drag, and friction (Fig. 5). The lift force is composed of the velocity of water and the cross-sectional area of the body. The gravity force is related to the submerged weight of the body. Drag is the force exerted on the body by the moving water. Lastly, the friction force is a function of submerged weight and lift. The mode of motion, that is, rolling or sliding, may be an important consideration in this force.

Motion along the bottom then occurs when the forces of drag or lift overcome the forces of friction and gravity. Motion may additionally be affected by secondary factors, such as the roughness of the bottom, the presence of snags or debris on the bottom, the presence and type of clothing on the body, and even the length and state of the body's hair. The type of substrate, whether mud or sand, and the relative compaction may be important factors. Snags offer the most significant consideration, however. All other factors wane in importance if the body is lodged in a crack or on debris.

Phase 3—Ascent to the Surface

In the absence of secondary bottom factors, a body will remain on the bottom until its buoyancy changes, that is, the body gains sufficient flotation force that it begins to rise. This change is caused by the accumulation of gases in the tissues from microbial metabolism during decomposition. The increase in buoyancy lifts the body slightly, and pressure on the body decreases. The volume of dissolved gases correspondingly increases (through Boyle's law again) and the body will lift again. This cycle will repeat until the body reaches the surface. The rising stage is thus an inverse occurence of the settling stage.

Phase 4—Drift along the Surface

The movement of a body floating on the surface of a river is controlled by current, wind, snags, strainers, and eddies. Of these factors, surface currents play the most important role. Surface currents are themselves composed of two parts: primary and secondary currents.

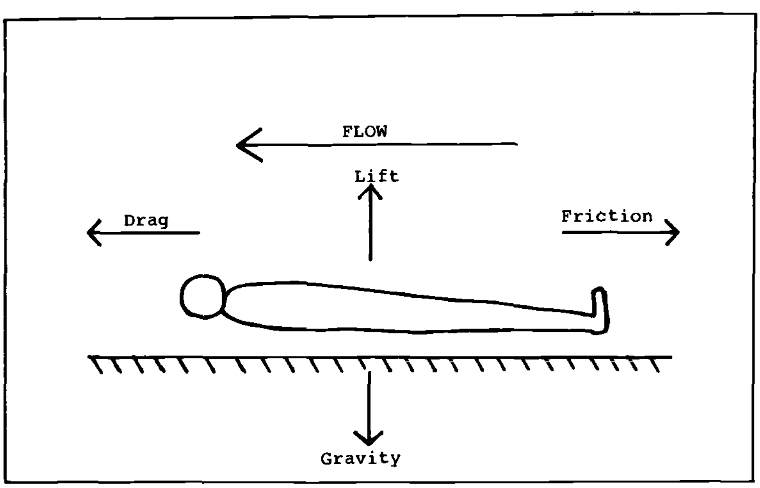

FIG. 5—*Lift, gravity, drag, and friction forces on a body.*

Primary currents flow in the downstream direction. Their exact path is governed by the steepness, shape, and amount of curvature of the river channel as discussed earlier. Secondary currents flow in a direction perpendicular to the primary currents. The secondary currents are of paramount importance in the movement of a body on the surface; these currents determine the ultimate direction of movement.

The effects of wind on a floating body is a function of the speed of the wind, the duration of the wind, and the amount of exposed surface area of the body. Light to moderate breezes generally do not affect the motion of a floating body. Stronger winds, and of significant duration, are required before any wind-induced movement occurs. A body floats with little exposed surface area, thus the overall effect of wind is minimum or negligible on the body itself. Wind-induced currents (generally secondary in nature) may be set up by strong winds of lengthy duration. These currents may play a more active role in the movement of a body as a result of wind. Hydraulic mechanisms, since the body is mostly submerged, play a much larger role in governing body movements than wind.

The most common type and location of snags and strainers in a river are tree limbs and roots along the river banks. As trees along the banks die and fall into the river they disrupt the flow of water along those banks. The limbs strain floating debris on their upstream sides, or may snag any object on the branches. Bridge piers are frequently another source of snags. Logs and other debris often become lodged against a pier on the upstream side causing an obstruction to objects drifting downstream. Tree roots, riparian vegetation, and miscellaneous debris may also serve as snags along a bank.

Closely related to strainers and obstructions in a river are eddies which are areas of quiet water immediately downstream from an obstruction. The surface flow in an eddy is generally circular, but the primary direction of the flow is upstream. Any object drifting into such an eddy generally remains captured in the eddy until either the object is found and removed, or the river stage (elevation) changes in a manner which dislodges the object.

Experimental Methods

Two sets of experiments were devised to test the movement of objects in a river. One set dealt with motion on the surface of the river, the other set was concerned with motion along the bottom. Surface movement examinations were conducted through the use of two types of objects: floating spheres and a floating dummy.

The spheres of 10 cm (3.9 in.) diameter were used as surface flow tracers. The spheres floated with about 80% of the volume of the sphere submerged, similar to the way a deceased and bloated body floats. These test spheres have as advantages their convenience in size and experimentation. An additional advantage in using these indicators is that a large number of individuals may be incorporated in one test, thus yielding a statistical summary of the surface flow patterns in one survey.

The two dummies used in the experiments were inflatable Resusi-Annies® manufactured by Armstrong Industries. One of the dummies was constructed as a surface model and the other as a submerged model. The surface dummy floated at the surface of the water and was used to determine the movement characteristics of a body at the surface. This dummy was simply filled with water to give it form for the floating tests. The head of the floating dummy, however, was filled with foam for weight and buoyancy.

The second model was used to determine the movement characteristics of a body along the bottom of the river. This submerged dummy was filled with foam and iron reinforcement bars to simulate bones, body form, and density. The specific gravity of the submerged dummy could be adjusted by the addition of small weights and extra foam flotation. These adjustments allowed its specific gravity to fall within the range of specific gravities that could be expected for recently deceased people [5]. The specific gravity of the submerged dummy was computed by weighing the dummy both submerged in water and in the air. The formula for computing specific gravity is:

$$SG = w_a/(w_a - w_s)$$

where w_a is the weight in air and w_s is the weight submerged. Balance of the dummy was considered in its construction; the center of gravity was near its abdomen (that is, neither the head nor the legs were disproportionate in weight). The head of the submerged dummy was filled with a combination of foam and reinforcement bars again to adjust for both weight and flotation.

The surface flow experiments involved the release of the test objects in the water near each bank and the monitoring of the subsequent drift downstream. One-hundred spheres were used in each experiment for the statistical comparison of floating objects through a study reach. The monitoring of test objects near each bank demonstrates flow patterns of surface currents along, or near, those banks. (An identical series of tests may be conducted in the center of the river, if the directions of principal and secondary currents are desired in this location. This test was not conducted in this study). Monitoring of the exact location and time of the subject as it moves downstream (if unimpeded) yields average travel times of an object through the reach.

The submerged dummy tests were conducted at several locations in the river at the downstream side of the Jackson Parkway bridge. The dummy was released near each bank and several times in different parts of the center of the channel. In each test the dummy was released at the surface and allowed to sink freely. Movement downstream of the dummy was noted during the settling phase. Once on the bottom, time and position of the dummy were continually monitored, thus indicating the motion (or lack thereof) of the subject. These measurements, taken over a range of discharges (flow velocities) in the river and a range of specific gravities of the dummy, yield a summary of initial conditions and criteria necessary for downstream motion of a body along the bottom.

Tracking of the surface samples was done visually from a boat as the samples drifted downstream. Tracking of the submerged dummy over short distances and shallow depths may be accomplished by monitoring a float connected to the body by lightweight monofilament line. Monitoring the submerged dummy in deeper water or over long distances may be better accomplished through the use of a Smith-Root underwater transmitter, hydrophone, and receiver.

Results

The monitoring of surface movements of objects along each bank showed that all objects tended to remain along their respective bank in their travel through the study reach. In other words, objects released near the left bank remained near the left bank throughout the reach, and objects released near the right bank remained near the right bank. No mechanism of crossover from hydraulics, topography, or wind was found in this reach of the river.

The submerged dummy, tested over a range of specific gravities, locations in the river, and flow conditions of the river, demonstrated downstream movement along the bottom in only one location and at one flow condition. The dummy only moved when released in the center (deepest) part of the river channel, at the highest flow velocity and with the smallest specific gravity (1.018). No bottom movement was observed near either bank for any combination of flow velocity or specific gravity of the dummy.

Discussion

General hydraulic theory (and social adage) suggest that objects on the surface of a river move toward the outside bank of a curve as the objects pass through a river bend. In a strong bend where a single, large spiral flow pattern is dominant, this theory holds true. In the study area of the Chattahoochee River in this report, however, no evidence of this type of dominant single-spiral flow has been found. Instead, theoretical examinations and field observations have demonstrated that the Chattahoochee River is composed of a fairly uniform double-spiral flow through the entire study reach.

The movement of objects on the surface suggests that the flow pattern of the coexisting spiral cells moves water on the surface in both a downstream and an outward direction in both cells. The direction of the surface water movement has been supported by the floating sphere experiments and the floating dummy experiments.

The results of the floating objects' tests show that an object floating in the river near one side or the other will remain adjacent to that side during the object's journey downstream throughout the reach. Objects floating near the right bank will remain near the right bank; objects floating near the left bank will remain near the left bank. For an object to change sides of the river either the physical dynamics of the river must change or some external force must be applied to the object. The physical dynamics of the Chattahoochee River remain fairly constant throughout the study reach. No major bends occur in the river, nor do dramatic changes in bottom topography or flow direction exist.

The most likely external force to be applied to a floating object is wind. Both wind speed and wind direction are potential factors. Upstream winds may retard downstream motion, and winds blowing downstream may accelerate the downstream travel. The trees along the banks of the Chattahoochee shelter the channel and the water surface. The trees and the channel may funnel the outside winds either upstream or downstream depending on the initial direction of the outside wind. The winds in the channel, however, may switch directions in a variable fashion.

The movement of a submerged dummy along the bottom was negligible for specific gravities ranging from 1.018 to 1.032 and for bottom velocities ranging from 0.07 to greater than 0.66 mps (0.2 to $>$ 2.0 fps). The submerged dummy showed no appreciable movement in the river under these conditions regardless of the location where the dummy was released on the downstream side of the Jackson Parkway bridge. Three possible explanations exist to explain these results. First, the bottom of the river contained numerous snags that could prevent the dummy from moving downstream. Once the dummy reached the bottom it may immediately have become caught and held on a snag.

A second explanation is simply insufficient velocity of the river along the bottom to move the dummy at low river stages, even at the lightest specific gravities of the dummy that was tested. The drag forces of the river were not sufficient to overcome the gravitational and frictional forces on the dummy.

The third possibility is that the dummy experienced negative lift once it reached the bottom. The dummy may likely have been oriented by the current on the bottom with the dummy's feet upstream and torso downstream. This orientation is suggested by the effects of fluid drag forces on the slightly triangular shape of the dummy. The velocity of water along the bottom of the river, under the dummy, may then have been sufficient at low flows to cause negative lift on the dummy and hold the dummy in place close to the bottom.

Study Limitations

Experimental studies of lift, drag, friction, and buoyant forces on human bodies in moving water are almost completely nonexistent. The study described in this paper had severe limitations both on the time available to accomplish the study and on monetary support; therefore it was impossible to generalize results in the form of estimates of these four forces. As a result, the conclusions of this study must necessarily be stated primarily in the form of interpretations of the specific experiments performed rather than in the form of more general results about the movement of bodies in other rivers and under other flow conditions.

The major specific limitation in this study is that the sinking dummy was constructed to have a single constant specific gravity during each trial. A human body has considerable air volume which causes variation of specific gravity with depth as a result of the compressibility of the air volume with pressure variations. The range of specific gravities investigated are thought to represent reasonable values for a human body in the initial state before decomposition begins.

Vertical lift in a body is a result of an increase in concentration of gases in the tissues because of decomposition by bacteria. The length of time that occurs until a body begins to lift is a function of temperature of the water; density (mass) of the body; and even the size, composition, and time of the last meal. These uncertainties and variations are not addressed in the present research. Future studies may examine the rising phase of motion through the use of an inflatable bladder located inside a submerged dummy and inflated through timed releases of a gas.

As a body begins to lift from decomposition it will likely move along the bottom for some period of time as it approaches neutral bouyancy. However, the author expects this phase of initial motion to be of limited duration because the body at this moment is unstable with respect to bouyancy; any upward motion of the body caused by debris on the bottom or turbulence in the water flow itself will result in marginal depressurization and expansion of the gases in the body. This process increases the buoyant forces which will tend to continue the motion to the surface. The scenario suggests that, for the flow conditions investigated, the period of body motion near the bottom is short-lived and that the body will rapidly ascend to the surface once it becomes light enough (that is, specific gravity < 1.018) to move at all. This scenario, however, was not explicitly investigated in the described project.

Conclusion

The results of the tests of the floating objects in this reach of the Chattahoochee River show that the initial (or entrance) location of a floating object in the river channel is paramount in determining the behavior of the object as it moves downstream. Objects floating in the river near the right bank can be expected to remain along the right bank; objects floating near the left bank will remain near the left bank.

A body that enters the river and immediately sinks to the bottom on the downstream side of the Jackson Parkway bridge, at river stages below at least 1.8 m (5.5 ft), can be expected to remain in approximately the same location where the body entered the water until either the body's condition changes (that is, increases in buoyancy occur from decomposition in the body tissue) or the river environment changes (for example, a major rise in river stage occurs).

Thus the shape (that is, the degree of sharpness of the bends), the roughness of the banks, the bottom conditions, and the velocity of a river are all important factors in determining the movement of bodies in that river. Each river must be examined in its own case and the characteristics of these parameters defined for the area of interest.

The biology and chemistry of decomposing bodies is a further element of importance. The mechanisms of decomposition are most relevant when combined with the hydraulics of the waterway. The precise nature of the movement of a body in a condition of significant decomposition as it proceeds both vertically and horizontally through a waterway has yet to be discovered.

The author has no desire to overestimate the precision with which the motion of a body in moving water can be predicted at the present time. The present study does offer initial guidelines and principles that can be used in the search and recovery of bodies in most rivers.

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Address requests for reprints or additional information to
David R. Dilen
HERC
3508 Stratfield Dr.
Atlanta, GA 30319