# CHAPTER 10

# 10.Specific Water Treatment Processes

# CHAPTER 10: SPECIFIC WATER TREATMENT PROCESSES

## 10.1 Introduction

Water treatment involves the removal of physical, chemical, and biological contaminants that transform raw water into potable water. The treatment process used in any specific instance depends on the quality and nature of the raw water.

Water treatment processes range from simple processes like sedimentation to complex physico-chemical transformations, as with coagulation. The specific treatment processes include control of algae, taste and odour, removal of colour, softening, removal of iron and manganese, arsenic, hexavalent chromium, mercury, nitrate and fluoride, as well as desalination.

## 10.2 Control of Algae

### 10.2.1 General

Algae impart odour, colour, and taste to water. Algae, like *Synura,* cause a perceptible odour; while *Asterionella, Meridion*, and *Tabellaria* produce an aromatic odour, and *Dinobryon, Peridinium, Uroglenopsis, Asterionella,* and *Tabellaria* produce fishy odour. Grassy odour is caused by *Aphanizomenon, Anabaena, Gomphosphaeria, Cylindro-spermum*, and *Rivularia*. Septic odour is caused by *Cladophora, Hydrodictyon, Ceratium, Aphanizomenon, Anabaena*, and *Cylindrospermum*. When algae like *Microcystis, Anabaena*, and *Aphanizomenon* die *en masse* and decay, they produce foul odours.

Some algae impart sweet, bitter, or sour taste to water. Algae like *Nitella, Geratium*, and *Synura* give rise to a bitter taste, while algae such as *Chara, Euglena, Aphanizomenon, Microcystis, Cryptomonas*, and *Gomphosphaeria* impart a sweet taste to water.

Algae interfere in the process of flocculation and sedimentation. Algae like *Asterionella* and *Synedra* prevent floc formation. Water containing *Gomphosphaeria* and *Anabaena* needs to be agitated for proper floc formation. They buoy up the flocs and carry them into the filters. They choke the filters and as a result, reduce filter runs. Algae associated with filter clogging are *Asterionella, Fragilaria, Navicula, Synedra, Cymbella, Diatom, Oscilatoria, Rivularia, Trachelomonas*, and *Closterium*. Algae like *Synedra* and *Oscillatoria* can pass through a rapid sand filter. Algae such as *Euglena, Phacus, Navicula, Nitzschia*, and *Trachelomonas* get through a slow sand filter. These algae in the distribution system cause biological corrosion.

*Lyngbya, Anabaena, Cylindrospermum, Nodularia*, and *Microcystis* are some of the common toxic algae associated with fish mortality. Hay fever is caused by *Anacystis* and *Lyngbya Contorta*. Gastrointestinal disturbances are also said to be due to algal toxicity.

Algae can be killed by treating the water with suitable chemicals. However, allowing the algae to grow and then adopting algicidal measures has the following disadvantages:

a) Dose of chemical required is greater than that needed if the treatment is adopted at the initial stages of growth;
b) Dead algae decay and produce acute odour problems;
c) Dead algae provide a pabulum for a second crop which is generally more prolific than the first and also more resistant to the action of algicides.

It is, therefore, preferable to take all possible measures to prevent the growth of algae at the initial stage and to reserve the use of algicides as a final treatment.

### 10.2.2 Causative Factors for Growth

Algal growth is influenced by several factors such as nutrients in the water, eutrophication, the availability of sunlight, the character of the reservoir, and temperature.

#### 10.2.2.1 Nutrients in Water

Nutrients like nitrogen and phosphorus favour the growth of algae. Swamp water or water in contact with decaying vegetation, as well as water polluted by sewage, contains a large number of organic matters favouring certain types of algal growth. Among the various mineral compounds, nitrogen and phosphorus are particularly favourable and are generally brought in by agricultural return waters and some industrial wastes. Algicidal treatments have limited value when the water is rich in such nutrients because the conditions are favourable for the growth of succeeding crops of algae.

#### 10.2.2.2 Eutrophication

Eutrophication is the process whereby lakes become enriched with nutrients that make the water undesirable for human use, both for water supplies and recreation. Limnologists (scientists specifically educated to study surface water sources such as lakes, ponds, etc.) categorise lakes according to their biological productivity. Oligotrophic lakes are nutrient-poor and typical examples are a cold-water mountain lakes and a sand-bottomed, spring-fed lakes, both characterised by transparent water, very limited plant growth, and low fish production. A slight increase in plant and algal fertility results in a mesotrophic lake with some aquatic plant growth, greenish water, and moderate production of game fish. Eutrophic lakes are nutrient-rich and produce significant growth in the form of microscopic algae and rooted aquatic weeds that produce a water quality undesirable for body contact and non-body contact recreation.

The process of eutrophication is directly related to the aquatic food chain. Algae use carbon dioxide, inorganic nitrogen, orthophosphate, and trace nutrients for growth and reproduction. These plants serve as food for microscopic animals (zooplankton). Small fishes feed on zooplankton and large fishes consumes small ones. Abundant nutrients destabilise the normal succession and promote blooms of blue-green algae that are not easily utilised as food by zooplankton, thus the water becomes turbid. Floating masses of algae are windblown to the shore where they decompose producing malodours. Decaying algae also settle to the bottom, reducing dissolved oxygen. Even a relatively mild algal bloom can result in the accumulation of substantial decaying scum along the windward shoreline because of the lake’s vast surface area. The most damaging aspect of eutrophication is that the process is difficult to slow down once started. Once a lake has become eutrophic, it remains so, for a very long time, even if nutrients from point sources are reduced. Non-point sources are also significant contributors to nutrient loading.

Eutrophic lakes also greatly increase the difficulty of water treatment.

#### 10.2.2.3 Sunlight

Algae require sunlight for their life processes and, hence, the growths are profuse in seasons of intense sunlight. Clear waters favour the growth of algae because they permit the penetration of sunlight to greater depths.

#### 10.2.2.4 Characteristics of Reservoirs

Shallow reservoirs offer more favourable conditions than deep reservoirs because their dissolved nutrients closer to the surface may stimulate algal growth. Irregular margins and shallow areas encourage the growth of aquatic weeds which offer anchorage for the epithetic algae.

#### 10.2.2.5 Temperature Effects

The temperature has a considerable influence on algal growth. The blue-green and the green algae make their presence when the water temperatures reach 20 to 30 °C.

### 10.2.3 Remedial Measures

#### 10.2.3.1 Preventive Measures

Preventive measures should, therefore, be based on control of those factors such as reduction of the food supply, change of the environment, or exclusion of sunlight though they are not always practical. Clearwater reservoirs, service reservoirs, and wells can be covered to exclude sunlight, but such a remedy is inapplicable in the case of large reservoirs of raw water. Turbid water prevents light penetration and thereby reduces the algal population, but turbidity provides other organisms protection that also must be removed in the water treatment process. Activated carbon (10.5 to 24.5 kg/ha) reduces the algal population by excluding sunlight but the disappearance of activated carbon in the water may support algal growth again. To a limited extent, the environmental conditions for the growth of algae may be made unfavourable by proper care in the construction and operation of reservoirs.

#### 10.2.3.2 Control Measures-Algicidal Treatment

Algicidal measures may be adopted to control algae in reservoirs. As it has been explained earlier, it is preferable to initiate the treatment in the early stages of algal growth.

**(i) Microscopic examination**
To decide on the best time at which the water should be treated, it would be necessary to have a regular schedule of microscopic examinations of the water. Such an examination is especially necessary during the season in which algal invasions may be expected.

**(ii) Time for treatment**
Generally, the practice has been to apply algicides when the total count reaches or exceeds 300 areal (measure of the algal strength/growth rate) units. Areal growth rate is the new biomass per area per time. This is usually used to express growth in a pond or in the ocean. The unit of measure used to quantitatively measure the growth is “areal” unit (mass per area-time, $g/m^2s$). Algae which are known to be particularly troublesome should be eradicated even though the total count is much less than 300 areal units. For example, algicidal treatment is indicated as soon as *Synura*, a type that causes severe smell troubles, is encountered, irrespective of the total count.

**(iii) Type of algicides**
A large variety of algicides are available and many new algicides are being synthesised. Many of these are complex organic compounds and are credited with specific actions against particular species. Chemicals such as ketones, aldehydes, organic acids, quaternary ammonium compounds, silver nitrate, chlorine dioxide ($ClO_2$), and rosin amines have also been tried as algicides. However, these are costly and have not come into general use. The most widely used algicides are copper salts, chlorine, and potassium permanganate in small-scale water supplies. The chemical to be used as an algicide should be species selective, non-toxic to aquatic life, particularly fish, harmless to human beings, have no adverse effect on water quality, as well as are inexpensive and easy to apply. The application of copper sulphate and potassium permanganate is discontinued due to several limitations; hence, they should not be used as algicides.

**Chlorine**
Chlorine is normally a bactericide and is also used as an algicide. Chlorine has a specific toxic effect and causes the death and disintegration of some species of algae. The essential oils

present in the algae are thus liberated and can cause taste and odour problems. Occasionally, these essential oils as well as the organic matter of the dead algae may combine with chlorine to form new or intensified odours and tastes. Such intensification of odours makes the control of algae by chlorine a problem that challenges the ingenuity of the operator. The lethal doses of chlorine for the more common types of algae are given in Table 10.1.

**Table 10.1: Amount of Chlorine Required to Destroy Microscopic Algae**

| Algae | Chlorine dose, mg/L |
|---|---|
| *Aphanizomenon* | 0.85 |
| *Cyclotella* | 1.00 |
| *Melosira* | 2.00 |
| *Dinobryon* | 0.5 |
| *Uroglenopsis* | 0.5 |
| *Synura* | 0.3 |

Chlorine may be applied either as a slurry of bleaching powder or as a strong solution of chlorine from a chlorinator and the latter is preferable. Small reservoirs may be treated by applying a slurry of bleaching powder at the influent end or by towing bags containing the bleaching powder in the water. Chlorination for algal growth is more commonly adopted in the pretreatment part of the waterworks. The point of application is generally at the point of entry of raw water into the treatment plant or just ahead of the coagulant feed. Algal growths in raw water conduits can get rid of by heavy doses of chlorine. The addition of chlorine along with coagulant is sometimes practiced.

**(iv) Surface aeration of lakes or ponds to control algae growth**

Algae blooms are more common during hot, calm, and sunny weather (Figure 10.1). The agitation at the surface that eliminates stagnant spots reduces the spaces accessible for algae to thrive (Figure 10.2). Simply moving the water assists in reducing the number of algae in the pond. Algae prefer quiet, stagnant regions to grow because they dislike moving water or surface agitation. Surface agitation in a pond or body of water is caused by aeration. This is advantageous in several ways. It aids in the elimination of still, stagnant water patches (stratification) and simulates natural breezes.

Surface agitation is also advantageous since it aids in the mixing of algae that are already present in the water column. Algae cannot sit at the water’s surface and absorb all of the sunshine it needs for photosynthesis, and it cannot survive without this enormous amount of sunlight. The agitation also helps to de-stratify the pond by mixing up the water and lowering the general pond temperature, making the environment less favourable to algae. Aeration can produce a shift in the carbon dioxide levels within the pond, which can then shift the pH levels, allowing beneficial plants to outcompete the unwanted algae and blue-green algae.

Finally, the agitation serves to refract some of the sunlight that strikes the water’s surface. The amount of sunlight that can enter the water column is thus limited. Algae and other aquatic plants struggle as sunlight diminishes throughout the water column. Some will remain, but it will assist in limiting algae and other aquatic plant overcrowding.

Aeration should not be considered as the panacea, but rather as one of many strategies that are often used in conjunction with other ways of algae control. Added aeration is always useful and, most of the time, there will be some additional water quality advantages from added oxygen, including that the increased oxygen levels are beneficial for fish, odour problems, and general pond ecosystem health.

Figure 10.1: Algal Sludge

Figure 10.2: Surface Agitation can be Achieved by Aerators or Recycling Pumps

#### 10.2.3.3 Control of Algae at Water Treatment Plants (WTPs)

Algae in WTPs can be removed by the application of chlorination, ozone, chlorine dioxide, or activated carbon. Pre-chlorination will help in killing the algae and facilitate their settling. Pre-chlorination will prevent the growth of algae in basin walls and will aid in the removal of algae by coagulation and sedimentation because the dead cells of these organisms are more readily coagulated. The chlorine in the settled waters will also destroy slime organisms on the filter sand and thus prolong filter runs and facilitate filter washing. Doses required for this purpose may have to be up to 5.0 mg/L to meet the chlorine demand of water, oxidise free ammonia, etc.; however, the water may have to be de-chlorinated in case of higher residual chlorine, so that it maintains 0.2 to 0.5 mg/L free residual chlorine in the settled water. It is seen that chlorine gas has more potential for oxidation than calcium or sodium hypochlorite.

Most economical results are secured with the use of pre-chlorination for initial disinfection by free residual chlorine and post-chlorination with chlorine dioxide. Chlorine dioxide doses sufficient to give an apparent content of 0.2 to 0.3 mg/L free residual chlorine in the filtered water are adequate. This amount of chlorine dioxide being equivalent in oxidising power to 0.5 to 0.75 mg/L free residual chlorine. Chlorine dioxide, along with chlorine, is effective in pre-oxidation. It reduces the potential for the formation of disinfection by-products (DBPs). The chlorine dose needs to be just enough to immobilise or kill the algae cells. An excessive chlorine dose is likely to rupture the cell structure and bring out intra-cellular compounds and toxins (cell lyses), which further complicates the treatment. The combination of coagulation with aluminium/ferric salts and polyelectrolytes with effective slow mixing and flocculation should ensure the settlement of “intact” dead algae mass from the clarifier. Excessive coagulant dosages during a low turbidity period (raw water) ensure “sweep flocculation” to trap the microscopic algal particles.

Ozone is very effective in the destruction and gives more consistent results since it is a very active oxidising agent. Ozone is slightly soluble in water and hence persists in the treated water for only about 30 minutes.

**Micro-strainer**

A special process known as micro-straining is being used in some WTPs. The micro-strainer is an open drum. The water is passed through a finely woven fabric of stainless steel. The size of the openings in the mesh determines the size of the plankton to be removed from the water.

**Ultrafiltration (UF)**

Details of UF are provided in the section related to membrane processes. UF can also be used in combination with granular activated carbon (GAC).

### 10.3 Monitoring and Control/Removal of TOC in Water

Drinking water specifications including bacteriological requirements, virological requirements, biological requirements, and pesticide residue limits shall comply with the requirements given in the Bureau of Indian Standards, IS 10500:2012 (reaffirmed year: 2018). To monitor this sampling and analysis of various parameters shall be conducted according to BIS IS 3025 (Parts 1 to 79) and IS 1622 (1981, reaffirmed 2019). However, TOC is not included in that standard.

Various sources of water are “rivers, lakes, canals, ground, rain, sea, etc.” which are contaminated due to the discharge of untreated municipal and industrial water. Consequently, organic carbon is present in freshwater as a constituent of many waste materials and effluents. The organic carbon also arises from living organic matter in freshwater. TOC is emerging as the most suitable parameter to measure organic load in both raw and treated water and is widely being recognised as an index of water quality in terms of the total index of organic substance in water.

Furthermore, the raw water containing TOC, when treated in WTP with chlorine as disinfectant, DBP like *Trihalomethanes* (THMs) and haloacetic acids (HAAs) may be formed, which are carcinogenic. Lower the TOC, better the quality of water and vice versa. TOC is the major cause of concern in developed countries which have notified TOC limits 4 to 5 mg/L in source water and 2 to 3 mg/L in drinking water. Therefore, these TOC limits are mainly to control the products formed when disinfection is done with chlorine. TOC removal shall be required mainly in WTPs that uses conventional methods to treat surface water. TOC is used as a surrogate measurement for DBPs, therefore, a detailed study for the same is needed. Nano bubble oxygen or ozonation technology may be considered as an emerging technology for TOC removal.

### 10.4 Control of Taste and Odour in Water

#### 10.4.1 General

Normally, in summer, the water level depletes below the maximum drawdown level (MDDL) in the reservoir. In such situations, the utility even consumes the water from the dead storage of the reservoir and, therefore, the colour, taste, and odour problem prevails. Colour, taste, and odour are formed due to decay of inundated vegetation at the bottom of the dam/impounding reservoir. The problems of taste and odour (one co-exists with the other) are more intensive and more frequent in surface water sources. Taste and odour are caused by dissolved gases like hydrogen sulphide, mercaptans, methane, organic matter derived from certain dead or living microorganisms (blue and green algae), decomposing organic matter, industrial liquid wastes containing phenols, cresols, ammonia, agricultural chemicals, high residual chlorine, and chloro-phenols. It is possible that some of the dissolved gases might be found in groundwater also.

Biological organisms are one of the most common causes of taste and odour in water. *Diatomaceae,* with *Asterionella* and *Synedra, Actinomycetes*, and free-swimming nematodes are the principal offenders causing earthy or musty odour. Apart from algae, decomposing leaves, weeds, or grasses also cause odour. Vegetation that grows in the low-water areas in the reservoir subsequently gets submerged and decomposes resulting in odour. Chemical and refinery effluents have the greatest potential for odour, followed by domestic sewage. Odour tests indicate that only a small quantity (in mg/L) of these materials is needed to produce a detectable odour.

In short, taste and odour producing materials in water are chemical compounds of many varieties with different physical and chemical characteristics present in water because of direct pollution or biological activity. Most of these compounds are in solution and some exist in the form of particulate and colloidal compounds. Those in solution are comparatively more difficult to remove.

### 10.4.2 Control of Taste and Odour

Preventive and corrective treatment of raw and processed water is necessary for the control and elimination of taste and odour problems. Wherever possible, preventive steps like control of microorganisms are to be undertaken where the source of raw water is from rivers, reservoirs, or lakes, whenever there is a control on effluent discharges. Special treatment is given to water in the treatment plant for the removal of odours by aeration, oxidation by chemicals, or adsorption by activated carbon.

### 10.4.3 Corrective Measures

Odours can be removed by mechanical aeration, oxidation by chemicals like chlorine or its compounds, ozone, permanganate, and adsorption of odour by agents such as activated carbon, floc, and clays. For removing dissolved gases like hydrogen sulphide and volatile matter, aeration can be practiced at the start of water treatment. Free available residual chlorination at the pre-chlorination or post-chlorination stage can bring about complete elimination of taste and odour. Inadequate chlorination will only intensify the odour of water containing phenolic compounds, tannin, and lignin. Even with breakpoint chlorination, it may not be possible to remove taste and odour from water in certain cases. Such compounds can be removed by super-chlorination. Super-chlorination is normally done either at the reservoir outlet or the WTP inlet to bring the maximum chlorine concentration and the maximum contact time together to effect oxidation. This should be followed by de-chlorination using sulphur dioxide or sodium sulphate to reduce the residual chlorine to acceptable limits.

Chlorine dioxide has been found extensively efficient and the general dosage values range from 0.2 to 2.0 mg/L. Chlorine dioxide gas is released in water on site by the inter-action of a solution of sodium chlorite ($\mathrm{NaClO_2}$) with a strong chlorine solution of 6000 to 7500 mg/L.

$$2NaClO_2 + Cl_2 \rightarrow 2ClO_2 + 2NaCl \qquad (10.1)$$

Though the theoretical ratio of chlorine to sodium chlorite is 1:2.6, values between 1:2 and 1:1 are employed in practice. It is applied at the first stages of the treatment plant. Thereafter, the final desirable residual chlorine may be adjusted by simple chlorination after filtration. Ozone at dosages of 1.0 mg/L has also produced good results. Chlorination is useful in the removal of phenol tastes.

### 10.4.4 GAC

The preferred method of treatment for taste and odour removal is activated carbon (preferably GAC). Odour-producing substances that cannot be removed by oxidation are physically adsorbed onto the surface. This treatment is usually applied before filtration. The contact time varies from 10 to 60 minutes. Activated carbon performs well at lower pH values. A bed of carbon or suspension kept in circulation could be used. The active surface must be preserved from the coating by other chemicals. Application of carbon can be made before sedimentation if the taste and odour are severe and frequent and in certain cases after sedimentation. The approximate dosage for routine continuous application as the suspension is 2 to 8 mg/L; for emergency treatment, 20 to 100 mg/L. Carbon beds are generally 1.5 to 3 m deep with sizes of 0.2 to 0.4 mm with loadings of about 4.8 $m^3/hr/m^2$ of bed. Filtration rates range from 7.2 to 15 $m^3/hr/m^2$ with expected efficiencies of about 90%. As many variables are involved, pilot plant tests are necessary. Carbon can also be used as a polishing agent to remove residual odours after other treatments.

Variables such as pH, temperature, quantity, and type of organic matter in the influent water and detention time have a marked effect on the efficiency of removal of odorous materials.

### 10.5 Removal of Colour

Colour in water may be due to natural causes or as a result of human activity. Waters occurring in peaty soils acquire colour because of the presence of colloidal organic matter. Colour is also due to mineral matter in solutions, as a colloid, or in suspensions as in the case of groundwater in certain areas. Waters containing oxidised iron and manganese impart characteristic reddish or black colour. Heavy growths of algae may also impart colour to the water. Discharge of industrial wastes or heavy sewage pollution can also bring in colour. The constituents in coloured water can consist of natural organic matter (NOM) or synthetic organic matter (SOM). NOM mostly consists of fumic and fulvic acids having a low molecular weight.

Colour due to iron and manganese may be removed by specific treatment for the removal of these constituents as discussed in Section 10.6. Water that is coloured because of the growth of algae has to be treated to eliminate the source by control of the algae as discussed in Section 10.2.

Coagulation at a low pH range by chemicals such as alum/PAC or ferric salts and polyelectrolytes (sweep flocculation) is used for removing colour due to colloidal organic matter (NOM). Ferric coagulants are generally superior to alum. After the removal of the colour colloids, the pH of the water will have to be corrected by treatment with lime. The colour colloids are often stabilised at a high pH value and, hence, the addition of lime to aid coagulation is fraught with danger in the case of waters that are coloured. It is essential that laboratory tests should be conducted to determine the most suitable chemical and its optimum dosage in the given conditions.

Treatment with GAC, as described earlier, is effective against most problems of colour in water. Carbon removes the colouring matter by adsorption. Application has been discussed in Section 10.4.4.

### 10.6 Softening

The hardness of water is due to the presence of calcium and magnesium ions in most cases. Bicarbonates, sulphates, and chlorides are the anions associated with the hardness. Calcium and magnesium associated with bicarbonates are responsible for carbonate hardness and that with sulphates, chlorides, and nitrates contribute to non-carbonate hardness. The purpose of softening is to remove these salts from the hard water. The acceptable limit and permissible limit (in the absence of any alternate source) of total hardness are 200 and 600 mg/L, respectively, as per drinking water quality standards (IS 10500:2012).

The two methods ordinarily used are lime and lime-soda softening and ion exchange softening.

#### 10.6.1 Lime and Lime-Soda Softening

This process is seldom employed in India; however, wherever water characteristics and other limitations exist then this can be used with precautions. More often, it is used for industrial use where the water has to be fed to the boiler since it also reduces colloidal silica. Softening with these chemicals is used particularly for water with high initial hardness (greater than 600 mg/L) and suitable for waters containing turbidity, colour, and iron salts because these have a tendency to inactivate the ion exchange bed, by a coating on the granules. Lime-soda softening cannot, however, reduce the hardness to values less than 40 mg/L while ion exchange softening can produce zero-hardness water. Computation of chemical doses is enclosed in **Annexure 10.1**.

### 10.6.2 Ion Exchange Softening

The ion exchange process is the reversible interchange of ions between an exchange medium and a solution and this process is used extensively in water softening. The hardness-producing ions preferentially replace the cations in the exchangers and hence this process is also known as "base exchange softening". The ion exchange can produce water of zero hardness. There is only a temporary change in the structure of the exchange material which can be restored by regeneration. The ion exchanger can work on the hydrogen or sodium cycle, the hydrogen ions being released into the water in the former case and the sodium ions in the latter. The regenerant agents are acid and sodium chloride, respectively. In general, the ion exchange materials used in softening, also called zeolites, are hydrated silicates of sodium and aluminium having the formula: $xNa_2O.yAl_2O_3.zSiO_2$. The reaction can be depicted as follows:

$$Na_2Z + \frac{Ca^{++}}{Mg^{++}} + 2A^- \leftrightarrow \frac{Ca}{MgZ} + 2Na^+ + 2A^- \tag{10.8}$$

Where $A^-$ represents the relevant anions of bicarbonates, sulphates, or chlorides and Z represents the anionic part of the zeolite.

Treatment with zeolite thus increases the dissolved solids in the ratio of 46:40 of the hardness removed. The reverse equation operates during the regeneration resulting in a strong solution of calcium and magnesium salts, which is run to waste.

#### a) Inorganic zeolites

The two common inorganic zeolites are the natural and synthetic types. The natural zeolite is available as green sand while the synthetic or gel type is obtained by the reaction of either sodium or aluminium sulphate with sodium silicate, which after drying is graded to suitable sizes by screening. A cubic metre of green sand weighs 1600 kg with a specific gravity of 2.1 to 2.4 and for regeneration, it requires 3.5 to 7 kg of salt for every kilogram of hardness removed. The synthetic inorganic zeolite weighs 900 to 1100 kg/m$^3$. The relevant exchange capacities and regenerant requirements are given in Section 10.6.2. (d).

#### b) Organic zeolites

They are lighter than the inorganic zeolites weighing 500 to 800 kg/m3. These consist of sulphonated-carbonaceous material and sulphonated styrene-type resins which have excellent cation-exchange properties, requiring for regenerating 2 to 4 kg of salt for every kilogram of hardness removed. These are resistant to attack by acid solutions and hence can be regenerated with acid also. They can be used for waters with a wide pH range. The loss due to attrition is negligible compared to the synthetic inorganic zeolites.

#### c) Raw water characteristics

For application to ion exchangers, the raw water should be relatively free from turbidity (≤1 NTU), as otherwise, the exchange material gets a coating that affects the exchange capacity of the bed. The desirability of using filters before zeolite beds or resorting to more frequent regeneration would depend upon the level of turbidity. Metal ions, like iron and manganese, if present are likely to be oxidised and can coat the zeolites, thus deteriorating the exchange capacity steadily since the regenerant cannot remove these coatings. Oxidising chemicals like chlorine and carbon dioxide, as well as low pH in the water, tend to adversely affect the exchange material, particularly the inorganic types, and the effect is more pronounced on the synthetic inorganic zeolites.

### d) Design criteria

The design criteria for a softening system are based upon the following:

- (a) The required flow rate:
- (b) The influent water quality;
- (c) Desired effluent water quality;
- (d) Exchange capacity and hydraulic characteristics of the exchanger;
- (e) Period between regenerations;
- (f) Type of operation;
- (g) Number of units required;
- (h) Rate, time of contact, uniformity, and concentration of brine application;
- (i) Rate and volume of rinse; and
- (j) Quality of regenerant.

A softening unit is similar to a rapid sand filter unit regarding hydraulics and equipment.

The volume of exchange material (*E*) to be used in cubic metre is calculated by the formula:

$$E = \frac{QH}{1000G} \qquad (10.9)$$

Where,
$Q$ = volume of water to be treated between regeneration, $m^3$
$H$ = hardness of water, mg/L
$G$ = exchange capacity of the material, $kg/m^3$

Generally, ion exchange beds are encased in shells, shell diameter, and bed depth being adjusted to maintain a rinse rate of flow in the range of 0.15 to 0.30 m/min. The vertical units are 2 to 3 m in diameter while the horizontal ones are 3 m in diameter and 8 to 9 m long. The ion exchange bed has a depth of 0.6 m usually and is placed over supporting gravel (size depending upon the composition of the exchange material but with similar specifications as those for rapid gravity sand filters) of 0.30 to 0.45 m depth with an underdrain system at the bottom for collecting softened water. After the softening cycle, the softener should be backwashed for 3 to 5 minutes to loosen the exchange resin and remove particulate matter. The rate of backwash should ensure at least 50% bed expansion.

In the ion exchange softening process, which uses regeneration with sodium-based compounds, about 0.5 mg/L sodium is added to water for each milligram per litre of hardness. Hence, after treatment, water that has 400 mg/L of total hardness will have about 200 mg/L of sodium. It is recommended that the hardness of treated water should be slightly less than 200 mg/L which will also comply with IS 1050:2012. Nevertheless, it also means that for every litre of water intake, there would be 100 mg of sodium intake (to bring down total hardness from 400 to 200 mg/L). Persons having restricted sodium diets because of health concerns may not be able to tolerate high sodium water. Therefore, drinking and cooking with soft water is normally avoided and, on the contrary, hard water is provided for drinking and cooking purposes. It is also not recommended to repeatedly use softened water for plants, lawns, or gardens due to the sodium content.

This restricts the use of soft water, hence, ion exchange for softening purposes should be used judiciously and avoided in normal cases.

### 10.6.3 Combination of Lime and Zeolite Softening

For waters that contain a large carbonate hardness, a combination of lime and zeolite softening can be practiced. The lime treatment, which is applied first, removes by precipitation a large part of the carbonate hardness, simultaneously decreasing the amount of dissolved solids in the water. After leaving the lime reaction tank, the water is settled and filtered and then passed through the zeolite softeners which by base exchange remove the residual carbonate hardness and all the non-carbonate hardness.

The combination of lime and zeolite offers the following advantages:

a) It gives water a lower hardness than can be obtained by lime and soda ash treatment.
b) It reduces the amount of total dissolved solids (TDS) which the zeolite treatment alone would not do.
c) It gives a lower cost of chemicals than with lime and soda ash and possibly lower than with zeolite alone, depending on the relative costs of salt and lime.

Surveys carried out in other countries have brought out the fact that the benefits of savings of soap alone justify the expenses of softening on a municipal scale. Other benefits like good public relations add to the attractiveness of the proposition. The practice has not, however, caught up with this trend even in those countries. With greater demands for higher quality water, water softening may have to be carried out on a municipal scale also.

## 10.7 Removal of Iron and Manganese

Appreciable amounts of iron and manganese in water impart a bitter characteristic and metallic taste, and the oxidised precipitates can cause the colouration of water which may be yellowish brown to black and renders the water objectionable or unsuitable for domestic and many industrial processes. In addition, staining of plumbing fixtures and laundered materials can also happen. The carrying capacity of pipelines in the distribution system is reduced due to the deposition of iron oxide and bacterial slimes as a result of the growth of microorganisms (iron bacteria) in iron-bearing water. The acceptable limits of iron and manganese are 1.0 and 0.1 mg/L, respectively, as per IS 10500:2012. Iron is present mostly in groundwaters and its concentration is shown in Figure 10.3.

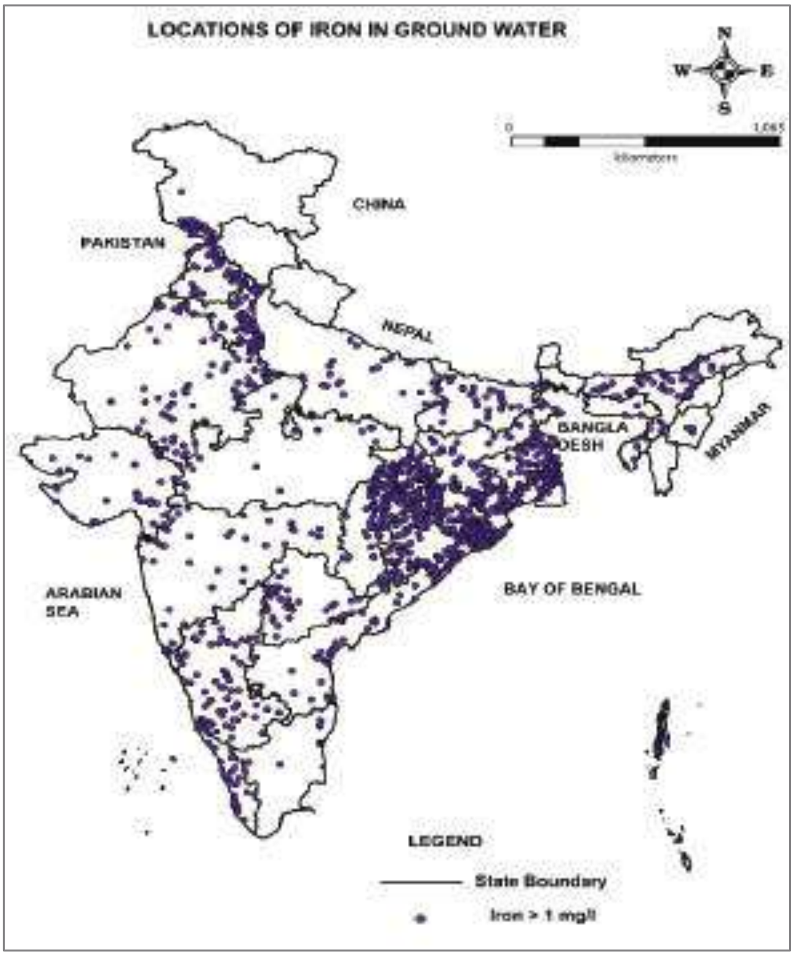

**Figure 10.3: Location of Iron in Groundwater**
(**Source:** *CGWB.*)

### 10.7.1 Sources and Nature

Iron and manganese occur in certain underground waters and springs, either alone or in association with organic matter, iron is generally predominant when they are together. They can also be found in surface waters occasionally. Iron and manganese are found in solution in water derived near the bottom of deep lakes, where reducing conditions develop. These conditions are usually seasonal. The presence of iron can also result from the discharge of certain industrial waste or mine drainage. Iron and manganese in groundwater are attributed to the solution of rocks and minerals, chiefly oxides, sulphides, carbonates, and silicates of these metals. This dissolution is enhanced by the presence of dissolved carbon dioxide present in groundwater.

Iron exists in water in two levels of oxidation: (i) as the bivalent, ferrous iron ($Fe^{++}$) and (ii) as the trivalent, ferric iron ($Fe^{+++}$), the latter generally occurring in precipitated form. Therefore, in clear groundwaters, if iron is present, it is all ferrous iron. Manganese is also naturally found in water in two oxidation states, bivalent and quadrivalent, with the latter being very sparingly soluble. Iron forms complexes of hydroxides and other inorganic complexes in solution with substantial amounts of bicarbonate, sulphate, phosphate, cyanide, or halides. The presence of organic substances induces the formation of organic complexes and chelates, which increase the solubility of iron and manganese.

The terminology of organic iron and manganese is used when difficulties in oxidation are encountered. There are no analytical techniques for the determination of organic iron or manganese.

Waters with high alkalinity have lower iron and manganese contents than waters with low alkalinity. If the water contains significant amounts of hydrogen sulphide, little or no iron or manganese is found in the solution, as most of it is precipitated.

### 10.7.2 Removal Methods

Chemical analysis of water alone may not always provide a clue to the removal method to be adopted. Hence, it is advisable that laboratory and pilot plant studies are made before any particular method is used. Oxidation by aeration or the use of chemicals like chlorine, chlorine dioxide, or potassium permanganate followed by filtration alone or by settling and filtration can bring about the precipitation of iron and manganese and their removal. The use of zeolites, as well as catalytic oxidation, also serves the purpose.

#### 10.7.2.1 Precipitation by Oxidation

Iron or manganese in water in the reduced form are converted to soluble ferric and manganic compounds by oxidation, and these are removed by filtration alone or by sedimentation and filtration. The reaction period is about 5 minutes or less at a pH of 7 to 7.5, and 0.14 mg of oxygen is needed to convert 1 mg of ferrous iron to ferric hydroxide. The rate of oxidation of ferrous iron by aeration is slow under conditions of low pH and increases 100% for every unit rise of pH. Rates of precipitation and flocculation are accelerated in practice by contact and catalysis. The contact beds for deferrization are normally 2 to 3 m deep, operating at a surface loading of 40 to 70 $m^3/d/m^2$ with the contact medium sizes from 50 to 150 mm. Accumulation of iron and manganese is flushed out by rapid drainage after filling the bed to near the overflow level. Sedimentation before filtration will be necessary when the iron content exceeds 10 mg/L. A settling period of two to three hours is adequate. The water has to pass through filters (gravity or pressure type) with a 75 cm depth of sand or sand and anthracite. Filter rates are usually 6 to 9 $m^3/h/m^2$.

Oxidation of iron can be inhibited possibly due to the binding of ferrous iron by organic substances and ammonia which behave like tannic, gallic, or ascorbic acids. All the organic material has to be oxidised before any perceptible oxidation of iron can be affected. Chlorination of many iron-bearing waters can bring about the oxidation of organic matter and other reducing agents facilitating the oxidation of ferrous iron. Deeper filter beds up to 2 to 2.5 m with a sand size of 0.6 mm have also been used with good results. In many waters, especially containing organics, pre-chlorination ahead of coagulation, sedimentation, and filtration at pH values between 6.7 and 8.4 usually will ensure iron removal to acceptable limits.

The plants will require washing of filter medium. The necessity of washing is ascertained as and when there is overflow through the overflow pipe provided in the filter compartment of the units. The interval between successive washings varies and depends on the initial turbidity and iron content. Experience indicates a closer interval of one week for high turbidity with an iron content of around 40 mg/L and 1 to 2 months for waters with low turbidities with an iron content of less than 10 mg/L. Washing of filter medium involves the removal of top 5 to 10 cm filter medium and washing it manually with water to free it from sediment and replace the same in position. The filter media needs washing/ replacement once in 6 to 24 months depending on the iron content in raw water.

Manganese removal requires a pH adjustment up to 10.4 to 10.6, and 0.29 mg of oxygen is needed to convert 1 mg of manganese. Pre-chlorination to free residual values up to 0.7 to 1.0 mg/L will affect the oxidation and precipitation of manganese.

#### 10.7.2.2 Zeolite

The method is applicable if the iron is present in a reduced state and in a soluble form in raw water. Such waters are encountered from the bottom strata of deep reservoirs or ground waters. It is usual to limit the application of this process to water having not more than 1 mg of iron or manganese for every 30 mg of hardness up to a maximum of 10 mg/L of iron or manganese.

The process consists of the percolation of the water through a bed of zeolite, which takes up the iron and manganese by a process of ion exchange. The base exchanger can be of the siliceous, carbonaceous, or synthetic resin type. Air should be excluded from the system to prevent the deposition of colloidal oxides on the ion exchange material. Therefore, airlifts, open tanks, or pneumatic tanks should not be used preceding the ion exchanger. If the water is to be softened, then the zeolite process offers a very simple method of iron and manganese removal as it can be carried out under pressure; therefore, usually obviates the necessity for double pumping, as required in most other processes. Many zeolite plants have been installed principally for iron and manganese removal, with softening being of secondary importance. The removal of iron and manganese is almost complete, and the exhausted bed of ion exchange material being regenerated with a salt solution.

#### 10.7.2.3 Catalytic Method

This method has limited application, but is of value if the content of iron and manganese is low, and if it is desirable to treat the water under pressure. It is applicable in the case of clear deep well waters, where the iron is held in solution by carbon dioxide. In municipal use, it is usual practice to restrict the use of this method to waters whose content of iron or manganese is not greater than 1 mg/L. For household use or smaller plants, it may be used with waters containing up to 10 mg/L of iron or manganese. The removal of iron and manganese is accomplished without affecting the hardness of the water, as this process is entirely one of oxidation and filtration and does not involve base exchange. The method consists of percolating the water through suitable contact materials which oxidise the iron and manganese. These contact materials, which are sold under various names, are made by treating a siliceous base exchange material successively with solutions of manganese chloride and potassium permanganate. They may be housed in a separate filter or a layer of this material may be sandwiched in the sand bed of a pressure filter. By percolation through this bed, iron and manganese are oxidised and also filtered out. At intervals, the filter has to be backwashed to remove the deposits. The backwash rates are generally of the order of 21 $m^3/h/m^2$. When the bed loses its capacity for oxidation of iron and manganese, it can be regenerated by treatment with a potassium permanganate solution.

Iron can also be removed at high flow rates, using nanostructured materials.

### 10.7.3 Iron Removal Plants

When the question of iron removal is under consideration for community water supply, it is important to decide and cover what other treatment of the water, if any, is necessary or desirable. Considerable free carbon dioxide and toxic substances are usually present in ferruginous waters. Hence, it is not advisable to remove iron alone, as leaving the free carbon dioxide which can cause corrosion of mains and pipes. The means by which iron, free carbon dioxide, and other toxic substances are removed from water in community systems consist substantially of their oxidation and removal of free carbon dioxide, followed by precipitation and its separation by sedimentation and/or filtration. Aeration may suffice for the preliminary precipitation but may not be adequate when concentrations are high and pH correction may be required by the addition of lime. The community water supply scheme makes provisions to meet such requirements and comprises a raw water storage tank, cascade tray aerators, chemical doses, sedimentation basin, filtration, and disinfection. Design of an iron removal unit is enclosed in **Annexure 10.2**.

Tray aerators are commonly used for aerating water. The trays are designed for an aeration rate of 1.26 $m^3/m^2/h$ and spaced at intervals of 1 m. Then the water is settled in a sedimentation basin having a detention period of 2.5 hours. The clarified water is filtered through a rapid sand filter having sand of effective size of 0.6 to 0.8 mm and uniformity coefficient 1.3 with an effective depth of 1.2 m. The head of water above the sand is 1.35 m and the rate of filtration is 5 $m^3/m^2/h$. The minimum backwash rate is 35 $m^3/m^2/h$ and the total head required for filter wash is 12 m.

The sand is supported over a gravel layer of depth 0.39 to 0.62 m, and it is arranged as per Table 10.2:

**Table 10.2: Arrangement of Sand**

| Size | Depth |
|---|---|
| 65-38 mm | 13-20 cm |
| 38-20 mm | 8-13 cm |
| 20-12 mm | 8-13 cm |
| 12-5 mm | 5-8 cm |
| 5-2 mm | 5-8 cm |

#### 10.7.3.1 Package Iron Removal Plants

Many package iron removal plants have been installed by authorities in various parts of the country. The plants are predesigned for specific requirements and are successfully being operated and maintained. There are various technologies recommended in the "*Handbook on Drinking Water Treatment Technologies*" published by the Department of Drinking Water and Sanitation, such as treatment units developed by NEERI, CMERI, CSIR-NEERI, IMMT, DRDO, CPERA, etc.

NEERI has designed package iron removal plants having different capacities of 0.5 $m^3/h$, 1.0 $m^3/h$, 1.5 $m^3/h$, and 2.0 $m^3/h$ depending upon the requirement of treated water. The plants are designed in rectangular/circular shapes having an aeration chamber, collection chamber, settling chamber, and filter. The settling chamber is provided with a plate settling device to enhance settling and reduce the detention time thereby reducing the dimension of the settling chamber. The aeration chamber contains media of size 2.0 to 5.0 cm gravel/stone chips to increase the surface area of the air–water interface. The iron contaminated water trickles over aeration media through a spraying device. The aerated water flows through pores over the baffle plate to the collection chamber to the settling chamber to filter. The filter bed of 20 cm depth contains sand media of size 0.8 to 1.4 mm, supported by a 5 cm deep gravel bed of size 0.8 to 1.0 cm. The filter is cleaned by making a backwash connection with a hand pump, scraping the sand bed manually, and opening the sludge scouring valve.

### 10.8 De-fluoridation of Water

Fluoride is one of the few substances that has been proved to have a substantial impact on human health when consumed through drinking water. Fluoride has good effects on teeth at low concentrations in drinking water, but excessive fluoride exposure in drinking water, or in combination with fluoride exposure from other sources, can have a number of negative health effects.

Excessive fluorides in drinking water may cause mottling of teeth or dental fluorosis, a condition resulting in the discolouration of enamel, with chipping of the teeth in severe cases, particularly in children. In Indian conditions, where the temperatures are high, the occurrence and severity of mottling increase when the fluoride levels exceed 1.0 mg/L. With higher levels, skeletal or bone fluorosis with its crippling effects is observed. The chief sources of fluorides in nature are (i) fluorapatite (phosphate rock), (ii) fluorspar, (iii) cryolite, and (iv) igneous rocks containing fluorosilicates. Fluorides are present mostly in groundwaters and high concentrations have been found in parts of Andhra Pradesh, Bihar, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Assam, and Tamil Nadu (Figure 10.4). While the majority of values for fluoride concentrations in fluoride-affected areas range from 1.5 to 6 mg/L, some values are as high as 16 to 18 mg/L, and in one solitary instance, even 36 mg/L has been reported. The acceptable limit and permissible limit of fluoride in drinking water, as per IS 10500:2012, are 1.0 and 1.5 mg/L, respectively.

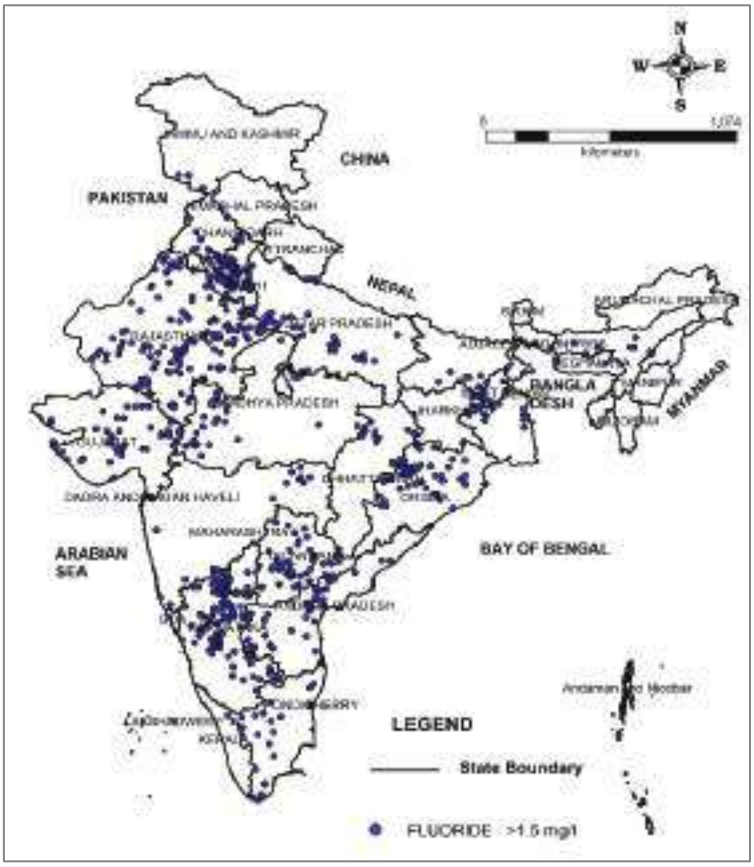

**Figure 10.4: Location of Fluoride in Groundwater**
(**Source:** *CGWB.*)

### 10.8.1 Removal Methods

The removal of excessive fluorides from public water supplies or individual water supplies is necessary on public health grounds. For fluoride-free water in the community, the first option must be the provision of a safe source having acceptable fluoride levels, transporting water from safe sources, blending high-fluoride with low-fluoride water to reduce fluoride level below 1 mg/L, and rainwater harvesting. After the exhaustion of these options, water treatment should be appropriately planned and implemented. This is a problem, particularly in rural/peri-urban areas and hence the simplicity of operation, cost-effectiveness, and applicability to small water supplies are of main concerns.

There are several de-fluoridation processes available and in practice globally. Several treatment techniques, such as adsorption, coagulation and precipitation, ion exchange, and membrane filtration, have been developed and implemented. However, the sustainability of these technologies is a major concern due to factors such as a lack of technical support, inadequate operation and maintenance, and improper monitoring.

The common methods used for the removal of fluoride from drinking water are categorized as follows:

- Adsorption and ion exchange
- Coagulation and precipitation
- Membrane filtration processes
- Capacitive De-Ionisation (CDI)

*Handbook on Drinking Water Treatment Technologies* (2023) published by the Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India, should be referred for de-fluoridation technologies.

### 10.9 Removal of Arsenic

Arsenic is a metalloid that occurs naturally and is very mobile in the environment. Its mobility is heavily influenced by the type of mineral present in the environment, oxidation state, and mobilisation mechanisms. Arsenic exists in four oxidation states: arsenite ($As^{3+}$), arsenate ($As^{5+}$), arsenic ($As^{0}$), and arsenide ($As^{-3}$). The predominant arsenic species found in water are inorganic arsenite and arsenate.

Arsenic exposure in humans can occur through ingestion of contaminated food and water, inhalation, and absorption through the skin. If consumed in greater amounts than the permissible limits, arsenic can cause various health disorders in humans such as respiratory distress, cardiac problems, gastrointestinal effects, anemia and leucopenia, skin disorders leading to hyperkeratosis (warts or corns on the palms and soles), and areas of hyperpigmentation interspersed with small areas of hypopigmentation in the face, neck, and back. Chronic exposure to arsenic can result in neural injury, skin cancer, and lung cancer.

According to the Central Ground Water Board, arsenic levels greater than 10 µg/L (ppb) have been detected in groundwater samples from 153 districts in 21 Indian states/UTs (Figure 10.5). However, the middle, lower, and deltaic regions of the Ganga basin are the most affected. Arsenic is also found in several other regions in the recent past whose source has been related to phosphate fertilisers.

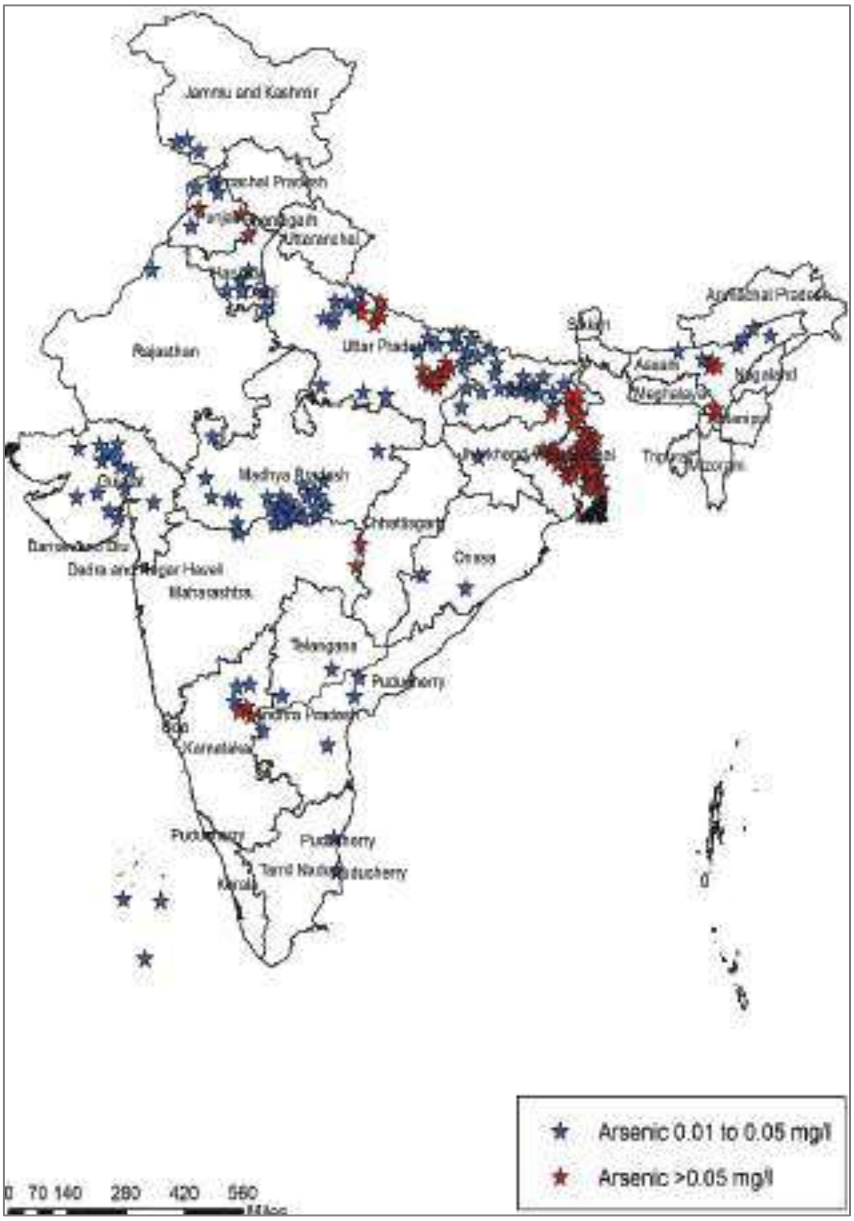

**Figure 10.5: Major locations of Arsenic in Ground Water**
(**Source:** *CGWB.*)

Arsenite is largely non-charged at pH below 10.2. This reduces the availability of the trivalent form of arsenic for precipitation, adsorption, or ion exchange. Hence, most available removal procedures are more efficient for arsenate. As a result, treatment technologies that use a two-step strategy consisting of early oxidation from arsenite to arsenate followed by an arsenate removal process are thought to be more effective. The approaches currently available for removing arsenic from water are summarised in Figure 10.6.

**Figure 10.6: Arsenic remediation methods**

Sustainability of the processes can be enhanced by online monitoring and appropriate residue management and reuse.

### 10.9.1 Arsenic Removal Techniques

### 10.9.1.1 Removal by Oxidation

The soluble arsenite is converted to arsenate by oxidation. As this does not remove arsenic from the solution, another removal process, such as adsorption, coagulation, or ion exchange, is also required. As arsenite is the predominant form of arsenic at near-neutral pH, especially when water is extracted from the ground, oxidation is a critical phase for anoxic groundwater. Many chemicals, ambient oxygen, as well as microbes, have already been employed to directly oxidise arsenite in water.

The most often utilised oxidants in developing countries are atmospheric oxygen, hypochlorite, and permanganate. Arsenite oxidation with oxygen is a very slow process that can take hours or weeks to complete. Chemicals, on the other hand, such as chlorine, ozone, and permanganate, can rapidly oxidise $As^{3+}$ to $As^{5+}$. Despite this improved oxidation, interfering chemicals in water must be addressed when selecting the appropriate oxidant, as these substances can significantly alter and determine the kinetics of $As^{3+}$ oxidation. Furthermore, this requires a sophisticated treatment that yields arsenic-containing residue at the end, which is difficult to dispose of. Thus, to effectively remove arsenic from a solution by oxidation, oxidants must be properly chosen.

### 10.9.1.2 Removal through Coagulation-Flocculation

Coagulation and flocculation are two of the most widely used and well-documented processes for removing arsenic from water. Positively charged coagulants [e.g., aluminium sulphate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$)] lower the negative charge of colloids causing them to collide and grow larger during coagulation. The addition of an anionic flocculant, on the other hand, produces bridging or charge neutralisation between the generated bigger particles, resulting in the development of flocs. During these processes, the chemicals convert dissolved arsenic into an insoluble solid, which then precipitates. Alternatively, soluble arsenic species can be co-precipitated by incorporating them into a metal hydroxide phase. In either case, solids can be removed later using sedimentation and/or filtration.

The efficacy of different coagulants in removing arsenic varies with pH. Under pH 7.6, $Al_2(SO_4)_3$ and $FeCl_3$ are both effective at removing arsenic from water. Most studies have found that arsenate is more efficiently eliminated than arsenite and that $FeCl_3$ is a superior coagulant than $Al_2(SO_4)_3$ at pH greater than 7.6. Despite their claimed decreased efficiency when compared to ferric chloride, aluminium-based coagulants were nevertheless capable of lowering arsenic concentrations below the acceptable maximum concentration level (MCL) of 10 µg/L.

The major drawback of coagulation-flocculation is the production of high amounts of arsenic-concentrated sludge. The management of this sludge is necessary to prevent the consequence of secondary pollution of the environment. Moreover, the treatment of sludge is costly. These limitations make this process less feasible, especially in field conditions.

### 10.9.1.3 Reduction, Coagulation & Filtration

An effective alternative to using bulk ferric chloride as an arsenic treatment reagent is to introduce ferric ions into the treated water stream in-situ by the controlled electrolytic dissolution of iron metal precursor (anode). These sacrificial electrodes corrode under controlled conditions to generate the reagent (ferric ion) on demand within a side stream of the treated flow. Then, the freshly generated reagent is re-injected into the treated flow to maintain the required coagulant dose and pH.

This electrolytic approach to ferric reagent generation is based on Faraday's laws of electrolysis. It is an accurate, and safe approach that conforms to Indian Standards. The modular design of the electrolytic generator allows a flexible treatment system scaling from as low as 20,000 LPD to 10 MLD. The compact electrolytic system integrates into existing treatment systems infrastructure and also can be retrofitted to replace bulk ferric solutions. The on-demand generation of electrolytic reagent has multiple benefits over bulk ferric salt solutions:

- The iron precursor used in the electrolytic process is certified and broadly available that minimises impact of reagent co-contaminants on treated water quality;
- Electrolytic reagent is less expensive than bulk ferric reagent due to the lower cost of consumables required for its generation;
- Fully automated system controls both ferric reagent dose and treated water pH during the arsenic treatment process. Such a capability allows to achieve lower arsenic levels in the effluent under optimal ferric reagent dose and pH;
- Optimisation of ferric dosing reduces entire material use, sludge volumes, filter backwash frequency, and water loss;
- Integration of online real-time monitoring contributes to entire system automation and optimisation. Monitoring permits the potential reuse of a proportion of backwash water thereby further reducing water loss;

- On-site reagent generation lowers greenhouse gas generation, supply chain risks, and logistical challenges associated with bulk ferric salts.

### 10.9.1.4 Adsorption

Adsorption is a process that uses materials as a medium for the removal of substances from gases or liquids. Substances are separated from one phase and accumulated on the surface of the adsorption medium. Van der Waals forces and electrostatic interactions between adsorbate molecules/ions and adsorbent surface drive this process. As a result, it is critical to initially characterise the adsorbent surface features (e.g., surface area, polarity) before using them for adsorption. Adsorption-based removal of contaminants is more sustainable as the process of adsorption does not need energy. The process of water purification itself can be environmentally friendly if the materials are green and if the used adsorbent does not have an environmental impact.

Activated carbon, coal, red mud, fly ash, animal-derived products such as bone-char, kaolinite, montmorillonite, goethite, zeolites, activated alumina, titanium dioxide, iron hydroxide, zero-valent iron, chitosan, and cation-exchange resins have all been explored in various field studies. Iron-based adsorption is a new approach for treating arsenic-contaminated water. This can be explained by the fact that inorganic arsenic species have a strong affinity for iron. Arsenic can be removed from water by iron-based materials serving as a sorbent, co-precipitant, or contaminant-immobilizing agent, or by functioning as a reductant.

Adsorption has been recognised as the most extensively used approach for arsenic removal due to various benefits such as relatively high arsenic removal efficiency, ease of operation and handling, cost-effectiveness, and no sludge creation. However, the adsorption of arsenic strongly depends on the system's concentration and pH. At low pH, arsenate adsorption is favoured, whereas, for arsenite, maximum adsorption can be obtained between pH 4 and 10. Furthermore, contaminated water contains more than just arsenic, as it is always accompanied by other ions, such as phosphate and silicate, which compete for adsorption sites. Aside from the system parameters, the type of adsorbent itself can reduce the effectiveness of adsorption in arsenic removal. A variety of adsorbents, including those listed above, have already been investigated for the removal of arsenic from water. Most traditional adsorbents, on the other hand, have irregular pore architectures and poor specific surface areas, resulting in limited adsorption capabilities. Lack of selectivity, relatively weak interactions with metallic ions, and regeneration challenges can also limit these sorbents' capacity to lower the arsenic concentrations to levels below the maximum concentration threshold.

These limitations of traditional adsorbents have led to the development of new materials, especially nanomaterials.

### 10.9.1.5 Ion Exchange

Synthetic ion exchange resins can be used for arsenic removal. Generally, these resins have a base of cross-linked polymer matrices to which charged functional groups such as amine or quaternary ammonium are attached. Ion exchange technologies are mostly used with water that has low TDS and where arsenic is the only significant contaminant. Their exchange capacity depends on the composition of the groundwater and the influence of interfering anions like sulphates, phosphates, silicates, and nitrates. Hence, ion exchange can be performed after other treatment processes such as coagulation. Various ion exchange resins for arsenic removal are loaded with $TiO_2$, zirconium oxide, iron oxides, or $MnO_2$. While ion exchange is useful, the contaminants must be in the ionic form and should be exchangeable with ions on the resin; however, this is not the case with neutral species. Resins loaded with iron oxides and oxyhydroxides have also been used to remove such species.

### 10.9.1.6 Application of Nanomaterials for the Removal of Arsenic from Water

Advances in nanoscience and nanotechnology have paved the way for the development of various nanomaterials for the remediation of contaminated water. Due to their high specific surface area, high reactivity, and high specificity, nanoparticles have been given considerable environmental attention as novel adsorbents of contaminants, such as heavy metals and arsenic, from aqueous solutions. Carbon nanotubes and nanocomposites, titanium oxide-based nanoparticles, iron-based nanoparticles, and other metal-based nanoparticles are among the most commonly researched nanoparticles for arsenic-contaminated water treatment. Many of these materials have also been modified with other metal oxides, such as zirconia, to improve the adsorption capacity. Although the literature may refer to them as nanoparticles, the materials used in the field are nanostructured materials in the form of beads of millimetre scale particles. A typical iron and arsenic removal community WTP in Punjab in shown in Figure 10.7.

**Figure 10.7: A typical iron and arsenic removal community WTP in Punjab. The blue-coloured unit, below the overhead tank, is the purification unit and the treated water is distributed to the village.**

(Source: *IIT, Madras.*)

One of the most notable nanoscale systems currently used for the efficient removal of arsenic is metastable two-line ferrihydrite, which adsorbs both arsenite and arsenate in natural pH conditions with excellent selectivity and in presence of the typical interfering ions present in natural waters. The technology is often referred to as Anion and Metal Removal by Indian Technology (AMRIT). The specific adsorbent used is confined metastable 2-line ferrihydrite (CM2LF) in biopolymer cages. Its arsenic uptake capacity is about 25 to 30 mg $g^{-1}$ in field conditions. Due to the large adsorbate capacity, the replacement of adsorption media is less frequent. The arsenic laden waste does not release arsenic in the ambient conditions of soil and it can be disposed off safely, following protocol. As a result of the lower cost, high efficiency of removal of arsenite and arsenate, safe disposal of the spent media and reduced maintenance cost, this method has been applied in various parts of the country. Besides, the media can be used for both domestic and community filtration. In cases where local sources are contaminated by other contaminants, such as uranium, the method is found to be effective. Although a reactivation protocol exists to regenerate the arsenic-saturated $CM_2LF$, given the high-adsorption capacity, the frequency of adsorbate replacement is as long as 2 to 3 years. In addition, reactivation produces sludge and its management is a concern.

A block diagram of a nanotechnology-enabled water purification plant for arsenic and iron removal is shown in Figure 10.8. Such integrated plants are desired in most places as both the contaminants exist together. The input water after initial oxidation is passed through iron and arsenic removal units in succession. Any other contaminant present may be removed by a polisher unit. Post-chlorination ensures the removal of microbes. The system may be fitted with sensors and devices at various locations for monitoring and control.

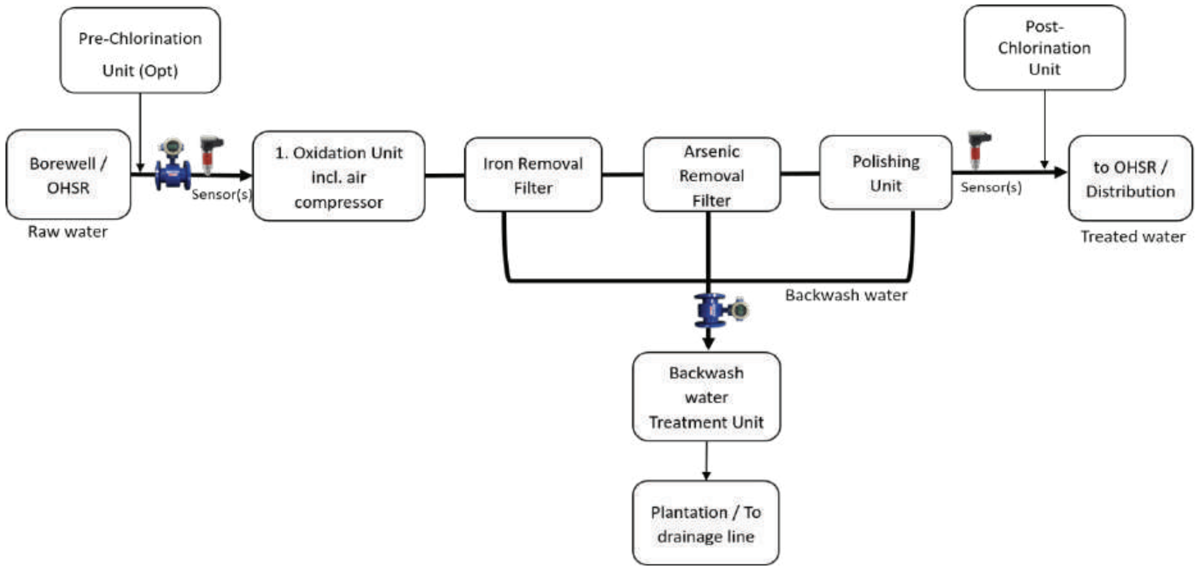

**Figure 10.8: Block diagram of a nanotechnology-enabled water purification plant for arsenic and iron removal**

### 10.9.1.7 Advanced Plants with Integrated Sensors

Integration of sensors along with water purification devices and treatment plants can promote substantial advancement in environmental water monitoring and industrial wastewater management. On-site and continuous monitoring of water quality can be performed using portable sensors, enabling adherence to effluent regulations and safety parameters as well as for the evaluation of efficiency of the treatment process. The entire plant can be Internet of Things (IoT)-enabled in terms of equipment automation and water analysis. Implementation of IoT-enabled plants can allow authorities to obtain real-time qualitative and quantitative information about the plant’s operation over a long-time window. Such an advanced water treatment/purification plant will also be beneficial for public awareness and establishing regulations for water quality. Figure 10.9 shows a block diagram for such an advanced plant for arsenic removal.

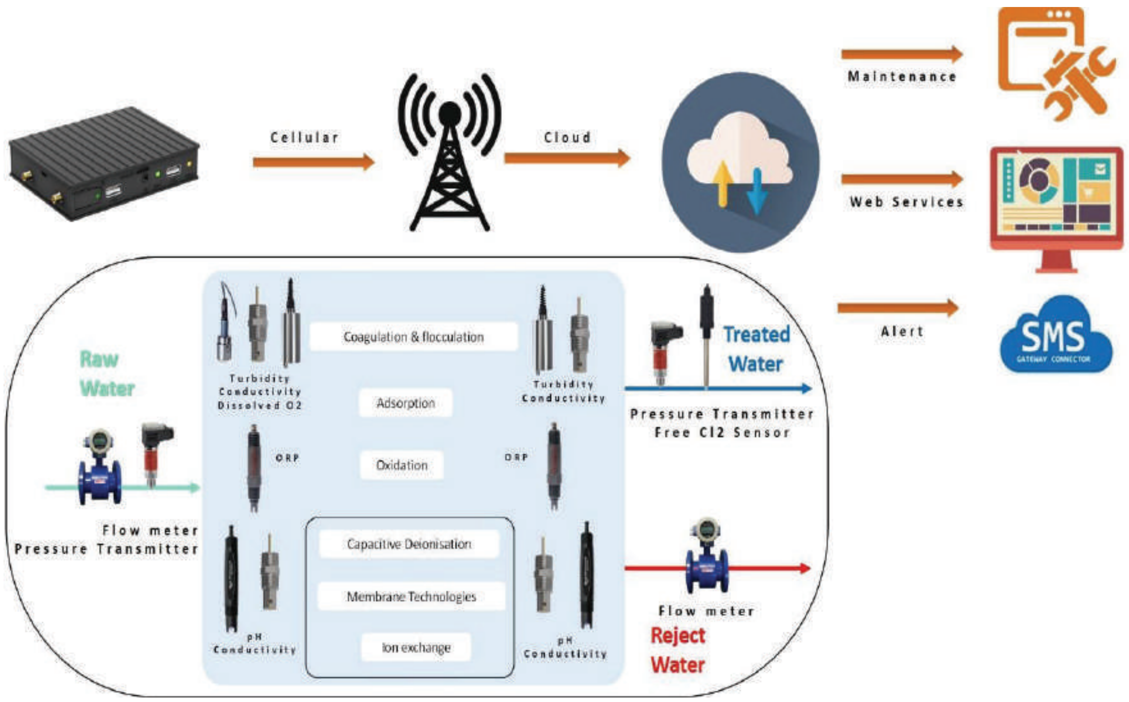

Figure 10.9: IOT-based monitoring of various arsenic removal technologies

Data from the treatment units on the time duration of operation, water dispensed, voltage at the pumping station, current used by the pump, and water quality in terms of TDS are collected and presented using a central dashboard. The data may be available and displayed at multiple locations and may be provided to the pump operator/user community in multiple ways. This ensures that all the treatment plants are used effectively and problems, if any, are addressed. Such problems may relate to the health of the motor, electrical supply, availability of the operator, clogging, efficiency of filtration, etc. More sensors and better controls can also be put in place and this has been implemented in select locations.

### 10.10 Reject/Residue Management of Arsenic, Fluoride, and Iron Removal Plants

In the preceding sections, various treatment techniques have been described for the removal of arsenic, fluoride, and iron from raw groundwater to produce potable water. These treatment plants generate hazardous liquid and solid residues/rejects containing a high concentration of arsenic/fluoride/iron posing a serious threat of contamination of groundwater/surface water/land if not properly and safely disposed of. The waste stream in arsenic, fluoride, and iron removal plants can be categorised as follows:

a) Backwash wastewater stream;
b) Sludge from treatment reactors;
c) Spent adsorbents/nanomaterials and replaceable catalysts.

The above rejects/residue need to be treated and safely disposed of to prevent contamination of groundwater/surface water/land. The residue/rejects from arsenic/fluoride removal plants are more hazardous/toxic as compared to that of iron removal plants, but IRPs produce more quantity of sludge.

The following residue/reject management should be employed:

- Backwash water generated from various techniques of arsenic, fluoride, and iron removal plants shall be analysed on a weekly basis.

- The backwash water shall be treated in the sedimentation tanks. A sedimentation tank for backwash water is designed based on the total backwash water generated with the provision of sludge produced. The sedimentation tank may be rectangular or square type with a side water depth of 1.2 to 1.5 m with a free board of 0.3 m. The sludge storage facility is designed for 13 to 15 years or based on the availability of land with a rectangular or square shape. A geo-membrane liner shall be used to restrict the percolation of leachate in the ground.
- For arsenic and fluoride removal plants, the supernatant of sedimentation tanks shall satisfy the effluent standards prior to disposal as per MOEFCC (2016). The supernatant of the sedimentation tank shall satisfy effluent standards of maximum permissible limit (mg/L) as given in Table 10.3 below.

**Table 10.3: Permissible Limit of As, F, and Fe (mg/L) for Supernatant of Sedimentation Tanks**

| Parameters | Into inland surface water | On land for irrigation |
|---|---|---|
| Arsenic | 0.2 | Not permitted |
| Fluoride | 2.0 | 2.0 |
| Iron | 3.0 | 3.0 |

- Sludge dewatering shall be carried out by sand drying beds, freeze assisted sand beds, vacuum assisted beds, solar drying beds, etc.
- Sludge may be used as building construction materials like bricks, cement, etc.
- Engineered landfills, if necessary, shall be designed and provided for arsenic, fluoride, and iron removal for a period of 15 years or the period decided as per the availability of land.
- Exhausted/spent media of arsenic, fluoride removal plants shall be tested for toxicity characteristics leaching procedure (TCLP) prior to transport to designated disposal facility.
- Supernatant after sedimentation and dewatering shall be tested before discharging into the environment.
- Sedimentation tank and sludge storage facility shall be included as a mandatory part of the WTP.
- The sludge shall satisfy standards for restricted landfills or will be used as construction materials with the specified standards. The long-term solution is to recycle the sludge and use it for beneficial purposes. One of the techniques which is adopted to treat hazardous/toxic waste is to solidify it, which results in stabilisation of the components of waste.

*Handbook on Drinking Water Treatment Technologies* (2023) published by the Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India, should be referred for additional arsenic removal technologies.

### 10.11 Removal of Nitrate

Nitrates are inorganic nitrogen and oxygen compounds that exist naturally and synthetically in the environment. Nitrates are found in the earth’s atmosphere, soil, and water. They are easily biodegradable and highly soluble in water. Plant breakdown, animal waste, and agricultural by-products all produce nitrates. Rainwater, floods, and soil erosion can all contribute nitrates into groundwater supplies.

Water containing less than 45 mg/L (acceptable limit as per IS 10500:2012) of nitrate (as $NO_3$) is safe to consume. Long-term exposure to high nitrate concentrations can cause major health problems in children, such as methemoglobinemia, popularly known as blue baby syndrome, and stomach cancer in adults. A child with blue baby syndrome will start displaying bluish or brownish colours around their lips and mouth, nose, and nail beds. It can also present flu-like symptoms, such as nausea, vomiting, and diarrhoea.

Nitrates enter the water supply via agricultural runoff, industrial waste, fertiliser, and herbicide use, leaking septic tanks, and broken sewage systems. Naturally occurring microorganisms in soil can also metabolise nitrogen, resulting in nitrate deposits in the ground. Manure from farmlands can be carried into streams and lakes by rainwater. Animal excrement is another prominent source of nitrate contamination in water systems. Crop irrigation can deeply embed nitrates in the soil and, as precipitation percolates down through the earth, the nitrates can enter aquifers. Increased amounts of nitrates in underground water storage utilised for drinking water supply systems can occur as natural deposits of nitrates erode.

Many districts in Andhra Pradesh, Bihar, Delhi, Haryana, Himachal Pradesh, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Tamil Nadu, Rajasthan, West Bengal, and Uttar Pradesh have high nitrate concentrations (greater than 45 mg/L) (Figure 10.10). The highest value was 3080 mg/L found in Bikaner, Rajasthan.

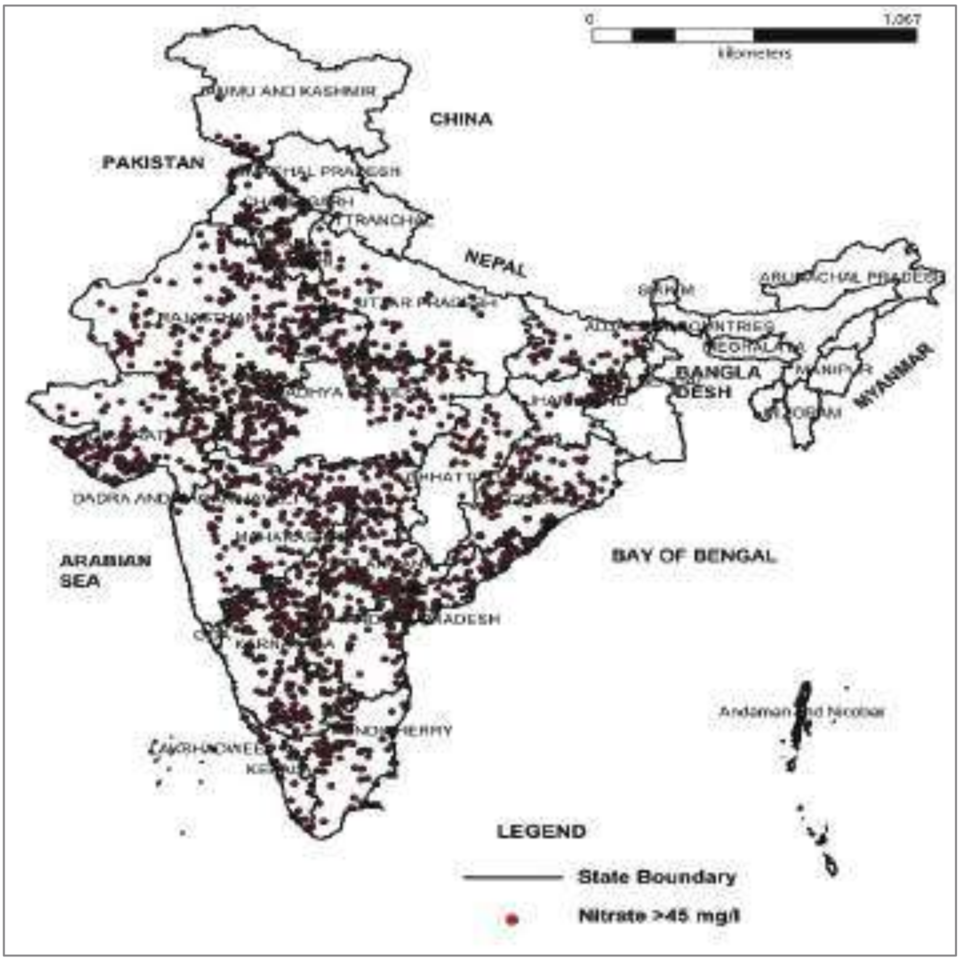

Figure 10.10: Location of Nitrate in Groundwater

### 10.11.1 Techniques for Removal of Nitrates

Nitrates in water can be removed via reverse osmosis (RO), distillation, or ion exchange resin. Nitrates are notoriously difficult pollutants to remove from water. Nitrates will not be removed by sediment filters, carbon filters, or a UF system's hollow fibre membrane. A typical ion exchange water softener, meanwhile, will neither reduce nor remove nitrates.

a) **Reverse osmosis**

RO eliminates pollutants by pushing pressured water across a semi-permeable membrane with small pores.

b) **Ion exchange**

Passing water through an ion exchange process is one of the most effective ways to remove nitrates. These nitrate removal devices, however, use chloride ions rather than the sodium ions normally used in traditional water softeners. When polluted water travels through the tank or cartridge, the resin beads capture the nitrate ions and replace them with innocuous chloride ions. Because both chloride and nitrate have a negative charge, this is known as anion exchange (making them anions). They will only be capable of processing a certain volume of water before all the chloride ions are exhausted and the media will either need to be regenerated or the cartridge replaced.

For backwashing the system, it will periodically need to be flushed with sodium chloride to regenerate the resin and flush out a brine solution. Because this brine solution contains nitrates, it should not be discharged into any natural water source or where animals could get it.

*Handbook on Drinking Water Treatment Technologies* (2023) published by the Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India, should be referred for additional nitrate removal technologies.

### 10.12 Uranium

Uranium is a naturally occurring radioactive element that occurs in low concentrations in nature. It is present in certain types of soils and rocks, especially granites and metasedimentary rocks. Uranium concentrations in groundwater in shallow aquifers across the country range from 0.0 to 2876 µg/L, suggesting that groundwater uranium concentrations vary by several orders of magnitude. Punjab (where 24.2% of groundwater samples have been detected to have uranium concentrations greater than the limit prescribed in IS 10500), Haryana (10.6% samples), Telangana (10.1% samples), Delhi (11.7% samples), Rajasthan (7.2% samples), Andhra Pradesh (4.9% samples), and Uttar Pradesh (4% samples) are the most affected states (Figure 10.11).

The radioactivity of naturally occurring uranium is extremely low. The chemical properties of uranium in drinking water, however, are far more concerning than its radioactivity.

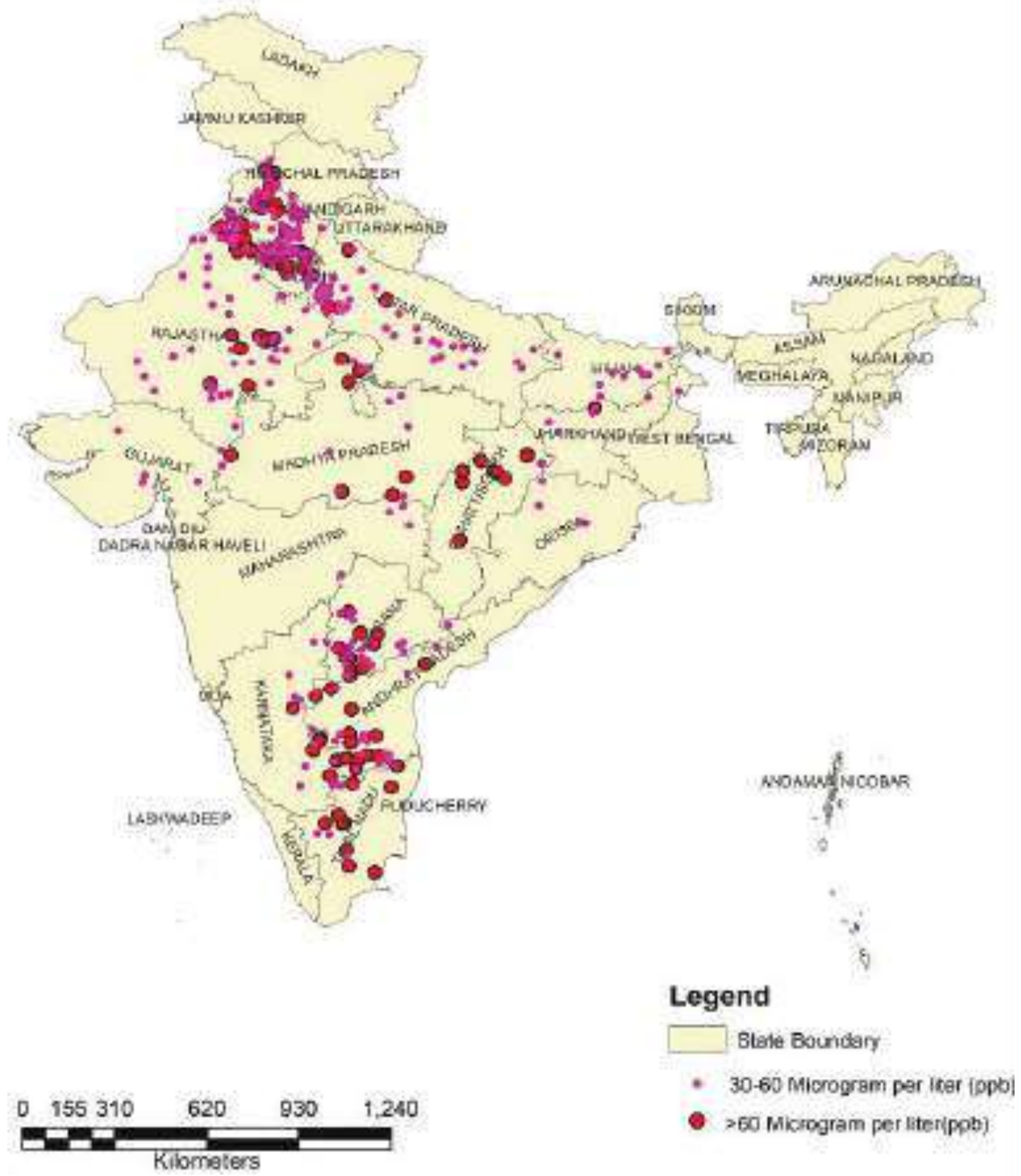

**Figure 10.11: Location of High Uranium in Groundwater**
[**Source:** https://www.cgwb.gov.in; *NDC CHQ* (8/4/2020).]

### 10.12.1 Remedial Measures

Ex-situ treatment of radioactive contaminants in groundwater falls into the following categories:

(i) **Adsorption or ion exchange:** The water-soluble contaminants are captured by sorption onto solid support that can be natural or synthetic material.

(ii) **Reactive sorption:** The process is based on the reaction of contaminants with a solid substrate. It is often applied in-situ as a barrier wall through which the contaminant is forced through and trapped.

(iii) **Nanomaterials**: Nanomaterials have been found to be effective in removing uranium in ground water. Several such community plants are working in Punjab at present. In several places, other contaminants such as arsenic and iron are found to co-exist with uranium.

(iv) **Precipitation:** This process is mostly practiced above ground and involves the addition of alkali to raise the pH and precipitate the oxide or hydroxide.

(v) **RO:** In this process, water is transported through a high-pressure gradient through a membrane essentially non-permeable to the contaminant.

(vi) **Stripping:** Only applicable to volatile contaminants like radon.

Remediation solutions based on in-situ chemical stabilisation are only as effective as the site's geochemistry allows. Such chemical technologies may be generally grouped according to the following paradigm:

(i) **Redox Technologies:** These technologies attempt to manipulate oxidation-reduction conditions of the subsurface to reduce uranium to uranous (uranium IV) forms. The techniques include in-situ redox manipulation using sodium dithionite, zero-valent iron, microbial-induced reduction, and calcium polysulfide technologies. The common deficiency of technologies in this category is that the reduced environment and corresponding uranium precipitate are easily re-oxidised over time. Consequently, over time the "treated" uranium remobilise in the system.
(ii) **Co-precipitated Iron Oxy-hydroxide:** This technology affects only temporary stabilisation because the reaction is reversed as the precipitate ages.
(iii) **Phosphate Precipitation Technologies**: These techniques use and alter phosphate with uranyl (uranium VI) forms to remove soluble uranium and prevent additional uranium dissolution by sequestration, immobilisation, or precipitation. The resulting reaction seeks to create a stable, long-lasting reaction that removes the source of ongoing uranium contamination in the groundwater. However, this group of technologies requires further development.
(iv) **Flushing Technologies:** This category of remediation procedures employs a variety of leaching solutions to dissolve solid-phase uranium and hydraulic extraction techniques to remove the dissolved uranium. Because of subsurface stratigraphic heterogeneities, thorough treatment is difficult to achieve. Hydraulic capture and capture of the mobilised uranium can be problematic.
(v) Groundwater with a greater uranium percentage can be made potable using procedures like RO. Based on a field study carried out in Punjab, it was established that uranium content in RO treated water is below 0.1 µg/L. However, rejecting water disposal of RO is an issue to be taken care of.
(vi) Spent media and discharges from the units must be handled as discussed in section 10.10.

### 10.13 Removal of Ammonia

Ammonia is utilised in the production of fertilisers and animal feed, as well as the production of fibres, plastics, explosives, paper, and rubber. It is used as a coolant, in metal processing, and as a starting product for many nitrogen-containing compounds. Ammonia and ammonium salts are used in cleansing agents and as food additives, and ammonium chloride is used as a diuretic. On dissolution in water, ammonia forms the ammonium cation. Hydroxyl ions are formed at the same time. Natural levels of ammonia in groundwater are usually below 0.2 mg/L. Higher natural contents (up to 3 mg/L) are found in strata rich in humic substances or iron or in forests. Surface waters may contain up to 12 mg/L. Ammonia may be present in drinking water as a result of chloramine disinfection. Ammonia levels above geogenic levels are a major indicator of faecal pollution. If drinking water contains more than 0.2 mg/L of ammonia and is chlorinated, taste and odour problems, as well as lower disinfection efficacy, are to be expected, since up to 68% of the chlorine may react with the ammonia and become unavailable for disinfection.

Excessive ammonia in drinking water can cause nitrification in the water distribution system, leading to many problems including corrosion, aesthetic issues, and pH decrease.

#### 10.13.1 Remedial Measures

(i) Breakpoint chlorination is an effective way to remove ammonium from drinking water. It has a low spatial requirement, non-sensitivity to temperature variations, and adaptability to existing facilities. However, it can result in excessive chlorine consumption and the development of harmful chlorinated by-products in drinking water.

(ii) In catalytic oxidation technology, iron–manganese co-oxide filter film (MeO) can remove ammonium from drinking water by chemical catalytic oxidation. Catalytic oxidation is a new way to remove high concentrations of ammonia from drinking water.
   a) Quartz sand coated with metal oxide filter film (MeO) (Generally, iron–manganese co-oxide filter film) can remove ammonium from drinking water by chemical catalytic oxidation.
   b) It is more resistant to low temperatures and requires less time to start up than other bio filtration methods.

(iii) Various other studies are also being carried out for the removal of ammonia from raw water for drinking water supply with concentration much higher.

### 10.14 Demineralisation of Water

Conventional methods of water treatment do not materially change the mineral content of water. Base exchange softening merely converts the calcium and magnesium salts to the corresponding sodium salts. Lime softening causes a slight decrease in the contents of total solids but does not bring about any decrease in the content of sodium chloride or sulphate. Hence, these methods are not effective in converting brackish water into potable water. For providing a potable supply in a brackish water area, the least mineralised water source could have been prospected. When potable water is unavailable, some method of treatment has to be adopted.

#### 10.14.1 Distillation

Of the processes of removing water from saline solutions, distillation is the oldest and in terms of established plants, the most productive. It differs from the other processes by its passage of water through the vapour phase. The plant design is directed at tapping the most economical source of heat energy and exploiting the most efficient processes of heat transfer. While relatively small quantities of water are to be distilled, straight or single-effect distillation is preferred because of the simplicity of operation and the lower capital cost of the installation. With larger outputs, improvement in efficiency acquires much greater importance because of the much higher rates of evaporation involved and the need for highly efficient heat transfer systems. Problems of scale formation also play a significant role.

The performance of an evaporator plant is measured by the specific heat consumption, i.e., the number of kilocalories required to produce 1 kg of distillate. Distillation plants are generally better for lower values of specific heat consumption. The introduction of the flash evaporator has helped in better economics of heat recoveries and more efficient plants can be built more cheaply. It is only in such situations where natural gas or fuel is available cheaply that low thermal performance evaporators can be used with the resultant saving in capital cost.

#### 10.14.2 Solar Stills

Solar energy can be harnessed with the help of a system of mirrors following the path of the sun to focus the sunlight on sheets of water. In one of the popular methods, the saltwater trickles down to trays mounted on an inclined compartment provided with glass sides and a heat-insulated base that screens the condensing chamber from the sun. Since the focusing mirrors form an important element in the cost of the stills, the development of cheaper non-focusing types of mirrors and the use of inexpensive construction materials have been resorted to. In basin solar stills, a commonly used design, saltwater tanks, filled either by gravity or by stainless steel impeller pumps, feed the solar still, the cover of which is at a shallow angle of $10^{\circ}$ to $18^{\circ}$ with the glass panes tightly sealed to the holding frame and the joints between the still cover and the vertical walls perfectly tight. The collecting troughs at the foot of the still cover must be built in such a way that water can freely drain to the pipe carrying the distillate to the freshwater tank while preventing any contaminated water from entering from the roof or ground on which it is built. In addition to the freshwater tank, it is a good practice to construct additional distilled water storage to balance out the fluctuations between production and demand.

The best situations for the use of solar distillation are the isolated areas and certain regions where freshwater is unobtainable, solar intensities are high, fuel resources are meagre, and industrial development is poor. Hence, this process is rarely used.

## 10.15 Membrane Processes

Certain natural and synthetic membranes have the property of permitting the solvent (water) to get through them but not the solute. Such semi-permeable membranes permit the separation of solute from solvent. This phenomenon is known as osmosis. The membranes are categorised based on pore size as microfiltration (MF), Ultrafiltration (UF), Nano filtration (NF) and RO, as described below:

### 10.15.1 Microfiltration

MF is a pressure-driven separation process that is commonly used to concentrate, purify, or separate macromolecules, colloids, and suspended particles from solution. Nominal pore diameters for MF membranes are typically in the range of 0.1 to 1.0 µm. Because of the vast range of pore size, MF membranes can be utilised in a variety of applications that need the separation of viruses, bacteria, aerosols, and other macromolecules from liquids. MF can be performed in two modes: dead-end (inline) filtration and cross-flow (tangential flow) filtration. The predominant flow direction in dead-end filtration is perpendicular to the membrane. The suspended particles are constantly drawn towards the membrane, where they settle on the surface or inside the membrane pores. Particle deposition results in a rising resistance to flow and, as a result, a decreased permeate flux rate. To decrease deposition, MF is frequently performed in the cross-flow mode (tangential flow), with the primary flow direction tangential to the membrane.

### 10.15.2 UF Membranes

UF is the most commonly used membrane-based water treatment process. Solutes/particles of a size of 0.03 microns and larger are rejected by UF membranes. Particles and microorganisms are removed using this process; however, ions are not. UF creates water with very high purity and low silt density by providing a pressure-driven barrier to suspended particles, bacteria, viruses, endotoxins, and other pathogens. Hydrostatic pressure presses a liquid against a semi-permeable membrane. UF employs hollow fibres of membrane material, with feed water flowing either within the shell or through the fibre lumen. Suspended solids and high molecular weight solutes are trapped, whereas water and low molecular weight solutes pass through. The UF has consistently treated water quality, low land requirements, and intensive automation. Moreover, it can eliminate microorganisms from water including viruses. UF technology can now offer better processing efficiency, greater treatment effect, and even lower energy usage as compared to conventional water treatment processes. The service life of UF membranes ranges from three to five years or longer. Hollow-fibre, tubular, spiral-wrapped, and plate and frame are commercially available in India for water treatment. The UF process has a greater removal rate of turbidity and particulate matter than the traditional process; effluent turbidity is constant below 0.1 NTU and particle removal is up to 99.9%.

### 10.15.3 Nano Filtration (NF)

NF membranes are presently used mostly for industrial applications, as stated above. Main applications are hardness removal, salt recovery, colour separation, applications in Food and

Beverage industries for juice concentration etc. Since their use is limited to small flows compared to Municipal requirements, present prices are on the higher side.

Many other technologies such as Lime soda softening, resin-based softening (in few cases), Reverse Osmosis (especially for Brackish and Sea water) are available for larger flows and at very competitive OPEX and CAPEX levels, it would take some time for NF to find a sweet spot in direct Municipal applications.

Details of MF, UF, and NF are provided in Figure 10.12.

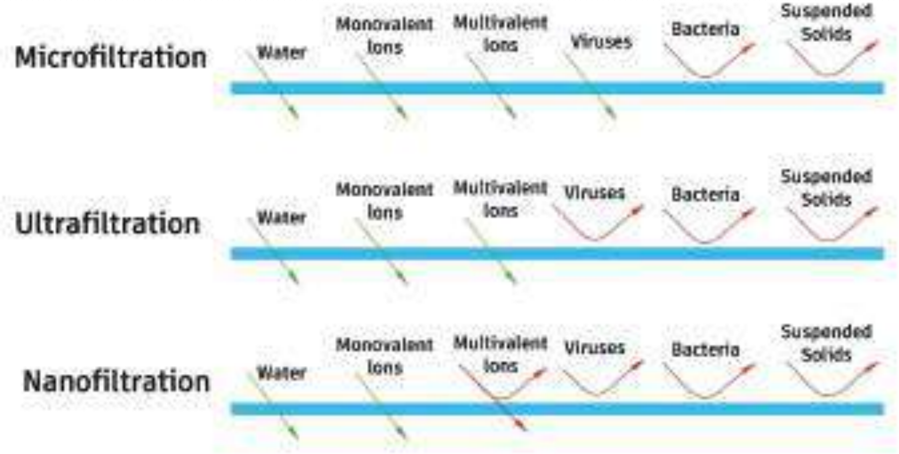

**Figure 10.12: Membrane Process Characteristics**

### 10.15.4 Reverse Osmosis (RO)

RO is a membrane permeation process for separating relatively pure water (or other solvents) from a less pure solution. Osmosis is a process of water diffusion through a semi-permeable membrane from a low TDS water to water having high TDS until both sides of the semi-permeable membrane have an equilibrium. In equilibrium conditions, the osmotic pressure of water is equal to the pressure difference on either side of the membrane. The potential gradient of TDS across the membrane causes the primary water flow. If the applied pressure on the membrane is more than the osmotic pressure, water passes through membrane pores on the permeate side, while the high TDS solution remains on the other side of the membrane. This process is commonly known as “reverse osmosis” since it is the reverse of normal osmosis. The solution is passed over the surface of an appropriate semi-permeable membrane at a pressure exceeding the effective osmotic pressure of the feed solution (Figure 10.13). The permeating liquid is collected as the product and the concentrated feed solution is generally discarded. The membrane must be highly permeable to water, highly impermeable to solutes, and capable of withstanding the applied pressure without failure. Because of its simplicity in concept and execution, RO appears to have considerable potential for a wide application in water and used water treatment.

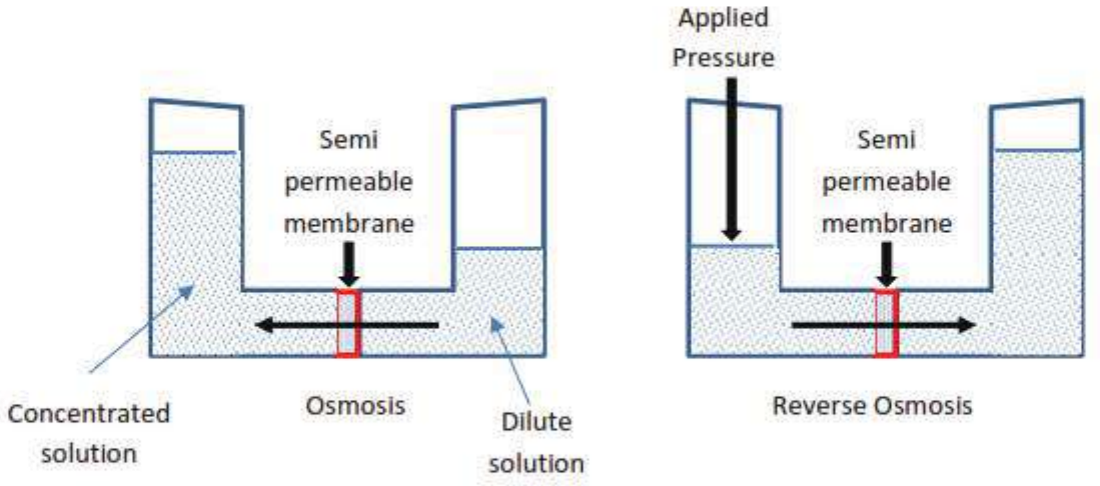

Figure 10.13: Reverse Osmosis (RO) Process

There are several materials used in manufacturing of RO membranes. Cellulose acetate was the first membrane material. Polysulfone having aromatic polyamides coating is very popular currently, and is also referred as thin film composite (TFC) membranes. RO membranes can literally stop all the ions present in the water making water highly corrosive. Hence, it is ensured that the treated water has sufficient quantity of TDS to avoid production of corrosive water.

### 10.15.5 Electrodialysis (ED)

Unaided osmosis is a relatively slow process and, hence, attempts have been made to combine it with electrolysis. The application of an external electromotive force can draw the ions away from the salt solution towards the electrodes so that the solution is impoverished of its salt content. The reunion of the ions by diffusion can be prevented by using suitable membranes to separate the cathode and anode chambers, also by continuously removing the relatively concentrated solution of the electrolytes from the electrode chambers. To obtain purification of sufficient magnitude, several electrolytic cells have to be used in series. In essence, the apparatus would consist of several electrolytic cells, each of which is composed of three compartments separated from each other by suitable membranes. The saline water circulates in series through the middle compartments of the cells and undergoes progressive purification. The number of cells and the rate of flow may be adjusted to give the degree of purification required. A direct current of 110 to 220 V is employed. The electrodes are continuously washed with the treated water. One of the main disadvantages of the ED process is that the membranes get badly damaged as a result of corrosion and scale formation. Another disadvantage is that the cost goes up steeply as the total solids content of the finished water decreases. Power loss is minimised if the water is demineralised only partially to final concentrations of less than 500 mg/L in a multi-compartment cell. Average power requirements are 1 kWh/m$^3$ of water per 1000 mg/L of TDS removed for waters with initial TDS values of 10,000 mg/L and less. Since power requirements rise sharply with higher initial values in this method compared to distillation and freezing, this process is adopted only for waters containing less than 10,000 mg/L of dissolved solids.

### 10.15.6 Pre-treatment Requirement for Membrane-based Treatment

As we have now seen, membranes are fine filters, similar to gravity sand filters, that provide a physical barrier for the removal of turbidity-causing particles and many water-borne pathogens. However, for the smooth and trouble-free running of membranes (specially pressurised ones), the feed water (to membranes) must be properly pre-treated.

One such pretreatment for “Out to In” type of membranes is either a standard sand filter or a 100 to 150 micron (self-cleaning or manual) filter. This ensures that the feed water does not contain more than 5 to 10 mg/L of suspended solids. For the “In to Out” category of membranes, the pretreatment becomes even more important since the inside diameter of membrane is quite small, and can get quickly choked, demanding frequent backwashing and cleaning.

Similar to gravity sand filter choking, membrane filters also get choked (or clogged) after a certain time interval by the accumulation of particles on the surface of the membranes. The deposits need to be removed before membranes are again put into the filter service cycle. This operation of getting away the dirt (or suspended solids) is called backwash or back pulsing. Like in the case of backwashing of sand filters, a small amount of filtered water is typically pushed in the opposite direction (to the filtration cycle). This way, the solids accumulated either on the membrane surface or inside the membranes are flushed out. The membrane backwash process occurs frequently (often every 30 to 40 minutes of operation) for a very short duration (typically two to three minutes).

As membrane filtration systems function, dissolved pollutants in the water may slowly precipitate on the membrane’s surface, lowering the membrane’s permeability and increasing the trans-membrane pressure (TMP) required to filter the water. When the TMP exceeds the normal operating limits for the system, the membranes require a recovery clean, also called a clean-in-place (CIP), to remove the precipitated contaminants and restore the membrane permeability.

### 10.15.7 Design Guidelines for RO-based System

For designing an RO system, the following information is necessary:

(i) The complete ionic analysis of feed water includes, but not limited to,
  a) the concentration of cations like Ca, Mg, Na, K, Al, Fe, Mn, Boron, etc.;
  b) the concentration of anions like $Cl^-$, $SO_4^{--}$, $CO_3^{--}$, $HCO_3^-$, $NO_3^-$, colloidal and reactive silica, etc.;
  c) the presence of organics (BOD/COD/TOC values);
  d) overall TDS;
  e) pH and temperature with all possible variations;
  f) expected recovery (and rejection) of ions;
  g) operating hours.

(ii) The above analysis is to be fed into the “projection software” provided by the selected membrane manufacturer.

(iii) Any amount of excess anion/cation will be shown in “warnings”, i.e., the system may not function properly if the input is not properly adjusted.

(iv) More often than not, projection software also needs inputs regarding the type of water, viz. groundwater/with pretreatment/UF treated, etc.

(v) If all the parameters are within design guidelines by the particular manufacturer, select the number of membranes and hence the number of pressure tubes.

(vi) Projection software also indicates pump pressure required with a lot of other data.

(vii) There are variables available in the design/sizing of the RO system, such as
  a) the use of 4” or 8” membranes (depending on the flow to be handled);
  b) recovery percentage;
  c) feed pH (adjustable with the addition of acid/alkali, etc.);
  d) variations in the number of membranes per pressure tube (usually varying from 2 to 7 membranes per tube) and different “arrays”;
  e) a variety of membranes that offer different performance.

(viii) There is also a provision to insert an “energy recovery device” (ERD) in case the designer is interested in recovering some energy from the rejects stream. The use of such devices is to be done in consultation with OEMs of ERD manufacturers.

### 10.15.8 Energy Efficiency of RO

To recover freshwater from seawater, RO technology takes a significant amount of energy. Because of advancements in RO technology, seawater RO (SWRO) has become the primary form of large-scale desalination around the world. However, the specific energy consumption (SEC) of SWRO remains significantly greater than that of surface water treatment and indirect potable recycling, making SWRO less cost-effective than other potable water production solutions. Furthermore, when non-renewable energy sources are employed to meet SWRO energy demand, larger quantities of greenhouse gas are emitted than when lower energy alternatives are used.

Energy causes 60% of the total cost in RO systems. Hence, optimisation of energy is essential to keep the overall cost optimum.

Following designs are used for efficient use of energy:

1) Use of ERDs
2) Selection of optimal flux
3) High efficiency of HPP
4) Use of VFDs
5) Use of high-efficiency drives
6) Prevention of biofouling in RO membranes

### 10.15.9 Membrane distillation

Membrane distillation (MD) is a thermal separation technique that uses a hydrophobic membrane to separate water vapour from water containing dissolved salts. The driving force in the MD process is the difference in vapour pressure between two sides of the membrane induced by vacuum. This process is particularly useful in desalination, treatment of brackish water and industrial wastewater treatment. The water recovery can be > 80% and with solar power, the energy requirement can be brought to a minimum. It can be integrated with existing roof-top solar water heaters to generate the driving force. Hence, it can be used at domestic scale as well. It is less prone to scaling and fouling issues and has low energy consumption as compared to other desalination techniques.

## 10.16 Desalination

It is recommended to use RO membranes for the treatment of

a) brackish water reverse osmosis (BWRO), and
b) seawater desalination (SWRO)

Details of BWRO and SWRO are discussed in following sub-sections.

### 10.16.1 BWRO Systems

BWRO systems are typically designed with raw water TDS ranging from about 1500 to 10,000 mg/L. Beyond this TDS level, SWRO is required to be employed. For groundwater or surface water having TDS less than 1000 mg/L, RO treatment is not required or not desirable.

RO process itself is extremely versatile but needs the feed water to be treated with great care. Some of the limiting conditions (of feed water to BWRO) are

- Total suspended solids : Below detectable limits (BDL)
- Silting density index (SDI) : Preferably below 3.0, but less than 5.0
- Oxidising chemicals : BDL
- Silica (colloidal) : BDL
- Other heavy metals : BDL
- TDS : Less than 10,000 mg/L
- Iron/manganese : Less than 0.1 mg/L
- Bacterial load : Preferably NIL

To achieve these parameters, in most cases, some pretreatment is necessary. Unit operations and unit processes involved in such treatment depend on the (raw water) source. The following block diagram indicates the combination of possible schemes (Figure 10.14).

BWRO systems usually operate at low or moderate pressure (8 to 20 Bar-G). Feed pressure required (at the membrane feed end) is usually 2 to 4 Bar-G and can have recoveries up to even 90%, depending on the array. If the feed water contains a large amount of heavy metals, silica, boron, etc., a more exhaustive pretreatment is called for.

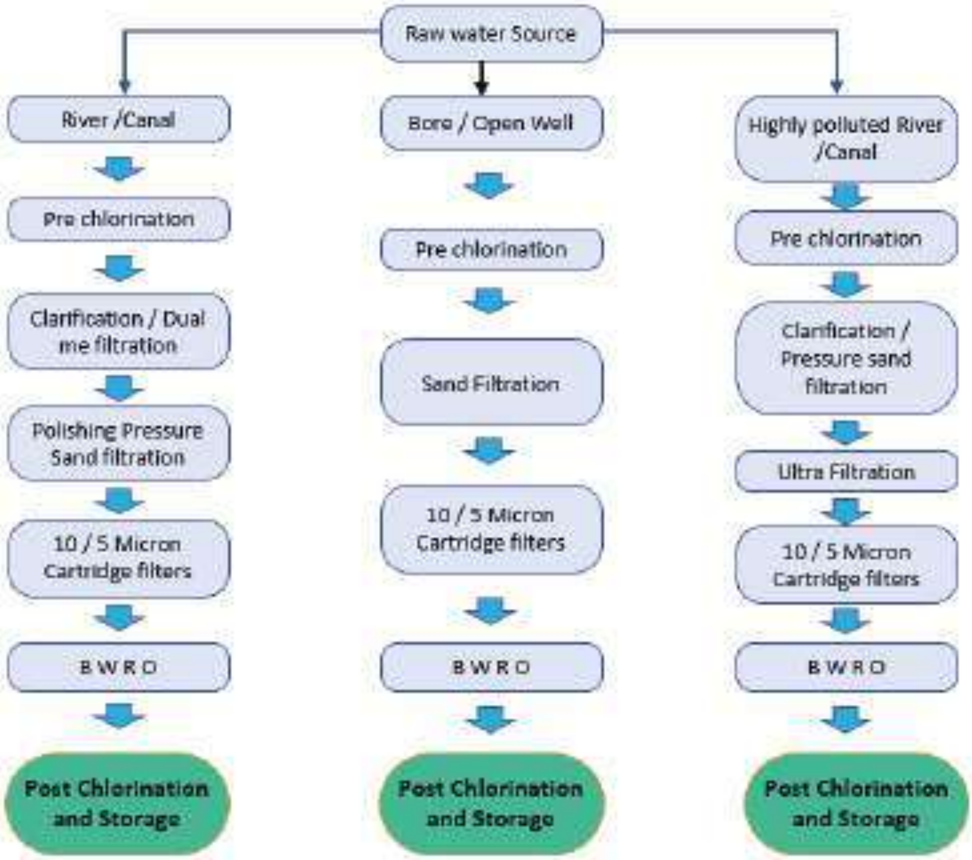

**Figure 10.14: Block Diagram showing combination of possible schemes with BWRO system**

### 10.16.2 Seawater Desalination (SWRO)

Pressure-driven RO has become the most preferred method to desalinate seawater across the world over the last two decades. RO is a membrane-based separation process, where high pressure is applied to the concentrated influent water to overcome the osmotic pressure through a semi-permeable membrane, to enable the separation of molecular/dissolved impurities from the water. This splits the feed into reject stream rich in salt molecules and another stream leans in salts thus reducing the TDS of the water.

**Limitations of Conventional RO**

Typically, SWRO process takes in feed water between 30,000 and 40,000 mg/L TDS and can concentrate reject streams up to 70,000 mg/L TDS. Concentration above this limit is capped by the prohibitive energy requirements. Thus, the ideal permeate recovery from the process is capped at ~ 40%.

Current desalination plants world over, need to increase their intake (by up to 2.5 times) due to this recovery constraint to meet ever-growing permeate demands. Further, brine generated from the SWRO process is sent back to the sea as it cannot be treated further.

### 10.16.3 Counter-flow Reverse Osmosis (CFRO)

CFRO system has been developed and scaled to take in existing brine streams (> = 70,000 ppm TDS) from your SWRO process to

- recover more water from brine streams and thereby increase recovery; and
- considerably reduce final brine generation.

CFRO is an advanced process innovation based on the conventional RO process developed for brine handling needs and starts where conventional SWRO systems stop. CFRO systems extract high-quality permeate from saline water sources, including high-salinity brine streams, at lower pressure, with less energy and lower capital and operating costs than alternative approaches.

With minimal intervention and maximised permeate extraction enable quick project turn-around, be it brownfield expansion or end-to-end greenfield desalination needs.

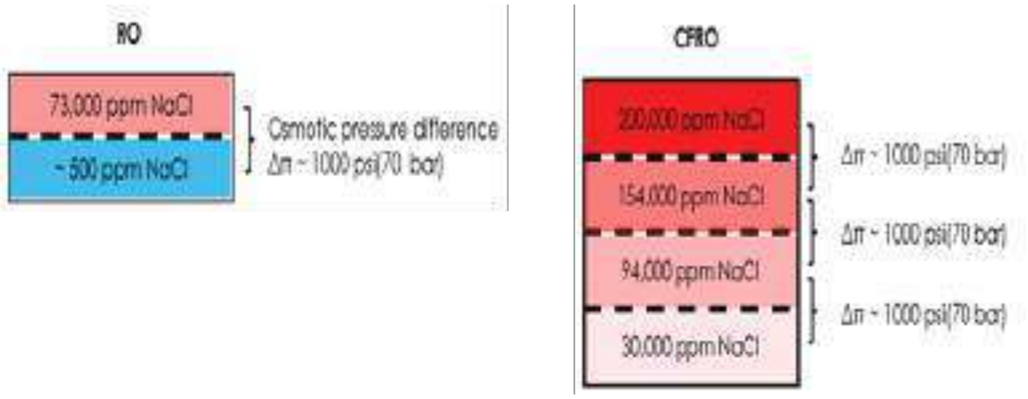

**Figure 10.15: CFRO Working**

The CFRO process works on the principle of osmotic assistance; diluted brine from succeeding stages is recirculated back into the system to decrease the relative osmotic pressure requirements and thus concentrate reject streams up to 200,000 ppm. This concentration level is comparable to thermal evaporators. Furthermore, the CFRO achieves the same with the standard spiral wound membrane architecture and similar operating pressures as conventional SWRO systems. Figure 10.15 shows CFRO working and Figure 10.16 shows CFRO configuration.

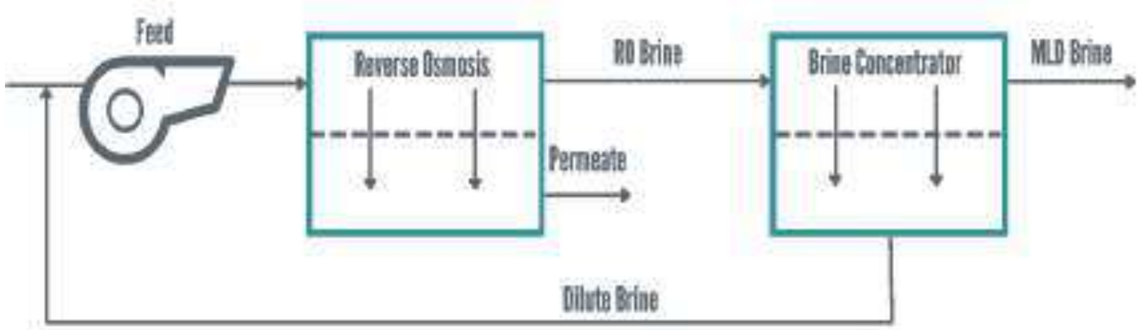

Figure 10.16: CFRO Configuration

Novel advantages for desalination needs

- High recovery desalination solution up to 90%;
- Minimise intake/outfall structures required for your desalination plants;
- Quick SWRO project turn-around to match your expansion ambitions;
- Meet future DM water quality demand with current desalination assets.

### 10.16.4 Design Criteria of Desalination Plant

The saline waters in India including the seawater, coastal, and inland brackish waters having salinity more than the limits recommended for potable use require treatment through the installation of desalination plants. Typically, water with a TDS concentration higher than 500 mg/L and not higher than 15,000 mg/L is classified as brackish. Seawater is classified as natural water sources with TDS values greater than 15,000 mg/L, such as sea, bay, and ocean waters. This concentration can range up to 36,000 mg/L at various locations and depths along the seacoast.

There is no one “best” method of desalination. Generally, distillation and RO are recommended for seawater desalination, while RO and ED are used for brackish water desalination. However, the selection and use of these processes should be very site-specific and must be selected very carefully.

One of the major considerations in the selection of a desalination process should be its cost and maintenance. However, despite the substantial costs involved, the availability of desalinated water in arid zones can be a boon to that area. Where the water is salty, alternative water for consumption is often transported over long distances by truck or animal. When the water is sold, its unit price often exceeds that of desalinated water. Therefore, the economic conditions to support desalination already exist in many water-short areas.

Apart from this, the following criteria should be given due consideration for site selection and designing a desalination system of water supply.

Site selection is critical for desalination plant design, finance, building, and operation. The following criteria should be considered when choosing a site:

a) It should be suitably located in a marine environment where an adequate quantity of feed water with a reasonably good, uniform, and steady quality of feed seawater is abstracted at a reasonable cost.
b) The area extent and shape (topography and geometry) must be appropriate so that the marine intake head structures, the marine pipelines, the inland pit, the seawater pumping station, the inland pipelines, the main facility structures, the post-treatment system, the

product delivery sub-system, and the power supply system (independent of national grid substation) are adequately accommodated and optimally located so that civil, electrical, piping interconnections, and other works costs are minimised.

c) It should be at a location where the brine, backwash wastewater, and other wastes are disposed of without environmental adverse effects.
d) Geologically and oceanographically are suitable for the construction and erection of the various structures at reasonable costs.
e) Environmental, town planning, and rural planning regulations, law requirements, and restrictions are met.
f) The desalination plant shall have the social acceptance of the neighbouring communities and other authorities.
g) Must be located in a place where access and interconnections to the power supply grid (or independent power production or alternate source of energy, especially renewable energy resources) and the water supply networks are technically and economically feasible.

### 10.16.5 Seawater Intake

**Site condition**

Physical site parameters, as well as meteorological and oceanographic data, must be considered while evaluating a site for seawater intake. In addition, potential sources of contamination such as fouling by marine organisms, oil spills, or other pollution should be evaluated.

When considering the location of an intake structure, it is important to remember that the ocean is in constant motion and is constantly changing. Water levels vary on a daily basis as the tide level changes. In addition, forces caused by waves and currents are constantly at work modifying the shoreline and the profile of the sea floor near the shore.

**Water quality**

The surf zone is the area in which waves approaching the shoreline break. Breaking waves create a great deal of turbulence. The churning motion of breaking waves suspends particles from the bottom, making the water in the surf zone more turbid and with higher amounts of suspended solids. For this reason, it is not advisable to take seawater directly from the surf zone. As a result, wave forces on structures can be reduced by situating them at an appropriate depth below the water’s surface.

Water temperature also varies with depth. It is important to keep water temperatures within a properly designed range for seawater intake. To reduce temperature fluctuations that can be experienced in stratified surface layers, it is preferred that seawater be obtained from a deeper layer.

One of the first considerations then, concerning the location of an intake for a desalination plant, is the proximity to the shore of a location deep enough to obtain cooler, less turbid water. Either a pipe or channel-type intake can then be selected, depending on seabed conditions, to bring the water to the plant. In alluvial soil formation on the shoreline, seawater may be collected through the construction of beach wells in coastal alluvial aquifers.

**Seabed conditions**

The seabed conditions will be one of the primary factors in determining the type of seawater intake structure for a particular location. If the intake is to draw water from the open coastline and not from a sheltered lagoon (preferred location, if available and pollution free), the two most common types of intakes are the pipe and the channel intake.

**Pipe-type intake**

In a pipe-type intake, a pipeline is run from the shoreline out past the surf zone (Figure 10.17 and

Figure 10.18). For sandy bottoms, a trench is usually dredged, the pipe is laid, and the trench is backfilled. For bottoms composed primarily of rock or coral, dredging and backfilling would be difficult and expensive. Pipelines are typically buried for anchorage and protection from wave forces and currents. Other methods of anchorage besides trenching and backfilling have been employed, including multi-helix anchors, concrete saddles, engineered backfill, and grouted neoprene-impregnated nylon bags or pillows filled with grout. There are other problems associated with laying pipelines on a rocky bottom. Pipes laid on uneven terrain will only be supported at the high spots. This bridging between support points results in stresses that must be carried by the pipe. In addition, the danger of abrasion of the pipeline is increased with rock bottoms. For these reasons, rock bottoms are not conducive to the installation of a pipe-type intake.

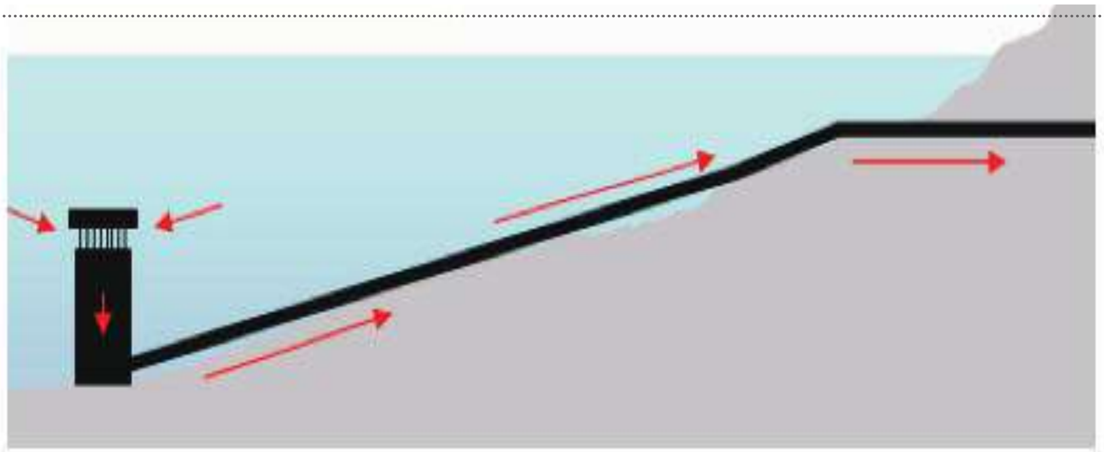

Figure 10.17: Side View of Sub-surface Intake

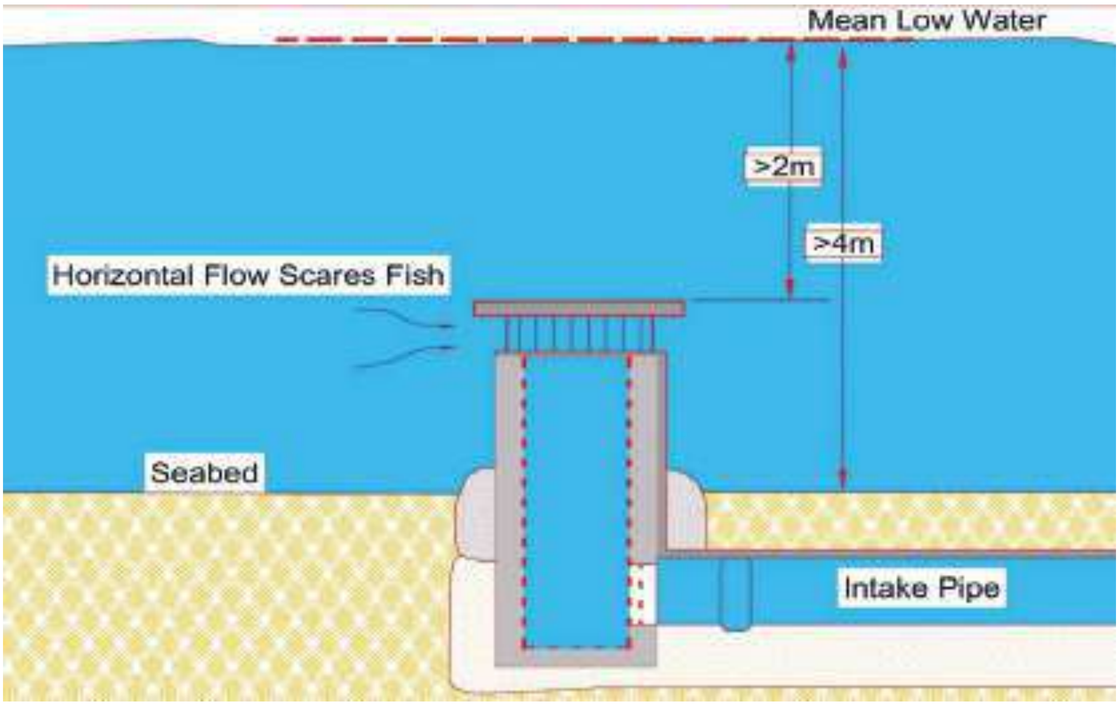

Figure 10.18: Pipe-type Intake

**Channel-type intake**

A channel-type intake can be constructed either by installing rocks to form walls along each side of the channel or by dredging (Figure 10.19). In sandy bottoms, there is a tendency for the movement of sand due to littoral transport. This littoral transport can either act to erode sand from the channel walls or result in sand being deposited in the channel and could result in the channel requiring re-dredging to keep the channel open. In addition, wave action in the channel will result in sand and silt being placed in suspension causing higher turbidity. For rocky bottoms, the problems of littoral transport, erosion, and suspension of particles due to wave activity are not significant considerations in designing channel-type intakes. The design of a channel-type intake on rock bottoms would primarily be concerned with resisting wave forces and eliminating debris.

As a result, a sandy bottom favours the construction of a pipe-type intake system, whereas a rocky bottom favours the installation of a channel-type intake system.

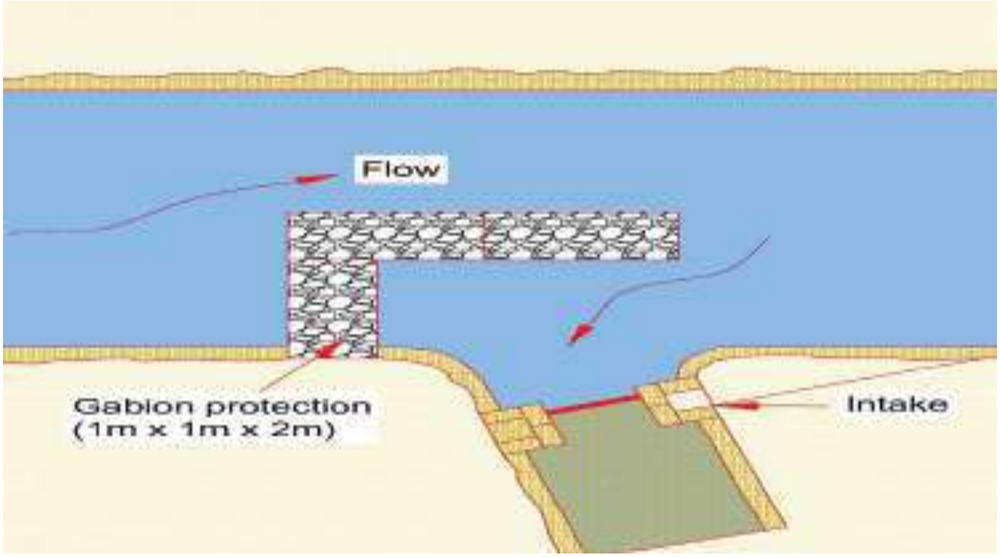

**Figure 10.19: Channel-type Intake (Gabion Protection)**

### Non-surface intakes

Non-surface intakes include beach wells, seabed filtration, and inflow galleries. These types of intakes are variations on the same basic approach of taking filtered seawater from below the surface near the shoreline (Figure 10.20). Each of these intakes has advantages, capabilities, suitability, and cost-effectiveness for different site conditions.

Due to natural filtration and underground detention, beach wells and galleries extracting groundwater of seawater quality can deliver a more consistent quantity and higher quality water than surface intakes. Although experience with similar beach wells and galleries as intakes for SWRO plants is limited, non-surface intakes promise an opportunity for improved efficiency, reliability, cost-effectiveness, and performance of desalination plants, particularly SWRO plants, due to their positive effects on feed-water quality.

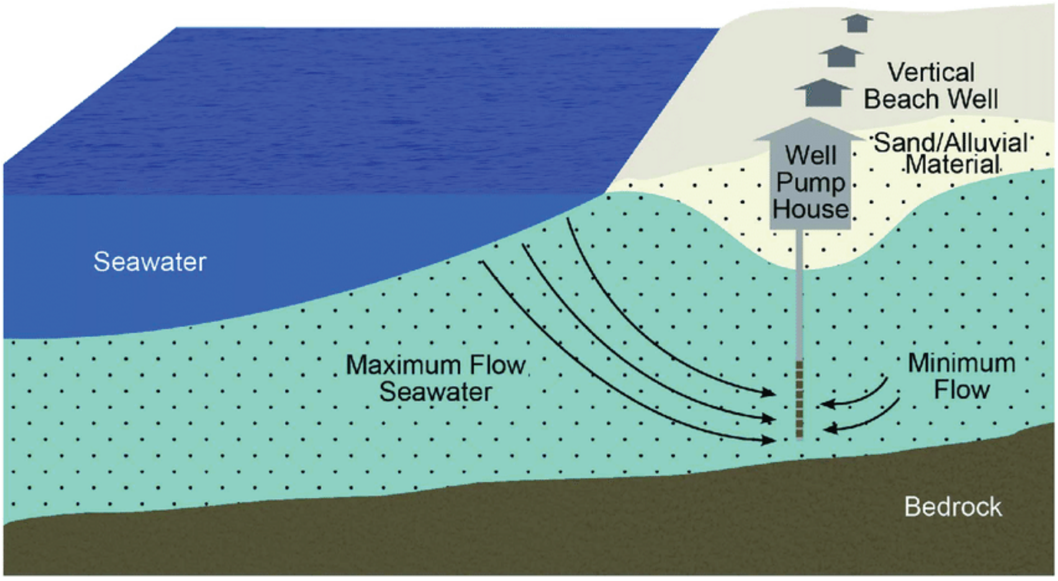

**Figure 10.20: Non-surface Intake**

**Other factors**

The oceans are extremely dynamic systems constantly in motion as a result of external forces, such as wind, and internal forces, such as temperature and salinity gradients. The rotation of the Earth results in oceanographic currents and wind forces cause waves and also affect the currents. Seismic forces on the Earth may also result in disruptive waves in the form of tsunamis and seiches (standing waves oscillating in a seawater body).

**Environmental impact assessment:** A detailed environmental impact assessment of the SWRO project has to be carried out before taking final decision on the site selection and implementation of the project.

### 10.16.6 Design of Desalination Plant

Table 10.4 provides a general indication of the range of source water salinity for which distillation, RO separation, Electrodialysis (ED), and Ion exchange can be applied cost-effectively for desalination.

**Table 10.4: Range of Source Water Salinity**

| Separation process | Range of source water TDS concentration for cost-effective application, mg/L |
|---|---|
| Distillation | 20,000–100,000 |
| RO separation | 2000–46,000 |
| Electrodialysis | 200–3000 |
| Ion exchange | 1–800 |

For processes with overlapping salinity ranges, a life-cycle cost analysis for the site-specific conditions of a given desalination project is typically applied to determine the most suitable desalination technology for the project.

#### 10.16.6.1 Thermal Desalination

All thermal desalination plants have five key streams: source water (seawater, brackish water, or brine) used for desalination; steam needed for evaporation of the source water; cooling water to condense the freshwater vapour generated from the source water’s evaporation; low-salinity distilled water (distillate); and concentrate (brine), which contains the salts and other impurities separated from the source water.

Multi-stage flash distillation (MSF), multi-effect distillation (MED), and vapour compression (VC) are the three most popular types of thermal desalination technologies. Each of these classes of technology has evolved over the past 40 to 60 years toward improvements in efficiency and productivity. The three types of thermal technologies mainly differ by the temperature and pressure at which the source water is boiled to generate freshwater vapour.

### a) Multi-stage flash distillation (MSF )

In the MSF evaporator vessels (also referred to as flash stages or effects), the high-salinity source water is heated to a temperature of 90 to 115 °C (194 to 239 °F) in a vessel (the heating section) to create water vapour. The pressure in the first stage is maintained slightly below the saturation vapour pressure of the water. So, when the high-pressure vapour created in the heating section enters the first stage, its pressure is reduced to a level at which the vapour “flashes” into steam. Steam (waste heat) for the heating section is provided by the power plant co-located with the desalination plant. Each flash stage (effect) has a condenser to turn the steam into the distillate. The condensers are equipped with heat exchanger tubes, which are cooled by the source water that is fed to the condensers.

Entrainment separators (mist eliminators or demister pads) remove the high-salinity mist from the low-salinity rising steam. This steam condenses into pure water (distillate) on the heat exchanger tubes and is collected in distillate trays, from where it is conveyed to a product water tank. Distillate flows from stage to stage and is collected at the last stage. The concentrate (brine) is generated in each stage and after collection at the last stage, some of it typically is recycled to the source water stream to reduce the total volume of source water that must be collected by the intake for desalination. The recirculated brine flowing through the interior of the condenser tubes also removes the latent heat of condensation. As a result, the recirculated brine is also preheated close to maximum operating temperature, thereby recovering the energy of the condensing vapour and reducing the overall heating needs of the source water. This “brine recycle” feature has been adopted in practically all of the most recent MSF facility designs and allows significant improvement of the overall cost competitiveness of MSF installations.

Each flash stage typically produces approximately 1% of the total volume of the desalination plant’s condensate. Due to the fact that a typical MSF unit contains 19 to 28 effects, the overall MSF plant recovery (i.e., the volume of distillate expressed as a percentage of the total volume of processed source water) is normally 19 to 28%. For comparison, RO seawater desalination plants have a recovery of 40 to 45%. The latest MSF technology has 45-stage units, i.e., can operate at 45% recovery. This feature allows it to compete with RO systems in terms of recovery.

Historically, MSF was the first commercially available thermal desalination technology applied to the production of potable water on a large scale, which explains its popularity. Over 80% of thermally desalinated water today is produced in MSF plants.

### b) Multiple-effect distillation (MED)

In MED systems, the saline source water is typically not heated; cold source water is sprayed via nozzles or perforated plates over bundles of heat exchanger tubes. This sprayed feed water boils, and the resulting vapour flows through mist eliminators, which remove brine particles from the vapours. The feed water, that turned into vapour in the first stage (effect) is introduced into the heat exchanger tubes of the next effect. Because the next effect is maintained at slightly lower pressure, although the vapour is slightly cooler, it still condenses into freshwater at this lower temperature. This process of reducing the ambient pressure in each successive stage allows the feed water to undergo multiple successive boiling without the introduction of new heat. Steam flows through the exchanger tubes is condensed into pure water and collected from each effect. Heating steam (or vapour) introduced in the heat exchanger tubes of the first effect is provided from an outside source by a steam ejector.

The MED system is also equipped with a brine recycle system, which allows the introduction of warmer-than-ambient water in the first effects of the system, thereby reducing both the volume of feed water that must be collected by the plant intake system and the overall energy needs of the system.

The main difference between the MED and MSF processes is that while vapour is created in an MSF system through flashing, evaporation of feed water in MED is achieved through heat transfer from the steam in the condenser tubes into the source water sprayed onto these tubes. This heat transfer at the same time results in condensation of the vapour to freshwater. MED desalination systems typically operate at lower temperatures than MSF plants (maximum brine concentrate temperature of 62 to 75 °C versus 115 °C).

#### c) Vapour compression (VC)

The heat source for VC systems is compressed vapour produced by a mechanical compressor or a steam jet ejector rather than a direct exchange of heat from steam.

In VC systems, the source water is evaporated and the vapour is conveyed to a compressor. The vapour is then compressed to increase its temperature to a point adequate to evaporate the source water sprayed over tube bundles through which the vapour is conveyed. As the compressed vapour exchanges its heat with the new source water being sprayed on the evaporation tubes, it is condensed into pure water. A feed water preheater (plate-type heat exchanger) is used to start the process and reach evaporation temperature.

VC and MED work based on similar principles. However, while in MED, the steam produced by source water evaporation is introduced and condensed in a separate condenser located in the downstream effect; in VC, the steam generated from the evaporation of new source water is sprayed on the outside surface of the heat exchanger tubes, recirculated by the vapour compressor, and then introduced into the inner side of the same heat exchanger tubes, where it condenses to form distillate.

### 10.16.6.2 Membrane Desalination

Two general types of technologies currently used for membrane desalination are RO and ED which are described in earlier sections. Table 10.5 provides a comparison of the removal efficiencies of distillation, ED, and RO systems for key source water quality compounds. One important observation from this table is that, as compared to distillation and RO separation, ED desalination only partially removes nutrients from the source water. This explains why EDR is frequently regarded as more desirable than RO or thermal desalination.

**Table 10.5: Contaminant Removal by Alternative Desalination Technologies**

| Contaminant | Distillation (%) | ED/EDR (%) | RO (%) |
|---|---|---|---|
| TDS | >91.9 | 50–90 | 90–91.5 |
| Pesticides, organics/VOCs | 50–90 | <5 | 5–50 |
| Pathogens | >99 | <5 | >910.99 |
| TOC | >95 | <20 | 95–98 |
| Radiological | >99 | 50–90 | 90–99 |
| Nitrate | >99 | 60–69 | 90–94 |
| Calcium | >99 | 45–50 | 95–97 |

| Contaminant | Distillation (%) | ED/EDR (%) | RO (%) |
|---|---|---|---|
| Magnesium | >99 | 55–62 | 95–97 |
| Bicarbonate | >99 | 45–47 | 95–97 |
| Potassium | >99 | 55–58 | 90–92 |

One important observation from this table is that, as compared to distillation and RO separation, ED desalination only partially removes nutrients from the source water. This fact explains why EDR is often considered more attractive than RO or thermal desalination (which removes practically all minerals from the source water) if the planned use of the desalinated water is for agricultural purposes, i.e., generating fresh or reclaimed water for irrigation of crops.

Construction and equipment costs for BWRO and EDR systems of the same freshwater production capacity are usually comparable, or EDR is less costly, depending on the RO membrane fouling capacity of the source water. However, since the amount of electricity consumed by EDR systems is directly proportional to the source water's salinity, at salinities of 2000 to 3000 mg/L, the energy use of EDR systems usually exceeds that of BWRO or NF systems for source water. As a result, EDR systems are not as widely employed as RO systems for BWRO desalination and are never used for SWRO. It should be pointed out, however, that salinity is not the only criterion for evaluating the cost-competitiveness of EDR and BWRO systems. Often, other compounds such as silica play a key role in the decision-making process.

Over the past two decades, RO membrane separation has evolved more rapidly than any other desalination technology, mainly because of its competitive energy consumption and water production costs. The all-inclusive energy consumption for freshwater production of thermal desalination plants is typically much higher than that for brackish or seawater desalination. BWRO desalination yields the lowest overall production costs of all the desalination technologies. It is also worth noting that the most recent MED projects undertaken in recent years have been finished at costs equivalent to those of comparable sized SWRO facilities. For the majority of medium and large projects, however, SWRO desalination usually is more cost-competitive than thermal desalination technologies.

### 10.16.7 Brine Management

Brine (also known as membrane concentrate, reject brine, and wastewater) is a high-concentration salt (NaCl) solution in water ($H_2O$). Brine can refer to salt solutions with concentrations ranging from around 3.5% to roughly 26%. Brine is formed naturally from evaporation of ground saline water, but it is also produced during sodium chloride mining. It is also a by-product of many industrial processes, such as desalination, so it requires wastewater treatment for proper disposal or further utilisation (fresh water recovery).

#### Disposal of Brine

Disposal of brine in desalination plants is of great significance both from economic and environmental standpoints. Improper surface disposal has the potential for polluting the groundwater resources that are used as feed water for many of the desalination plants. The groundwater pollution is likely to result from high salinity and the presence of other harmful chemicals in the brine. For the disposal of rejected brine from inland desalination plants, the following solutions should be examined:

a) Pumping into specially designed lined evaporation ponds;
b) Deep well injection;
c) Disposal into surface water bodies;
d) Disposal through pipelines to municipal sewers;
e) Concentration into solid salts; and
f) Irrigation of plants tolerant to high salinity (halophytes).

Options a) and f) are seasonal and, therefore, a backup alternative is required to improve their reliability.

**The following factors influence the selection of a disposal method:**

a) The volume or quantity of concentrate;
b) The quality or constituents of concentrate;
c) The physical or geographical location of the discharge point of the concentrate;
d) The permissibility of the option;
e) Public acceptance;
f) Capital and operating costs; and
g) The facility's ability to be expanded.

**The main environmental issues for an appropriate location for brine discharge are:**

a) Finding a region with no endangered species or stressed aquatic ecosystems;
b) Finding a location with a high underwater current to allow fast dissipation of high-salinity discharge;
c) Avoiding areas with ship traffic to avoid damaging the brine discharge system and altering the mixing pattern;
d) Identifying a discharge point near the shoreline or relatively shallow water to minimise construction;
e) Ensuring that discharged brine descends to the seabed and travels along the seabed thereafter;
f) Ensuring no dressing or alteration of the sand dunes, or natural features including landscape changes for beautification, recreation, and other such purposes; and
g) To meet the CPCB's water quality standards for coastal waters marine outfalls (Vide: EPA, 1986 -GSR 7, dated December 22, 1998).

### Importance of Brine Reduction

Brine salts change the chemical and physical properties of soils. Brine has a deleterious impact on soils in a variety of ways due to the high concentrations of soluble salts [most notably sodium chloride (NaCl)]. Many biological species are poisoned by chloride levels in and around the spill location. Sodium is a natural dispersant, causing soils to inflate and spread. The salts in brine reduce the plant's ability to absorb water and nutrients. High salt concentrations in the soil limit the plant's ability to absorb water even when ample water is available in the soil, causing the plant to exhibit drought symptoms. This is due to an osmotic action, which causes water to migrate from low salt concentration locations, such as the roots, to high salt concentration areas, such as the soil.

Plant growth is reduced in damaged areas due to the effects of excessive salt concentrations on soil and vegetation. This is exacerbated by the inability of many seeds to germinate.

### Methods of Brine Reduction

The following methods are generally used for reduction of brine:

(i) Membrane treatment system;
(ii) Thermal evaporation;
(iii) Evaporation ponds.

#### (i) Membrane treatment system

RO is the membrane system most widely used to desalt brine waters. RO generates freshwater as well as a more concentrated brine, which is referred to as RO brine, reject, or concentrate. This brine concentrate will typically include dissolved salts and chemical concentrations that are close to scaling limitations. If you intend to use a thermal system to further concentrate the brine or generate solids, you must treat it to reduce the scaling potential.

#### (ii) Thermal evaporation

When considering thermal evaporative systems, optimising freshwater recovery through lower cost membrane systems before adopting expensive thermal systems would result in the best project economics. Based on their residual outputs, thermal systems are classified into two types: (1) evaporators, which create concentrated, low volume brine but do not precipitate solids, and (2) crystallisers, which exceed salt saturation and produce solids.

#### (iii) Evaporation ponds

Evaporation ponds are an artificial solution to waste brine discharge from inland surface water. The water evaporates under the correct climatic circumstances, allowing you to discharge more brine into the ponds. One limitation of ponds is that they require large areas of land to increase the surface area where the water can evaporate, and can represent a future environmental liability due to either animal entry or future decommissioning. If solids must be recovered for disposal or reuse, numerous evaporation ponds may be required to alternate between brine evaporation and solids extraction. Evaporation is also faster in hotter, arid areas.

### 10.16.8 Capacitive Deionization (CDI)

CDI is an emerging technology that can be used to treat brackish water. The principle of this technique is electro adsorption of ions on the surface of the electrodes. Various electrode materials used for CDI are activated carbon, carbon cloth, ordered mesoporous carbon, carbon nanofibers, carbon nanotubes/multiwall carbon nanotubes (CNTs/ MWCNTs), and graphene and graphene-based composites. A CDI cell comprises of a pair of porous electrodes separated by a non-conducting separator. When a potential difference (below 2V) is applied to the electrodes, they get charged and the ions present in the feed water migrate to the electrical double layer (EDL) of the oppositely charged porous electrodes. The ions are electrostatically held at the EDL until an equilibrium is reached when no more ions get adsorbed. Desorption happens when the potential is reversed, or the external power supply is shorted and the ions leave the electrodes as the brine stream thereby regenerating the electrodes. Energy can be recovered from the charge that is leaving the cell. Some of the important parameters for defining the performance of a CDI unit are maximum salt adsorption capacity, average salt adsorption rate, charge efficiency and charge storage capacity. CDI has several advantages over other desalination techniques such as energy efficiency (high pressure pumps are not required), less water rejection compared to RO, the possibility to work on solar/wind power as it requires only 0.8-2.0 V, and the possibility of energy recovery as it works as a capacitor. The limitation of CDI lies in the availability of electrodes with high electro adsorption capacity.

In the last decade, there has been many developments in membrane capacitive deionization (MCDI) wherein, an ion exchange membrane is introduced on top of the porous electrodes. This enables complete regeneration of the electrode surface during the desorption step. Flow electrode/flow electrode capacitive deionization (FCDI) cell is yet another advancement wherein a carbon slurry is continuously passed between the electrode compartments and the ions get adsorbed. The desorption step takes place in a separate compartment downstream. The continuous flow of uncharged carbon particles increases the desalination capacity by increasing the effective capacitance. Therefore, FCDI can desalinate water of higher salinity and even sea water having TDS of 31g/L with an efficiency of 95% and can overcome the limitation of conventional CDI.

Currently CDI has been has implemented for brackish water desalination with a water recovery of up to 82% has been achieved, with output TDS below 150 ppm. It can also address ionic contaminants such as fluoride, nitrate, uranium, arsenic, etc., as well. Units with remote monitoring and powered by photovoltaics have also been implemented. Individual units delivering 3-10 KLD are generally preferred.

### 10.17 Case Studies on SWRO Applications

Such plants, which are under operation in India, are discussed in the section below

**Nemmeli, Chennai Metro, Tamil Nadu**

The SWRO plant of Chennai Metro at Nemmeli receives the raw seawater from the Bay of Bengal located on the eastern side of India. The output capacity of SWRO is 100 to 110 MLD. Presently, the plant operates at 70 to 75 MLD capacity. As reported, the produced water cost is Rs. 32 per cum. The treated water is supplied (pumped) to the drinking water supply and distribution network of South Chennai at a heavily subsidised rate. The plant was designed and supplied by M/s Wabag-IDE and has been maintained by Wabag since 2013. Seawater has TDS in the range of 36,000 to 39,000 mg/L. It is designed for a maximum TDS value of 41,700 mg/L. The TSS in the fair-weather season is 20 mg/L. However, during monsoon, it goes as high as 300 mg/L. It also receives a moderate load of organics and seashells.

To produce 100 MLD of treated water, 240 MLD of raw seawater is required to be pumped into the pretreatment system. The plant has a deep-sea submerged intake (15 m below water level). Raw seawater is conveyed by HDPE pipe buried under the seabed to the plant's receiving well. The receiving well is provided with vertical travelling bar screens. Most of the seashells and other coarse impurities are arrested and removed by the screens. The raw water is then pumped from receiving well to the pretreatment plant consisting of flash mixers, flocculators, and lamella clarifiers. Pre-chlorination is done at the inlet chamber. Ferric chloride ($FeCl_3$) is dosed as a coagulant. The TSS of treated clarified water ranges from 10-15 mg/L. There are five parallel streams of lamella clarifiers preceded by flocculators. Lamella plates are made out of polypropylene (PP). The clarified water is stored in an underground reservoir.

The clarified water is further pumped at 18 bar (183.55 m $H_2O$) pressure to Disk Filters followed by UF membranes. The disk filters are self-cleansing and automated to have a cleaning cycle. There are twenty-two parallel chains of skids each comprised of four disk filter vessels. The disk filters produce water of quality less than 10 NTU. It is further conveyed to UF membrane skids (Figure 10.21). The membrane flux has a design value of 85 L/sqm/hr. The treated water from UF has a turbidity of less than 1 NTU. The feed water quality to RO (TSS, turbidity, and organics) is practically BDL due to the combination of Chlorine dosing and polishing off of all suspended particles by disc filters and UF.

The RO feed water is then injected with sodium-meta-bisulphite for de-chlorination of residual chlorine as RO membranes are generally non-tolerant to chlorine presence. The SDI of RO feed water is achieved in the range of 2 to 3. High-pressure pumps (72 bar) convey the water to RO skids (Figure 10.22). The total recovery rate is 40%. The RO treated water TDS is reduced to a range of 400 to 500 mg/L. The membranes are designed for flux values of 14 to 15 $L/m^2/h$. After the commissioning of the plant, the CIP cycle was 60 days. After seven years of operation, it is 20 days.

For re-mineralisation, part of RO treated water (30%, side stream) is injected with carbon dioxide and then passes through columns of lime flakes. This raises the finished water pH above 7.5. It is further dosed with chlorine (post-chlorination) for complete disinfection. The treated water is stored in the ground reservoir and then pumped to the consumer end (drinking water). The waste, UF, and RO reject (TDS 70,000 mg/L) is disposed of in the sea. An elaborate diffuser arrangement is made at the disposal point so as not to disturb the marine life and environment due to shock loading.

The treated water is of excellent quality, according to the drinking water criteria mentioned in IS 10500:2012. The plant is well designed including pipe and cable routing. It has a sound layout from a process, operation and maintenance logistics point of view. The plant is automated, and manpower is trained and skilled.

During the initial construction of the project in the year 2010, pretreatment consisting of lamella clarifiers was not incorporated. However, to tackle the seasonal variations of TSS, it was required to be provided at a substantial additional cost later. As confirmed during the site visit and with the plant officials, pretreatment of seawater is of utmost importance for plant performance. The degree of pretreatment differs according to the quality of seawater. Seawater quality directly influences the overall project cost.

**Figure 10.21: UF Membranes Skids**

**Figure 10.22: RO Membranes Skids**

(**Source:** *Chennai Metropolitan Water Supply and Sewerage Board*.)

## 10.18 Horizontal or Roughening Filters

The water quality of contaminated surface water can be significantly improved in terms of removing/reducing turbidity when filtered through gravel and sand layers. Therefore, favourable hydrogeological conditions allow polluted and turbid river water to be drawn as clear and safe groundwater from a shallow well located next to a river. These are useful for very small communities where alternative full-fledged treatment is not possible. Roughing filters are typically made up of different-sized filter material that decreases in size in the direction of flow (Figure 10.23 and Figure 10.24). The bulk of the solids is separated by the coarse filter medium located next to the filter inlet. The subsequent medium and fine filter media further reduce the suspended solids concentration. A roughing filter's filter media is made of moderately coarse (rough) material ranging in size from around 25 to 4 mm. Filtration velocity, synonymous with hydraulic load, usually ranges between 0.3 and 1.5 m/h. The accumulated solid matter is periodically flushed out of roughing filters by hydraulic filter cleaning. These filters need to be cleaned manually by excavating the filter material from the filter compartment, and washing and refilling it into the filter boxes. The approximate rate of filtration is given below in a study based in Maharashtra, as shown in Table 10.6 below.

**Table 10.6: Approximate rate of filtration is given below from a study based in Maharashtra**

| Media size | No. of media boxes | Rate of filtration ($m^3/m^2$) |
|---|---|---|
| 12–20 mm | 5 | 3 |
| 20–25 mm | 5 | 4 |
| 25–40 mm | 5 | 5 |
| 40–50 mm | 5–7 | 7 |

Figure 10.23: Horizontal Flow Filters

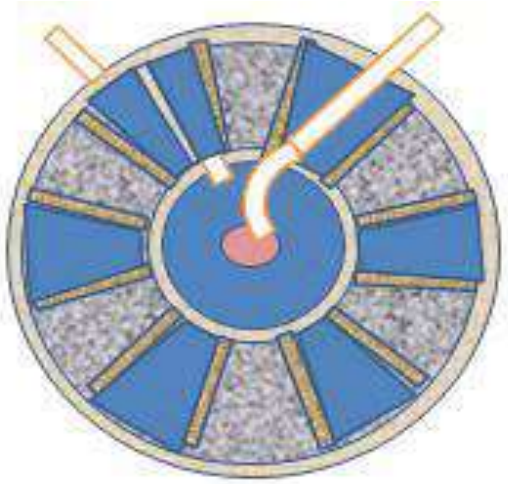

Figure 10.24: Well in Well-type Horizontal Flow Filters

The maintenance can be done by unskilled labour. It is essential to clean the filters before monsoon and after monsoon when they are used as the front pre-filter unit ahead of intake well. For the remaining period, it can be as required based on the observations, normally after 2 to 3 months. It can take any turbidity up to 2000 ppm.

### 10.19 Water Treatment Technologies for Different Climate

The problems of water treatment in extreme and different climates, high altitudes, and difficult terrains are similar to many other engineering problems in those areas. The major problem is the extreme temperature, which varies between (+) 50 °C to (-) 40 °C. Problems with transportation of equipment, construction, and pipe materials are also present. Behaviour of materials becomes different in extreme climatic conditions. Materials tend to become brittle in extreme cold. The problem of extreme cold combined with lack of oxygen due to height exists in the Himalayas. There is a large variation in atmospheric pressure, which is very low at high altitudes.

#### 10.19.1 Effect of Low Temperature

a) **Physical:** At 4°C water is at its maximum density. Further reduction in temperature will result in the expansion of the sample of water and at 0°C, it will solidify and turn to ice having expanded approximately one-twelfth of its volume. This is the reason why bursts in pipes take place by the expansion of water as it changes to ice. The viscosity of water increases with falling temperature. Waters at low temperatures are capable of carrying a greater load of suspended materials than is carried in tropical regions. Settling velocities decrease with temperature. It takes almost twice as much time for particles to settle at 4°C as it does for them to settle at 23.3°C, which is very important in the design of sedimentation tanks.

b) **Chemical:** In general, most chemicals react much slower at a temperature near freezing than they do at normal temperatures. Consequently, a longer reaction time is required for satisfactory performance in the treatment units. Coagulation, precipitation, oxidation, water softening reactions, solubility, etc., all are affected due to low temperature.

   The chlorination process also poses difficulty at low temperatures. At temperatures between 1.10°C and 10.55°C, solid chlorine hydrate is formed due to removal of the chlorine from the solution. There is practically no chlorine at 0 °C. Gaseous chlorine cylinders are heated up for chlorine apparatus to work properly.

### 10.19.2 Effect of High Altitude

**Low barometric pressure:** Low barometric pressure limits the pump suction head. To summarise, the effect of low temperature is to retard biological and chemical reactions and make the physical state of fluids, solids, and other materials appreciably different. Because low temperatures change most of the warm weather characteristics of water, the conventional methods of water collection, treatment, and distribution need modification for use in low-temperature regions.

### 10.19.3 Cold Deserts

Cold deserts are primarily located in high altitudes in the Himalayan region of Arunachal Pradesh, Ladakh, Himachal Pradesh, Uttarakhand, etc. The primary source of water in these areas is glacial melt, which is being impacted because of climate change. Further, the water gets frozen in the pipelines during winters disrupting the water supply. Solutions to improve and store run-off water in small tanks — a conventional water harvesting structure, i.e., zing may be investigated. Furthermore, artificial glacial reservoirs can be produced by redirecting run-off and allowing it to freeze and store as a glacier. During early spring, it will serve as both drinking water and irrigation source. Promoting the use of micro-irrigation can reduce the irrigation requirement and increase the drinking water security.

### 10.19.4 Hilly Areas

In hilly areas, especially at higher altitudes, it is uneconomical to pump water from the valley for a very small number of houses. In these places, adopting spring-based sources, rainwater harvesting, and standalone bore-well systems (if feasible) will be economical. Spring-based systems would require careful identification and delineation of spring sheds, locating the aquifers contributing water to springs, and injection recharging them for sustaining them. Communities may be encouraged to adopt the traditional wisdom of rainwater harvesting (like bamboo-based ones in the NE States) for water security. In such areas, there is a need to focus on Water Quality Monitoring and Surveillance (WQM&S).

### 10.19.5 Coastal Areas

In coastal areas, augmentation of services can be done with energy-efficient small desalination plants with a high recovery ratio. Further, to avoid the ingress of sea water, sub-surface dykes can be constructed in rivers that can also improve the groundwater-based drinking water sources in the adjoining areas.

## 10.20 Emerging Contaminants (ECs)

Chemicals that had not before been detected in the water supply are occasionally discovered. These chemicals are known as “emerging contaminants”. ECs are significant because the dangers they pose to human health and the environment are not completely understood. Because these contaminants were introduced or detected relatively recently, there is a knowledge gap in their fate, behaviours, and impacts, as well as treatment strategies for their efficient removal. Furthermore, despite the advances in treatment technologies, the design of existing treatment plants is not suited to remove these ECs. They may be industrial in origin or may originate from municipal (domestic), agricultural, hospital, or laboratory wastewater.

Pharmaceuticals and personal care products (PPCPs) are increasingly being detected at low levels in surface water, and these compounds may be present inadvertently in various compartments of the aquatic environment (e.g., water, sediments, and biota) at concentrations capable of causing detrimental effects to aquatic organisms and the inherent ability to induce physiological effects in humans at low doses. This has become a major concern due to the widespread and rising use of PPCPs in human and veterinary medicine, resulting in their ongoing release into the environment. The substances in question come from three broad categories: pharmaceuticals (PHACs), personal care products (PCPs), and endocrine-disrupting compounds (EDCs). Endocrine disruptors are substances that can interfere with hormone function in the body. Trace quantities of these pollutants have been found in water in several nations. However, they are not limited to the above and may include nanomaterials (NMs), EC metabolites, illegal medications, modified genes, and so forth. PHACs are a class of emerging environmental pollutants that are increasingly being used in human and veterinary medicine. Antibiotics, legal, and illegal pharmaceuticals, and other substances of environmental importance are among them.

Municipal wastewater is regarded as one of the primary discharge sources for developing contaminants, such as non-point and point sources, industry and storms, home wastewater, and water treatment facilities, into the environment. Also, there is a growing concern about sludge management due to the high levels of ECs in them. The current design of WWTPs cannot limit the elimination of developing pollutants and their metabolites where they are released as sewage effluents into rivers or streams with high biodiversity. So far, considerable work has been done regarding the performance of wastewater technologies in the case of nutrient removal, while there is an absence of data on the ability to remove ECs, and additionally on the adverse eco-toxicological impacts of these compounds on surface water bodies.

Per- and polyfluorinated alkyl substances (PFAS) are a class of nearly 4000 man-made chemicals that have lately emerged as emerging pollutants with substantial deleterious effects on human health, even at low concentrations in the parts per trillion range. Non-stick cookware, upholstered furniture, clothing, food packaging, and firefighting foam used to extinguish petroleum fires are all products that contain PFAS. These compounds do not occur naturally in nature. They do not degrade readily and are exceedingly persistent in the environment, particularly in water, as well as in the human body. PFAS has been linked to health risks including developmental effects in foetuses and infants, various forms of cancer, and decreased liver, thyroid, and immune system function.

Thus, the presence of developing pollutants at trace levels in used waters, as well as their behaviour during wastewater treatment and drinking water production, are critical topics that need to be investigated further.

Activated carbon filters are used to reduce PPCPs but cannot completely remove them. Treatments such as RO, NF, and ozone as part of advanced oxidation also reduce PPCPs and other ECs in drinking water. These technologies are described in earlier sections.