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ARTIFICIAL GROUNDWATER RECHARGE FOR WATER SUPPLY OF MEDIUM-SIZE COMMUNITIES IN DEVELOPING COUNTRIES

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ARTIFICIAL GROUNDWATER RECHARGE FOR WATER SUPPLY OF MEDIUM-SIZE COMMUNITIES IN DEVELOPING COUNTRIES

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PREFACE

Artificial groundwater recharge schemes have the advantage that they can produce water that is hygienically safe and fit for domestic use, without requiring extensive provisions for water treatment. This fits in the current trend of eliminating where possible treatment plants especially for medium-size communities in rural areas of developing countries, where the organizational infrastructure is often weak, supplies of power and chemicals unreliable, financial resources limited, and skilled staff difficult to obtain. It is, therefore, appropriate to study the potential application of artificial groundwater recharge for community water supply so that adequate assessment can be made of its merits and limitations.

This document integrates material selected from many sources, both published and unpublished. The focus is on potential application of artificial groundwater recharge for water supply of medium-size communities. Published material mainly concerns large-scale schemes in the industrialized countries of Western Europe and North America, and most of this information has little specific application for this document. However, selected information and pertinent data from these sources have been incorporated.

The purpose of this document is to provide planners and engineers with practical information to assess the potential for application of artificial groundwater recharge schemes in rural water supply programmes or projects.

The study was carried out with financial support of the Netherlands' Ministry of Housing, Physical Planning, and Environment. The study was supported by, and benefitted greatly from, the comments and suggestions of the Infiltration Committee of Netherlands' Testing and Research Institute for the Water Industry (KIWA).

We wish to acknowledge with appreciation the work of Mr. P. Tollenaar who carried out an extensive literature survey, and made the compilation of selected information which served as the basis for this report. Ms. C. van Wijk-Sijbesma is thanked for her valuable comments and suggestions which greatly contributed to improvement of the document.

SUMMARY

Artificial groundwater recharge schemes involve measures for infiltration of water into pervious underground formations, to augment the yield capacity of these formations. The quality of the infiltrated water improves in most respects, and the storage capacity of the formation can be used to ensure availability of water collected in the wet season, for use in dry periods. Technically, artificial recharge schemes are likely to be feasible in most areas where aquifer formations are suitable for recharge and storage of water.

Recharge schemes are economically attractive, and worth consideration in rural areas of developing countries, where they are a viable alternative to treatment works for medium-size water supplies. While the capital costs of recharge schemes are comparable to those of water treatment works, the recurrent costs for operation and maintenance are likely to be lower.

No data are available on the social and cultural acceptability of recharge schemes to the beneficiary communities, and their suitability for community participation in planning, construction, operation and maintenance needs to be ascertained.

Tentative criteria for small-scale artificial recharge schemes are given in Appendix I. However, such criteria need to be validated by field studies, pilot schemes, and practical experience in operation and maintenance.

1. INTRODUCTION

1.1 Groundwater as a source of water supply

Groundwater as a source of water supply has great advantages over surface water from streams, rivers, or lakes. Due to the long retention time underground, often for ten years and longer, groundwater is generally hygienically safe for drinking and domestic use, and it can be stored for use in periods when drought conditions have depleted the surface sources.

Most groundwater resources receive natural recharge from infiltrating rainwater or surface water. The water slowly flows underground to places where it is discharged into streams, rivers, lakes, or directly into the seas and oceans.

In most areas of the world there is groundwater available at some depth, but the quantities involved vary widely for different types of formations. Sedimentary formations which consist of deposits of granular rock fragments and precipitates (e.g., sand, gravel, sandstone, shale, limestone), can hold large quantities of water in the pores and crevices between the granular particles. Metamorphic formations, such as gneiss, quartzite and slate, formed out of sedimentary or igneous rocks by the effects of heat and pressure can hold only limited quantities in the small and unconnected voids and pores in the rocks. However, there are often fractures, joints, and bedding planes in these rocks where groundwater can occur in appreciable quantities. Igneous rocks derived from cooled magma (e.g., granite, marble, and crystalline rocks, such as the African Basement Complex) are dense and only small quantities of water occur in fissures and fault zones. However, often more water is held and transmitted in the weathered and fragmented upper zones.

Thus, the quantities of groundwater found in underground formations are largely governed by the nature and composition of the formations and by the natural recharge. The yield capacity of different types of aquifer varies widely. In crystalline rock, a borehole should not be expected to give more than one or two litres per second, and even depends on striking a water-bearing fissure. By contrast, wells and boreholes in sedimentary formations may have a yield of up to several hundreds of litres per second.

Another important characteristic of water-bearing formations or aquifers is whether they are unconfined or confined. Unconfined aquifers are open to recharge by infiltrating surface water and the groundwater table will fluctuate with the amount of recharge in relation to the water outflow from the aquifer (Figure 1.1). Confined, or artesian aquifers are water-bearing formations having an impervious base, mostly bedrock, and an impervious overlaying formation. The water in a confined aquifer is often under pressure (Figure 1.2).

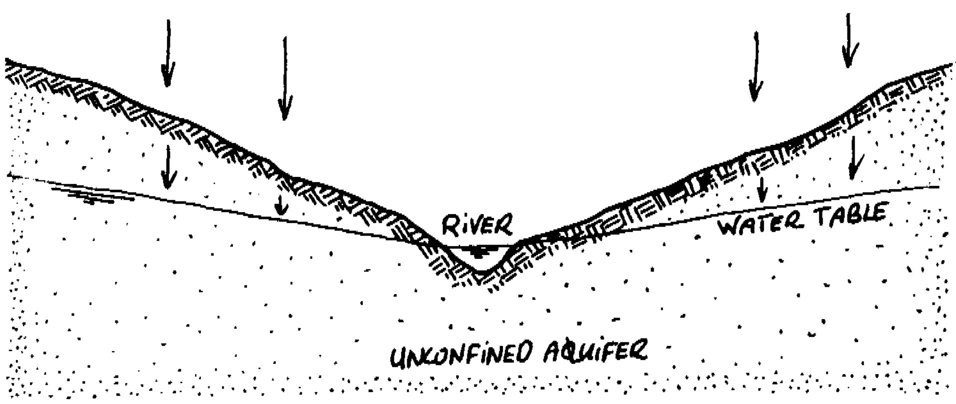

Figure 1.1: Unconfined aquifer

Artificial recharge of a confined aquifer by direct infiltration of surface water is not possible without special provisions, such as a recharge borehole to penetrate the impervious overlayer, and therefore are not considered further here.

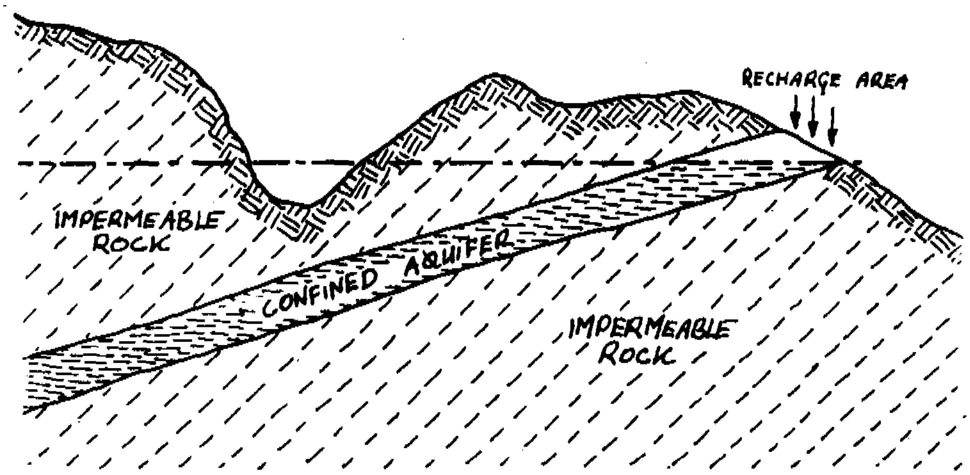

Figure 1.2: Confined aquifer

1.2 Artificial groundwater recharge

Artificial groundwater recharge involves measures to infiltrate surface water into pervious underground formations to augment yield capacity. These measurers are particularly useful in areas where the natural recharge of aquifers is small. There are various types of artificial recharge schemes, but only open infiltration means are considered here. Attention is given to the potential of artificial groundwater recharge for water supply of medium-size communities of 5000-15 000 inhabitants in developing countries.

While it may seem inefficient to infiltrate water into underground formations, and then abstract it for community water supply, the benefits of these operations in terms of improved water quality and assured availability are considerable. Firstly, the process of artificial recharge reduce the number of pathogenic bacteria and other micro-organisms in the water; polluted surface water can be converted into a groundwater resource which is safe for drinking and domestic use. Secondly, water stored underground is largely protected from pollution and evaporation, as compared with water storage in open surface reservoirs. Thirdly, water taken from surface sources in the wet season and infiltrated for storage underground, is available for abstraction in the dry season. Availability of water throughout the year is particularly assured if deep underground strata are used for artificial recharge; shallow groundwater resources are less reliable, because they may dry up in the dry season.

The main components of an artificial groundwater recharge scheme are (Figure 1.3) :

- recharge means;
- pervious underground formation;
- recovery means;
- system boundaries, e.g. the impermeable base and confining impervious layers on the sides of the scheme.

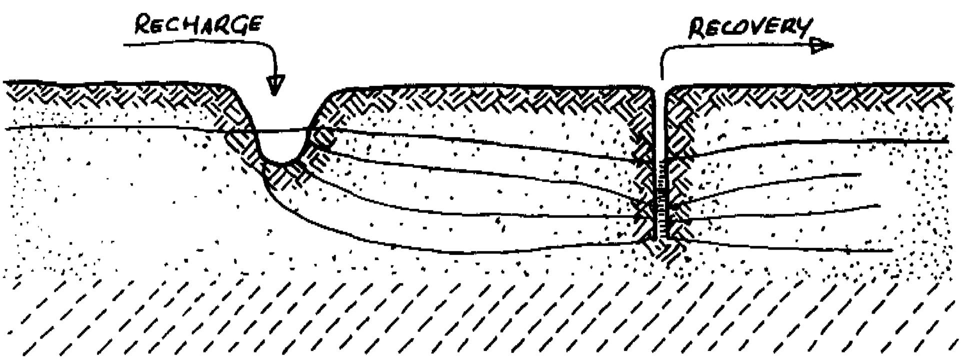

Figure 1.3: Main features of artificial recharge scheme

To allow for adequate purification of the water, artificial recharge schemes must be designed for a water retention time of at least three weeks, and preferably one to two months. This is the period during which the water travels underground from the recharge area to the recovery means which must be at a sufficient distance from the point of recharge, depending on the velocity of water flow through the underground formation. The degree to which the movement of the infiltrated water through the recharged formation can be controlled, depends on the system boundaries, such as an impermeable base and confining layers to limit water losses from the artificial recharge system.

2. ARTIFICIAL GROUNDWATER RECHARGE FOR COMMUNITY WATER SUPPLY

2.1 Water quality aspects

As already stated, various biological, chemical and physical processes occur in the water during artificial recharge. In most recharge works the water is in open contact with the atmosphere so that it is aerated, for absorption of oxygen and release of carbon dioxide. Some settling of oxidized organic matter and suspended solids occurs, thus forming a filter matting of deposited material on the bottom of the recharge means.

As the water enters the infiltration zone impurities are filtered out, because all particles larger than the soil pores are retained. Active colonies of predatory micro-organisms and bacteria develop and feed on the organic matter and other nutrients present in the infiltrating water. Most of the bacteria and other micro-organisms are removed or retained in the top few decimeters of the infiltration zone, and very few are carried deeper into the ground than 1-2 m. Suspended solids are removed by sedimentation and adsorption on the soil particles. There is active oxidation of both organic and inorganic compounds. Various colloidal and dissolved impurities are retained by adherence on the surfaces of soil particles. The water purification processes are more active in the top layer of the infiltration zone, and in the filter matting of deposited material and microbial life which forms on top of it.

After passing the infiltration zone, the water percolates downward in the underground formation to reach the groundwater table. Initially, oxygen is available in the water and further oxidation of organic matter occurs. Because of the continuing breakdown of organic matter, accumulation of pollutants in the underground should not be a problem for small-scale artificial recharge schemes. Die-off of bacteria and other micro-organisms continues because most of the suitable nutrients have been removed from the water (Table 2.1).

Table 2.1: Survival time for pathogenic bacteria and viruses in underground formations

Bacteria/viruses	Survival time
Faecal coliforms	6 days
Entamoeba histolytica	8 days
Entero virus	12 days
Cyst of Ascaris	6 months

Source: Fildier, 1983.

Not all the chemical and physical processes working in the water during its underground travel, produce improvement of the water quality. Some effect changes which can make the water less suitable for drinking and domestic supply. The water will dissolve various constituents from the formation strata through which it flows. For example, calcium and manganese carbonates can be taken up by the water, especially if it is acidic. Iron and manganese are leached out if present in the formation. In formations containing peat or the remains of animal life, organic compounds are likely to be taken up by the water. In an anaerobic water environment, ammonia, sulphides and nitrites can be formed by reduction processes. Some treatment of the water, such as, aeration and filtration is then needed to produce drinking water of acceptable quality.

2.2 Storage

Storage is a very important aspect of artificial recharge schemes, because water can be infiltrated during the wet season and stored underground for use in dry periods. Sedimentary formations especially sand and gravel aquifers, generally have the largest storage capacity. As water can only occur in the joints, fractures and fissures of consolidated rocks, the storage capacity of these formations therefore is very limited.

2.2.1 Effective porosity

The effective porosity is the pore space in a unit volume of rock in which the water can move freely. It is less than the void porosity because the pores also contain water which is bound by absorption to the surface of the formation particles (Table 2.2). Apart from the type of rock, the effective porosity also depends on the size distribution of formation particles, and how dense the packing of the particles is (Figure 2.1).

Table 2.2: Porosity and effective porosity of various types of rock

Type of rock	Void porosity (%)	Effective porosity (%)
clay	40 - 35	1 - 10
sand	35 - 40	10 - 30
gravel	30 - 40	25 - 30
sand & gravel	20 - 25	15 - 25
sandstone	10 - 20	5 - 15
shale	1 - 10	0.5 - 2
lime stone	1 - 10	0.5 - 2
igneous rock	0.001 - 1	negligible

Based on Campbell & Lehr, 1973

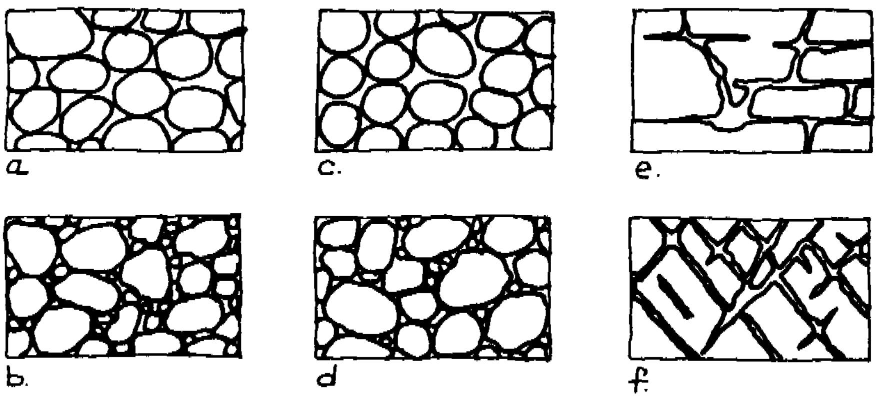

Figure 2.1: Rock porosity

- (a) well-sorted sedimentary deposit having a high porosity;
- (b) poorly-sorted sedimentary deposit having a low porosity;
- (c) well-sorted sedimentary deposits with a very high porosity;
- (d) sedimentary gravel deposit with the pores filled up by sand particles, so that porosity is reduced;
- (e) fragmented rock with unevenly distributed porosity;
- (f) fractured rock having a relatively low porosity.

(Source: Meinzer, 1959)

In unconsolidated formations of granular material which is neither cemented nor compacted, the effective porosity depends mainly on the packing of the grains, which in turn depends on the size distribution, shape and stapling of the rock particles. In consolidated formations, which are densily packed or cemented, the effective porosity is generally very small. These formations have a limited hydraulic transmissivity and are generally unsuitable for artificial recharge operations.

2.2.2 Storage capacity

The storage capacity of an area underground volume of a width B = 400 m and a length L = 1000 m, and an effective porosity p_e of 20%, to a depth D = 5 m, is:

$$
\begin{aligned}
Q &= p_e.B.L.D \\
&= 0,20.400.1000.5 \\
&= 400.000\ m^3
\end{aligned}
$$

2.3 Hydraulic design of artificial recharge schemes

The hydraulic design of artificial recharge schemes is governed by the following parameters:

- infiltration rate
- retention time
- effective porosity
- permeability
- hydraulic transmissivity

2.3.1 Infiltration rate

The infiltration rate depends mainly on the vertical permeability of the infiltration zone, and should be designed to allow the scheme to operate over a long period at an acceptable rate without excess clogging of the infiltration zone. The design rate thus should be less than the maximum infiltration rate. The infiltrating water should be largely free of suspended and colloidal matter. Surface water may need to be pretreated to remove excess turbidity. Sedimentation basins may be used for this purpose. If the turbidity in the infiltration water is mainly caused by fine silt and colloidal matter, it is generally more effective to use roughing filtration, that is filtration through a gravel bed, for pre-treatment (Figure 2.2). Alternative, two infiltration basins can be used. While one basin is in use, the other is drained to allow silt deposits on the bottom to dry out. This dry material can be blown away by the wind, or it can be removed manually by local workers.

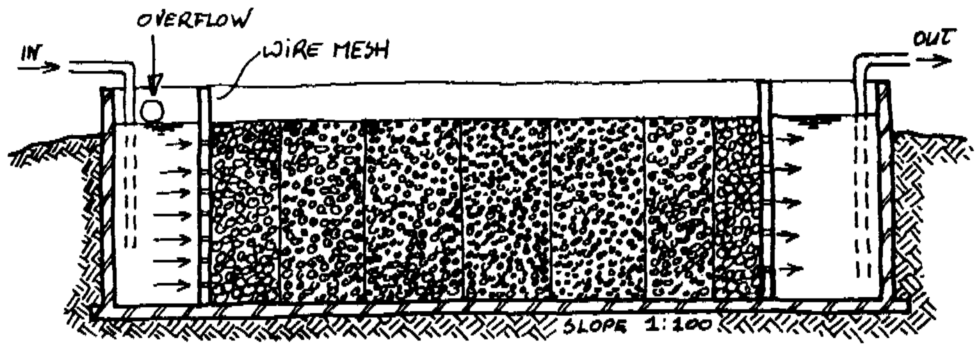

Figure 2.2: Pre-treatment of infiltration water by roughing filtration

The maximum infiltration rate can be determined by the standard test with an infiltrometer which consists of two concentric rings, the inner ring of 0.7 m diameter, the outer ring of 1.0 m diameter, and both 0.4 m high (Figure 2.3). The rings are driven half in the bare soil of the infiltration area, and then filled with water. The topsoil at the site should be removed because of its limited infiltration capacity. The amount of water infiltrating is determined by measuring the drop of the water every quarter-hour or half-hour over a period of several hours. Infiltration rates for various types of soil are given in Table 2.3.

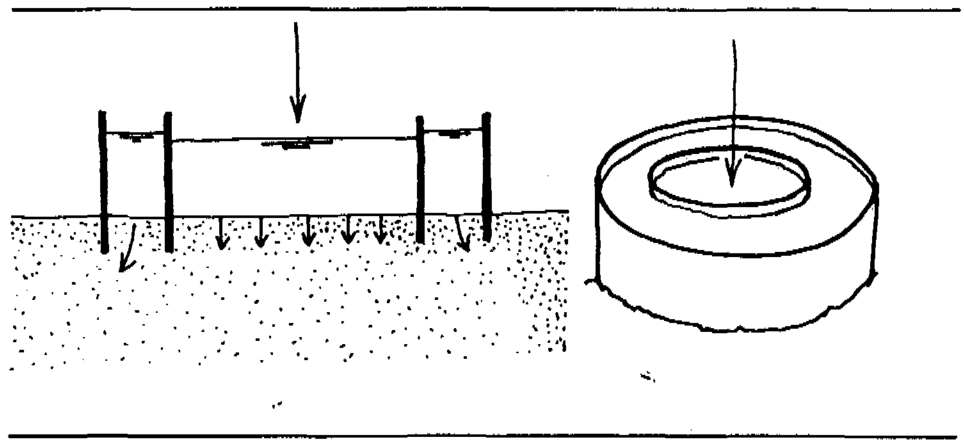

Figure 2.3: Infiltrometer

Table 2.3: Infiltration rates for various types of soil.

Type of soil	Infiltration rate ($m^3/m^2/d$)
Fine sand	0.2 - 0.4
Sandstone	0.3 - 0.5
Medium-sized sand	1 - 2
Coarse sand	4 - 6
Gravel	10 - 20

The design filtration rate must allow for a degree of clogging, and should be about 20-30% of the standard test infiltration rate. Lower design rates may be appropriate where special care must be taken to prevent clogging of the soil.

2.3.2 Retention time

To ensure hygienic safety of the recovered water, artificial recharge schemes should be designed to provide a retention time of at least three weeks, and preferably two months. The time the water remains underground is the important criterion, not the distance over which the water flows from the recharge area to the recovery means. The retention time is controlled mainly by the infiltration rate and the hydraulic transmissivity of the formation.

2.3.3 Permeability

The permeability of a formation is the flow rate at which water would move through it under a head of one metre across a distance of one metre. The main factors affecting permeability are the effective porosity and the degree to which the pores in the formation are interconnected. Table 2.4 gives the permeability of some types of rock.

Table 2.4: Permeability of some types of rock

Type of rock	Permeability (m/d)
fine sand	1 - 5
coarse sand	20 - 100
gravel	100 - 1000
mixed sand and gravel	50 - 100
sandstone	0.1 - 1.0
clay	0.01 - 0.05
shale	negligible
limestone	negligible
fractured or weathered rock	0 - 30
solid rock	negligible

Source: Campbell & Lehr, 1973

2.3.4 Hydraulic transmissivity

The hydraulic transmissivity is the product of the permeability and the water-filled depth of the formation, and denotes the water transmission capacity of the formation. With the permeability k and formation depth D, the hydraulic transmissivity is often given as the k.D factor, expressed in m^3/d per m width.

3. PLANNING AND ORGANIZATIONAL ASPECTS OF ARTIFICIAL GROUNDWATER RECHARGE SCHEMES

3.1 Planning

In most countries, there is likely to be little know-how and experience with the planning, design and organizational aspects of artificial groundwater recharge schemes. Important issues in planning such schemes are the selection of a suitable source of water, the location of the artificial recharge area, the geohydrological conditions, community involvement, and cost. The schemes should be planned in accordance with the available technical skills, manpower, and management capabilities, and the capacity and willingness of the user community to bear the costs.

3.2 Community involvement

Active involvement of the beneficiary communities is increasingly being recognized as of major importance in rural water supply projects. This also applies to artificial groundwater recharge schemes. Full involvement means that the local population can participate in the siting of the scheme, planning and design, the choice of recovery means, and the provisions for operation and maintenance (Table 3.1). It also means that a timely and satisfactory agreement can be made on the contributions, the rights and obligations of both the community and the water supply agency.

Careful appraisal of local needs during the pre-feasibility studies for artificial recharge schemes will ensure that those communities which have a felt need for, and true interest in an improved water supply are served first. Subsequent information and consultation of the community during the local planning stages of the project makes it possible to take into account the needs of various user categories (e.g. women, livestock owners, lowest-income group). Where necessary, compromises for conflicting interests should be sought, which are acceptable to all.

Table 3.1: Suggested sequence of technical and community involvement project activities

Technical activities	Community involvement activities
Geo-hydrological investigations	Consultations with community members on siting of the scheme
Investigations on capacity and willingness for cost recovery	Consultations with community on cost of scheme, and their contribution
Site investigations for scheme	Community involvement in site investigations
Selection of type of pumping equipment to be used for water recovery	Participation in choice of pumping technology (especially by the women)
Preparations for construction of scheme	Hygiene education activities
Construction of the scheme	Participation by provision of labour
Local training in operation and maintenance work	Community elects candidates for training in operation and maintenance
Evaluation	Participation in evaluation

Source: van Wijk, 1985

Competition over water use and payment problems should be avoided. In particular, the level of financial contributions of the community to recurrent costs, and also to the capital cost, should be settled in consultations before the scheme is constructed.

There are numerous examples of water supply schemes which cannot be used for part of the year because the water source has dried up; such costly mistakes could have been avoided if the local community had been involved and consulted. The local knowledge should be used to prevent schemes being inappropriately sited. Without prior consultation with the community, water supply schemes have sometimes been sited in culturally unacceptable places, for example, in the vicinity of a graveyard, or at a place which is flooded in the rainy season. Adequate exchange of information between the community and the water supply agency is required for reasoned decision-making. Ensuring that project information also reaches the local women, and consulting them on their views, is important because they are the main users of the water supply for domestic purposes.

Involvement of the communities in construction work can reduce the construction costs. The willingness to contribute to construction work, in kind or money, is closely related to the benefits expected from the scheme. Digging of infiltration channels or basins, and recovery wells and construction of simple water intake works, lend themselves particularly to involvement of the local population. It is necessary to schedule these activities for periods in which the work-load of the community is limited, and not in the harvesting season or similar periods.

Periodic cleaning of the infiltration channels, and of pre-treatment facilities if incorporated in the recharge scheme, are maintenance tasks for which the local community can readily assume responsibility. Collection of financial contributions from the community should also be organized locally, for example by a local water committee. For more details the reader is referred to IRC's forthcoming publication "What Price Water: User Participation in Paying for Community-Based Water Supply".

Consultation with the local community is also particularly helpful to find the most appropriate solution for specific local problems. For example, in the village of Alto de los Idolos, in Colombia, the surface water source was seriously polluted by manure of cattle allowed to graze on the banks and surrounding area. Fencing the area with chicken wire was suggested by the water supply agency, but the village water committee did not consider this the appropriate solution because of the high cost involved and the risk that the wire fence would be stolen. Requiring people to keep their animals from the water intake area, was considered not to be compatible with local custom and the right of access to land. After consultation, the community understood the need to protect the intake area, and came up with their own solution.

Voluntary labour from all user-households was organized to plant thorn bushes to form a natural fence. The work was quickly completed, and the thorn bush fence effectively kept the grazing cattle away from the water intake area.

The technical project work required for an artificial recharge scheme, and the community involvement activities, are both essential components of the water supply project. The sequence of these activities should be planned and implemented for mutual reinforcement.

3.3 Organizational aspects

At the village level, it is preferable to work through an existing organization, such as a village committee. However, if these committees may have too many broad responsibilities to be effective, then a special water committee need to be established. It is important to ascertain through consultations with the village or water committee whether it can and will accept responsibility for operation and maintenance. Agreement should be reached on the contributions they will make, and those which they may expect from the water supply agency. General assemblies or separate meetings with the different population sections, including women, may serve to ascertain whether the proposed design and community contributions in construction, operation and maintenance of the artificial recharge scheme are acceptable to all, or whether further adaptation in necessary.

A clear and realistic distribution of responsibilities and tasks within the water supply programme is required to support the installation of artificial recharge schemes. A possible division of responsibilities at the national, district, and local level is set out in Table 3.2.

It must be recognized that the operation and maintenance requirements of artificial recharge schemes will place considerable demands on the user community's organizational infrastructure and financial capacity.

Table 3.2: Possible division of responsibilities within a rural water supply programme

Level	Responsibilities
National	Overall planning and organization of the water supply programme Overall allocation of programme funds Provision of technical support Provision of methodology for evaluation
District	Implementation of schemes Administration of programme funds Promotion of community involvement Health education Participation in evaluation
Local	Participation in local planning contribution to construction Promotion of acceptance of recharge schemes Operation and maintenance of schemes Organization and collection of local contributions Participation in evaluation

The type of expertise and numbers of staff required to implement recharge schemes varies, according to the local conditions. Tasks to be carried out include digging of infiltration channels or ponds, cleaning and maintenance, operation of pumping plant, collection and administration of local contributions, and promotion of hygiene education. Not all staff required can be recruited locally. However, it will often be possible to attract potentially suitable people, and train them for specific tasks. A fairly successful approach in several instances has been to use the construction stage for training of those who will afterwards be responsible for maintenance and repair of the scheme. This provides opportunities for the recruited staff to learn how the scheme works, and so obtain essential information for operation and maintenance.

3.4 Hygiene education

Hygiene education is an essential part of any water supply project and its importance has been confirmed by many studies. Safe water supplied by an artificial recharge scheme can be re-polluted by the users, if no preventive measures are taken. Hygiene education can bring the people understand the need for proper handling of the water. One important objective is to explain the need for exclusive use of safe water, although this will not by itself be sufficient to achieve the desired health impact. Improvements in general hygiene, such as sanitary waste disposal, hygienic food handling and preparation, balanced nutrition, and insect and rodent control, are also required.

Thus, hygiene education should be part of the promotional and motivational activities in every project for building a recharge scheme. Preferably it should begin in the planning stage, but always before the scheme is actually constructed. It must be recognized that the hygiene education activity has a cost which needs to be budgeted for in the overall programme budget.

In some areas, the abstraction of groundwater to provide a safe supply for drinking and domestic use may encounter reservations, especially where the local population has traditionally used flowing water from streams or rivers. Sometimes, people believe that flowing water is more wholesome and healthy than groundwater. Users need to understand why groundwater is safer to use and generally of better quality. Where water from existing wells tastes salty, it should be explained that the artificial recharge scheme will produce water that is fresh and of a lower salt content.

Discussions with all local groups are useful to identify particular local problems, and to ensure that the siting of the artificial recharge scheme and its design promote hygienic conditions and a reliable supply of the water. Co-operation with community workers interested in health and hygiene, such as dispensary staff, school masters, and adult educators, should be sought. Knowledge of local circumstances, behaviour, beliefs, and constraints, is necessary to design an effective hygiene education programme which should be based on identified health hazards and behaviour patterns which affect, the transmission of diseases. Dirty latrines, unwillingness to use latrines, failure to wash hands before handling food, inadequate drainage, and unhygiene disposal of refuse, are health hazards and behaviour to which the hygiene education programme should be directed. For a more detailed discussion of planning and implementation of a local hygiene education programme with active involvement of the community (see Boot, 1985).

Hygiene education should also be effectively integrated with the primary health programme; the provision of a water supply being an important element. Even when water supply improvement has to be planned and implemented as a separate activity, the water supply agency staff must discuss with the community the role of water in health improvement. They should encourage other agencies involved in local development to integrate their programmes with the water supply project.

4. TYPES OF ARTIFICIAL RECHARGE SCHEMES

The main types of artificial groundwater recharge schemes for water supply of medium-size communities are:

- infiltration ditches, ponds and basins;
- induced recharge from rivers and streams;
- retention of river bed underflow;
- retention of river flood water.

4.1 Infiltration ditches, ponds and basins

Ditches, ponds, and basins are used to infiltrate water into formations of good permeability which are not overlain by an impervious layer. Recovery of the water can be provided by collector drains (Figure 4.1). Ditches are especially used for artificial recharge of shallow aquifers, whereas infiltration ponds are more suited to relatevely large-scale recharge of medium-depth formations. For recovery of the water, a battery of wells surrounding the pond can be used (Figure 4.2).

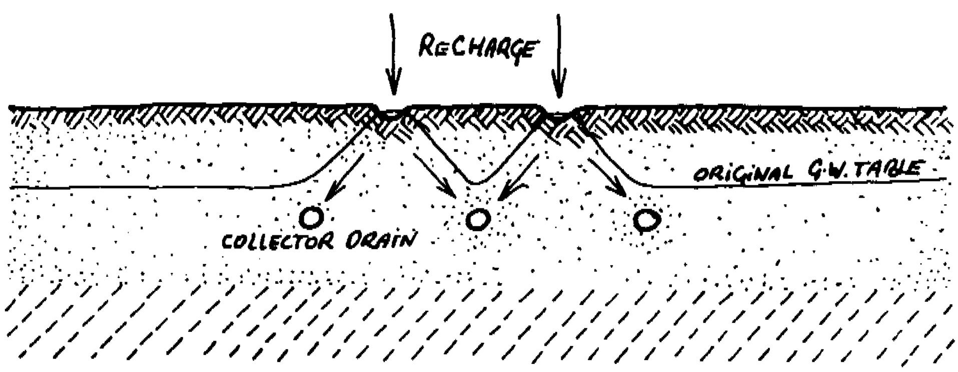

Figure 4.1: Artificial recharge of shallow formation

Ditches and ponds are generally 1-4 m deep which is enough to prevent excessive growth of algae or water plants, and shallow enough to prevent anaerobic conditions developing except at the bottom.

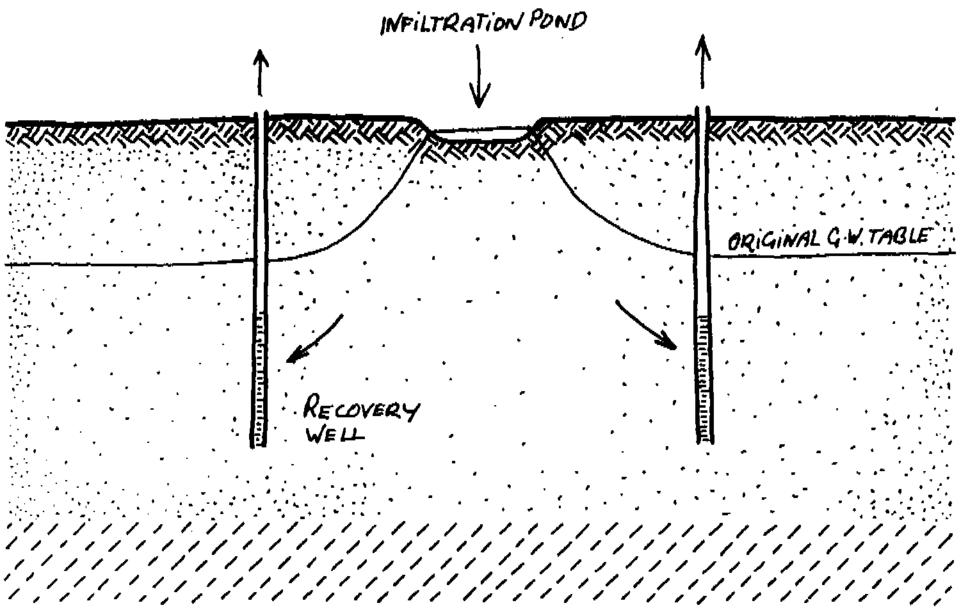

Figure 4.2: Artifical recharge of coarse granular formation

Small-scale artifical recharge schemes using ditches or ponds

Small-scale artificial recharge schemes using infiltration ditches or ponds can be quite suitable for water supply of medium-size communities in rural areas. To serve 200 people at a rate of 30 l/c/d requires a capacity of 6 m^3/d only. With a retention time for underground water flow of 40 days, a formation with effective porosity of 20% would need to be of 1200 m^3 water filled volume. If the wetted depth is 3 m, the required surface area would be 400 m^2, for example 10 m wide and 40 m long. This sort of pervious formation may be readily found in many places (Figure 4.3).

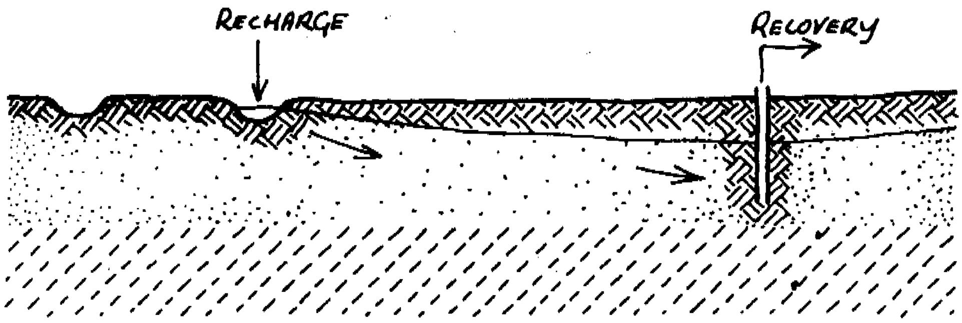

Figure 4.3: Small-scale recharge scheme

The application of small-scale artificial groundwater recharge schemes is of considerable interest, for rural water supply because these schemes can produce water for domestic use, without the need to provide extensive treatment.

Large-scale artifical recharge schemes using infiltration basins

Infiltration basins for large artificial recharge schemes have been constructed in industrialized countries, but these systems are too expensive and complicated for medium-size community water supplies. The river water is pumped to the basins and allowed to infiltrate; after recovery the water is pumped into supply. Pre-treatment of the river water is generally required to prevent accumulation of silt deposits and microbial slimes in the transmission main (Figure 4.4).

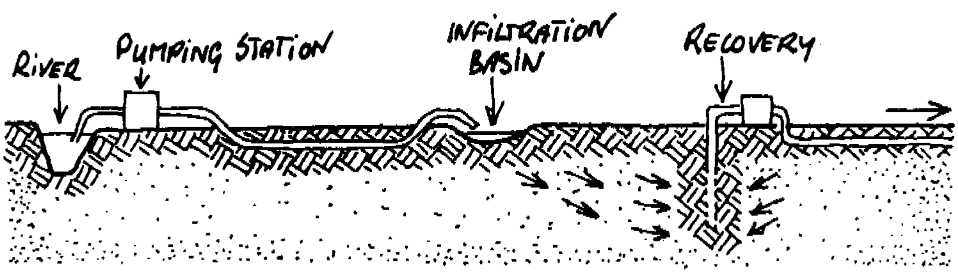

Figure 4.4: Large-scale artificial recharge scheme using specially constructed infiltration basins

Some advantages of this type of recharge scheme are:

- the formation used for recharge can be at a distance from the river;
- there is little or no clogging of the recharge basins because the water is pre-treated; fairly high infiltration rates can be applied;
- the basins can be easily emptied for cleaning or repair;
- during periods when river water is of poor quality, intake of water can be stopped, while supply of water continues, using the large amount of water stored underground.

4.2 Induced recharge

Induced recharge, or bank infiltration, occurs when water is abstracted from underground formations alongside or near a river or stream (Figure 4.5). In the original situation, groundwater flows out into the river. As water abstraction begins, the outflow of water is reduced, and at high abstraction rates the groundwater table is likely to be drawn down below the water level in the river. As a result river water is induced to enter the formation and supplement the groundwater resource. The water abstracted is a mixture of natural groundwater and recharge water from the river.

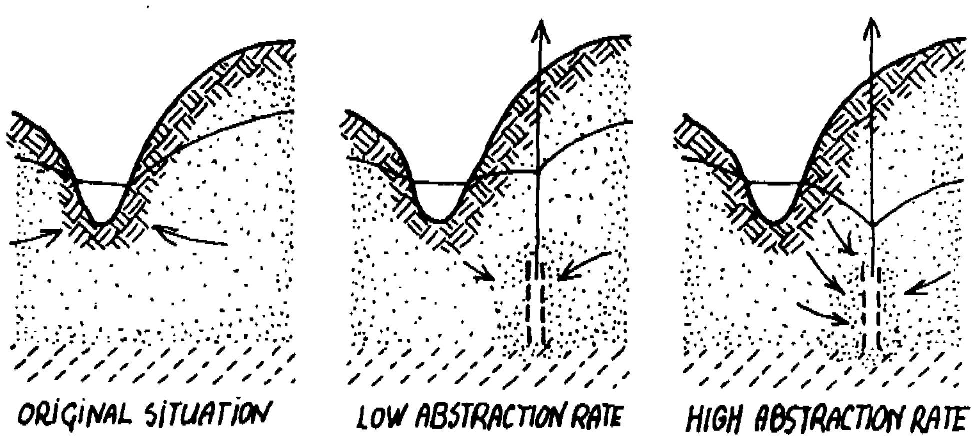

Figure 4.5: Induced recharge of formation

The design of induced recharge schemes is mainly governed by the water abstraction rate, the hydraulic transmissivity of the formation adjacent to the river, and the distance the recharge water flows underground to the recovery means (Figure 4.6).

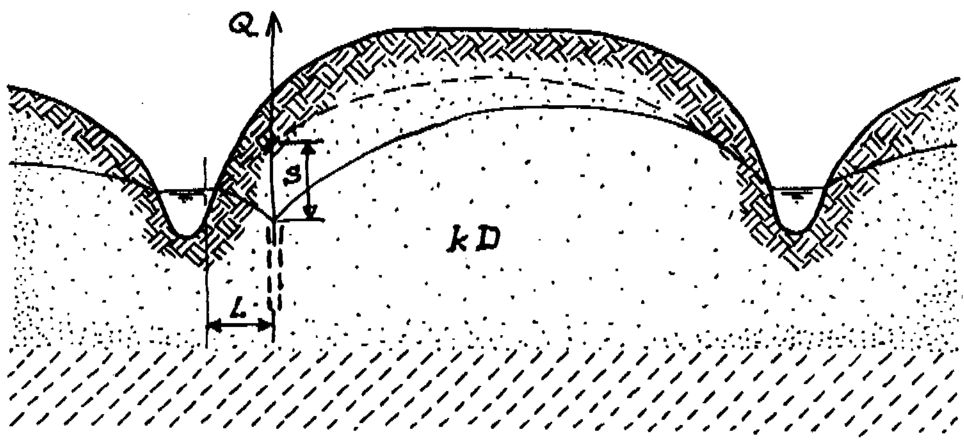

Fig. 4.6: Design parameters for induced recharge schemes

Induced recharge improves water quality through river bank infiltration. These schemes are particularly effective where there are good permeable underground formations alongside a river, for example, sedimentary deposits in a river valley.

In induced recharge schemes some clogging of the river bed generally occurs, and as a result, an infiltration head will develop (Figure 4.7). Clogging will not generally be a problem in rivers where flood flows are strong enough to scour the river bed and wash away the deposited materials. In rivers with controlled flow, the scouring of the river bed may be too weak to prevent clogging.

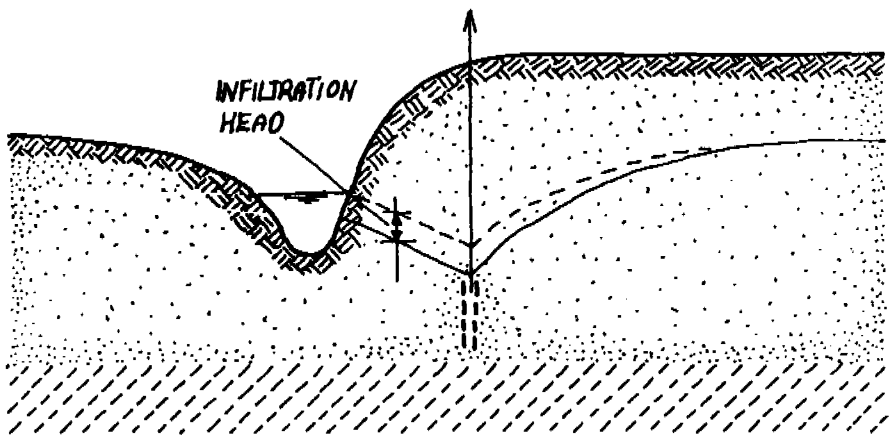

Figure 4.7: Infiltration head due to clogging of river bed

4.3 Retention of river underflow

A potential source of water for recharge schemes frequently overlooked, is river bed underflow, that is the flow of water underneath the river bed in sedimentary formations. This underflow may be intercepted by building a sub-surface dam across the river bed, and down to the impervious base (bedrock). This will raise the groundwater level and thus increase the yield of the aquifer (See Figure 4.8).

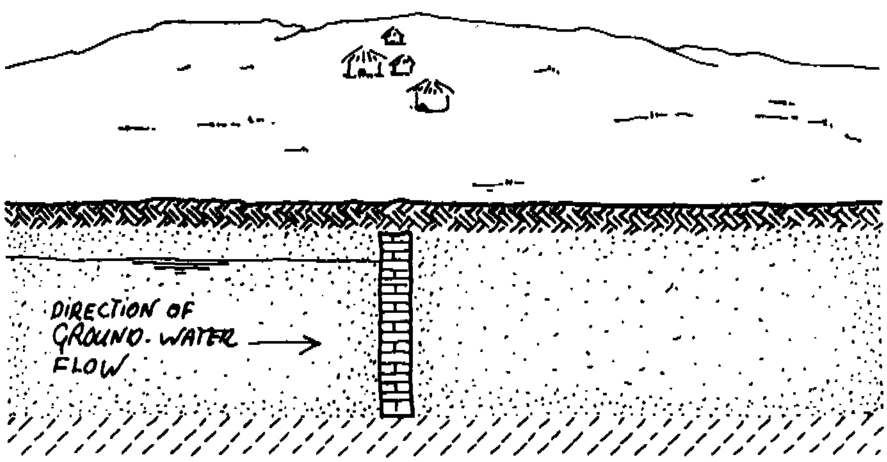

Figure 4.8: Sub-surface dam in the river bed

Often formations underneath a river bed have a high hydraulic transmissivity, and considerable amounts of water can be retained for abstraction even in the dry season.

Construction materials used for sub-surface dams include brick and stone masonry, compacted clay, and concrete. Lateral seepage of water around the dam or flow through cracks or fissures underneath it may cause considerable leakage, and even may undermine the structure of the dam itself. Preferably, the dam base should be anchored firmly onto the bedrock. If this is not feasible, a drain may be laid at the upstream foot of the dam for pressure relief. Slotted pipe with gravel packing has been used for this purpose.

4.4 Retention of river flood water

River flood flows can be retained by building sand-filled dams, often called sand dams (see Figure 4.9). These dams are particularly worth considering in arid areas where water evaporation rates are very high. Water collected in the rainy season can be stored within the body of deposited sand. Even during extended drought periods water will be available from these dams.

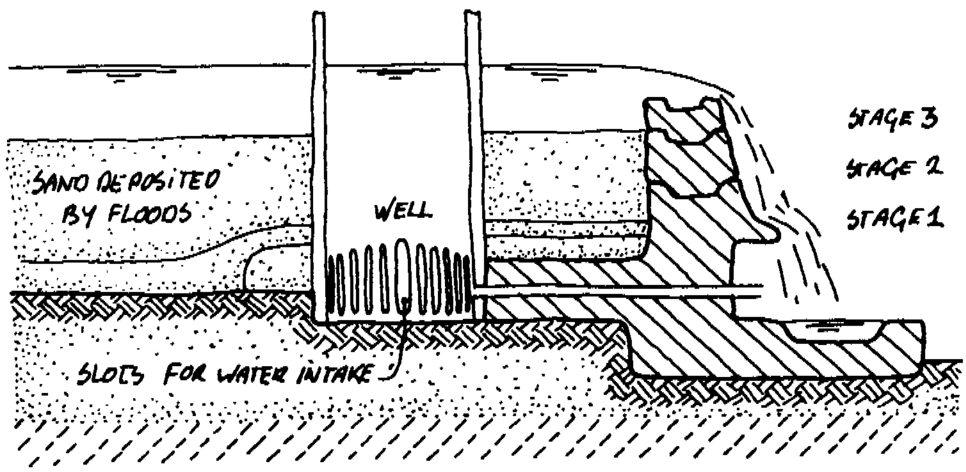

Figure 4.9: Sand dam

To build a sand dam, a trench is dug across the river bed and down to the impervious base (bedrock) and filled with clay or other impervious material. Sandy or gravel river-bedshaving a gradient of 1.5 to 4.9% are generally the most suitable for sand dams.

Sand dams are built in stages. To ensure that the dam reservoir is filled only with coarse sand and loose gravel, silt and fine sand sediments have to be carried over the dam by the flood waters. In semi-arid areas rain-fed river floods often come in short intensive bursts and flood water carries a high sediment load because there is little vegetation to prevent soil erosion. Thus, considerable amounts of coarse sand and gravel are deposited behind the dam during each flood. To ensure that the overflow water carries the fine sand and silt over the dam, the first stage of the dam should not be more than about 2 m above the river bed. When coarse sand and gravel deposits have accumulated to the first stage level, another stage can be added, which is usually done during the dry season. Built in stages, the dam will reach its full height of about 6-12 m within 4-5 years (Figure 4.10).

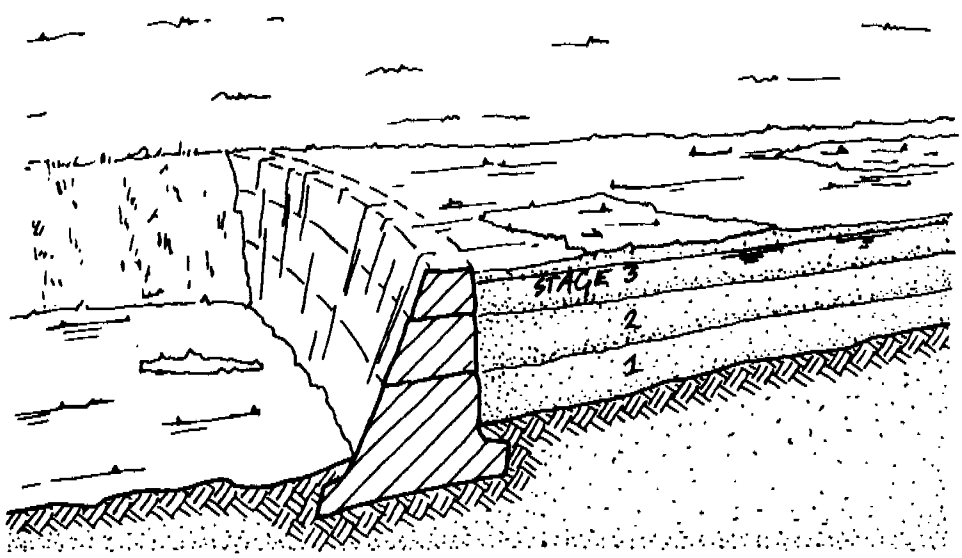

Figure 4.10: Sand dam built in stages

An alternative to raising the dam in stages is to use an outlet opening in the dam crest which is filled up stage by stage at the beginning of each rainy season.

4.5 Recovery means

Water collection means used for recovery include: collector drains (galleries), dug wells and boreholes.

4.5.1 Collector drains

Collector drains, or galleries, are only economical for recovery of shallow groundwater, not more than 6-8 m below the surface, because of the excavation costs. The drain is constructed of slotted or porous pipes or pipes laid with open joints (Figure 4.11).

In fine sand aquifers, slotted drains and drains with open joints should be packed in one or more layers of gravel to prevent fine sand from entering the drain. The top of the gravel pack should be at least 0.5 m below the lowest groundwater level, and deeper if iron and manganese are present in the water. Collector drains are also used in river beds, across or alongside the stream channel, for withdrawal of river water infiltrate.

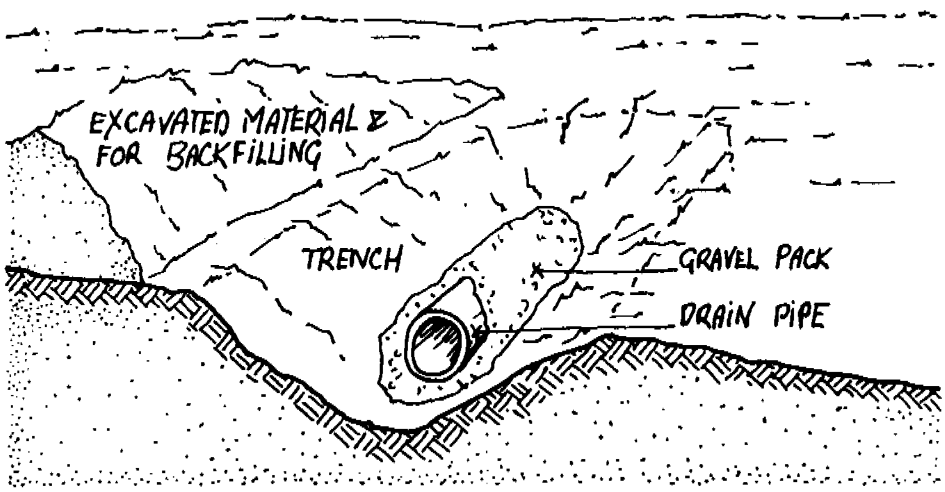

Figure 4.11: Collector drain

4.5.2 Dug wells

Dug wells are mostly used to withdraw water from shallow or medium-depth aquifers of considerable thickness. The depth to which a well can be dug largely depends on the groundwater level; depths of 10-30 m are common, but deeper wells have been dug. The well diameter usually is 1.5-3.0 m; 1.3 m is the minimum to allow enough space for the well to be dug (Figure 4.12).

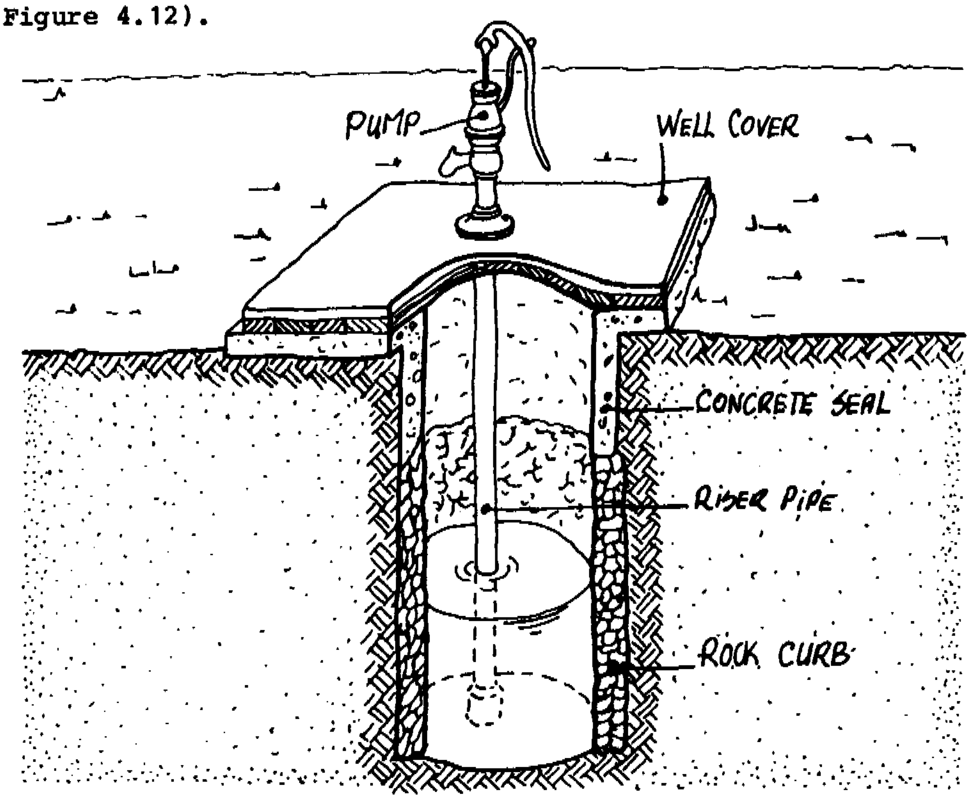

Figure 4.12: Dug well

The types of geological formations that are suitable for dug wells, include sand, gravel, soft sandstone, and soft fractured limestone. Except in very stable formations, all dug wells must be lined with stones, masonry, concrete cast in situ, precast concrete rings, or similar materials. The lining protects the well from caving and collapse, and from being filled with crumbling soil. In unconsolidated formations, the well should be lined over its entire depth, with a perforated, open-jointed, or porous section facing the aquifer, whereas in consolidated formations, it may be sufficient to line the upper part of the well only. In fine sand aquifers, the lining is often extended over the whole depth of the well without any perforations, openings, or porous section. Water can then enter the well only through the bottom which is covered with several layers of gravel to keep the fine sand of the formation in place.

4.5.3 Boreholes

Boreholes are more suitable for groundwater withdrawal from greater depths, but are sometimes also used for recovery of shallow groundwater (see Figure 4.13). The capacity of boreholes varies from less than 1 l/s for small-diameter wells in fine sand aquifers to more than 100 l/s for large diameter wells in coarse sand or gravel deposits. There are various well drilling methods including auger boring, well driving, well jetting, percussion (cable-tool) drilling, rotary drilling, and down-the-hole hammer drilling. For each location or area, the most suitable method should be carefully selected (Table 4.1).

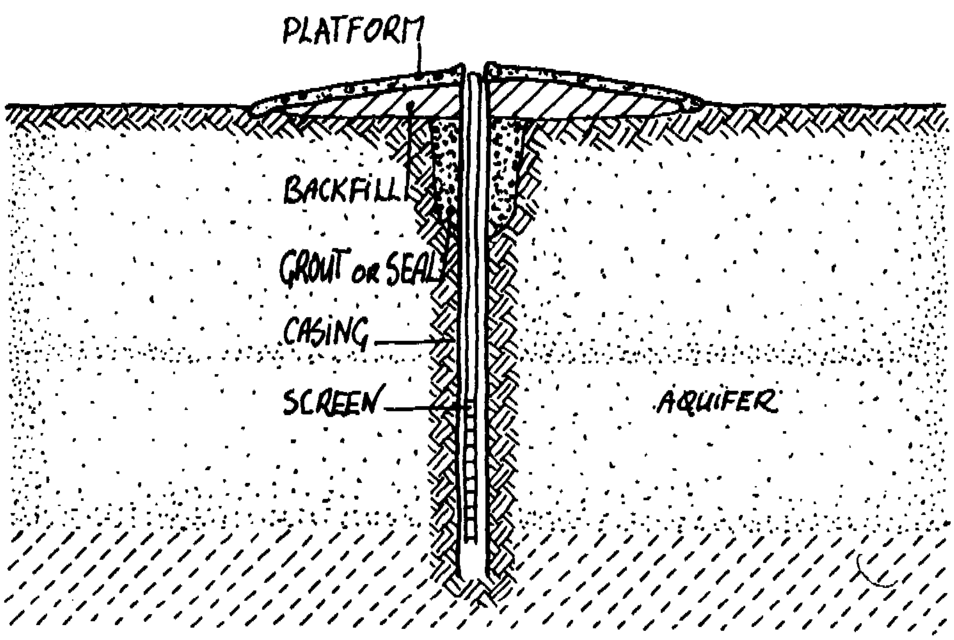

Figure 4.13: Borehole

Table 4.1: Characteristics of various well drilling methods

Type of well drilling method	Maximum practical depth (m)	Typical diameter (cm)	Suitable for:	Unsuitable for:
			Type of rock	
Boring with auger (hand-operated)	25-30	10-25	clay, silt, sand, chalk, gravel, alluvial deposits in river flood plains	consolidated formations, unstable formations
Driving	15-20	5- 8	clay, silt, sand, fine gravel soft sandstone	all consolidated formations, especially when boulders are present
Jetting	30-40	5-20	clay, silt, sand, fine gravel	all consolidated formations, especially when boulders are present
Percussion (cable-tool) drilling	300	10-30	clay, silt, sand, gravel, cemented gravel, boulders (in firm bedding), sandstone, limestone, and igneous rock	unstable formations, loose sand
Hydraulic rotary-drilling (with drilling fluid circulation)	300	10-50	clay, silt, sand, gravel, cemented gravel, sandstone, limestone, and igneous rock	unstable formations; loose sand; problems in all formations, where boulders are present
Down-the-hole air hammer drilling	200	10-30	particularly suitable for: dolomite, basalts, methamorphic rocks	loose sand gravel, clay, silt, sandstone

5. BASIC DESIGN PROCEDURE FOR ARTIFICIAL GROUNDWATER RECHARGE SCHEMES

5.1 Principal design parameters

The principal design parameters for artificial recharge schemes are:

- design infiltration rate v_i together with the width W of the recharge area gives the infiltration capacity per unit length q_i;
- head between the water level in the recharge works and the groundwater table when the scheme is in operation s;
- the effective porosity p_e the permeability k of the aquifer formation, and its wetted depth, D;
- the distance L between the recharge works and the recovery means (see Figure 5.1).

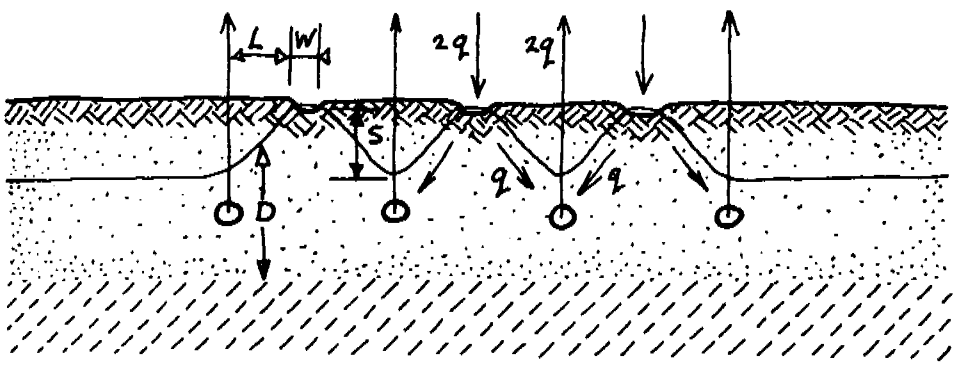

Figure 5.1: Principal design parameters for artificial recharge schemes

The water flow through the aquifer formation in an artificial recharge scheme may be calculated with a simplified form of the Darcy equation used for groundwater flow:

$$q_i = kD \frac{s}{L}$$

where:

q_i = infiltration capacity per unit length ($m^3/m/d$)

k = permeability (m/d)

D = wetted depth of formation (m)

s = head of water between the recharge works and the groundwater table, when scheme is in operation (m)

L = horizontal distance between recharge works and recovery means (m)

5.2 Example design

Consider an artificial groundwater recharge scheme which uses an aquifer formation of sand. The wetted depth D of the aquifer is 9 m. Channels with a bottom width W of 4 m are to be constructed as recharge works.

Basic design procedure is as follows:

(1) Infiltrometer tests conducted on site, indicate an infiltration rate v_e of 5-6 $m^3/m^2/d$, and the design infiltration rate is fixed at v_i = 3 $m^3/m^2/d$.

(2) The infiltration capacity per unit length of recharge channel is:

$$q_i = 1/2.v_i.W$$
$$= 1/2.3.4 = 6\ m^3/m/d$$

(3) The effective porosity p_e of the formation is determined by tests on undisturbed samples, and found to be 20%; based on a pumping test or field experience in similar schemes in the area, the permeability k is fixed at 12 m/d.

(4) The original groundwater table is measured to be at 5m below ground surface; for the recharge scheme in operation it is estimated to be one metre higher; with the water level in the recharge channels at ground level, the available head s, thus is 4m, and the wetted depth of the formation, D, is 9 + 1 = 10m.

(5) Using the simplified design equation, the horizontal distance between the recharge channel and the recovery means is calculated:

$$q_i = kD \frac{s}{L}$$

$$L = \frac{k.D.s}{q_i}$$

$$L = \frac{12.10.4}{6} = 80\text{m}$$

(6) The retention time Td for the underground flow of water in the recharge scheme is checked to determine whether it is sufficient to ensure bacteriological safety of the water abstracted. First, calculate the effective pore volume of the formation with a wetted depth of 10 m, and an effective porosity of 20%, per m of width:

$$V_{eff} = p_e.D.L. = 0.2 \times 10 \times 80 = 160 \text{ m}^3/\text{m}$$

With an infiltration rate of 6 $m^3/m/d$, the average retention time is:

$$T_d = \frac{V_{eff}}{q_i} = \frac{160}{6} = 27 \text{ days}$$

This is considered to be adequate.

(7) A length B of 50 m is selected for the infiltration channel. The infiltration capacity Q_i of the infiltration channel can now be calculated:

$$Q_i = 2.q_i . B = 2.6.50 = 600 m^3/d$$

(8) If the required capacity of the recharge scheme is 1200 m^3/d, then two infiltration channels should be used.

(9) Thus the preliminary design for the artificial recharge scheme consists of two infiltration channels constructed in parallel, 50 m long and 160 m apart with the recovery means placed at a distance of 80 m on each side. The total aquifer area used for the scheme is thus 50 m x 320 m.

6. FIELD EXPERIENCE AND COSTS OF ARTIFICIAL RECHARGE SCHEMES

6.1 Field experience

Most artificial recharge schemes for which field experience and cost data have been reported are in the industrialized countries; virtually no descriptive material concerning is available for such schemes in developing countries.

Most problems of operation of recharge schemes are related to clogging of the infiltration works because of excessive amounts of suspended solids, colloidal and organic matter in the recharge water. In many cases, occasional drainage of the infiltration works, followed by drying out and simple tilling or harrowing of the bottom, appears to solve the problem. In some instances, however, interruption of the recharge operation for cleaning of the recharge works is frequenty required. Pre-treatment of the incoming water then is needed, or expansion of the infiltration area to reduce the infiltration rate. Research into the optimal combination of infiltration area and infiltration rate, under differing conditions, would be very useful.

Excessive algae growth and disturbance of the infiltration process by decaying organic matter can be a serious problem when the infiltration water is rich in nutrients, either from natural sources or from upstream discharges of domestic waste water. A similar problem is excessive growth of water plants, e.g. water hyacinth.

The storage capacity in the underground formation allows intermittent operation of artificial recharge schemes. This is a major advantage of these schemes, because it allows drainage of the recharge works at regular intervals to eliminate any excessive algae growth or water plants. It also will interrupt any breeding of mosquitoes or snails. Aftre digging out silt deposits and organic matter, can be removed by manual labour, and, in some instances, it should be possible to rely on wind blowing away the dried-out deposits.

6.2 Costs

Very few cost data are available and most are for large artificial recharge schemes in industrialized countries. Often, data include the cost of pre-treatment works, transmission mains and water distribution systems, and thus it is difficult separate the cost of the recharge works. However, it has been estimated that the cost of the schemes varies from US$ 7 to 100 per m^3 of daily infiltration capacity. A comparison of the investment costs of equivalent recharge schemes and treatment works is given in Table 6.1.

Table 6.1: Comparison of the level of capital costs for equivalent recharge schemes and treatment works

Cost item	Artificial recharge scheme	Treatment works
Land acquisition	high	low
Excavation	high	low
Pumping plant	medium	low
Civil works	low	high
Mechanical equipment	low	high
Power supply	low	medium

The capital costs of artificial recharge schemes are comparable with those of treatment works for surface water for drinking water supply, but costs of operation and maintenance in recharge schemes are likely to be less. Estimates of operation and maintenance costs for artificial recharge schemes vary from of $ 0.05 to 0.30 per m^3 of water through put (Table 6.2).

Table 6.2: Comparison of operation and maintenance costs for artificial recharge schemes and equivalent water treatment works

Cost item	Artificial recharge scheme	Treatment works
Skilled operators	low	high
Unskilled labour	high	medium
Power	low	medium
Chemicals	none	high
Maintenance operations	low	high

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APPENDIX

CRITERIA FOR SMALL-SCALE ARTIFICIAL RECHARGE SCHEMES

The information and data collected by literature survey, and synthesized in the present document, are neither adequate nor reliable enough to allow the establishment of firm criteria that could be applied in small-scale artificial recharge schemes for rural water supply. However, on the basis of the findings and results of the knowledge synthesis study, the following tentative criteria may be presented.

A. Technical geohydrological criteria

Characteristics of recharge formation

Water-filled thickness	at least 5 m, preferably more, 25-30m
Effective porosity	not less than 10%
Permeability (K_h)	greater than 10 m/d
Composition	preferably sedimentary, granular material, with well-interconnected pores; no fissures or fractured zones; practically free of iron and manganese; no peat or similar organic matter; no sulphur-containing layers.
Impervious cover	if impervious subsoil (e.g. clay) present, overlaying the recharge formation, then not thicker than 4-5 m, in order to allow excavation of infiltration channels (or ponds) down to the water-bearing formation.
System boundaries	presence of natural system boundaries e.g. bedrock in river-valleys is a great advantage for artificial recharge systems.

B. Organizational and institutional requirements

Local organization	local committee or other local organization available, which is able and willing to assume responsibility for operation and maintenance, and for organization and collection of local contributions.
Community involvement	sufficient interest and support for construction and management of the artificial recharge scheme.
Support from water supply agency	water supply agency involved, and adequately organized to provide technical support for planning, design and construction, as well as technical backstopping for operation and maintenance.
Capabilities and skills (manpower)	some technical background, skills, and experience with the type of work involved, such as control of water flow, excavation of ground, and construction of structures.
Pumping equipment and plant	skills, technical support, supplies of spare parts and fuel.
Construction materials and equipment	local materials, such as clay, bricks, cement, available for construction; tools for excavation work.

C. Costs and financing

Capital cost	generally, less than for water treatment works of same output capacity.
Recurrent costs	likely to be far less than for water treatment works of same output capacity.
Financing	programme funds to cover capital cost of recharge schemes.

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