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Treatment methods for water supplies rural areas of developing countries

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Preface

By invitation from the International Reference Center in Voorburg, The Netherlands, I undertook to prepare a document about drinking water supply problems in rural areas of developing countries. To provide the necessary back-ground material, Messrs. van Gorkum and Kempenaar carried out an extensive literature study about this subject. I am very grateful for the scope and quality of their work, but I am also sorry to note that only little material became available beyond that already generally known. To obtain the desired data, it is clearly necessary to adopt other procedures. The sending out of questionnairies has already been undertaken by the IRC, but replies were not available for incorporation in this document*. As a consequence, the ideas in this report are largely my own and I welcome any positive criticism for improvement.

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* Footnote IRC
Just before finalizing this document it turned out to be possible to incorporate in the annexes information, derived from the IRC questionaires, to which due reference is given.

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1. Introduction

Also in rural areas of developing countries, people do have access to water for domestic purposes. The efforts involved in obtaining this water, however, are often tremendous, while in most cases the water is unreliable and properly speaking should be boiled before drinking , at the same time exercising the utmost care to prevent post-contamination. This is seldom feasible, with as result that the water supply itself endangers the health of the people concerned.

Many governments, often with outside aid, have taken upon theirselves to improve this situation, to provide a better source at a shorter distance from the consumers. In the past these efforts were not always successful and it is wise to recognise the underlying causes for failure. As most important may be mentioned

a. in particular in non-market economies, the people are terribly poor, and for a water supply as a self-paying proposition, only the cheapest methods are available. Even this may prove too expensive, meaning that in rainy periods the population goes back to their former unreliable sources, negating any health benefit the public supply has brought. Providing the people with water free of charge is neither a solution. It makes them indifferent and causes a high consumption, resulting in a waste water disposal problem;

b. everyone, even completely lacking any formal education, has a in-born feeling how drinking water should be, namely clear and without colour, taste or odor. With these standards, bacteriological pollution of surface water is not recognised, resulting in a rejection of ground water when it has a bitter taste due to small amounts of iron. Any public water supply scheme should therefore be preceded and accompanied by a campaign to inform the population. Trained personnel, speaking the local language are indispensible for this, but seldom available in the numbers required;

c. only in (large) cities is it possible to engage the artisans and technicians necessary for operation and maintenance and even here organisational and managerial skills are in short supply, often with detrimental results. In rural areas recruitment must be done locally and an intensive training programme is now required. After the contractor has left, the operator is on this own. He can only do a good job when the installation is simple and its technology as much as possible adapted to local skills. For the water supply itself, lack of adequate operation and maintenance is the most frequent cause for failures. When a dug well is equiped with a pump, but repairs cannot be effected in the immediate neighbourhood, the well cover will eventually be removed and the water abstracked with rope and buckets!

d. it should be realised that a safe drinking water is not enough to prevent the spread of water related diseases. Nature has many other possibilites in store and people should learn how to avoid them. This is only possible by providing primary education to all children of school-going age. By the lack of adequately trained teachers, however, this is a dream that will not be fullfilled in the present century.

Taking all the above-mentioned factors together, it is clearly impossible to provide the rural population of developing countries with drinking water that satisfies western world standards. Here the first concern of the water engineer should be the quantity of the water, making adequate amounts easily available. As regards water quality, he should do the best he can, at the same time avoiding complicated and costly equipment and never aiming at perfection. As prevention is better than cure, he should first of all give his attention to ground water recovery, when necessary spread over various sites or increased in yield by artificial recharge. Private supplies, one for each family, greatly reduce the propagation of water borne diseases and should be given high priority, while for a dispersed population they often form the only possibility. Flowing rivers are able to cary local pollutions over distances of tens to a few hundred kilometers and treatment of such a water is always necessary. Appropriate technology should now be applied, commensurate with the skills locally available as well as with the prevailing social attitudes. Involvement of the local population finally is a pre-requisite for success and great care should therefore be given to obtain and to maintain good communication with the local political and religious leaders.

When contemplating to provide a region with a public water supply, properly speaking a masterplan is necessary, followed by detailed feasibility studies about technical, financial, organisational, managerial, etc., aspects. Before the water engineer can start his work, many investigations should have been carried out of which those on hydrology, hydro-geology and limnology are extremely time consuming and require the help of (foreign) high-level experts. In many cases the project cannot suffer the delay, neither bear the cost of such data collection and the water engineer has to start from scratch, using his ingenuity to solve the problems as they arrive. His capabilities are now the deciding factor for success or failure and all pains should be taken to select the best man available.

As indicated by the tittle of this paper, the contents will be limited to rural supplies, unpiped for a dispersed population having only small nucleated settlements and piped for (larger) villages. Public water supplies to cities are left out of consideration. Their financial scope must be made large enough to engage properly trained personnel, allowing the application of western technology, adapted in one way or another to local circumstances and avoiding the sophistication that is nowadays required to save on unskilled labour.

2. Water consumption

Water is indispensable for life. To perform its physiological functions properly, the adult human body needs 2 - 5 liters per day, depending on climate and work-load. Water in the meanwhile is also required for other duties, for cleaning cooking utensils, dish washing, personal hygiene, laundry, housecleaning, etc. Strange as it may seem, the latter amounts do not vary much with the household size, allowing to calculate the total consumption per family as

$$Q = q_o + n\, q_c$$

with n as number of family members. This relationship was first discovered for the city of the Hague in the Netherlands, giving

$$Q = 120 + n(50) \text{ liters/day}$$

and meaning for a family of 4 an average per capita consumption of 80 liters per day. From data provided by White, Bradley and White (Drawers of water, page 123) about water consumption in Tanzania the follwing formules may be derived

unpiped households $Q = 25 + n(5)$

households with piped connections $Q = 200 + n(80)$

meaning for a family of 5 an average per capita consumption of 10 and 120 liters per day respectively. Already from these figures it will be clear that consumption increases tremendously when water becomes more easily available. As always, such an increase has an ever diminishing return. In case consumption is low, the provision of more water decidedly improves health, by reducing water-washed diseases, by growing of vegetables, etc. When consumption is already high, however, a further increase must be considered as a luxury item, to be used for car washing, watering of the lawn or similar non-essential purposes. Moreover, it should be realised that a major part of the domestic water supply is converted into sewage. As long as the per capita consumption is small, say less than 20 - 40 liters per day depending on soil conditions, disposal is easy, using cess-pools and soak-away pits. With higher consumptions a system of sanitary sewers is required and these are rather expensive to construct.

Taking the above mentioned factors into account, it is proposed to base water consumption in rural areas of developing countries on the following formulas, in which q is the average per capita one for a family of 5

unpiped supplies
- minimum $Q = 10 + n(5)$ $q = 7$ l/day
- adequate $Q = 30 + n(7)$ $q = 13$

piped supplies with standpipes
- $Q = 50 + n(10)$ $q = 20$

households with piped connection
- small village $Q = 100 + n(20)$ $q = 40$
- large village $Q = 125 + n(25)$ $q = 50$

In tropical climates, the variation in daily domestic consumption is less than in temperate ones, while the variation in hourly consumption is somewhat larger. For municipal supplies and piped households connections this means all together about the same capacity for the distribution system and only a sligthly larger clear water storage. With unpiped households on the other hand, the situation is quite different. Here the pattern of daily consumption may be schematized as follows

30% during one hour at the beginning of the day
30% during one and a half hour at the end of the day
40% more or less evenly divided over the remaining day-light hours.

This means a ratio between maximum and average hourly consumption equal to a factor of no less than 7.2, while the clear water storage necessary to flatten out the demand variations rises to one half of the daily consumption. This certainly increases the cost of water supply. Money could be saved with a alternating supply, providing each sector of the community with water during 2 hours per day only. As serious disadvantage must be mentioned, however, that during the remaining 22 hours, the distribution system is without pressure, allowing polluted ground water to enter the system through the always present leaks. Again the water supply becomes a menace to public health.

3. Water sources

3.1. Hydrological cycle

Water is indispensable for man, plant and animal and in this respect it is very fortunate that enormous amounts are available on earth. According to fig. 1, however, only 0.62% of these amounts are fresh water and only 2% of the latter quantity is surface water in rivers and lakes, where it is easily demonstrable and seizable.

Luckily the water on earth, whether as water vapour in the atmosphere, as surface water in streams, lakes, seas and oceans or as groundwater in the interstices of the sub-soil is not at rest, but in a continuous circulatory movement. There is a never-ending transformation from one state to another, known as the hydrologic cycle (fig. 2). Water from the atmosphere falls to the ground as rain, hail, sleet and snow and condenses above ground as well as in the openings of the earth crust. Not all this downward moving atmospheric water, however, adds to surface and groundwater supplies, since there is a continual return to the atmosphere. Part of this water does not reach ground surface at all, but is intercepted by the vegetation and evaporates from there. The water on the ground, in pools and marshes, is exposed to evaporation, as well as that which flows in rivers and lakes. Water in the pores of the sub-soil is also subjected to these losses, while some moreover is consumed by vegetation (transpiration losses). That which remains either flows over or directly beneath ground surface to open water courses, or moves further downward, through the aerated upper strata until it reaches the ground water table and recharges the ground water supply. This ground water is not stagnant, but flows through the soil in the direction of the downward slope of the ground water table. Sooner or later it appears again at the surface, visible in the form of springs and invisible as ground water overflows in rivers and lakes. The smaller streams combine to form larger rivers which carry the water to the sea. Here, evaporation returns it to the atmosphere and the cycle begins once more.

The volume of the hydrologic cycle, that is the amount of water flowing yearly from land to sea and conversely may be calculated by drawing up a water balance for the combined land and sea areas of the world. As an average over a long period (to smooth out climatic fluctuations), the resulting flows are represented in fig. 3. Over the land surface of the earth, the circulatory movement has a capacity of 105.000 km^3/year or $(0.105)10^{15}$ m^3/year, which for a total fresh water stock of $(8.4)10^{15}$ m^3 corresponds with an average detention time of 80 years. Related to the surface exchange between land and sea at 30.000 km^3/year or $(0.03)10^{15}$ m^3/year, this detention time rises to 280 years, meaning that it takes nearly 3 centuries, on average, before the fresh water stock on the land surfaces of the world is replaced by new water coming from the sea.

For the water supply of a particular region, global figures are of little value and here the volume of the hydrologic cycle is determined on one hand by rainfall and on the other hand by residual rainfall, being the difference between rainfall and losses due to evapo-transpiration. Rainfall shows great seasonal and geographic variations (fig. 4), but many times greater are the fluctuations in residual rainfall, varying from strongly negative values in tropical desert areas to values over 2000 mm/year in mountainous regions.

Water for domestic use may be abstracted from the hydrologic cycle at various points

as roof drainage before it reaches the ground,
as ground catchment before it runs off or percolates downward,
as ground water,
as springwater at the point of re-emergence to ground surface

and as surface water from rivers and lakes. To these natural possibilities may be added man-made ones such as abstracting water vapour from the atmosphere by condensation and creating or increasing ground water supplies by induced or artificial recharge. Not all these possibilities are available everywhere and always, while each of them has special advantages and disadvantages. They will be described in more detail in the subsequent sections.

3.2. Rain Water

Where people have their permanent homes, rainwater is always available and from times immemorial it has been a major source for domestic supplies all over the world. As drawback must be mentioned that in dry climates the amounts are rather small with sometimes many rainless months in succession. Assuming an annual rainfall of 0,5 m and a roof catchment (fig. 5) with an efficiency of 80 - 90%, an amount of 0,425 m^3/m^2, year becomes available. For a family of 5 and minimum requirements (section 2), the consumption equals 35 l/day or 12.8 m^3/year for which a catchment area of 30 m^2 is sufficient. In case the rainless period has a duration of half a year, a storage of theoretically 6.4 m^3 is required. Taking into account evaporation losses this amount must be raised to 7.5 m^3, which may be accomodated in a cistern of for instance 2 m diameter and a depth of 2.5 m. When water requirements are larger, the roof area will not longer suffice and ground catchments must be used. For the same rainfall of 0.5 m/year, an efficiency of 60 - 80%, again a family of 5 but an adequate provision at 65 l/day, the required area rises to 68 m^2 and the necessary storage to 14 m^3. In general, the size of the catchment area will provide no problems, but the volume of the cistern is too large an effort for a single family. By combining forces, the economy of scale helps and for a small village or a limited sector of a larger one, the cisterns of fig. 6 en 7 may be applied.

Rainwater harvested with the help of ground catchments will always be polluted, by bird droppings, by wind blown dust and when left unprotected, also by the excrements of animals. This is the reason that the cisterns of fig. 6 and 7 are provided with sand filters, certainly able to produce a clear water which in many cases will also be fairly reliable in hygienic respect. Better results in this respect can be obtained with the system of fig. 8, developed for rural supplies in Germany. Roof catchments are less polluted while as individual supplies they tend to get better care, in this case a regular cleaning of catchment surfaces and collecting troughs. Some purification is still desirable, for which fig. 9 shows a simple sand filter.

The construction shown in the preceding figures were developed by and for use in the western world. It goes without saying that they cannot be applied unchanged in rural areas of developing countries. Adaptation to local circumstances is necessary, taking into account locally available materials, skills, etc. To stimulate the imagination of the designing engineer, Annex 1 shows a number of roof catchments and Annex 2 a number of ground catchments, including systems which properly speaking belong to the artificial recharge of section 3.6.

3.3. Springwater

Without any doubt, groundwater is the best source for domestic supplies. Since it was born as downward percolating rain- or river-water, tens to hundred of years have elapsed during which period all pathogenic organisms have died away, resulting in a water safe in hygienic respect. Groundwater does have as disadvantage that it is invisible and therefore unknown and that for its recovery more or less elaborate works are necessary. These drawbacks, however, do not hold true for groundwater that returns to ground surface in the form of springs (fig. 2), where it is directly recognisable and seizable.

Leaving outward appearances out of consideration and looking only at the etiology of springs, four different types may be distinquished, shown together in fig. 10. The depression springs on the left of this figure are rather variable in yield, while in dry periods and a lower groundwater table, they may cease to flow altogether. Gravity springs (fig. 11, 12) are more reliable in this respect, in particular the artesian contact spring (fig. 12) with a catchment area a great distance away.

To maintain the hygienic purity of spring water, it must be recovered in such a way that any possibility of pollution is avoided. For larger amounts of water, drains (fig. 13) and galleries (fig. 14) may be used, while smaller amounts can also be recovered with wells (fig. 15). An interesting possibility is the use of drains (fig. 16) or perforated pipes driven more or less horizontally into the hill side, whereby protection against pollution from ground surface is easier to obtain. For the provision of a group of houses or a small village, fissure springs (fig. 17) are particularly attractive. Abstraction is easy, reliable and cheap, as shown in fig. 18 and 19. Again it must be realized that not all the constructions mentioned above can be applied under more primitive conditions. Annex 3 shows examples of the ingenuity applied in using locally available materials and skills to tap spring water.

3.4. Groundwater

Large scale recovery of groundwater, for irrigation and domestic use, started in the first millenium B.C. In Persia of that time galleries (qanats) were constructed (fig. 20) with average lengths of 10 - 15 km, while in other countries of the Middle East dug wells (fig. 21) were sunk to depths of commonly 5 - 30 m. Tube wells of small diameter so as to be able to reach greater depths, have their origin in China (fig. 22) and their application in other parts of the world is only a few centuries old. As mentioned before, groundwater has the enormous advantage of being safe in bacteriological respect. To this must be added that under suitable conditions it can be recovered at many places, also in the direct neighbourhood of population clusters, shortening the distance it must be carried to the various households. Individual supplies, one for each family, may also be considered, in which case they will be kept in better condition while the consequences of pollution are appreciably less.

Galleries for groundwater abstraction are simple to build (fig. 23), but due to their shallow depth below ground surface, they are difficult to protect against contaminated water percolating down from ground surface. Due to point abstraction, dug wells are better suited in this respect, while their construction is still so simple that they can be made by local artisans from local materials without specialized equipment or skills. As a consequence of their method of construction, dug wells have a large diameter, at least 1 m, by which they are able to store great quantities of water, thus allowing periodic abstractions at a larger rate than that of the groundwater that actually flows into the well. This reservoir effect is particularly important for agricultural societies where the amount of water needed varies enormously with time (section 2).

To prevent pollution of the groundwater abstracted by a dug well, the curb must be water tight over its upper part, if possible to a depth of a few meters below the lowest groundwater level during operation. To protect the water inside the well against pollution by wind blown material or by objects falling into the well opening, a tight cover made of durable material is a strict requirement. This precludes water abstraction by rope and bucket (fig. 21) and a (hand) pump must now be installed (fig. 24). Due to wear and tear, this pump is bound to fail after some time of use with as consequence that in the neighbourhood a reserve pump must be available as well as the skills to install it. When the upper soil layers are stiff, clay for instance, the annular space produced around the well during sinking will not be self-sealing and must be filled with grout to prevent incursion of surface drainage around the well perimeter. This is demonstrated in fig. 25, which picture also shows that around the well an artificial mound is desirable, provided with pavement to let rain- and spilled water flow away from the well as quickly as possible.

When water has to be tapped at greater depths, tube wells must be used. For depths of a few tens of meters, driven (fig. 26) or jetted wells offer an attractive solution, but they do have the disadvantage that all materials must be imported. For larger depths drilling methods have to be applied. In western-type countries, straigth or reverse hydraulic rotary drilling is used almost exclusively, but for developing countries percussion methods (fig. 27) are better suited. They are certainly slower and more labour intensive, but on the other hand they are safer, more reliable, require less skilled personnel and are better adapted to the local ways of living. In case only unconsolidated formations must be penetrated, the entire tool string can be replaced by a mud-scow, acting both as bit and bailer. Also with percussion methods the drilling rig must be imported, but for the well itself local materials may be used, such as wood stave pipes both for casing and screen.

Tube wells require little in the field of sanitary protection. Due to the great depth at which the screen is set, the groundwater is reliable in bacteriological respect while the small diameter of the casing makes pollution prevention of the water abstacted quite easy. A disadvantage must be noted that pumps are necessary for recovery of the water.

3.5. Surface water

For rural supplies in developing countries, surface water sources show many disadvantages. Rivers are not always perennial. By contact with human and animal life the water is polluted and always needs treatment before domestic use. It is only locally available and when situated at a greater distance from the community, a pumping station with pipelines and standposts are at least required. Individual supplies finally are not feasible.

The least objectionable solution is the abstraction of water from natural or artificial lakes. Here the water is at least clear and when abstracted at some distance from the shoreline (fig. 28), the pollution is rather small, allowing an adequate treatment by slow sand filtration only. Due to turbulent mixing, river water has about the same quality over the full cross-sectional area and abstraction near the shore (fig. 29) will show little disadvantages. In particular with turbid waters, an extensive treatment is now required, comprising at least plain sedimentation and slow sand filtration and under more severe conditions chemical coagulation, flocculation, settling, rapid filtration and disinfection. Needless to say that in many instances the help of foreign firms is required for construction, while for operation imported chemicals, technical know-how and managerial skills must be available. In case that during dry periods the river water fails in quantitative or qualitative respect, storage reservoirs must be constructed, offering the added advantage of quality improvement by self-purification. Simpler treatment mehtods may now be used as otherwise would be required.

3.6. Artificial recharge

Artificial recharge may be defined as the planned activity of man whereby surface water from streams or lakes is made to infiltrate the ground, in the context of this paper to allow or to increase the recovery of groundwater. According to Meinzer, the methods of artificially increasing groundwater supplies may be classified in two broad groups

a. indirect methods, in which increased recharge is obtained by locating the means for groundwater abstraction as close as practicable to areas of rejected recharge or natural discharge;

b. direct methods in which water from surface sources is conveyed to points from which it percolates into a body of groundwater.

The indirect methods are better known as induced recharge and are commonly accomplished by inducing movement of water from a stream or lake into the ground as a result of groundwater recovery at a short distance from the shoreline. Schematically this is shown in fig. 30, where the drawdown accompanying groundwater abstraction causes river water to enter the aquifer. Provided that the distance from the well, line of wells or gallery to the river is larger than about 50 m and that the river water needs at least one month to reach the collectors, the water recovered is safe in bacteriological respect.

The direct methods are more complicated and require at least transportation of the water, but do have greater potentialities as here the source of surface water and the aquifer to be replenished are separate items so that for each the best possibility can be chosen. Depending on local geo-hydrologic conditions, the actual recharge may be accomplished with spreading basins, with the help of pits and shafts or by injection wells. Spreading basins are most simple to construct and operate and are shown in fig. 31, in this case at a short distance from the river. For the same situation fig. 32 demonstrates how the quality of the recharge water may be improved by a simple pre-treatment, consisting of aeration, roughing filters and again aeration. The quality of the groundwater abstracted in this case can complete with the best treatment systems available. It is, moreover, a natural treatment, less likely to fail with inexpert operation.

4. Water treatment

4.1. General

The quality of domestic water has to satisfy two requirements, it must be safe and it ought to be attractive to use. Both aspects may be realized by a judicious selection of the source or by purification after recovery. By lack of money and skills, treatment is always a difficult proposition in rural areas of developing countries and when unavoidable, it should be realized in the simplest way, using an appropriate technology adapted to local possibilities and preferences. To make a water supply system under these conditions a success, the local population should feel involved in the efforts and this is only feasible by using as much as possible local materials and skills. For good health in the meanwhile, also the amounts of water available must be adequate. In some cases, such as rainwater, this may be limited by the size of the source while with spring water or surface water supplies the distance to the source is commonly the limiting factor. This may be alleviated by a piped supply, but this involves large amounts of local labour and foreign currency. When transport by gravity is not possible and pumps must be used, the cost of construction shows an additional rise, while operation and maintenance will now require skilled labour, seldom locally available.

Taking the above mentioned factors into account, a list of declining preferences could be set up as shown below

a. groundwater, requiring no treatment, recovered at various places at short distances from the consumers;
b. springwater, requiring no treatment, recovered at some distance and carried to the consumption area by a gravity system;
c. groundwater, requiring simple treatment, recovered locally;
d. individual rainwater supplies;
e. springwater, requiring simple treatment and a gravity supply;
f. lake water, requiring simple treatment, recovered at some distance and carried to the distribution area by a pump driven piped supply;

g. water from rivers, requiring an extensive treatment and pumping to the supply area.

Spring- and natural or artificial groundwater are safe in hygienic respect, but when they are anaerobic, they may contain too high amounts of iron and manganese. Removal is easy by aeration, sedimentation and mechanical filtration. In case (post) pollution of spring-, ground and rainwater is not excluded, biological (slow sand) filtration should be used, if necessary preceded by aeration. The same slow sand filters may be applied for the treatment of surface water with little turbidity. For river water with a high suspended matter content and perhaps a large load of organic and bacteriological pollutants, a number of unit operations must be set one behind the other such as plain sedimentation, chemical coagulation with flocculation and settling, rapid filtration and disinfection or slow sand filtration.

When considering treatment systems, it should be realized that one treatment is able to perform various functions such as clarification, deferrisation and removal of pathogenic organisms by slow sand filtration, while on the other hand one purpose can be served by different treatments such as removal of suspended matter by sedimentation as well as by filtration.

4.2. Aeration

Aeration is the process whereby water is brought into intimate contact with air for the purpose of raising the oxygen content, lowering the carbon dioxyde content and removing obnoxious gases such as methane and hydrogen sulfide. Aeration may be necessary for groundwater, but when it is required for surface water this points to such a heavy organic pollution that a better source should be sought.

Aeration may be accomplished in many ways, commonly classified in three broad groups, waterfall aerators, bubble aerators and mechanical aerators. With waterfall aerators, the water falls though the air, in fine droplets or thin sheets. They are simplest to construct, give excellent results and should therefore be preferred when working under more primitive conditions. In their turn, waterfall aerators may be constructed in different ways, as spray aerators with upward or downward water outflow, as multiple tray aerators and as cascade aerators, the latter having as advantage that the loss of carbon dioxyde can be made small. Spray aeration needs an elaborate pipe distribution system to deliver the water to the various nozzles, making its construction rather expensive. Without any doubts, multiple tray aerators (fig. 33) offer the cheapest and simplest construction, requiring only little space and doing an excellent job both with regard to oxygen absorbtion as to removal of undesired gases. Cascade aerators (fig. 34) require more space (loading 20 to 100 m^3/hour per m width), are more expensive to construct but must be used when the water recovered is in carbon dioxyde - bicarbonate equilibrium, meaning that a loss of carbon dioxyde would result in a precipitation of calcium carbonate.

Under all circumstances, the water during aeration must be protected against pollution, by contact with people or animals or by wind blown material. This may be obtained by setting the aerator on a fenced-in pasture and removing all shrubs and trees to a distance of about 30 m.

When groundwater is anaerobic and needs aeration, it may also contain minerals such as iron and manganese in amounts too high for domestic use. During aeration these substances are converted into insoluble ferric- or manganic oxyde hydrates, which may subsequently be removed by sedimentation or filtration.

4.3. Plain sedimentation

In a flowing river, a classification of undissolved particles takes place. Those with a mass density less than that of water accumulate at the surface. Particles much heavier than water, e.g. sand, are transported rolling and trumbling over the river bottom, while particles with a mass density only slightly larger than that of the surrounding fluid are kept in suspension by turbulence and bottom scour. As shown in section 3.5, river water intakes can be constructed in such a way that the abstraction of floating matter or bottom transport is avoided. It is impossible, however, to prevent the carrying along of suspended particles, meaning that the water taken in may be turbid and so unacceptable as drinking water.

Removal of turbidity may be accomplished in different ways, of which plain sedimentation is the simplest. With this process, the water to be treated flows through a tank of large cross-sectional area, creating a state of virtual quiescence. This allows the (slightly) heavier particles to move downward and to accumulate at the bottom, after which the water leaves the tank in a clarified condition. For particles which do not tend to coalesce during settling, the overflow rate, that is the ratio between the amount of water to be treated and the surface area of the tank, is the deciding factor. The depth of the tank is of little importance and may be kept quite small, say 1 m. For flocculating mud particles, the purifying effect also depends on the detention time, requiring a greater depth, 2 m or more when possible. To avoid short-circuiting, the ratio between the length and the width of the tank should be chosen quite large, between 3 and 6. For the same reason the inflow and outflow of water should be divided evenly over the whole width, which can be accomplished quite easily with straight weirs.

Basins for plain sedimentation can be constructed as simple dug basins with an overflow rate of 1 to 10 m/day. Taking a common value of 2 m/day, a village of 1000 inhabitants and a per capita and day consumption of 30 liters would require a pond of say 1.5 m depth with side slopes of 1 to 1.5, a bottom, width of 2 m and a bottom length of 10.5 m of which 7.5 m between the inlet and outlet weirs (fig. 35). With regard to cleaning, by draining, drying and excavation of the accumulated material, two of such tanks should be constructed.

It should be realized in the meanwhile, that plain sedimentation alone is seldom sufficient to produce a water of the desired clarity, while it is superfluous for water abstracted from lakes or from storage reservoirs, created to bridge over dry periods with unsufficient amounts or inadequate quality of the water in the river.

4.4. Chemical coagulation, flocculation and settling

The efficiency of plain sedimentation is greatly enhanced and also extended to colloidal matter (including colour), when the suspended particles in the raw water can be made to coalesce, thus forming larger flocs with a higher rate of subsidence. In case these particles carry a (like) electric charge, this is only possible after neutralization by the addition of chemicals. Commonly three-valent iron or aluminium salts are used for this purpose, which after dissolution in the water form micro-flocs almost instantanuously. By stirring (flocculation) these flocs combine with the suspended matter naturally present in the water, producing the desired aggregates of high settling velocity (25 - 75 m/day). By subsequent sedimentation these flocs can easily be removed.

From the description given above, it will be clear that a number of different operations can be distinguished

a. acquisition and storage of chemicals;
b. dosing of chemicals in an amount dependent on the quantity and quality of the water to be treated;
c. mixing of the chemicals with the water;
d. flocculation;
e. settling.

In rural areas of developing countries it is difficult to obtain chemicals from far away places, while the lack of managerial skills will endanger the continuity of the supply. In some areas, however, locally available materials can be used, either as such or after a simple treatment (annex 8). The amount of chemicals needed per unit volume of water varies with water quality, that is with the time of the year, and is fairly complicated to assess correctly, in particular when the acidity of the water needs adjustment. This problem can be made somewhat easier to solve when coagulating chemicals are used which are able to work in a wide p_H range and which are rather indifferent to the size of the dose. Once this dose has been determined, the quantity of chemicals to be added to the water, either in a constant rate or proportional to a varying flow of water, can be ascertained. For the addition of the chemicals itself, many simple devices have been developed (fig. 36), which with proper care are able to work to satisfaction (Annex 9). Mixing of the chemicals with the water is best done mechanically (flash mixers), but also with hydraulic means adequate results can be obtained. Hydraulic mixing is most efficient with a hydraulic jump, but in many cases the turbulence downstreams of an overflow weir is also able to do the job (fig. 37). Modern flocculators are again of the mechanical type, but also here hydraulic ones using the turbulence created by the flow of water around baffles can do an adequate job and are simple to construct (fig. 38). Somewhat larger detention times are now necessary, say between ½ and 1 hour. Settling finally offers little difficulties. It can be accomplished in the same way as described in the preceding section for plain sedimentation, with the only provision that the depth should be somewhat greater to accomodate the larger amounts of sludge.

Summing up, it must be said that chemical coagulation is a complicated and expensive treatment to say the least. It should therefore be avoided as long as possible, preferably by choosing a better source for raw water. The effluent of the settling tank always contains some suspended flocs and a subsequent treatment is therefore necessary to obtain the desired clarity.

4.5. Slow sand filtration

Filtration is the purification process, whereby the water to be treated is passed through a porous substance. During this passage water quality improves by removal of suspended and colloidal matter, by reduction of the number of bacteria and other organisms and by changes in its chemical constituents. In principle the porous substance mentioned above may be any stable material, but in the field of domestic supplies beds of granular material are used exclusively, in 99% of the cases consisting of sand. Sand is cheap, inert, durable, widely available and gives excellent results. As long as sand can be applied, other materials do not need to be considered.

When during the process of filtration impurities are removed from the water, they accumulate on and between the grains of the filterbed, reducing the effective pore space by which the resistance against the flow of water increases. After some time this resistance becomes so high that cleaning the filter is necessary to maintain its capacity. With slow filters the bed is composed of ungraded fine sand, effective size between 0.1 and 0.3 mm. This sand is so fine indeed, that the suspended and colloidal matter from the raw water is retained in the very top of the filterbed. The clogged material here may be removed and the filter restored to its original capacity by scraping off this top layer of dirty sand, to a depth varying from one to a few centimeters. To increase the length of filterrun, that is the interval between two consecutive scrapings, to workable values of one to a few months, the filtration rate must be quite small with values commonly between 2 and 5 m/day.

Essentially a slow filter consists of a water tight box (fig. 39), provided with an underdrainage system to support the filtering material. The filterbed has commonly a thickness of 0.8 to 1.3 m, while on top the water to be treated is present to a depth of 1 to 1.5 m. Inlets and outlets should be provided with controllers to keep the raw water level and the filtration rate constant. Modern slow sand filters tend to be of complicated design (fig. 40), often covered to prevent algae growth and provided with mechanical cleaning equipment to save on labour. Older constructions (fig. 41), however, are also able to do a good job, while all over the world designs have evolved to use locally available materials and skills to the utmost extends (Annex 10).

Slow sand filters have a tremendous purifying capacity, not to be surpassed by any other single unit operation. They are able to supply a water of excellent clarity, free from obnoxious dissolved impurities and safe in bacteriological respect. As prerequisite must be mentioned, however, that the raw water is not too polluted, with in particular a low suspended matter content. This gives as application the sole treatment of water from lakes and reservoirs and the final treatment after settling of river water. Slow sand filters can also be used to advantage for the removal of iron and manganese from groundwater after aeration. With regard to cleaning, at least 2 units should be provided of such a capacity that one is able to do the job.

4.6. Rapid filtration

When greater amounts of water must be treated, slow sand filters certainly have the disadvantage of a small filtration rate, asking for large areas of filterbed. Basically this is due to the small silt storage capacity, in the very upperpart of the filterbed only. Improvement is possible by deep bed filtration, using coarser and in particular more uniform sand grains (say 0.8 - 1.2 mm). Impurities from the raw water now penetrate to such great depths in the filterbed, that cleaning by scraping is impossible. This must be effected by back-washing, reversing the flow of water which expands the filterbed and scours the grains, carrying the dislodged impurities to waste (fig. 42). Such a way of cleaning a filter is easy and quick, by which the length of filterrun may be reduced to one or a few days, again allowing a higher rate of filtration or the use of more turbid river waters. Common filter rates vary from 100 to 250 m/day, that is fifty times as high as with a slow filter with a corresponding reduction in filterbed area.

It should be realized in the meanwhile, that rapid filtration plants are quite complicated (fig. 43). Not only design and construction, but also operation and maintenance are a matter for experts. This makes them unsuited for rural supplies in developing countries. In developed countries they are either used as pretreatment, to lighten the load on subsequent slow sand filters or as treatment after chemical coagulation, flocculation and settling, to be followed by disinfection only. Even here the lack of trained personnel has forced an integration of a large number of small supplies into a small number of big ones, encompassing a whole province or more and limiting surface water intakes to one or a few points only. This certainly increases the cost of transportation, but it reduces the number of treatment plants which are difficult to supervise adequately.

4.7. Activated carbon filtration

With the preceding treatments, removal of taste and odour producing substances is only possible to a limited extend, meaning that when the raw water is of low quality in this respect, also the quality of the water going into supply will suffer. This may affect the health of the population concerned as they are now apt to go back to their old, unsafe sources to obtain a better tasting water for drinking purposes. Removal of taste and odour producing substances can be improved by adsorbtion on activated carbon, for which in developing countries many sources are often available (Annex 11). Activated carbon filtration can be effected prior to slow sand filtration in separate units, using high filtration rates and correspondingly smaller filterbed areas or it can be achieved by topping the bed of a slow sand filter with a 0.1 or 0.2 m thick layer of activated carbon. When the grain size of this material is 2 to 3 times coarser than that of the underlying sand, the length of filterrun will be greatly extended, for instance to 6 months, compensating the additional labour necessary to remove the carbon layer prior to cleaning the slow sand filterbed by scraping.

4.8. Disinfection

Disinfection serves to kill pathogenic organisms by chemical action. Mostly oxidants are used for this purpose, meaning that for proper results the organic matter content of the water must be small, which can best be obtained by applying disinfection as the last step in the purification process. The majority of the most widely used disinfectants cannot be applied in rural areas of developing countries. Gaseous chlorine is too cumbersome and too expensive to transport over great distances, while chlorine dioxyde and ozone must be made locally for which the necessary skills are unavailable. This leaves as possibilities the chlorine compounds $NaOCl$ and $CaOCl_2$, next to the halogens bromium and iodine. During storage chlorine compounds are partly degraded into $NaCl$ and $CaCl_2$ respectively, decreasing their disinfective powers. Bromium and iodine may be lost by evaporation, but what remains has the same strength as before.

By virtue of its origin, groundwater is safe in hygienic respect and does not need any disinfection at all. This may become necessary when after recovery pollution occurs, such as is unevitably when abstracting groundwater by a dug well with an open top. The proper dosing of disinfectants is now rather difficult. Annex 12 shows a few constructions which have been used with success. By contact with man and animals, surface water is always contaminated and needs treatment. With a good quality surface water, from lakes and reservoirs or from fairly clear rivers after plain sedimentation, slow sand filtration is able to produce a safe water. In other cases, disinfection is again required. Dosing and feeding are in principle the same as for chemical coagulation. Annex 12 shows a number of constructions.

Privately the hygienic quality of drinking water can be assured by boiling. This is completely effective, provided that post-contamination during cooling is avoided.

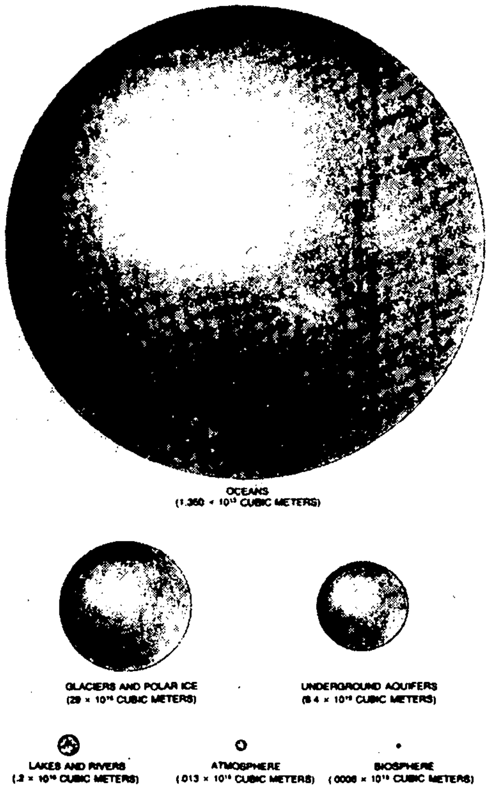
5. Water transport and distribution

In case groundwater is available, it mostly can be recovered at many places. When a few are chosen inside the village, there is no need for transportation or distribution, the aquifer itself taking care of these requirements.

Springs as well as lakes and rivers only occur locally and water from these sources mostly needs transportation to the area of consumption. When the spring is at a higher elevation than the village to be supplied, gravity flow can be used, doing away with the need for pumps and engines. Rivers and lakes nearly always are at a lower elevation and here pumping is strictly required. Pumps can never be obtained locally and must be bought from elsewhere. Once installed they need only simple maintenance and their useful length of life is long. Internal combustion engines again need to come from far, but their proper operation and maintenance is fairly complicated and in many cases cannot be entrusted to the local population. They also require fuel, creating additional financial and managerial problems. When possible locally available energy sources should therefore be sought. In some instances good results have been obtained with wind or hydraulic power.

For rural supplies in developing countries only small amounts of water are necessary, according to section 4.3 not more than 30 m^3/day (in average 0.35 l/sec) for a village of 1000 inhabitants. Small diameter pipes will suffice and they are best made of plastic or asbestic cement, depending on local circumstances. For a gravity supply during 24 hours per day, the capacity need not to be larger than the average consumption at 0.35 l/sec, provided that an elevated storage tank with a volume of 15 m^3 is installed (section 2). With a pumped supply during 12 hours per day, the capacity of the pipeline must be increased to 0.7 l/sec, while the clear water storage may be reduced to 12 m^3. These are sizable amounts, but they may be accomodated in a number of (steel) tanks, while the elevation above ground surface does not need to be more than a few meters.

To prevent a sewerage problem to arise, it is essential to keep water consumption down and this can best be achieved by limiting the number of house connections, serving the majority of people with standpipes. This also allows a simple lay-out of the distribution system, with a minimum number of auxiliaries, limiting the cost of construction and facilitating maintenance and operation.



DISTRIBUTION OF WATER on the earth is indicated in this illustration, in which the amount of water present in various natural reservoirs is represented in terms of comparative spherical volumes. The number under the name of each reservoir denotes the contents of that reservoir in cubic meters. Although the atmosphere contains a mere hundred-thousandth of all the water in the hydrosphere, the influence of this small amount on the climate of the earth and on the location of hydrologic resources is far out of proportion to its mass.

Fig. 1. Distribution of water on earth

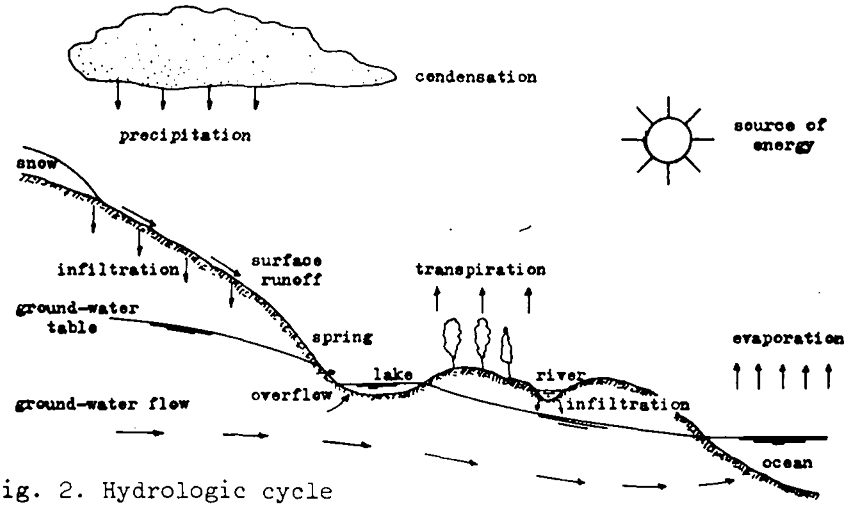


Fig. 2. Hydrologic cycle

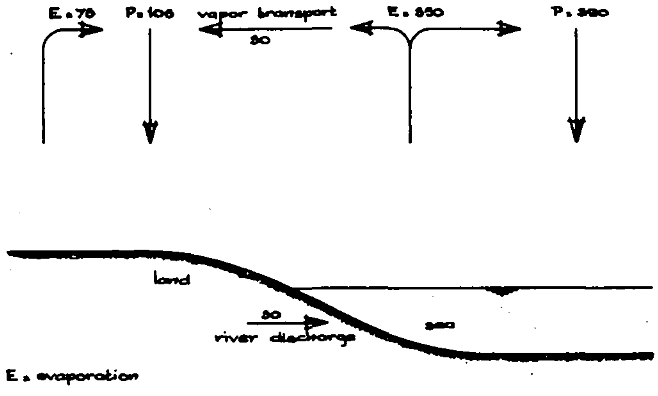


Fig. 3. Global water movements in 1000 km^3/year

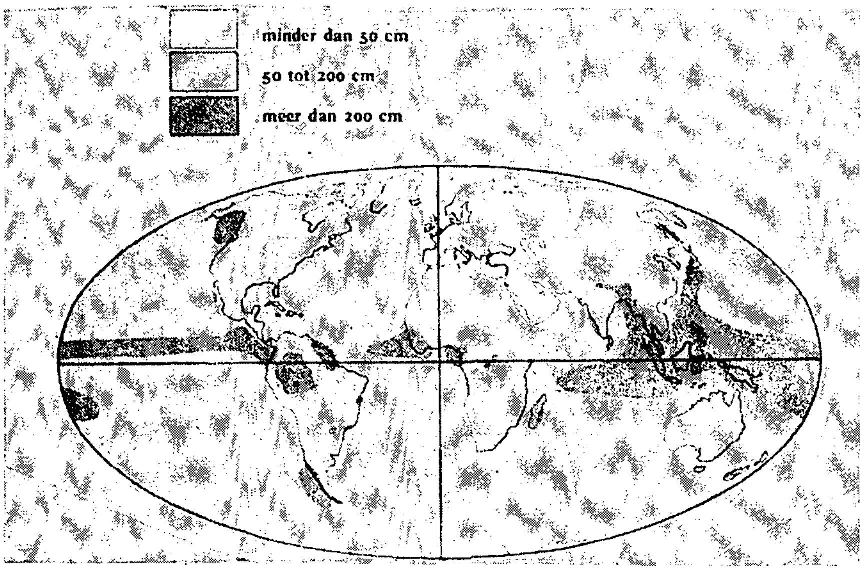


Fig. 4. Global rainfall distribution

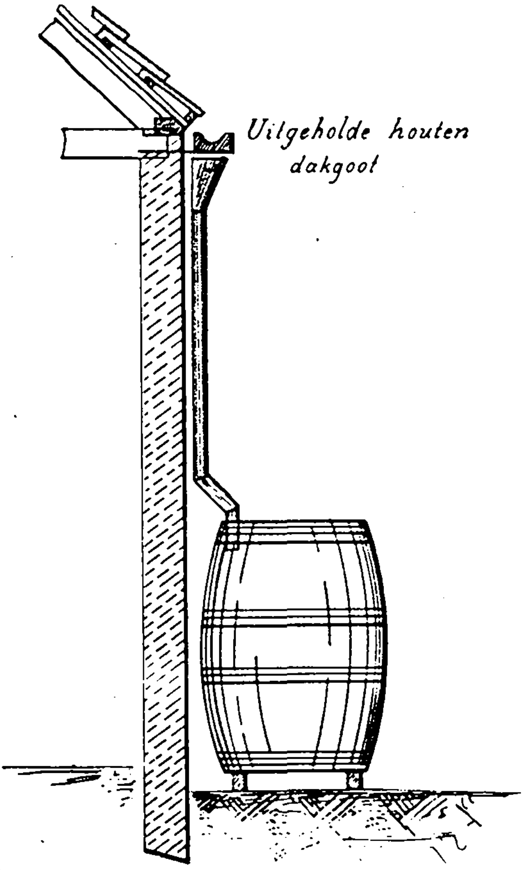


Fig. 5. Roof catchment

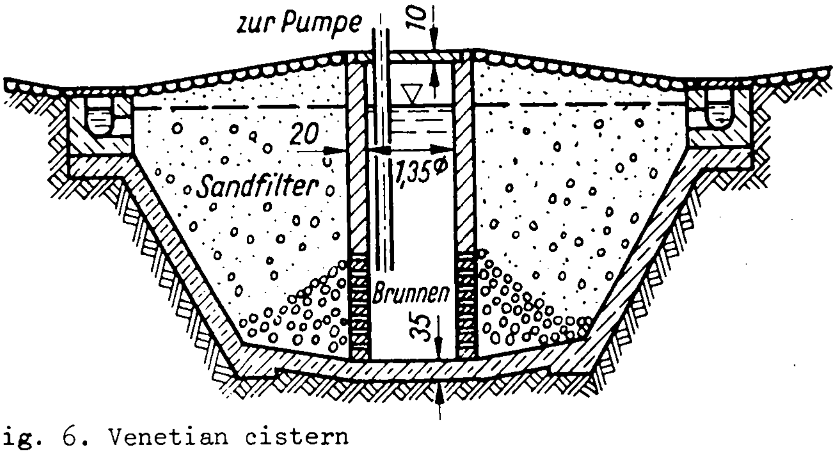


Fig. 6. Venetian cistern

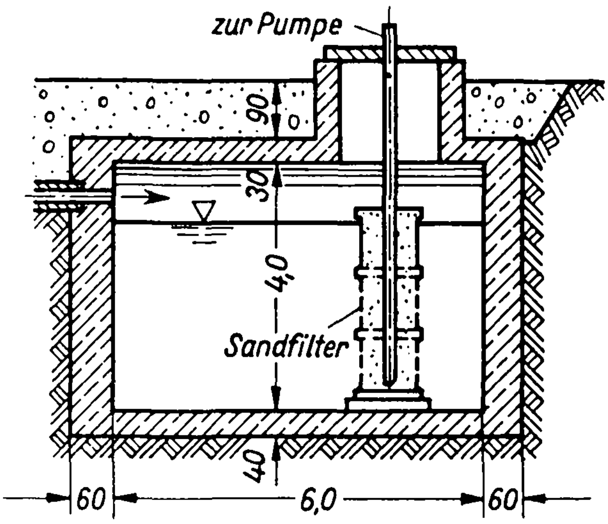


Fig. 7. American cistern

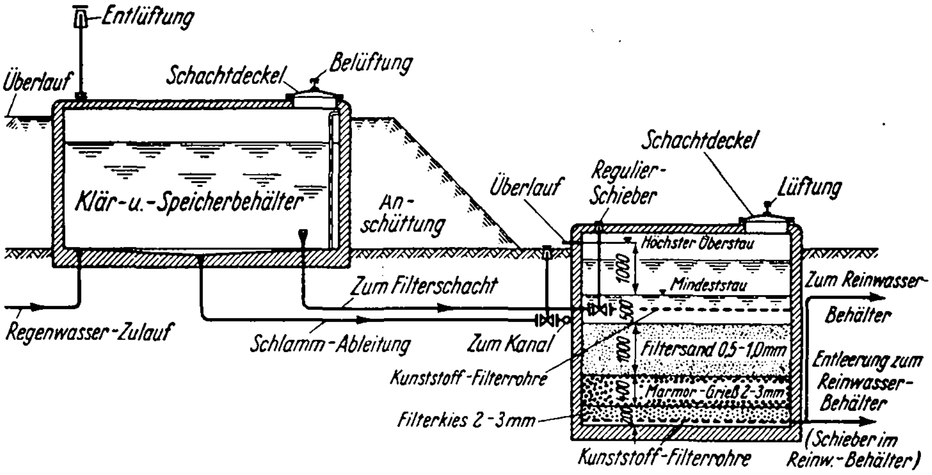


Fig. 8. Purification of rainwater for a public supply

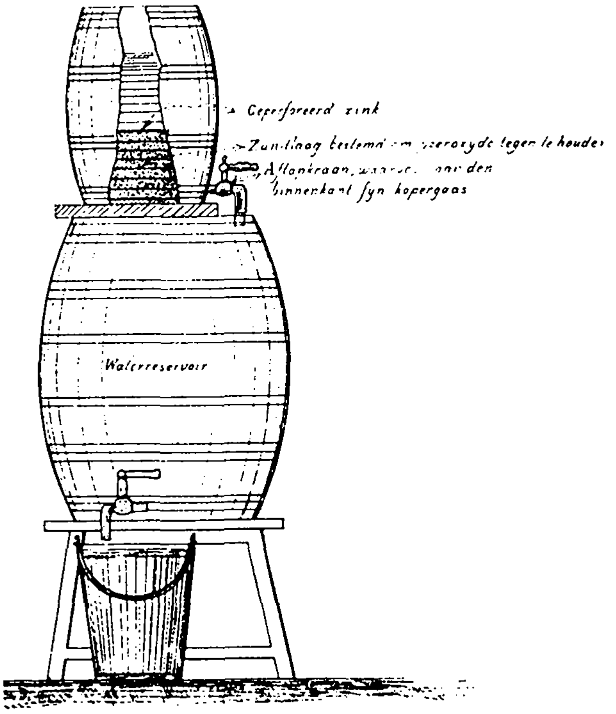
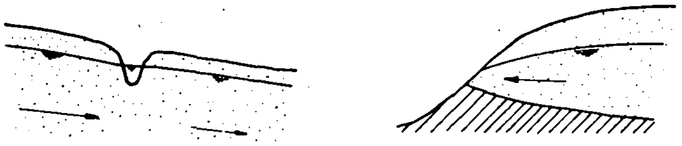


Fig. 9. Purification of rainwater for an individual supply



gravity depression spring

gravity contact spring

artesian depression spring

artesian contact spring

Fig. 10. Springs

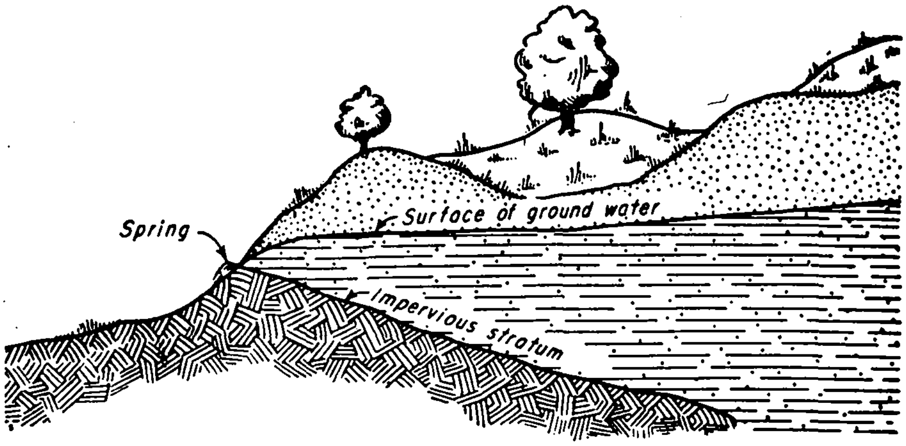


Fig. 11. Overflow spring

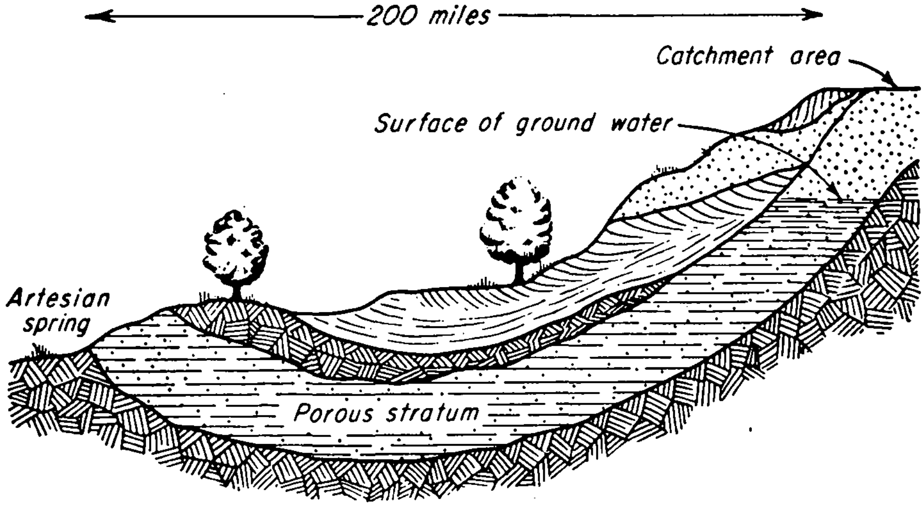


Fig. 12. Artesian spring

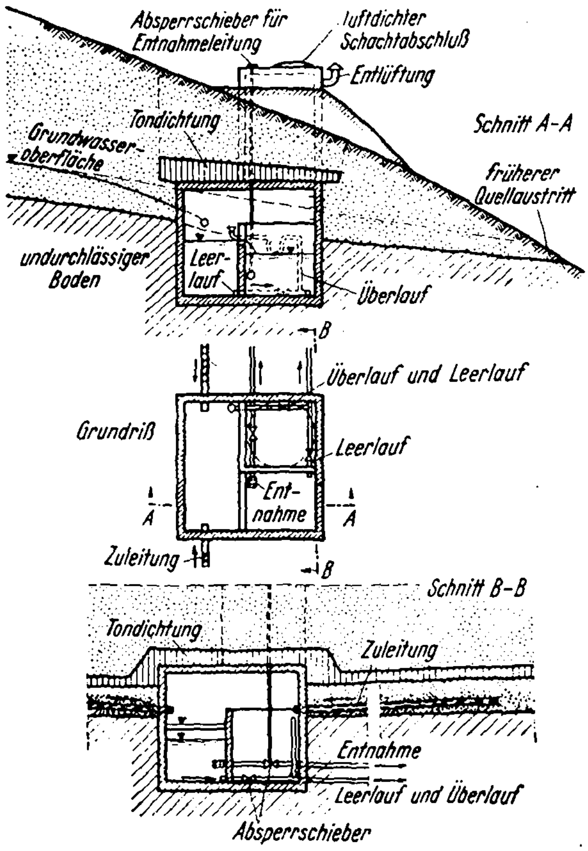


Fig. 13. Recovery of spring water with drains

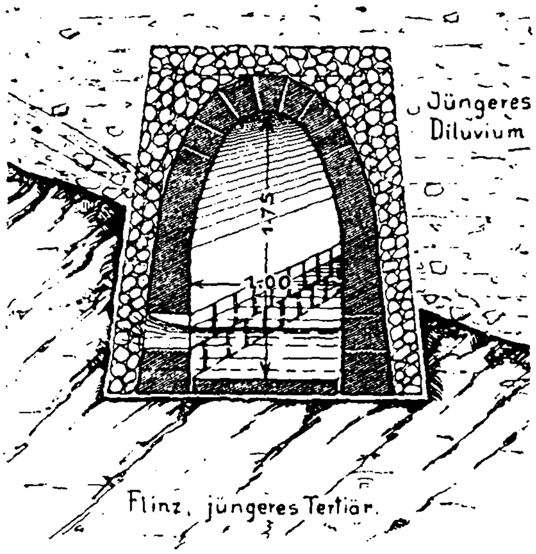


Fig. 14. Recovery of spring water with galleries

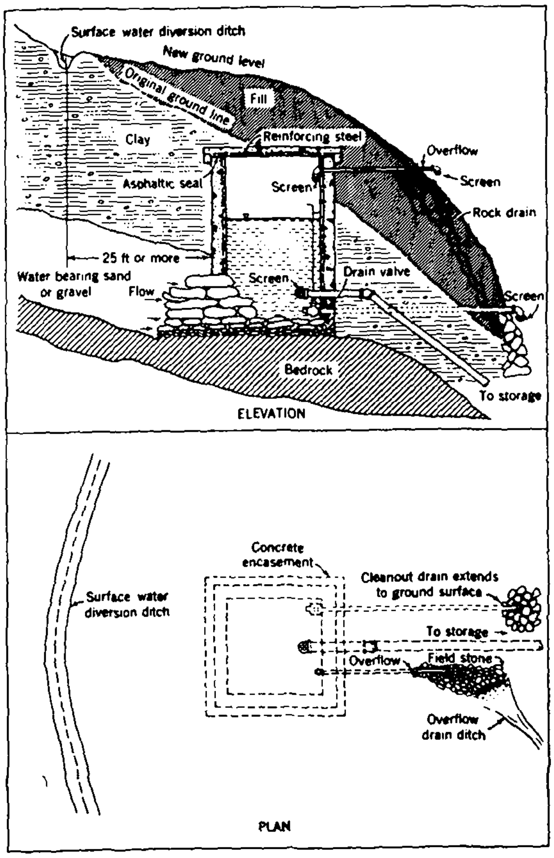


Fig. 15. Small capacity recovery of spring water

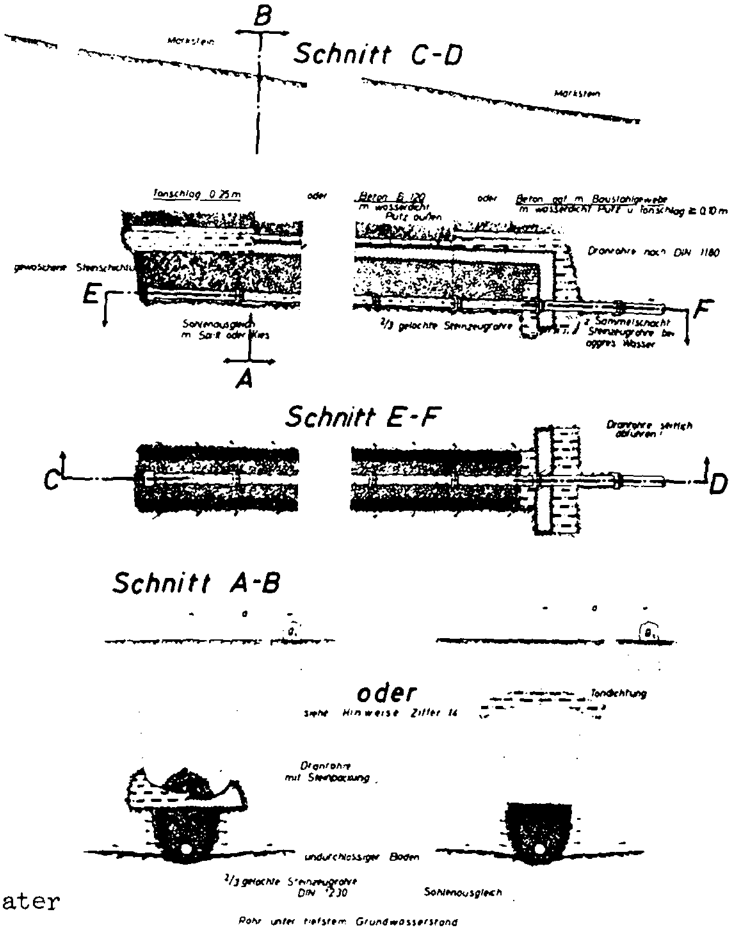


Fig. 16. Drain driven into the hill side

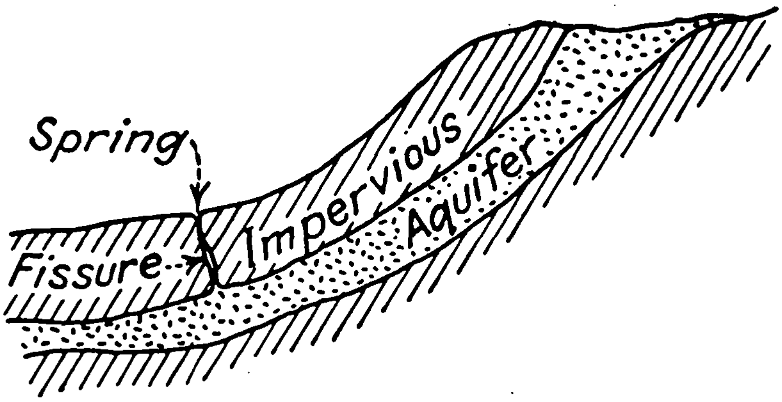


Fig. 17. Fissure spring

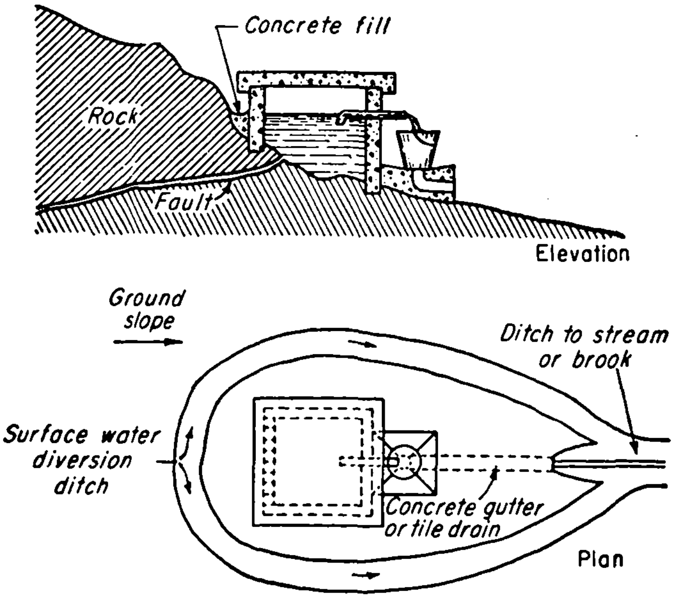


Fig. 18. Recovery of water from a fissure spring

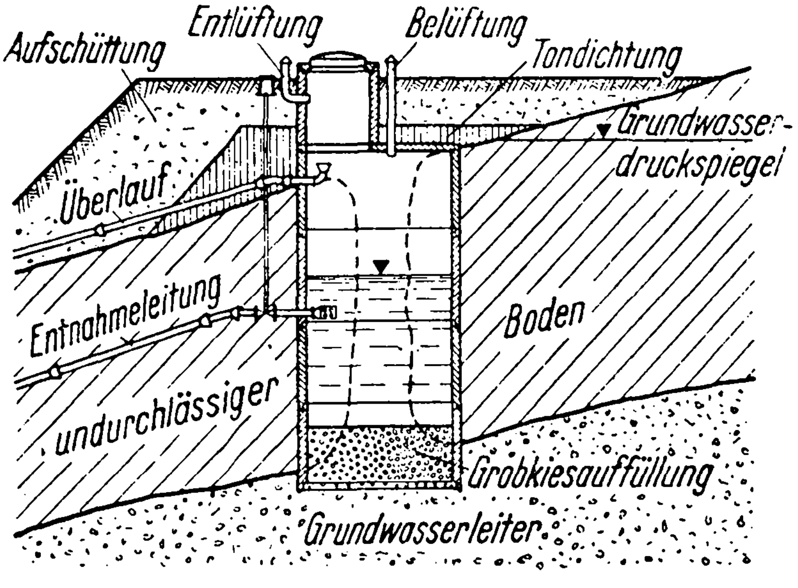


Fig. 19. Recovery of water from a fissure spring

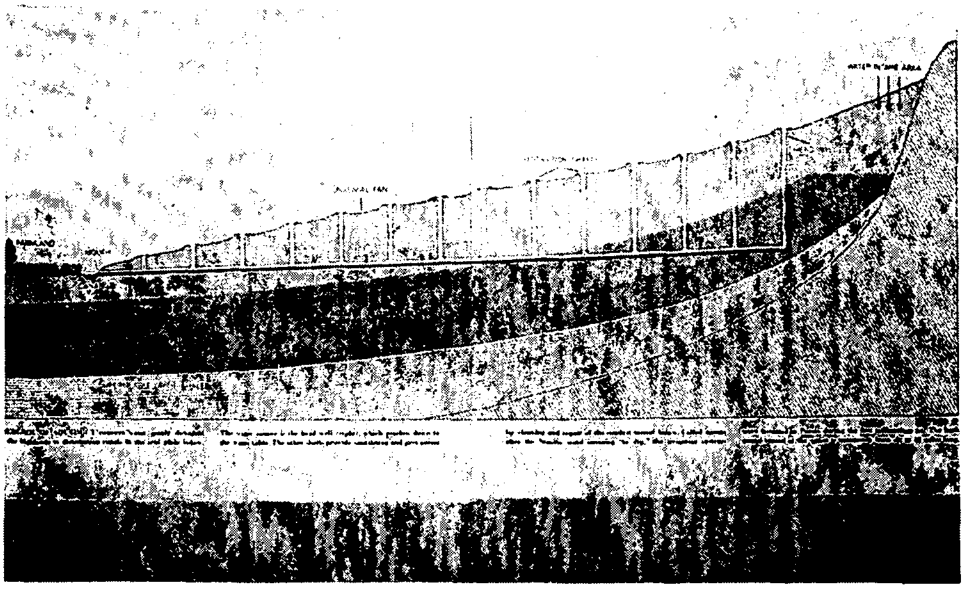


Fig. 20. Qanat in Iran

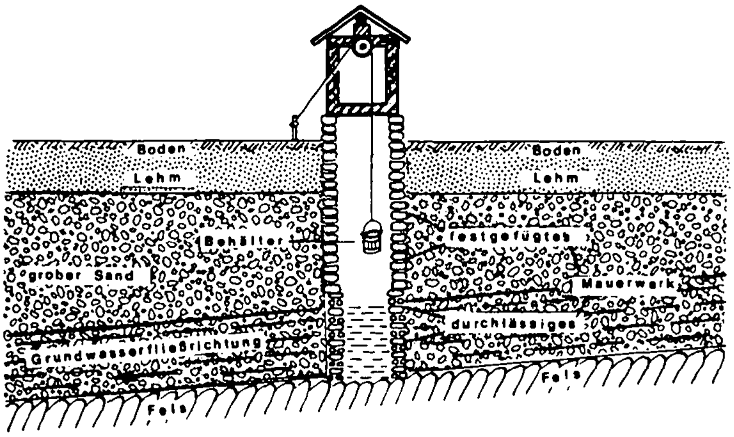


Fig. 21. Roman dug well

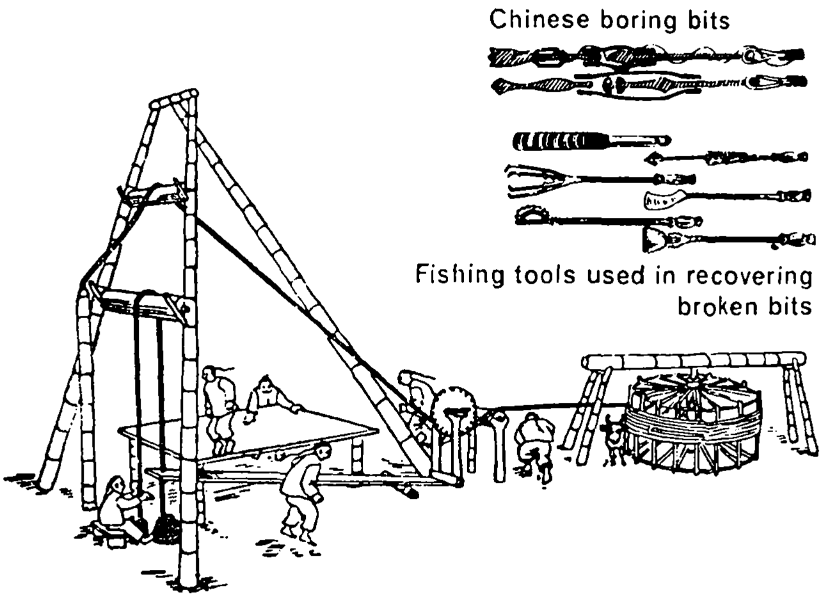


Fig. 22. Construction of tube well

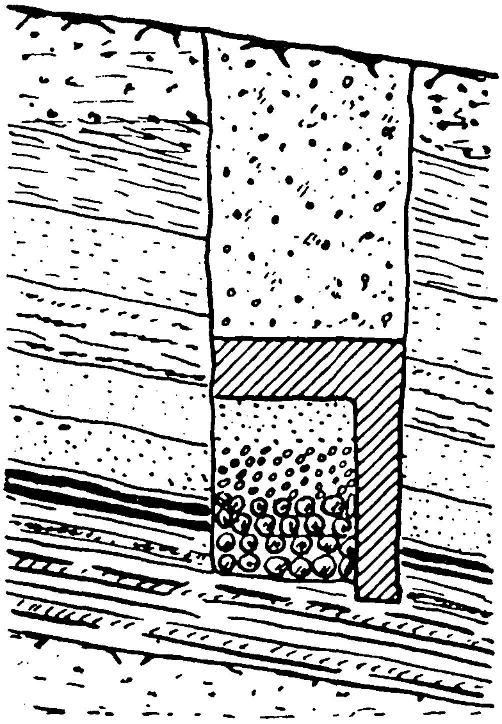


Fig. 23. Gallery

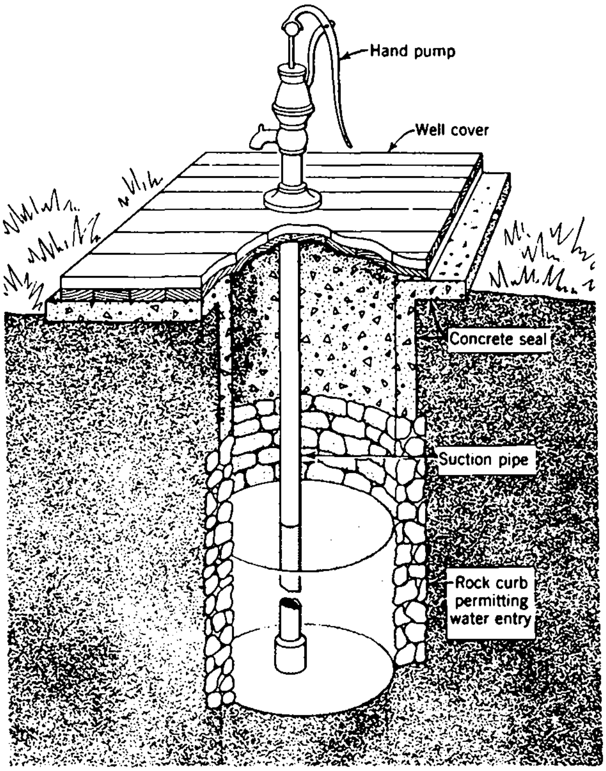


Fig. 24. Dug well

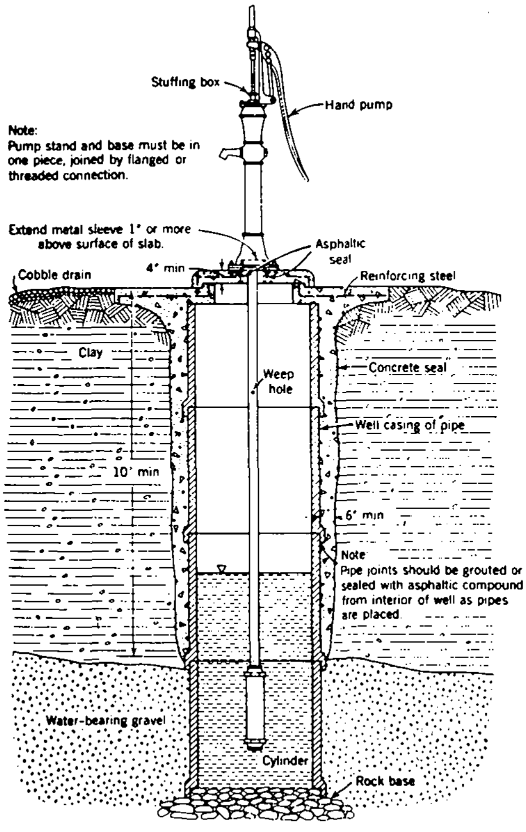


Fig. 25. Dug well sealed for sanitary protection

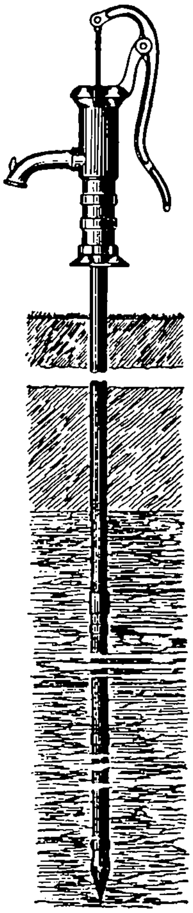


Fig. 26. Driven well

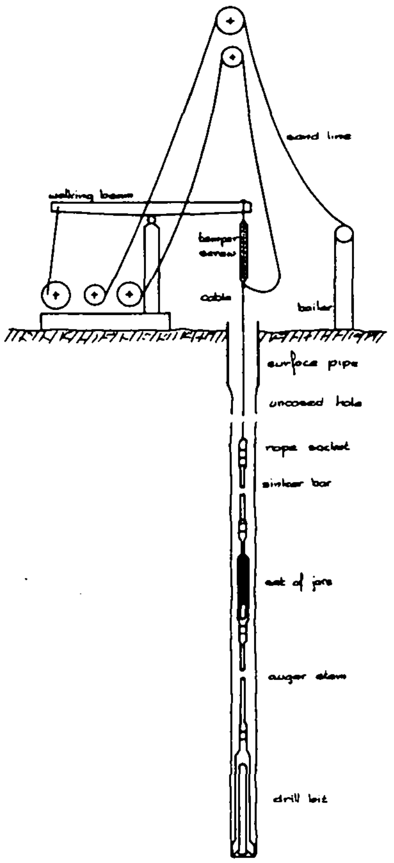


Fig. 27. Cable-tool percussion drilling

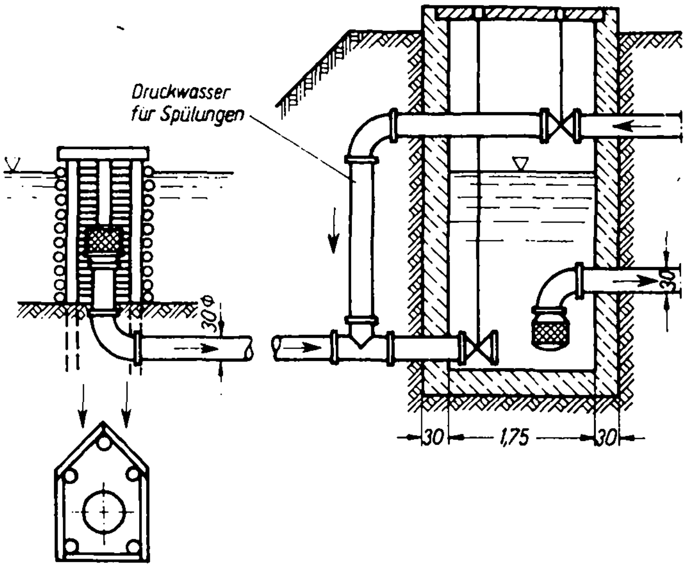


Fig. 28. Abstraction of lake water

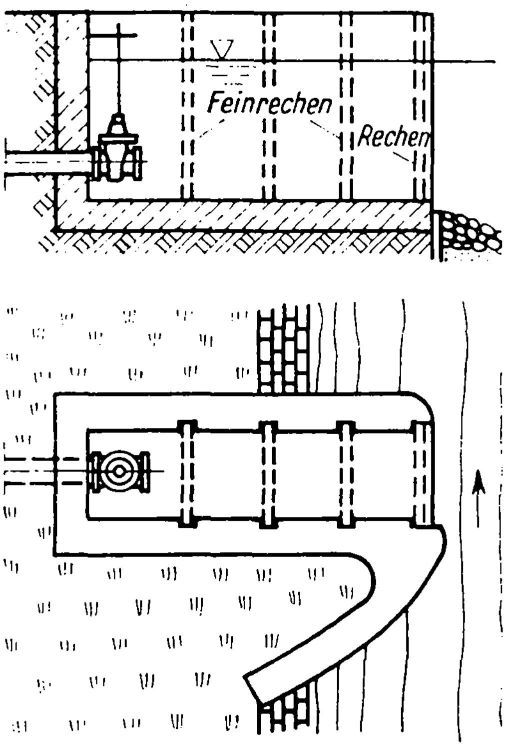


Fig. 29. Abstraction of river water

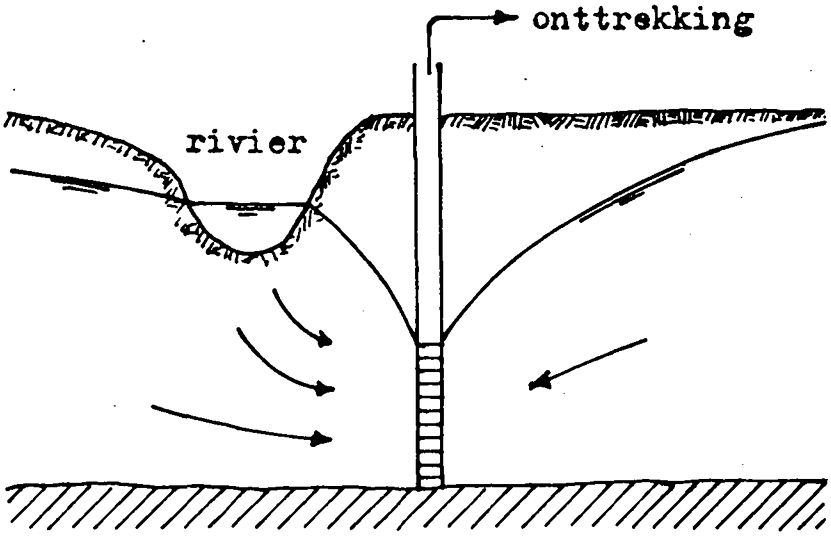


Fig. 30. Induced recharge

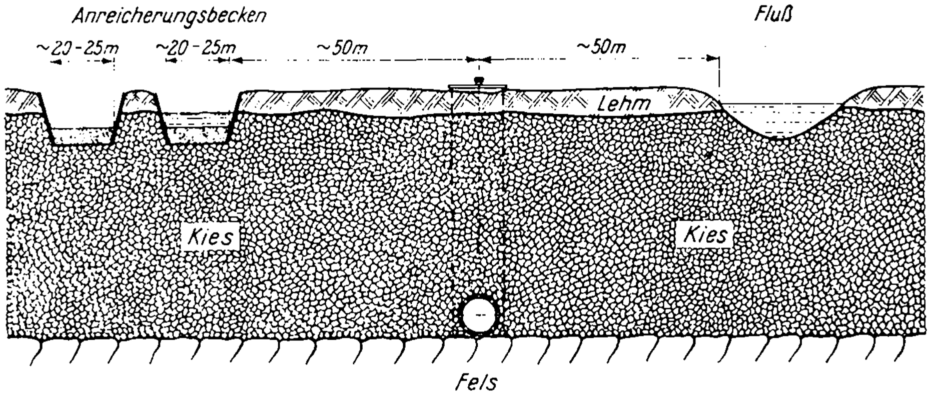


Fig. 31. Artificial recharge

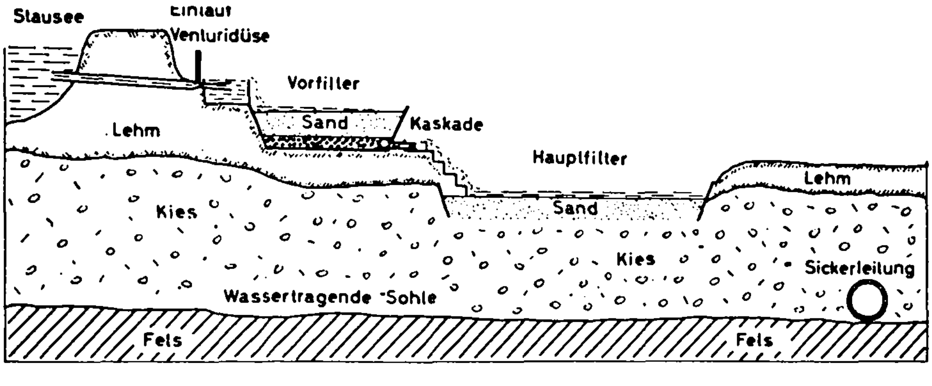


Fig. 32. Treatment preceding artificial recharge

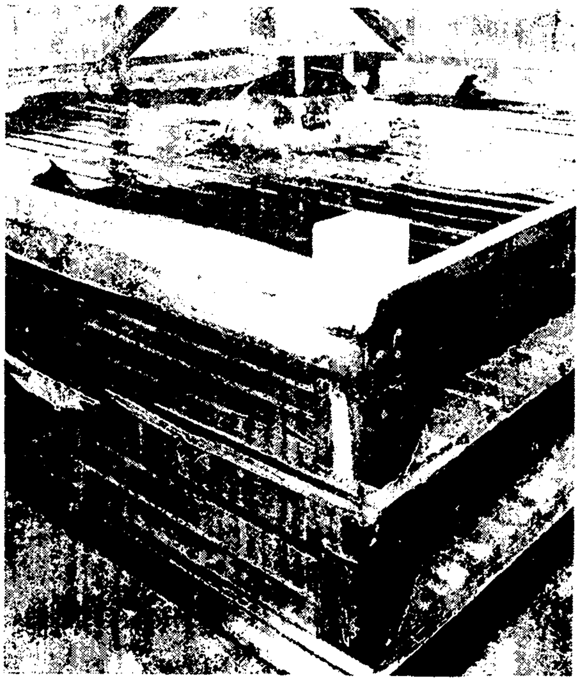


Fig. 33. Multiple tray aerator

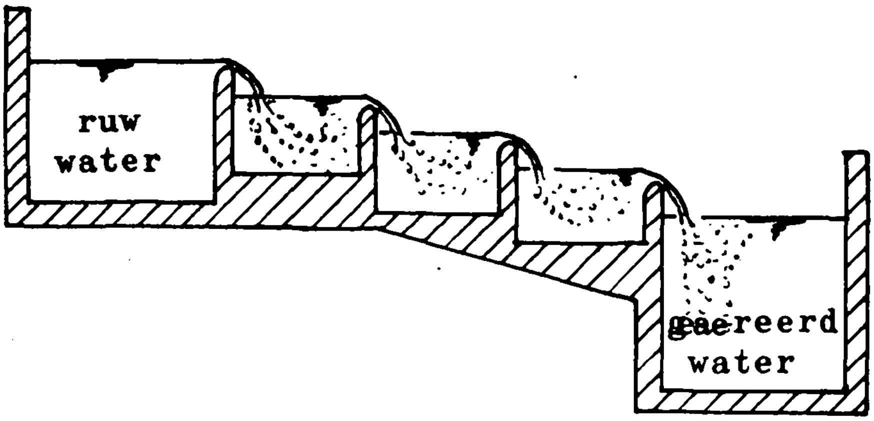


Fig. 34. Cascade aerator

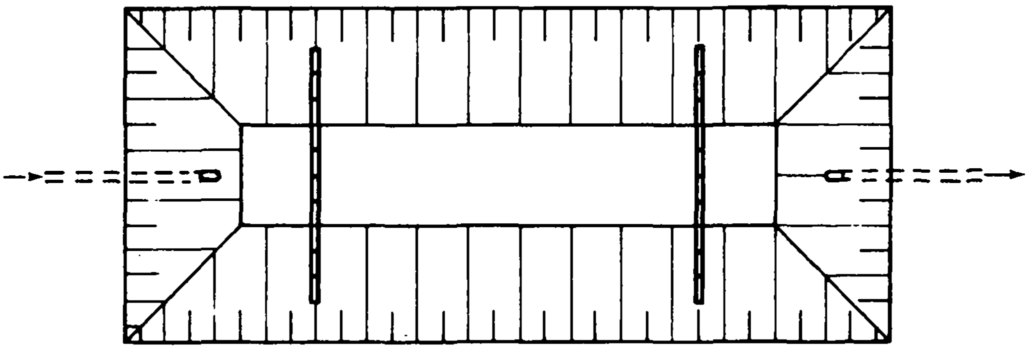


Fig. 35. Plain sedimentation with dug basin

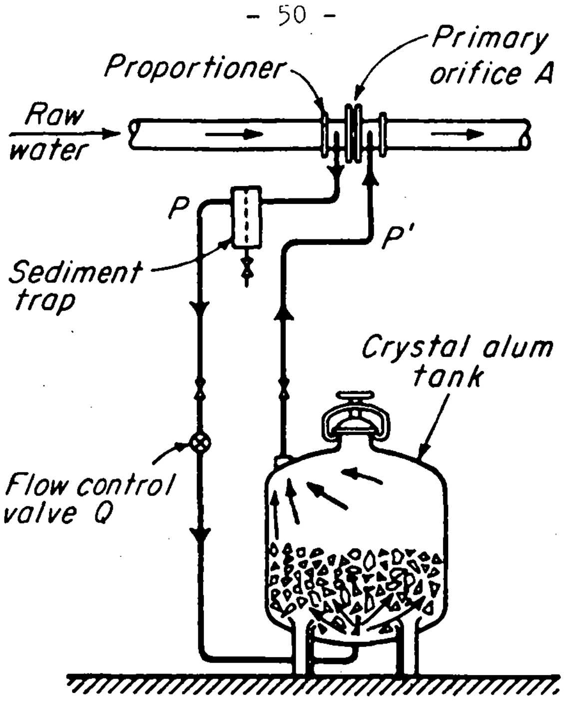


Fig. 36. Pot-type chemical feed

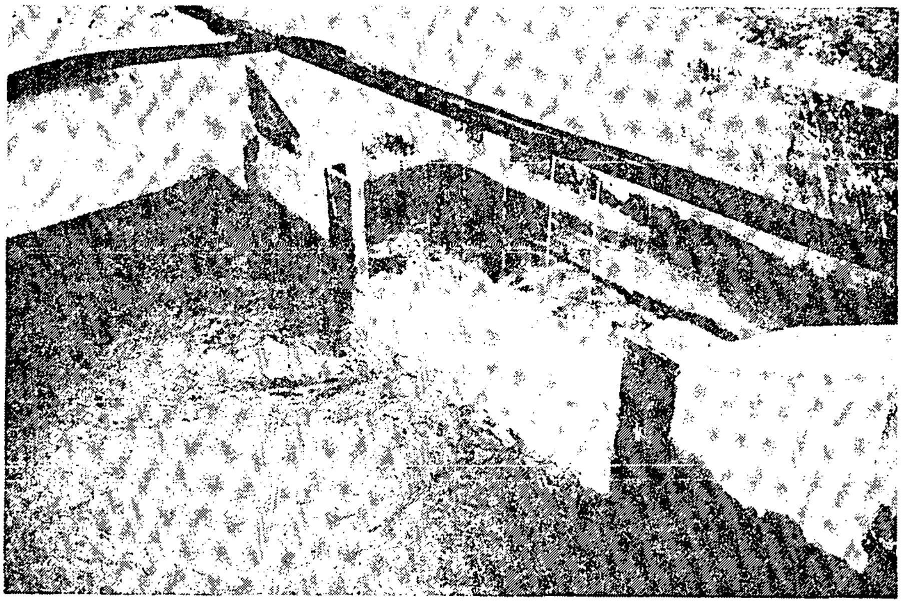


Fig. 37. Hydraulic mixing

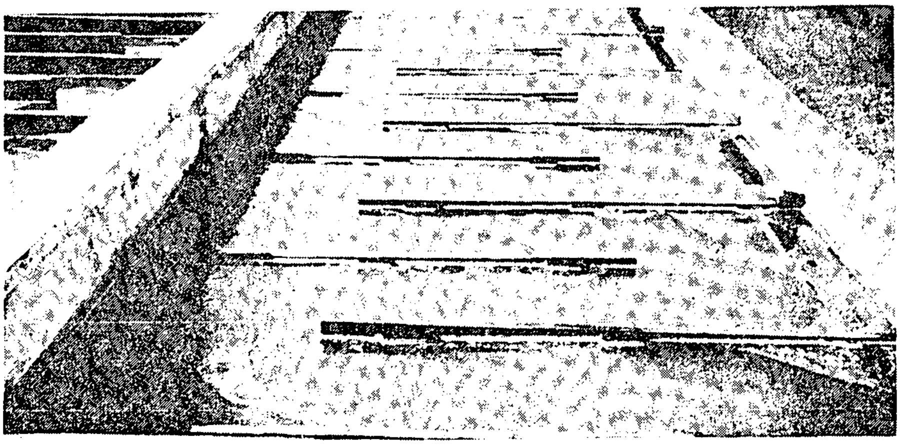


Fig. 38. Baffled flocculation tank

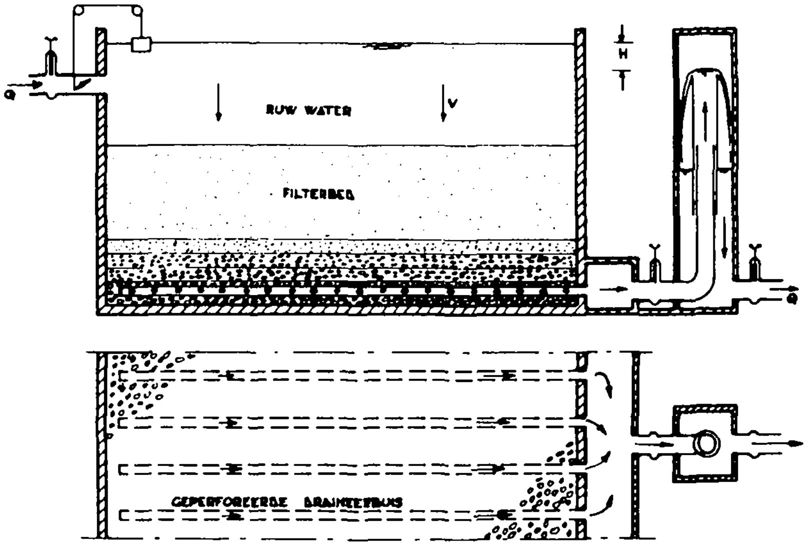


Fig. 39. Slow sand filter

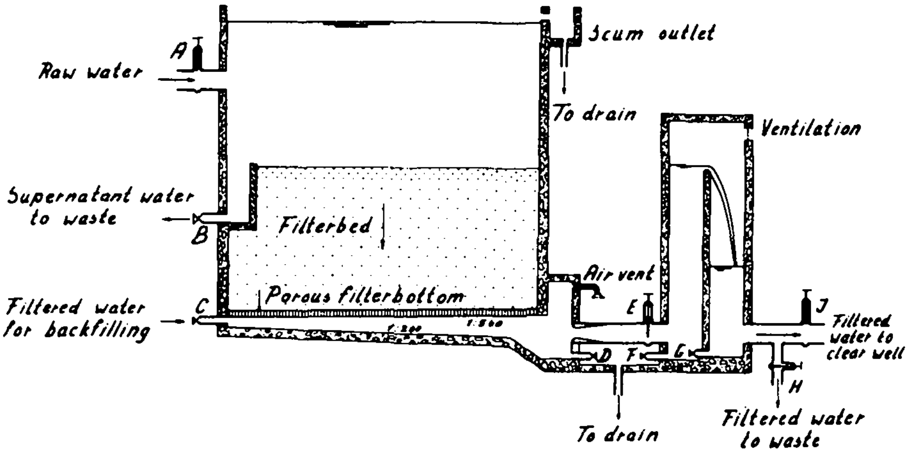


Fig. 40. Slow sand filter

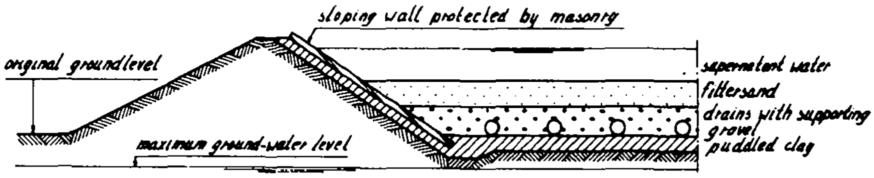


Fig. 41. Slow sand filter

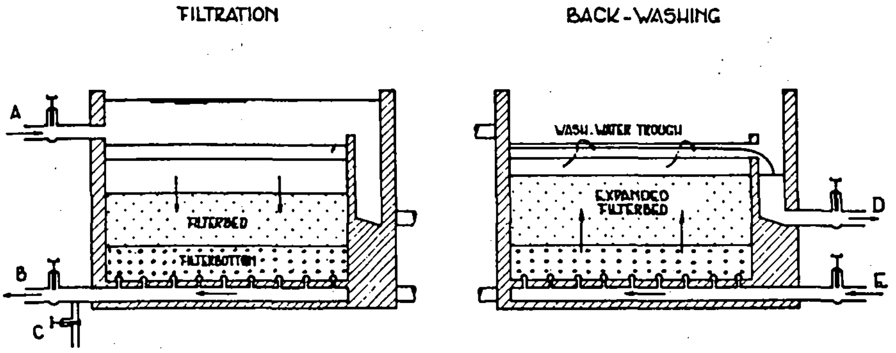


Fig. 42 Rapid sand filter

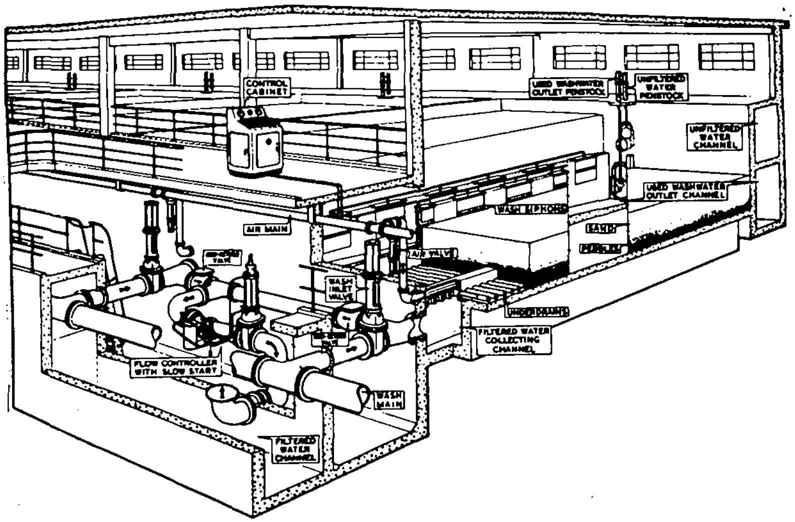


Fig. 43. Rapid filtration plant