not merely between the pores of the rocks but in crevices and tunnels which it has no doubt to a large extent opened for itself along numerous natural joints and fissures, is proved by the occasional rise of leaves, twigs, and even live fish, in the shaft of an Artesian well. Such evidences are particularly striking when found in districts without surface waters, and even perhaps with little or no rain. They have been met with, for instance, in sinking wells in some of the sandy deserts on the southern borders of Algeria. In these and similar cases it is clear that the water may, and sometimes does, travel for many leagues underground away from the district where it fell as rain or snow, or where it leaked from the bed of a river or lake.

The temperature of springs affords a convenient but not always quite reliable indication of the relative depth from which they have risen. Some springs are just one degree or less above the temperature of ice. Others in volcanic districts issue with the temperature of boiling water. Between these two extremes every degree may be registered. Very cold springs may be regarded as probably deriving their supply from cold or even snow-covered mountains. Certain exceptional cases, however, occur where ice forms in caverns (*glacières*) even in warm and comparatively low districts. Water issuing from these ice caves is of course cold.[1] On the other hand, springs whose temperature is much higher than the mean temperature of the places at which they emerge must have descended far enough to be warmed by the internal heat of the earth. The hottest springs are found in volcanic districts. But even at a great distance from any active volcano, *thermal springs*, as they are called, appear with a temperature of 120° Fahr. (which is that of the Bath springs) or even more. These have probably risen from a great depth. If we could assume a progressive increase of 1° Fahr. of subterranean heat for every 60 feet of descent, the water at 120° issuing at a locality whose ordinary temperature is 50°, should have been down at least 4200 feet below the surface. But from what has been stated in a previous section (p. 224) regarding the irregular stratification of temperature within the earth's crust, such estimates of the probable depth of the sources of springs are liable to various errors.

Apart from its vast importance in a social point of view, the underground circulation of water has a profound interest for the geologist, from the light which it affords as to the changes that rocks undergo, and the manner in which these changes are effected. For, like all the other geological agents, it does not move on its course without doing work. We have now to inquire what is the nature of that work. A convenient arrangement will be to group its study under two heads—(1) chemical action, and (2) mechanical action.

(1.) Every spring, even the most clear and sparkling, contains mineral matter in chemical solution, obtained from the rocks through which the water travels in its journey from the surface into the interior, and back to the surface again. The nature of the mineral ingredients depends partly upon the composition of the rocks traversed, partly upon the gases, acids, or other reagents which may have been present in the rain, or may have been obtained by the water in its subterranean journey, and partly upon the depth to which the water may have reached and the temperature to which it may have been raised.

We have already (*ante*, p. 267) considered the substances extracted by rain from the air and used by it in the disintegration of rocks. The same reagents are of course carried underneath the ground, when the rain-water sinks out of sight, and continue there the processes of decomposition and alteration which they are seen to effect at the surface. But other sources are open to the subterranean water for the augmentation of its chemical reagents. (1.) In descending through the soil the meteoric water encounters abundant organic matter, which abstracts its oxygen and replaces it by carbonic acid. This interchange probably in many cases far more than compensates for the expenditure of these gases employed in subaerial disintegration. In so far as the water carries down from the soil any oxidizable organic substance, its action must be to reduce the oxides it encounters among rocks. It is remarkable that ordinary vegetable soil possesses the power of removing from the water which permeates it potash, silica, phosphoric acid, ammonia, and organic matter, elements which had been already in great measure abstracted from it by living vegetation, and which are again taken up by the same organic agents. (2.) Carbonic acid gas is sometimes largely evolved within the earth's crust, especially in regions of extinct or dormant volcanoes. Subterranean water coming in the way of this gas greedily dissolves it, and thereby obtains an enormously increased power of attacking even the most obdurate rocks. (3.) Whenever the water has its temperature considerably raised, its solvent capacity, especially for silica, is largely augmented. Hot springs often contain a large proportion of that substance in solution. (4.) The production of some of the compounds which are due to decompositions effected by the water, and are carried along with it in solution, increases its ability to accomplish further decompositions. Thus the alkaline carbonates, which are among the earliest products of the action of the water, enable it to dissolve silica and decompose silicates.

The study of these alterations belongs to the subject of Metamorphism, of which some account has already been given (*ante*, p. 262). Let us look at the results achieved by them, as shown in the composition of the water which issues from different springs. Considered from this point of view, springs may be treated as (1) common or ordinary springs, that is, those which contain only such average proportions of mineral matter as occur in ordinary potable water, and (2) mineral springs, or those where the proportion of foreign ingredients is large enough to give a marked character to the water. These two groups, however, merge insensibly into each other.

Common Springs.—The materials ordinarily present in common spring water are, besides atmospheric air and its gases, carbonate and sulphate of lime, common salt, with chlorides of calcium and magnesium, and sometimes organic matter. The amount of dissolved contents in ordinary drinking water does not exceed ·5 or at most 1·0 gramme per litre; the best waters contain even less.

Mineral Springs.—These may be roughly but conveniently classified according to the prevailing mineral substance contained in them, which may range in amount from 1 to 300 grammes per litre.[2]

Calcareous—containing so much lime that it is deposited as a white crust as the water evaporates. Spring water when saturated with carbonate of lime contains about 105 parts in 100,000. Springs of this kind are common in limestone countries. As the water flows away from its point of exit, it throws down a deposit of calcareous tufa or travertine, which, as it encrusts moss, twigs, and other objects, gives them the appearance of having been turned into stone, whence the springs are popularly termed "petrifying." Enormous accumulations of this kind have been formed in some parts of Italy, where the rock so produced is extensively quarried as a building material.

Ferruginous or Chalybeate—containing a large proportion of iron in the total mineral ingredients. Such waters have an inky taste, and often deposit along their course a yellow, brown, or red ochry deposit, consisting mainly of hydrated peroxide of iron. They may be frequently observed in those districts where beds or veins of ironstone occur, or where the rocks contain much iron in combination.

Siliceous—depositing silica or flint. Although silica may be dissolved and retained in solution even in cold water, it is in the hot water issuing in volcanic countries that it occurs most abundantly, and where true siliceous springs exist. The geysers of Iceland, New Zealand, the Yellowstone region, and other districts are illustrations. When the heated water of these thermal springs cools and evaporates, the silica is deposited as siliceous sinter round their basins, or in picturesque mounds at the point of escape. One of the sinter beds in the geyser region of Iceland is said to be two leagues long, a quarter of a league wide, and a hundred feet thick. As already stated (*ante*, p. 263), the effect of pressure is to enable water at great depths to retain a larger amount of mineral matter in solution. Hence, when the water ascends, it deposits its mineral contents, not only because it cools, but because the pressure is removed. There must in many cases be a copious deposit along the walls of the fissures up which the water flows on its way to the surface. Doubtless in this way many mineral veins have received their successive coatings of quartz, jasper, gypsum, calcite, and other minerals.

Brine—bringing to the surface a solution, more or less nearly saturated, of chloride of sodium. Springs of this kind appear where beds of solid rock-salt exist underneath. The water in its passage encounters the salt, dissolves it, and brings it to the surface. The brine springs of Cheshire in England, the Salzkammergut in Austria, Bex in Switzerland, &c., have long been well known. Some of the English brines contain about one per cent. of salts, of which the chloride of sodium may range from a half to three-fourths or more. Other brines, however, yield a far larger amount; one at Clemenshall, Würtemburg, gave upwards of 26 per cent. of salts, of which almost the whole was chloride of sodium. The other substances contained in solution in the water of brine springs are usually such as exist also in sea-water, such as sulphate and carbonate of lime, chlorides of magnesium and potassium, &c.

Medicinal—a vague term applied to mineral springs which have or are believed to have curative effects in different diseases. Medical men recognize various qualities, distinguished by the particular substance most conspicuous in each—as *Alkaline Waters*, containing lime or soda and carbonic acid, as those of Vichy or Saratoga; *Bitter Waters*, with sulphate of magnesia and soda—Sedlitz, Kissingen; *Salt* or *Muriated Waters*, with common salt as the leading mineral constituent—Wiesbaden, Cheltenham; *Earthy Waters*, lime, either a sulphate or carbonate, being the most marked ingredient—Bath, Lucca; *Sulphurous Waters*, with sulphur as sulphuretted hydrogen and in sulphides—Aix-la-Chapelle, Harrogate.

Oil.—Mineral oil is carried up by some ordinary springs, and floats in dark drops on the surface of the water. But in some parts of the world, as in a wide region in the Northern States of the American Union and in Canada, the oil ascends with little or no water, and forms the oil-springs which in recent years have become so remarkable and abundant a source of illuminating oils, paraffin, and other hydrocarbon compounds.

Results of Chemical Action of Underground Water.—Since every spring is busily engaged in bringing mineral substances from below ground to the surface, there must evidently be a vast amount of subterranean waste, and many tunnels, channels, and caverns must in consequence be formed. To take one illustration: the warm springs of Bath, with a mean temperature of 120° Fahr., are impregnated with sulphates of lime and soda, and chlorides of sodium and magnesium. Professor Ramsay has estimated their annual discharge of mineral matter to be equal to a square column 9 feet in diameter and 140 feet in height. It is in calcareous regions that the extent of the subterranean loss can be most strikingly seen. Sometimes a district of limestone is drilled with vertical cavities (*swallow-holes* or *sinks*) formed by the solution of the rock by the descent of carbonated rain-water. Surface-drainage is there intercepted, and passes at once under ground, where, in course of time, an elaborate system of channels may be dissolved out of the solid rock. Such has been the origin of the Peak caverns of Derbyshire, the intricate grottoes of Antiparos and Adelsberg, and the vast labyrinths of the Mammoth Cave of Kentucky. In the course of time the underground rivers open out new courses, and leave their old ones dry. By the falling in of the roofs of caverns near the surface, brooks and rivers are occasionally engulphed, which, after a long subterranean course, may issue to the surface again in a totally different surface area of drainage to that in which they took their rise, and sometimes, as in Florida, with volume enough to be navigable almost up to their outflow. In such circumstances lakes may be formed over the sites of the broken-in caverns; and valleys may thus be deepened, or perhaps even formed. Mud, sand, and gravel, with the remains of plants and animals, are swept below ground, and sometimes accumulate in deposits there. This has been the origin of ossiferous caverns, and of the loam and breccia so often found in them.

These wonderful results of the subterranean circulation of water appeal to the imagination, and are those usually most dwelt upon as evincing the potency of this kind of geological agency. And yet the thoughtful observer who reflects upon this subject will perhaps be led to perceive that even more important than these visible caverns and grottoes are the silent unobtrusive changes so constantly in progress in the solid heart of rocks. As far down as percolating water reaches there is not a particle of mineral matter safe from its attacks. And as we have seen, it is hardly possible to find any rock which does not bear throughout its minute grains and pores evidence that water has filtered through it, removing some substances and putting others in their place.

(2.) *Results of Mechanical Action.*—In its passage along fissures and channels of the rocks, the underground water not merely dissolves materials chemically and removes them in solution, it likewise loosens some of the finer particles from the sides of these subterranean conduits and carries them along in mechanical suspension. We may occasionally observe, where a spring gushes forth at the surface, that grains of sand are brought up in the clear sparkling water. This removal of material sometimes produces remarkable surface changes when it takes place along the side of a steep slope or cliff, such as occur in river valleys, or by the sea-coast. Let us suppose a thin layer of some porous material, like loose sand or ill-compacted sandstone to lie between two more impervious rocks such as masses of clay or limestone, and that this porous stratum sloping down from higher ground comes out to the surface near the base of a line of abrupt cliff. The water which finds its way down into this layer will use it as its channel of escape, and travelling along its course will issue in springs or in a more general oozing forth along its outcrop at the foot of the declivity. Under these circumstances the support of the overlying mass of rock is apt to be loosened. The water not only removes piece-meal the sandy layer on which that overlying mass rests, but as it were lubricates the rock underneath. Consequently at intervals portions of the upper rock may break off and slide down into the valley or plain below. Such dislocations are known as *landslips*. Many illustrative examples might be cited. Thus in the year 1839 a mass of chalk on the Dorsetshire coast slipped over a bed of clay into the sea, leaving a rent three-quarters of a mile long, 150 feet deep, and 240 feet wide. The shifted mass, bearing with it houses, roads, and fields, was cracked, broken, and tilted in various directions, and was thus prepared for further attack and removal by the waves. On many parts of the coasts of Britain there are landslips on a large scale which doubtless took place many centuries ago, or even in some cases beyond the times of human history. The undercliff of the Isle of Wight, the cliffs west of Brandon Head, county Kerry, the basalt escarpments of Antrim, and the edges of the great volcanic plateaus of Mull, Skye, and Raasay furnish illustrations of such prehistoric landslips. Of Continental examples, the well-known fall of the Rossberg, behind the Righi in Switzerland, is one of the most memorable. After a rainy summer in 1806 a large

---

[1] The most remarkable example of a glacière yet observed is that of Dobschau, in Hungary, of which an account, with a series of interesting drawings, was published in 1874 by Dr J. A. Krenner, keeper of the national museum in Buda-Pesth.

[2] Paul, in Watt's *Chem. Dict.*, v., 1016.

part of one side of the mountain, consisting of sloping beds of hard red sandstone and conglomerate, resting upon soft sandy layers, gave way. Thousands of tons of solid rock suddenly swept across the valley of Goldau, burying four villages, with about 500 of their inhabitants. In 1855 a mass of debris, 3500 feet long, 1000 feet wide, and 600 feet high, slid into the valley of the Tiber, which, dammed back by the obstruction, overflowed the village of San Stefano to a depth of 50 feet, until drained off by a tunnel.

§ 3. *Brooks and Rivers.*

These will be considered under four aspects:—(1) their sources of supply, (2) their discharge, (3) their flow, and (4) their geological action.

I. Sources of Supply.—Rivers are the natural drains of a land surface. They carry out to sea the surplus water after evaporation, and not water only, but a vast and almost incredible amount of material annually worn off the land. Their contents are derived partly from rain (including mist and dew) and melted snow, partly from springs. In a vast river system like that of the Mississippi, the area of drainage is so extensive as to embrace many different climates and varieties of rainfall, so that on the whole the amount of discharge, being in a great measure independent of local variations in the weather, remains tolerably uniform. But in smaller rivers, such as those of Britain, whose basins lie in a region having the same general features of climate, the quantity of water is regulated by the local rainfall. A wet season swells the streams, a dry one diminishes them. Were rivers entirely dependent, however, upon direct supplies of rain, they would only flow in rainy seasons, and disappear in dry weather. This does not happen, because they derive a great deal of their water not directly from rain, but indirectly through the intermediate agency of springs. Hence they continue to flow even in very dry weather, because, though the superficial supplies have failed, the underground sources still continue available. In a long drought, however, the latter begin to fail, the surface springs ceasing first, and gradually drying up in their order of depth, until at last only deep-seated springs furnish a perhaps daily diminishing quantity of water. It is a matter of great economic as well as scientific interest to know how long any river would continue to yield a certain amount of water during a prolonged drought. So far as we can tell, no rule could possibly be laid down for a generally applicable calculation, every area having its own peculiarities of underground drainage. Mr Joseph Lucas gives some particulars which show what may happen in a chalk district. The river Wandle drains an area of 51 square miles of the chalk downs in the south-east of England For eighteen months, from May 1858 to October 1859, as tested by gauging, there was very little absorption of rainfall over the drainage basin, and yet the minimum recorded flow of the Wandle was 10,000,000 gallons a-day, which, Mr Lucas says, represents not more than ·4090 inch of rain absorbed on the 51 square miles of chalk. The rock is so saturated that it can continue to supply a large yield of water for eighteen months after it has ceased to receive supplies from the surface, or at least has received only very much diminished supplies.[1]

II. Discharge.—As the natural drains of the land, rivers carry the surplus moisture out to sea. What proportion of the total rainfall is thus discharged by them is a question of great geological and industrial interest. From the very moment that water takes visible form as mist, cloud, dew, rain, snow, or hail, it is subject to evaporation. When it reaches the ground, or flows off into brooks, rivers, lakes, or the sea, it undergoes continual diminution from this cause. Hence in regions where rivers receive no tributaries, they grow smaller in volume as they move onward, till they sometimes even disappear. Apart from temperature, the amount of evaporation is very largely regulated by the nature of the surface from which it takes place, one soil or rock differing from another, and all of them probably from a surface of water. There is no question in meteorology where full and detailed observations are more wanting than in the determination of the relation of evaporation to rainfall and river discharge.[2] During severe storms of rain, the water discharged over the land of course to a very large extent finds its way at once into brooks and rivers, where it causes floods, and whence it reaches the sea. Mr David Stevenson remarks that, according to different observations, the amount carried off in floods varies from 1 to 100 cubic feet per minute per acre.[3] But though floods cannot be deemed exceptional phenomena, forming as they do a part of the regular system of water circulation over the land, they do not represent the ordinary proportions between rainfall and river discharge in such a climate as that of Britain, where the rainfall is not crowded into one season, but is spread more or less equally throughout the year. According to Beardmore's table,[4] the Thames at Staines has a mean annual discharge of 32·40 cubic inches per minute per square mile, equal to a depth of 7·31 inches of rainfall run off, or less than a third of the total rainfall. The most carefully collected data at present available are probably those given by Humphreys and Abbot for the basin of the Mississippi and its tributaries as shown in the subjoined table:—

	Ratio of Drainage to Rainfall.
Ohio River	0·24
Missouri River	0·15
Upper Mississippi River	0·24
Small tributaries	0·90
Arkansas and White River	0·15
Red River	0·20
Yazoo River	0·90
St Francis River	0·90
Entire Mississippi, exclusive of Red River	0·25

Perhaps in Great Britain not more than a fourth part of the total moisture deposited on the land from the atmosphere is carried out to sea by streams.[5] But this is a point on which, until far more facts have been gathered, no definite statement can be accepted as at all trustworthy.

III. Flow.—Rivers, in obedience to the law of gravitation, always move from a higher to a lower level. Where the channel of a river becomes vertical, or nearly so, a waterfall is formed; a steep rocky declivity in the channel gives rise to rapids; a flat plain allows the stream to linger with a scarcely perceptible current; while a lake renders the flow nearly or altogether imperceptible. Thus the rate of flow is regulated in the main by the angle of inclination and form of the channel, but partly also by the volume of water, an increase of volume in a narrow channel increasing the rate of motion even without an increase of slope.

The course of a great river may be divided into three parts:—1. *The Mountain Track*,—where, amidst the clouds and snows it takes its rise as a mere brook, and, fed by innumerable similar torrents, dashes rapidly down the steep sides of the mountains, leaping from crag to crag in endless cascades, growing every moment in volume, until it enters lower ground. 2. *The Valley Track.*—It now flows through the lower hills or undulations which traverse or flank a great mountain chain, and is found at one time in a wide fertile valley, then in a dark gorge, now falling headlong in a cataract, now expanding into a broad lake. This is the part of its career where it assumes the most varied aspects, receives the largest tributaries, and fulfils most characteristically the various conditions which are present to our minds in the idea of a river. 3. *The Plain Track.*—Having quitted the undulating region, it finally emerges upon broad plains, probably wholly, or in great part, made by itself. Here it winds sluggishly in wide curves, perhaps divides so as to enclose tracts of flat meadow or marsh, and finally, amid banks of mud and sand, passes out into the great ocean. In Europe the Rhine, Rhone, and Danube, in Asia the Ganges and Indus, in America the Mississippi and Amazon, in Africa the Nile, more or less fully illustrate this typical course of a great river.

If we draw a longitudinal section of the course of any such river from its source, or from the highest peaks around that source to its mouth at the sea, we find that the line forms a concave curve. Steep at first, where it slopes from the mountain crests down into the valleys, the curve grows less and less through the middle portion, until it finally can hardly be distinguished from a horizontal line. Though characteristic of great rivers, this feature is not confined to their courses, but belongs to the architecture of the continents.

It is evident that a river must flow, on the whole, fastest in the first portion of its course, and slowest in the last. The common method of comparing the fall or slope of rivers is to divide the difference of height between their source and the sea-level by their length, so as to give the declivity per mile. This mode, however, often fails to bring out the real resemblances and differences of rivers, even in regard to their angle of slope. For example, two streams rising at a height of 1000 feet, and flowing 100 miles, would each have an average slope of 10 feet per mile; yet they might be wholly unlike each other, one making its descent almost entirely in the first or mountain part of its course, and lazily winding for most of its way through a vast low plain, the other toiling through the mountains, then keeping among hills and table-lands, so as to form on the whole a tolerably equable and rapid flow. The great rivers of the globe have probably a less average slope than 2 feet per mile. The Missouri has a descent of 28 inches per mile. The average slope of the channel of the Thames is 21 inches per mile; of the Shannon about 11 inches per mile, but between Killaloe and Limerick about 6½ feet per mile; of the Nile, below Cairo, 3·25 to 5·5 inches per mile; of the Doubs and Rhone, from Besançon to the Mediterranean, 24·18 inches per mile; of the Volga, from its source to the sea, a little more than 3 inches per mile. Higher angles of descent are those of torrents, as the Arve, with a slope of 1 in 616 at Chamounix, and the Durance, whose angle varies from 1 in 467 to 1 in 208. The slope of a navigable river ought not, if possible, to exceed 10 inches per mile, or 1 in 6336.[1]

But not only does the rate of flow of a river vary at different parts of its course, it is not the same in every part of the cross section of the river taken at any given point. The sides and bottom, being retarded by friction against the channel, move less rapidly than the centre. The central piers of a bridge have thus a greater velocity of river current to bear than those at the banks. It follows that whatever tends to diminish the friction of the moving current will increase its rate of flow. The same body of water, other conditions being equal, will move faster through a narrow gorge with steep smooth walls than over a broad rough rocky bed. For the same reason, when two streams join, their united current, having in many cases a channel not much larger than that of one of the single streams, flows faster, because the water encounters now the friction of only one channel. The average rate of flow of rivers is much less than might be supposed, even in what are termed swift rivers. A moderate rate is about 1¼ mile in the hour; even that of a torrent does not exceed 18 or 20 miles in the hour.[2] Mr D. Stevenson states that the velocity of such rivers as the Thames, the Tay, or the Clyde may be found to vary from about one mile per hour as a minimum to about three miles per hour as a maximum velocity.[3]

It may be remarked, in concluding this part of the subject, that elevations and depressions of the land must have a powerful influence upon the slope of rivers. The upraising of the axis of a country must increase the slope, and consequently the rate of flow which, on the contrary, will be diminished by a depression of the axis or by an elevation of the maritime regions.

IV. Geological Action.—Like all the other forms of moving water, the streams which traverse a country have both a *chemical* and *mechanical* action. The latter receives most attention, as it undoubtedly is the more important; but the former ought not to be omitted in any survey of the general waste of the earth's surface.

i. *Chemical.*—The water of rivers must possess the powers of a chemical solvent like rain and springs, though its actual work in this respect can be less easily measured, seeing that river water is directly derived from rain and springs, and necessarily contains in solution mineral substances supplied to it by them and not by its own operation. Nevertheless, it is sometimes easy to prove that streams dissolve chemically the rocks of their channels. Thus in limestone districts the base of the cliffs of river ravines may be found eaten away into tunnels, arches, and overhanging projections, presenting in their smooth surfaces a great contrast to the angular jointed faces of the same rock where exposed to the influence only of the weather on the higher parts of the cliff.

The composition of the river waters of western Europe is well shown by numerous analyses. The substances held in solution include variable proportions of the carbonates of lime, magnesia, and soda; silica; peroxides of iron and manganese; alumina; sulphates of lime, magnesia, potash, and soda; chlorides of sodium, potassium, calcium, and magnesium; silicate of potash; nitrates; and organic matter. The minimum proportion of mineral matter among the analyses collected by Bischof was 2·61 in 100,000 parts of water in a mountain stream 3800 feet above the sea. On the other hand as much as 54·5 parts in the 100,000 were obtained in the waters of the Beuvronne, a tributary of the Loire above Tours. The average of the whole of these analyses is about 21 parts of mineral matter in 100,000 of water, whereof carbonate of lime usually forms the half, its mean quantity

---

[1] Lucas, *Horizontal Wells*, London, 1874, pp. 40, 41. See also Braithwaite, "On the Rise and Fall of the Wandle," *Minutes Proc. Inst. C.E.*, xx.

[2] In the present state of our information it seems almost useless to state any of the results already obtained, so widely discrepant and irreconcilable are they. In some cases the evaporation is given as usually three times the rainfall! and that the evaporation always exceeded the rainfall was for many years the belief among the French hydraulic engineers. (See *Annales des Ponts et Chaussées*, 1850, p. 383.) Observations on a larger scale, and with greater precautions against the undue heating of the evaporator, have since shown, as might have been anticipated, that as a rule, save in exceptionally dry years, the evaporation is lower than the rainfall. As the average of ten years from 1860 to 1869 Mr Greaves found that at Lea Bridge the evaporation from a surface of water was 20·946, while the rainfall was 25·534 (Symons's *British Rainfall* for 1869, p. 162). But we need a vast accumulation of observations, taken in many different situations and exposures, in different rocks and soils, and at various heights above the sea. (For a notice of a method of trying the evaporation from soil, see *British Rainfall*, 1872, p. 206.)

[3] *Reclamation and Protection of Agricultural Land*, Edin., 1874, p. 15.

[4] *Hydrology*, p. 201

[5] In mountainous tracts having a large rainfall and a short descent to the sea, the proportion of water returned to the sea must be very much greater than this. Mr Bateman's observations for seven years in the Loch Katrine district gave a mean annual rainfall of 87½ inches at the head of the lake, with an outflow equivalent to a depth of 81·70 inches of rain removed from the drainage basin of 71½ square miles.

[1] D. Stevenson, *Canal and River Engineering* p. 224.

[2] Contjean, *Géologie*, p. 225.

[3] *Reclamation of Land*, p. 18.

being 11·34. Bischof calculated that, assuming the mean quantity of carbonate of lime in the Rhine to be 9·46 in 100,000 of water, which is the proportion ascertained at Bonn, enough carbonate of lime is carried into the sea by this river for the annual formation of three hundred and thirty-two thousand millions of oyster shells of the usual size. The mineral next in abundance is sulphate of lime, which in some rivers constitutes nearly half of the dissolved mineral matter. Silica amounting to 4·88 parts in 100,000 of water has been found in the Rhine, near Strasburg. The largest amount of alumina was 0·71 in the Loire, near Orleans. The proportion of mineral matter in the Thames, near London, amounts to about 33 in 100,000 parts of water, 15 of which (nearly half of the whole) consist of carbonate of lime.

It requires some reflection properly to appreciate the amount of solid mineral matter which is every year carried in solution from the rocks of the land and diffused by rivers into the sea. According to recent calculations by Mr T. Mellard Reade, C.E., a total of 8,370,630 tons of solids in solution is every year removed by running water from the rocks of England and Wales, which is equivalent to a general lowering of the surface of the country from that cause alone at the rate of ·0077 of a foot in a century or one foot in 12,978 years. The same writer computes the annual discharge of solids in solution by the Rhine to be equal to 92·3 tons per square mile, that of the Rhone at Avignon 232 tons per square mile, and that of the Danube at 72·7 tons per square mile; and he supposes that on an average over the whole world there may be every year dissolved by rain about 100 tons rocky matter per English square mile of surface.[1]

ii. *Mechanical.*—The mechanical work of rivers is threefold:—(1) to transport mud, sand, gravel, or blocks of stone from higher to lower levels; (2) to use these loose materials in eroding their channels; and (3) to deposit these materials where possible, and thus to make new geological formations.

1. Transporting Power.—It is one of the distinctions of river water, as compared with that of springs, that, as a rule, it is less transparent, that is, it contains more or less mineral matter in suspension. The same stream differs much at successive intervals in the amount of material thus transported. In dry weather when the water is low it may be tolerably clear; but a sudden heavy shower or a season of wet weather will render it turbid. The mud thus so frequently noticeable in rivers is partly derived from the surface of the ground on either side, whence it is washed into the main streams by rain and brooks, but partly also by the abrasion of the water-channels through the operations of the streams themselves. In the mountain tributaries of a river we find the channels choked with large fragments of rock disengaged from the cliffs and crags on either side. Traced downwards the blocks are seen to become gradually smaller and more rounded. They are ground against each other and upon the rocky sides and bottom of the channel, getting more and more reduced as they descend, and at the same time abrading the rocks over or against which they are driven. Hence a great deal of debris is produced, and is swept along by the onward and downward movement of the brooks and rivers. The finer portions, such as mud and fine sand, are carried in suspension, and impart the characteristic turbidity to rivers; the coarser sand and gravel are driven along the river bottom.

The transporting capacity of a stream depends (*a*) on the the volume and velocity of the current, and (*b*) on the size, shape, and specific gravity of the sediment. (*a*) According to the calculations of Hopkins, the capacity of transport increases as the sixth power of the velocity of the current; thus the motive power of the current is increased 64 times by the doubling of the velocity, 729 times by trebling, and 4096 times by quadrupling it. It has been found by experiment that "ordinary sandy soil is moved by a current having a velocity of about half a mile an hour, and that a current of about one mile per hour will move fine gravel, while heavy gravel resists a current of upwards of two miles per hour." Mr David Stevenson[2] gives the subjoined table of the power of transport of different velocities of river currents.

In. per Second.		Mile per Hour.	
3	=	0·170	will just begin to work on fine clay.
6	=	0·340	will lift fine sand.
8	=	0·4545	will lift sand as coarse as linseed.
12	=	0·6819	will sweep along fine gravel.
24	=	1·3638	will roll along rounded pebbles 1 inch in diameter.
36	=	2·045	will sweep along slippery angular stones of the size of an egg.

We must never lose sight, however, of the fact that it is not the surface velocity, nor even the mean velocity, of a river which can be taken as the measure of its power of transport, but the bottom velocity—that is, the rate at which the stream overcomes the friction of its channel. (*b*) The average specific gravity of the stones in a river ranges between two and three times that of pure fresh water; hence these stones lose from a half to a third of their weight in air when borne along by the river. Huge blocks which could not be moved by the same amount of energy applied to them on dry ground are swept along with ease when they have found their way into a strong river current. The shape of the fragments greatly affects their portability, when they are too large and heavy to be carried in mechanical suspension. Rounded stones are of course most easily moved; flat and angular ones are moved with comparative difficulty.

Besides their ordinary powers of transport, rivers gain at times considerable additional force from several causes. Those liable to sudden and heavy falls of rain acquire by flooding an enormous increase of transporting and excavating power. More work may thus be done by a stream in a day than could be accomplished by it during years of its ordinary condition.[3] Another source of increase to the action of rivers is provided when, from landslips, formed by earthquakes, by the undermining influence of springs, or otherwise, a stream is temporarily dammed back, and the barrier subsequently gives way. The bursting out of the arrested waters produces great destruction in the valley. Blocks as big as houses may be set in motion, and carried down for considerable distances. Again, the transporting power of rivers is greatly augmented in countries where they freeze in winter. As the ice gathers along the banks it encloses gravel, sand, and even large blocks of rock, which, when thaw comes, are lifted up by the ice and carried down the stream. Ground-ice likewise appears in cold latitudes on the bottoms of the rivers, whence, rising in cakes to the surface, it carries with it sand, mud, or stones lying on the bottom, which are then swept seaward. When rivers such as those of northern Russia and Siberia, flowing from south to north, have the ice thawed in their higher courses before it breaks up farther down, much disaster is sometimes caused by the piling up of the ice, and then by the bursting of the impeded river through the temporary ice-barrier. In another way ice sometimes vastly increases the destructive powers of small streams where avalanches or an advancing glacier cross a valley and pond back its drainage. The valley of the Dranse, in Switzerland, has several times suffered from this cause. In 1818 the glacier barrier extended across the valley for more than half a mile, with a breadth of 600 and a height of 400 feet. The waters above the ice-dam accumulated into a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice, the water was drawn off without desolating the plains below.

That rivers differ vastly from each other in the amount of material they transport is made evident by the great diversities in their relative muddiness. It should be borne in mind that the actual amount of sediment borne downwards by a river is not necessarily determined by the carrying power of the current. The swiftest streams are not always the muddiest. The proportion of sediment is partly dependent upon the hardness or softness of the rocks of the channel, the number of tributaries, the nature and slope of the ground forming the drainage basin, the amount and distribution of the rainfall, the size of the glaciers (where such exist) at the sources of the river, &c. A rainfall spread with some uniformity throughout the year may not sensibly darken the rivers with mud, but the same amount of fall crowded into a few weeks or months may be the means of sweeping a vast amount of earth into the rivers, and sending them down in a greatly discoloured state to the sea. Thus the rivers of India during the rainy season become rolling currents of mud.

In his journeys through equatorial Africa Livingstone came upon rivers which appear usually to consist more of sand than of water. He describes the Zingesi as "a sand rivulet in flood, 60 or 70 yards wide, and waist-deep. Like all these sand-rivers it is for the most part dry; but, by digging down a few feet, water is to be found, which is percolating along the bed on a stratum of clay. In trying to ford it," he remarks, "I felt thousands of particles of coarse sand striking my legs, which gave me the idea that the amount of matter removed by every freshet must be very great. . . . These sand rivers remove vast masses of disintegrated rock before it is fine enough to form soil. In most rivers where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other. This attrition, being carried on for hundreds of miles in different rivers, must have an effect greater than if all the pestles and mortars and mills of the world were grinding and wearing away the rocks."

The amount of mineral matter transported by rivers can be estimated by examining their waters at different periods and places, and determining their solid contents. A complete analysis should take into account what is chemically dissolved, what is mechanically suspended, and what is driven or pushed along the bottom. We have already dealt with the chemically dissolved ingredients. In determinations of the mechanically mixed constituents of river water, it is most advantageous to obtain the proportion first by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the water. The Ganges, according to Everest, contains during the four months of flood earthy matter in the proportion of $\frac{1}{428}$ by weight or $\frac{1}{856}$ by volume,—the mean average for the year being $\frac{1}{510}$ by weight or $\frac{1}{1020}$ by volume. According to Mr Login, the waters of the Irrawaddy contain $\frac{1}{1700}$ by weight of sediment during floods, and $\frac{1}{5725}$ during a low state of the river. The most elaborate measurements and calculations yet made regarding this aspect of the operations of a river are those by Messrs Humphreys and Abbot on the Mississippi, who found, as the mean of many observations carried on continuously at different parts of the river for months together, that the average proportion of sediment contained in the water of the Mississippi is $\frac{1}{1500}$ by weight, or $\frac{1}{2900}$ by volume. But besides the matter held in suspension, they observed that a large amount of coarse detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750 million cubic feet of sand, earth, and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,500,000 million cubic feet, and consequently that the weight of mud annually carried into the sea by this river must reach the sum of 813,500 million ℔. Taking the total annual contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height, with a base of one square mile.

2. Excavating Power.—In transporting its freight of sediment a river performs a vast amount of abrasion. In the first place it rubs the loose stones against each other, breaks them into smaller pieces, rounds off their edges, reduces them to rounded pebbles and finally to sand or mud. In the next place by driving these loose materials over the rocks it wears down the sides and bottom of its channel which is thereby widened and deepened.

The familiar effect of running water upon fragments of rock, in reducing them to smoothed rounded pebbles, is expressed by the common phrase "water-worn." Every stream which descends from high rocky ground may be compared to a grinding mill; large boulders and angular blocks of rocks, disengaged by frosts, springs, and general atmospheric waste, fall into the upper end, and only fine sand and silt are discharged into the sea. M. Daubrée has instituted some ingenious experiments for ascertaining the circumstances under which angular fragments are converted into rounded pebbles with the production of sand and mud. Using fragments of granite and quartz, he caused them to slide over each other in a hollow cylinder partially filled with water, and rotating on its axis with a mean velocity of 0·80 to 1 metre in a second. He found that after the first 25 kilometres (about 15½ English miles) the angular fragments of granite had lost $\frac{4}{10}$ of their weight, while in the same distance fragments already well-rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river bed. A second product of these experiments was an extremely fine impalpable mud, which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment the water acted chemically upon the granite fragments, for after a day or two it was found, even though cold, to have dissolved a very sensible proportion of silicate of potash. After a journey of 160 kilometres, 3 kilogrammes (about 6½ ℔ avoirdupois) had yielded 3·3 grammes (about 50 grains) of soluble salts consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any felspar, almost the whole of the latter mineral having passed into the state of clay. The sand grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But, as M. Daubrée points out, a limit is placed to this attrition by the size and specific gravity of the grains. So long as they are carried in suspension they will not abrade each other, but remain angular; for he found that the milky tint of the Rhine at Strasburg in the months of July and August was due not to mud but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing tumultuous river from the Swiss mountains, and had

---

[1] *Address to Liverpool Geological Society*, 1877.

[2] *Canal and River Engineering*, p. 315.

[3] The extent to which heavy rains can alter the usual characters of rivers is forcibly exemplified in the graphic account of *The Morayshire Floods*, by the late Sir T. Dick Lauder. In the year 1829 the rivers of that region rose 10, 18, and in one case even 50 feet above their common summer level, producing almost incredible havoc.