CHAPTER 15
LABORATORY TESTS AND PROCEDURES

15.1 GENERAL

Laboratories with adequate facilities and manned by qualified personnel are essential for inspection and evaluation of the suitability of water supplies for public use as well as for controlling the water treatment processes. The ultimate aim of laboratory examination of water is to ensure that potable water conforming to the drinking water standards is supplied to the consumers.

Tests carried out in the laboratory are intended to assess the quality and classify the raw water to be treated; to determine the need and extent of treatment; to check that water has been properly prepared for each phase of treatment process; to ensure that each phase of treatment proceeds according to plan and to examine the finished water to ascertain that it conforms to the standard. Other objectives that could be served by a regular testing programme include: (i) determination of trends in drinking water quality over time, (ii) provision of information to public health authorities for general public health protection purpose and (iii) identification of sources of contamination.

Laboratory facilities are thus indispensable for controlling plant operation and to record and improve plant performance which help research and development.

15.2 TYPES OF EXAMINATIONS

The laboratory examination comprises of physical, chemical, bacteriological and biological analyses.

Physical analysis determines the aesthetic quality and assess the performance of various treatment units.

Chemical analysis determines concentrations of chemical substances which may affect the quality of water and be indicative of pollution and which reflect variations due to treatment – a requirement for control of water treatment processes.

Bacteriological examination indicates the presence of bacteria characteristic of pollution and hence the safety of water for consumption.

Biological examinations will find application in providing information on causes of objectionable tastes and odours in water or clogging of filters and dictating remedial measures.

15.3 SAMPLING

The value of any laboratory analysis and test depends upon the method of sampling. Failure to observe proper precautions in securing a representative sample may result in an analysis which is of little use since it may unnecessarily condemn a good water supply or more frequently it may certify a bad water as satisfactory. Physical, chemical and bacteriological analysis are necessary for drinking water, while physical analysis may be adequate for industrial waters excepting in food or beverage industries. Biological analysis will be required for limnological work or where taste and odour problems are encountered.

All samples of water should be properly labelled and should be accompanied by complete and accurate identifying and descriptive data. Data should include date and time of collection, type of source of the sample and temperature of water at the time of collection. When samples are being collected from the same sampling point for different analysis, it is essential that the sample for bacteriological examinations be taken first. The particulars to be supplied with the sample are enumerated in the Appendixes 15.2, 15.3, 15.4, 15.5, 15.6 and 15.7.

For transport, bottles may be packed in wooden, metal, plastic or heavy fibreboard cases, with a separate compartment for each bottle. Boxes may be lined with corrugated fibre paper, felt or other resilient material or may be provided with spring-loaded corner strip to prevent breakage. Polythene bottles do not need such elaborate care.

15.3.1 SAMPLING FOR PHYSICAL AND CHEMICAL ANALYSIS

Samples should be collected in containers of Pyrex glass or other inert material like polythene.

Sample bottles must be carefully cleaned before use. Glass bottles may be rinsed with a chromic acid cleaning mixture by adding one litre of concentrated sulphuric acid slowly with stirring to 35 ml saturated sodium dichromate solution or with an alkaline permanganate solution followed by an oxalic acid solution. After having been cleaned, bottles must be rinsed thoroughly with tap water and then with distilled water.

About 2.5 litres of the sample is required for analysis. Prior to filling, the sample bottle should be rinsed out two or three times with water to be collected. Care should be taken to obtain a sample that is truly representative of existing conditions and to handle it in such a way that it does not deteriorate or become contaminated before it reaches the laboratory.

The sample should reach the place of analysis as quickly as possible within 72 hours of collection. The time elapsed between collection and analysis should be recorded in the laboratory report.

Some determinations are likely to be affected by storage of samples. Walls of glass containers are likely to absorb cations like aluminium, cadmium, chromium, copper, iron, lead, manganese, silver or zinc which are best collected in a separate bottle and acidified by concentrated hydrochloric or nitric acid to a pH approximately 3.5 to minimise precipitation and adsorption on the walls of the container.

Certain parameters like temperature, pH dissolved gases like carbon dioxide, hydrogen sulphide, chlorine and oxygen may change significantly during transport. For this reason, determinations of pH, carbon dioxide, ferrous iron, dissolved oxygen and chlorine should be carried out on the spot. Hydrogen sulphide can be preserved by fixing it with zinc acetate until the sample is ready for analysis.

Hot samples collected under pressure should be cooled while under pressure. Sample from wells should be collected only after the well has been pumped for a sufficient time to ensure that the sample will be representative of the ground water.

15.3.2 Sampling for Bacteriological Analysis

15.3.2.1 Sampling Bottles

Sterilized glass bottles provided with ground glass stopper having an overlapping rim should be used. The stopper and the neck of the bottle should be protected by brown paper. The sterilization is carried out in an autoclave at 1 kg/cm^2 pressure for 15 minutes or by dry heat at 160^{0}C for 1 hr.

15.3.2.2 Dechlorination

Dechlorination is necessary for chlorinated water samples. For this, sodium thiosulphate should be added to the clean, dry sampling bottles before sterilization in an amount to provide an approximate concentration of 100 mg/l in the sample. This can be done by adding 0.2 ml of 10% thiosulphate solution to a 250 ml bottle and the bottle is then sterilized.

15.3.2.3 Sample Collection

The sample should be representative of the water to be tested and they should be collected with utmost care to ensure that no contamination occurs at the time of collection or prior to examination. The sample bottle should not be opened till the time of filling. The stopper with the cap should be removed with care to eliminate soiling. During sampling, the stopper and the neck of the bottle should not be touched by hand and they should be protected from contamination. The bottle should be held near the base, filled without rinsing and the stopper replaced immediately. The bottle should not be filled completely but sufficient air space left for shaking before analysis. Then the brown paper wrapping should be tied to protect the sample from contamination.

(a) Sampling from Taps

The tap should be opened fully and the water allowed to run to waste for two to three minutes or for a sufficient time to permit clearing of the service line. The flow from the tap should then be restricted to permit filling the bottle without splashing. Leaking taps, which allow water to flow over the outer surface of the bottle, must be avoided as sampling points. If it becomes necessary to collect from that point, the leak should be attended to before sampling. When a tap is not in continuous service, it is advisable to wipe the tap free of any grease or preferably flamed before collection of the sample. It should be ascertained whether

the tap from where the sample is collected is supplying water from a service pipe directly connected with the main or with a cistern or a storage tank. This information should be sent along with sample.

(b) Sampling Direct from a Source

When the sample is to be collected directly from a stream, river, lake, reservoir, spring or a shallow well, it should be representative of the water that will be taken for treatment. Hence, a sample should not be taken from a point which is too near the bank or too far from the point of draw-off or at a depth above or below the point of draw-off. Areas of relative stagnation in a stream should be avoided.

Sample from a river, stream, lake, or a reservoir can often be taken by holding the bottle in the hand near its base and plunging its neck downward, below the surface. The bottle should then be turned until the neck points slightly upward, the mouth being directed against the current. If no current exists, as in a reservoir, a current should be artificially created by pushing the bottle horizontally forward in a direction away from the hand. If it is not possible to collect samples from this situation, in this way, a weight may be attached to the base of the bottle which can then be lowered into the water. In any case, damage to the bank must be guarded against, as otherwise fouling of the water can occur. Special apparatus which permits mechanical removal of the stopper of the bottle below the surface is required to collect samples from the depths of a lake or a reservoir. If the sample is to be taken from a well, fitted with a hand-pump, water should be pumped to waste for four to five minutes before the sample is collected. If the well is fitted with a mechanical pump, the sample should be collected from a tap on the discharge end. If there is no pumping machinery, the sample can be collected directly from the well by means of a sterilized bottle attached with a weight at the base. In this case, care should be taken to avoid contamination of the sample by any surface scum. Where it is not possible to collect the sample directly into the bottles as for example where there is a high bank, the sample may be obtained by means of suitable metal jug. The jug is sterilized by pouring into it 3 to 5 ml of methylated spirit and tilting the jug in such a way that the spirit comes in contact with the entire inner surface of the jug and igniting. The jug should be lowered to the required depth and then drawn up and down two or three times before it is brought to the surface. It should be rinsed out atleast twice before the sample is taken. Should the jug come in contact with the bottom or skid along the surface so that it may have collected the surface film, the sample should be discarded, the jug resterilized and another sample drawn. The water from the jug should be poured into the bottle and the glass stopper of the bottle be replaced, care being taken to avoid the cover being caught between the stopper and the neck of the bottle.

15.3.2.4 Size Of The Sample

The volume of the sample should be sufficient for carrying out all the tests required and in no case, it should be less than 250 ml.

15.3.2.5 Preservation And Storage

Water samples should be examined immediately after collection. However, this is seldom practical and hence it is recommended that the samples should be preferably analyzed within one hour after collection and in no case this time should exceed 24 hours. During transit, the temperature of the sample should be maintained as close as possible to that of the source of the sample, at the time of sampling. The time and temperature of storage of all samples should be recorded since they will be considered in the interpretation of the laboratory results. If they can not be analyzed within 24 hours, the samples must be preserved in ice until analysis. No sample is fit for bacteriological analysis after 72 hours.

15.3.3 Sampling for Biological Analysis

For this purpose, two samples should be collected in clean two litre wide mouthed bottles with a glass stopper or a bakelite screw cap.

In making this collection, the bottle, after the stopper is removed, is thrust as far as possible mouth downward into the water. It is then inverted and allowed to fill.

One bottle is to be stoppered as such. To another bottle, add 5 ml of commercial formalin for every 100 ml of water sample immediately after collection. Both the bottles would be despatched with the label on the sample stating the one with formalin.

If two litres of samples could not be collected, even 200 ml of the sample may be collected as above and formalin added to one sample (10 ml of formalin added to 200 ml of water.)

15.3.4 Frequency of Sampling

The frequency of collection of samples for chemical analysis depends on the variability of the quality of tested water, the types of treatment processes used and other local factors.

Samples for general systematic chemical examination should be collected atleast once every three months in supplies serving more than 50,000 inhabitants and atleast twice a year on supplies upto 50,000 inhabitants. More frequent sampling for chemical examination may be required for the control of water treatment processes.

It is necessary to collect samples of both raw and treated water for examination of toxic substances atleast every three months and more frequently when subtolerance levels of toxic substances are known to be generally present in the source of supply or where such potential pollution exists.

For bacteriological sampling, which controls the safety of supply to the consumer, the frequency of sampling and the location of sampling points at pumping stations, treatment plants, reservoirs and booster pumping stations, as well as the distribution system, should be such as to enable a proper evaluation of the bacteriological quality of the entire water supply.

The minimum number of samples to be collected from a distribution system should be as prescribed in Table 15.1.

The samples should be taken from the different points on each occasion to enable overall assessment.

In the event of an epidemic or immediate danger of pollution, it should be borne in mind that much more frequent bacteriological examination will be required than the recommended minimum frequencies for routine bacteriological examination.

For biological examinations, where seasonal growth of plankton are known to be a regular occurrence, samples may need to be taken at weekly or even shorter intervals, in order to determine the type of treatment. During treatment operations, samples for examination would need to be taken at short intervals, probably daily. When growth of plankton is not anticipated, samples should be drawn on a monthly or less frequent basis. Greater frequencies, determined by experience may be needed in tracing possible entrance of pollution into water sources or more particularly into distribution systems.

TABLE 15.1

MINIMUM SAMPLING FRE-QUENCY AND NUMBERS FROM DISTRIBUTION SYSTEM

Population Served	Maximum Intervals between successive sampling	Minimum No. of samples to be taken from entire distribution system
Upto 20,000	One month	One sample per 5,000 of population per month
20,000-50,000	Two weeks	
50,001-100,000	Four days	
More than 100,000	One day	One sample per 10,000 of population per month.

15.4 STANDARD TESTS

The standard tests that are employed in the analysis of water are as follows:

15.4.1 PHYSICAL EXAMINATION

The parameters tested are temperature turbidity, colour, taste and odour,

15.4.2 CHEMICAL EXAMINATION

(a) This includes tests for consistency and characteristics of water that affect the health of the consumers and the potability of water, viz. pH, acidity, alkalinity, hardness, calcium, magnesium, iron, manganese, copper, zinc, aluminium, sulphates, fluorides, chlorides, nitrates, total dissolved, and suspended solids.

(b) Tests for efficacy of treatment, viz., chlorine demand, free and combined residual chlorine, coagulant dosage.

(c) Tests for chemical parameters which are indicators of pollution such as total nitrogen and nitrogen in various forms like ammonia, nitrite and nitrate, phosphate, dissolved oxygen and BOD.

(d) Tests for toxic chemical substances-lead, arsenic, mercury, selenium, chromium, cyanide, phenolics, pesticides and hydrocarbons and

(e) Test for radio-activity

15.4.3 Bacteriological Examination

Microscopic tests for identification and enumeration of microorganisms other than bacteria are included in this category.

15.4.4 Schedule of Tests

The schedule of laboratory tests followed by a particular undertaking will vary with the size of the plant and character of water treated, though for ordinary plants the minimum schedule should include turbidity, colour, alkalinity, pH, hardness, residual chlorine, bacterial count at 37^0C and coilform bacterial numbers, both presumptive and confirmed.

Occasionally special tests may be necessary such as residual alum, iron and manganese, taste and colour and other undesirable constituents of finished water. Where prechlorination is practised, residual chlorine should be tested at each major stage of treatment. Chlorine demand tests should be carried out in raw water.

15.5 METHODS OF EXAMINATION

The physical, chemical, bacteriological and biological procedures for the analytical laboratory examinations given in the Manual of methods for the Examination of Water, Sewage and industrial Wastes published by the Indian Council of Medical Research, are to be followed. For procedures regarding trace and other elements not covered by the ICMR, the procedures recommended in Standard Methods for the Examination of Water and Waste water prepared and published by American Public Health Association, American Water Works Association and Water Pollution Control Fedration are to be followed.

Conformity to standard analytical methods is important if the results of tests carried out by different laboratories are to be meaningful.

15.5.1 Reporting of Results

Specimen forms for reporting results of a short chemical examination, a complete chemical examination and bacteriological examination of water are given in Appendices 15.5 and 15.6. For purposes of uniformity, standard expressions should be used and this should be clearly stated in the report.

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15.6 LABORATORY EQUIPMENT AND FACILITIES

A well equipped laboratory is a prerequisite for efficient analytical control. The size and equipment of the laboratory depends more upon the nature of the processes to be controlled and to a lesser extent on the size of the plant. The laboratory could be divided into several units; viz. a physical and chemical laboratory, a bacteriological laboratory, a biological laboratory, a preparation room and a store. For a small plant, the various units could be combined into one laboratory.

15.6.1 RECOMMENDED MINIMUM TESTS AND EQUIPMENT

It is necessary that all waterworks should be provided with the equipment and facilities for tests mentioned in Appendices 15.7, 15.8 and 15.9.

The lists provide for the categories of water works:

Category I is applicable to all State laboratories and for large water works with an output greater than 7.5 mld or serving a population larger than 100,000 and dealing with polluted surface water and practising coagulation, filtration and post chlorination. Such laboratories would be equipped for conducting complete chemical, bacteriological and biological tests. It is expected that such laboratories may also undertake simple research problems, stream sanitation studies and other investigations and will assist the smaller laboratories in their vicinity by supplying standard solutions and providing guidance.

Category II is applicable to the water works with an out put upto 7.5 mld or serving a population upto 100,000 and when the water is coagulated, filtered and chlorinated. The tests laid down are routine chemical and bacteriological examinations only. Thus, the bacteriological procedure would consist of the presumptive test for coilform organisms followed by confirmation (in the case of finished water only) by the use of liquid broth. Isolations on solid media and differentiation of coliforms into feacal and non feacal forms, if is felt necessary, may be carried out by sending samples to a suitable laboratory with this facility.

Category III is applicable to all other water works, mostly with the only treatment of storage or settlement followed by chlorination. They should be equipped for routine chemical tests included under category II. The bacteriological examinations necessary may be undertaken by the nearest available large laboratory.

The expression, parts per million (ppm), still used to express chemical concentrations, should be replaced by milligrams per litre (mg/l), which is much more appropriate, unless there is a special need to use some other chemical concentration unit like 'millequivalents per litre' (me/l) or microgram per litre (μ/l). The expression me/l facilitates the summation of several anions or cations responsible for imparting a particular characteristic to the water like hardness.

Volumes are expressed in milliliters (ml) and temperatures in degree centigrade (0^0C). The total number of micro-organisms developing on solid media should be given in significant numbers per ml of water, the medium, time and temperature of incubation being stated. The

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number of coliform organisms and other organisms indicative of pollution should be expressed in terms of "Most Probable Number" (MPN) per 100 ml or as a determined number obtained by direct plating procedures. In biological examinations, the concentration of organisms per ml of sample is expressed in many instances as a simple numerical count. Occasionally the results are expressed in mg/l , but more usually in terms of area standard units or volumetric standard units.

Reporting analytical results of a particular examination should include the proper use of significant digits and the expression of confidence limits, where appropriate.

15.6.2 FACILITIES

The working benches should be of suitable height (o.75 to 1 m) with acid resistant tops. Adequate gas, electric power and water points must be provided along the benches and services for gas, electricity and water can be fitted against the walls, under the bench work, as much cupboard space as possible should be built-in, finishing flush to the bench work, thus providing unobstructed floor space throughout. There should be ample sinks and drain lines. The analytical work in the laboratory requires provision of ample window space and fluorescent artificial lighting. A minimum area of 150 m^2 is required for category I laboratories, a minimum of 50 m^2 being sufficient for other categories.

15.6.3 EQUIPMENT

The equipment in the laboratory must be adequate to permit proper analytical laboratory control of purification processes. Careful planning is necessary while equipping the laboratory to effect proper utilization of the equipment. Proper maintenance of equipment and storage of chemicals must be in the hands of responsible analysts. A needbased planning to acquire consumable materials like glassware, chemicals and reagent is in general more important than the procurement of various special equipments. Calibrated instruments should frequently be checked using standards.

15.7 RECORDS

A continuing programme of examination of water and controlling its quality to determine its conformity with established water quality standards calls for proper maintenance of accurate and complete records. These records are essential for a review of the working of the plant and also for adequate and intelligent operation of water works processes and for laboratory activities.

All details of actual specific determinations, burette readings, weights and calculations should be recorded. These information should, of course, remain as laboratory records and only the final result should be reported. This makes all laboratory data available at any time for review any important factor when unusual findings are called to attention.

Depending upon the specific needs of the laboratory forms and cards could be designed providing spaces for entering the data and for calculations. Monthly reports may be in single sheets and annual reports may be furnished in two sheets grouping physical and chemical data on one sheet and bacteriological and biological data on the other.

Representation of data collected over a period of time by means of charts and graphs makes it an easy and useful study for the staff and visitors.

15.8 LABORATORY PERSONNEL

Laboratory personnel must be qualified and suitably trained in laboratory control. Water analysts with sufficient experience in treatments and quality control may be kept in charge of the laboratory.

The minimum staff required for water works laboratories is given in Appendix 15.1. The recommended minimum staff required for water works laboratories for groundwater source is presented in Appendices 13.6 and 13.7

CHAPTER 16
COMPUTER AIDED OPTIMAL DESIGN OF WATER TREATMENT SYSTEM

16.1 GENERAL

The unit processes in conventional water treatment include coagulation-flocculation, gravity separation, sand filtration and disinfection. The individual units in the treatment train are usually designed based on the norms recommended in the Manual. These design, when implemented, may give satisfactory level of performance but not necessarily be optimal, both functionally and costwise, The performance of each treatment unit affects the efficiency of the subsequent units. However, decisions are often made with no regard to the interacting nature of the various unit operations and the treatment systems are designed on individual unit basis. This is largely due to the non-availability of appropriate Operations Research (OR) tools for total system analysis to enable development of designs which will produce potable water of specified quality at minimum cost. This chapter presents an approach to the computer aided functional and minimal cost design of water treatment systems.

16.2 DYNAMIC PROGRAMMING

16.2.1 CONCEPT

A conventional water treatment system shown schematically in Fig. 16.1 favours application of Dynamic Programming (DP) for minimal cost design and it is a technique useful in solving sequential decision problems, each decision influencing the subsequent decision (s). The main advantage of dynamic programming is the reduction of efforts required to find optimum. Dynamic Programming is a simple procedure from computational point of view, and one which can treat non-convex non-linear, discontinuous objective and constraint functions. Since it is an iterative procedure, a relatively small number of computer instructions is required. Further constraints imposed on system reduce the number of feasible solutions and therefore time required to establish the optimal policy. Other advantages of DP are with respect to availability of feasible solutions with costs and hence selection of most acceptable optimal solution based on site conditions.

Dynamic Programming can generally be applied to any system with multi-decision problems. The system is broken into stages. The stages may be unit processes with inter relationships and each stage having only a few variables. In such an analysis, each stage is characterized in terms of four factors as depicted in Fig. 16.2.

1. The input state 'Sn' which depends on decisions made in the previous stages and/or on fixed external conditions.

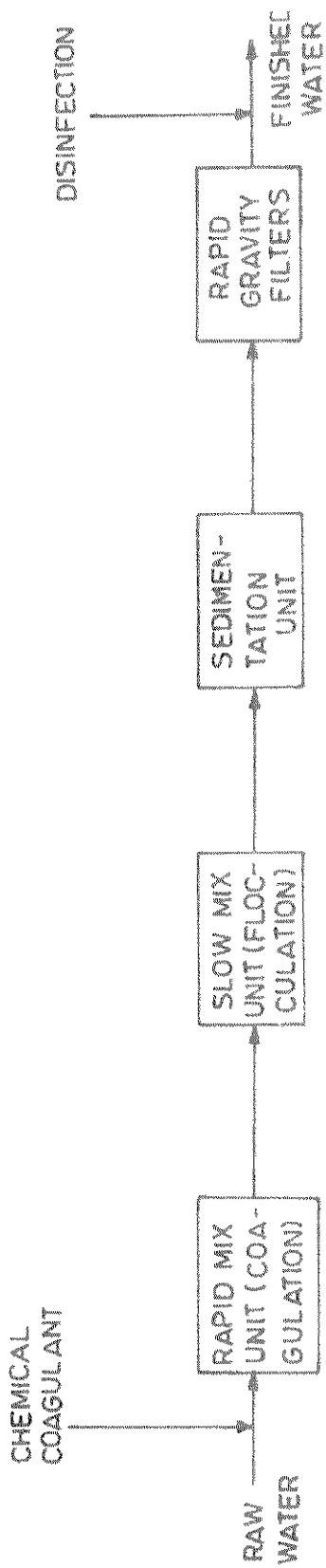

FIGURE 16.1: CONVENTIONAL WATER TREATMENT SYSTEM-SCHEMATIC

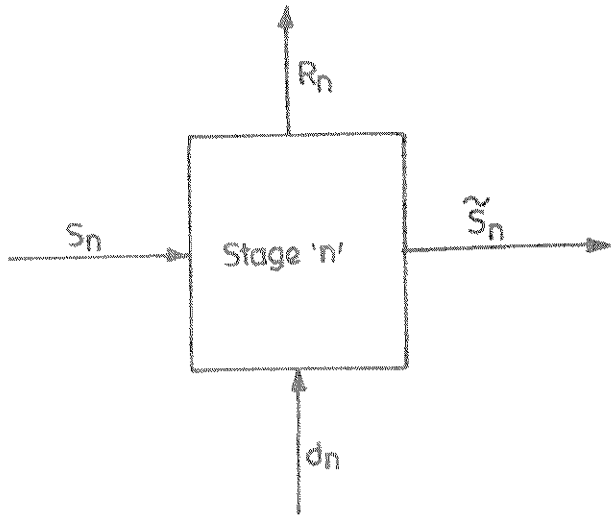

FIGURE 16.2: FUNCTIONAL DIAGRAM OF DYNAMIC PROGRAMMING

2. Decision 'dn' which fixes the design and/or operating conditions of the stage.

3. The output state '$\overline{Sn}$' which depends on Sn and dn, i.e., '$\overline{Sn}$' = ϕn (Sn,dn), and
4. The stage return, 'Rn' which is dependent on Sn, dn and '$\overline{Sn}$' i.e., Rn = gn (Sn, dn, '$\overline{Sn}$')

16.3 APPLICATION TO WATER TREATMENT SYSTEM DESIGN

Water treatment system can be considered as a multistage process with stages represented by various unit processes, viz. coagulation-flocculation, sedimentation, and rapid gravity filtration; and states represented by the levels of water quality parameters like turbidity or suspended solids. The decision variables would be the design parameters depending on the type of unit process, i.e. stage. The information flow diagram showing the sequence of stages; input, decision and output variables for each stage and the stage return for each input-decision combination is shown in Fig. 16.3. The range of design variables, for conventional treatment units, as summarised from the earlier chapters of the Manual are given in Table 16.1.

In order to optimize the system logically and methodically, a thorough knowledge of the major variables of all the unit processes and their influence on performance and cost of the subsequent units is necessary. Further, information on the process models relating the design variables to the behaviour of the systems and cost models for the individual treatment units is essential. These enable the formulation of an objective function and constraints enabling solution of optimization problems through Dynamic Programming.

16.4 PERFORMANCE MODELS

16.4.1 RAPID MIX UNIT

The rapid mix unit is an an adjunct to the flocculator and hence is not modelled separately for its functionality and should be designed as per the norms recommended in the Manual. Its performance is expected to be satisfactory when the appropriate coagulant dose is applied.

TABLE 16.1
RANGE OF MAJOR DESIGN VARIABLES FOR WATER TREATMENT PLANTS

Sl. No.	System Component	Design Variable	Range
1.	Rapid Mix Unit	Velocity Gradient	300 to 900 Sec^{-1}
		Detention Time	20 to 60 Sec
2.	Slow Mix Unit	Velocity Gradient	10 to 75 Sec^{-1}
		Detention Time	10 to 40 min
3.	Sedimentation Unit	Surface Overflow Rate	1.25 to 1.66 $m.hr^{-1}$
4.	Rapid Sand Filter	Filtration Rate	4.8 to 6.0 $m.hr^{-1}$

Assuming that SS_4 is the raw suspended solids concentration, pH and alkalinity of raw water are within the desirable range for effective coagulation and that all Al(III) is precipitated as $Al(OH)_3$, the mass balance, then leads to:

$$SS_4 + KA = '\overline{SS_4}' \qquad (16.1)$$

Where KA = suspended solids in mg/l due to the addition of A mg/1 of coagulant;

(K = 0.247 for $Al_2(SO)_3$. 16 H_2O based on stoichiometry)

$'\overline{SS_4}'$ = suspended solids concentration in mg/1 in the effluent from rapid mix unit.

It is generally accepted that the principle design parameters of rapid mix are velocity gradient (Gr) and duration of mixing (Tr), although chemical factors such as pH and alkalinity of water to be treated also influence the process of coagulation-flocculation. The intensity of agitation is expressed in terms of power input or the velocity gradient. The value of G_r. T_r, has been assumed as 1. 8 x 10^4.

16.4.2 Slow Mix (Flocculation Unit)

The flocculation should be designed to generate particle aggregates such that the settleability and filterability of the suspension are improved. The important attributes in the settling are the floc size, density and viscosity of water. The effluent from the rapid mix unit is the influent to the flocculation unit. Assuming that no settlement of floc particles occurs in the flocculation basin, then the concentration of suspended solids in the effluent would remain unchanged.

Hence,

$$'\overline{SS_4}' = SS_3 = '\overline{SS_3}' \qquad (16.2)$$

Where SS_3 = suspended solids concentration in the influent to the flocculation unit.

$'\overline{SS_3}'$ = suspended solids concentration in the effluent from the flocculation unit.

Although the mass of suspended solids remains unchanged in the process of flocculation, the size of floc particles is increased due to interparticle contact brought about by the applied velocity gradient. The size of floc aggregates thus formed is related to the velocity gradient as under:

$$d = a\ G^b \qquad (16.3)$$

Where, d = volume average diameter of the floc, mm

G = applied velocity gradient, S^{-1}

'a' is a constant and 'b' is an exponent, the values of which can be determined experimentally.

For this recommended range of velocity gradient, the following relationship has been developed for alum floc.

$$d = 26.88\ G^{-0.91} \qquad (16.4)$$

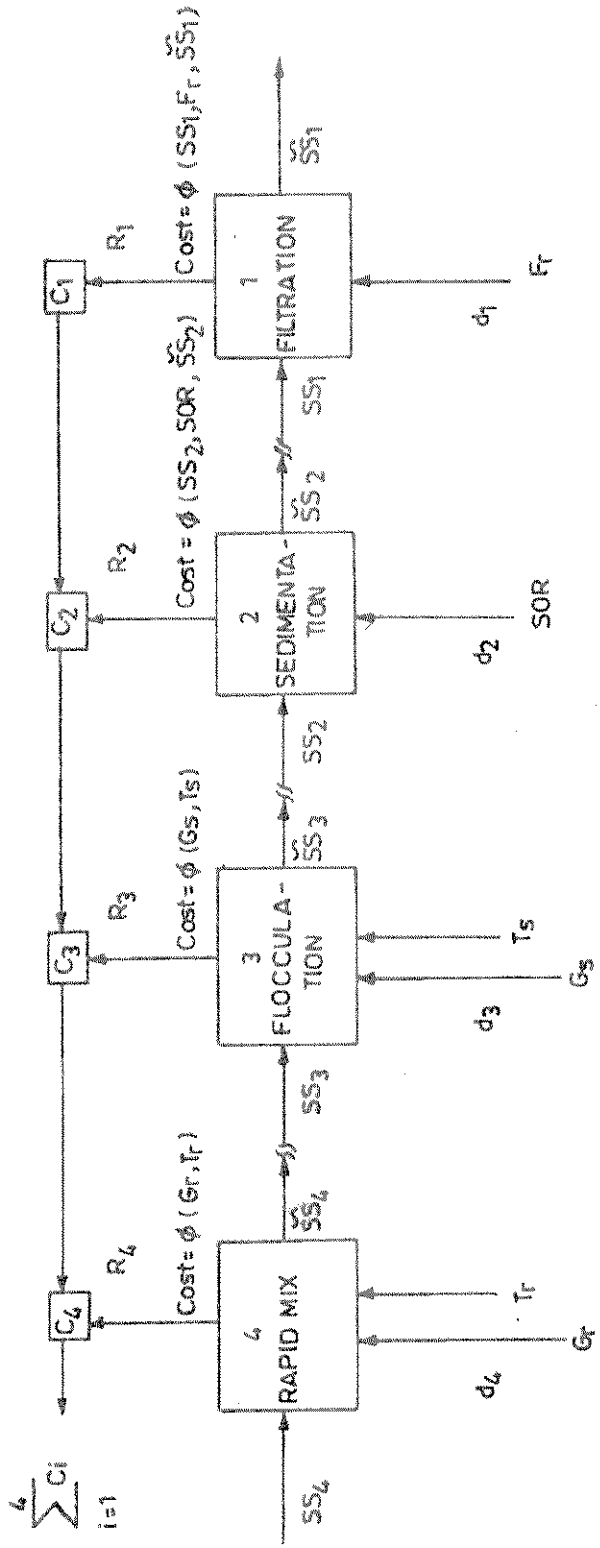

FIGURE 16.3: INFORMATION FLOW DIAGRAM FOR WATER TREATMENT PROCESS

In the derivation of the above relationship, it is assumed that the velocity gradient is uniform and constant in the flocculation unit.

The currently accepted criteria for design of slow mix unit are based on the concept that performance is a linear function of "Gs" and "Ts" which are independent and hence their dimensionless product "Gs.Ts" is regarded as the most significant parameter. The value of Gs . Ts in the range 2 to 4 x 10^4 has been assumed.

16.4.3 SEDIMENTATION UNIT

Efficiency of settling is primarily governed by the size and density of floc particles and the settling basins are designed on the basis of surface overflow rate which is related to the settling velocity of the suspended particles. It is presumed that floc aggregation is complete in the flocculator itself and that any further agglomeration during settling is insignificant. For Reynolds number less than 1, the settling velocity can be estimated using well known Stock's equation given below:

$$V_s = \frac{g}{18}(S_s - 1)\frac{d^2}{\nu} \qquad (16.5)$$

Where,

V_s = settling velocity of floc particles, m/s

g = acceleration due to gravity, m/s^2

S_s = specific gravity of floc particles

d = volume average diameter of floc, m

ν = Kinetic Viscosity, m^2/s

For floc particles of size larger than 1mm, the Reynold's number exceeds 1 and the Stoke's law is not applicable. In such cases and for Reynold's number upto 50, the settling velocity can be estimated using Hazen's Equation:

$$V_s = \frac{g^{0.8}}{10}(S_s - 1)^{0.8}\frac{d^{1.4}}{\upsilon^{0.6}} \qquad (16.6)$$

For an ideal sedimentation tank, surface overflow rate represents the settling velocity of particles which are removed 100 percent. However, in practice, the efficiency of the basin is reduced due to various factors such as currents induced by inertia of the incoming water, turbulent flow, wind, density and temperature gradients, etc. which result in short circuiting of the flow. Mathematically the efficiency of suspended particles removal is expressed as:

$$\frac{SS_2 - \overline{SS_2}}{SS_2} = 1 - \left[1 + n\frac{V_s}{\left(Q/A\right)}\right]^{-1/n} \qquad (16.7)$$

where,

$\frac{SS_2 - \overline{SS_2}}{SS_2}$ = suspended solids removal efficiency

n = coefficient that identifies basin performance

V_s = surface overflow rate for ideal basin

Q/A = required surface overflow rate to achieve the desired efficiency.

the value of n is assumed '0' for best possible performance, '1/8' for very good performance, '1/4' for good performance, '1/2' for poor performance and '1' for very poor performance.

A well designed sedimentation basin, irrespective of the influent suspension concentration, should produce a settled water of turbidity less than 20 NTU or suspended solids less than 50 mg/l.

16.4.4 Rapid Sand Filtration

Filtration is an important step in the solids removal chain. Mathematical formulations presented by most of the researchers for predicting filter performance have limitation. In the development of models, some idealised assumptions are made with regard to the nature of suspension which often deviate significantly from real life situations. Also these models do not eliminate the need for some empirical constants. A method has been proposed for prediction of filter performance and demonstrated its usefulness for a variety of suspensions using different chemical coagulants and filter media. It was observed that the removal of particles per unit depth through a filter bed is quite similar to the Chi-square probability distribution. The variate 'U' of this distribution is considered a measure of the clogging process and is related to the filtration data as follows:

The ratio of concentration at any time 't' and sand depth 'L' to the influent concentration is equated to the cumulative probability 'P,' in the Chi-square distribution, i.e.

$$\frac{SS_1 - \overline{SS_1}}{SS_1} = P_c \qquad (16.8)$$

The filtration time 't' in hours is equated to the degrees of freedom 'v', i.e. 1 hr = 1 degree of freedom.

The variables such as filtration rate, diameter of sand grain and the filter run time are grouped into a single term 'G' as under:

$$G = 0.725\ F_r^{0.29}\ d^{0.62}\ t \qquad (16.9)$$

Where,

F_r = filtration rate, m/hr

d = 0.5 (ES) (1 + UC), mm

t = filter run time, hrs.

Similarly the variables headloss at time 't', sand size, filtration rate and the filter influent suspension concentration have been grouped in to a single term 'R' :

$$R = \frac{4.55 d^{2.5} H}{F_r^{1.2} SS_1} \tag{16.10}$$

Where,

H = increase in headloss at the end of `t`, m

SS_1 = influent suspension concentration , mg/1

From the above two group terms, the performance prediction models developed as under:

$$\log\left(\frac{U}{13.3L}\right) = -0.208 + 1.950 \log\left[\frac{G}{(13.3L)^{1.2}}\right] - 0.645\left[\log \frac{G}{(13.3L)^{1.2}}\right]^2 \tag{16.11}$$

$$\log\left(\frac{R}{(13.3L)^{1.6}}\right) = -3.250 + 1.013 \log\left[\frac{G}{(13.3L)^{1.2}}\right] - 0.036\left[\log \frac{G}{(13.3L)^{1.2}}\right]^2 \tag{16.12}$$

From the value of variable 'U' obtained from above relationships, the probability `$P_C$` (which can be expressed as removal efficiency $\left(\frac{SS_1 - \overline{SS_1}}{SS_1}\right) = P_e$ could be read from the cumulative table of Chi-square distribution or computed mathematically using the expression:

$$P_C = \sum_{J=0}^{(t/2)-1} \frac{e(-U/2)(U/2)^J}{LJ} \tag{16.13}$$

Using the above functional relationships, the filter performance can be predicted for various combinations of influent suspended solids concentrations (SS_1), size of filter sand (d), filtration rate (Fr), depth of filter bed (L), length of filter run (t), filtrate quality $\overline{SS_1}$ and headloss (H). A properly designed rapid sand filter should be capable of producing a filtered water with turbidity of less than 1 NTU or SS concentration less than 2 mg/l.

16.4.5 DISINFECTION

Treatment processes such as coagulation flocculation, sedimentation and rapid sand filtration reduce to varying degrees the bacterial content of water. However, they do not necessarily always produce a water safe from bacteriological point of view. Terminal disinfection is, therefore, essential to ensure bacteriological safety of the finished water. Chlorine and chlorine compounds are commonly used for disinfection in India. The dose of chlorine depends on the quality of the filtered water. If the filtrate turbidity is consistently less than 1 NTU, the chlorine dose required may remain more or less uniform.

16.5 COST MODELS

The cost of the water treatment system includes costs of rapid mix unit, slow mix unit, sedimentation tank and rapid sand filters. These costs (civil, mechanical and electrical) depend on the size(s) of the individual treatment units adopted. While civil cost mainly includes cost of construction, the mechanical and electrical costs, relate to the equipments and accessories necessary for effective operation of the treatment units. These costs include the costs of turbine agitator/flocculating propeller, motor and gear assembly etc. for rapid and slow mix (flocculation) units, costs of scraper bridge, end carriage drive, traction drive unit for circular clarifier and the costs of appurtenances such as rate setter, rate of flow controller, flow indicator, headloss indicator, air-blower, backwash water pump etc. for rapid gravity filters. The costs can be modeled separately for individual treatment units and expressed in the functional form as under:

Cost = f (surface area or volume or diameter)

For a given design flow, the costs of other components of water works such as raw water pumps, transmission mains, clear water reservoir, disinfection, clear water pumps etc., as also the manpower component would remain the same irrespective of variation in the size(s) of the treatment units and therefore are not considered in the economic analysis.

16.6 PROBLEM FORMULATION

There could be a number of designs which would satisfy the product quality standards prescribed in the Manual. The objective, therefore, should be to minimize the system cost satisfying all the constraints. A rational comparison of various feasible designs should be based on the capitalized cost or total annual cost of the system. Hence, the objective function will be:

$$\text{minimize } Z, \quad Z = \sum_{i=1}^{4} Ci \tag{16.14}$$

Where,

Ci = annual cost (AC) of individual treatment unit

AC = ACC + DCW + DMEQ + ENERGY

Where,

ACC = annualized capital cost

DCW = annual maintenance cost of civil works

DMEQ = annual maintenance cost of mechanical equipments/ machinery

energy = annual energy cost

$$ACC = CC \frac{(1+r)^n r}{(1+r)^{n-1}}$$

Where,

CC = Capital cost, i.e. cost (both civil and mechanical) of the treatment unit

r = rate of interest

n = number of years over which the capital cost is to be repaid

CONSTRAINTS

- Suspended solids concentration in the effluent from clarifier $\leq$ 50 mg/l
- Suspend solids concentration in the filtered water $\leq$ 2 mg/l
- Diameter of clarifier $\leq$ 60 m
- Detention time, DT in clarifier $2 < DT < 4$ hrs
- Weir loading rate < 600 $m^3/m/d$
- Length of filter run $\geq$ 24 hrs.
- Maximum headloss in the filter bed $\leq$ 2m.

SOLUTION

A flow chart for computer aided functional and minimum cost design of water treatment system is presented in Fig. 16.4. The major inputs required are:

(i) Design data on input, decision and state variables and step length

(ii) Data for formulating the cost models for treatment units.