U.S. GEOLOGICAL SURVEY CIRCULAR 1022

Catalog of Worldwide Tidal Bore Occurrences and Characteristics

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Catalog of Worldwide Tidal Bore Occurrences and Characteristics

By SUSAN BARTSCH-WINKLER and DAVID K. LYNCH

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Catalog of Worldwide Tidal Bore Occurrences and Characteristics

By Susan Bartsch-Winkler *and* David K. Lynch[1]

Abstract

Documentation of tidal bore phenomena occurring throughout the world aids in defining the typical geographical setting of tidal bores and enables prediction of their occurrence in remote areas. Tidal bores are naturally occurring, tidally generated, solitary, moving water waves up to 6 meters in height that form upstream in estuaries with semidiurnal or nearly semidiurnal tide ranges exceeding 4 meters. Estuarine settings that have tidal bores typically include meandering fluvial systems with shallow gradients. Bores are well defined, having amplitudes greater than wind- or turbulence-caused waves, and may be undular or breaking. Formation of a bore is dependent on depth and velocity of the incoming tide and river outflow. Bores may occur in series (in several channels) or in succession (marking each tidal pulse). Tidal bores propagate up tidal estuaries a greater distance than the width of the estuary and most occur within 100 kilometers upstream of the estuary mouth. Because they are dynamic, bores cause difficulties in some shipping ports and are targets for eradication.

Tidal bores are known to occur, or to have occurred in the recent past, in at least 67 localities in 16 countries at all latitudes, including every continent except Antarctica. Parts of Argentina, Canada, Central America, China, Mozambique, Madagascar, Northern Europe, North and South Korea, the United Kingdom, and the U.S.S.R. probably have additional undiscovered or unreported tidal bores.

In Turnagain Arm estuary in Alaska, bores cause an abrupt increase in salinity, suspended sediment, surface character, and bottom pressure, a decrease in illumination of the water column, and a change in water temperature. Tidal bores occurring in Turnagain Arm, Alaska, have the hydrological characteristics typical of tidal bores worldwide, and confirm models of turbulence and diffusion in naturally occurring waves described by others.

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[1]Thule Scientific, 22914 Portage Circle Drive, Topanga, CA 90290.

INTRODUCTION

A tidal bore is a tidally generated wave whose amplitude, in some regions, may exceed 6 m (Tricker, 1965; Rowbotham, 1964; Lynch, 1982). Tidal bores occur both in estuarine and freshwater environments. A bore is a solitary wave that typically propagates up a slowly flowing estuary with the incoming tide (fig. 1). Those that ascend the estuary a greater distance than the width of the estuary are contained in this listing, with the exception of the Araguari River bore which forms at sea. Exposed mudflats and broad, beach-like washes which experience a bore-like incoming tide, such as occurs at Mont St. Michel in France, are not included.

Only a few bores have been described in detail (Champion and Corkan, 1936; Waters, 1947; Dalton, 1951; Destriau, 1951; Barnes, 1952; Chitale, 1954; Abbott, 1956; Rowbotham, 1964; Tricker, 1965; Roy, 1972; Jouanneau and Latouche, 1981). Early explorers made accounts of bores that are now primarily of historical interest (Martius, ca. 1837; Moore, 1888, 1893; Branner, 1884; Beaver, 1914). Sykes (1937, 1945) studied the now-rare bore on the Colorado River in Mexico. Many bores are mentioned incidentally in scientific papers and unpublished field reports which discuss other subjects (for example, Maxwell, 1968; Komori, 1979; Amos and Long, 1980; Bartsch-Winkler, 1982; Murphy, 1983; Bartsch-Winkler and Ovenshine, 1984).

Worldwide tidal bore localities document the characteristics of known tidal bores, existing now and in the past, and facilitate locating additional areas where undocumented bores might exist. Unreported bores undoubtedly occur in inaccessible and unpopulated regions and have never been witnessed by scientists;

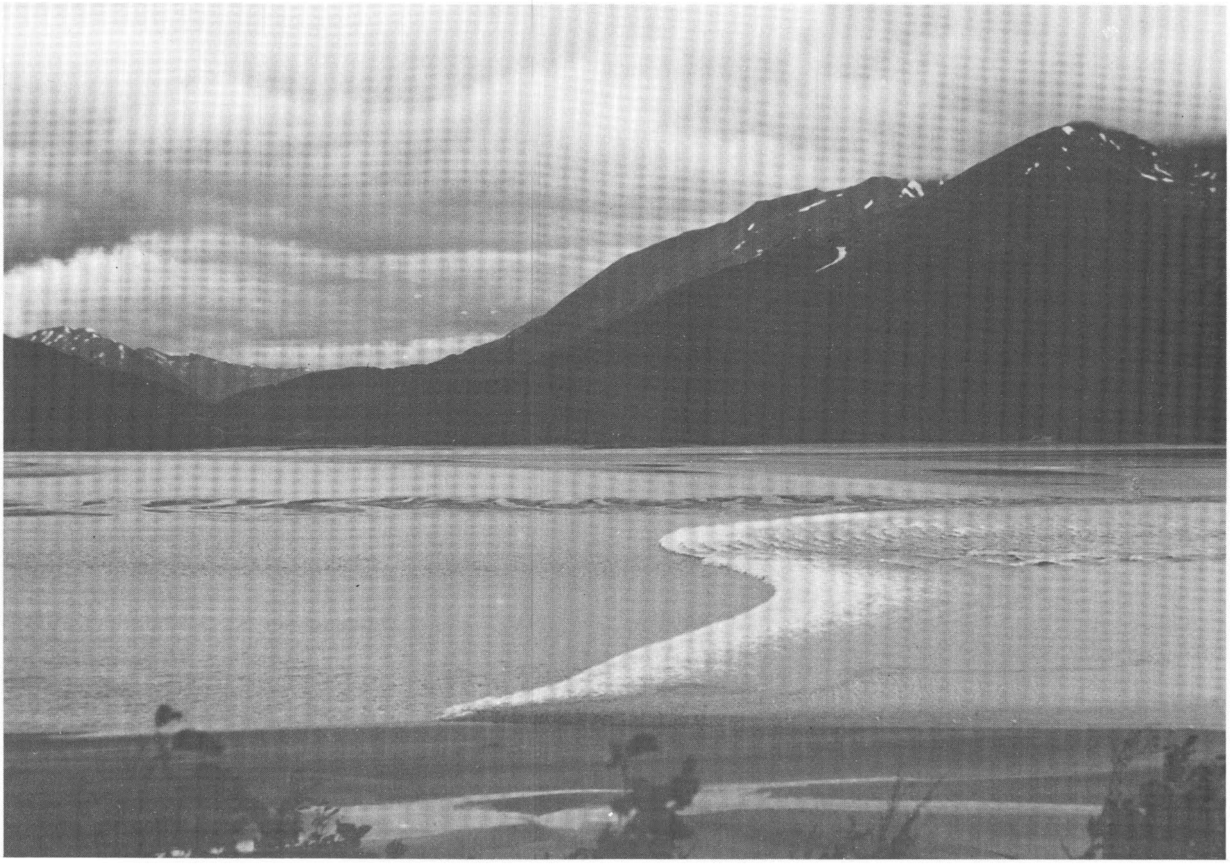

Figure 1. Tidal bore of about 1.5 m amplitude; marks low tide in Turnagain Arm, Alaska. The bore is moving from right to left, followed by the flood tide.

some identified herein may have existed at one time but are now eliminated or diminished by dredging of harbors and channels and otherwise altering the hydraulic characteristics of an estuary. A very large bore once occurred on the Seine River in France, but, in about 1970, was eliminated by harbor dredging at the mouth. The once common (but now rare) bore that occurred in the Gulf of California at the mouth of the Colorado River has been greatly diminished by the reclamation projects on the Colorado River, located many kilometers upstream from the mouth in Arizona and California.

FIELD METHODS AND DATA COLLECTION

Several means were utilized to collect information on tidal bore characteristics and on their worldwide occurrence. These methods include sending questionnaires to agencies and earth scientists, conducting computerized library searches, and undertaking field and laboratory experiments on the Turnagain Arm bore in Alaska.

Survey and Literature Search

Almost 270 questionnaires requesting specific information about bores, tides, and rivers, and published or unpublished documents on these topics, were sent to hydrological, geological, and educational institutions in 108 countries bordering the oceans (table 1). Listings of geological and hydrological organizations were taken from Bergquist and others (1981) and American Geological Institute (1981); when possible, at least three organizations in each country were contacted. A total of 41 percent of the countries responded to the questionnaire.

A literature search on tidal bores was conducted utilizing such computerized indices and sources as GeoRef, Selected Water Resources Publications, Smithsonian Institution, and the Library of Congress. In addition, a request was made for information on tidal bores from attending scientists at the XXI International Congress on Sedimentology, held in Hamilton, Ontario, Canada (Lynch and Bartsch-Winkler, 1982). Certain institutions thought to have such knowledge were contacted for information on specific tidal bores.

ACKNOWLEDGMENTS

This survey could not have been accomplished without the cooperation of the many respondents to the questionnaire and that of colleagues with whom we conferred during the data-gathering phase of the study. We are indebted to The Cousteau Society for providing valuable photographs and films of the Araguari River bore. We especially wish to thank those whose extra effort contributed much to the catalog: J. Baldwin (U.S.A.), John Boon (England), G. Boss (Canada), C. Brossard (France), J. Byrne (U.S.A.), P.N. Cornish (Ireland), C. Desplanque (Canada), B.W. Flemming (South Africa), Stephen G. Gassaway (U.S.A.), A.M. Haigh (England), R.M. Hillman (Australia), V. Josanto (India), C.G. Kershaw (England), Lung-fa Ku (Canada), J.A. Lawrie (Australia), D. Luo (China), Y. Mailvaganam (Malaysia), John McManus (Scotland), Afranio Mesquita (Brazil), A. Mitchell (Australia), Richard Murphy (U.S.A.), P.P. Periera (Brazil), G.S. Quraishee (Pakistan), Yan Quinshang (China), K.S. Richards (England), J. Richardson (England), J. Rottman (England), Ir. A. Shahrizaila (Malaysia), P. Sheehan (Australia), J. Simpson (England), M.A. Sweeney (England), R.B. Thorne (England), S. Tovey (Australia), R.A.R. Tricker (England), P. Valls (France), J. Vasdev (India), H.J. Walker (U.S.A.), G. White (Australia), Michael Woodward (Canada), Shao Xusheng (China), Brian Zaitlin (Canada), D. Zeheng (China), and H. Zengcui (China). We thank J. Simpson and J. Rottman for valuable theoretical discussions on tidal bores, and T.D. Hamilton, J.S. Kelley, and H.S. Schmoll who carefully reviewed the manuscript.

CATALOG OF TIDAL BORES

Figures 2 and 3, respectively, show the worldwide types and ranges of tides (Davies, 1977). Table 2 lists the tidal data collected in the survey arranged alphabetically by river name in each country; figure 4 locates each occurrence on the world map. Tidal information in table 2 includes data on the major bodies of water into which the estuaries flow.

Approximately half the world's coasts have mixed diurnal and semidiurnal tides, or diurnal tides; the rest have semidiurnal tides. Because semidiurnal tides that occur nearly every 12 hours rise approximately twice as fast for the same tide range as diurnal tides that occur nearly every 24 hours, bores are restricted to regions with semidiurnal or nearly semidiurnal tides with ranges in excess of 4 m (figs. 2, 3, 4). Nearly all tidal bores occur in regions of high amplitude (greater than 4 m) semidiurnal tides (table 3). Thus, tidal bores form in regions where the tide influx is rapid. In addition, the fluvial discharge must be relatively slow moving. A requirement for the formation of the hydraulic jump (a sudden change in water height) represented by the bore is that fluvial discharge in the estuary must flow more slowly than the shallow water wave velocity (Tricker, 1965; Lynch, 1982). Therefore, bores typically form on gently sloping riverbeds commonly identified as meandering and having large deltas. Typically, bores occur in settings where the estuary crosses broad lowland regions along the coast, but this characteristic is not limiting. One exception to this is the bore or bores that occur in Turnagain Arm of Upper Cook Inlet, Alaska. Turnagain Arm estuary is surrounded by glaciated peaks of the Chugach Range which exceed 1,200 m within 2 km of tidewater, but it is also a Late Holocene fiord that has been infilled with unconsolidated intertidal sediment. Bore-bearing riverbeds are typically composed of unconsolidated clay, silt, or sand that is easily transported and deposited contemporaneously in relatively broad intertidal zones.

Most bores occur within about 100 km of the estuary mouth even though the tidal effects are evident much farther inland. The deepest inland penetration of bores is apparently in the Amazon Basin where bores on the Capim, Guajara, and Moju Rivers, which flow into the Amazon, occur more than 150 km inland. Due to the large size and great width of the Para River, into which the Capin, Guama, and Moju Rivers flow, and the Amazon River, into which the Guajara River flows, bores may form 100 km inland. Conversely, due to the vast Araguari River delta built into the Atlantic Ocean, an undular bore occurs as much as 10 km offshore from the river mouth (fig. 5).

Tidal bores apparently form at all latitudes, although reports in areas from about lat 60° to 90° N. and 60° to 90° S. are missing. The most northerly region reported in this survey is in upper Cook Inlet, Alaska, at lat 61° N. However, bores are suspected to occur in the Baffin Island region, Canada, at lat 65° N.

This survey is intended to be a general guide to tidal bore occurrence in the world and not an all-inclusive or final documentation. Undoubtedly more tidal bore locations exist than are listed here, but either they occur in remote settings from which no information is available, they are ephemeral, or they are insignificant and go unnoticed by commercial interests. Our information, in some cases, was limited to older or rare published

Table 1. Responses of countries sent questionnaires inquiring about the existence of tidal bores in their country

[(+), tidal bores exist in country; (-), no tidal bores exist in country; undesignated, no reply]

Angola		Guyana		Pakistan	(+)
Argentina	(-)	Haiti	(-)	Panama	(-)
Australia	(+)	Honduras		Peru	(-)
Bangladesh	(+)	Hong Kong	(-)	Philippines	(-)
Belgium	(-)	Iceland		Poland	
Benin		India	(+)	Portugal	
Brazil	(+)	Indonesia	(-)	Qatar	
Burma	(+)	Iran	(+)	Reunion	
Cameroon		Iraq	(+)	Saudi Arabia	
Canada	(+)	Ireland	(+)	Scotland	(+)
Chile	(-)	Israel	(-)	Senegal	(-)
China, People's Rep.	(+)	Ivory Coast	(-)	Sierra Leone	(-)
Colombia	(-)	Jamaica	(-)	Solomon Islands	(-)
Congo		Japan	(-)	Somalia	
Costa Rica	(-)	Kenya		South Africa	(-)
Cuba		Korea, North		Southwest Africa	(-)
Denmark		Korea, South		Spain	
Djibouti		Kuwait		Sri Lanka	
Dominican Republic		Liberia		Sudan	
Ecuador	(-)	Madagascar		Surinam	(-)
Egypt		Malaysia	(+)	Sweden	(-)
El Salvador		Martinique		Taiwan	(-)
England	(+)	Mauritania		Tanzania	
Ethiopia		Mauritius	(-)	Thailand	(-)
Finland	(-)	Mexico	(+)	Togo	
France	(+)	Morocco		Tonga	
French Guiana		Mozambique		Trinidad/Tobago	
Gabon		Netherlands	(-)	U.S.A.	(+)
Gambia		New Caledonia		U.S.S.R.	
Germany, Fed. Rep.	(-)	New Guinea		Uruguay	
Germany, Dem. Rep.		New Zealand	(-)	Vanuatu	(-)
Ghana		Nicaragua		Venezuela	(+)
Greenland	(-)	Nigeria	(-)	Viet Nam	
Guadeloupe		Norway	(-)	Western Samoa	(-)
Guatemala		Oman		Yemen	
Guinea				Zaire	
Guinea-Bissau					

papers, which may be inaccurate today because of changes in the estuary concerned. Much of the data comes from unpublished government documents, obscure scientific publications, popular articles, and reports from knowledgeable lay persons and scientists who took an interest in, and sporadically observed, particular bores. Some tidal bores are known locally by special names unfamiliar to scientists ("pororoca" is the name of the bore on the Amazon River, and "eagre" is the name given to bores in England). In some cases, only one bore in a series of bores that occur along many waterways in a region is well known and publicized, and the others receive no recognition. For example, in Canada the Petitcodiac bore is well reported, though bores on the Maccan, Shubenacadie, Hebert, and Salmon Rivers also occur (all draining to Bay of Fundy; table 2). Several countries consider information on tidal bores as classified, limiting knowledge, in these cases, to older publications. It is also possible that some bores (for example, the Orinoco) do not exist at all, the reports being erroneous or misinterpretations.

The best data on tidal bores result from detailed studies performed as part of a systematic engineering effort to eliminate them. Bores occasionally cause damage to river commerce and, as a result, have become targets for control (Komori, 1979; Zeheng, 1982). Also, tidal bores may have once occurred in rivers that have been dammed for irrigation or flood control, and have, thus, been eliminated. The large bores on the Seine (France), Colorado (Mexico), and Qiantang Jiang (China) have decreased to relative insignificance or have been eliminated by engineering and hydrologic projects.

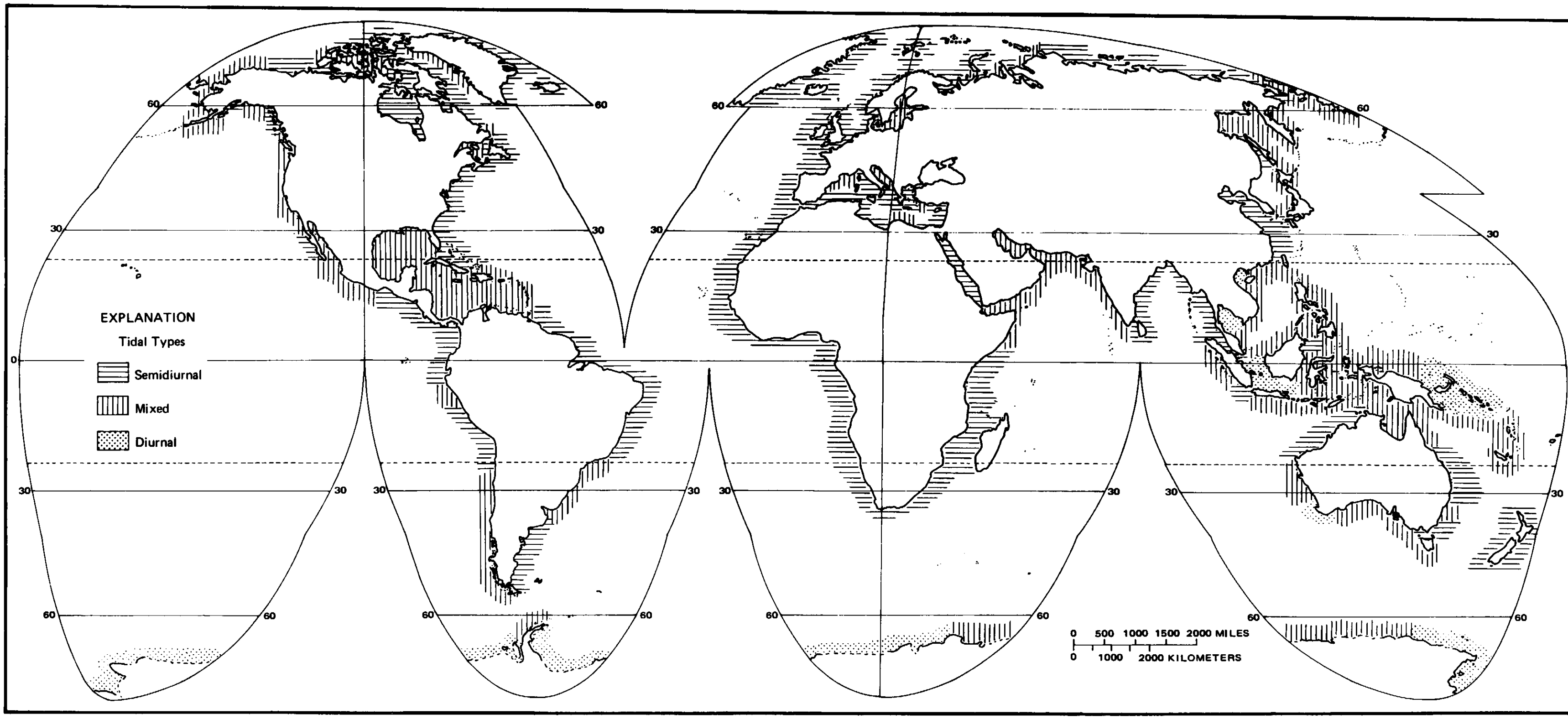

Figure 2. Worldwide distribution of tidal types (modified from Davies, 1980, fig. 32, p. 49).

Table 2. Known tidal bore locations in the world and their characteristics

[Numbers are keyed to map locations shown on figure 4. Where river name is enclosed in parentheses, information source is an historical document or eye-witness account unaccompanied by photography or other documentation. Latitude and longitude of river mouths are approximate and do not represent any officially accepted geographic location. Usual location of the bores is given; where two locations are given, the bore typically forms near first and dissipates near second. References listed include most detailed reports on the specific bore; degree of uncertainty of occurrence is inferred by list of information sources. Leaders (---), no information]

Map No.	River	Location		Tidal information		Characteristics						References[6]
		Latitude	Longitude	Source[1]	Range (m)[2]	Type[3]	Channel[4] w (m)	d (m)	Tidal Bore Location, extent[5]	ht (m)	sp (m/s)	
						Australia						
1	Daly	13°21'S	130°21'E	Timor Sea-I	r, 6-7	s	15	5	30 km from mouth 13°31'S, 130°29'E.	1.5	4-5	*, p.
2	Herbert	22°25'S	149°53'E	Coral Sea-P	r, 10.8	s	30-1,000	0-5	Charon Pt to Banyon Cr---	0.6	---	Maxwell, 1968; Cook and Mayo, 1977.
3	Howard			Timor Sea-I	D, >6	s	---	---		---	---	*.
4	Keep	15°13'S	129°10'E	Timor Sea-I	r, 3.5;D, >6	s	600	0-3	15°45'S, 129°07'E--------	---	---	*.
5	King	15°29'S	128°05'E	Timor Sea-I	D, >6	s	---	---		---	---	Wright and others, 1973.
6	Mickett's			Timor Sea-I	D, >6	s	---	---		---	---	*.
7	Ord	15°01'S	128°13'E	Timor Sea-I	r, 5.9	s	---	---		---	---	Wright and others, 1973.
8	Prince Regent	15°24'S	125°00'E	Timor Sea-I	D, >6	s	---	---		---	---	*.
9	Victoria	15°00'S	129°41'E	Timor Sea-I	D, >6	s	---	---		---	---	Bird, 1972.
						Bangladesh						
10	(Brahmaputra)	24°12'N	091°48'E	B Bengal-I	D, 2-4	s	---	---	---	---	---	Branner, 1884.
11	(Ganges)	22°00'N	090°00'E	B Bengal-I	D, 2-4	s	---	---	---	5-6	---	Darwin, 1898.
12	Meghna	23°00'N	090°30'E	B Bengal-I	D, 2-4	s	---	---	---	---	---	NOAA, 1982a.
						Brazil						
13	Amapa	02°10'N	050°58'W	-A	D, 4-6	s	---	---		4	---	*.
14	Amazon	00°14'N	050°45'W	-A	D, 4-6	s	var	var	C Norte, Ile Verte, Ile Norte, Ile Cazeau, C Macau, Ile Caviana.	1-3	---	Branner, 1884; Magalhaes, 1943; Clancy, 1968; McIntyre, 1972; *.
15	Araguari	01°14'N	049°55'W	-A	D, 4-6	s	500-3,000	0-5	20 km upstream; reputed to form offshore.	2.0-4.5	---	Lynch, 1982; NOAA, 1982b; Murphy, 1983; *.
16	Capim	01°40'S	047°47'W	Guama R Para R B de Marajo -A	---	s	---	---	Capim; confluence of Guama R and Capim R.	---	---	Martius, c. 1837; Clancy, 1968; *.
17	Cassipore	03°57'N	051°05'W	-A	D, 4-6	s	---	---	---	2.0	---	*.
18	Guajara	01°47'S	053°04'W	Amazon	---	s	---	---	---	---	---	Wylie, 1979; NOAA, 1982b.
19	Guama	01°20'S	048°31'W	B de Marajo -A	---	s	---	---	Confluence of Guama R and Capim R.	4.5, spring		Martius, 1837; NOAA, 1982b; *.
20	Mearim	03°09'S	044°58'W	-A	D, 4-6	s	---	---	---	1.2	---	*.
21	Moju	01°41'S	048°27'W	Para R B de Marajo -A	---	s	---	---	---	3	---	*.
22	(Tocantins)	01°45'S	049°12'W	Para R B de Marajo -A	---	s	---	---	---	---	---	*.

Map No.	River	Location: Latitude	Location: Longitude	Tidal information: Source[1]	Tidal information: Range (m)[2]	Type[3]	Channel[4]: w (m)	Channel[4]: d (m)	Tidal Bore: Location, extent[5]	Tidal Bore: ht (m)	Tidal Bore: sp (m/s)	References[6]
									Burma			
23	Pegu	16°29'N	096°19'E	Andaman Sea B Bengal-I	D, 4-6	s	---	---	---	3	---	NOAA, 1982a.
24	Sittang	17°24'N	096°53'E	Andaman Sea B Bengal-I	D, 4-6	s	---	---	---	0.5	---	NOAA, 1982a.
									Canada			
25	Hebert	45°47'N	064°18'W	B Fundy, -A	St. John,>13	s	---	---	Amherst Pt to Hebert R---	0.3	---	*, p.
26	Maccan	45°47'N	064°18'W	B Fundy, -A	St. John,>13	s	---	---	Amherst Pt to Athol------	0.3	---	*, p.
27	Petit-codiac	45°52'N	064°35'W	B Fundy, -A	St. John,>13 r, 17.5	s	600	dry at MLW	Dover to 10 km upstream from Moncton; Bore View Park at Moncton.	1.0-1.5	---	Doodson and Warburgh, 1941; Dalton, 1951; Mitchell, 1968; NOAA, 1982c; *, p.
28	Salmon	45°21'N	063°24'W	B Fundy, -A	St. John,>13 r, 17.5	s	---	---	Truro---------------------	1.0	4-5	Redfield, 1981; *, p.
29	Shubena-cadie	45°09'N	064°14'N	B Fundy, -A	St. John,>13 r, 16.3	s	---	---	---	0.3	---	Amos and Long, 1980;Dalrymple and others, 1982; NOAA, 1982c.
									China			
30	Qiantang-Jiang	30°15'N	120°49'W	East China Sea -P	D, 4-6	s	2,000-10,000	2-10	Jianshan to 40 km upstream from Hangzow; daily.	1-3	5-12	Moore, 1888; 1893; Zeheng, 1982; NOAA, 1982a.
31	Zhu-Jiang (Pearl)	22°00'N	114°00'E	East China Sea -P	D, 2-4	m	---	---	Hong Kong to Zhao-ching, Shi-chiao, Shi-long; bores in tributaries.	---	---	*.
									England			
32	Dee	53°21'N	003°15'W	Liverpool B Irish Sea, -A	D, >6	s	---	---	---	---	---	Doodson and Warburgh, 1941; Chitale, 1954; Zerbe, 1972.
33	Kent	54°11'N	002°52'W	Morecambe B Irish Sea, -A	D, >6	s	---	---	---	---	---	Tricker, 1965; *.
34	Mersey	53°27'N	003°02'W	Liverpool B Irish Sea, -A	D, >6	s	---	---	---	---	---	Tricker, 1965; Clancy, 1968; Zerbe, 1972; *, p.
35	Ouse	53°42'N	000°42'W	Humber R, North Sea, -A	Blacktoft, 6-7	s	---	---	---	---	---	*.
36	Parrett	51°13'N	003°01'W	Bristol Ch, -A	Sharpness, >10	s	---	---	Near Bridgewater---------	0.5	---	Chitale, 1954; Tricker, 1965; NOAA, 1982c; *, p.
37	Severn	51°30'N	002°45'W	Bristol Ch, -A	Sharpness, >10	s	---	---	Severn Bridge, Gloucester	1-2	2-6	Waters, 1947; Abbott, 1956; Rowbotham, 1964; Tricker, 1965; Lynch, 1982; *.
38	Trent	53°42'N	000°42'W	Humber R, North Sea, -A	Blacktoft, 6-7	s	---	---	Burton Strather (mi. 6) to Gainsborough (mi. 46).	1-2	6	Champion and Corkan, 1936; Doodson and Warburgh, 1941; Barnes, 1952; Tricker, 1965; *; p.
39	Wye	51°37'N	002°41'W	Bristol Ch, -A	Sharpness, >10	s	---	---	---	---	---	Darwin, 1898; Doodson and Warburgh, 1941.

Table 2. Known tidal bore locations in the world and their characteristics—Continued

Map No.	River	Location: Latitude	Location: Longitude	Tidal information: Source[1]	Tidal information: Range (m)[2]	Type[3]	Channel[4]: w (m)	Channel[4]: d (m)	Tidal Bore: Location, extent[5]	Tidal Bore: ht (m)	Tidal Bore: sp (m/s)	References[6]
						France						
40	(Charent)	45°47'N	001°06'W	B Biscay, -A	D, 4-6	s	---	---	---	---	---	*.
41	(Coues-non)	48°39 N	001°30'W	G St. Malo, English Ch, -A	D, >6	s	---	---	---	---	---	*.
42	Dordogne	45°02'N	000°35'W	Gironde R B Biscay, -A	---	s	---	---	Ambes I to Vignonnet; small bore in Isle R.	var	1.0	Destriau, 1951; Jouanneau and Latouche, 1981; *, p.
43	Garonne	45°00'N	000°35'W	Gironde R B Biscay, -A	---	s	---	---	Bordeaux to Cadillac-----	---	---	Destriau, 1951; Jouanneau and Latouche, 1981; *, p.
44	Gironde	45°31'N	001°00'W	B Biscay, -A	D, 4-6	s	---	---	Below Bec D'Ambes, Canal Macau.	---	---	Destriau, 1951; Jouanneau and Latouche, 1981; *, p.
45	Orne	49°19'N	000°13'W	B Seine, English Ch, -A	D, >6	s	---	---	---	---	---	Defant, 1958; Wylie, 1979; *.
46	Seine	49°26'N	000°20'E	B Seine, English Ch, -A	D, >6	s	---	---	LeHavre to Rouen; reduced by engineering works.	0.5, spring	---	Tricker, 1965; *, p.
47	(Vilane)	47°30'N	002°26'W	B Biscay, -A	D, >6				---	---	---	*.
						India						
48	Hooghly	22°00'N	88°07'E	B Bengal, -I	Saugor (5.6)	s	700-1,000	4-9	Hooghly Pt to Balagarh---	2.0; spring	7.5	Chitale, 1954; Roy, 1972; NOAA, 1982a; *.
49	Mahi	22°15'N	72°30'E	G Cambay, Arabian Sea,-I	D, 4-6	m	---	---	---	---	---	*.
50	Narmada	21°36'N	72°53'E	G Cambay, Arabian Sea,-I	D, 4-6	m	---	---	---	---	---	*.
						Iran and Iraq						
51	(Shat el Arab)	29°58'N	48°30'E	Persian G Arabian Sea,-I	D, 2-4	m	---	---	---	---	---	Waters, 1946.
						Ireland						
52	(Cashen)	52°29'N	009°41'W	St George, -A	D, 4-6	s	---	---	---	0.5-1.0		*.
53	(Suir-Barrow)	52°08'N	006°58'W	-A	D, 4-6	s	---	---	---	0.5-1.0		*.
						Malaysia (Sarawak)						
54	Lupar	01°38'N	110°58'E	South China Sea, -P, I	D, 2-4	m	---	---	Lingga to Lui-----------	1.0	5.0	Maugham, 1949; Komori, 1979.
55	Sadong	01°38'N	110°48'E	South China Sea, -P, I	D, 2-4	m	---	---	Buluku to Sebamban-------	---	---	Komori, 1979.
56	Samarahan	01°50'N	110°44'E	South China Sea, -P, I	D, 2-4	m	---	---	Malaya to New Samarahan--	1.0	5.0	Komori, 1979.
57	Saribas	01°45'N	111°05'E	South China Sea, -P, I	D, 2-4	m	---	---	Supa to Padah------------	---	---	Komori, 1979.

Map No.	River	Location: Latitude	Location: Longitude	Tidal Information: Source[1]	Tidal Information: Range (m)[2]	Type[3]	Characteristics: Channel[4] w (m)	Channel[4] d (m)	Tidal Bore: Location, extent[5]	Tidal Bore: ht (m)	Tidal Bore: sp (m/s)	References[6]
									Mexico			
58	Colorado	31°40'N	114°37'W	Sea of Cortez	r, 7	m	---	---	Formerly Montague I to El Mayor.	5-6	---	Gordon, 1924; Sykes, 1937; 1945; Waters, 1946; *, p.
									New Guinea (Papua)			
59	Aramia	08°03'S	143°40'E	Coral Sea, -P	D, 2-4	m	---	---		1.0; spring	---	Beaver, 1914; *.
60	Bamu			Coral Sea, -P	D, 2-4	m	---	---	---	---	---	Beaver, 1914; *.
61	Fly	08°30'S	143°27'E	Coral Sea, -P	D, 2-4	m	---	---	Domori I to Strickland R	2.0; spring	---	Blake, 1972; MacKay, 1976.
									Pakistan			
62	(Indus)	23°55'N	67°53'E	Arabian Sea, -I	r, 3.3; D, 4-6	m	1,000	10	---	2.0	---	Doodson and Warburgh, 1941; Clancy, 1968; Zerbe, 1972.
									Scotland			
63	Forth	56°05'N	003°00'W	North Sea, -A	r, 5.5; D, 4-6	s	---	---	Near Allon---------------	0.1	---	Clancy, 1968.
64	Solway Firth	54°55'N	004°30'W	Irish Sea, -A	D, >6	s	---	---	---	---	---	Doodson and Warburgh, 1941; Chitale, 1954; Clancy, 1968; Zerbe, 1972.
									United States			
65	Knik Arm	61°15'N	150°00'W	Cook Inlet, G Alaska, -P	Anchorage, 11.5	s	---	---	Knik village; simultaneous bores in tidal channels.	0.2 daily	>4	Bartsch-Winkler, 1982; NOAA, 1982d; Bartsch-Winkler and Ovenshine, 1984; p.
66	Turnagain Arm	61°00'N	150°00'W	Cook Inlet, G Alaska, -P	Anchorage, 11.5	s	---	---	Fire I to Twentymile R; simultaneous bores in tidal channels.	1.5 daily	>4	Bartsch-Winkler and Ovenshine, 1984; Bartsch-Winkler and Schmoll, 1984; p.
									Venezuela			
67	(Orinoco)	09°00'N	061°30'W		D, 4-6	s	---	---	---	----	---	*.

[1] I, Indian Ocean; A, Atlantic Ocean; P, Pacific Ocean; B, Bay (of); R, River; G, Gulf (of); Ch, Channel.
[2] Spring tidal range at the indicated location or station; r, river mouth; D, information from Davies, 1980; >, greater than.
[3] s, semidiurnal tide; m, mixed tide (from Davies, 1980).
[4] w, width; d, mean depth; var, variable; MLW, mean low water.
[5] Cr, Creek; Pt, Point; C, Canal; R, River; I, Island; B, Bay.
[6] *, data obtained from unpublished material or survey response; p, photograph of bore in authors' files or published in cited reference.

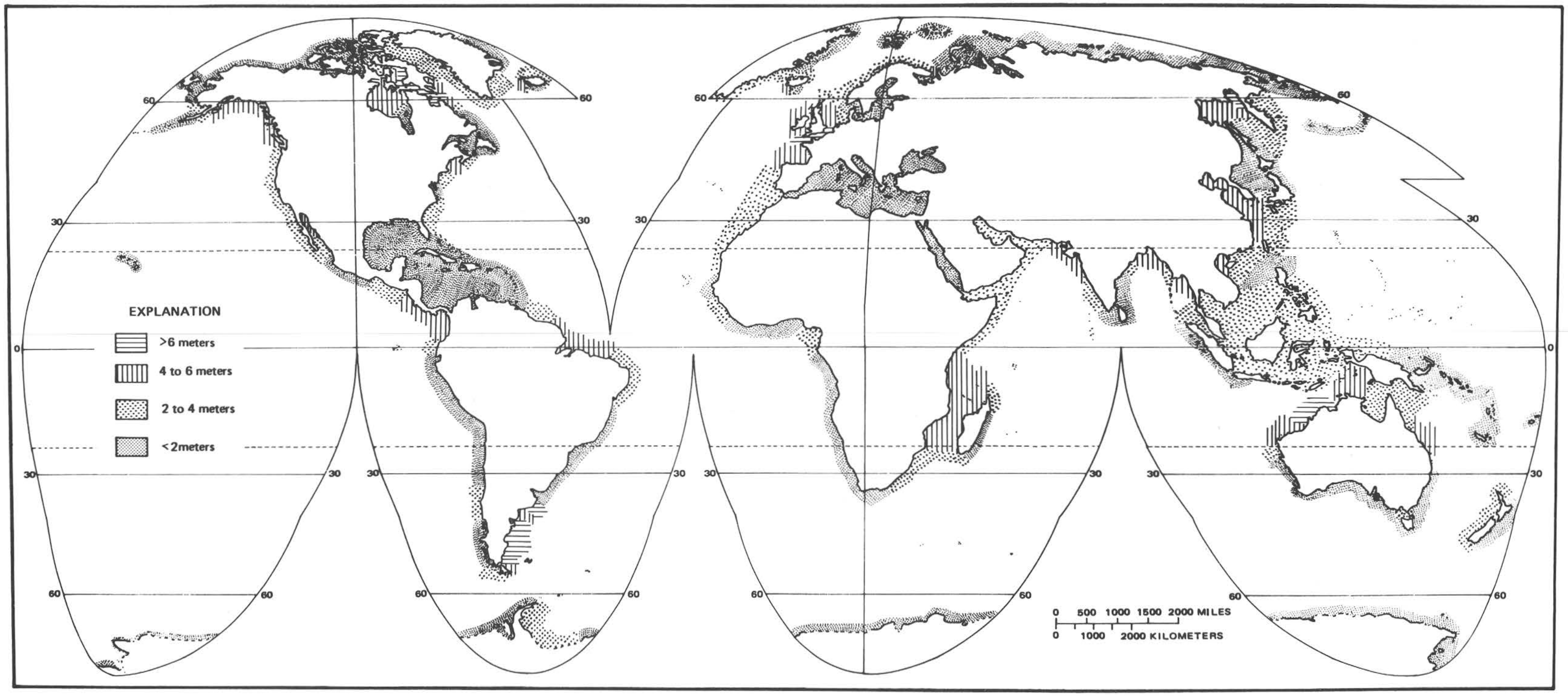

Figure 3. Worldwide distribution of tidal range, given in meters at springs (modified from Davies, 1980, fig. 33, p. 51).

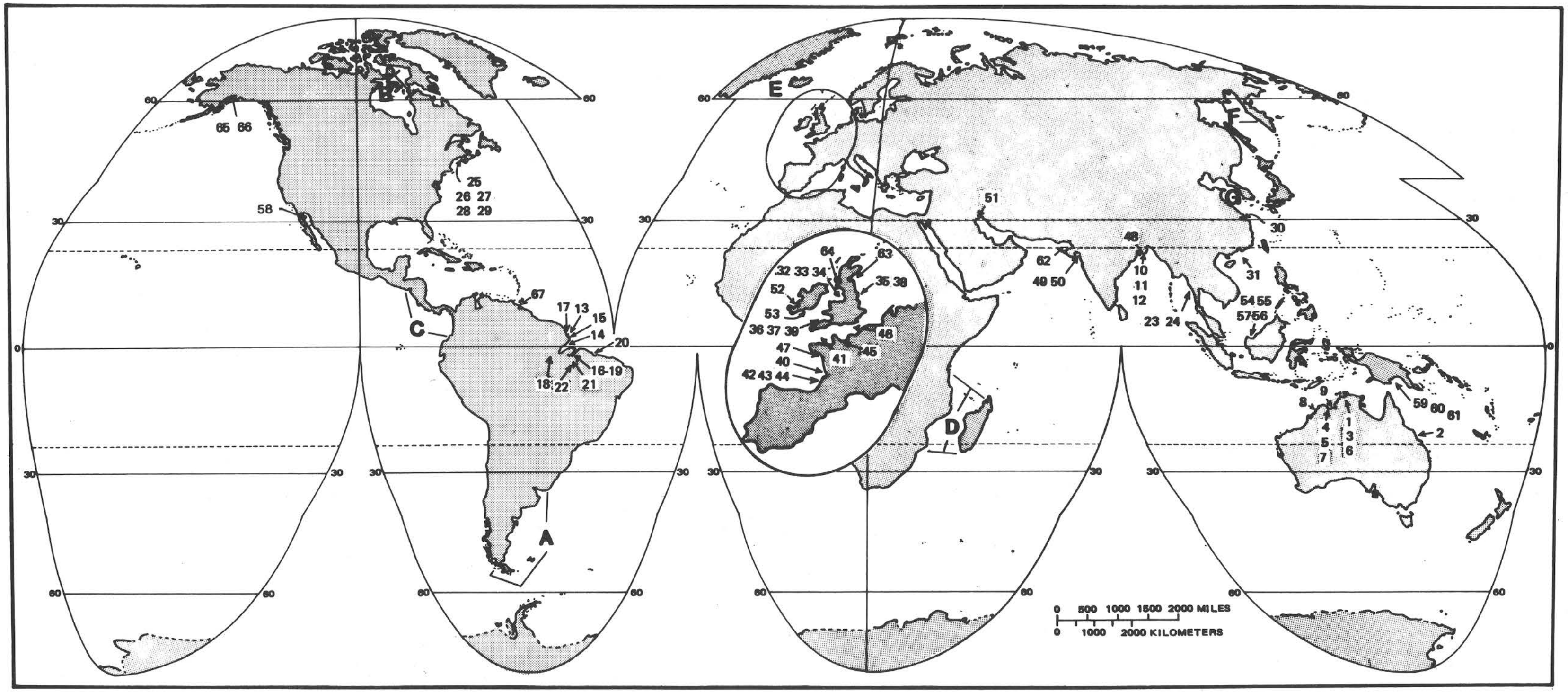

Figure 4. Worldwide distribution of tidal bores. Numbers are keyed to locations in table 2. A–G show regions where additional or undocumented bores are likely to occur.

Table 3. Bore-producing regions classified according to tidal type

	Country	Tidal body	Ocean
		Semidiurnal tides	
1.	U.S.A.------	Cook Inlet----------	Pacific.
2.	China-------	East China Sea------	Pacific.
3.	Australia---	Timor Sea-----------	Indian.
4.	New Guinea--	Coral Sea-----------	Pacific.
5.	Burma-------	Bay of Bengal-------	Indian.
6.	Bangladesh--	Bay of Bengal-------	Indian.
7.	India-------	Bay of Bengal-------	Indian.
8.	England and Ireland.	North Sea, Irish Sea, English Channel.	Atlantic.
9.	Canada------	Bay of Fundy--------	Atlantic.
10.	Brazil------	Amazon River--------	Atlantic.
		Mixed tides	
11.	Mexico------	Sea of Cortez-------	Pacific.
12.	Malaysia----	South China Sea-----	Pacific.
13.	India-------	Arabian Sea---------	Indian.
14.	Pakistan----	Arabian Sea---------	Indian.

The data display a large variation in tidal bore characteristics, in part due to the diverse sources and to the various estuarine settings. In some cases, estuary mouths are not well defined and tidal stations are at a distance from them, resulting in only approximate tidal information. Properties of tidal bores may change in any given location from one year, season, month, or week, to the next. Certain tidal bores may form only during specific times of the lunar monthly cycle (for example, during spring tides, when tide range is the highest). Deposition and erosion by the river may result in a change in channel configuration. River outflow may increase at certain times of the year, changing the ratio of outflow to inflow. Thus, tidal bore occurrence is unpredictable, in some cases, because the formation of the wave depends on such variable properties as tide range, amount and velocity of runoff and inflow, and channel depth and configuration.

TIDAL BORE CHARACTERISTICS

Tidal rhythms in shallow estuaries are asymmetric in time due to deceleration of flood current speeds caused by bottom friction and the adverse outflow current; that is, the length of time required for the flood cycle is less than the time required for the ebb cycle. At points further up the estuary this asymmetry becomes progressively pronounced; flood cycle duration becomes shorter and ebb cycle duration grows longer. The result of this fact is that the water rises faster than it falls, inferring faster flood current speed. In extreme cases, the first flood stage (at low tide) occurs as a bore. Bores typically occur in series, moving simultaneously up closely spaced river systems or intertidal channels within an estuary with the incoming tide. They also may occur in succession within a tidal channel, marking tidal pulses or plateaus following the initial pulse, each separated by a bore.

Initially, the bore may be an impulsive influx of brackish or fresh water depending on the accumulation of fresh water at the estuary mouth prior to the turn of the tide, but rapid increase in salinity occurs at any given location shortly after the bore passes (for example, Roy, 1972; Bartsch-Winkler and others, 1985). The bore also causes an abrupt increase in turbidity, temperature, surface structure, and bottom pressure at any given location, and, of course, flow direction is reversed after passage of the bore. The kinetic energy of bores is partially dissipated within the channel and at the shoreline, causing rapid erosion and consequent increase in suspended load.

A tidal bore, a hydraulic jump, forms in response to the increased shallowing in the estuary upstream from the mouth, producing disequilibrium in the opposing energy levels of the incoming tide and the river outflow. In high tide range areas with the proper characteristics, a bore is the leading edge of the incoming tide and, at various locations in the estuary, the bore may be either turbulent (breaking, fig. 1) or undular (nonbreaking, fig. 5). The form of the bore depends on the ratio of the water depth on either side of the bore (downstream or oceanward depth/upstream or landward depth). If the ratio is small or close to unity, the form is nonbreaking; as it nears a ratio of 1.4, the form becomes breaking (Tricker, 1965; Lynch, 1982). Most bores change form and decrease in height as they move upstream into shallower water due to increase in friction and due to change in the bottom configuration of the estuary.

Numerous smaller waves (whelps) may form immediately behind a bore (fig. 5). Where the bottom configuration and river depth remain relatively constant, whelps increase in number and propagate in time downstream (oceanward) relative to the leading edge (Favre, 1935; Benjamin and Lighthill, 1954). Whelps, because they have less height, do not propagate as rapidly as the larger leading wave and are left behind to eventually dissipate.

The surface transverse (shore-to-shore) profile of a bore depends on the depth profile of the channel and the flow velocity in the river, with those portions of the bore in deeper water propagating faster than those in shallower water (fig. 6). Where the bottom configuration changes (shallows) upstream, a secondary wave with greater height may form behind the leading wave (because it is in relatively deeper water). This secondarily formed wave may temporarily propagate faster than the leading wave. Also, since the bore propagates perpendicular to the leading edge, the near-shore parts

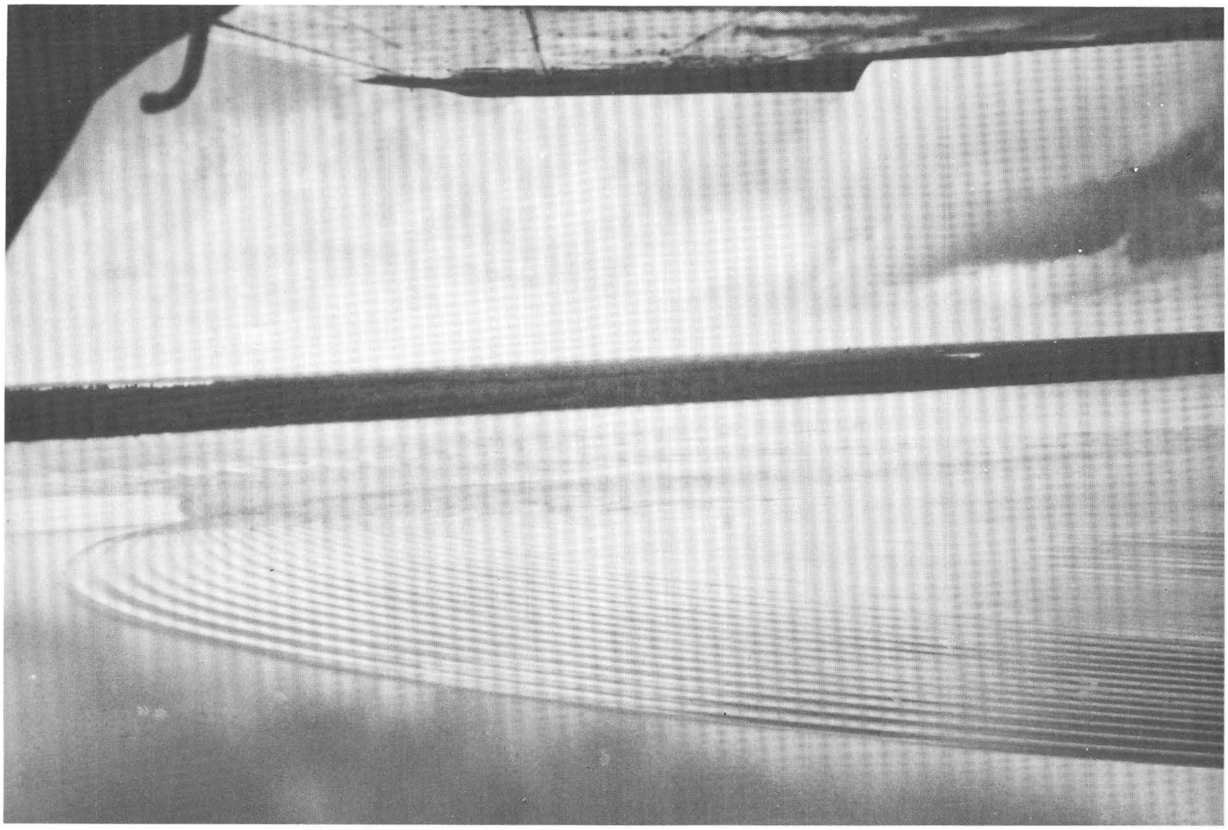

Figure 5. Undular bore and whelps near the mouth of Araguari River, Brazil. View is oblique toward mouth from airplane at approximately 100 ft altitude.

develop a transverse velocity component and approach the shore obliquely. Refraction and reflection of the wave continuously transfer energy between deeper parts of the river and shallower parts. The effects of depth and flow speed variation combined with refraction and reflection lead to subtle and complex patterns in transverse profile; bores may get larger, smaller, and, in some cases, dissipate in one area, only to reappear in another.

Bores reach their maximum height soon after formation, and decay gradually upstream due to bottom friction and shore break (Roy, 1972). The average amplitude of tidal bores is about 1 m, but they range in amplitude from 0.2 to 6.0 m. One of the last occurrences of the 6-m-high bore on the Seine River was photographed by Tricker (1965; also see Lynch, 1982) just prior to its eradication by engineering techniques. Bores whose amplitudes are reputed to exceed 6 m have been reported from the Amazon and Qiangtang Rivers (Branner, 1884; Moore, 1888, 1893). Although these are not verified in this report by recent scientific investigations or scaled photographs, they are not rejected, and could well occur or have occurred owing to the variability of bore height and occurrence with season, stage in the lunar month, and frequent change in sediment accumulation within an estuary that will affect bed configuration.

OBSERVATIONS AND EXPERIMENTS IN TURNAGAIN ARM, ALASKA

In Turnagain Arm, Alaska, tidal bores form with each incoming tide (marking low tide), range to 1.5 m in height, and occur throughout the year. In an effort to elucidate and verify tidal bore characteristics, experiments were conducted and measurements were made on various aspects of the Turnagain Arm tidal regime. During July 1982, mixing experiments were carried out on the daily tidal bores in order to observe the surface mixing between pre- and post-passage flow. Lightweight plastic bags containing approximately 10 g of red fluorescein dye and a small sharp rock were dropped from aircraft at 300–600 m altitude near the leading edge

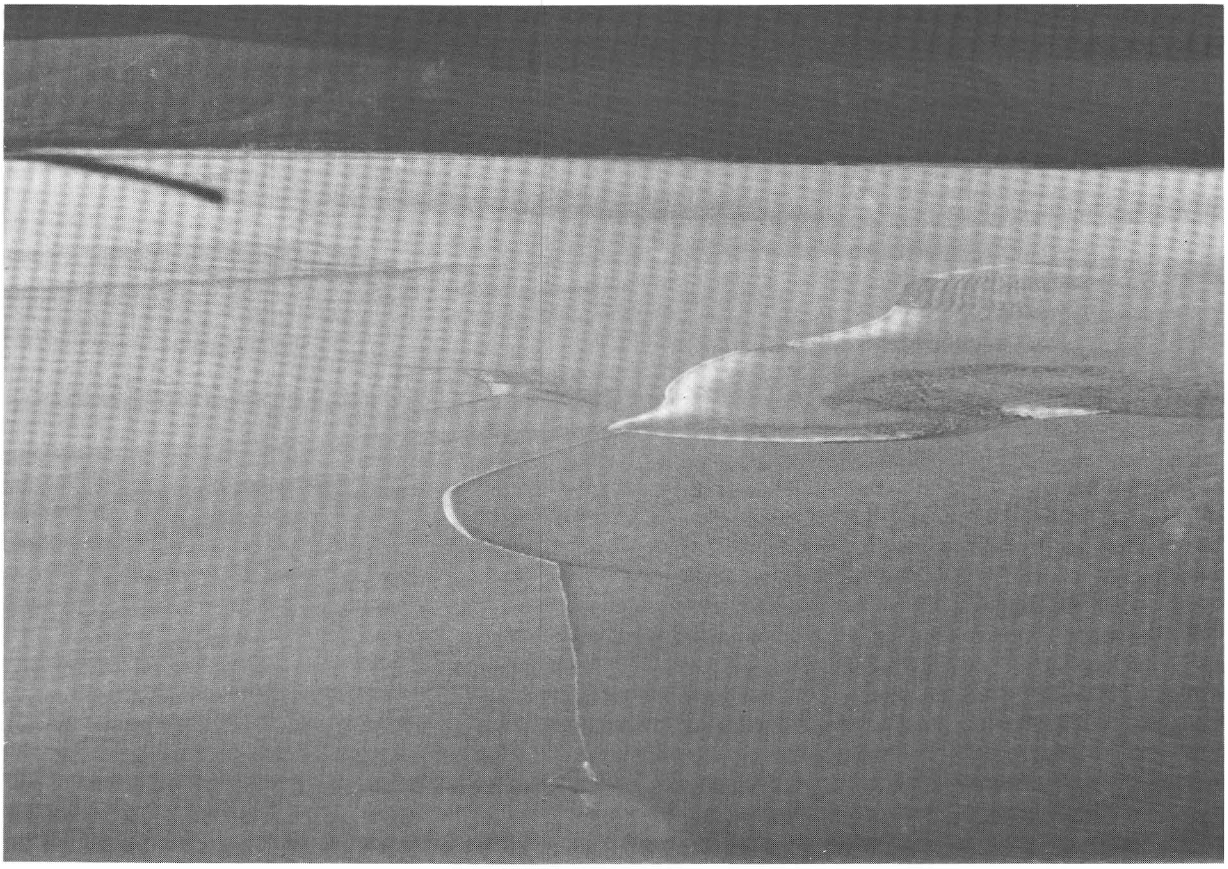

Figure 6. Complex wavefront of the Turnagain Arm bore. The bore is moving from right to left and is followed by flood tide. Photograph taken from airplane at approximately 100 ft altitude.

of 10 tidal bores occurring simultaneously in a single tidal cycle in various channels in the estuary. Dye was released upon impact by the weight and angularity of the rock which broke the plastic bag. The dye was observed and photographed for 2 minutes after impact in bores with estimated heights ranging from 0.3 to 1.5 meters and estimated upstream water depths ranging from nil to 2 m.

Interpretations from dye experiments in Turnagain Arm are limited to surface observations because of the turbidity of the water, rendering it opaque; subsurface or boundary layer dynamics were not visible. In cases where the dye was dropped onto exposed banks adjacent to the channel (upstream depth nil), upon its arrival, the bore carried the dye upstream laterally along the leading edge, presumably by turbulent diffusion; the dye showed little tendency to diffuse with the stream. In these cases, the persistence of the dye at the leading edge of the bores moving over exposed tidal channel banks suggests a trapping of the dye by a horizontal vortex or turbulence in the bore, as described by Longuet-Higgins and Turner (1974) and Madsen and Svendsen (1983). When dye was dropped into upstream water of the tidal channel, however, the amount of mixing (spreading) varied in proportion to upstream water depth. Under these conditions, the dye patch was spread in the direction of stream flow after passage of the bore, showing little lateral mixing; the dye patch moved upstream at a slower rate than the rate of the leading wave, increasing the distance between dye patch and bore. Such streamwise spreading of the dye is consistent with models of bores defined by Tsubaki (1950) and Madsen and Svendsen (1983).

Changes in tidewater were monitored in Turnagain Arm at various tidal stages and cycles during the spring and summer months (May through September) of 1981 and 1982 (Bartsch-Winkler, Emanuel, and Winkler, 1985). In the study, suspended sediment samples were collected from tidal channel surfaces at regular intervals throughout a single tidal cycle during both flood and ebb tide. Specific conductance, water and air temperature, and water level changes were measured from several field sites; grain size analyses were undertaken. All the measurements show immediate change in amount or character soon after passage of the tidal bore.

In addition to a change in direction and a rapid rise in surface level of the water in the tidal channels after passage of the bore, the water also showed a marked increase in suspended sediment. The turbulent wave scours into the channel bottoms, and is a major force in sediment redistribution. The saline wedge, a feature typical of most estuaries caused by freshwater flow atop saltwater, is diffuse in this dynamic hydrologic system. Near the mouth of Turnagain Arm, salinity increased markedly after the change in tide, but near the head of the arm, the salinity patterns were more complex (Bartsch-Winkler and others, 1985). At the head, the arrival of saline water occurred on the flood-dominant south side as much as 30 min after arrival of the bore. Although most streams in the area are glacially derived and frigid, on some days shallowing outflow water had a temperature that was higher due to solar heating than incoming tidewater temperature. Thus, though the freshwater temperature varied with the weather, the temperature of the deeper marine water was more constant. Upon passage of the bore, surface water temperature typically changed by several degrees.

CONCLUSIONS

Settings in which tidal bores occur are generally meandering river systems having gentle gradients, where discharge is relatively slow moving with respect to the tidal flow. The mouths of the rivers typically are large deltas. Tidal bores generally occur within the estuary less than 100 km from the mouth, although the Araguari bore forms offshore. Formation of tidal bores is dependent on the rapid rate in the rise of tide level, so they occur in regions with high tides where the range exceeds 4 m and the tides are semidiurnal or nearly semidiurnal. Tidal bores in this catalog propagate up the tidal estuary a greater distance than the width of the estuary. In some places in the world, tidal bores have been purposely eradicated because they have caused havoc in port areas.

Tidal bores are solitary, tidally generated, naturally occurring, moving waves that range from 0.2 to 6.0 m in height. They have a greater amplitude than wind- or turbulence-caused waves. The wave is undular if the ratio of downstream to upstream depth is less than about 1.4; greater than that, the wave is breaking. The transverse profile of a tidal bore changes with the depth configuration of the channel up which it moves and with the depth and velocity of incoming tidewater and river outflow. Subtle variations due to the effects of refraction and reflection along the shore also may take place. Bores may form as initial waves of the flood tide, and may occur in several channels simultaneously, or as successive waves that identify tidal pulses or plateaus. The speed of a bore is faster in deeper water than in shallower water. Refraction and reflection of the wave at the channel edges transfer energy from deeper to shallower water. Whelps, slower moving, undular waves, may form behind and follow the bore.

Tidal bores occur or have occurred throughout the world in at least 67 locations in 16 countries. Areas (see fig. 4) favorable for tidal bore occurrence but where no occurrences are documented, or areas where there may be additional occurrences to the ones reported, include: (A) Argentina from Montevideo to Tierra del Fuego, (B) northern Canada in the region of lower Baffin Island and upper Hudson Bay, (C) Central America along the Pacific Coast from Guatemala to Colombia, (D) southeastern Africa and western Madagascar, (E) western Iceland, the United Kingdom, and Northern Europe, (F) northeastern U.S.S.R. in the Sea of Okhotsk west of Kamchatka Peninsula, and (G) North and South Korea in Korea Bay and the Yellow Sea. Such areas are suspect to have bores because they have high tide ranges and semidiurnal tidal characteristics. If bores are never reported from these areas, it will probably be due to the presence of either swiftly moving rivers with steep gradients or ephemeral river systems, both of which generally are associated with mountainous coastlines.

In Turnagain Arm, Alaska, bores occur daily with each incoming tide. They cause an increase in salinity, suspended sediment, surface character, and bottom pressure, a decrease in water illumination due to turbidity, and a change in temperature. Studies of bores show that their behavior corresponds to that modeled for turbulence and diffusion in naturally occurring waves, as has been hypothesized by others.

REFERENCES CITED

Abbott, M.R., 1956, A theory of the propagation of bores in channels and rivers: Proceedings, Cambridge Philosophical Society, v. 52, pt. 2, p. 344–362.

American Geological Institute, 1981, A directory of societies in earth science: Geotimes, v. 26, no. 8, p. 26–35.

Amos, C.L., and Long, B.F.N., 1980, The sedimentary character of the Minas Basin, Bay of Fundy, *in* McCann, S.B., ed., The coastline of Canada: Geological Survey of Canada Paper 80–10, p. 123–152.

Barnes, F.A., 1952, The Trent Eagre: University of Nottingham, Survey 3, no. 1, pages not available.

Bartsch-Winkler, Susan, 1982, Physiography, texture, and bedforms in Knik Arm, Upper Cook Inlet, Alaska, during June and July, 1980: U.S. Geological Survey Open-File Report 82–464, 6 p.

Bartsch-Winkler, Susan, Emanuel, R.P., and Winkler, G.R., 1985, Reconnaissance hydrology and suspended sediment analysis, Turnagain Arm estuary, Upper Cook Inlet, *in* Bartsch-Winkler, Susan, ed., The United States Geological Survey in Alaska—Accomplishments during 1984: U.S. Geological Survey Circular 967, p. 48–52.

Bartsch-Winkler, Susan, and Ovenshine, A.T., 1984, Macrotidal subarctic environment of Turnagain and Knik Arms, Upper Cook Inlet, Alaska—Sedimentology of the intertidal zone: Journal of Sedimentary Petrology, v. 54, no. 4, p. 1221–1238.

Bartsch-Winkler, Susan, and Schmoll, H.R., 1984, Guide to late Pleistocene and Holocene deposits of Turnagain Arm: Anchorage, Alaska Geological Society, 70 p.

Beaver, W.N., 1914, A description of the Girara district, Western Papua: Geographical Journal, v. 43, p. 407–413.

Benjamin, T.B., and Lighthill, M.J., 1954, On cnoidal waves and bores: Proceedings of the Royal Society of London, A224, p. 448.

Bergquist, W.E., Tinsley, E.J., Yordy, L., and Miller, R.L., 1981, Worldwide directory of national earth-science agencies and related international organizations: U.S. Geological Survey Circular 843, 87 p.

Bird, E.C.F., 1972, Coasts: Melbourne, Australian National University Press, 246 p.

Blake, D.H., 1972, Western District, *in* Ryan, P., ed., Encyclopedia of Papua and New Guinea: Melbourne University Press, 1187 p.

Branner, J.C., 1884, The "pororoca," or bore of the Amazon: Science, v. 4, p. 488–490.

Champion, H.H., and Corkan, R.H., 1936, The bore in the Trent: Proceedings of the Royal Society of London, v. A154, p. 158–180.

Chitale, S.V., 1954, Bores on tidal rivers with special reference to Hooghly: Irrigation and Power, v. 2, no. 1, p. 110–120.

Clancy, E.P., 1968, The tides—Pulse of the Earth: Garden City, N.Y., Doubleday and Co., 228 p.

Cook, P.J., and Mayo, W., 1977, Sedimentology and Holocene history of a tropical estuary (Broad Sound, Queensland): Australia Bureau of Mineral Resources Geological and Geophysical Bulletin 170, 206 p.

Dalrymple, R.W., Amos, C.L., and McCann, S.B., 1982, Excursion 6A—Beach and nearshore depositional environments of the Bay of Fundy and southern Gulf of St. Lawrence: International Congress on Sedimentology, Hamilton, Ontario, 116 p.

Dalton, F.K., 1951, Fundy's prodigious tides and Petitcodiac's tidal bore: Journal of the Royal Astronomical Society of Canada, v. 45, no. 6, p. 225–230.

Darwin, G.H., 1898, The tides and kindred phenomena in the solar system: New York, Houghton Mifflin and Co.; reprinted 1962, San Francisco, W.H. Freeman and Co., 378 p.

Davies, J.L., 1977, Geographical variation in coastal development: New York, Longmans, 204 p.

Defant, A., 1958, Ebb and flow—Tides of the Earth, air, water: Ann Arbor, University of Michigan Press, 121 p.

Destriau, B., 1951, Le Mascaret dans les rivières de Gironde: Annales des ponts et chaussées, v. 121, no. 5, p. 609–635.

Doodson, A.T., and Warburgh, H.D., 1941 (reprinted 1961), Admiralty manual of tides: London, Her Majesty's Stationery Office, 270 p.

Favre, H., 1935, Etude theorique et experimental des ondes de translation dans les Canaux descouverts, Paris: Dunod, pages not available.

Gordon, J.H., 1924, Tidal bore at the mouth of Colorado River: Monthly Weather Review, v. 52, p. 98–99.

Jouanneau, J.M., and Latouche, C., 1981, The Gironde estuary: Contributions to Sedimentology, v. 10, 118 p.

Komori, Y., 1979, Bank erosion by tidal flow: Malaysia, Drainage and Irrigation Department, unpublished report.

Longuet-Higgins, M.S., and Turner, J.S., 1974, An entraining plume model of a spilling breaker: Journal of Fluid Mechanics, v. 63, p. 1–20.

Lynch, D.K., 1982, Tidal bores: Scientific American, v. 247, no. 4, p. 146–156.

Lynch, D.K., and Bartsch-Winkler, Susan, 1982, Worldwide survey of tidal bores: Abstracts, XXI International Congress on Sedimentology, Hamilton, Ontario, Canada, p. 97.

MacKay, R.D., 1976, New Guinea: Amsterdam, Time-Life International, 87 p.

Madsen, P.A., and Svendsen, I.A., 1983, Turbulent bores and hydraulic jumps: Journal of Fluid Mechanics, v. 129, p. 1–25.

Magalhaes, A.A.B. de, 1943, Do rio Amazonas e da pororoca : Revista Brasileira de Geografia, Jan-Mar.

Martius, K.F.P. von, circa 1837, Flora Brasiliensis.

Maugham, W.S., 1949, A writer's notebook: Garden City, N.J., Doubleday, 367 p.

Maxwell, W.G.H., 1968, Atlas of the Great Barrier Reef: Amsterdam, Elsevier, 256 p.

McIntyre, L., 1972, The Amazon—Mightiest of rivers: National Geographic, v. 142, no. 4, p. 445–495.

Mitchell, D.G., 1968, Report on tidal measurements in the Petitcodiac River, 1968: Canadian Hydrographic Service, Tides and Water Levels, Fisheries and Oceans, v. 2, 29 p.

Moore, R.N., 1888, Report on the bore of the Tsien-Tang-Kiang: London, Potter, Poultry, pages not available.

______ 1893, Further report on the bore of the Tsien-Tang-Kiang: London, Potter, Poultry, pages not available.

Murphy, R.C., 1983, Pororoca!: Calypso Log, v. 10, no. 2, p. 8–11.

NOAA (National Oceanic and Atmospheric Administration), 1982a, Table 2, *in* Central and Western Pacific Ocean and Indian Ocean, tide tables 1982: p. 342.

______ 1982b, Table 2, *in* East Coast of North and South America including Greenland, tide tables 2: p. 236–237.

______ 1982c, Table 2, *in* Europe and the West Coast of Africa including the Mediterranean Sea, tide tables: p. 174.

______ 1982d, Table 2, *in* West Coast of North and South America including the Hawaiian Islands, tide tables 1982: p. 165–188.

Ovenshine, A.T., Bartsch-Winkler, S., O'Brien, N.R., and Lawson, D.E., 1976, Sedimentation in the high tidal range environment of upper Turnagain Arm, *in* Miller, T.P., ed., Recent and ancient sedimentary environments in Alaska: Anchorage, Alaska Geological Society Symposium, p. M1-M26.

Redfield, A.C., 1981, Introduction to tides: Woods Hole, Mass., Marine Science International, 37 p.

Rowbotham, F.W., 1964, The Severn Bore, 2nd edition: Newton-Abbot, North Ponfret, Vt., David & Charles, 104 p.

Roy, S.C., 1972, Inception and propagation of the bore on the Hooghly, *in* Bagchi, K.G., ed., The Bhagirathi-Hooghly Basin: Proceedings of the Interdisciplinary Symposium, p. 133–142.

Sykes, G.G., 1937, The Colorado Delta: American Geographic Society Special Publication 19, New York, 193 p., and Carnegie Institute, Washington, Publication 460, 193 p.

——— 1945, A westerly trend: Tucson, Ariz., University of Arizona Press, 325 p.

Tricker, R.A.R., 1965, Bores, breakers, waves, and wakes—An introduction to the study of waves on water: New York, Elsevier, 250 p.

Tsubaki, T., 1950, Theory of hydraulic jump: Report of the Research Institute of Fluid Engineering, Kyushu University, Fukuoka, Japan, v. 6, p. 2.

Waters, B., 1947, Severn tide: London, J.M. Dent and Sons, 183 p.

Waters, F., 1946, The Colorado: New York, Rinehart and Co., 400 p.

Wright, L.D., Coleman, J.M., and Thom, B.G., 1973, Processes of channel development in a high-tide range environment—Cambridge Gulf–Ord River delta, Western Australia: Journal of Geology, v. 81, no. 1, p. 15–41.

Wylie, F.E., 1979, Tides and the pull of the Moon: Brattleboro, Vt., Stephen Green Press, 246 p.

Zeheng, D., 1982, Reclaiming against the Qiantang bore: Publication of the Provincial Institute of Estuarine and Coastal Engineering Research, Hangzhou, China, 13 p.

Zerbe, W.B., 1972, Alexander and the bore: NOAA (Magazine), v. 2, no. 4, p. 30–32.

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