IRRIGATION WATER RESOURCES

1.1 Irrigation

Irrigation is generally defined as "the manual or artificial application of water to soil for the purpose of supplying moisture essential for plant growth". However, in the broader sense, it may be defined as the application of water to the soil for any number of the following purposes:

1. To supply the moisture essential for plant growth,
2. To transport nutrients from soil to the plant,
3. To provide crop insurance against short duration droughts,
4. To cool the soil and the atmosphere, thereby making more favorable environment for plant growth.
5. To protect the crop from hazard of frost.
6. To washout or dilute salts in the rootzone of soil,
7. To soften tillage pan and clods for facilitating seed bed preparation and planting operation
8. To encourage plant root development.

1.2 Importance of Irrigation

Under arid and semi-arid climatic conditions of Pakistan where average annual rainfall is 10–14 inches against a potential demand of about 70 inches of water for agriculture, irrigation is considered essential. Increasing pressure of population demands increased crop production. This necessitates multiple cropping and better use of fertilizers and crop varieties which cannot be practiced without providing requisite irrigation water.

1.3 Sources of Irrigation Water

Primarily there are three sources of irrigation water in Pakistan, namely, surface water (canal water), ground water and rainfall.

1.3.1 Surface Water

The major sources of surface water in the Indus Basin are the snowmelts and precipitation, over the mountainous region. Runoff water through streams and rivers is stored in reservoirs or is diverted directly through canal systems to the fields for irrigation. In Pakistan, the surface water resources as a result of Indus Water Treaty that was implemented in 1960, are now limited to the waters of Indus, Jhelum and Chenab. Since, Pakistan has been deprived of eastern rivers namely, Ravi and Sutlej, water from western rivers has been diverted to eastern rivers through link canals to supply water to the areas previously irrigated by Ravi and Sutlej.

The irrigation system of the Indus Basin comprises rivers, dams, main canals that supply water to a net work of branch canals, distributaries, minors, watercourses and field channels. The irrigation system of Pakistan is shown in the map (Fig-1). According to IIMI (1995), the total annual flow into the river system of the Indus Basin is estimated to be 139 maf, out of which 104 maf is diverted to the canal irrigation system. A significant portion is lost through conveyance system (canals, distributaries, minors and watercourses) allowing only 43 maf at field inlet and 31 maf for crop use in the field as shown in Fig-2.

About 84 percent of the total annual river flow occur during kharif season and about 16 percent during Rabi season giving a Rabi:Kharif ratio of 1:5.2. The crop water requirements on the other hand occur at the ratio of 3:5 between Rabi and Kharif . Thus there exists incompatibility between the water availability and requirements, which is regulated through managed releases from dams and reservoirs. Presently, there are 3 major reservoirs in Pakistan namely, Tarbela, Mangla and Chashma having a tota capacity of about 16 maf. An estimated annual flow of 35 maf doe not become part of the canal irrigation system and escapes to th sea unused. Out of this, 10 maf are claimed to be required f harbor development and fish culture. The remaining 25 maf can b beneficially conserved and stored in proposed storage dams su as kalabagh, Bhasha and Dhasu etc. Development of stora reservoirs is the prime need of the country to overcome the defic particularly during winter season.

1.3.2 Groundwater

The groundwater has been in use since ancient times. Groundwater, which meets about 40 to 50 percent of the irrigation water requirements, is obtained by pumping water from ground (aquifer). Pakistan is very fortunate to possess a rich source of groundwater. According to the Planning Division (1990), about 48.5 maf are being pumped for use on agricultural lands, for human consumption and industrial uses. Presently, in the Indus Basin, about 500,000 private tubewells and about 2500 public tubewells including SCARP tubewells are pumping groundwater to supplement surface water supplies. Historically on the average, about 10,000 tubewells have been added to the system annually. According to IIMI (1995), the public and private tubewells contributed about 44 maf at the field outlets, which allowed about 29 maf groundwater contribution for crop use (Fig-2)

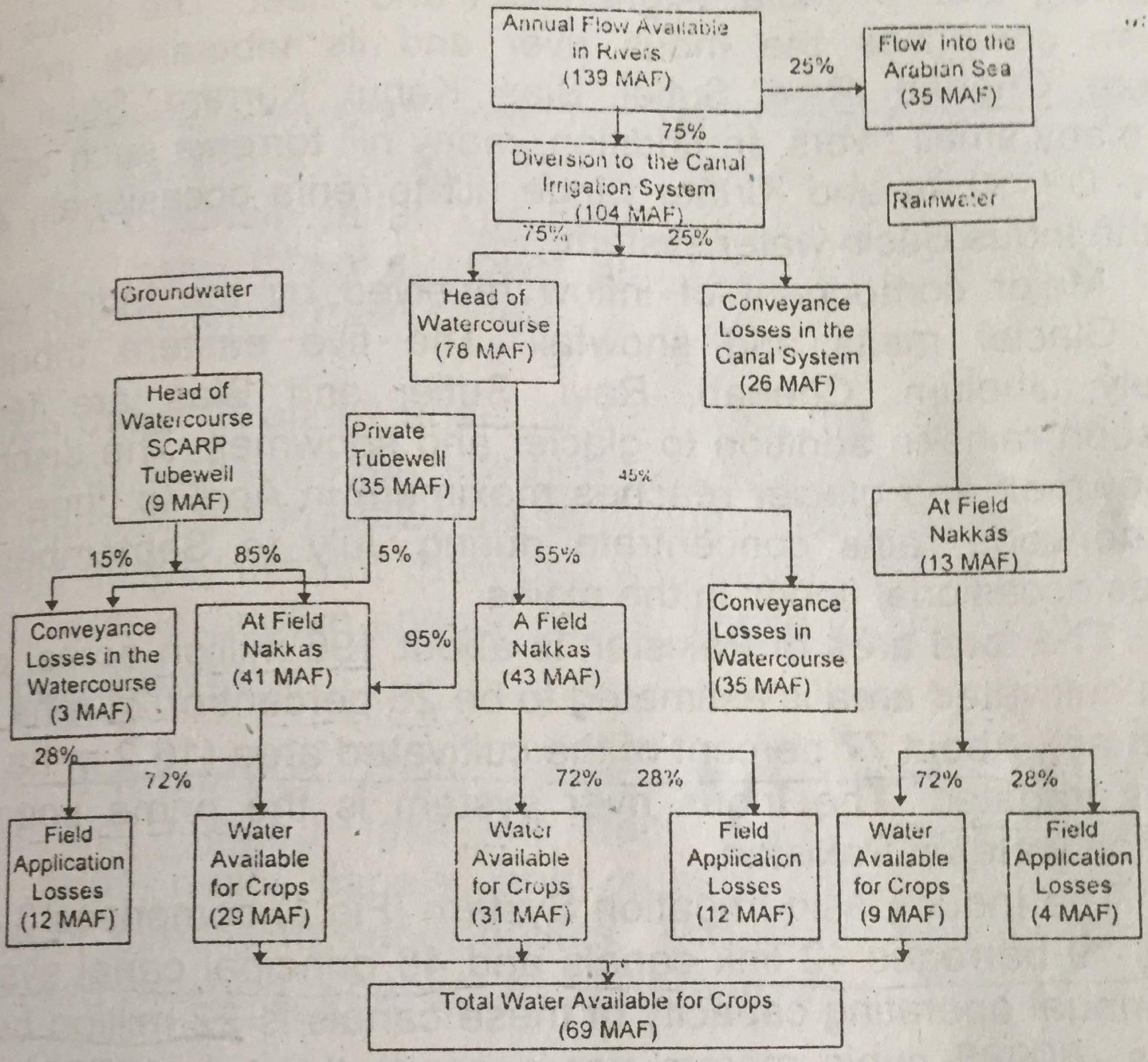
1.3.3 Rainfall

The third major source of water is rainfall, which is neither sufficient nor reliable. Practically whole of the Pakistan lies in arid to semi arid zone. The annual rainfall over the Indus Basin varies from 5 to 14 inches in plains and above 20 inches in the northern areas. The rainfall zones can be roughly described as under.

Table 1. Areal distribution of rainfall zones in Pakistan

Rainfall Zone	Percent of land	Average annual rainfall
(Arid)	67	Less than 10"
(Semi-arid)	24	(10-20)"
(Humid)	5.5	(20-30)"
(Para humid, very wet)	3.5	30"

Annually about 9 maf net rainfall is estimated to reach the irrigation system for crop use. This makes a total of 69 maf which meets only 64 % of the annual requirements from all sources.



Source: Paki‿an National Conservation Strategy, 1993:37.

Fig. 2 Flow Chart of Indus Basin Irrigation Syste

1.4 Indus Basin Irrigation System

The total watershed area of the Indus Basin is 944000 square kilometers. Out of this, 16 percent area lies in Pakistan and remaining area in India, Afghanistan and Tibet. The Indus river system comprises the Indus river and its tributaries including Jhelum, Chenab, Ravi, Sutlej, Bias, Kabul, Kurram, Soan, Haro and many small rivers. In addition, many hill torrents such as D.G. Khan, D.I. Khan and Kirther range hill torrents occasionally drain into the Indus Basin water system.

Major component of inflow received by the Indus comes from Glacier melts and snowfall. The five eastern tributaries namely, Jhelum, Chenab, Ravi, Sutlej and Bias are fed by monsoon rains in addition to glacier and snowmelt. The discharge of snowmelt and glacier reaches maximum in April to June, while the monsoon rains concentrate during July to September that causes occasional floods in the plains.

The total area of Pakistan is about 196 million acres, out of which cultivated area is estimated to be 26 percent or 21 mha (51.8 million ac). About 77 percent of the cultivated area (16.2 m ha or 40 ma) is irrigated. The Indus river system is the prime source of irrigation water in Pakistan.

The Indus Basin Irrigation System (Fig.1) comprises 3 major dams, 19 barrages 12 link canals and 48 principal canal systems. The annual operating capacity of these canals is 22 million hectare meters (60985 cubic meters per second) through 107000 canal outlets or turnouts. The total length of canals and distributaries is about 63000 kilometers. On an average, these canals annually draw about 12.9 million hectare (104 maf) meters at canal heads.

The perennial canal system delivers water throughout the year and commands nearly 8.6 million hectares of cultivable area. The non-perennial canals deliver water only during kharif season and command nearly 5.4 million hectares of land. About 15.2 mha (37.5 ma) of Pand which is about 48.6 % of culturable land, is considered culturable waste. This area is not being cultivated due to shortage of water in the country.

1.5 Components of Irrigation System

The flow line diagram of the Indus Basin Irrigation System (Fig. 3) shows various components of the system as summarized below.

i) **Main Canal:** Main canal takes its supply directly from the river through a dam or a barrage. Direct irrigation is usually not carried out from the main canal. The upper Jhelum, lower Jhelum, upper Chenab, Lower Chenab, Upper Bari Doab and Lower Bari Doab are the examples of main canals.

ii) **Branch Canal:** Branch canals take off from the main canals through diversion structures such as head works and convey water to different parts of the irrigated areas through distributaries. The branch canals usually are not provided with outlets for delivery of water to the fields except in special cases. These include Gugera and Rakh branches etc.

iii) **Major Distributary:** Major distributaries (usually called distributaries or "rajbah") take off from branch canals and sometimes from main canals and supply water to minor distributaries or directly to canal outlets. The examples of major distributaries are Niazbeg, Shahkot and Nasrana etc.

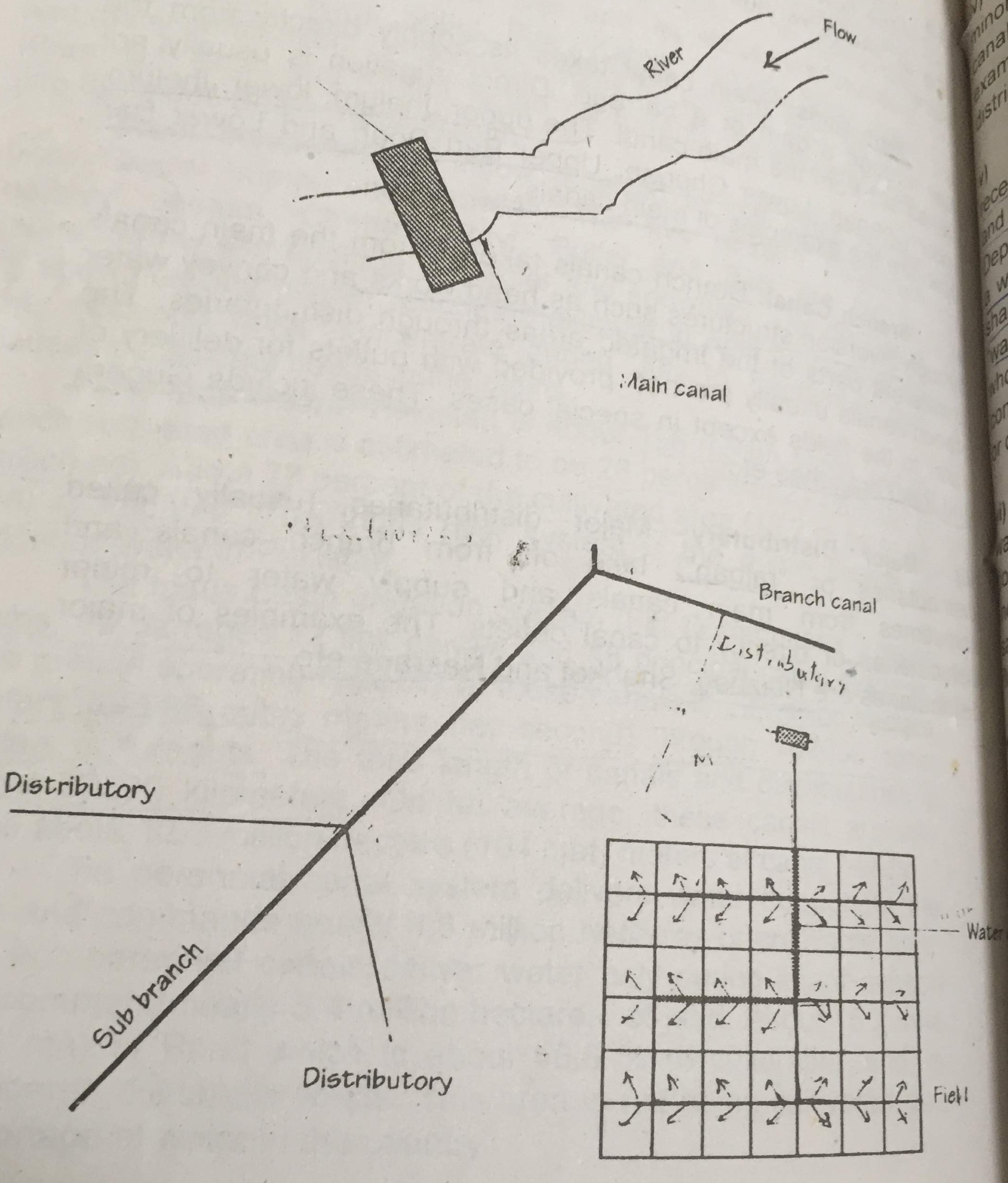


Fig. 3 Components of an irrigation system in the Indus Basin Irrigation sys

iv) **Minor Distributary:** Minor distributaries (usually called minors) take off from major distributaries and rarely from branch canals. These supply water to watercourses for irrigation. As an example, Kamogil minor and Thatti minor are the minor distributaries of Niazbeg distributary.

v) **Watercourse:** A watercourse is defined as any channel that receives water from a canal or distributary and leads to the farms and fields. It is operated and managed by the Provincial Irrigation Department (PID) but maintained by the farmers. On the average, a watercourse commands about 400 acres of land and water is shared by about 50 farmers according to a rotation called "warabandi". Each watercourse receives water from canal outlet whose location and size is approved by the PID. Water flows continuously in a watercourse as long as there is water in the minor or distributary.

vi) **Field Channel:** Field channels or farmer branches carry water to the individual fields from the main watercourse. These are constructed, operated and maintained by the farmers themselves individually or in-groups. Generally, the size of field channels is the same as that of main watercourse because they have to carry full flow received from the main watercourse.

1.6 Irrigation System Management

The irrigation system in Pakistan is primarily managed and operated by the Provisional Govt. At federal level, however, a separate ministry of water and power exists to administrator planning and development of water resources through Water and Power Development Authority (WAPDA). The responsibility of large-scale construction and operation of water resources facilities such as storage dams, barrages, and link canals lies with WAPDA. It is also responsible for planning and execution of groundwater development and management schemes such as Salinity Control and Reclamation Projects (SCARPs). These projects after completion are transferred to the Provisional Irrigation Departments for operation and maintenance. The Provisional Irrigation Department (PID) undertakes construction, operation and maintenance of irrigation facilities extending from barrages downward to main canals and to canal outlets feeding the main watercourses.

The release of water from dams and barrages to main system is controlled by Indus River System Authority (IRSA) and received by the provincial irrigation departments for further operation and maintenance. IRSA also manages to resolve disputes among the provinces pertaining to their share of water.

The irrigation system below canal outlet comprising main watercourses is managed by the Provincial Irrigation Department of Irrigation (PID) but constructed and maintained by the cultivators/ shareholders. PID also administers water distribution and resolution of conflicts among water users. Whenever a distributary is in operation, a watercourse continues receiving an authorized share of discharge at almost constant rate round the clock. (The farmers receive water in accordance with a predetermined water distribution system on weekly or 10.5 days rotation cycle.)

1.7 Warabandi System

(Warabandi (on-farm water distribution system) is a rotational method for equitable distribution of the available water supply in an irrigation channels (main watercourse) by turns fixed according to a predetermined schedule specifying the day, time and duration of supply to each irrigator in proportion to the size of his land holding in the outlet command (Singh 1981 and Malhotra 1982).)

The primary objectives of Warabandi system are high water use efficiency and equity in water distribution. Higher water use efficiency is achieved through the imposition of water scarcity on each farm or share holder's land. The equity in distribution is attempted through supplying equal share of available water per unit holding among all users.

In watercourse command, Warabandi proceeds from head to tail. The rotation time once started continues even when the distributary ceases to deliver water or there is no water in the watercourse. Thus, (each cultivator is entitled to receive the entire water in a watercourse in accordance with his land holding for a predetermined period of time (about 16-20 minutes/acre) on a specific week-day and at a specified time including night time. (There are two major types of) warabandi, i.e., fixed or "pacca" warabandi and flexible or "Kacha" warabandi.

1.7.1 Fixed rotation or pacca warabandi

It is established by the Irrigation Department and provides for each farmer his fixed share of water to irrigate his land.

1.7.2 Flexible Rotation or Kacha Warabandi

In this system, a known amount of water is distributed by the farmers among themselves on the basis of area solely on their mutual agreement without formal involvement of any Govt. agency. As long as the farmer group can amicably and collectively manage the distribution, there is no need for official intervention. However, Kacha warabandi has become increasingly unpopular among majority of the farmers due to unfair exploitation by the influential farmers. Disputes arising in Kacha warabandi are resolved by the irrigation department administration. The Kacha warabandi is still in operation as the preferred method in southern Punjab and province of Sindh because this system favours the large land owner in these areas. In central Punjab, the majority of the watercourse commands have pacca warabandi; administered by the Provincial Irrigation Department.

1.7.3 Problems and constraints of Warabandi

The warabandi system has been in operation for about one hundred years but still there are several unsolved problems pertaining to the design and operation as summarized below:

- 1) A major problem is the conveyance loss in the watercourses, which are not accounted for in warabandi system. As the length of watercourse proceeds, the conveyance loss continues to increase from head to tail. Consequently, the cultivators near the head of watercourse are maximum gainers and those near the tail are the maximum sufferers.
- Share holders receive proportionate running time but not necessarily a proportionate quantity of water. Practically nothing has been done to solve this problem.
- 2) The system does not provide flexibility to accommodate farming and crop needs. It is the farmer who has to adjust his cropping pattern and cropped acreage accordingly.
- The canal system originally designed for 75 % cropping intensity has to cater the needs of 100-170 % cropping intensity.

- 3) Decreasing land holdings present more difficulties in implementing improved irrigation practices.
- The cropped area charging system presents a number of operational problems such as the use of tubewell water, mal practices of "Abiana " assessment, encouraging inefficiency by over irrigation practices etc.
- 4) The present system lacks consideration of rainfall or droughts and continues to deliver the same amount of water as scheduled.
- 5) The existing time allocation time per acre (approximately 12 minutes per acre) is not enough to accomplish irrigation of even one acre field during a given irrigation turn.
- 6) The water allocation to a farmer is based on the area of the farm and does not consider the location of the farm along the watercourse. Consequently, the water losses occuring during the conveyance creates inequity in the system.

1.7.4 Recommended Improvements in Warabandi System

Based on the research carried out during the past few decades, the following improvements in warabandi have been suggested.

- 1 ☑ Equitable water distribution models should be used to develop equitable water allocation among the share holders at a watercourse command.
- 2) ☑ The transitional water losses in the watercourses should be assessed to reflect the proportionate time allocation to each water user.
- ☑ The filling and draining time as influenced by the watercourse improvement/ lining activities should be reevaluated and reflected in warabandi schedule.
- 3) ☑ The cropped-area based water charging system should be replaced by time-area based system to remove the bureaucratic bottlenecks and improve the water use efficiency.
- 4) ☑ The beneficiaries should be involved in decision making process of water distribution at watercourse command level.
- ☑ The duration of turn cycle should be increased to enable a farmer to accomplish irrigation of his field during a given turn.
- 5) ☑ Update the century-old warabandi rules to be consistent with the present day needs.

1.7.5 Roster of Turns

The rotation of turn begins at the head farm, i.e., the fields closest to the canal outlet (mogha) usually on Monday at 6 a.m., and the turn is passed on to the next farmer on completion of a farmer's turn. Usually, the rotation of turn for a complete pacca warabandi is of seven days but it may be $10^{1}/_{2}$ days rotation at some places. By a shift in turn, once a year, usually in April, the night irrigators become day irrigators and vice versa by rotating the roster by 12 hours.

After the completion of allocated time of a cultivator, the second cultivator located at some distance downstream requires some time to fill the empty watercourse. This time is called Filling Time or "***Bharai***". Therefore, filling time is added to the second and subsequent share holders at the rate of 5 minutes per 210 feet length of watercourse.

When water reaches the last farmer at the tail, he receives the total quantity of water present in the watercourse, in addition to his net allocated time. This water being additional supply is subtracted from his gross allocated time at the rate of 3 minutes per 210 feet length of watercourse. This is called Draining Time or "Nikas". After the last farmer has taken his turn of irrigation, the cycle is completed and the turn is shifted to the first farmer at the head to start a new weekly cycle.

Filling time is debited to the common pool time of 168 hours (one week) and credited to the individual accounts of each farmer. The discount value of cumulative "Bharai" time is the "**Nikas**" time which is also credited to the common pool. After considering allowance for cumulative 'Bharai' and 'Nikas' times, the flow time for a unit area i.e. the Unit Flow Time (UFT) in hours per acre is given by the flowing equations:

$$\text{U FT (hr/ac)} = \frac{\text{8 (hr) - Total fill time (hr)+ Total drain time (hr)}}{\text{Total area (ac)}} \qquad (1)$$

The Turn Time (TT) for an individual farmer (hours for the land holding) in a weekly rotation cycle is determined using the equation:

$$\text{TT} = \text{(UFT x Land holding) + Filling time - Draining time for the farmer} \qquad (2)$$

Filling Time is generally zero in case of the last farmer and draining time is zero for all the farmers except the last one.

1.8 Hill Torrents And Rod Kohi Irrigation In Pakistan

Pakistan covers about 80 million hectares of land. out of which about 40 % is suitable for agriculture and forestry. The cultivated land comprises about 20.2 mha, of which 15.3 mha is irrigated through canal irrigation system while the remaining is under barani cultivation. Such barani areas receive various degrees of flood flows called hill torrents emerging from different hill ranges. Thus, a hill torrent is a perennial/ non perennial stream descending from a hilly area having a very high ratio of normal or minimum flow to its peak which is of very short duration and generally impregnated with high silt charge.

1.8.1 Importance of Hill Torrents

Conventional water resources of river flow and groundwater are being harnessed to support agriculture. However, water supply from these resources can meet only less than 65 % of the requirements in irrigated areas. In barani areas the situation is more grave than irrigated areas. The water available from rains can meet only one-fifth to one-fourth of the crop requirements. The ~~major~~ exploitable potential source of water in barani areas are hill torrent flows which offer great prospects for agricultural development. If left unmanaged, a large amount of unconserved flood flows annually result in serious damage to the crops, livestock, houses and infrastructure.

The watershed command for hill torrents in various parts of the country drain about 55 % of total area. If properly managed and used, hill torrents can not only cater the agricultural needs of large tracts of barani land, but also help to safeguard the people and properties. Harnessing of flows from hill torrents can also play a great role for socio-economic development of the areas.

1.8.2 Rod Kohi Irrigation

The low flows from hill torrents are diverted by constructing temporary dikes (bunds) across the bed of the torrent to store and raise water which is led into embanked fields. Once the a set of fields are filled, water is allowed to percolate slowly into the soil.

After these fields are filled, temporary bunds are breached to allow the water to be diverted into the downstream areas to fill another set of fields. This system of diversion continues till the flood flows are completely exhausted or all the fields are filled. A typical Rod Kohi irrigation system is shown in Fig.4

1.8.3 Major Hill Torrent Areas

There are a number of hill torrents which have been grouped into various sub basins as given in Table . Accordingly, various hill torrent area of Pakistan constitute about 2.34 million hectare of culturable land and gross water potential of 1.50 million hectare meter.

Table 2. Potential of Hill Torrents in Pakistan

Hill Torrent Area	Catchment Area (Sq. Km)	Annual Culturable Area (m ha)	Runoff Area (m ha m)
Balochistan Hill Torrents			
- Indus Basin	10,200	0.20	0.52
- Makran Coastal area	122,507	0.20	0.12
- Kharan Desert	122,030	0.10	0.05
NWFP Hill Torrents			
- Kabul River Basin	15,015	0.20	0.24
- D.I.Khan, Bannu and Kohat	25,650	0.10	0.26
- Hazara	2,932	0.10	0.03
Sindh Hill Torrents			
- Khirther Range	16,058	0.04	0.16
- Karachi Area	3,056	0.01	0.01
- Sehwan and Petaro Area	13,200	0.07	0.01
Punjab Hill Torrents			
- Pothohar Area	19,600	0.10	0.20
- D.G.Khan	23,732	0.14	0.32
FATA Hill Torrents	27,220	0.24	0.42
Total	493,000	1.50	2.34


ROD KOHI
(Hill Torrent)
IRRIGATED LAND
FLOW
(TRAIL DYKE) SA'D
GANDI
(Earth Dyke)
KHULA
(Shallow Channel)
FLOW
Flow
FIELD
FIELD
BUNDS
(IMPOUNDING DYKES)
FLOW FROM FIELD TO FIELD
FLOW DISTRIBUTOR
GANDI
GANDI

The location of these hill torrents are shown in Fig.4 Enormous land as well as water potential exist in most of the hill torrent areas. Therefore, management of hill torrents can bring vast areas under irrigated agriculture which are presently lying uncultivated and barren because of unavailability of irrigation water.

1.8.4 Hill Torrent Structures

For harnessing of hill torrents, the following structures may be constructed to suit the local geophysical as well as traditional practices, water rights and warabandi etc.

- ☞ Dispersion structures
- ☞ Diversion structures
- ☞ Detention dams
- ☞ Storage dams
- ☞ Channels

The detention dams are useful for the augmentation of groundwater which may be exploited by tubewells. These dams may help recharging aquifers of the area for sustained tubewell water supplies. Excess water from hill torrents can be stored in storage dams during high flood periods. Presently, Manchhar and Kinjhar lakes are serving the purpose of such reservoirs.

Channelization of hill torrents may save enormous quantities of flows by preventing overspills and seepage losses. Uncontrolled hill torrents also bring quite large silt load which tend to reduce the channel capacity at downstream reaches. Therefore, provision of various structural improvements is necessary for harvesting the benefits of such flood flows.

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4.4 Sources of irrigation water

There are three sources of irrigation water in Pakistan: precipitation, surface water and ground water.

A → **Precipitation.** The source of all water supplies is atmospheric precipitation: rainfall, dew, mist/fog, hail, and snow. Amongst these, however, rainfall is the most important because it contributes substantially to crop water requirements.

The cultivable canal-commanded area of the Indus plain and Peshawar Vale receives 25 maf (22.5 cm) rainfall annually (Ahmad and Chaudhry (1988:3.1). However, distribution and intensity of this rainfall is so erratic that successful crop husbandry is not possible with rainwater alone. Therefore, surface and ground water are needed to supplement the crop water requirements on a continuous basis to harvest the maximum potential of crops.

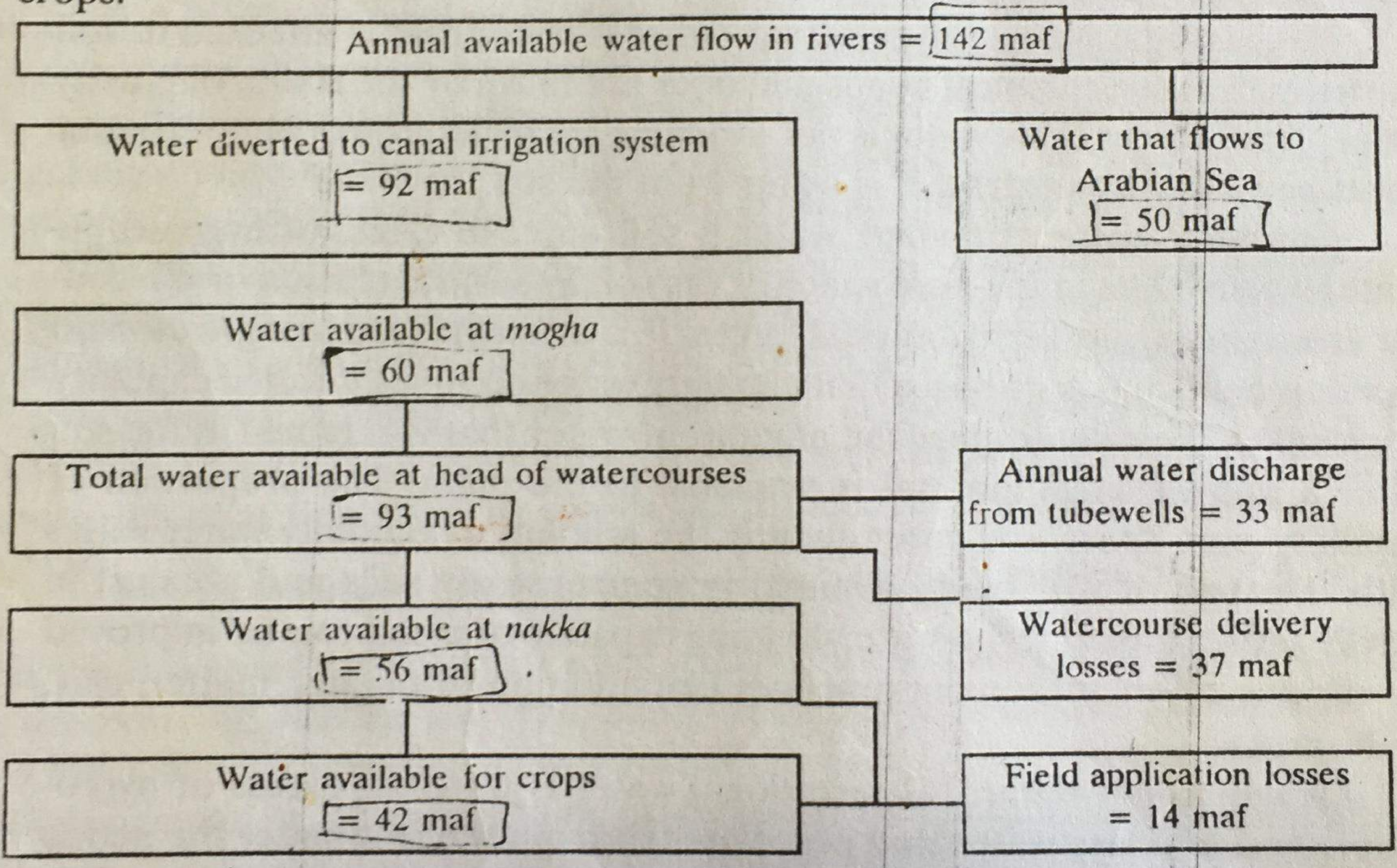

Figure 4.3 Flow chart of the Indus Basin Irrigation System (Cheema 1982:48).

B → **Surface water.** Surface water is mainly derived from the Indus River system, which is one of the great fresh water resources of the world. The annual available river flow in Pakistan is 142 maf, of which 92 maf (65%) is diverted into the canal irrigation system, and 50 maf (35%) flows into the Arabian Sea (Fig. 4.3). Of the 92 maf water diverted to the canal irrigation system, only 65% is available at *mogha* while the remaining is lost through seepage from canals.

Ground water. Ground water is lifted to the soil surface through (i) natural springs, (ii) wells, (iii) galleries and karezes, and (iv) tubewells (Afzal 1976:50). Tubewells are, however, the most important source of ground irrigation water. Currently, the annual water discharge of tubewells in Pakistan is 33 maf (Fig. 4.3).

Regardless of the source, irrigation water is primarily applied to soil, from where it is absorbed by a plant. Thus, an understanding of soil water is essential for applying the desired level of irrigation water to a field.

4.5 Soil water

4.5.1 Classes and availability of soil water

Water present in the pore space of soil is of three types: hygroscopic, capillary, and gravitational.

Hygroscopic water. Hygroscopic water is water that is attached to soil particles by loose chemical bonds and does not move by the action of gravity or capillary forces. This water is not available for plant growth because plant roots are unable to extract this water from the soil.

Capillary water. Capillary water is soil water in excess of hygroscopic water which exists in the pore space of the soil by surface tension or molecular attraction against gravitational forces. It is available for plant growth and development. Soil pore space that capillary water occupies is called **capillary pore space**. This determines the amount of water that is retained in the soil after a rain or irrigation and is available to the plant. The proportion of capillary pore space and consequently the amount of capillary water varies with the type of soil, being minimal in coarse, sandy soils and greatest in clayey soils. However, the water-holding capacity of a soil can be improved by various soil management practices like addition of organic matter, clay, or both.

Gravitational water. Gravitational water is water in excess of hygroscopic and capillary water that percolates through the soil under the action of gravity if favourable conditions for water drainage are provided. This water passes down to the ground water table, and hence is not available for plant growth if the water table lies very far below the root zone.

4.5.2 Measuring the availability of soil water

The availability of soil water to plants can be measured by determining soil water potential, saturation capacity, field capacity, permanent wilting percentage, and available water content (Kramer 1983:68). However, **soil water potential** is the most reliable indicator of water availability to plants.

a. Water potential. Water potential refers to the chemical potential of water. It depends on the mean free energy per molecule and the concentration of water molecules. Water always flows from a higher potential to a lower potentiai.

Soil water potential comprises four components: ① **osmotic potential** (also called solute potential) produced by various solutes in soil water; **matric** ② **potential** produced by capillary and surface forces (water adsorption to soil constituents); ③ **gravitational potential** ④ produced by gravitational forces operating on soil water; and **pressure potential** produced by actual hydrostatic pressure (Kramer 1983:69). However, the former two components are much more important in determining soil water potential than the latter two.

b. Saturation capacity. This term refers to the amount of water present in the soil when it is completely saturated with water. It is also called **total capacity or maximum moisture-holding capacity.** During and immediately following surface irrigation or heavy rainfall, the soil below the water surface is nearly saturated. The pore space of the soil is almost completely filled with water, and there is little air present in saturated soil. Since plants, with the exception of rice, need air as well as water, some of the water from the larger pores must leave in a reasonable length of time to prevent damage to the crop. If the soil is well-drained, part of the water will move downward by gravity and, to a limited extent, laterally by capillarity. The water moving downward by the force of gravity is called **gravitational water** or **free water.**

c. Field capacity. The amount of water retained by soil after drainage of saturated soil by gravitational force is called the **field capacity** of a soil. Field capacity is also called **field carrying capacity, normal moisture capacity, and capillary capacity** (Kramer (1983:70). At field capacity, each soil particle is completely surrounded with a relatively thick film of water. Soil water content at field capacity can be determined by using the formula:

$$\text{Field capacity} = \text{Saturation capacity} - \text{Gravitational water} \tag{4.3}$$

Soil water reaches field capacity several days after soil saturation, the specific time varying with the soil type. Sandy and deep soils reach field capacity in a much shorter time than clayey and shallow soils. The presence of hardpan/plough pan or high water table prolongs the time required to reach field capacity.

d. Permanent wilting percentage. The soil water content at which plants can no longer extract sufficient water from the soil for their growth is called permanent wilting percentage. If sufficient water is not available to the plant to meet its requirements, the plant will wilt permanently and will not recover even when placed in a saturated atmosphere. By contrast, soil water content at which plants wilt during the hot windy part of the day (at noon and afternoon) but regain turgidity during the cooler part of the day (dawn and early morning hours) is called **temporary wilting percentage.**

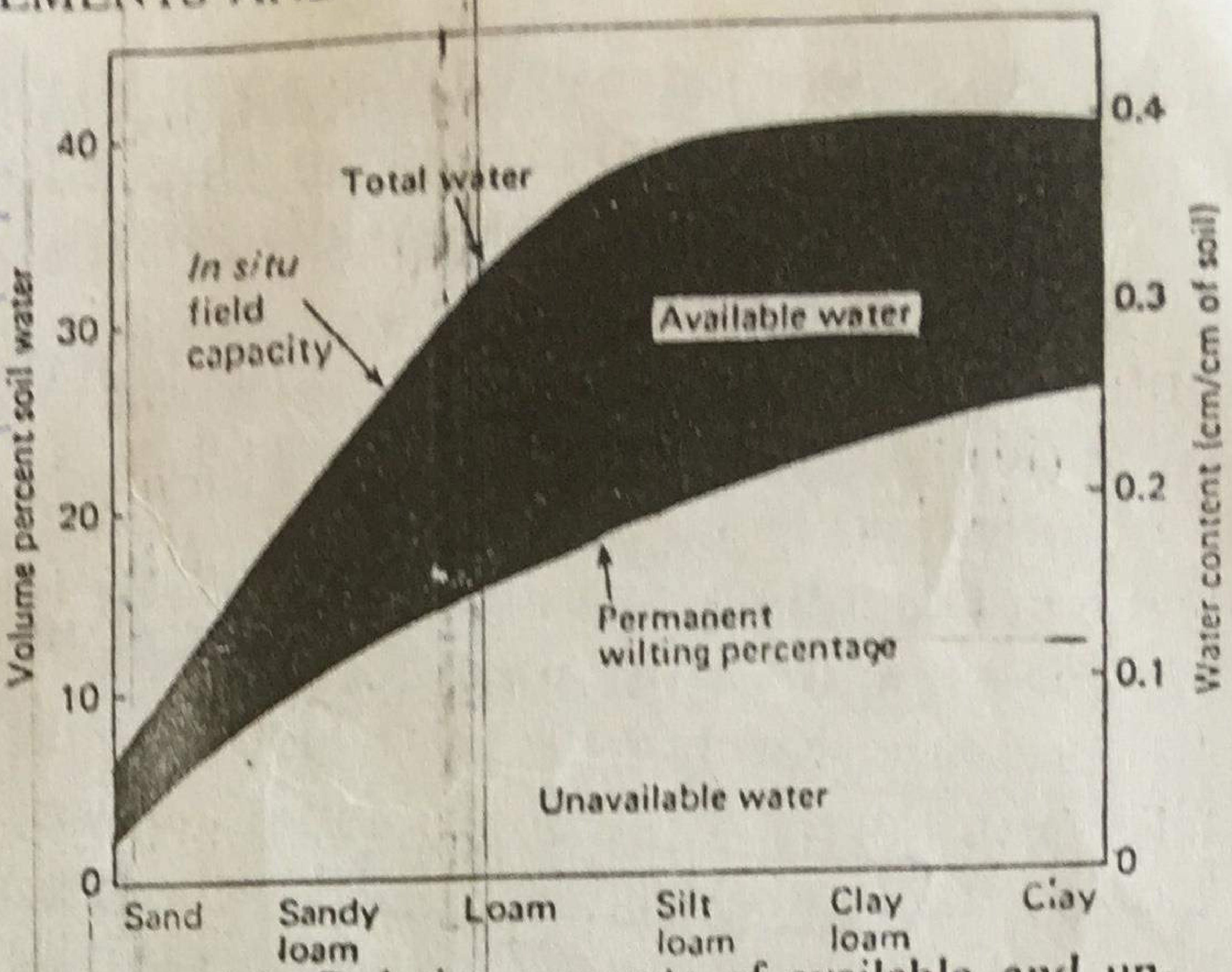

Figure 4.4 Relative amounts of available and unavailable water in soils ranging from sand to clay. Reproduced with permission from Kramer (1983:69).

e. Available water. The water retained in a soil which represents the difference between field capacity and the permanent wilting percentage is the **available water.** The amount of available water depends on several factors like size, shape and depth of root system, soil texture, level of underground water table, and the presence of an impervious soil layer. The available water capacity of different soils varies widely (Fig. 4.4). The portion of the available water that is most easily extracted by a plant is called **readily available water;** it is about 75% of the available water.

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4.6 Quality of irrigation water

The water of rivers in Pakistan, like all rivers of the world, contains soluble salts, the content of which ranges between 200 and 250 ppm (Ahmad and Chaudhry 1988). This concentration increases as the water approaches the delta. Total soluble salt content varies for each river because of differences in catchment areas and sources of water supply, and with the season. Moreover, with the rapid, unplanned expansion of industry, risk of both surface and ground water pollution has greatly increased because little attention is being paid to the proper disposal of industrial chemicals. Many of these chemicals, heavy metals, etc. may be injurious for both plant and soil health. Determination of the quality of irrigation water is essential, therefore, in order to ensure good quality water to crops and obtain maximum yields as well as to avoid the risks of soil salinization and sodification.

Regardless of the source of irrigation water, some soluble salts are always dissolved in it. However, the nature and quantity of dissolved salts depend on the source of water and its course before use. Among the soluble constituents, calcium, magnesium, sodium, chloride, sulphate, bicarbonate, and boron are of immense importance in determining the quality of irrigation water and its suitability for irrigation purposes. Ions of selenium, molybdenum, and fluorine, if absorbed by plants in excessive amounts, may prove harmful to animals which eat them. Other factors including the structure and texture of soil, soil drainage, depth of the water table, presence of hardpan respects, this appears to be a good approach to irrigation timing; but unfortunately it is too complex for everyday use on a farm.

Among the early visual indicators of water stress are changes in leaf colour, change in the angle of leaves, and rolling of leaf blades. If plants show such visual symptoms early in the morning, the soil water supply is beginning to retard plant growth. Some of these symptoms have been used successfully as indicators of the need for irrigation. Currently, however, there is no best method of irrigation scheduling, and the choice of method depends on experience and the information available to the manager.

4.8 Irrigation efficiency

Irrigation efficiency is a term used to indicate how efficiently the available water supply is being used for crop production. Unfortunately, the efficiency of our irrigation systems is very low. About 35% of the canal water supplied from diversion headworks is lost in main and branch canals, while losses during the delivery of canal water from *mogha* to *nakka* (field head) amount to about 24% (Table 4.4). Thus, about 59% of the irrigation water supplied from diversion headworks is lost before it reaches the fields for irrigation. Similarly, 13% of the tubewell water is lost in watercourses and field water channels. The total irrigation water (canal water + tubewell water) available at the *nakka* is 56 maf (Fig. 4.3), of which 25% is lost during field application due to surface evaporation, surface runoff, deep percolation, and uneven distribution over the field. Thus, it is evident that the amount of water effectively utilized by the crops in the form of evapotranspiration or consumption is less than 20% of the total water released from diversion headworks or discharged by tubewells.

Table 4.4 Water losses in canal irrigation system of Pakistan

Source	**Water losses (%)**	**Factor**
Canal head to outlet	35	Seepage/percolation, evaporation
Watercourses delivery	24	Seepage, overflow, evaporation
Field application	25	Unlevelled field and over irrigation

Source: Data derived from publications of Government of Punjab, Agriculture Department, Directorate of Agricultural Information.

The huge loss of irrigation water in Pakistan can be reduced only by adopting appropriate off-farm and on-farm water management practices that ensure the efficient and economical use of irrigation water. The principal of lime or clay, type of crop grown, and climatic conditions are also important in determining the suitability of irrigation water for agriculture.

Factors that influence quality of irrigation water are: (i) total soluble salt concentration (TSS) as measured by electrical conductivity; (ii) relative proportion of cations as expressed by the sodium adsorption ratio (SAR); and (iii) bicarbonate and boron content. $CaCO_3$ content in the soil and K^+ and NO_3^- ions in the water also indirectly affect the suitability of irrigation water. The criteria presented in Table 4.3 are internationally recognized for judging water quality (Afzal 1976).

Table 4.3 Criteria for judging the quality of irrigation water

Type of water	TSS (ppm)	SAR (ppm)	Residual sodium carbonate (ppm)	Use for irrigation
Very good	<1000	<10	Negligible	Suitable for all crops and all soils.
Good	1000–2000	<10	<5	Acceptable for permeable soils and hardy crops.
Poor	1000–2000	10–15	5 (approx.)	When used on ordinary soils, will bring about deterioration of topsoil except in the case of sandy and gypsiferous soils.
Bad	>2000	10–15	5 (approx.)	Not suitable for use in agriculture.

Source: Afzal (1976:60).

4.7 Irrigation scheduling

Irrigation scheduling refers to the number of irrigations for a crop and their timing. Assuming that water is available, the most important problem is to determine when and how much to apply. This depends on several factors including type of crop, its stage of development, extent of the root system, rate of evapotranspiration, and the water-holding capacity of the soil.

There are three common approaches to the problem of determining when to irrigate. They are based on measurement of soil moisture, estimates of water usage from climatic data, and measurement of plant water stress. However, the water-stress approach for scheduling of irrigation is probably most useful, as it is based on the plant's water status itself. Plants should be the best indicators of the need for irrigation because they integrate the soil and atmospheric factors controlling the plant water balance. In many factors that affect irrigation efficiency are: design of the irrigation system, degree of land preparation, and the skill and care of the irrigator. Loss of irrigation water occurs in the conveyance and distribution system and because of non-uniform distribution of water over the field, percolation below the crop root zone, and sprinkler irrigation evaporation from the spray and retention of water on the foliage. In large fields, loss may occur by runoff at the end of irrigation borders and furrows. Losses can be minimized by adequate planning of the irrigation system, proper design of the irrigation method, adequate land preparation, and efficient operation of the system.

Since Pakistan's irrigation systems are very inefficient, improvement can occur only by the concerted efforts of both engineers and agriculturists.

Crop water use efficiency. Water use efficiency is the ratio of crop yield (Y) to the amount of water depleted by the crop in the process of evapotranspiration (ET).

$$\text{Water use efficiency} = Y/ET \qquad (4.4)$$

Water use efficiency is influenced by (1) on-farm watercourse improvement and (2) crop and soil management practices. Crop yield can be changed appreciably by these management practices. However, it is very difficult to significantly alter evapotranspiration because it largely depends on the temperature of the physical environment and the availability of water. Thus, practical water use efficiency can be increased only by adopting various crop and soil management practices.

4.8.1 Improvement of on-farm watercourses

A large part (24%) of irrigation water is lost from watercourses during delivery as a result of seepage, overflow, and evaporation. It is therefore necessary to improve watercourses to minimize these losses and enhance water availability to the crop. The impact evaluation studies of the On-Farm Water Management Training Institute in Lahore and the Punjab Economics Research Institute, Lahore indicate numerous advantages of watercourse improvement (Table 4.5).

Table 4.5 Assessment of the benefits of on-farm watercourse improvement

Type of benefit	Magnitude of benefit (%)
Increase in water delivery efficiency	30
Water saving to irrigate an area (reduction in loss)	24
Increase in cropped area	7.5
Increase in cropping intensity	14
Increase in crop yields	14

2

MEASUREMENT OF IRRIGATION WATER

Accurate measurement of irrigation water permits more efficient use of this valuable natural resource. Systematic water measurements properly recorded, interpreted and used, constitute the foundation upon which increasing efficiencies of water conveyance, application and use must be based.

2.1 Importance of Water Measurement

Present-day knowledge of soil-moisture-plant relations permits irrigation system to be designed for applying water in correct quantities when needed. The water application rates are based on the soil intake rates, thereby obtaining maximum efficiency of water use and increased crop yields. Water measurement prevents poor crop growth resulting from insufficient water application and also reduces chances of waterlogging problems as a result of over-irrigation. Therefore water measurement forms an important component of irrigation scheduling.

Limited availability of surface water and increased cost of groundwater development require that water be used economically and efficiently. Water measurement is also important component of evaluation of existing irrigation systems and designing new projects. Accuracy of water measurement is, therefore, of prime importance in the design and operation of any water distribution system.

2.2 Units of Water Measurements

Water can be measured either at rest or in motion. Water at rest, i.e., in reservoirs, ponds and tanks is measured in units of volume such as liters, cubic meters, cubic feet, acre feet, acre inches, hectare-cm, hectare-m, second-foot-day etc. Measurement of water in motion, i.e., flowing in rivers, canals, pipelines, field channels and channel structures, is expressed in the units of volume per unit time (flow rate) such as gallons per minute, cusec, liters per second, cubic meters per second and cubic meters per day etc. Commonly used conversions in water measurement are summarized in Table.

Table 1. Conversion factors for commonly used units in irrigation

To Convert From	To	Multiply By
Cu meter	Cu feet	35.315
Liters	Cu feet	0.03531
Sq. cm	Sq inches	0.155
Hactare	Acre	2.417
Liters/sec	IMP gpm	13.199
Liters/sec	Cu ft. /sec	0.0353
Watts	Ft.lb /sec	0.7376
Watts	hp	0.00134
Kw	hp	1.341

2.2.1 Volume Units

Volume can be measured in a number of units but the commonly used in the field are defined as follows:

Hectare-meter: A volume required to cover an area of one hectare (10,000 m^2) to a depth of one meter.
1 hectare-meter = 10,000 m^2 x 1 m = 10,000 m^3.

Acre-foot: A volume required to cover an area of one acre to a depth of one foot.
1 Acre-foot = 43560 ft^2 x 1 ft = 43560 ft^3

Acre-inch: A volume required to cover an area of one acre to a depth of one inch.
One Acre Inch = 43560 ft^2 x 1/12 ft = 3630 ft^3

Second Feet Day (SFD): If the water flowing at a rate of one cubic foot per second (CFS) is collected for 24 hours, the volume of water will be one SFD.
1 SFD = 1 ft^3/sec X 24 X 3600 sec = 86400 ft^3

2.2.2 Flow Rate or Discharge Units

Flow rate or discharge can be measured in terms of volume per unit time. There are many units of measuring discharge, but the commonly used ones are given below:

Liter per second: If a volume of one liter of water is passing through a given cross section in one second, the discharge is called one liter/sec, commonly abbreviated as lps.

Cubic feet per second (Cusec): If one cubic foot volume of water is passing though a cross section of channel in one second, the discharge is called one cubic foot per second (1 ft^3/sec) or one cusec.

Cubic meter per second (Cumec): If one cubic meter volume of water is passing through a cross section of channel in one second, the discharge will be one cubic meter per second (1m^3/s) or one cumec.

2.3 Methods of Water Measurement

Several methods are available for measuring irrigation water. They can be grouped into four categories:

1. Volumetric method
2. Velocity-area method
3. Measuring devices (orifices, weirs, flumes etc.)

2.3.1 Volumetric Method

A simple method of measuring small irrigation streams is to collect the flow in a reservoir of known volume for a measured period of time. The time required to fill the container is recorded with a stopwatch. The rate of flow is measured as:

$$\text{Discharge (liters/sec)} = \frac{\text{Volume of reservoir (liters)}}{\text{Time required to fill (sec)}} \qquad (3)$$

Volumetric method is the most accurate one and can be used in hydraulic laboratories for calibrating other devices and instruments used for measuring flow rate.

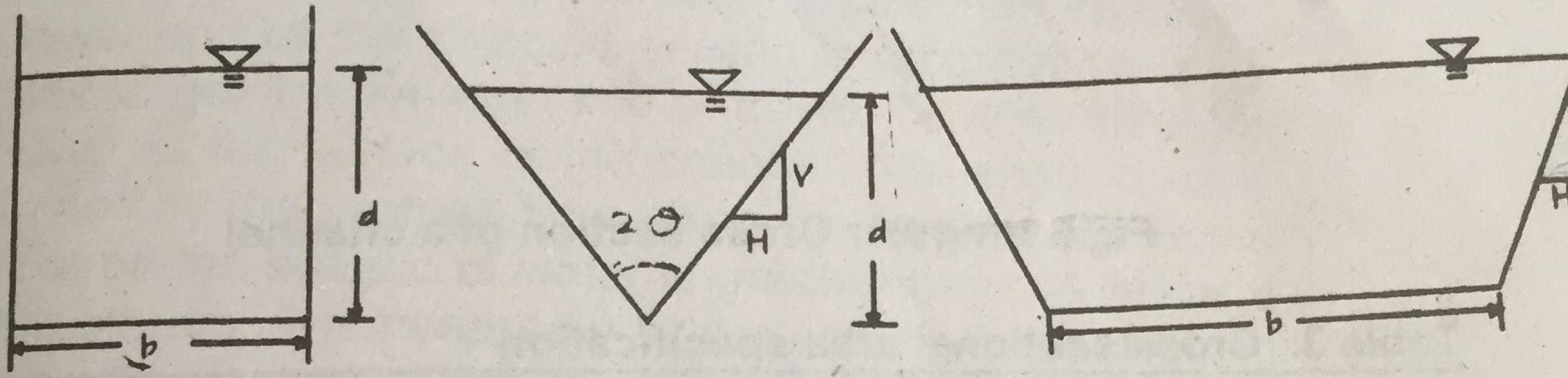
2.3.2 Velocity-Area Methods

The rate of flow passing through a section of a pipe or open channel is determined by multiplying the cross sectional area of the flow section at right angle to the direction of flow by the average velocity of water. Methods to measure cross sectional area and velocity in a channel are separately explained below.

2.3.2.1 Measurement of Cross Sectional Area

An open channel conveying water may have regular or an irregularly shaped cross section. Regular cross sections having fixed shape and dimension are generally found in lined channels where as unlined channels have irregular sections, which are exposed to erosive forces.

i) *Regular cross-section*. The most commonly used regular cross-sections are rectangular, triangular and trapezoidal as shown in Fig.5.



Rectangular Triangular Trapezoidal

Fig.5 Regular channel cross sectional shapes

Where

b = bottom width of the cross-section
d = flow depth of the cross-section

$$z = \frac{\text{Horizontal}}{\text{Vertical}} = \frac{H}{V}$$

A = cross sectional area as detailed below:

Rectangular $A = bd$ (4)
Triangular $A = zd^2$ (5)
Trapezoidal $A = bd + zd^2$ (6)

ii) *Irregular cross-section*: There is no fixed bottom width, flow depth and side slope in irregular cross-sections. The cross-sectional area in this case is estimated as under:

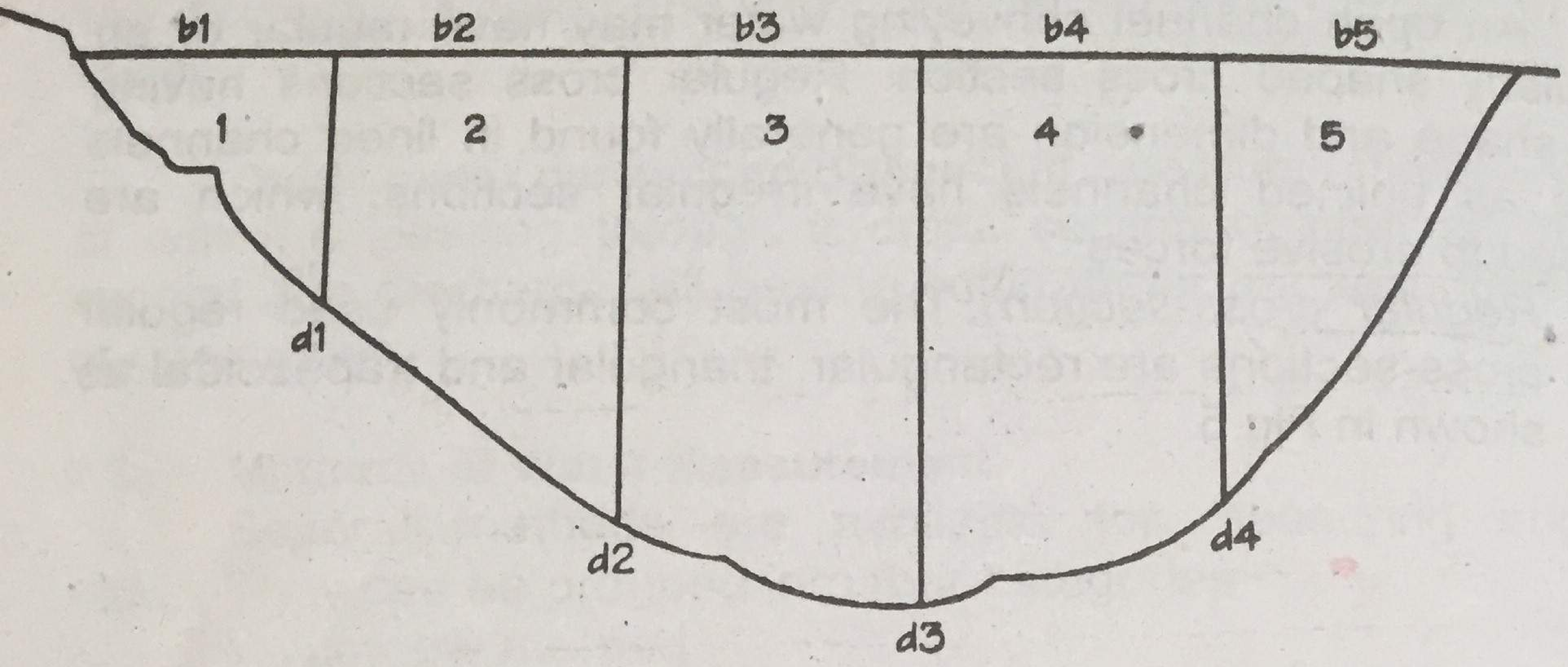


Fig.6 Irregular Cross section of a channel

Table 3. Cross sectional area specification

Subsection	Top width	Average depth	Area (Width X Depth)
1	b_1	$(0+d_1)/2$	$A_1 = (b_1 \text{ X } d1))/2$
2	b_2	$(d_1+d_2)/2$	$A_2 = b_2\ (d_1+d_2)/2$
3	b_3	$(d_2+d_3)/2$	$A_3 = b_3\ (d_2+d_3)/2$
4	b_4	$(d_3+d_4)/2$	$A_4 = b_4\ (d_3+d_4)/2$
5	b_5	$(d_4+0)/2$	$A_5 = b_5\ (d_4+0)/2$

Total cross-sectional area (A) = $A_1+A_2+A_3+A_4+A_5$

The area of an irregular cross section can also be estimated by plotting the dimensions of 'b' and 'd' in each sub section to some predetermined scale on a graph paper. Count the numbe of small squares or divisions and multiply with the area represente by each small division to find the area of a cross section.

2.3.2.2 Measurement of Average Velocity

Two procedures used to measure velocity under velocity area method include **float method** and **current meter metho** depending on the size of open channel as explained below:

a) **Float Method:** It is a rough method of flow measurement which consists of noting the average rate of movement of a floating body and the average cross-sectional area of channel measured at right angle to the direction of flow. The product of average velocity and average cross sectional area gives the discharge.

A straight section of the channel about 15 to 30 m long with fairly uniform cross-section is selected. Measurements of depth and width are made at several locations within the trial section, to arrive at the average cross-sectional area. The average velocity in a channel with float is measured as explained below.

A string is stretched across the section at right angle to the direction of flow. The float is placed a short distance upstream from the trial section. The time taken by the float to pass from the upper end to the lower end of the selected section is recorded. Several trials are made to get the average time of travel. To determine the velocity of water at the surface of the channel, the length of trial-section is divided by the average time taken by the float. Since the velocity of float on the surface of water is greater than the average velocity of the stream, it is necessary to correct the measurement by multiplying with a constant factor, which is usually assumed to be 0.85.

b) **Current Meter Method:** The velocity of water in a stream or river may be measured directly with a current meter (Fig.7). Current meters of two general types are used (I) Cup type with vertical axis (ii) Propeller type with horizontal axis. The cup meter is more sensitive to disturbances. The propeller meters have been used for higher ranges of velocities, (20-30 m/s) than the cup meters (10-15 ft/s). For field observation, the cup meter has generally been found superior where as for pipe measurement and laboratory observations, the propeller meter has been found to be more useful. The discharge is estimated by multiplying the mean velocity of water by the area of cross-section of the stream.

The cup type current meter is a small instrument containing a revolving wheel carrying a set of vanes that is rotated by the movement of water (water currents). It is of two types (a) Price Current Meter (b) Pygmy Current Meter. Both types have similar features except the size of wheel. The pygmy wheel is 2 inches in diameter compared with 5 inches diameter wheel in price meter. The pygmy has no provision for cable suspension but the price has.The use of pygmy meter is limited to velocities up to 3-4 feet per second which mostly prevail i8n smaller channels (watercourses). The price type is suited to canals and bigger channels having velocities greater than 4 m/s.

Components of Current Meter

A standard cup type current meter has the following components (Fig. 7).

1. Vanes to keep the wheel heading towards currents.
2. A cable or a rod for handling the meter.
3. Weights for sinking price meter.
4. Tail
5. Electric circuit for signaling the number of revolutions by sounding clicks.
6. Round wading base in case of rod.

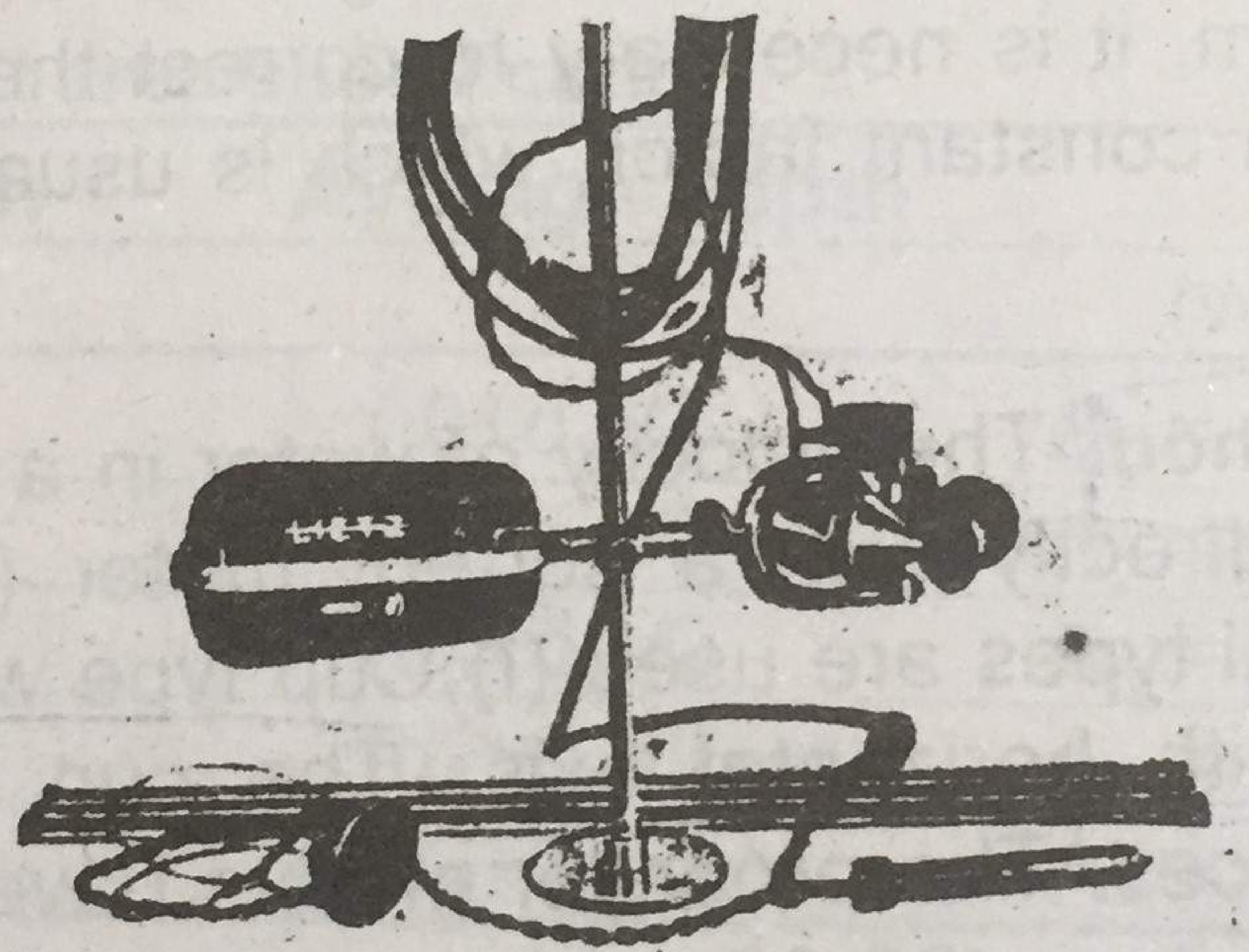


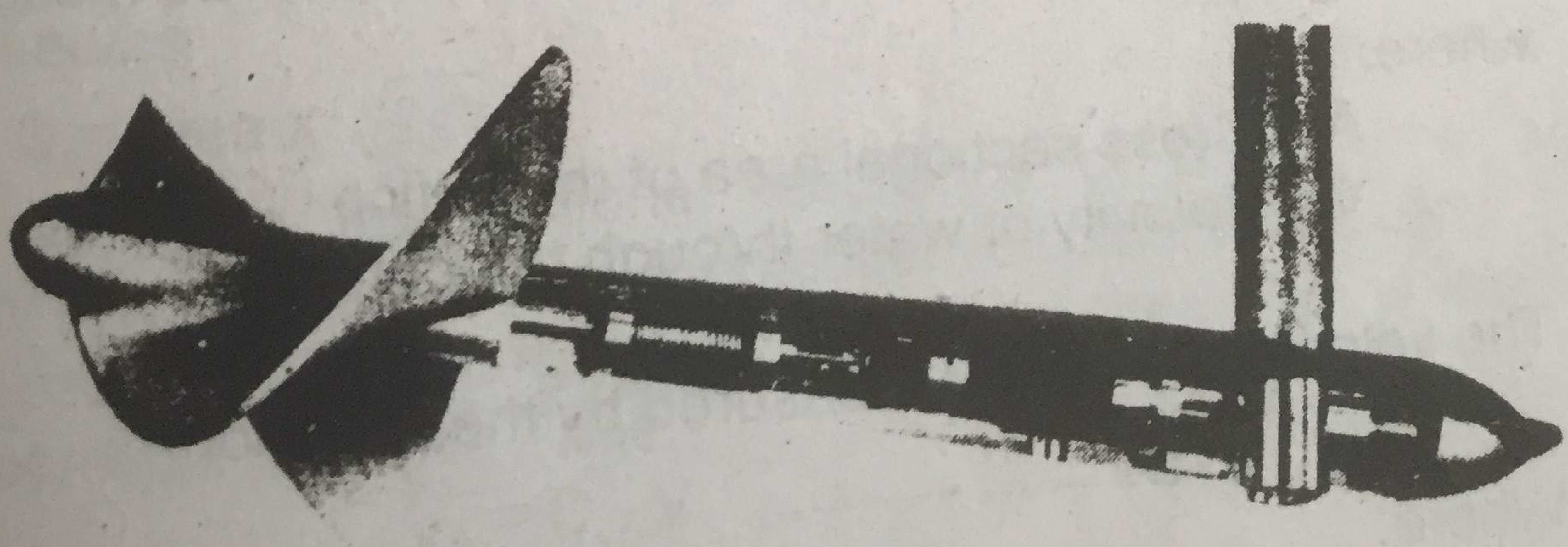
Fig. 7 Current Meter

How to Use Current Meter

The instrument may be suspended by a cable for measurements in deep streams or attached to a rod for measurement in shallow streams. The number of revolutions of the wheel in a given time interval is obtained and the corresponding velocity is reckoned from a calibration table or graph of the instrument. Current meter measurements in canals and streams are generally made at metering bridges, cable ways, or at other structures giving convenient access to the stream. The channel at the measuring section should be straight, with a fairly regular cross-section.

When the mean velocity of a stream is determined with a current meter, the cross-section of flow channel is divided into a number of sub-areas as shown in fig.5. Separate measurements are made for each sub-area. The width of sub-areas may vary from 1 to 6 m, depending on the size of the stream and the precision desired. Not more than 10% discharge should occur in one section. It has been found that the average of readings taken at 0.2 and 0.8 m of the depth below the surface of water is an accurate estimate of the mean velocity in a vertical plane. For sub-areas at the ends of cross section such as (1) and (5) in Fig.5, only one measurement of velocity at 0.6 of depth is sufficient. The discharge for each sub-area is measured by multiplying the cross-sectional area and velocity of each sub-area. The total discharge is obtained by summing over the discharges of all sub-areas for the given channel cross section.

The average velocity in streams not over 1.5 feet in depth, is at about 0.6 of the depth from the surface. In streams over 1.5 feet in depth, the average velocity is represented by the average of velocities at 0.2 and 0.8 of depth. (Israelsen and Hansen 1990). Another method of the determining average velocity in a stream is the integration method in which current meter is raised and lowered at a constant rate from bottom to the top of the stream. As the water velocity varies with depth, each depth will influence the resulting number of revolutions differently in a given period of time.



2.3.2.3 Measurement of Discharge

Discharge (Q) = Area X velocity

or Q = A X V (7)

Q = discharge rate, m^3/sec
A = area of cross-section, m^2
V = velocity of flow, m/sec

2.3.3 Flow Measuring Devices

In farm irrigation practices, the most commonly used devices for measuring water are flow meters (for pipe flow) and orifices, weirs and flumes for open channel flow. The choice among these measuring devices depends on the expected flow rates, available head and specific site conditions. Some of these devices and the procedure of measuring discharge are described below:

2.3.3.1 Orifices

An orifice is an opening, usually round or rectangular in a plate or bulk head, the top of which is well below the upstream water level and through which water flows. It may be used for measuring flow from a reservoir or through a pipe. The main feature of orifice flow is that most of the potential energy of water is converted into kinetic energy of the free jet issued through the orifice. Orifices may operate under free flow or submerged flow conditions. Under free flow conditions, the flow from orifice discharges entirely into air. Under submerged conditions, the downstream water level is above the crest of orifice. The loss of head as water flows through a submerged Orifice is the difference in elevation of water surfaces upstream and downstream.

The discharge (Q) through an orifice can be measured as:

Q = AV

where:

A = Cross sectional area of the orifice
V = Velocity of water through the orifice

The velocity (V) can be measured by the equation:

$$V = \sqrt{2gh} \quad (8$$

Where:

h = Head of water from the center of the orifice
g = Acceleration due to gravity, 9.81 m/s

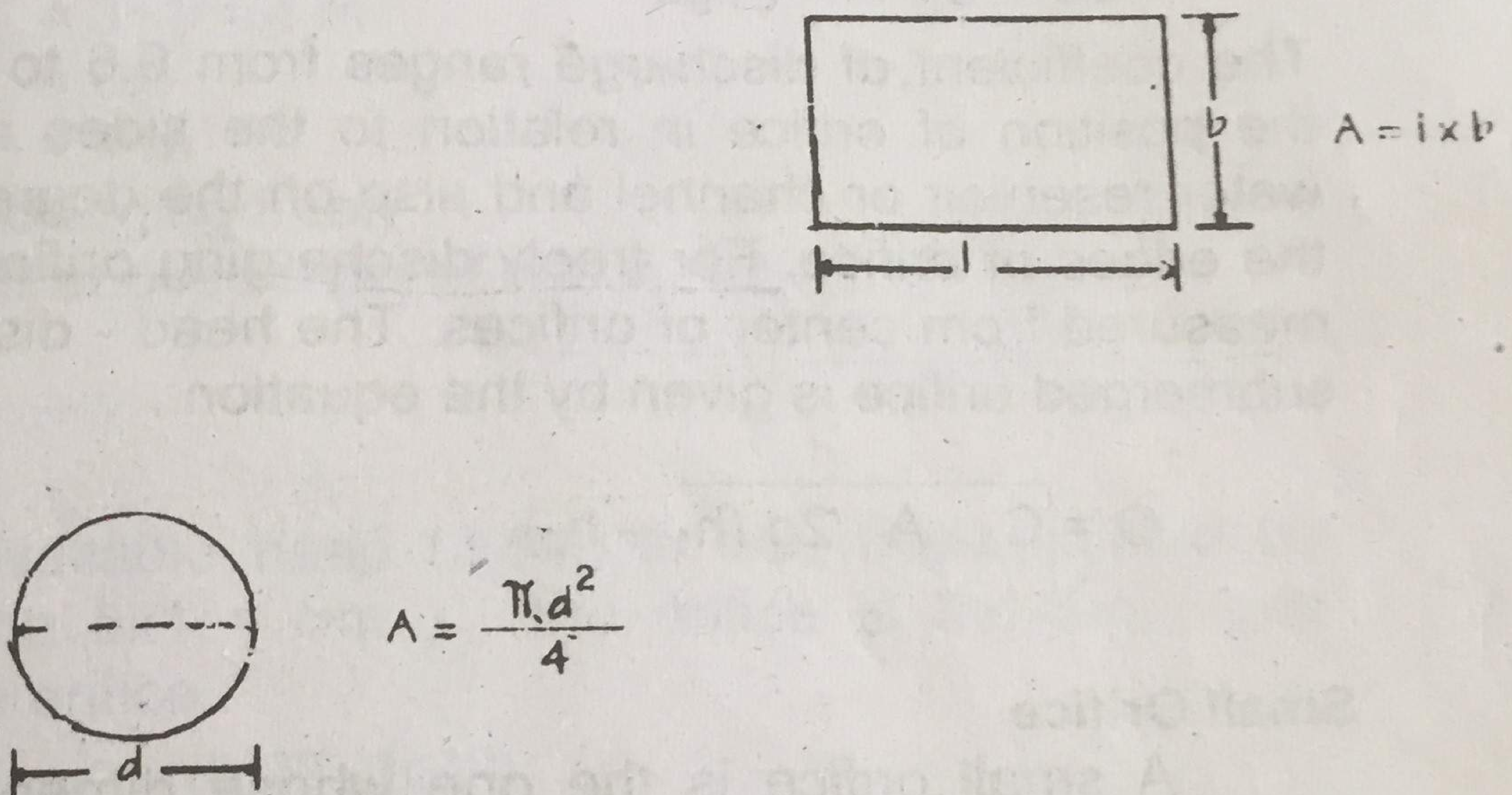


Fig.9 Cross sections of orifice

Thus for an orifice the theoretical discharge may be measured as

$$Q = \text{Area} \times \sqrt{2gh} \tag{9}$$

Owing to the frictional resistance of orifice, the actual velocity (V_a) is less than the theoretical velocity (V). Moreover, due to contraction of discharging jet, the actual area (A_a) is less than the theoretical area (A). Thus,

$$V_a = C_v . V$$

$$A_a = C_c . A$$

Therefore $$Q_a = C_d . Q$$