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all the grain required far cheaper than a white man, who can trade it from them and then sell it. This is generally done in preference to white men attempting to grow it. The country is very suitable for cattle and sheep farming, the grass being sweet and cattle thriving well on it. Many more farmers would settle and go in for it if the various cattle diseases the country has lately been visited with could be got rid of permanently.

Gold-mining is gradually increasing throughout the west and north of Mashonaland and Matabeleland, which districts are more populated by whites than the south-east, and it is supposed on the best authority that there is a good mining future before the country. The distances between towns are so great and the expense of moving about very heavy, and very little doing in the country generally, therefore many good men who otherwise would have remained in the country have left for the Transvaal, and Rhodesia is the loser.

PROGRESSIVE WAVES IN RIVERS.*

By VAUGHAN CORNISH, D.Sc., F.G.S., F.C.S., F.R.G.S., M.J.S., Associate of the Owens College, Manchester.

ON "ROLL-WAVES," OR DOWN-STREAM BORES.

WHEN the upper reaches of a river are swollen by rains, room is made for the flood by the gravitational rise of the water further down-stream. As in deep rivers the rate of propagation of a long wave is many times greater than the velocity of flow, the effect of this wave-transmission is to diminish the initial inequality of slope caused by the rain-water, and no wave is *visible*. The fact that in the lower reaches the level of the river rises before the arrival of turbid waters, alone attests the fact that flood-water has caused a progressive wave.

In certain rivers, however, of small depth (therefore propagating a wave slowly) and subject to sudden accessions from swollen tributaries, the "first rise" of water in the lower reaches frequently takes the form of a steep-fronted wave, or bore, travelling down-stream. On the Tees the phenomenon is called a roll-wave. Mr. F. R. Glyn, F.R.G.S., from whom I first received an account of the phenomenon, describes it as 2 or 3 feet high, reaching from bank to bank. He observed it on no less than six occasions during the course of one summer and autumn. It is a source of considerable danger to anglers, coming as it does wholly without warning and travelling at a considerable speed, viz. the speed

* Illustrated by photographs taken by the author.

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of the stream *plus* the speed of a long wave in water of the actual depth.

A similar wave is known at Aysgarth on the Ure, which has also been described to me by an eye-witness as "2 or 3 feet high." The character of the channels of the rivers Tees and Ure is somewhat similar. At Aysgarth there are alternately pools and shoals, and the wave would of course mount up and appear more like a single wall of water in passing over the latter. The cross-section is very different to that of a river flowing through alluvium, the channels being carved in solid rock, and the depth of water at the sides being almost the same as in the centre.

On the Swale, the roll-wave just above Richmond (Yorks.) has been described to me by an eye-witness as apparently about 4 feet high. The upper portion of the Tyne is also subject to these waves. Roll-waves are said to be known also on the river Wye as a sequel of rains in the upper reaches, and in the rivers among the foothills of the Himalayas they are not uncommon.

The production of a roll-wave by a landslip has been occasionally observed. A notable case was that in which a big slip of mountain-side into Lake Chusenzi sent a roll-wave down the Nikko torrent, wrecking the celebrated "Thousand Buddhas," of which I had a description from the owner of a tea-house on the banks, who narrowly escaped the advancing wave.

It may fairly be asked, if floods cause down-stream waves, may not the ordinary inequalities of motion, *e.g.* those due to the formation and disengagement of eddies, also produce them? If so, down-stream waves must always be present in rivers. I find that in rapid streams their presence is revealed by the waves which come in where there is a shore shelving like a beach, as is sometimes the case on the inner side of a bend. Steep-fronted waves roll in there and break upon the shingle, their direction where they first become visible being diagonally down- and across-stream. Thence they swing round to face the shore, turning on the shallow end as pivot, in the manner of the breakers on the sea-shore. From this it follows that in the deep water of mid-stream these waves are also present, travelling down-stream, but invisible on account of their flatness.

Water flowing in a thin film inevitably does so in a series of miniature roll-waves or roll-ripples. This may be seen, for instance, on the sloping marble slab on which fish are laid in the front of a fish-monger's shop. Where a film of water slides down the rocks on steep mountain-sides it frequently is seen to take on the appearance of a series of progressive wavelets, but when the water follows, as is usual, a narrow channel, these wavelets have small lateral extension, and their

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front assumes a V-shape, the wave being retarded at the edges of the channel where the water is shallower.

In a film of water these wavelets cannot grow, for the increase of depth at crest being accompanied by diminution at trough, growth would immediately be arrested by complete drying up at the troughs.

Beside the funicular railway from Territet to Glion (Switzerland), in a conduit 12 inches wide, with a uniform floor of cement (and vertical sides of the same material) with an average slope of 1 in 2, the water may commonly be seen to flow as a series of roll-waves which, commencing as confused ripples near the footbridge, grow in the space of a few yards to a uniform wave-length of about 2 feet, the depth at trough being, on one occasion, ascertained to be 0·1 inch, and at the crest 0·2 inch. When a large amount of water was turned into the conduit the roll-waves ceased, ordinary diagonal standing waves replacing them. When the excess of water ran off and the depth was again reduced to less than an inch, the stream began once more to flow gushingly as a series of roll-waves.

The explanation I offer is as follows: The velocity of flow is small when the water is very shallow, owing to friction against the bed. The slightest excess of retardation at any point momentarily increases the depth there. But the mere fact of increasing the depth increases the velocity, at any rate in the upper layer. Continuous motion is therefore impossible for very shallow water on a steep slope, and is necessarily replaced by gushing flow. If the bed be of uniform cross-section, the gushes take the form of regular transverse progressive waves. If, on the other hand, the channel be irregular, there may be no lateral coordination, and the intermittance of flow is only noticeable in the rushing sound, or in the beating action of the water against an immersed body.

At Merligen, on the Lake of Thun, is an open conduit 15 feet wide, 7 feet deep, 1360 feet long, and having a slope of about 1 in 14. The ordinary flow of the Grünnbach torrent, which is conveyed to the lake in this conduit, supplies a depth of from 1 to 3 inches at the entrance of the paved channel, the great depth of the conduit being designed for the accommodation of sudden floods. The floor of this conduit is paved with flat slabs of stone of rectangular form, with open junctions which are respectively parallel and at right angles to the flow of the stream. The transverse junctions form a series of inequalities across which the shallow stream flows. At the entrance of the paved channel the shallow water flows with a flickering appearance, caused by numerous steep-fronted progressive waves of minute amplitude and small lateral extension following one another at intervals of some inches, and passing the observer on the bank in a succession too rapid to admit of exact counting, but about 120 per minute. The regularization and growth of the waves takes place rapidly. Thus on June 6, 1904, although at

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465 feet from the entrance, there was still some confusion from the presence of minor waves along with the larger ones, yet at 567 feet from the entrance the stream was flowing as a single series of roll-waves extending quite across the channel, passing the observer 33 per minute. At 1121 feet from the entrance the number passing was twenty, the height and length having increased in inverse proportion, and at the outflow, 1361 feet from the entrance, seventeen waves passed per minute. The mouth of the conduit is several feet above the lake, and the roll-waves impart to the waterfall a regular cadence (Fig. 1). This slow pulsation is often visible to the naked eye at a distance of 2 miles. Most of the observations were made when the uniform depth of water at the entrance of the conduit was about 1 or 1½ inch. The greatest observed depth there was 3 to 3½ inches, which was converted at the end of the flow to a succession of progressive waves about 6·5 inches in amplitude, the depth at trough being reduced to about 1·5 inch, and that at the crests increased to 8 inches. The wave-length near the exit was 66 feet. The time of flow of the water from entrance to exit was only 90·2 seconds, and the time of transit of the wave was less, so that the growth which occurs may well excite surprise. Measurements taken on several days indicate that the true velocity of the roll-wave is that calculated for a long wave.

Date.	Depth at crest. Inches.	Depth at trough.	Observed speed. f.p.s.	Calculated speed. f.p.s.
August 26, 1904	2·5	1	2·06	2·58
September 8, 1904 ...	4·0	1	3·275	3·27
June 15, 1905	4·5	2	3·54	3·47
September 16, 1904 ...	8·0	1·5	3·00 *	4·60

In the Grünnbach conduit it is apparent to the eye that the growth of the roll-waves is partly due to the fairly regular transverse inequalities, so that we have in this case a cause additional to that of friction, with a uniform, but not perfectly smooth, bed. In deeper water transverse inequalities produce *stationary* transverse ridges of water, the familiar standing or stationary waves. Close observation enabled me to detect in some shallow conduits the co-existence of stationary and progressive waves, the former caused wholly, the latter partly by transverse ridges on the bottom. This was particularly well seen on a short, steep conduit at Ralligen, between Merligen and Gunten. The relative conspicuousness of the two kinds of waves depended to a considerable extent upon the mode of observation.

* The observed speed of *current* this day was probably too great, for the foaming waves whirled along the floating matter. Hence the wave-speed comes out too low.

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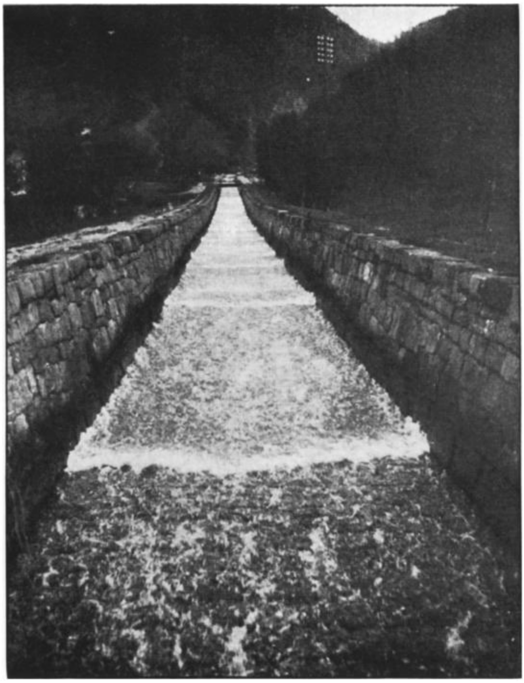

FIG. 1.—ROLL-WAVES IN THE GRÜNNBACH CONDUIT.

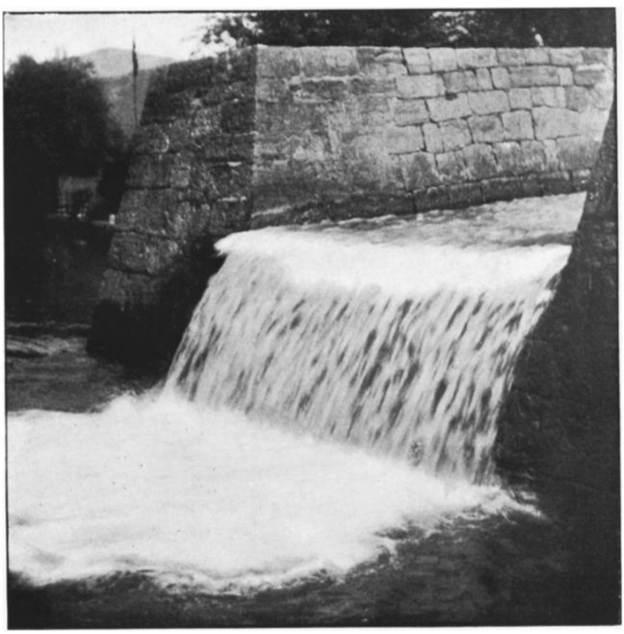

FIG. 2.—ROLL-WAVE LEAPING THE OUTFALL OF THE GRÜNNBACH CONDUIT.

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When regarded with a steady, wide-eyed gaze, the fixed waves were clearly seen (as is usual), and only a very slight and irregular flicker was noticeable in the moving water. But when the eyes were more than half-closed, so that the outline of the fixed objects became blurred, the passage of transverse roll-waves could be very distinctly seen. The discovery of this device I have found to be of great assistance in studying waves in running water. One of the reasons why they are so little known is that the eye is usually dominated by objects which are stationary relatively to the bank.

At Gunten, also on the lake of Thun, is another conduit, comparable in size to that at Merligen, but with a rougher pavement, and sloping instead of vertical sides. It has a gradient of about 1 in 22. The waterfall by which this conduit discharges into the lake has usually a regular cadence, due to the succession of well-defined roll-waves, which can be seen in the lower part of the channel. Their production, however, takes place in a different manner from that observed in the Grünnbach conduit. Indeed, for the greater part of the course no roll-waves are formed, and their formation is *sudden*. At or near some position, which varies somewhat from day to day, a sound like that of the word "flop" is heard from time to time, and on looking in the direction of the noise the roll-wave (perhaps half an inch in amplitude) is seen to be already formed, and it grows rapidly as it rolls on. The cause appears to be that there are long shallow "pools" in the channel difficult to distinguish on account of the roughness of the pavement. It is at the lower lip or sill of one of these that the infinitesimal down-stream waves, which are always present in a stream, particularly a rapid one, congregate and swell until they burst over the obstruction in the form of a bore. The preparation for this is generally a slight failure of the current, reducing the depth on the sill.*

Another paved conduit where the roll-waves arose in the same way was found near St. Maurice, in the Rhone valley. Longitudinal inequalities of depth greatly hinder the formation of roll-waves, and even destroy them after they have definitely formed. This was seen in the St. Maurice conduit, which terminated, not in a waterfall, but in a winding channel between sandy shores. Here the wave-front immediately *lost its transversality*, and the wave was no more seen. The circumstances that both current and wave are more rapid where the depth is greater, and that current and wave are travelling in the same direction, combine to rapidly destroy the transversality of the wave-front. It is less visible when not transversal, and also soon destroys itself by running upon the shelving shores. Vertical walls (as in the Grünnbach conduit) do much to preserve the roll-waves. In the case

* After thunderstorms, with a depth of 4 to 6 inches, no roll-wave was formed.

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of tidal bores, where current and wave are opposite in direction, there is no such co-operation to destroy the transversality, and this is one reason for the superior stability of bores which travel up-stream.

The break-up of a high waterfall into conical masses was described by Livingstone,* who compares them to "small comets." They have also been called "water-rockets." Their formation marks an intermediate stage in the process which finally dissipates the water in spray, a process due to the dynamic instability of a sheet of water falling under the acceleration of gravity. In most waterfalls the "comets," or "rockets," though visible, are not conspicuous, but in some, as for instance those of the Tschingelbach, at Burglauenen, in the Lutschenthall (Switzerland), when the amount of water is suitable, the regular procession of falling cones is the chief beauty of the fall.

In this instance the water, before its leap, slides in a shallow sheet over a slab of steeply sloping rock, where it goes into fairly regular roll-waves, and this is the cause of the development of the cone structure from a subordinate to a principal feature of the fall.

On Tidal Bores as observed in the River Severn.

This paper deals only with visible waves, and the tide-wave in rivers in its ordinary form is therefore outside our purview. In some rivers, having large tides and sandy estuaries, the "first rise" of the tide takes the form of a visible steep-fronted wave, or waves. These the author has observed at various times and places on the river Severn,† and in the present paper, omitting mere description as much as possible on account of considerations of space, some account is given of these observations as far as they tend to advance our knowledge of the *character* of this class of wave, of the conditions which determine its *place of origin* in an estuary, and of the causes which produce the apparently capricious *variations* of its magnitude.

The Severn bore is seen between Gloucester and Severn Bridge. The places where it approaches with the appearance of a wall of foaming water are the shallows. In the deep pools it generally takes the form of rounded swells, which rapidly multiply in number; and there it often ceases to be visible, reappearing afterwards when it comes to shallow water. It seems, therefore, that an error is made in regarding the bore as the steepened front of the whole tide-wave, for on that supposition it would be "long" as compared with the depth of the pools, and would even there be a steep-fronted and solitary wave. The rise of a tide is never a steady process, as is shown by the

* 'Missionary Travels and Research in South Africa,' description of Victoria Falls.

† See *Nature*, June 7, 1900, and *Geogr. Journ.*, January, 1902, "On Cinematographing the Severn Bore."

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"notches" in the curve of tide-gauges, and as may be seen in the way the incoming tide (*e.g.* at Montrose, N.B.) bursts over sands and then recedes before finally covering them. In the windings of an estuarine channel the rise of the tide would be specially subject to such pulsations, and it appears likely that the bore is the front of such a partial swelling, and the sudden overcoming of obstruction. The preceding remarks on roll-waves illustrate this view.

The Severn bore originates where the low-water gradient of the estuary is *steep*, which is between Hock Cliff and (about) Shepherdine Sands. It occasionally starts below the Severn Bridge, which is between these places, but vanishes again, the true start being only made between Severn Bridge and Hock Cliff. It is not difficult to understand why the bore should start where the gradient is steep (with shallow water and an opposing current to cause obstruction and local swelling), but observation on the spot was needed to show why it originates in the upper instead of the lower half of the steep slope of the river. I find the cause to be a matter of alternative low-water channels. In the lower part of the "Steep slope" from Hock to Shepherdine the "first of the flood," meeting the ebb in the main channel, fills up a swatch-way or side channel, and then overflows the intervening sandbank, entering the ebb channel laterally. There ensues a circulation of waters instead of a wave. Higher up there is, as a rule, no alternative channel, and the ebbing current stems the rising tide until a sufficient "head" accumulates, and a visible wave moves slowly up the shallow channel with a foaming front.

In this part of the river, however (between Awre on the right bank and Frampton on the left), the low-water channels vary considerably, according to the wetness or dryness of the season, much land-water cutting a deep and strongly curved trench on the Frampton side, whereas, when there is little land-water, the flood-tide has more effect in determining the low-water channel, which is then straighter,* and nearer to the Awre side. In the latter case (as I observed well on October 30, 1901), the tide reaches Hock Cliff with a considerable bore, but the water then turns and flows *down* the empty Frampton channel. The bore subsides, and, after a large area has been covered or filled, the tide advances quietly towards Newnham, where, on this occasion, the bore was small, although the total rise of tide was great.

The very existence of a bore in a riverine estuary is the sign that a stable *régime* has not yet been attained in the part where the bore originates. Below Severn Bridge, the ebb and flood respectively have so adjusted the sandbanks that the bore is for the most part avoided. Between Severn Bridge and Hock Cliff that adjustment is not yet

* See the author's paper in *Geogr. Journ.*, August, 1901, on "Sand-waves in Tidal Currents."

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affected. Towards the end of each set of "spring" tides it is more nearly effected than at the beginning, for (as Mr. D. Wintle, of Newnham-on-Severn, has pointed out to me) the bore is less on the later days. It is, in fact, the flood tide which makes the alternative channel whereby the bore is avoided.

In Prof. Osborne Reynold's experiments with model estuaries,* bores were sometimes formed in the earlier stages before the sandbanks had attained their final shapes.

On Cross-stream Progressive Waves.

There remains yet another variety of progressive waves in rivers, which is generated from the familiar stationary or standing waves.

By introducing an obstruction in a stream, it is easy to see the process of formation of a group of standing or stationary waves (Fig. 3). The formation of the first wave is instantaneous, and the production of the other waves to leeward occupies a very short time. Thereafter the waves are fixed in position, size, and form, as long as the current is constant. In actual rivers, however, slight variations of current are going on all the time, and the standing waves fluctuate slightly about their mean position, the range of their excursion being usually, however, less than the length of the visible mound of water. Accompanying this slight fluctuation of position is a corresponding change of shape, which sometimes causes an intermittent breaking (upstream) of the steepest member of the group.

In the Whirlpool Rapids of Niagara river (in which locality I spent three weeks for observations on waves in 1903) the standing waves are of great size, in some cases attaining a total height of 15 to 20 feet; and, the river being narrow, there is a superposition of waves, the stationary waves extending in diagonal ridges from the opposite banks to, and beyond, the middle of the stream. The fluctuation of the standing waves is much greater than in quieter and less rapid rivers. A wave will slowly wax to a maximum (say 12 feet), and then, more suddenly, drop to its minimum height (say 10 feet), and in doing so it disengages a visible progressive wave, of which the steep and foaming front faces diagonally up-stream, in the same direction as the parent wave. As we follow the disengaged progressive wave in its course, we see, although the foaming crest faces somewhat up-stream, as well as across, that the whole *drifts* down-stream, so that the resulting motion relatively to the bank is across-and-down-stream, at an acute angle with the direction of the current. At the centre of the river, where cross the ridges of the standing waves, are those great, steep, and foam-capped mounds of water which are the most striking individual wave-forms of

* Reports, British Association, 1890 and 1891.

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FIG. 3.—STATIONARY WAVES ON THE RIVER AARE.

FIG. 4.—LEAPING WAVE, WHIRLPOOL RAPIDS, NIAGARA.

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the rapids. Upon these, at irregular intervals, converge several of the cross-stream progressive waves, and then occurs that sudden leap and shattering of the great water-mound, which constitutes the Leaping Wave, which is the climax of all the tumults of Niagara. The great "leaps" take place always at the same spots, namely, where the standing ridges cross. The development of cross-stream progressive waves as a secondary phenomenon of standing waves is much greater where there is a superposition of two sets of waves, because wave motion is essentially differential, and the fluctuation of a "waved-wave" (as I may term it) is in a high degree more sharp and sudden than that of a simple wave. This fact I confirmed by observation on several of the St. Lawrence rapids.

Those who wish to understand these phenomena must carefully guard against the logical error of attributing the cross-stream progressive waves *directly* to the effect of resistances upon the current, the primary and principal effect of which is the production of *stationary* waves.

When standing on the bank of the Whirlpool Rapids, surges rush in, which cause alterations in the level of the water of 2 feet or more. In what proportion these are due to the above-described cross-stream progressive waves, and in what proportion down-stream progressive waves may contribute, I am unable, at present, to say.

DR. STEIN'S EXPEDITION IN CENTRAL ASIA.*

From Kashgar, where, with the valuable help of Mr. Macartney, the Indian Government's representative, I had succeeded in organizing my caravan within a fortnight of my arrival, I commenced my journey south-eastwards by the end of June. The intense summer heat of the Turkestan plains precluded all thought for the next two months of archæological exploration in the desert. For the journey to Khotan, the intended starting-point of my archæological labours, only two weeks' marching was needed, and I was thus free to utilize the rest of the interval for geographical and anthropological work in the westernmost Kuen-lun range.

While I myself was busy at Kashgar, Rai Ram Singh had under my instructions carried a systematic survey by plane-table and theodolite through a still unexplored section of the Tashkurghan river valley, and thence along the eastern slopes of the Mustagh-ata range to the latitude of Yangi-Hisar. After he had joined me at Yarkand, we marched by a

* Communication from Dr. M. A. Stein, dated Keriza (Kiria), October 10, 1906.

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