

Tidal Bores

A bore is the hydraulic analogue of a sonic boom: a moving wall of water that carries the tide up some rivers that empty into the sea. For several hours after it passes the river flows upstream

by David K. Lynch

We huddled together on the bank of the river in the cool spring night, drinking tea and warming our hands at the fire. The full moon shone intermittently through the clouds, illuminating the river below. Suddenly from downstream came the cry "Flood—O!" We ran higher up the bank with a low, rumbling sound in our ears. As we reached the top of the bank a wall of water four feet high passed below us, moving faster than we could run. The wave was moving upstream, carrying with it pieces of wood and other debris. In the few minutes it took for the wave to move out of range of our hearing the water level rose another two feet. Gradually the turbulence subsided into gentle eddies, and after an hour the river began flowing toward the sea again.

Thus in 1978 did I get my first sight of the tidal bore on the River Severn in southwestern Britain. A tidal bore is a remarkable hydrodynamic phenomenon: it is the incoming tide in the form of a wave going up a river that empties into the sea. After the bore passes, the river flows upstream for some time before the current reverses again. For a river to have a bore two conditions must be met. The tides in the adjoining tidal body must be exceptionally high; a difference of more than 20 feet between high and low water is generally required. In addition the river must be shallow with a gently sloping bottom and a broad, funnel-shaped estuary. As the incoming tide is forced into the narrowing river mouth it builds in height until a single wave materializes and moves upstream.

A bore is a member of the class of solitary waves. Such waves appear in many forms and in many mediums besides water; they are even observed in the atmosphere of Mars. Their most intriguing property is that they do not disperse. Like all waves, a tidal bore is made up of many sinusoidal waves with many different wavelengths. In deep water the component waves move with different speeds and separate from one another. Because of the way shallow-water waves interact with the bottom in the

estuary, the component waves of the bore move at the same speed. Hence instead of dispersing they travel upriver together as a single wall of water. Such solitary waves are curious and attractive for their own sake, but they are of particular current interest because they represent the solution to problems in several scientific disciplines.

Bores are elusive. They vary from river to river and even from tide to tide. Moreover, they have not been much studied in the 20th century. For these reasons any generalization about bores must be carefully qualified. As we have seen, a bore is a solitary wave that carries a tide upstream. The bore can be as low as a few inches or as high as 25 feet. Most bores are higher near the banks than they are in mid-channel. The formation of the bore represents the turn of the tide. Bores are largest and most powerful around the time of the new moon or the full moon, when the tides are highest.

Since the river flows upstream after the bore passes, the wave front divides the river into parts with opposite directions of flow. It should be noted that the river does not flow uphill as the bore passes. Since the water level behind the bore is higher than the level in front of it, the water flows upstream but downhill.

As the bore moves upriver it may have a breaking crest like the crest of a wave on a shelving beach or it may be a smooth, gently rounded wave. A breaking bore is a foaming wall of turbulent water that advances noisily upstream. Bores that do not break are called undular bores. Several smaller waves usually follow an undular bore. Along the River Trent in Britain the smaller waves are known as whelps; along the Seine they are known as *etueles*, or stubble. I have seen as many as 55 of the smaller waves following a bore on one of the tributaries of the Amazon.

Whether a particular bore is breaking or undular depends on the height of the tide, the depth of the river, the shape of the bottom and the speed and the direc-

tion of the wind. Many bores are undular in mid-channel and breaking on the bank. In some rivers the bore can be undular on one tide and breaking on the next. A bore can even change from one form to the other as the depth of the river changes.

Bores are distributed widely over the globe. They are not concentrated in any one region, although they do tend to form in places where the tides are greatest, such as on the coasts of Britain and France, in rivers flowing into the Indian Ocean and at the mouth of the Amazon. Whether a bore forms is determined by the local conditions at the mouth of a river. Since little attention has been paid to bores in recent decades, precisely how many rivers have bores is not known. With Susan B. Bartsch-Winkler of the U.S. Geological Survey I am compiling a catalogue of the major bores of the world.

North America has several notable tidal bores. The most striking is the one on the Petitcodiac River in Nova Scotia, which empties into the Bay of Fundy. There are also dramatic bores on Turnagain Arm and Knik Arm, which flow into Cook Inlet near Anchorage, Alaska. On Turnagain Arm and Knik Arm bald eagles hunt fish by following the bores moving inland from the Pacific; the fish are brought to the surface by the turbulence of the bore.

Perhaps the most celebrated of all bores is the one on the lower Seine known as the Mascaret. The Mascaret has been greatly reduced by the silting of the Seine near its mouth, but the bore was once notorious for its destructiveness. In 1843 Victor Hugo's daughter Léopoldine and her husband Charles Vacquerie were boating near Rouen when the Mascaret rolled upriver. The bore knocked Léopoldine out of the boat. Charles jumped in to save her, but neither of them could swim and both drowned. Hugo memorialized them in the poem "À Villequier" but did not mention the bore.

Certain tidal bores are associated with myths or ceremonies. The passage at



BORE MOVES UP THE SEINE through the town of Caudebec in a photograph made in 1963. Since that time harbor-control measures

at Le Havre have greatly reduced the size of the bore. Known as the Mascaret, the Seine bore was once feared for its destructive force.



BORE MOVES UP THE ARAGUARÍ, a river in the Amazon basin, in this aerial photograph made by the author. Known as the pororoca, the bore of the Amazon and its tributaries reaches a height of 25 feet. Here it is about five feet high and moving at about 10 miles per hour. Bores can be breaking, like the surf on a beach, or smooth and round-

ed; smooth bores are called undular. Many bores are undular in mid-channel and breaking near the bank where the shallow water slows the wave. The pororoca shows such a configuration here. Immediately in front of an undular bore the water is smooth, but a series of smaller crests often follow the main wave up the river, as they do here.



BORE ON TURNAGAIN ARM, near Anchorage, Alaska, is one of the few in North America. It is usually from two to five feet high and, as shown, its leading edge is not straight or uniform. The depth of Turnagain Arm varies greatly. The parts of the bore in deep water move faster than those in shallow water. The faster parts are undular and the slower parts breaking.



BORE ON THE SEVERN is the largest in Britain. It is a powerful breaking bore with a crest large enough for surfers to ride upstream for miles. The bore forms near the Severn bridge above Sharpness and extends to Gloucester. Two conditions must be met for a bore to form. First, there must be a broad estuary that narrows toward the river mouth and has a shallow, gently sloping bottom. Such a configuration funnels the incoming tide, increasing its height. The Severn estuary from Cardiff to Bristol has the required narrowing shape. Second, the tides in the adjoining tidal basin must be very high. A difference of more than 30 feet between high water and low water at Sharpness is generally necessary for the Severn bore to form.

the beginning of this article describes my experience at the annual celebration held in the spring on the Severn near Gloucester. The transparent baby eels, known locally as elvers, that live on the bottom of the Severn are the traditional Good Friday meal. When the bore comes upriver, it disturbs the eels. When the Severn is flowing downstream again, the inhabitants of Gloucester gather the eels with nets. Those that are not eaten or taken to the local market are sold to merchants who fly them to eel farms, many in the Orient. By day the Severn bore is caught by surfers, who ride it upstream for miles.

The broad Amazon basin has a bore known as the pororoca that sweeps up the river and its tributaries. The pororoca can be 25 feet high and many miles across. Its size and force render the Amazon completely unnavigable during the bore's passage. Because of the Amazon's gradual slope, tidal effects can be detected 500 miles upstream from the mouth of the river.

The mightiest tidal bore of all is the one on the Tsientang River in China. The Tsientang bore reaches a speed of about 15 knots and was once exploited by local fishermen as a means of propulsion. The bore is largest near Hangchow, which was at one time an imperial capital. According to a Chinese myth, the Tsientang bore was unleashed on Hangchow to punish an emperor who had arranged the assassination of a popular general who was a potential rival. When ceremonial paper burnings and offerings of food failed to conciliate the angry spirits, the emperor had a large pagoda put up as a grander propitiatory gesture. The Bhotia pagoda still stands near Hangchow, and although the bore did not disappear after the building of the pagoda, it is said to have become somewhat less violent.

The elusiveness of bores is suggested by the fact that Marco Polo, who spent 18 months in Hangchow in the 13th century and wrote a detailed account of his stay, does not mention the bore. The Tsientang bore is so impressive that it is difficult to believe the Italian adventurer could have seen it and not remarked on it. It is more likely that the bore was much smaller in the 13th century than it is today. Changes in local terrain caused by earthquakes and slower changes in the river bed make some bores intermittent. Contemporary accounts of the Taiping rebellion in the 19th century indicate that the Tsientang bore was much smaller a century ago than it is now.

Although the large majority of bores form near the mouth of a river, bores can form under other circumstances. In coastal regions where broad sandy flats lie between the high-tide level and the low-tide level the rising tide can spill

onto the flats and rush toward the land as a single well-defined wave. The region of Mont-St.-Michel in France is celebrated for a tide that rushes across the flats faster than a horse can gallop. A tsunami, an ordinary water wave with a long wavelength generated by a seismic movement of the ocean floor, can cause a bore to move up a river that does not ordinarily have one.

Certain other conditions can also cause bores. In February, 1976, a rare combination of a high tide, heavy rain, 115-mile-per-hour winds and low atmospheric pressure sent a tidal surge up the Penobscot River in Maine. At Bangor the river rose 20 feet in 15 minutes and caused the only flood in the history of Bangor that came from downstream. As an example of a bore in a medium other than water, a borelike wave forms in the atmosphere of Mars near Tharsis Ridge during the morning hours in the late spring and early summer. These solitary waves appear as local changes in the refractive properties of the Martian atmosphere over a relatively short distance.

To move beyond the drama visible from the river bank (or on Mars) to an understanding of the physics of bores calls for an appreciation of the tides, of wave motion and of the topography of the mouth of rivers. The tides are themselves due to gravity and inertia. The gravitational force is mainly that of the moon. Since the force of gravity is inversely proportional to the square of the distance between the two objects that are attracted, the moon exerts a stronger pull on the near side of the earth than it does on the far side. The difference between the attraction on the two sides is about 13 percent. The difference tends to elongate the earth along the axis between its center and that of the moon. The inertia of the earth as it orbits the center of the system made up of the earth and the moon tends to stretch the planet out of its spherical shape.

The oceans naturally respond more to such forces than the continents. Hence the oceans flow into two tidal bulges. One bulge faces the moon and the other faces away from the moon; between them the water is shallower. Since the moon takes about 28 days to orbit the earth, the tidal bulges take the same period to travel around the earth as they follow the moon. The daily revolution of the earth on its axis causes each point on the surface of the earth to go into and out of each tidal bulge about once per day. To an observer on the earth the tides appear to rise and fall twice a day. An observer suspended above the earth, however, would see that each point on the earth actually spins into and out of the tidal bulge.

The moon orbits the earth in the same direction in which the earth revolves. By the time a point on the earth has re-

volvied halfway the tidal bulges have moved forward with the moon and the point must move forward to enter the bulge again. Hence there is slightly more than 12 hours between high tides: the period is 12 hours 25 minutes.

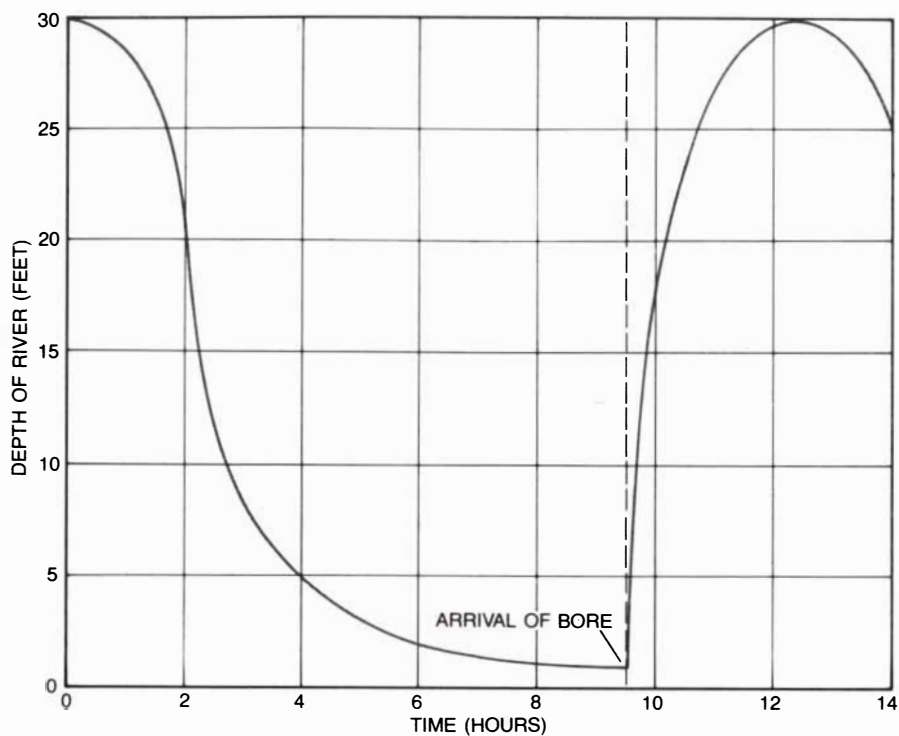
If there were no continents to impede the motion of the tides, every point on all coasts would have two tides a day. Many places do have such tides, which are designated semidiurnal. Other places, however, have a different tidal pattern. The wave of the tide is reflected and broken up by the continents and forms a complicated series of crests and troughs thousands of miles apart. Moreover, in some regions the tides are coupled with the motion of large nearby bodies of water. As a result some places have only one tide a day, which is called

a diurnal tide. A few places (including Tahiti) have virtually no tide at all because they lie on a tidal node. Such a node is a stationary point about which the standing wave of the tide oscillates.

The sun also raises a tide. Since the sun is so much farther from the earth than the moon is, its tide is only about half the magnitude of the lunar tide. The overall tidal amplitude (the difference between the high-water level and the low-water level) depends on the relation of the solar tide to the lunar tide and therefore on the positions of the sun, the moon and the earth. The tidal amplitude is at its maximum twice a month at the time of the new moon and the full moon, when the three bodies are aligned in the configuration known as syzygy; this is the time of the "spring" tides. The am-

COUNTRY	RIVER OR CHANNEL	TIDAL BODY	LOCATION OF BORE (WHERE KNOWN)
BANGLADESH	GANGES	BAY OF BENGAL	—
BRAZIL	AMAZON	ATLANTIC OCEAN	—
	CAPIM	ATLANTIC OCEAN	CAPIM
	CANAL DO NORTE	ATLANTIC OCEAN	—
	GUAMA	ATLANTIC OCEAN	CAPIM
	TOCANTINS	ATLANTIC OCEAN	—
CANADA	ARAGUARI	ATLANTIC OCEAN	—
	PETITCODIAC	BAY OF FUNDY	MONCTON
CHINA	SALMON	BAY OF FUNDY	TRURO
	TSIENTANG	EAST CHINA SEA	HAINING TO HANGCHOW
ENGLAND	SEVERN	BRISTOL CHANNEL	FRAMILODE TO GLOUCESTER
	PARRETT	BRISTOL CHANNEL	BRIDGWATER
	WYE	BRISTOL CHANNEL	—
	MERSEY	IRISH SEA	LIVERPOOL TO WARRINGTON
	DEE	IRISH SEA	—
	TRENT	NORTH SEA	GUNNESS TO GAINSBOROUGH
FRANCE	SEINE	ENGLISH CHANNEL	CAUDEBEC
	ORNE	ENGLISH CHANNEL	—
	COUESNON	GULF OF ST.-MALO	—
	VILAINE	BAY OF BISCAY	—
	LOIRE	BAY OF BISCAY	—
	GIRONDE	BAY OF BISCAY	ÎLES DE MARGAUX
	DORDOGNE	BAY OF BISCAY	LA CAUNE TO BRUNNE
GARONNE	BAY OF BISCAY	BORDEAUX TO CADILLAC	
INDIA	NARMADA	ARABIAN SEA	—
	HOOGHLY	BAY OF BENGAL	HOOGHLY POINT TO CALCUTTA
MEXICO	COLORADO	GULF OF CALIFORNIA	COLORADO DELTA
PAKISTAN	INDUS	ARABIAN SEA	—
SCOTLAND	SOLWAY FIRTH	IRISH SEA	—
	FORTH	IRISH SEA	—
U.S.	TURNAGAIN ARM	COOK INLET	ANCHORAGE TO PORTAGE
	KNIK ARM	COOK INLET	—

CATALOGUE OF TIDAL BORES shows that bores are distributed widely throughout the world. Little systematic attention has been given to tidal bores in the 20th century; therefore the catalogue is incomplete. The author is currently compiling a list of major bores that is expected to include about twice as many as there are in the table. Bores are not concentrated in any one region of the world because the existence of a bore depends on local conditions: the tides and topography at the mouth of the river. Such conditions can be changed by harbor-control measures, damming or natural changes in the river bed. For this reason the extent of the bore given in the table is approximate. The bore on the Colorado River has been greatly reduced by silting near the mouth of the river. The largest of all bores is on the Tsientang in China.



DEPTH OF THE PETITCODIAC shows the sudden increase associated with the arrival of the bore. The curve indicates the depth of the river near Moncton. At the time of low water the Petitcodiac is only a few feet deep. The arrival of the bore immediately increases the depth by from two to three feet. After the bore passes, the river continues to rise for more than two hours, ultimately reaching a depth of about 30 feet. The graph shows the tidal asymmetry that is common on rivers with bores. More than nine hours elapse between high water and low water because the tide goes out gradually with the current. It is only about two and a half hours between low water and high water, however, because the tide comes in suddenly as a bore.



PETITCODIAC BORE goes up the Petitcodiac River through the city of Moncton, New Brunswick. Chignecto Bay is the narrowing body that serves to confine the incoming tide. The adjoining tidal basin is the Bay of Fundy which is known for its great tidal range: the difference between high water and low water can be more than 50 feet. The range is greatest during the spring tides around the time of the new moon and the full moon. Most bores form on the spring tides. The Salmon River has a smaller bore extending from Cobequid Bay to Truro, Nova Scotia.

plitude is at its minimum at the time of the first quarter and the third quarter of the moon, when the sun, the moon and the earth form a right angle and the solar and lunar tides oppose each other; this is the time of the neap tides.

It therefore becomes evident why bores generally form at about the time of the new moon and the full moon: it is then that the tidal amplitude is greatest. The amplitude can be increased further by resonance. Every container of liquid has a natural frequency of oscillation. If the liquid in the container is set in motion, it can move back and forth in a single coherent wave with the natural frequency. On the scale of a coffee cup the oscillation is seen as a sloshing motion. There can also be waves with a number of different frequencies in the motion of the liquid. The lowest frequency, the fundamental, is the most important with respect to resonance.

The amount of time it takes a wave with the fundamental frequency to move from one side of the container to the other and back is called the fundamental period. That period is determined by the depth of the water and the size of the container. For a closed basin the fundamental period is about twice the longest dimension of the basin divided by the speed of the waves. In a lake, which constitutes such a closed basin, large-scale natural oscillations are called seiches. Seiches are common on Lake Michigan. They are often caused by a low-pressure atmospheric system at one end of the lake; on occasion they can be quite destructive.

In a basin open at one end to a larger body of water the fundamental period is about four times the longest dimension divided by the speed of the wave. The tidal basin near the mouth of a river constitutes such a basin, with the ocean providing the tidal impulse. The effect of the natural oscillation is to make the water at one end of the basin high at the beginning and the end of the fundamental period and low in the middle of the period as the water sloshes back and forth in a crest-and-trough pattern. For example, if the fundamental period is 12 hours, the water at one end will be high at, say, noon, low at 6:00 P.M., high at midnight and so on.

If the fundamental period is close to the tidal interval of 12 hours 25 minutes, the basin will resonate with the incoming tide. The incoming tide sets the water of the basin oscillating. The motion of the tide coming in toward the mouth of the river and the motion of the oscillation are synchronized. Thus the oscillation reinforces the tide in the bay and makes the high tide higher than it would otherwise be and the low tide lower than it would otherwise be.

The resonance can also result in an asymmetry between the tide at the

ocean end of the basin and the tide near the mouth of the river. In some cases the mouth of the basin is at a node of the wave that represents the oscillatory motion; as we have seen, a node is a fixed point about which the water oscillates. The tide at the node is much smaller than the one near the river mouth.

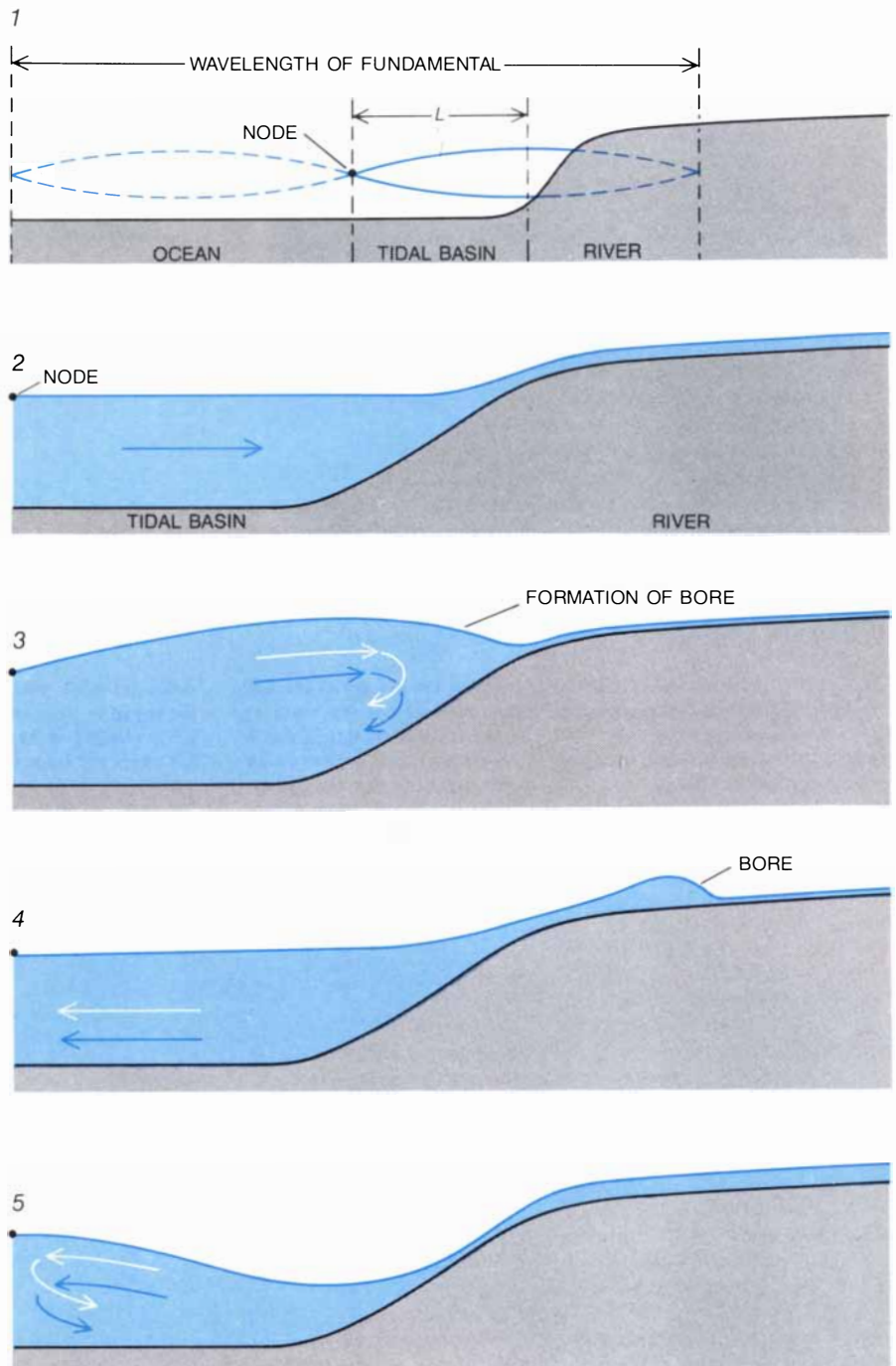
Although any body of water with high tides can generate a bore, about half of the known bores are associated with resonance in a tidal basin. An excellent example of such resonance is in the Bay of Fundy, which is well known for its tidal range of more than 50 feet. The fundamental period of the Bay of Fundy is 11 hours, which is close enough to the semi-diurnal tidal interval for the tides to force the bay to resonate and send a tidal bore up the Petitcodiac. Cook Inlet in Alaska resonates so strongly that the 14-foot tide at its mouth is amplified into a tide of more than 30 feet at Anchorage.

The seaward ends of many rivers have a tide. At the mouth of the river the tides are symmetrical: ebb and flood last about six hours each. Upstream the tides become increasingly asymmetric: less time elapses between low water and high water than elapses between high water and low water because the tide comes in quickly but goes out gradually with the current. The presence of a bore tends to exaggerate the asymmetry because the tide comes up the river very rapidly as a solitary wave.

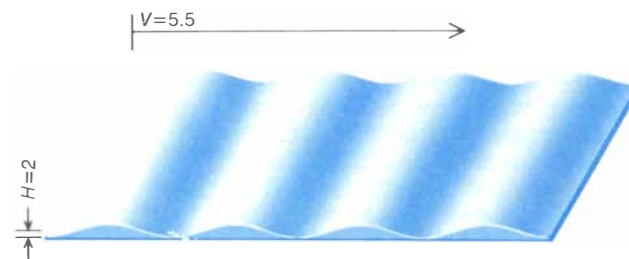
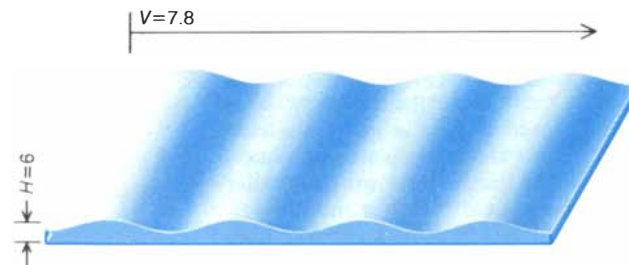
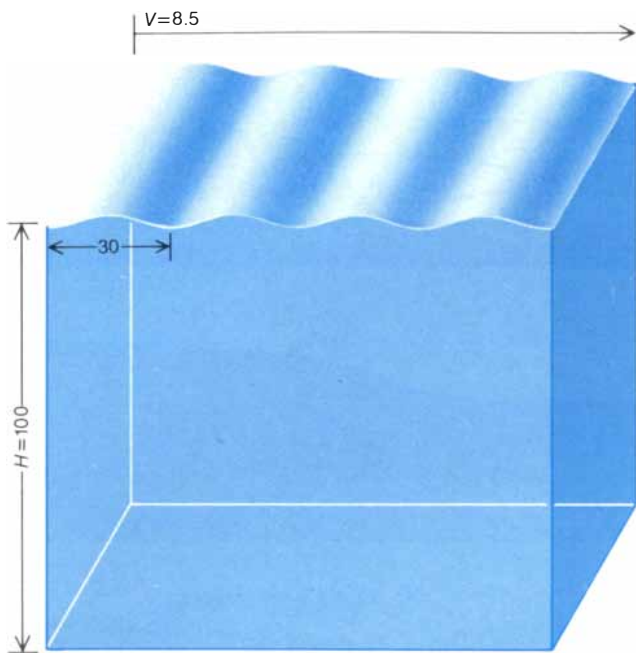
Therefore the tides and their resonance with the oscillation in a tidal basin provide the energy for the tidal bore. The form of the bore, however, is influenced mainly by the dynamics of waves. There are two classes of waves in water: capillary waves and gravity waves. Capillary waves have a wavelength of a few millimeters or less, and the force that restores the surface of the water to its undisturbed state as they pass is surface tension. Such waves are of little interest in connection with tidal bores.

With gravity waves the force that restores the surface to its undisturbed state is gravity. Such waves can be divided into two types on the basis of the relation between the wavelength and the depth of the water through which the wave propagates. Gravity waves with a wavelength much shorter than the depth are known as deep-water waves. Such waves move at a speed that is proportional to the square root of the wavelength. A deep-water wave with a long wavelength moves faster than one with a shorter wavelength.

This property of deep-water waves causes them to disperse. Actual waves in water are not simple sinusoidal waves with a single wavelength; they are made up of many sinusoidal components each with a different wavelength. Since each component travels at a different speed, the shape of the deep-water wave is con-

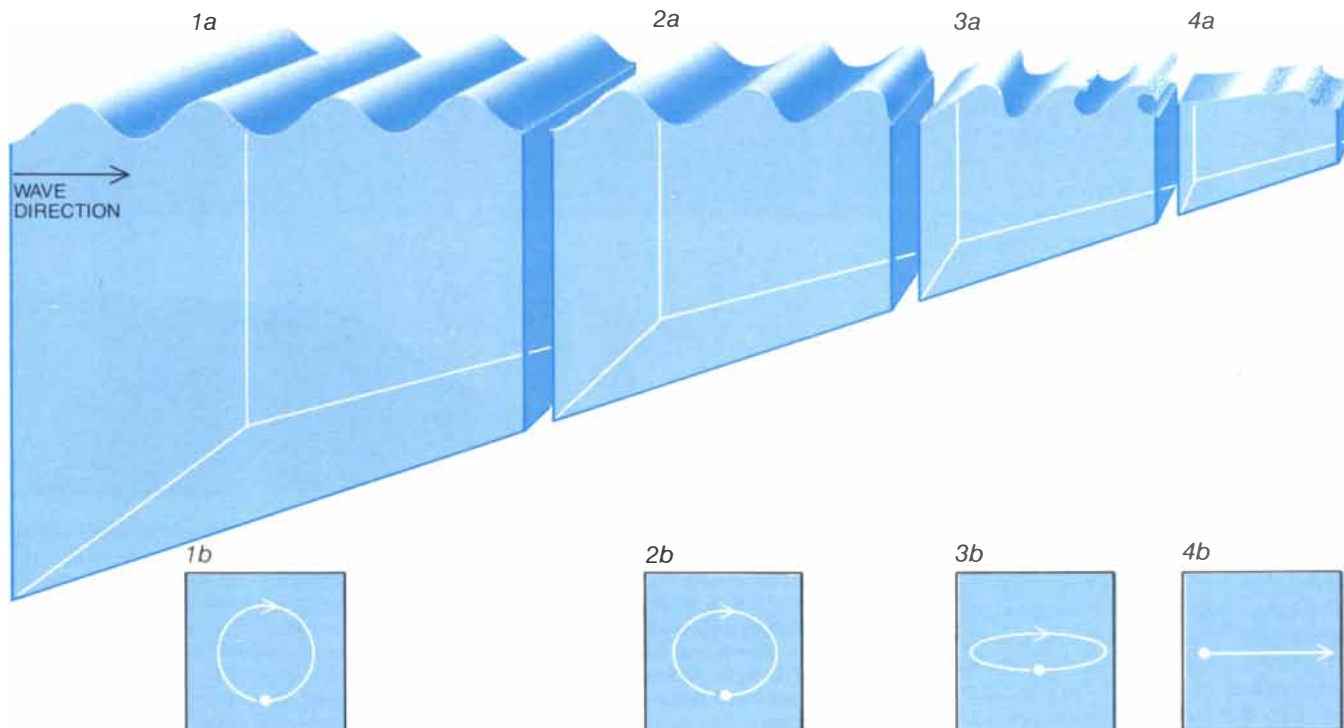


OSCILLATION OF THE WATER in the tidal basin near the mouth of a river can contribute to the formation of the bore by increasing the range of the tide. The diagrams show the tidal basin in schematic form with the ocean at the left and the mouth of the river at the right. If the liquid in a container is disturbed, it will move back and forth in a single coherent wave with a motion similar to that of coffee sloshing in a cup. The time it takes the wave to go from one side of the container to the other and back is the fundamental period. In a tidal basin the fundamental period is roughly equal to four times the length (L) divided by the speed of the wave. The speed is in turn proportional to the square root of the depth. A quarter of the wavelength fits into the basin at one time (1). In some instances there is a node, or a fixed point of the wave, at the ocean end of the basin. The tides at the node are small; at the river mouth they are large. If the fundamental period is approximately equal to the 12-hour-25-minute period between high tides, the oscillation will reinforce the high tide near the river mouth. The effect is resonance, and it is shown in panels 2 through 5 of the illustration. The period between panels is one-fourth of the fundamental period. The tide (blue arrow) comes into the basin from the ocean as a wave moving toward the mouth of the river (2). The incoming tide is synchronized with the oscillation (white arrow) of the water in the basin (3). The wave propagates through the basin toward the mouth of the river. If the tide rises fast enough, a bore is formed at the river mouth. The tide turns and the sloshing motion reverses its direction. Water is carried toward the ocean end of the basin (4). The bore is moving upstream and the tide is still rising upriver. The water level near the river mouth falls as the slosh returns to the ocean end of the basin to join the incoming tide. The cycle is repeated (5). About half of the known bores are associated with resonance.



SPEED OF WAVES IN WATER depends on the relation between the wavelength (the distance from trough to trough) and the depth of the water. For deep-water waves (*left*), where the wavelength is much smaller than the depth (H), the speed (V) is proportional to the square root of the wavelength. (In the diagram the height of the wave is assumed to be small compared with the water depth.) A wave with a wavelength of 30 feet in water 100 feet deep moves at a speed of 8.5

miles per hour. When the wavelength is much greater than the depth, the speed is proportional to the square root of the depth. A wave with a wavelength of 30 feet in water six feet deep moves with a speed of 7.8 miles per hour (*top right*). In water two feet deep a wave with the same wavelength will move at 5.5 miles per hour (*bottom right*). Since the speed of shallow-water waves depends only on the depth, waves with different wavelengths have the same speed and do not disperse.



FORMATION OF A BORE, shown schematically, is similar to the development of a breaking wave on a beach. The process by which the bore forms is the conversion of the fast-moving deep-water waves carrying the incoming tide into slower shallow-water waves with a shorter wavelength. The conversion occurs in the estuary. In deep water offshore the waves are symmetrical (*1a*). Both sides of the wave have the same slope and the crests and troughs travel at the same speed. Within each wave the path of a "particle," or small volume, of water is circular (*1b*). Hence although the wave transports energy, no water is actually carried forward as the wave passes. As the waves enter the estuary they begin to interact with the sloping bottom and

to move as shallow-water waves. The interaction "compresses" the waves and decreases the wavelength. Moreover, since the crests are deeper than the troughs, they move faster and overtake them (*2a*). The waves become asymmetric, with the advancing side steeper than the following side. In addition the path of the water particles within the wave is flattened into an ellipse (*2b*). When the height of the wave becomes greater than about half the depth, the crest overtakes the trough and breaks into it (*3a*). The path of the water particle has become flatter (*3b*). When the wave breaks, it forms a bore: a turbulent wall of water (*4a*). The particle's path has become linear toward the shore (*4b*). Thus the bore carries water as well as energy upriver.

stantly changing as the faster components overtake the slower ones, unite with them and then leave them behind.

Gravity waves with a wavelength much longer than the depth of the water are called shallow-water waves. The speed of a shallow-water wave depends only on the depth of the water; it is proportional to the square root of the depth. Therefore in water of a particular depth all the waves move at the same speed. As a result they do not disperse but travel together with their waveforms relatively undisturbed. It should be kept in mind that deep-water and shallow-water are terms based on the relation between the wavelength and the depth and not on the absolute depth of the water or the wavelength. For example, a wave with a wavelength of three feet would travel across the oceans as a deep-water wave but would move across a bathtub as a shallow-water wave.

The difference between deep-water and shallow-water waves provides much of the basis for understanding the formation of tidal bores. The incoming tide arrives in a tidal basin in the form of rapidly moving waves with a long wavelength. As the waves enter the basin they are confined at the sides and the bottom by the narrowing estuary. As a result of this funneling action the height of the waves increases. The transition of the tide into a bore, which follows the increase in height, is much like the development of breakers from waves moving onto a shelving beach.

The transition from deep-water waves to shallow-water waves is associated with refraction. As the tide comes in and begins to interact with the bottom, refraction slows the waves. Since the offshore waves are in deeper water, they move faster than the waves closer to the shore. As a result, farther inshore the distance between successive crests is reduced. Furthermore, since the crest of each wave is in deeper water than the adjacent troughs are, it begins to overtake the trough in front. The wave, which was previously symmetrical, becomes asymmetric: the leading side gets steeper and the trailing side gets flatter. If the difference in the depth is great enough, the crest will begin to break into the trough and form a bore.

Another significant process develops as the wave moves toward the shore. In deep water the waves transport energy but do not transport the water itself. Each "particle," or small volume of water, at or near the surface describes a circular course and returns to its original position as the wave passes. When tidal waves advance toward the shore, however, refraction changes the circular path. The refraction is due to the interaction of the wave with the bottom. (It is refraction that slows down the waves in shallow water in proportion to

UNDULAR JUMP
 $F = 1.0-1.7$



WEAK JUMP
 $F = 1.7-2.5$



OSCILLATING JUMP
 $F = 2.5-4.5$



STEADY JUMP
 $F = 4.5-9.0$



STRONG JUMP
 F GREATER THAN 9.0



FROUDE NUMBER gives much information about the shape and force of a hydraulic jump such as a tidal bore. Abbreviated F , the number is named for William Froude, a 19th-century English civil engineer who worked on hydraulic jumps. F is equal to the ratio of the speed of the bore to the speed of the shallow-water waves on the undisturbed river in front of the bore. In each schematic diagram the observer is assumed to be moving at the same speed and in the same direction as the bore. In this frame of reference the bore's motion upstream disappears and the overall flow is from left to right, with the velocity decreasing as the flow passes through the bore. If F is from 1.0 to 1.7, the bore is undular. Above 1.7 all bores break. From 1.7 to 2.5 a weak jump is formed. From 2.5 to 4.5 a violent oscillating jump is formed; such a jump can send large waves downstream. From 4.5 to 9.0 a steady jump is formed; it is the best-defined type of bore. If F is greater than 9.0, large jets of water often extend ahead of the advancing bore.

their wavelength and therefore causes all shallow-water waves to move at the same speed.)

The path of the water particles is flattened into an ellipse by refraction. As the wave moves up the estuary the ellipses of particles near the top of the wave become longer and flatter than those of particles farther down in the wave. When this happens, the wave is said to be unstable; the paths of particles within it tend to become linear in the direction the wave is moving. At a certain point water begins to be carried toward the land as well as energy.

There are thus two velocities that are significant in analyzing the bore: the velocity of the wave and the velocity of the water particle. The relations between these velocities are an important part of the hydrodynamics of the bore. The study of the hydrodynamics of solitary waves has a long history. John Scott Russell, a hydraulic engineer, made the first report of a solitary wave on the Glasgow and Ardrossan Canal in Scotland in 1840. His account stimulated the

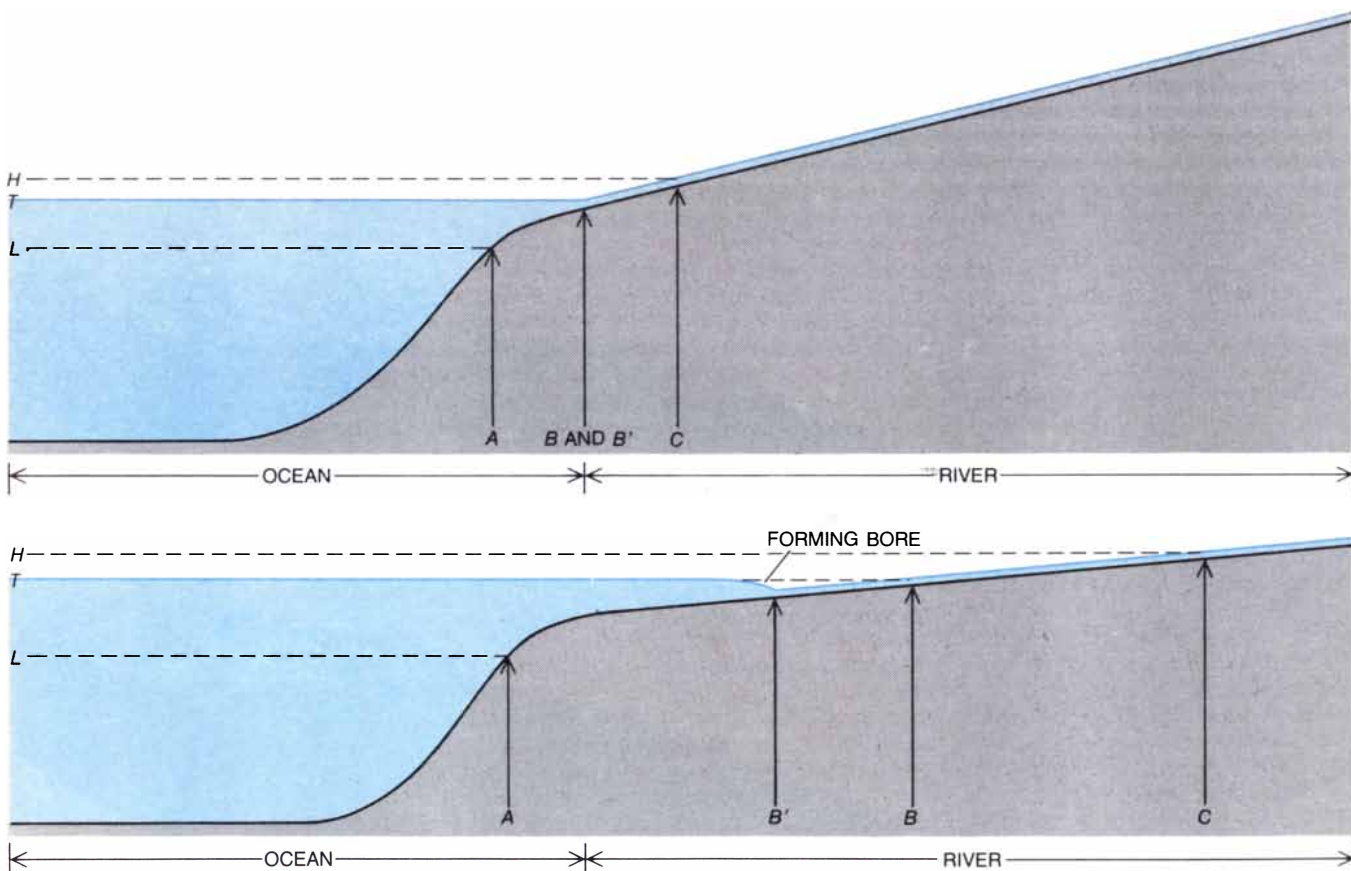
interest of many workers; among them was the 19th-century British physicist Lord Rayleigh (John William Strutt), who made numerous contributions to the theory of solitary waves. Solitary waves were long thought to be merely an elegant mathematical curiosity. They now appear to have important applications in crystal-lattice theory, nonlinear optics, particle physics and molecular biology, among other disciplines.

As we have seen, the velocity of the water particle and the velocity of the wave can be related in several different ways. When the flow speed of the particle is less than the shallow-water wave velocity of the wave, the flow is said to be subcritical; when the speed of the particle is greater, the flow is supercritical. The transition between subcritical flow and supercritical flow is called a hydraulic jump; a tidal bore is a hydraulic jump moving upriver. As the tide enters the estuary the water particles begin to move forward. At the point where the particles assume the shallow-

water wave velocity the bore forms.

Hydraulic jumps are common, although they rarely assume a form as dramatic as that of a tidal bore. For example, when the column of water from a faucet meets the surface of a large sink, a shallow layer of water spreads out to a certain radius, where it rises up in a circular wall of water. Outside the wall the water is deeper than it is inside.

The circular wall of water is a hydraulic jump. It results from the fact that when the column of water meets the surface of the sink, it spreads out with decreasing speed. Since the depth of the water flowing out from the base of the column is small, the shallow-water waves generated by random motions of the water in the column move slowly; indeed, the shallow-water wave velocity is much less than that of the flow. The flow is therefore supercritical and the waves are carried outward with the flowing water. Farther away from the column the water slows down and the flow becomes subcritical. The transition between the two regions is the hydraulic



CROSS-SECTIONAL VIEWS of the topography of the tidal basin and river mouth in two types of estuary show why bores form in some rivers but not in others. For a bore to form there must be a substantial tide and a gently sloping estuary. The diagrams show why that is so. In both the upper panel and the lower panel H indicates the high-tide level, L the low-tide level and T the current tide level. Because of the slope of the river bed the low tide intersects the river at A ; the high tide intersects the river at C . The current tide would intersect the river at B if the tide level in the basin were extrapolated inshore. B' is the point to which the current tide actually extends. The speed of the in-

tersection point B inshore depends on the slope of the estuary and the speed with which the tide rises. The actual extent of the tide inshore (B') is limited by the velocity of the shallow-water waves that carry the tide. In most rivers (*top*) the tide rises slowly and the estuary is steep; the intersection point moves slowly and the tide can keep up. Therefore B and B' are at the same point. If the tide rises rapidly, however, and the estuary is gently sloping, as it is in some rivers (*bottom*), the intersection point will move inshore faster than the shallow-water waves of the tide can move. Therefore B' falls behind B and a difference in water level at the river mouth results. This is the bore.

jump. The elevated region beyond the jump is the accumulation of waves that propagate inward with a velocity equal to that of the flowing water and so are not swept away.

As we have seen, the formation of the hydraulic jump that constitutes a tidal bore requires a high tide and an estuary of the right shape. In addition the tide and the estuary must have the proper relation to each other. This relation can be explained as follows. As the tide rises it flows inshore to cover the previously exposed ground. The level of the tide can be extended horizontally inshore to the point where it intersects the surface of the river. The intersection point moves inshore as the tide rises. In most estuaries the intersection point moves inshore relatively slowly and the waves of the tide can propagate as fast as the intersection point moves inshore. In such estuaries no bore forms. In some instances, however, the estuary has a gradual slope and the intersection point moves inshore faster than the tidal waves can propagate. When the velocity of the shallow-water waves of the tide falls below that of the intersection point, the tide wells up higher than the river level and forms a bore.

As the tidal bore moves upstream it must move faster than the current of the river; otherwise it would be swept downstream. To an observer on the bank the bore is seen to move with a speed equal to the difference between the propagation speed of the hydraulic jump and the speed of the river.

The shape and the dynamics of the tidal bore, however, are not affected by the speed of the river. Indeed, the bore is most conveniently studied in a coordinate system that moves at the same speed as the bore, so that the bore appears to be stationary. In such a coordinate system the bore can be described by means of the Froude number (F), named in honor of the 19th-century English civil engineer William Froude. The Froude number is the square root of the ratio of the kinetic energy of the moving water to the gravitational energy in the waves. If F is smaller than 1, the flow is subcritical; if it is greater than 1, the flow is supercritical.

It turns out that the Froude number is equal to the ratio of the speed of the waves behind the bore to the speed of the waves on the undisturbed river in front of the bore. This fact yields a simple method of calculating F when the height of the bore is much less than the depth of the river. Since the speed of the waves on each side of the bore is proportional to the square root of the depth of the water, F is equal to the square root of the ratio of the depth behind the bore to the depth in front of it.

The Froude number is a compact description of the appearance and shape of



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a tidal bore. When F is between 1.0 and 1.7, an undular bore results; the advancing tide moves gently upriver. Only in the shallows near the river bank, where F is higher, does the bore break. When F is greater than 1.7, all bores are breaking bores. Between 1.7 and 2.5 the bore is called a weak jump; small rollers slide down the leading edge and the water behind the bore is smooth. Between 2.5 and 4.5 the jump is called oscillating; a vertical jet oscillates between the river bottom and the surface and generates surface waves with a large amplitude. Between 4.5 and 9.0 the jump is called steady; the leading edge is turbulent but the surface of the trailing edge can be smooth. Above 9.0 the jump is called strong; its energy is dissipated rapidly and the bore moves upstream in a thrashing, jerky way, with high-speed jets extending ahead of the main jump.

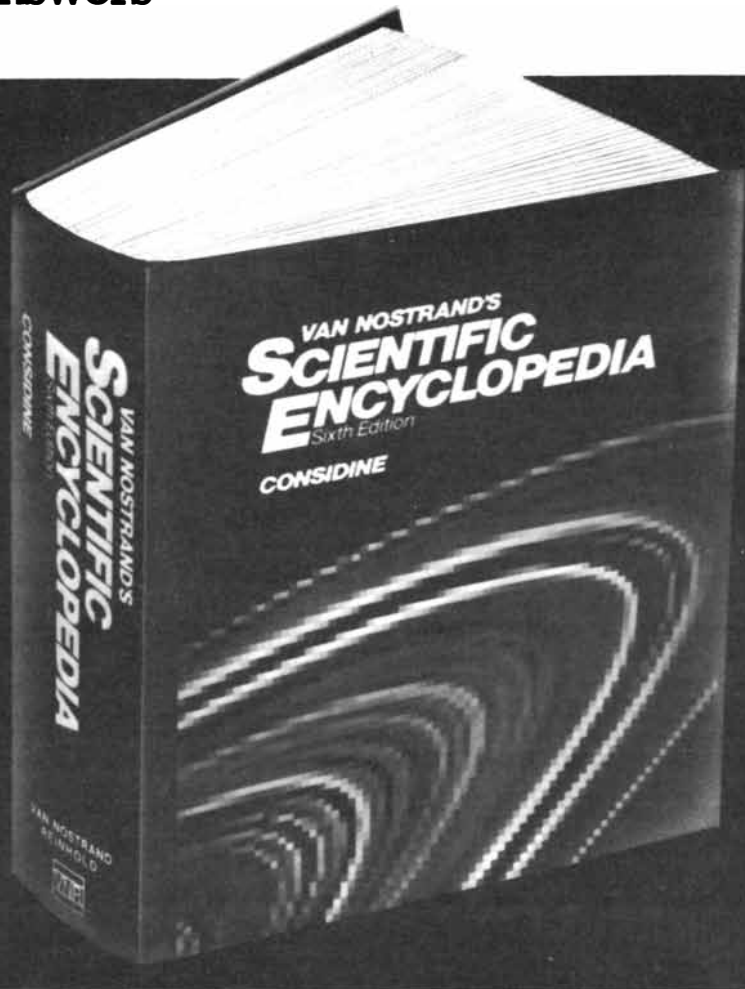
A common property of tidal bores is that their front is neither straight nor uniform. Some parts of the wave front lag behind the main wave and some propagate ahead. The cause of the variation is the change in the depth of the river from bank to bank. The parts of the wave in deeper water propagate faster and have a smaller Froude number. As a result bores are often led by a low undular wave; where there is a local shallow spot near the shore the bore will be higher and can be breaking.

If bores are dispersionless waves, how can they end? Two mechanisms drain the energy of the bore as it moves upstream. One is friction between the water and the bottom; such friction converts the kinetic energy of the moving water into heat. The other is viscosity, which is much like friction between adjacent molecules. Viscosity in the breaking wave transforms the propagation energy into turbulence and ultimately into heat. In addition, in rivers that become deeper or wider inland the bore can disappear because the funneling action that raised it in the estuary is reversed. When enough energy is dissipated, the speed of the bore becomes less than that of the river and the bore is carried downstream.

Bores, like many other phenomena on the earth, are vulnerable to the activities of man. A powerful bore known as the burro, which was as much as 15 feet high, once regularly went up the Colorado River. Over the past 15 years, however, agricultural water control and silting have transformed the mouth of the river. As a result the bore has been greatly reduced and is usually little more than a ripple lost in the river's other waves. The burro is still occasionally reported; other bores have been lost altogether. Still, the wonderful sight of a tidal bore surging upstream can be seen in many places by those willing to follow the new or full moon to where the river meets the sea.

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