A Reading Course of Instruction
in
Irrigation Practice
UNIVERSITY OF HAWAII

EXTENSION DIVISION

A READING COURSE OF INSTRUCTION

IN

IRRIGATION PRACTICE

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Outline to Subject Matter and Index to Paging,
Reading Course in Irrigation Practice

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LESSON I.

INTRODUCTION TO IRRIGATION PRACTICE

The present reading course in irrigation practice deals with irrigation in its agricultural rather than in its engineering phases. In general, the plantation agriculturists and irrigation overseers in Hawaii are only indirectly interested in the discussions preliminary to the selection of a type of dam suitable for local conditions, nor need they be familiar with methods of main ditch locations and construction. Such work lies in the field of the irrigation engineer, while the intelligent and economic use of that water is the specific charge of the agriculturist; the acre is the unit of the engineer, while the individual plant must be the unit of the agriculturist. However, these two fields are not entirely distinct. There are some subjects such as methods of water measurement in the field and problems in small ditch capacities which are of interest to both the engineer and agriculturist. This material is included in the present course.

No attempt to develop formulae is made in this reading course. When such expressions are necessary a citation will be made to a simple derivation when the formula is rational and to a non-technical discussion when empirical.

Although the course is designed primarily for agriculturists in Hawaii, examples and illustrations will be drawn from irrigation practice elsewhere. This will be especially true in a discussion of methods of land preparation in Lesson IV, since some of the flooding methods used on the
mainland may be applicable to plantation conditions. Other illustrations of practice elsewhere, such as the depletion of water resources on one hand and the destruction of valuable land by over-irrigation on the other, may be valuable notes of warning.

It is patently impossible for a reading course of this nature to be monographic in character. Each of the lessons might be elaborated into a bulk greater than that of the entire course as now organized. At best it can be only a guide to the independent study of parts of particular interest.

This is especially true of the sections having to do with soil moisture and with plant and water relations. Here the authorities differ widely in interpretation and conclusion. These sections could have been prepared with more confidence ten years ago; many of the debated points may be unquestionably established ten years hence.

The student is warned to differentiate carefully between established fact, probability and speculation as the evidence is presented in the following pages.

The Challenge of Permanent Agriculture Under Irrigation

Irrigation is a word to conjure with. Perhaps no other word in the English language is so rich in connotations. To the reader of romantic western novels the word immediately suggests prosperous, high producing areas which spring into being almost overnight in the heart of the desert. To a buyer of securities during the early struggles of irrigation finance,
the word too often means financial loss. To a community in an arid region, which possesses some water resources, the word promises phenomenal increases in land prices. To a plantation agriculturist the word suggests dozens of unsolved problems of immediate personal application. To the trained investigator irrigation is a science as exacting as its allied fields of hydraulics, physics and plant physiology.

These widely separated points of view make development of interest in irrigation problems a slow process on the mainland, but irrigation is too vital in Hawaii to be ignored. When the nearest irrigation enterprise, except lawns and gardens, is a thousand miles away, thinking people in humid areas may be excused for lack of interest in the theoretical considerations of soil-moisture movement and relative rates of transpiration. Problems of irrigation finance are of slight appeal to the average citizen. But the problem involved in creating a permanent agriculture under irrigation is serious enough to demand the sympathy and help of all.

In 1901 and 1902 during a campaign which ended in the passing of the Reclamation Act by Congress, opponents of this measure insisted that agriculture under irrigation could not be lasting. They demanded that supporters of the proposed Reclamation Act recall a single irrigation enterprise which had proven permanent. The ruins of prehistoric irrigation works in Mesopotamia, China and Central America were offered as evidence of the fact that the agriculture and consequently, the civilizations which had been based upon irrigation, had been failures. Upon this insufficient evidence was raised the doctrine
of impermanence of irrigated agriculture.

And this opinion was not held exclusively by those inexperienced in agriculture or by those who for political or selfish reasons wished Federal support for irrigation development withdrawn. In 1918, one high in the United States Department of Agriculture in Washington had the following statement read into the minutes of a hearing before the Committee on Expenditures of the department, "I will even go so far as to say, what I have said before, that as far as I know, there has never been any long continued successful irrigated agriculture in any arid climate anywhere in the world."

It must be admitted that the challenge remains unanswered; for although extensive irrigation on the mainland began only about 80 years ago, some deterioration of land which must be charged against irrigation has been noted. Brown reports that "the most productive lands of these (irrigated) regions and those which were first brought under cultivation are, in many instances, now abandoned or fit only for wet pasturage." In some particular locations damage to irrigated lands has been caused by an accumulation of alkali which has rendered the lands unproductive. In other cases, areas irrigated by the recovery of underground waters have been abandoned because of the exhaustion of water resources which represented the accumulation of centuries.

But in most cases the deterioration of agricultural lands under irrigation can be traced to an excessive use of irrigation water and to the creation of a high water table.
with its consequent difficulties. During any early period of irrigation, water is abundant and cheap. There is no necessity for careful use; there is no clear understanding of the principles which make for the economic use of water.

Recent researches give some evidence of the relations between irrigation and plant growth; water shortages both real and imminent have made for a more conservative use of existing resources; the dangers of a local high water table have been too plainly demonstrated to permit excessive application. With our present knowledge of the mechanics of soil-moisture and with our present high costs of irrigation water, we may hope for no increase in the abandoned area. Furthermore, many drainage engineers believe that much of the land now abandoned may be reclaimed for agriculture when economic necessity is apparent.

The islands of the Hawaiian group are remarkably free from the dangers of over-irrigation which have threatened most irrigated areas. Here land is of such high producing capacity when irrigated that excessive irrigation of local areas is economically improbable. This fact, coupled with the usual adequate surface and sub-surface drainage, minimizes the danger which is ever present in less favored irrigated districts.

**Elemental Conceptions of Water Rights**

Successful irrigation farming on arid lands depends largely upon the permanence of the water supply used by the individual. No farmer nor corporation would be justified in the investment of time and money required in the construction
of canals and the preparation of land for the application of irrigation water unless that farmer or corporation were convinced of a right to water in the future. In areas where land is of little value for agriculture without water and of great producing ability if irrigated, the value of land may be measured, to a great extent, by the validity of an individual's claim to a share in the insufficient water supply in the area. A water right is legal assurance granted to an individual that his use of water from a given source may be permanent and unaffected by future development. It is not to be considered as a guarantee that the specified amount will be available for delivery nor that the specified amount is sufficient for the area to be irrigated.

Contentions over the legality of certain claimed water rights are as old as irrigation history. Widstoe, quoting Carpenter in "Principles of Irrigation Practice," gives the word "rivals" as derived from the Latin "rivus" meaning an artificial water channel or ditch; users from the same channel were "rivals." The implication of ancient controversies over water rights is evident.

The subject of water rights is more complicated than any other class of property right and although the laws of the many states vary widely among themselves, the basic legal conceptions of the subject are common to all.

R. P. Teele gives the following basic legal conceptions of water law upon which the most western states agree:

The use of streams and other surface water supplies
for irrigation and like purposes is subject to control by the states.

Water may be taken from streams and other sources for irrigation and other purposes but only in accordance with state laws. This is known as the right of appropriation.

Actual use of water is a necessary step in the holding of a right and when the use ceases, the right is abandoned or forfeited. That is, no one may acquire a right to water, and hold it without actually using the water, either immediately or within a reasonable time thereafter. This is known as the doctrine of beneficial use.

Among users of the same source, the first in time is the first in right. When there is not enough water for all, the rights are supplied in the order of the dates upon which they were acquired. This is known as the doctrine of priority.

In many states the undisputed use of water for a term of years, regardless of its source, may establish a tenable right. Such a right is a prescribed right; it is gained under the doctrine of prescription.

Some states, especially those most directly influenced by English law, recognize riparian rights as well as those of appropriation. A riparian right is the right to use water from a stream which flows through or along the borders of the land involved. In such cases use does not create nor disuse destroy the right. When riparian rights are recognized, each owner of riparian lands has the right to make any reasonable use of the water in the stream as
long as that use does not interfere with similar rights of others. The doctrine of riparian rights had its origin upon streams used for the generation of power and is patently unsuited as a basis for irrigation law. The complications arising from an effort to conform to the doctrines of appropriation and riparian rights, at the same time, are apparent.

The philosophy of water law in use in continental United States is quite distinct from that in force in Hawaii and is not to be confused with local practice. Here, water ownership is, in general, much more clearly defined and the subject is relatively free from legal complexities.

In the days of the early Hawaiian monarchy natural resources were considered as the property of the king and subject to his distribution. Favored chiefs received more or less definite grants of land, called ahupuaas. These were usually long narrow strips, extending from the mountains to the sea and bounded by such topographical features that natural drainage made the water resources of each grant easily determinable. Further subdivision lay in the hands of the chief, he being able to allot small tracts of land, or kulianas, to individuals for the growing of taro. The tenure of the individual on the kuliana depended upon the pleasure of the chief, while the chief might be removed from the ahupuaa by the king.

Since the taro-growing kulianas were of little value without water, the water resources of the ahupuaa were distributed among them in accordance with a time schedule,
each tract using the entire flow for a period commensurate with its size. Scattered records and legend seem to show that this distribution was rather highly organized, officers similar to the water masters on some modern projects enforcing equitable division of the available water.

This simple system was completely changed by Kamehameha III in about 1845. Land titles were made permanent at this time and by satisfying certain conditions of the newly established Land Commission, chiefs were able to establish legal ownership of their ahupuaas, while individuals gained title to their smaller areas.

Although the decree of land division, or the Grand Mahele, dealt chiefly with land titles, it has been tacitly understood that the existing water rights at the time of the Mahele were subject to the same division. Consequently the owner of an ahupuaa became owner of the water within that drainage basin except for the necessity of supplying patented kulianas with their usual and required amount. Since that time water rights have been considered as appurtenant to the land, although there is no necessity of using the water upon the specified tract.

Distribution was so effected at the time of the mahele that one-third of the land, together with its water resources, remained in the hands of the king. The king's lands were again divided, one-half becoming his personal property and one-half the property of the crown. Crown lands subsequently became the property of the Territory of Hawaii and are now administered by its properly appointed
officers. In general, the water resources of territorial lands are leased for discrete periods to responsible parties upon terms established at public auction.

As has been indicated, other water rights are private property and may be bought or leased, along with the lands to which they are appurtenant.

The use of underground water is not, at present, subject to the legal restrictions involved in the use of surface waters. In principle, rights to underground waters are subject to the same interpretation as surface streams when they flow in definite and well established water courses. Evidence of such a condition is difficult to secure, especially in Hawaii where the nature of the underlying lava tends to promote diffuse percolation.

In general, water rights in Hawaii are well defined and controversies are relatively infrequent. If ancient ahupuaas had run parallel with the shore line, so that each one contained a part of many drainage basins, the situation would doubtless be much more complex.

The Future of Irrigation Development

Modern irrigation development, especially upon Hawaii, is a costly and complicated venture involving an accurate knowledge of the land's potential producing ability, probable prices to be secured for crops, and the cost of transportation to large centers of consumption. In general, irrigation farming can only be justified if a local demand is
to be supplied or if the yields to be secured from the enterprise can be expected to exceed the yields obtained from more favorably located lands to such an extent that transportation and handling charges can be absorbed and a profit left in the hands of the irrigator. The days when a man with a shovel and boundless will could bring a barren tract into fruitfulness and make himself economically independent are gone.

There is some evidence that irrigated land suitable for highly diversified agriculture has a greater appeal to proponents of intensive culture than it has to producers of staple crops of great marketability. As a result, a temporary overproduction of these highly specialized crops is now threatened. The number of people undertaking the growing of crops of limited marketability is too often measured by the optimism of newcomers and promoters and not by an economic demand which must be satisfied.

Due to the world-wide sugar market, Hawaii is rather free from local overproduction of its most important irrigated crop. Other regulating factors, however, exist. Most of the easily available water has already been developed for irrigation and it is highly probable that further development will be at an ever increasing cost per unit quantity of water. In this way irrigation development in Hawaii, as elsewhere, will gradually approach a limit, not necessarily because potential irrigation resources are fully utilized but because further utilization is unprofitable.
**Collateral Reading**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Title</th>
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</table>
LESSON II
THE MEASUREMENT OF IRRIGATION WATER

The accurate measurement of irrigation water is essential for its highest use in irrigation, since the proper distribution of a given amount between areas of different water requirements is possible only when such measurements are made. Water measurement in studies of a crop's response to irrigation is patently necessary, while such measurement is essential in a study of transmission losses in any given irrigation system.

Water measurement by methods which are useful in the field should not be regarded as an exact procedure. Even under laboratory conditions where hydraulic factors are carefully controlled, surprising and unexplainable variations in results occur under conditions which are supposedly similar. In the field where the velocity of the water as it enters the measuring device may be subject to considerable variation and where other modifications in hydraulic conditions may be expected such as those occasioned by the deposition of silt above the device, the departure of the measured discharge from the true quantity may be relatively great.

Errors as great as five percent of the true quantity may be anticipated with weirs, although the use of these structures is commonly assumed to be our most accurate method of field measurement. Errors with other devices may be larger, although the nature of the possible errors involved with such structures as the submerged orifice makes it impossible to
set a limit as to their probable accuracy.

Field measurements of rates of flow are rarely, if ever, more accurate than may be expressed by three significant figures. In fact, weir and orifice tables are ordinarily limited to this refinement. Computations of volumes obtained by multiplying a rate of flow by a time unit cannot be more accurate than either of the factors involved. Consequently the product should be expressed with no more significant figures than occur in the least accurate factor. To report the result of the entire multiplication may give a false sense of security.

Units of Water Measurement

Rates of Flow

Cubic foot per second (c.f.s.). This unit represents the rate of flow required to fill a vessel with a capacity of one cubic foot, in one second. Since the rate of discharge always equals the cross sectional area of a stream times its mean velocity, the cubic foot per second is sometimes defined as the equivalent of a stream one foot wide and one foot deep flowing with a mean velocity of one foot per second. Second-foot and cusec (in British colonies) are other names for this unit.

Gallon per minute (g.p.m.). Since many irrigators receive their water supply from pumps, the discharges of which are ordinarily reported in terms of gallons per minute, this is sometimes a convenient unit to use. One cubic foot per second is approximately 450 gallons per minute.
Millions of gallons per day (M.G.D.). Some large displacement pumps are reported in this unit, especially when they are to be used for municipal water supply. The first pumps used in Hawaii for sugar cane irrigation were apparently described in terms of this unit and the use of this unit has become practically universal. One million gallons per day is approximately equivalent to 1.55 c.f.s.

Millions of gallons per 10 hours. This is a larger unit for rates of flow and is, of course, equivalent to 24/10 M.G.D. It is not used in irrigation work outside the Territory of Hawaii.

One man's water. This is a variable unit and is of little value in quantitative irrigation work. It is supposedly equal to the amount of water that a man can effectively handle in irrigating sugar cane.

Quantity

Acre foot. This is the equivalent of a body of water one acre in area and one foot deep or 43,560 cubic feet. One cubic foot per second, 450 gallons per minute or 0.646 million gallons per day running continuously for twelve hours will supply approximately one acre foot.

Acre Inch. This is one-twelfth of one acre foot. One cubic foot per second or an equivalent rate of flow, running continuously for one hour will supply one acre inch.

One Million Gallons. This unit which needs no definition is equivalent to 3.06 acre feet.
Transversion Factors

The following table will be found useful in changing the expression of a quantity of water from one of these units to another:

<table>
<thead>
<tr>
<th>c.f.s.</th>
<th>G.P.M.</th>
<th>M.G.D.</th>
<th>M.G.</th>
<th>per 10</th>
<th>per</th>
<th>Acre</th>
<th>Acre</th>
<th>Million</th>
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</thead>
<tbody>
<tr>
<td>M.G.</td>
<td>:10</td>
<td>:1</td>
<td>:1</td>
<td>:1 in</td>
<td>:1 in</td>
<td>:1 in 37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c.f.s.</td>
<td>--</td>
<td>450</td>
<td>0.646</td>
<td>:12</td>
<td>:1</td>
<td>:1 in</td>
<td></td>
<td></td>
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<tr>
<td>G.P.M.</td>
<td>1</td>
<td>--</td>
<td>0.00144</td>
<td>:5,400</td>
<td>450</td>
<td>:16,500</td>
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<td>M.G.D.</td>
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<td>--</td>
<td>:7.74</td>
<td>:0.65</td>
<td>:24</td>
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<tr>
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<td>:3.72</td>
<td>:1,680</td>
<td>:2.4</td>
<td>:2.24</td>
<td>:0.27</td>
<td>:10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acre</td>
<td>:1</td>
<td>:12</td>
<td>:1</td>
<td>:1 in</td>
<td>:1 in</td>
<td>:1 in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>:1</td>
<td>:12</td>
<td>:1</td>
<td>:1</td>
<td>:1</td>
<td>:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acre</td>
<td>:12</td>
<td>:1</td>
<td>:1</td>
<td>:1</td>
<td>:1</td>
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<td></td>
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</tr>
<tr>
<td>Inch</td>
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<td>:0.0271</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mil.</td>
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Weirs

A weir is one of the simplest and most accurate means of measuring irrigation water on the plantation. Unfortunately, local conditions often prohibit its use. Although the word originally meant any sort of a dam or barrier in a stream, its use is now limited to such barriers as have been modified to permit the measurement of the water flowing over them. A modern weir as adapted to use in a small irrigation canal is a
water tight bulkhead placed across the stream, the water passing in a relatively thin sheet over the top of the bulkhead or through a notch cut for that purpose. The opening is called the weir notch. The depth of water pouring through this notch is the measure of the amount of water in the stream. The arithmetical relation between depth, or "head", and discharge is usually quite complex, tables being provided for the rapid and accurate determination of the rate of flow when the measured depth is known. In some cases the weir bulkhead is placed in a short section of flume and the structure is called a weir box; in others it is placed directly across an earthen ditch section and is independent of any other structure. The method of weir measurement remains the same in either case.

There are certain conditions which must be observed before a weir can be used for the accurate measurement of water, if only ordinary tables are available. In general, it may be said that the "weir crest", or bottom of the weir notch, should be so short that the amount of water to be measured will never give a depth of less than two inches over the crest, and long enough that the depth will never be more than one-third of the length of the crest. Care should also be taken to see that the weir crest is long enough so that the water can pour through the notch without having to back up in the channel to a greater height than can be done with safety to the ditch bank. A number of other conditions are usually laid down as necessary for the weir. The most important of these are as follows:
1. The weir crest or bottom of the weir notch must be absolutely level.

2. The water passing over the weir must have a free "overfall". If the water in the ditch below the weir is allowed to rise to such a height that this free fall is not possible, the weir is said to be submerged. Measurements made on a submerged weir are unreliable unless complicated corrections are introduced.

3. The distance from the crest of the weir to the bottom of the canal or to the floor of the weir box above the weir crest need only be great enough to check the velocity of water flowing in the bottom of the stream, say about 0.5 foot for small weirs.

4. The distance from the ends of the weir crest to the sides of the weir box or canal or ditch should be about twice the depth of the water on the weir, or, say from ten to twelve inches in the case of a weir with an eighteen inch crest measuring about two cubic feet per second.

5. The bottom and sides of the weir notch should have a narrow edge. The use of a galvanized iron crest to give such a narrow edge is quite common and very satisfactory but not necessary. Sometimes thin pieces of strap iron are fastened on the up-stream side of the weir notch. In other cases the board in which the weir notch is cut is merely beveled on the down-stream side to a crest thickness of one-eighth or one-quarter of an inch.

6. Water should not be allowed to approach the weir with a velocity exceeding six inches per second. Also, it should
flow to the weir in a smooth stream free from eddies or swirls. Both of these conditions are most easily met by placing the weir in a straight section of the ditch and, when necessary, by placing baffle boards across the channel.

7. The depth of water on the weir crest must be measured sufficiently above the weir to be free from the downward curve of the water as it passes over the weir. For convenience in making this measurement of depth a stake with its top level with the crest of the weir is usually set at one side of the ditch two or three feet above the weir, the measurements of depth being made from the top of this stake to the surface of the water.

It will be noted from these conditions that the weir is not a suitable means of measuring water under all conditions. In ditches where the grade is very slight, placing a bulkhead across a stream and raising the level of the water above the weir often results in a break in the ditch bank. In such cases it is also difficult to keep the weir from becoming submerged.

In streams heavily laden with silt the weir is not a practical means of measurement, since reducing the velocity of the water to the point necessary for weir measurement soon precipitates such a quantity of solid matter above the weir that suitable weir conditions no longer exist.

Weir Notches

Although weir notches of many shapes have been proposed from time to time by engineers who have hoped to simplify methods of water measurement, the notches used in
irrigation practice are limited to three common types. These are the rectangular notch, the Cipolletti notch and the triangular notch.

The hydraulic characteristics of each of these notches have been carefully studied by Victor M. Cone at the hydraulic laboratory of the U. S. Department of Agriculture at Fort Collins, Colorado. Although it is theoretically possible to compute the discharge through a notch of any of the common shapes by the principles of hydraulics and the integral calculus, Cone finds that such rational computations do not adequately represent the real performance of the notch. His weir tables are therefore based upon actual volumetric determination, the discharge at a given and carefully maintained head being collected in a large tank and measured after a given time interval. By computation he secures the rate of discharge during that time interval, this figure being used in the preparation of his discharge tables. The empirical relation between head and discharge as provided by Cone is mathematically complex. A table of logarithms and some skill in arithmetic manipulation is required unless a table in which these computations are already made is at hand. Such tables are provided in Farmers' Bulletin 813, "Construction and Use of Farm Weirs" by Victor M. Cone. A copy of the bulletin should be in the hands of every irrigation overseer and agriculturist. They can be had without charge by addressing Division of Agricultural Engineering, Bureau of Public Roads, U. S. Department of Agriculture, Box 180, Berkeley, California.
**Rectangular Notch**

This notch is the earliest form used in experimental work and is today the most popular in irrigation measurement. It consists of a level crest, of a length determined by the quantity to be measured, and sides which meet the crest at exactly 90°. It is easily constructed with tools ordinarily at hand and may be easily checked for accuracy when installed.

**Cipolletti Notch**

The Cipolletti weir is trapezoidal in shape, the crest being level. The sides are not vertical but slope outward on a 1 to 4 slope. The shape was first proposed by an Italian engineer who believed that discharge would be directly proportional to crest length with such a notch. In such a case all weir tables except that for unit length might be abolished. Subsequent work however has demonstrated that this assumption is no more true for the trapezoidal notch than for the rectangular shape. The Cipolletti notch is more difficult to construct than the rectangular notch and since it does not have the advantage originally credited to it, it is rapidly going out of use. Cone's bulletin carries discharge tables for the Cipolletti weir for the use of irrigators who already have weirs of this type.

**Triangular Notch**

The triangular notch ordinarily used in irrigation practice carries an angle of 90° and is so installed that the bisector of the angle is vertical. Since the crest length is zero, only one discharge table is required. This is provided in Cone's bulletin, cited above.
Notches of this type are especially adapted to the measurement of relatively small flows, since for such heads a slight error in observation of depth in the notch may be insignificant in the determination of the discharge. The advantage disappears as the flow increases. Since small flows cannot be accurately measured with either the rectangular or Cipolletti notch, the triangular weir finds its greatest usefulness in that range of discharges in which it gives the greatest promise of accuracy.

Submerged Orifices

In cases where the grade of ditch is so flat that the required free fall over a weir cannot be easily obtained, and in cases where the waters are so heavily charged with silt that there is danger of a weir pond silting up, some type of submerged orifice is commonly used.

The measurement of water through orifices has long been common in irrigation practice and various forms of orifices have been developed. The essential condition in the use of an orifice, eliminating the question of form, is that the water on the up-stream side of the orifice shall completely submerge it. If, when in use, the surface of the water on the lower side of the orifice is below the bottom thereof, the orifice is said to have a free discharge. If the surface of the water on the lower side of the orifice is above the top of the orifice, completely submerging it, it is classed as a submerged orifice. Except in the case of the miner's inch box as used on the mainland and which is really but a form of orifice with
free discharge, use of the orifice in irrigation practice is mainly confined to the submerged form.

Submerged orifices as used can be divided into two general types, viz: those with orifices of fixed dimensions and those built so that the height of the opening may be varied. Orifices of fixed dimensions are usually made with sharp edges similar to the crest of a weir. The most usual type of adjustable orifice is the simple head gate, the height of opening and loss of head being adjusted to the amount which it is desired to turn out and to the loss of head available. Of these two types, the sharp-edged orifice of fixed dimensions is much the more accurate in practice.

With either of these types of submerged orifices, the quantity of water passing through the orifice is measured by the difference in water level above and below the orifice. Such a difference in water level always exists in devices of this sort. This difference in water level is commonly called the "difference in head" or "loss of head." The small "h" is usually used to represent this difference.

The amount of water which passes through a submerged orifice of fixed dimensions increases but not directly as "h" increases. Theoretically, if "h" could be indefinitely increased, any quantity of water could be passed through an orifice with an area of one square foot. Practical difficulties make it impossible for this difference in head in small ditches ever to become larger than about eighteen inches. In ditches on very flat grades this difference in head can not become more than four or five inches without endangering the ditch bank.
above the orifice.

In cases where sufficient discharge can not be obtained through the orifice with the loss in head that is permissible, a larger orifice may be used. With a given difference in head, the discharge as a first approximation may be considered as directly proportional to the area of the orifice and unreasonable difference in head can be reduced by increasing this area.

Computation of Discharge Through Submerged Orifices

As has been indicated the discharge through any orifice, when it is completely submerged, is a function of the area of the orifice and the difference in head acting upon the orifice. The computation for discharge may be readily made by use of the following equation.

\[ Q = A \times C \times \sqrt{gh} \]

Where \( Q \) = Discharge in c.f.s.

\( A \) = The area of the orifice in square feet.

\( C \) = A coefficient of discharge having a value of about 0.61 for metal-faced openings with full contraction.
\[ g = \text{The acceleration of gravity} = 32.2 \]
feet per second per second.

\[ h = \text{Difference of head in feet}. \]

The greatest source of error in the use of this formula lies in selecting the proper value of \( C \). The U. S. Reclamation Service uses a value of 0.61 for \( C \) when the orifice is metal-faced and provided with complete side and bottom contractions. There is some reason to believe that this value should increase as the contractions are reduced or eliminated.

Adjustable submerged orifices of the headgate type are not used in Hawaii. The value of \( C \) with this type of orifice is reported as decreasing with the area of the opening.

**The Venturi Meter**

This device is based upon unquestioned hydraulics and when accurately manufactured, calibrated and installed is capable of great precision in measurement. The device is based upon Bernoulli's theorem. The stream to be measured is introduced
into a converging section of a closed conduit, through a throat of relatively small cross section and then into a third diverging section. Piezometer tubes in the converging section and in the throat indicate the pressure head lost by the increase in velocity due to the constricted cross section in the throat. Such difference of pressure then becomes functions of the velocity through the throat and consequently functions of the discharge.

It is evident that the Venturi meter is adapted only to flows under pressure. It consequently finds its greatest field in Hawaii in the measurement of pump discharges. Ingenious recording attachments for Venturi meters are available. These devices not only do away with the necessity of personally measuring the pressure loss between the points of measurement but also interpret the existing pressure loss in terms of rate of flow. They also keep a graphic record of such changes of rate.

At one time the Builder's Foundry at Providence, Rhode Island designed a Venturi meter for the measurement of water delivered from a main gravity ditch to a lateral. This adaptation did not prove practical and is now rarely used.

The Venturi meter is costly and heavy. The recording device is elaborate and requires considerable attendance. When properly installed it is more accurate than most water measuring devices.

The Venturi Flume

The Venturi flume is an adaptation of the hydraulic
principles of the Venturi meter to the conditions of the open ditch. In its original form the Venturi flume consisted of three sections of flume on a level floor. The first section was converging, the walls of the middle section were parallel, while the third section was divergent. From the hydraulics of the Venturi meter it was believed that as a stream passed from the converging section to the parallel section, velocity head would be gained at the expense of pressure head and the water level in the parallel section would be lower than in the converging section. Furthermore, the loss of head between these points might be assumed to measure the discharge through the device. This speculation was verified by experimental work under the direction of R. L. Parshall at Fort Collins, Colorado. The practical difficulty with the old type of Venturi flume was the extreme care required in the measurement of the water levels in the converging section and in the throat. Since this difference was often less than one eighth of an inch, the accuracy required in the two readings practically eliminated the device from field use.

A modification of the original flume has been perfected by Mr. Parshall. The new device is called the Improved Venturi Flume. Although it abandons the rational conception of the Venturi meter and the original Venturi flume, it does perform with surprising accuracy. It promises to find a useful field in irrigation water measurement. In the improved flume the floor is no longer level throughout its length but breaks sharply downward at the end of the converging section until at the beginning of the diverging section the floor is
nine inches below the level of the intake section. At this point the floor slopes upward again until at the outlet it is three inches below the floor of the intake section.

Only one point of measurement is required, this being at a point in the intake section one third of the distance from intake to the throat. The discharge through the flume is obtained from a table.

The new flume possesses certain valuable advantages in addition to its accuracy which is of about the same order as that of a well built weir. It has no moving parts to require attention. It can operate accurately with a much smaller loss of head than can a weir of similar capacity. There is no tendency for the device to clog when used with water heavily charged with silt, since the velocity of the water is increased during passage through the device and scourging action effected.

The Improved Venturi flume has been tested by engineers of the Division of Water Rights of the State of California and has been adopted by them as a standard device for measuring water.

Tables of discharge and working drawings for this device in its many sizes may be obtained from the Experiment Station of the H. S. P. A.

The Rated Section

The rated section may be any flume, box or ditch section in which the height of water on an arbitrarily established gage may be evidence of the amount of water flowing at the time of observation. The determination of the relation between gage height and discharge is called "rating the section," the future accuracy of observations made upon the section being determined
primarily by the care used in rating. When a section is adequately rated, a rating curve indicates the discharge through the rated section for every probable gage height. Such a curve may be used in conjunction with a rated section in the same manner as a weir table is used with a weir.

It is evident that the rating of the section requires the use of some other measuring device. The current meter is ordinarily used for this purpose. This device, in skillful hands, furnishes a close approximation of the mean velocity of the stream in question, while this velocity multiplied by the cross sectional area give the discharge in c.f.s. Noting the gage height corresponding to this discharge furnishes one point on the rating curve.

Under usual conditions in the field the permanence of the relation between gage height and discharge demands a control of some sort below the gaging station. This may be a low dam across the stream or a long length of lined ditch section. In the case of a natural stream it may be a rock outcrop or a lava dyke. Its purpose is to protect the relation between gage height and discharge in case of change in the ditch section below the control.

It is interesting to note that the rating curves for most rated sections, except in the case of natural stream beds, become straight lines on logarithmic paper. In such a case the most probable position of the rating curve can be quickly and accurately determined.

The literature dealing with the use of the current meter and the selection and rating of sections for water measure-
ment is voluminous. The books by Hoyt and Grover and by Liddel as given in the collateral reading are especially good. They should be carefully studied by anyone who newly undertakes the manipulation of the current meter and the use of rated sections in a well planned water measuring program.

Water-Stage Recorders

It will be noted that the water measuring devices so far described have simply indicated the rate of flow at the instant of the observation. In order that the total discharge in a given time may be determined, observations upon the head must be made with a frequency depending upon the rate of its fluctuations. Since such frequent observations are impractical under usual plantation conditions, important measuring devices are provided with water-stage recorders. They are not measuring devices.

They simply provide a graphic record of the fluctuations of the water level in the device upon which they are installed. From such a record it is possible to compute the daily or weekly discharge through standard devices or through adequately rated sections.

The use of the planimeter or other device for the determination of the average ordinate from water register charts is subject to strict limitations if accuracy is desired. Major O.V.P. Stout, in some unpublished work at the University of California, concludes that the average discharge as calculated from the average head on a water register sheet is too small in the case of weirs and too great in the case of orifices. For weirs this difference is not material when the smallest
ordinate on a single sheet is greater than 3/4 of the greatest ordinate on that sheet. For orifices this difference is not material when the smallest ordinate is greater than 2/3 of the greatest ordinate on that sheet. When greater variations in ordinates than those indicated above occur, the sheet may be divided into zones and each zone considered separately in the casting of the average ordinate; or a new curve in which rate of flow is plotted against time may be prepared. The average rate of discharge obtained by means of the planimeter on this new curve may then be multiplied by the proper time factor to give the total flow for the time interval in question.

**Mechanical Devices for Measuring Water Volumetrically**

It frequently is desirable that a measuring device should record the volume of water delivered to irrigators, rather than the rate of flow. Numerous mechanically recording devices have been designed to accomplish this, several of these being described below. Without discussing the individual merits of these devices, it may be said that although several of them are in common use and are believed by those using them to be giving more or less satisfactory service, there are many practical difficulties involved in operating devices of this nature. It would, therefore, seem that when a mechanical device is selected for measuring individual deliveries of irrigation water, the practical limitations of the device chosen should be understood. This is desirable in order that care may be taken to provide the conditions necessary for satisfactory measurements,
and also that the need for occasional tests of the operating accuracy of the devices may be appreciated.

Reliance Meter

The Reliance meter consist of a brass vane, shaped something like a propeller wheel, set in a throat, and a brass rod which connects the vane to the recording head. This recording head contains gearing which is connected with a counter. The figures in this counter show the number of acre-feet of water which have passed through the device.

This apparatus is set so that the water to be measured pours between a series of plates or vanes and on to the propeller shaft in the throat. It can be used in either open ditches or pipe lines operating under low pressures.

The great advantage of such a device lies in the fact that it shows at a glance how many acre-feet of water have passed through the meter. With most devices some computations are necessary to change the expression of the flow in cubic feet per second into terms of acre-feet.

Dethridge Meter.

In the Reliance meter only a part of the stream hits the propeller wheel and turns it. In the Dethridge meter the whole flow of the stream is directed against the wheel. The wheel in this case is a large sheet-iron drum, three feet, four inches in diameter and two feet, six inches wide. Attached to the outer surface of this drum are a series of heavy blades which extend ten inches beyond the circumference of the drum.

This drum turns in hardwood bearings attached to a heavy base. When the wheel turns the projecting blades fit closely into a depression in the concrete floor of the device.
Water, when turned into the device, presses successively against the blades on the cylinder and turns it in the bearings. A counter can easily be arranged to record these revolutions. With a Dethridge meter of the size described above, the discharge per revolution is about 30.5 cubic feet of water, regardless of the speed at which the wheel revolves. Each wheel installed should be accurately calibrated to determine the quantity of water discharged by the wheel per revolution. The Dethridge meter has been very popular in Australia where a large number are in use. A description of the Dethridge meter is included here because it involves a new principle.

The Sentinel Meter.

This meter is mounted in a two-foot section of steel pipe designed to be set in an irrigation pipe line, the size of the meter and of the steel section depending upon the size of the pipe line. A simple turbine wheel is mounted on a bracket coming from an upper element of the steel section. The turbine is rotated by the velocity of the water in the pipe line, the speed of rotation supposedly being proportional to the rate of flow since the cross sectional area is constant. Suitable gear trains actuated by the rotation of the turbine record discharge in terms of acre-feet. It is evident that the sentinel meter in its present form can be used only on pipe lines operating under pressure.

Great Western Meter or Lyman Meter

This device is an attachment for existing structures for the measurement of irrigation water, such as submerged
orifices or Venturi Flumes and permits the immediate
determination of the amount having passed through the device
since the last observation. Essentially, the device consists
of a delicately balanced turbine which is subjected to the
same pressure head as the structure. The rotation of the
turbine is carried into a gear-housing above the surface of
the water where suitable gear trains operate counters which
indicate the discharge in volumetric units.

Collateral Reading

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York.
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Parshall, R. L.  1925 - The Improved Venturi Flume, Colo.
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LESSON III
THE PHYSICS OF SOIL MOISTURE

The soil is a complex mixture of rock fragments, organic remains, living organisms and those peculiar, finely divided, insoluble final products of previous weatherings which, in ordinary speech and writing, are grouped together under the generic term of soil colloids. The relative importance of these various constituents in the physical and chemical behavior of a soil depends upon the point of view of the soil scientist who is called upon to rate them. The pure soil physicist, at least until a few years ago, conceived of the soil as a jumbled mass of clean, inert rock fragments of many sizes and shapes. Many times he idealized his problems by substituting minute glass beads or similar material for soil particles in order that the number of variables involved might be reduced. The soil bacteriologist and zoologist might readily attribute many soil processes to the activity of microscopic soil organisms, while the colloidal chemist is apt to attribute all soil characteristics to the finely divided, insoluble hydrates of iron, aluminum and silica which, according to Hubbard, necessarily result from the natural weathering of igneous rock.

Some Physical Properties of Soils

These many factors which affect the physical characteristics of a soil make an accurate yet concise description of a particular soil rather difficult. The U. S. Bureau of
Soils classifies soils by mechanically separating a sample of that soil into component lots each one containing soil particles, the average diameters of which lie between certain arbitrary limits. The soil can then be described in terms of the percentages of the material found in the several lots. In the literature of the Bureau of Soils such terms as "sandy loam" and "silt loam" have rather definite meanings since a soil to be classed as a definite type must have a preponderance of soil particles of certain sizes. In popular writing and colloquial speech these terms may mean something quite different. The method of mechanical separation used by the Bureau of Soils is complex and tedious. Bouyoucos proposes a more rapid analysis by means of an especially calibrated hydrometer.

Although this method is open to serious question as pointed out by Keen, it seems to offer a fairly accurate short cut to the results of the more elaborate mechanical analysis.

If the soil is conceived to be a mass of irregularly shaped rock fragments, several relations immediately present themselves which, although simple, are of importance in water relations. It is evident that the number of soil particles found in a given volume increases as the mean diameter of the particles decreases and as the degree of packing approaches the maximum. Furthermore, the surface area increases rapidly as the soil particles become smaller. It may also be assumed that an individual pore space lying between adjacent soil grains will become smaller as the soil grains decrease in size, although the number of such pore spaces will be tremendously increased. For this reason a clay soil carries a greater percentage of pore space.
than a soil of coarser texture. If the real specific gravity of a soil grain is assumed to be constant regardless of the fineness of division, it is evident that the weight of a unit volume of clay when dry will be less than that of a similar volume of sand. The terms "light soil" and "heavy soil" refer to the difficulty experienced in working them and not to their actual weight.

The following table, after King, illustrates the relation between the quantities discussed above.

**Effective diameters of particles, pore space and surface areas in common soil types.**

<table>
<thead>
<tr>
<th>Soil</th>
<th>Effective Diameter of average soil grain in millimeters</th>
<th>Percent of pore space</th>
<th>Effective surface area exposed in one cubic foot of soil, in sq. feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sandy soil</td>
<td>0.1432</td>
<td>32.9</td>
<td>8,318</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.0755</td>
<td>34.3</td>
<td>15,870</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>0.0303</td>
<td>38.8</td>
<td>36,880</td>
</tr>
<tr>
<td>Loam</td>
<td>0.0219</td>
<td>44.1</td>
<td>46,510</td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.0140</td>
<td>45.3</td>
<td>71,316</td>
</tr>
<tr>
<td>Clay</td>
<td>0.0086</td>
<td>48.0</td>
<td>110,500</td>
</tr>
<tr>
<td>Fine clay</td>
<td>0.0049</td>
<td>52.9</td>
<td>173,700</td>
</tr>
</tbody>
</table>

The physical properties of Hawaii soils have never received the detailed study they deserve in view of their unusual nature as well as their great economic importance. They are patently highly colloidal, the proportion of particles falling into this arbitrary size group, ranging between 50
percent and 60 percent for many of the soils studied. The great preponderance of small sized particles is reflected in a great pore space and a consequently low weight per unit volume. In general they are easily worked and drain quickly. Although the mechanical analysis of a typical Hawaiian soil would classify that soil as a clay or fine clay, the soil lacks most of the properties of this class. In general they do not bake upon drying nor do they "puddle" if worked when wet.

**Volume Weight**

The volume weight of a soil is the weight of a certain volume of that soil when oven-dry, divided by the weight of an equal volume of water. Volume weight is sometimes called apparent specific gravity, the absolute specific gravity being the true density of the individual grain without reference to the pore space. For example: if a soil with a pore space of 45% weighs 88 pounds per cubic foot when oven-dry, its volume weight or apparent specific gravity would be $\frac{88}{62.4} = 1.41$. The true volume of the soil grains themselves is only 0.55 cubic feet; however, in view of the 45% pore space, the absolute specific gravity would be $\frac{88}{0.55 \times 62.4} = 2.56$.

Lyon, Fippen and Buckman suggest that for most mineral soils the specific gravity of the soil particles is about 2.7. A value of 2.6 was secured as the real specific gravity of a certain Waipio soil.

It is evident that the volume weight of a soil varies with the pore space in the soil and the specific gravity of the
individual grains. This relation may be expressed:

$$\text{Volume Weight} = \text{Specific Gravity} \times \frac{100 - \text{Percentage of pore space}}{100}$$

This equation is of little practical use since a measurement of pore space in the field is difficult if not impossible. It must be remembered that the percentages of pore space for various soil separates as given in the table above are computed upon the assumption that the soil grains are spheres of a given diameter and arranged in rigorous geometrical pattern in the soil. The value of volume weights as determined by the formula above and based upon theoretical pore space is usually greater than that which actually exists in the field.

Several methods have been devised for the field determination of volume weight since this ratio is an important factor in the determination of the surface irrigation needed in given conditions. In all of these, two quantities must be measured: first, the oven-dry weight of a sample of soil taken from the field at the desired point and, second, the volume occupied by the soil sample before removal. By converging the volume factor into the weight of an equal volume of water the required ratio may be easily determined.

In all methods of volume weight determination now in common use in Hawaii, the soil sample is taken with the common type of post hold soil-auger, all the soil being carefully saved for oven drying. Israelson suggests determining the volume of the hole, previously occupied by the sample, by inserting a long, thin walled rubber tube into the hole and carefully measuring the amount of water required to fill the
rubber-lined hole to the ground surface. This method assumes that the pressure of the water in the tube is sufficient to distend the tube into the minor irregularities of the sample hole. If this is not the case the measured volume is less than the real volume and the apparent volume is greater than the real value. Another disadvantage to the rubber tube method is the difficulty of handling the tube in the field and the fact that it deteriorates rapidly when not in use.

Beckett eliminates the tube entirely and measures the volume of the hole by filling it with a viscous liquid such as heavy engine oil, road oil or cheap molasses. By measuring the required volume of liquid by a graduated cylinder, or by gravimetric means when the specific gravity of the liquid is known, the volume of the sample hole can be quickly and accurately determined. An evident, theoretical objection to this method is the loss of liquid by seepage during the time required to fill the hole. This error would tend to indicate a volume greater than the real volume and result in a low volume weight. However, materials of the viscosity indicated above often stand in such holes for as long as ten minutes without appreciable loss by seepage. Since thirty seconds at most is required to fill the hole, the error due to this cause must, indeed, be negligible.

As has been indicated above, Hawaiian soils are soils of low volume weight. Determinations at Waipio (Oahu), Eleele (Kauai), and the experiment farm of the University of Hawaii at Honolulu give a consistent value of 1.1 for this important soil constant. This result is remarkable for two reasons; first, because it is so low, mainland soil ranging from 1.2 to 1.5, and
second, because it is so consistent among samples from widely separated points, although Hawaiian soils are supposed to be highly variable. Deere also gives a value of 1.1 for the volume weight of Hawaiian soils.

The Nature of Soil Moisture

No soil in the open air can be absolutely dry. Soils are hygroscopic in nature and when an oven dry soil is exposed to a damp atmosphere, the soil gains in weight due to the incorporation of moisture, the percentage of gain being much more pronounced with fine soils than with those of coarser texture.

The position of this moisture in the soil is a cause of much speculation. The conception of the soil physicist of only a few years ago was that this moisture was held in thin films around the inert soil grains by surface tension and in small wedge shaped masses lying between these films near their points of tangency, by the same minute and poorly understood force. Bouyoucos seems to believe that soil grains are more complex than previously supposed and tentatively coats each grain with an envelope of colloidal material which holds part or all of the hygroscopic water as absorbed water. Whitney intimates that small, partially indurated fragments of colloidal aggregate may be mixed throughout the soil mass and that they supply a part, at least, of the hygroscopic capacity. Neither Whitney nor Bouyoucos suggests the proportion of water in the soil colloids as compared with that held in the more commonly accepted films and wedge-shaped masses.
A discussion of the nature of the bond holding water in the soil is perhaps academic; but whatever the force may be it is surprisingly great. Shull has shown that a certain clay soil when air-dry holds moisture with a force equal to about 70 atmospheres of pressure. Further evidence of the tenacity with which relatively dry soils hold water is furnished by observations upon the slow rate of drying when air-dry soils are subjected to a constant and relatively high temperature.

The hygroscopic coefficient of a soil is the percentage of moisture, on the dry basis, which an oven dry soil will absorb when exposed to a saturated atmosphere at a specified temperature. Although this term is frequently encountered in the literature of the subject it is difficult to determine accurately and is not now widely used in quantitative soil-moisture work.

**Maximum Water Holding Capacity of Soils**

As might be indicate from observation of the rate of drying under conditions of constant temperature and humidity, the tenacity with which moisture is held in a soil mass decreases with increasing soil-moisture contents. Consequently it might be expected that at some point in the soil-moisture range, for a particular soil type, there would be a point where moisture was held around the grains, or in the colloidal aggregate, with a force exactly equal to the force of gravity. If a soil could be wetted to such a moisture content, drainage from the soil mass could not occur because of a balance, analogous to a static equilibrium.
This moisture content is of vital importance in irrigation practice. It represents the soil-moisture content in a field shortly after an irrigation. It is patently impossible to irrigate to a lower moisture content than that indicated by the maximum water holding capacity. If such a result is attempted by a scanty application of irrigation water, only a part of the soil mass will be affected, that part being wetted to its maximum water holding capacity, while soil lying below this depth remains at its original moisture content. Attempts to irrigate to a greater soil moisture content than the maximum water holding capacity result in wetting a greater depth to that moisture content where adequate drainage is provided and in the saturation of the lower depths when an impervious intercepting stratum is encountered.

In many cases the line separating the wetted soil resulting from an irrigation, from the dry soil below can be readily located by trenching or soil-moisture sampling. This is most easily done if the soil is relatively dry prior to irrigation, for in this case the line of demarcation can be detected by a change of color. Veihmeyer shows the results of such observations in Figure 22, page 192, Hilgardia Vol. 2, No. 6, "Some Factors Affecting the Irrigation of Deciduous Orchards." Here a rainfall of 2.15" is shown as penetrating about 14 inches, each increment of depth above that line being filled to maximum water holding capacity. Below this line of demarcation the original dryness of the soil mass was apparent.

It must be carefully noted that the depth of penetration resulting from a given surface application depends
upon the original moisture content, the local water holding capacity of the soil and its volume weight. In order that the surface separating the wetted soil from the dry soil below might be a geometrical plane, the soil would necessarily be uniform in all its physical properties throughout the mass above that plane. Such conditions are rare in the field.

The importance of this conception of soil moisture distribution cannot be overestimated. The words "light irrigation" and "heavy irrigation" lose their meaning except insofar as they determine the resulting depth of penetration. And an accurate knowledge of the rooting habit of the plants in question becomes increasingly important, since moisture can reach the lowest zone of root activity only when the entire soil mass lying above it has been wet to maximum water holding capacity.

Saturation

Although the term saturation is used synonymously with maximum water holding capacity in some of the older literature, modern use confines the term to the moisture content resulting from a complete filling of all the pore spaces in a soil mass with water. In general, water will drain from a saturated soil if adequate drainage is provided, until the soil mass retains only its maximum water holding capacity. Exceptions to this simple rule, encountered when small containers are used, make it difficult to determine maximum water holding capacity in this way.
The Moisture Equivalent

From its definition the maximum water holding capacity of a soil might be determined by sampling that soil immediately after irrigation and determining its moisture content. Although this method may be used to good advantage under certain conditions it has the disadvantage of requiring rather large areas of soil. As has been indicated above, the wetting of small masses in containers is not a satisfactory way of determining the maximum water holding capacity.

The determination of the moisture equivalent, however, gives a close approximation of the water holding capacity of most soil and requires only small samples of material. When this method is used, samples of the soil are placed in small brass boxes provided with screen and filter-paper bottoms. The samples are saturated and subjected to a centrifugal force equivalent to 1000 times the force of gravity. The percentage of moisture remaining in the soil after 30 minutes in the centrifuge is the moisture equivalent.

Although the original work by Briggs and McLane in this field of soil research was done without any appreciation of its modern application, the moisture equivalent is now assumed to be a function of the internal surface of the soil, the moisture equivalent increasing as the internal surface increases. An interesting example of this conception of the moisture equivalent is to be found at the new Alexander dam of the McBryde Sugar Company. Here the hydraulic material used for the dam was so distributed that the moisture equivalent of the material in the core-wall was kept at about 80%. This value indicates a great surface area per unit volume and consequently a mean size of soil grain within the range needed
As has been suggested, a more useful application of
the moisture equivalent lies in the fact that for many soils
the moisture equivalent is approximately equal, numerically,
to the maximum water holding capacity. The reason for this
close agreement is not well understood but the relationship
is widely used and furnishes a good measure of the maximum
water holding capacity of a soil when only small samples
are available for laboratory study. An illustration of
this agreement is to be found in Figure 22 in Hilgardia, Vol.
2, No. 6, referred to above. Here the upper figure at each
point of sampling is the moisture equivalent of the sample at
that point, while the lower figure is the maximum water holding
capacity. The average of ten observations of the moisture
equivalent is 22.2 while the average of the maximum water hold-
ing capacities for the same samples is 22.7.

Some workers assume that the moisture equivalent is
not exactly equal to the maximum water holding capacity but is
directly proportional to it. If the few figures used above
can be accepted as indicative, the moisture equivalent might
be multiplied by 1.02 for the determination of the more
valuable constant.

The use of the moisture equivalent is new in Hawaii.
Ten samples from a small plot at Waipio give an average moisture
equivalent of 32.1 plus or minus 0.2, while the sampling of
the same area shortly after irrigation gave a maximum water
holding capacity of 34.3. The ratio in this case is 1.07,
or practically unity in view of the relative accuracy of the
contributing factors.

The moisture equivalent is the only common denominator for the interpretation of soil moisture percentages. When irrigation control is based upon actual soil moisture sampling the moisture equivalent provides a means of analyzing the results. It is, however, a costly and perhaps unnecessary refinement to plantation procedure and should only be adopted after mature consideration.

The Wilting Coefficient

Land plants obtain moisture from the soil by extending absorptive root hairs into the films of water adjacent to soil particles. When soil-moisture is so tightly held in a soil by the forces indicated above that osmotic forces occasioned by the more concentrated cell sap of these hairs is not able to maintain normal turgor within the plant tissue, the plant is said to wilt.

Briggs and Shantz define the wilting coefficient as the moisture content in the soil (expressed as a percentage of the dry weight) at the time when the leaves of a plant growing in that soil first undergo a permanent reduction of their moisture content as a result of a deficiency of soil moisture supply. By permanent reduction is meant a condition from which the leaves cannot recover, in an approximately saturated atmosphere, without the addition of water to the soil. These investigators working with more than a score of soils and hundreds of species report results which lead them to conclude that the wilting coefficient is a definite soil-moisture
constant in the same sense that the hygroscopic coefficient and the moisture equivalent may be considered as definite soil-moisture constants. Slight differences in residual moisture constant which occurred in a single soil, when different species were used as indicator plants, were attributed to a more perfect root distribution with one species as compared to another and not to the ability of some species to exert a greater attractive force upon the soil moisture than others.

A mathematical analysis of the results obtained from those experiments suggested the following equation:

\[
\text{Wilting Coefficient} = \frac{\text{Moisture Equivalent}}{1.84}
\]

Although Veihmeyer and Hendrickson have verified the results of Briggs and Shantz with respect to the insignificance of the botanical nature of the indicator plants, these investigators report a greater variation in the constant factor used in the denominator than is indicated in the original paper of Briggs and Shantz. In fact, a value as high as 2.27 is reported as the proper factor for Stockton Clay Adobe, which according to the U. S. Bureau of Soils carries about 60% colloidal clay. Observations upon the wilting coefficient of a selected Waipio soil indicated that although this critical moisture content was constant with respect to species, it exhibited the remarkably high ratio between moisture equivalent and wilting coefficient of 1.37. Subsequent work with soils from the experimental farm of the University of Hawaii and from the Pineapple station at Wahiawa, verified this result within the limit of experimental accuracy.

Work by Shull in 1916 gives reason for the belief that the wilting coefficient should be independent of the nature of the plants used for indicators. Professor Shull
measured the force with which moisture is held around soil grains in a heavy soil at many moisture contents between practical saturation and oven dryness. His findings indicate that at relatively high moisture contents the moisture is lightly held in the soil and is practically equally available. At a certain moisture content, in his case at about 19%, a sharp change occurs and further reduction of the moisture content results in greatly increasing the force holding the remaining water in the soil. This point of change in Shull's work occurred at about the wilting coefficient and at this point moisture was held in the soil with a force of about ten atmospheres. It is commonly believed that the osmotic concentration of the cell sap of most land plants is from ten to fifteen atmospheres. From this logic it is apparent that the variation in osmotic concentration between species should not be significant in the determination of the wilting coefficient. Students interested in the physiology of wilt are advised to consult Shull's paper as noted in the collateral reading.

When sugar cane is used as an indicator plant in the determination of the wilting coefficient the general procedure as outlined by Briggs and Shantz must be modified. The leaves of this plant seem to exhibit the unusual physiological property of being able to restore lost turgidity over night, regardless of the moisture content in the soil supporting the plant. However, a change in the transpiration rate, under constant environmental conditions may be noted when the soil moisture has been depleted to the moisture
content identified as the wilting coefficient with other plants. This period of retarded transpiration is apparently characterized by a retardation in the rate of growth and by a consistent curling of the leaves. If the term "wilting coefficient" is to be applied to soils of interest to sugar cane growers it must be redefined or used with reservation.

Not all investigators will grant that the residual moisture in a soil at the time of wilting depends entirely upon the soil type. Caldwell and Shive and Livingston seem to find that the wilting coefficient is dependent upon the intensity of the evaporating power of the air for the period during which permanent wilting is attained.

Most research workers in irrigation believe the results of Briggs and Shantz to be sound in principle at least.

Since the wilting coefficient is the lower limit of readily available soil moisture, its application to irrigation studies is evident.

**Soil Moisture Computations**

In irrigation studies it is frequently necessary to express soil-moisture in terms of equivalent surface applications or to determine the depth of penetration which might result from a given application. The relation between the factors involved may be conveniently expressed by the following equation:

\[ P \times V \times d = D \]

*Here*  
\( P \) = the range of soil moisture content under consideration  
\( V \) = the volume weight of the soil  
\( d \) = the depth of the soil mass involved  
\( D \) = the equivalent surface application. (\( d \) and \( D \) may be expressed either in feet or inches as long as both are in the same unit.)
The following illustrative example may be of value.

A soil with a maximum water holding capacity of 32.3% and a volume weight of 1.1 must be irrigated to a depth of 4 feet. If the average moisture content prior to irrigation is 25%, how many acre inches per acre should be applied to provide the irrigation?

Here \( P \) equals \((0.323 - 0.25)\) equals \(0.073\)

\( V \) equals 1.1
\( d \) equals 4 feet

and \(0.073 \times 1.1 \times 4\) (feet) equals \(0.322\) (feet).

The equation is perfectly general when three of its factors are known; the 4th may be determined.

The Role of Capillarity in Soil Moisture Movement.

When a column of dry soil is supported above a free water table, moisture is made to rise through the soil mass by forces which are commonly spoken of as capillary forces. In fact the entire process in elemental text books is made to appear similar to the "capillary" rise of water in minute glass tubes as noted in the physics laboratory.

More recent investigations seem to suggest that the processes involved are much more complex than suggested by most text books on the subject. Without attempting to discuss the basic experiments involved, the following statements may, at least, indicate that "capillary" distribution of water from a free water table is not clearly understood.

(1) Although there is a rather definite upper limit to the extent of capillary rise with a given soil type, the moisture content at various points in this column is by no means constant.
as one might expect from the capillary tube analogy.

(2) In fact, a zone of maximum moisture content has been observed some 5 inches above the water table. Above this plane the moisture content becomes less with distance above the water table. There is also a falling off in moisture content below this zone. This zone of maximum moisture content in soil columns supported over free water is called McLaughlin's hump and although frequently cited in modern literature has never been adequately explained.

(3) When the rate of rise of moisture through such columns is subjected to close scrutiny, a distinct change in rate is noted when the moisture reaches an elevation approximately equal to the height of McLaughlin's hump.

(4) There is evidence that some of the phenomena involved in what is commonly called the "capillary rise of water in soils" are colloidal in origin.

Regardless of the causes for the so-called "capillary rise", the action is real and of considerable value in agriculture. It is to be carefully noted that the distribution discussed so far has been that observed when a soil mass is supported over free water. In agriculture, especially in Hawaii, such conditions occur only rarely, due to a general adequacy of subsurface drainage. However, a water table within reasonable limits is to be found in the reclaimed areas of the Kekaha Plantation and in parts of the lowlands of the Kailua substation of the H. S. P. A. Here moisture from this water table which has been drawn into the root zone by the "capillary complex" is doubtlessly of agricultural importance.
It is commonly assumed in agricultural literature that water is carried from damp soils to dry soils in much the same manner as water is drawn into a column of dry soil when such a column is supported over a water table. The same unbalanced forces of surface tension are doubtlessly at work when a dry soil is in contact with a wet soil, but the actual transfer of water to effect an equilibrium is not only relatively slight but at an extremely slow rate.

Veihmeyer studied the magnitude and rate of this movement by field trials and by means of soil boxes so packed that the middle third carried soil at a high moisture content while the end sections were relatively dry. The resulting distribution in the soil columns after 144 days was observed through the glass plate which formed one face of each column. From such experiments Veihmeyer concludes that the "capillary movement of moisture from moist soil to dryer soil, when the soil is not in contact with a free water table, is too limited in extent and probably in rate to be effective for the use of plants."

The logical assumption from such evidence is that irrigation practice should be so planned that water is delivered to the soil zone occupied by roots and that little confidence should be placed in the belief that inequalities of distribution will be rectified by subsequent capillary distribution.

Cultivation as an Aid in Soil-Moisture Conservation

Further speculation upon the limited field of soil-moisture distribution, in the absence of a free water table,
leads to question as to the effectiveness of cultivation in soil-moisture conservation. For if it can be accepted that capillary movement from a damp soil to a dry one under such conditions is not a factor in field management the ineffectiveness of a mulch is at once apparent.

One important factor which is usually lost sight of during the creation of a dust mulch is the inevitable destruction of plant life which must go hand in hand with such an operation. It is undoubtedly true that the greatest losses from stored soil moisture, below the surface six inches, are caused by plant transpiration and not by evaporation. Since cultivation cannot be accomplished without killing weeds, the real causes for soil-moisture decrease are done away with although the physical means of eliminating them is usually undertaken with an entirely different purpose in mind.

The work in this field of Rotmistrov, Alway and McDole, Call and Sewell, Burr, Thysell, Veihmeyer and others should be studied in the original and need not be reviewed here.

Summary

The following resume may be of value in reviewing the subject matter of this lesson:

(1) When water is applied to the surface of a soil each successive increment of depth is wetted to its maximum water holding capacity before water is available for a lower depth.

(2) Soils vary widely in their water holding capacities. Fine soils such as silts and clays can hold more water against
the pull of gravity than sands. The maximum water holding capacity for the few Hawaiian sugar soils studied is about 32%.

(3) Plants do not wilt because the supporting soil is dry but because the residual water is so tightly held around individual soil particles or in the colloidal fraction, that the osmotic concentration of the root hairs cannot extract it at the rate required to maintain normal turgor.

(4) "Capillarity" is practically uneffective in moving appreciable quantities of water from damp soils to dry soils, except in the presence of a free water table.

(5) Cultivation is relatively ineffective in the conservation of soil moisture except insofar as weeds are destroyed and transpiration losses eliminated.

Collateral Reading


<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Title</th>
<th>Journal/Source</th>
</tr>
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<tbody>
<tr>
<td>Deere, Noel</td>
<td>1921</td>
<td>Cane Sugar.</td>
<td>Rodger, London.</td>
</tr>
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<td>Author(s)</td>
<td>Year</td>
<td>Title and Details</td>
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<tr>
<td>King, F. H.</td>
<td>1910</td>
<td>Physics of Agriculture. Published by the Author, Madison, Wis.</td>
<td></td>
</tr>
</tbody>
</table>


LESSON IV.

THE EFFECT OF IRRIGATION UPON PLANT GROWTH

It is evident that intelligent irrigation requires some considerable knowledge of the normal responses of crop plants to water. Knowledge in this field is by no means complete. In fact, the best work in studies of plant and water relations in the last ten years has been destructive. It has cast serious doubt upon the accepted ideas of the plant's relation to soil-moisture, but in addition it has laid a foundation for a new philosophy which gives decided promise.

As in the lesson on soil physics, dogmatic statements in this field are unwise. There are two distinct schools of thought in studies of plant and water relations which must be considered, one because it is classical and has proved valuable throughout the history of agriculture, the other because it is extremely logical and bases its conclusion upon experimental findings.

It is the purpose of this lesson to present the evidence supporting these two diametrically opposed philosophies. General conclusions are impossible. The student may draw his own.

Water Absorption and Conveyance

As has been indicated under the discussion of the wilting coefficient, soil-moisture is drawn into the roots of most crop plants by osmotic forces due to the cell sap concentration in root hairs which occurs just behind the root cap. As the root advances into moist soil masses, new root hairs are developed and the old ones cease to function and in time drop off.
It has been adequately demonstrated that plants are not dependent upon the capillary movement of soil moisture; the feeding zone moves as the root system develops and as unexhausted areas of soil-moisture are invaded.

The forces which make for the subsequent distribution of soil moisture into all parts of a plant are subjects of great speculation among plant physiologists. Varying osmotic concentration at different points in the plant, electrical phenomena as a result of colloidal activity and mechanical pumping by successive contraction and expansion of cells in the medullary rays have all been advanced in an effort to account for the conveyance of moisture from root hairs to leaves. Dixon attributes the rise of sap to the fact that liquids which adhere completely to a rigid envelope are capable of transmitting tensile stresses. This hypothesis is subject to less objection than others and is more generally accepted. Dixon presents his belief in "Transpiration and Ascent of Sap", noted in the collateral reading. In another little volume, "The Transpiration Stream," he answers some of the criticism brought about by his hypothesis. The second of these is a very human document.

The Use of Water in Plant Growth

The uses of water in plant growth are commonly listed as follows:

(1) It is an essential raw material for food manufacture.

(2) It serves as a solvent for gases and solid material which are incapable of entering the plant except in solution.

(3) It conveys raw material from place to place in the plant.
It maintains essential turgor in the living cells.

It is a necessary component of protoplasm.

In addition to these uses it is sometimes stated that the evaporation of water from the plant prevents excessive heating.

The greater part of the water which enters the roots of the plant is evaporated from the surface of the leaves. This loss is called transpiration. The current of water from the roots to the leaves is called the transpiration stream.

**Losses of Water by Transpiration**

The evaporation of water from the leaves of most plants occurs from openings between pairs of specialized cells which are most abundant on the under surface, although species vary widely in this regard. The openings themselves are called stomates, the cells around them being guard cells.

In cactus and other xerophytes the stomates are deeply seated, relatively few, and are distributed over the swollen parts of the stem which serve as leaves. As might be expected the transpiration loss from such plants is relatively small, partly because of the few transpiring members and partially because of their protection.

The rate of transpiration is commonly supposed to be affected by the following factors:

1. Light intensity.
2. Air temperature.
3. Relative humidity of the atmosphere.
4. Air movements.
5. Soil moisture conditions.
Of these five external factors, the intensity of the illumination is probably the most important within humidity ranges as experienced in the field. It is commonly believed that the illumination of the guard cells distends them in such a manner that the stomatal opening is enlarged and transpiration facilitated. Holman and Robbins report that 100 square centimeters of Indian Corn leaf transpired 97 milligrams of water per hour in the dark, 114 milligrams in diffuse sunlight and 785 milligrams in bright sunlight, other environmental conditions remaining the same.

Transpiration is increased by increases in temperature of the air surrounding the transpiring member for much the same reason that evaporation from a free water surface is increased with increases in air temperature. Relative humidity influences transpiration as might be expected from the physical conceptions involved, a greater rate of loss being noted under conditions of low humidity than with a more nearly saturated environment. However, some transpiration has been noted in water-saturated atmospheres. It is to be noted that most crop plants grown under conditions of low humidity are subjected to intense sunlight. Under such conditions the increased rate of transpiration due to low humidity may be insignificant as compared with the high rate resulting from the intensity of the light.

Although air movements may result in an increase in transpiration, the relations seem to be destroyed when the velocity of the wind over the transpiring member reaches a certain maximum. Apparently when such velocities are great enough to whip molecules of water away from the stomates as
rapidly as they are released, eliminating in this way a local region of high humidity, further increases in velocity do not increase the rate of transpiration. The well recognized damage done to sugar cane by dry winds of high velocity is probably not due to a great increase in the rate of real transpiration but to breakage and other mechanical damage to the tissue. This relation is not well understood and deserves further study.

Recent investigations seem to indicate that the rate of transpiration is independent of the moisture content in the soil as long as that moisture content is above the wilting coefficient. The details of these investigations will be considered under the discussion of the availability of soil moisture.

In general, transpiration is a purely physical process and is closely analogous to the evaporation of water from an open pan. Here the rate of loss depends upon the temperature, relative humidity and wind velocity in the immediate environment. Conditions are much the same with transpiration except that the areas from which evaporation can take place is subject to adjustment under the influence of light intensity.

**The Water Requirements of Plants**

The amount of water required to produce one pound of dry matter with a certain plant is called the water requirement or transpiration ratio of that plant. Since all the water that enters a plant, except the insignificant amount but otherwise important quantity used in metabolic processes, is lost by transpiration, it follows that statements of the water require-
ments of plants are of little value unless the factors which
determine the rate of transpiration are accurately defined.

However, many observations of the water requirement
of certain crops are to be found in the literature. The
following table, assembled from many papers, will illustrate
the inconsistency mentioned above.

Water Requirements of Selected Crops Illustrating the Incon­
sistency Between Such Figures When Not Adjusted for Local
Environmental Conditions.

<table>
<thead>
<tr>
<th>INVESTIGATOR</th>
<th>Water Required per Unit Mass of Dry Matter</th>
</tr>
</thead>
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<tr>
<td>Laws and :Wollney :Gilbert :Hillreigel :King :Briggs &amp;</td>
<td></td>
</tr>
<tr>
<td>Crop : (Germany) : (England) : (Germany) : (U.S.) : (U. S.)</td>
<td></td>
</tr>
</tbody>
</table>

Recent work with alfalfa at the California Station
indicates that the water requirement for that crop, under the
conditions of the Sacramento Valley, is about 500 pounds of
water to each pound of field cured hay produced. There is no
assurance that this ratio would hold true with the more intense
heat of the San Joaquin Valley nor in the relatively cool and
partly cloudy conditions of the Los Angeles coastal plain.

With our present knowledge each district must be
studied with the aid of growing plants under careful control,
before the water requirement for crops grown in that district
can be stated with any assurance. The problem is still further
complicated by the fact that seasons vary, the transpiration
ratio as determined during one growing season being but little evidence of the normal use.

The transpiration ratio for sugar cane under Hawaiian conditions has never been carefully studied, although a ratio of 1,000 pounds of water to one of sugar is frequently referred to. The problem is now being investigated by the H.S.P.A. in cooperation with the University.

The Availability of Soil-Moisture

It will be remembered from Lesson III that Professor Shull measured the surface forces which held moisture around the grains of a particular soil when that soil had been wetted to various moisture contents. His results are usually presented in the form of a curve, the ordinates of which are moisture percentages and the abscissae the corresponding surface force. The soil in question had a moisture equivalent of 35.2% and a computed wilting coefficient of 19.1%. Shull's curve between these points is practically straight and is almost exactly parallel with the vertical axis. This means, of course, that moisture, in this case at least, is held around the soil grains with equal tenacity regardless of the moisture contents, provided the moisture content is held between the maximum water holding capacity and the wilting coefficient.

If Shull's results are considered as typical of general soil-moisture relations, interesting corollaries immediately suggest themselves. These may be expressed as follows leaving the proof, if any is possible, to a later time.

(1) Since water is held with equal tenacity at all moisture contents between the maximum water holding capacity and the

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wilting coefficient, it should be equally available at all moisture contents between these limits and the so-called "optimum moisture content" ceases to be a specified moisture content but widens into a broad band extending between the limits specified above.

(2) If water is equally available at all moisture contents between these critical limits, it seems impossible to affect the normal habit of growth or the maturation of annual plants by untimely irrigation.

It is upon these corollaries that the well established texts in soil-physics, agronomy and fruit production disagree with the results of carefully planned and unprejudiced experimentation. An appreciation of the significance of an optimum moisture content is carefully drilled into every student of soils and indeed it seems perfectly reasonable to assume that there should be some moisture content at which the plant is most comfortable, to paraphrase a popular but slightly vitalistic definition. And more advanced students are instructed that the untimely irrigation of wheat results in a grain of low protein content while a similar treatment with peaches may swell the fruit with water and make it of poor canning quality. Indeed the instructor in such courses has a wealth of published matter from which he can draw his illustrations, although the details of the experiments involved may not endure statistical inquiry.

The Rate of Soil-Moisture Depletion by Plant Transpiration

Veihmeyer bases his studies of the availability of soil moisture upon the assumption that a uniform rate of transpiration,
under specified environmental conditions, must indicate equal availability. He seems to hold that if water is obtained by the plant with ever increasing difficulty as the soil dries, the amount transpired per unit time would become consistently less; and the resulting curve of time against accumulative loss of water would be concave. On the other hand, if water is equally available between the limits given above, accumulative loss of moisture when plotted against time would be a straight line. In other words, the transpiration loss would be proportional to time regardless of moisture content. It is understood in the reasoning that the moisture content is never allowed to fall below the wilting coefficient nor are the external factors of environment subject to significant variation during the observations.

The assumptions outlined above were subjected to test with the aid of a two year old prune tree in a tank of Yolo loam soil and mounted as described in Hilgardia Vol. 2, No. 6, page 208. The device described consists of an automatic weighing device so arranged that a continuous, graphic record of the weight of the tank, soil, tree and residual soil-moisture was obtained. The soil in this tank was irrigated to maximum water holding capacity and a waterproof seal fitted to the tank and around the trunk. All losses in weight are attributed to transpiration; the increasing weight of the tree with growth is regarded as negligible.

Results from record sheets covering a seven month period are compiled in figure 28, page 213 in the reference cited above. During this period the tank was irrigated 16 times to
maximum water holding capacity, the tank ordinarily being near the wilting coefficient prior to irrigation. It is interesting to note that the lines indicating rates of depletion are essentially straight throughout their entire length. This is especially noticeable during the middle of the summer when environmental conditions during the interval between irrigations are practically constant. Since a straight line indicates uniform slope and a uniform slope means constant loss per unit time, the hypothesis of equal availability seems well substantiated. The flatter slopes during May may be partially attributed to the fact that the tree was only in partial leaf during this period, although relatively low temperatures may also be a contributing factor.

Field trials in mature prune groves in the Santa Clara Valley in California gave similar evidence as reported by Veihmeyer. The moisture contents of these groves were determined by moisture sampling and although the same general tendency as that indicated in the balanced tank is indicated, unavoidable error in sampling caused some distortion of the curves.

Veihmeyer also reports a high degree of correlation between the leaf area of prune trees grown in tanks and water lost by transpiration within a given time interval, although the trees were grown in soil held within various ranges of moisture content. The results seem to indicate that each square inch of leaf area transpires a given quantity of water under given environmental conditions, regardless of the soil-moisture content. Prune trees are the only plants which have been intensively studied in this manner, although, as has been indicated, work
is now under way with sugar cane.

From these experiments, and others, Veihmeyer concludes that there appears to be no reason either from physical consideration of the forces involved, or from the physiological water requirements of plants, why optimum moisture conditions for growth should not vary from the maximum field capacity to about the wilting point.

It should not be thought that transpiration ceases abruptly when the wilting coefficient is reached. Continued loss does occur but at a slower rate. In fact, the only evident way of determining the wilting coefficient of a soil, with sugar cane as an indicating plant, is to note the residual moisture content at the time when the uniform rate of transpiration under constant environmental conditions give place to a slower rate.

There seem, moreover, to be certain disturbances in a plant's normal functioning when the soil moisture is allowed to fall below the wilting coefficient. This disturbance may result in a shriveling of kernels in the case of grains, a loss of quality in the case of fruit and a cessation of growth in the case of such crops as sugar cane. Recent work at the Experiment Station of the H.S.P.A. indicates that growth of cane does stop rather abruptly when the wilting coefficient is reached, although no evidence is furnished from the incomplete records that growth is at a normal rate until that time.

**Plant Responses of Varying Moisture Contents**

As might be expected, most of the experimental work indicating that rate of growth and other functioning of crop
plants is independent of the soil-moisture content, with the limitations indicated above, has been done by Veihmeyer; and his published observations to date deal with only two crops, peaches and prunes. Muir peaches were submitted to various irrigation treatments, some plots being irrigated shortly before harvest, some early in the season and some at the period of maximum wood growth. Veihmeyer reports no difference in the quality of the product as judged by average size, number of fruits per tree or drying ratio. When plots of canning peaches were irrigated under many schedules, some of them being forbidden by the usual canning contract under which such a crop is ordinarily grown, fruit of such uniform quality was produced that a committee of experts from leading canneries in San Francisco was unable to detect an inferior quality in any of the samples. Studies with young prune trees were confined to determination of the length growth resulting from varying soil-moisture contents within a given time interval. The coefficient of correlation between length grown and water loss is reported as 0.995 plus or minus 0.002, although the moisture content, during the time interval represented, varied between wide limits.

It must be carefully noted that in no case did the moisture content in the soil carrying these experimental plants fall below the wilting coefficient.

However, the great bulk of the experimental evidence upon this important point leads to an entirely different conclusion. Widstoe and Stewart grew wheat in Utah under seven irrigation treatments, the differences in yield and protein

-73-
content being small and inconsistent. However, these differences are attributed to differences in the treatment involved. The same station reports that irrigation definitely modifies the composition of the corn plant and its parts, the seed being affected more than any other part. Powers, of Oregon, seems to find that irrigation alters the shape and size of plants and affects the seed product, causing a higher percentage of germination in corn and a lower percentage of germination in beans.

This list might be almost indefinitely extended. The literature is voluminous and in review one is impressed with the unsatisfactory and contradictory nature of much of it. Differences in the behavior of plants, associated with differences in irrigation treatment may be noted, but the causal relationship between the water supply and the variations observed is not always clear.

In 1905, Eckart published his findings with respect to the influence of variation of water supply upon composition and yield of sugar cane. Plots, planted with Lahaina and Rose Bamboo were given different amounts of irrigation so that, combined with the natural rainfall, supplies of one, two and three inches per week were maintained. Dr. A. L. Dean has compiled Eckhart's results in the following table which contains the most salient facts in the report.

<table>
<thead>
<tr>
<th>Inches</th>
<th>Lb. Water per</th>
<th>Lb. Water per</th>
<th>Gallons</th>
<th>Gallons</th>
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<td>Water per Week:</td>
<td>Cane</td>
<td>Sugar</td>
<td>Sugar</td>
<td>Cane</td>
</tr>
<tr>
<td>3</td>
<td>: 177,906</td>
<td>: 30,422</td>
<td>: 226</td>
<td>: 139,283</td>
</tr>
</tbody>
</table>

-74-
Such results may be subject to reinterpretation upon the philosophy of soil moisture distribution discussed in Lesson III. In the case above, heavy weekly irrigations result in a wasteful use of water as measured by the ratio of sugar produced to water used. If the water lost by transpiration during one week was less than two acre inches per acre, applications exceeding this figure would be increasingly wasteful, since water would be finding its way below the zone of root recovery and consequently unable to affect the real ratio of sugar to water although from gross field measurements the ratio would appear as above. This explanation, however, is incapable of explaining the consistently increasing yield of both cane and sugar with increasing application of irrigation water to Lahaina cane. For if a weekly application of two inches a week resulted in losses by deep penetration as suggested above the yield from a two inch application and a three inch application should be about equal. More information is needed for a satisfactory interpretation.

The Effect of Irrigation Upon Root Development

Intelligent irrigation evidently depends upon a definite knowledge of the position of the roots of the plants in question. If an area is irrigated with an application more than sufficient to wet the soil to the depth of maximum root penetration, water is wasted, while if only a part of an established root system is wetted, part of the root system ceases to function normally and the plant is liable to suffer from wilt unless the irrigation interval is correspondingly decreased.
Ballantyne and Weaver suggest that the root distribution of irrigated crops depends primarily upon the irrigation treatment to which those crops are subjected. And it seems logical to believe that a deep root system would be provided if irrigation were heavy and infrequent for in this case deep penetration is provided. On the other hand, frequent light irrigations would provide moisture in only a shallow depth and surface roots would be encouraged.

The root studies of the authorities cited above were made in arid regions. Here irrigation was the only source of soil-moisture and their findings were as one might suppose.

It is unwise, however, to assume that root distribution under humid or semi-arid conditions can be adjusted by manipulation of the irrigation schedule. This is especially true under such seasonal distribution that the large part of the rainfall comes in a relatively short period. Under such conditions, the accumulation of soil-moisture due to seasonal showers may be sufficient to wet the soil to five or six feet and roots will find ample opportunity for development into the deeper depths regardless of subsequent treatment.

This point is well illustrated by Beckett and Huberty who studied the root distribution of certain alfalfa plants in the Sacramento Valley. These plants had been irrigated throughout their entire life of six years in accordance with a definite schedule. This schedule provided each plot with 30 acre inches per acre per year, some plots receiving 15 - 2 inch irrigation during the year while others received 6 - 5 inch applications, 4 - 7\frac{1}{2} inch applications and 2-15 inch applications.
No significant difference in the root distribution under these various treatments could be noted after excavation and screening. It is evident that the deeper roots in the plots of light, frequent applications ceased to function early in the dry season due to low moisture content. They seemed vital, however, and capable of continuing operation when the soil around them was once more brought to maximum water holding capacity by rainfall. Differences in yield between these various treatments were slight, the plots receiving frequent light applications being a little more productive than those irrigated more infrequently.

**Collateral Reading**


<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Title</th>
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<td>The Relation of Moisture and Available Nitrogen to the Yield and Protein Content of Wheat. Soil Sci. Vol. 18, No. 3.</td>
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</table>
LESSON V

PREPARATION OF LAND FOR IRRIGATION
AND METHODS OF IRRIGATION

A perfect irrigation is an application of water in such an amount and by such a method that the moisture content of every cubic foot of soil, which contains a significant concentration of feeding roots, may be increased to the maximum water holding capacity for that particular soil, with no water being lost by penetration into depths below the zone of the root spread. Such irrigations rarely, if ever, result from our common methods of distributing water. Such refinement could only be hoped for if economic conditions demand the utmost economy in the use of water and if local topography allowed the use of one of the more efficient methods of application.

Experience and custom indicate the distance which should separate plants in a field for best results. Many deciduous trees are planted twenty-four feet apart, vines about eight feet and corn in rows from three to six feet apart, while cane is ordinarily closely planted in rows which are about five feet apart. If the logic upon which these commonly accepted planting distances are based is sound, one might suppose that the entire soil mass to a depth of four or five feet is permeated with roots and this entire mass should be wetted during the progress of an adequate irrigation. It is evident, from the previous discussion, that if a less complete distribution is effected, the frequency of the irrigations must be increased.

-79-
Economic Limits in Land Preparation

The justifiable investment in land preparation as an aid toward the efficient distribution of irrigation water depends upon (1) the value of the water, (2) the cost of labor suitable for irrigation, (3) the value of the unprepared land, and (4) the value of the crop grown. When land is cheap, water inexpensive and low-valued crops are being grown, there is no economic need for maximum yields per acre. On the other hand, limited areas may be found which are practically frostfree and are suitable for the production of sub-tropical fruits and vegetables. If such favored districts lie close to large centers of consumption, costly terracing may be economically undertaken, for local conditions require maximum production.

Sugar cane presents a peculiar problem. Here the crop value per acre is high, land values and water costs are high and labor, although costly in the aggregate in terms of dollars per man day, is relatively cheap. Yet the topography and the thin soil usually found in the mauka land has thus far limited the common method of irrigation to one which is recognized as being relatively inefficient as compared with some others.

Many methods of preparing land have been devised. Some of these have their principal appeal in the fact that no great amount of capital is invested in the work. Other methods, which have been developed in areas which demand a more economic use of irrigation water, are used because a
more efficient distribution of water may be gained.

It is impossible to irrigate effectively and economically unless the land to be served has been adequately prepared.

It is the purpose of this lesson to describe some of the methods of irrigation which have been found of value, together with the land preparation required for them. Methods may be suggested which would be valuable additions to Hawaiian practice.

Methods of Irrigating Field and Forage Crops

Wild Flooding

Wild flooding requires little or no preparation of land other than rough leveling, which consists in leveling down knolls and filling swales if any exist. It is perhaps the most inefficient method of irrigation in common use if the efficiency of an irrigation is measured by the percentage of the potential root system of a crop which is actually reached by water and by a consideration of excessive penetration.

Wild flooding is sometimes called "flooding from field ditches". Small temporary ditches are constructed with a ditcher or double mold-board plow so that a large part of the field can be covered by water breaking out from them. Such ditches can best be located with an engineer's level, the necessary slope being determined largely by the amount of water to be carried. Most Hawaiian soils do not erode under high velocities, although maximum velocities for certain soil types
are carefully specified for mainland soils. The size of ditch and the grade required for the conveyance of given quantities of water will be discussed in Lesson VII.

Ditches should be located at such frequent intervals in the area to be served that water pouring through an opening in one of them reaches the next one below before excessive penetration has occurred near the upper ditch. Estimates of the proper spacing of such field ditches are of no value because of variations of soil type and slope in different areas and in different parts of the same field. Evidently a large head of water in the field ditch, a heavy, impervious soil, and a rather steep slope are factors which tend to justify a distant spacing of field ditches.

It is practically impossible to obtain a uniform penetration by the wild flooding method. The most conscientious irrigator will leave some areas dry because they cannot be reached and may inefficiently, and perhaps dangerously, over-irrigate the low spots.

Except in the Rocky Mountain states where wild flooding is the standard method of irrigation for alfalfa and clover, this method is usually considered as an emergency measure suitable for crops which are not ordinarily irrigated but which need additional moisture in years of deficient rainfall. The method has little or no application to Hawaiian conditions.

**Furrow Method**

The furrow method, with its many modifications, is widely used for the irrigation of row crops. Water is distributed from parallel, although not necessarily straight furrows, which
usually run down the steepest slope, although excessive grade may be taken up by directing the furrows obliquely to the general contour. With field crops such as beans, corn or cotton, the direction of furrows is determined by the rows since in the irrigation of such crops the furrows lie between them. The field must consequently be laid out in such a way that the rows extend down a slope which, in view of the existing soil type, can be used advantageously with the furrow method.

From a standpoint of the resulting soil-moisture distribution, the proper spacing of irrigation furrows is primarily determined by soil type. Water entering the soil by vertical seepage moves laterally under the influence of the "capillary" forces discussed in Lesson III, since the running water in the furrow may be regarded as a free water table. The lateral spread is thus closely limited and depends in magnitude and rate upon the many factors which influence "capillarity". It is evident that furrows in the field should be only so far apart that the lateral spread from one furrow may meet that of the next. The efficiency of an irrigation is seriously affected if dry zones are allowed to remain between adjacent furrows, since such zones, if a row crop is being irrigated, probably lie in the region of greatest root concentration.

It is evident from a consideration of the forces involved that the lateral spread of moisture from a furrow should rather quickly reach a maximum and then remain fixed, regardless of the time the water is allowed to run in that furrow. For sandy soils this maximum width of wetted area is reached in
about twenty-four hours, longer periods resulting in deeper penetration but not in greater lateral movement.

The desirable length of a furrow should be carefully determined if satisfactory distribution is to be secured. This length depends upon the soil type, the grade of the furrow and to a lesser extent upon the head of water delivered to it. As the stream moves down the furrow a greater soil surface is exposed to penetration. Consequently less water is available for further advance and the rate of advance decreases. Water in a long furrow in a sandy soil might run indefinitely and never reach the lower end. In such a case the loss by penetration is so rapid that the stream is exhausted before the entire furrow is served.

The advantages and disadvantages of the furrow method may be summarized as follows:

(1) It is adapted to the utilization of small heads of water.

(2) It can be adapted to a wide variety of soil types and slopes.

(3) It requires no expensive land preparation.

(4) Evaporation losses during application are small.

(5) The labor cost in irrigation is high since one man can handle a small head.

(6) As ordinarily practiced the efficiency of this method, as measured by the percentage of the potential root zone actually wetted, is low.

(7) Good judgment and considerable attendance is required to secure acceptable distribution.

The commonly used method in Hawaii for sugar cane irrigation is a highly modified furrow system. Here the furrows are very short and are level throughout their length. This
method will be further discussed later in this lesson.

The **Corrugation Method**

The corrugation method of irrigation is a modification of the **farrow** method. It is not widely used although it has some application in the pastures and hay fields of the mountain states.

Water is distributed by means of small depressions or corrugations which are about twenty inches apart and which extend down the slope. The corrugations are more or less permanent and are used until they become so deteriorated that they are no longer effective or until the field goes into a cultivated crop for the irrigation of which the method is not well adapted.

The **Border Method**

The border method is a refined flooding method. Water is delivered through a suitable ditch system to a series of long and relatively narrow strips of land which run down a slight but significant slope. The strips, or borders, are level from side to side and are separated by low levees. Such levees are high enough to confine the flow of water but need not be so high that their complete coverage by such a crop as alfalfa or sudan grass cannot be secured. When a stream of water is delivered at the head of such a border it spreads from side to side within the strip and moves down the strip in a thin sheet under the influence of the slope.

Uniform distribution of water by the border method demands a close correlation between soil type, the slope on the center line of the strip, the size of the border and the head of water which will be available for its irrigation.
As the sheet of water progresses, the area submerged and consequently the area subject to losses of water by percolation increases. Consequently the water available for continued advance is decreased and the rate of advance is consequently reduced. A border 600 feet long and 50 feet wide in a sandy soil and on a relatively flat grade could not be completely irrigated by a head of 2 M.G.D. or about 3 c.f.s. Under such conditions an advance of perhaps 300 feet down the border is all that could be attained regardless of the duration of the flow. At this point the rate of penetration would equal the rate of application and further advance would be impossible. Enough water might enter such a border to give an adequate irrigation but the distribution would be entirely unacceptable.

Possibilities for the correction of this condition at once suggest themselves. Cutting the border in two pieces each 300 feet long and serving the lower section from an additional ditch is the most obvious and most practical method. Improvement can be secured, in some measure, by narrowing the border or by increasing the head of water. Increasing the grade within the border would also be effective in the correction as would a changing of the soil type to one with a slower rate of penetration. Of these the first is ordinarily economically impractical while the second is almost impossible on a commercial scale.

With heavy soils a tendency for unequal distribution in borders is also apparent; but in this case the greater penetration is at the lower end. Due to the slow rate of penetration in such soils, water should be turned out of such a border when the advancing stream is still some distance from the lower
end. Even with this precaution am accumulation with excessive penetration at the lower end is almost unavoidable. Correction for this condition should aim toward a reduction of the rate of advance or an increase in the rate of penetration. As has been suggested, a change in the factors which determine these rates can only be effected with difficulty after the leveling has been finished.

The relationships indicated above are so complex that a mathematical determination of suitable sizes of borders under specified conditions is practically impossible. Experience seems to be the only guide. In the early days of the border method strips were half a mile long and perhaps 100 yards wide, the head of water being the total capacity of the canal serving that particular area. Steady refinement of methods has resulted in a continuous decrease in the sizes of strips used. One seldom encounters borders at present which are more than 800 feet long or 50 feet wide even on the most impervious clays.

The following schedule of sizes for borders under various conditions is based upon experience in California and is included here only as a guide. Hawaiian soils have never been studied with such an application in mind. Considerable investigational work will be required before the border method can be recommended for the irrigation of cane in the islands.

Suggested Sizes (x) for Borders for Use on Varying Soil Types and With Varying Heads of Water. (Based upon California Conditions. Not applicable to Hawaii.)

<table>
<thead>
<tr>
<th>Head of Water: in C.F.S.</th>
<th>Soil Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sands: 20-30 x 200-300; loam: 30 x 300; clays: 30 x 440-660</td>
</tr>
<tr>
<td>1 - 2</td>
<td>30-40 x 300-400; 30-40 x 440-660; 30-40 x 660</td>
</tr>
<tr>
<td>2 - 4</td>
<td>30-40 x 440; 40 x 440-660; 40-50 x 660-800</td>
</tr>
<tr>
<td>4 - 8</td>
<td>40 x 440-600; 50 x 660-800; 50 x 800</td>
</tr>
</tbody>
</table>

(x) Dimensions of borders are in feet.
As has been indicated, the distribution of water over a border is partially dependent upon the slope within it. Although it is important that this slope be consistently downward, it is not at all necessary that the slope be uniform throughout the length of the border. In fact, a very flat grade for the first fifty feet in a border of ordinary length aids in the lateral spread.

Experience in California, which must be used with reservations in Hawaii since local soils differ in many particulars from those on the mainland, indicates that acceptable distribution within borders on varying soil types can be secured if the grade within the border is within the following limits:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Limiting Grades in Feet per Hundred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Sand</td>
<td>0.30 - 0.90</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>0.30 - 0.60</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>0.20 - 0.50</td>
</tr>
<tr>
<td>Clay</td>
<td>0.10 - 0.30</td>
</tr>
</tbody>
</table>

In some cases a desirable layout in a field suggests the use of grades slightly in excess of those indicated. The resulting inequalities of distribution can be corrected to some extent by building low auxiliary levees normal to the center line of the border. The distribution can be somewhat improved by extending such levees about three quarters of the distance across the border at intervals of about 100 feet and staggering them down the length of the check. In cases where the available grade is less than that indicated, the border method should be abandoned and a method of irrigation which is more suitable to
flat slopes adopted.

The cost of preparing land for irrigation by the border method depends upon so many variable factors that estimates of this cost are of little value. With an easily worked soil and a uniform grade which is naturally adapted to this method the cost of the earthwork necessary for preparation may be as low as $20.00 per acre. Maximum costs are governed by economic conditions. In general the usual cost of preparing land by irrigation by the border method ranges from $25.00 to $75.00 per acre under mainland conditions. This estimate is exclusive of the cost of ditch and headgate structures.

The advantage of this method as a method of irrigation may be summarized as follows:

(1) With skillful design and operation satisfactory moisture distribution can be effected.

(2) The labor cost of irrigating is low.

(3) Fewer lineal feet of supply ditch per acre are required than with any other method used in intensive practice.

(4) The field is laid out in large blocks which can be conveniently handled.

(5) The crop may be planted in straight rows or on a rectangular pattern.

There are, however, several disadvantages which are particularly pronounced under Hawaiian conditions.

(1) Relatively large heads of water are required for an economic unit.

(2) The soil should be deep and uniform with respect to
productivity in order that infertile subsoil may not be exposed in the necessary leveling.

(3) The necessary land leveling is relatively costly and requires the use of tools not ordinarily used in Hawaii.

The Basin Method of Irrigation

This method of irrigation is widely used in Hawaii at present, but is limited to such crops as rice and taro which require constant submergence. The basins are consequently built on very heavy soils in order that losses by seepage may be reduced.

The use of basins need not be restricted to this use; on the mainland the method is used on all soil types and with all crops. The principal limitation is that the original field must be level enough to permit the building of a series of level basins without prohibitive earthwork.

Water should be delivered to every basin by means of a supply ditch. The practice of flooding a series of basins from a single headgate by allowing separating levees to overflow is not to be recommended except in the irrigation of crops of low value on heavy land. Under such circumstances the reduction of yield due to inequalities of distribution may be offset by the saving in the simpler ditch system. In cases where grades are very flat and where square basins may be used to advantage, the supply ditches may be separated by a distance equal to twice the side of a basin. In such a case headgates may be installed on each side of such a ditch and water diverted into basins on either side. When the maximum slope in a field is as much as three or
four tenths of a foot per hundred and the main supply ditch runs on or near the natural contour, this practice cannot be used and a separate ditch must be supplied for each tier of basins.

As with the border method, the uniform distribution of water over a level basin depends upon its size and upon the head of water available to it. Experience and observation must again serve as guides.

The following table based on mainland conditions may be of value, although as suggested for a similar table for the border method, it must be used with caution upon the unusual soils of Hawaii.

Suggested Sizes \((x)\) for Basins for Use on Varying Soil Types and With Varying Heads of Water. (Based upon California Conditions, Not Applicable to Hawaii.)

<table>
<thead>
<tr>
<th>Head of Water</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sands</td>
</tr>
<tr>
<td>1</td>
<td>50 - 75</td>
</tr>
<tr>
<td>1 - 2</td>
<td>75 - 100</td>
</tr>
<tr>
<td>2 - 4</td>
<td>100</td>
</tr>
<tr>
<td>4 - 8</td>
<td>100 - 125</td>
</tr>
</tbody>
</table>

\((x)\) It is assumed that basins are to be square or nearly so. The dimensions given are for one side of this square and are in feet.

The advantages of the use of basins as an aid in irrigation may be tested as follows:

(1) They are suitable for use on grades which are too flat for other methods.

(2) They are well adapted to soils which are ordinarily difficult to irrigate, such as the sand and clays.
(3) Uniform penetration can be secured with correct design and intelligent operation.

(4) The labor cost of handling water is low.

Disadvantages are:

(1) More field ditching is required than with other methods under comparable conditions.

(2) A relatively large number of structures is required per acre.

(3) The field is badly cut up by ditches and cultural operations handicapped.

In view of the irregular topography of most of the cane lands in Hawaii, it is doubtful if the basin method ever comes into common practice. The method finds its greatest use in the desert flats on the mainland or on the gently sloping alluvial fans of great rivers. However, some possibilities of local application suggest themselves. Basins may form a useful supplement to the more standard method and be most valuable where the present method is least efficient.

The Contour Basin Method

This method finds its greatest use in areas of cheap and abundant water, cheap land and a crop of low value. It is used exclusively in extensive rice farming on the mainland. It can never become widely used in Hawaii.

The basins in this case are not square, nor are they level. They are bounded on two sides by levees along contours, and may differ in elevation at their bases by as much a half a foot. The other two sides are enclosed by levees built along the side of the field or by random lines through the field if the
area is large.

The great, irregularly shaped area is flooded from one end until the upper side is wetted. Since the lower side is half a foot lower than the upper, the levee must be high enough to carry this depth.

No claim for uniformity of distribution can be made for this method. Its only advantage lies in the cheapness of the preparation necessary for it.

Methods of Irrigation with Sugar Cane

The method of irrigation in common use needs no description in this course. It is an interesting combination of one of the furrow methods and flooding since it employs the principles of each. The method of preparing land with a water way between adjacent rows of cane is essentially the same as for more standardized furrow methods. Yet the layout, when completed, is operated as a basin system; but in this case the basins have degenerated into narrow "watercourses" about thirty-five feet long and some two feet wide at the water level, when flooded. In its application to the steepest slopes the local practice approaches the method of contour basins as it is used in some of the costly, high producing avocado lands of southern California.

How closely the distribution from the usual water courses approaches that of a perfect irrigation as defined earlier in this lesson is not known. The existence of a dry zone between adjacent water courses after an irrigation would be a decided drawback to the general practice especially in areas limited, perhaps by a shortage of labor, to a long irrigation interval.
for in such a case the potential soil moisture reservoir would be limited. Nor could this limitation be removed by filling the lines on each of two successive days. The water of the second day would doubtlessly effect a deeper penetration, but an increase in lateral spread would be very doubtful.

The present system lacks flexibility in other ways. It is generally recognized that plant cane during its early months should be irrigated frequently and lightly. The lines to be irrigated must be filled at each of these supposedly light applications, there being little or no control over the resulting penetration. Flexibility and an undoubted saving of water would result if each filling of the lines could be expected to fill the soil to maximum water holding capacity to a specified depth, say two feet. For young cane a single application at the required interval might suffice, while for more deeply rooted stools two irrigations on successive days would increase the potential root zone to four feet, a depth which would, in popular belief be sufficient to include the greater part of the root system. Opinion, however, seems to hold that with the usual land preparation each filling of the lines wets the soil to four feet. If this be true, the suggested improvement of practice is of no value.

Irrigation by overhead sprinkling provides flexibility of operation, in addition to its other advantages which have been set forth in the Planter's Record and elsewhere. The development of this method into a practical plantation practice depends primarily upon the development of a superior type of
sprinkler head. It is far easier to describe the characteristics of such a head than it is to design one. It may be said, however, that the future of overhead irrigation with sugar cane lies in the hands of mechanical and hydraulic engineers.

Collateral Reading

<table>
<thead>
<tr>
<th>Author/Editor</th>
<th>Year</th>
<th>Title / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(__________)</td>
<td>1926</td>
<td>The Use of Water in Irrigation. McGraw-Hill, N. Y.</td>
</tr>
</tbody>
</table>
LESSON VI

THE CONVEYANCE OF IRRIGATION WATER

Although most problems of ditch and pipeline design lie in the field of irrigation engineering and are consequently well taken care of by men of training and experience in the engineering departments of plantation organizations, it is highly desirable that agriculturists and irrigation overseers be sufficiently familiar with the basic principles involved to prepare suitable specifications for the local work required by maintenance and improvement. The basic conceptions behind all such problems are derived from theoretical hydraulics. Few engineers at present, however, resort to first principles in the solution of practical problems of this sort. Tables, diagrams and empirical formulas of sufficient accuracy have been devised which form valuable short cuts.

It is the purpose of this lesson to familiarize the student with the elements of these methods and to review some of the factors influencing the flow of water in open and closed conduits. The student is warned against a too general application of the formulas and tables included in this lesson.

The Flow of Water in Open Ditches

One of the most commonly used equations for the determination of velocities of water in open ditches was suggested by Chezy in 1775, and is \( v = \frac{Q}{w} \sqrt{R} \).

where \( v \) = the mean velocity of the stream in feet per second
r = hydraulic radius = cross sectional area in sq. ft.
    wetted perimeter in lineal feet

The wetted perimeter does not include the length of
the contact between the water surface and the atmos-
phere.

s = the sine of the angle of slope or the total fall
    in the ditch section divided by its length.

c = a coefficient which varies with the size and shape
    of the stream, the material of the bank and the
    slope.

As an example of the use of this formula, suppose a
wooden flume is rectangular in section with a bottom width of
4 feet and a depth of water of 2 feet and is laid on a slope
of 1 foot per thousand. Here

s = \frac{1}{1000} = 0.001

r = \frac{\text{cross sectional area}}{\text{wetted perimeter}} = \frac{4 \times 2}{4 + 2 + 2} = 1

v = c \sqrt{rs} = c \sqrt{0.001} = 0.0316 c

The complete solution depends upon the numerical value
of the constant c. The complicated interrelation of the several
factors which determine its value have been incorporated into a
second equation known as Kutter's formula and the proper value
of c may be computed when the contributing values are known.

The Kutter formula in its usual form is:

\[ c = 41.65 \sqrt[\frac{n}{s}]{0.00281} \cdot 1.811 \]

In this expression s and r have the meanings indicated
for the Chezy formula while n is a numerical constant which is
indicative of relative degrees of retardance to flow due to the
material of sides and bottom. Much of the engineering literature dealing with stream flow has to do with the evaluation of this constant.

One schedule of values of $n$, which may be used, is as follows:

- $n = 0.010$ for plaster of pure cement
- $n = 0.012$ for unplanned timber
- $n = 0.015$ for rough brick
- $n = 0.0225$ for canals in earth, good order
- $n = 0.025$ for canals in earth, fair order
- $n = 0.030$ for canals in earth, bad order
- $n = 0.035$ for canals in earth encumbered with debris

Returning to the illustrative example we are now in a position to complete the determination of the velocity through the flume for $c$ can be determined by selecting the proper value of $n$, which in this case would be 0.012 and substituting this, and other values in Kutter's formula, thus

$$c = \frac{41.65}{0.00281} \frac{1.811}{0.012} = 127$$

$$1 + \frac{1}{n} \left( \frac{41.65}{0.00281} \right)$$

and $v = 0.0316 \times 127 = 4.01$ feet per second.

Tables and charts for the solution of Kutter's formula eliminate the tedious arithmetic involved in the solution above. An especially useful table for this determination is to be found in King and Wisler, "Hydraulics," as listed in the collateral reading.

Since the discharge from any water conduit is equal to the product of its cross sectional area and the mean velocity of the water within it, the capacity of our flume becomes $4.01 \times 8 = 32.08$ cubic feet per second.
Small Ditch Design

Although the method of the problem used for illustration is of considerable value in engineering practice, such as in determining the probable discharge of natural streams when \( n \) can be closely estimated, irrigation problems usually have to do with the required ditch section for the conveyance of a given quantity of water on a specified location. Such a problem is essentially one of "cut and try" methods. The area of the section is, of course, subject to adjustment, but as the section is changed, the values of the hydraulic radius change, and so does the value of \( c \) in the Chezy formula. As usual in engineering practice, short cuts have been devised which eliminate a great deal of the adjustment suggested above. One of these, especially prepared for use with irrigation ditches of small size, is given in the table on page 100.

This table is based upon the assumption that ditch sections are to be trapezoidal in section, the bottom being level and straight and side slopes being \( 1\frac{1}{2} \) to 1, that is, one foot up to \( 1\frac{1}{2} \) out. Natural earth fills usually assume such slopes. A value of 0.030 is used for \( n \).

Although the use of this table is evident, an illustration may be of value. Suppose a ditch is to carry 16 c.f.s. on a slope of 0.50 feet per 1000. Here at least two possibilities present themselves. The ditch may have a 5 foot bottom and carry water 1.7 feet deep, the resulting velocity being 1.15 feet per second, or the bottom may be 4 feet wide, water about 1.9 feet deep and the resulting velocity about 1.15 feet per second. The first alternative would, doubtlessly,
### Capacities and Velocities of Typical Farm Ditches

**Side Slopes 1\frac{1}{2}:1**  
Kutter's \( n = 0.030 \)

#### Bottom Width = 2.0 Feet

<table>
<thead>
<tr>
<th>Depth of Water</th>
<th>Area Sq. Ft.</th>
<th>( S=0.0001 )</th>
<th>( S=0.0005 )</th>
<th>( S=0.001 )</th>
<th>( S=0.002 )</th>
<th>( S=0.004 )</th>
<th>( S=0.005 )</th>
<th>( S=0.01 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1.04</td>
<td>0.14</td>
<td>0.15</td>
<td>0.36</td>
<td>0.37</td>
<td>0.52</td>
<td>0.54</td>
<td>0.74</td>
</tr>
<tr>
<td>0.6</td>
<td>1.72</td>
<td>0.20</td>
<td>0.35</td>
<td>0.48</td>
<td>0.84</td>
<td>0.70</td>
<td>1.22</td>
<td>1.0</td>
</tr>
<tr>
<td>0.8</td>
<td>2.56</td>
<td>0.24</td>
<td>0.61</td>
<td>0.57</td>
<td>1.46</td>
<td>0.84</td>
<td>2.15</td>
<td>1.2</td>
</tr>
<tr>
<td>1.0</td>
<td>3.50</td>
<td>0.27</td>
<td>0.95</td>
<td>0.67</td>
<td>2.35</td>
<td>0.97</td>
<td>3.39</td>
<td>1.4</td>
</tr>
<tr>
<td>1.2</td>
<td>4.55</td>
<td>0.32</td>
<td>1.46</td>
<td>0.78</td>
<td>3.55</td>
<td>1.13</td>
<td>5.03</td>
<td>1.6</td>
</tr>
<tr>
<td>1.4</td>
<td>5.74</td>
<td>0.34</td>
<td>1.95</td>
<td>0.84</td>
<td>4.82</td>
<td>1.2</td>
<td>6.89</td>
<td>1.73</td>
</tr>
</tbody>
</table>

#### Bottom Width = 3.0 Feet

<table>
<thead>
<tr>
<th>Depth of Water</th>
<th>Area Sq. Ft.</th>
<th>( S=0.0001 )</th>
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be the more desirable.

**Allowable Velocities in Open Ditches**

As has been suggested in previous lessons, Hawaiian soils are peculiar in many of their relations to soil moisture. They are also peculiar in their resistance to erosion. The maximum velocity in open, unlined ditches in soils of more common occurrence is under careful control to guard the ditch bottom from washing. Such maximum, tolerable velocities are usually given as 1 foot per second for sandy soils and 4 feet per second for stiff clays. Hawaiian soils seem to offer no such restrictions, velocities as great as 10 feet per second without erosion of sides and bottom being common.

**The Flow of Water in Pipe Lines**

It is common knowledge that pressure is lost in the transference of water through closed conduits. It is equally true that pressure lost in overcoming friction in the conduit is directly proportional to the length of pipe involved, provided, of course, that the conduit is uniform in size and material throughout its length. Thus, if one knew the friction loss in a certain size of pipe for a certain flow in a given length, say 100 or 1000 feet, he might compute the pressure drop in any length of pipe under similar conditions. But here the proportionality ceases. Doubling the flow does not double the pressure loss nor does changing the diameter of the pipe affect the pressure loss per unit length in any simple ration. It is evident that the nature of the interior of the pipe is significant.
and relations between pressure loss, size of pipe and quantities delivered in unit time for wood stave pipe would be useless in problems involving steel pipe.

Pressure losses in pipes of different materials and with different rates of flow cannot be determined except by experiment. Such experiments, if carefully done, are both elaborate and costly. Most of the pipe materials commonly used for the conveyance of irrigation water have now been adequately studied and the results published in such convenient form that one is inclined to minimize the detail of their preparation. Such tables are to be found in standard books and bulletins on hydraulics and in engineering handbooks. For this reason they are not reproduced here; references will be found in the collateral reading.

Regardless of the form in which this material is presented, it contains the inter-relation between three factors: the diameter of the pipe in feet or inches, the rate of flow in one or more of the units discussed in Lesson II and the pressure loss per unit length. This pressure loss may be expressed in equivalent feet of water or in pounds per square inch. A convenient equivalent is that a pressure of 1 pound per square inch is equivalent to the pressure exerted by a column of water 2.31 feet high. The unit of length in friction tables may be either 100 feet or 1000 feet. It is always carefully specified.

When tables of this sort are available the pressure difference required for the delivery of given quantities of water through level pipe lines is simply determined, while similar determinations for lines on a slope are not much more complex. If such lines run uphill, the specified difference in pressure
between the inlet and the outlet must still exist and since the elevation at the inlet is less than that at the outlet, the required pressure difference must be added to the difference in elevation to effect the desired flow. If the line extends down a slope, the required pressure difference may be entirely absorbed by the difference in elevation.

There are other causes for pressure loss than that indicated above. Elbows, bends and abrupt changes of diameter, even when the diameter is increased, all tend to increase resistance to flow and consequently should be carefully considered in a complete design. Such fittings are, however, rather rare in the simple problems falling within the scope of this lesson and will not be considered here. These losses are discussed and evaluated in hydraulic texts and engineering handbooks to which the student is referred.

Types of Irrigation Pipe in Common Use

Concrete Pipe

Although concrete pipe is seemingly unpopular and but little used in Hawaii, it plays a large part in water conservation programs elsewhere. Whether this unpopularity is due to some deteriorating effect of local soils or inexperience in manufacture and laying is not known.

For many years such pipe was made in two foot lengths, concrete being cast by hand tamping, or by machine, between removable forms of that length. More modern pipe is centrifugally cast and may come in lengths as long as eight feet. Such pipe may carry reinforcing of heavy wire to supply additional tensile
strength. Concrete pipe is usually equipped with bell and spigot joints which may be cemented together in the field. Considerable experience is required for good work.

All manner of control and outlet fittings are available from manufacturers who specialize in irrigation equipment.

Wood Stave Pipe

Recent improvements in methods of manufacture of wood stave pipe have led to great increases in use. Being well adapted to low heads and large diameters, such pipe has proved to be one of the best and cheapest means of conveying large volumes of water from the source of supply to the place of use. It finds a particular field of usefulness in the construction of inverted siphons. It is likewise well adapted to rolling ground where the building of canals on grade might be impractical. In its smaller sizes it is often used in irrigation distribution.

Wood stave pipe falls into two general classes. These are (1) continuous wood stave pipe which is assembled in the field from carefully milled staves and (2) machine banded pipe which is delivered in assembled sections which can be joined together by means of specially designed couplings.

Pipe of this sort has not enjoyed great popularity in Hawaii except in a few widely scattered areas. Wood boring bees seem to attack the pipe badly, causing local areas of weakness; when buried, the material seems to be short-lived.

Steel Pipe

This material is rarely used in irrigation except for long lines with few branches. Its lightness for given strength is often an advantage when proposed locations are relatively
inaccessible. The use of steel pipe for distribution within a field is limited to screw pipe which can be supplied in diameters up to 12 inches. Such material is costly and is only used when water of high value is being used. Groves in southern California, irrigated with domestic water, use some screw pipe for distribution.

**Surface Pipe**

The distribution of water by surface pipe is resorted to when seepage losses must be eliminated and when lined ditches and concrete pipe lines are unavailable. Such pipe may be made of ten foot sections of galvanized iron pipe of an appropriate gage provided with quickly detachable joints, or of waterproof canvas sewed into hose. Since there is unavoidable loss of pressure in the distribution of water with surface pipe, this method of conveyance is ordinarily used in conjunction with pumping plants.

Pipe of this sort is not yet used in Hawaii, although galvanized iron surface pipe may be of value in the elimination of seepage losses from unlined ditches.

**Losses of Water in Conveyance in Open Ditches**

Exposed water surfaces are always subject to losses by evaporation, the magnitude of this loss depending upon the temperature, relative humidity and wind velocity. Although such losses may be great under certain conditions, there is little that can be done to prevent them. Deep, narrow ditches might reduce this loss by exposing a relatively small water surface to evaporation, but the evident disadvantages accruing
from sections of this shape are usually out of line with the saving effected.

A much greater source of loss in unlined ditches lies in seepage. This is especially true in Hawaii where factors making for evaporation are not excessive and where water rapidly penetrates the usual cane soils, although those soils are similar to clays in other respects.

Fortier gives the following as factors which determine the seepage losses in unlined canals:

1. Size and shape of soil particles.
2. The possibility of silt deposits on sides and bottom.
3. The relation of wetted perimeter to other hydraulic elements.
4. Depth of water in conduit.
5. Velocity of water in conduit.
6. The possible inflow of seepage water.
7. Temperature of soil and water.

Although the factors listed above may all be of importance in ditch seepage, it has been found impossible to correlate them into an algebraic expression which might be used to determine seepage if the contributing factors were known.

**Prevention of Seepage Losses**

Methods of minimizing losses of water by seepage fall into three classes:

1. Puddling the bare earth in sides and bottom of the canal.
2. Lining the section with impervious material.
3. Adding water resisting material to sides and bottom.
Of these, the first has been tried in Hawaii and found ineffective. Importing true clays which might be used as a rough coating for the exposed surfaces of ditches and reservoirs and then puddling the soft lining by tramping when wet has been suggested but never tried. At best, the puddled lining is impermanent and rapidly loses its impervious nature upon successive wetting and drying.

Concrete linings are water tight, when well built, and costly. Such linings are usually cast in place, the carefully finished ditch section being used for the outer form, although pre-cast concrete slabs may be assembled and cemented together in the required position.

Thin plaster linings of concrete over a reenforcing of coarse wire screen is unpopular in Hawaii, although extensively and satisfactorily used elsewhere. Such linings need not be more than 3/4 of an inch thick and, when well laid, are impervious. The local difficulty may be due to a rapid rusting out of the reenforcing material with consequent loss of strength. In spite of its bad reputation under Hawaiian conditions, the plaster lining has promise and should be more carefully investigated.

The use of oils and asphalts as a means of waterproofing ditch sections is in the experimental stage. Crude oil is sometimes applied by means of the equipment employed in road sprinkling. This material may either be incorporated into the surface by means of hand tools or allowed to form a continuous surface coat. In neither case can permanence be expected. Much of the oil is washed away with the first use of the canal, while
hardy weeds which are not killed by such an application break up
the impregnated surface soil to such an extent that little
protection against seepage losses is evident. The use of
asphalt, even when applied hot, as in road work, is subject to
the same limitation.

One of the large oil companies, which at one time did
considerable advertising aimed toward increasing the use of oil
and oil products in ditch linings, has now withdrawn from the
field. None of their products possessed sufficient structural
strength to withstand the thrust of vigorous weeds beneath the
lining.

The problem of ditch lining in Hawaii is an open one.
Experimental work in this field would doubtlessly be of value.

Collateral Reading

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King, H. W. and
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<td>Stanley, F. W.</td>
<td>1921</td>
<td>Use of Concrete Pipe in Irrigation</td>
<td>Bul. 906, U. S. Dept. of Agr.</td>
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<td>Williams, G. S. and Hazen, Allen</td>
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<td>Hydraulic Tables</td>
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LESSON VII

IRRIGATION CONTROL AND EXPERIMENTATION

Experiments in irrigation fall into two general fields which seem widely separated with respect to the point of view and training of the investigator, although both tend toward the same end. All agricultural research aims toward the production of crop plants or animal products with the lowest cost per unit of product. This is true with investigational work in irrigation. There are, in general, two ways in which irrigation costs entering into crop production may be lowered. One lies in providing irrigation water at an ever decreasing cost per unit volume. Such work lies within the field of the irrigation engineer and in Hawaii, is well handled. The construction of dams for the storage of cheap flood waters, the construction of aqueducts from areas of cheap and abundant water to irrigable lands and the constant improvement in pumping efficiencies are all bits of evidence of the activity of the irrigation engineer in providing the plantations with water at a low unit cost. A discussion of the methods involved lies outside the scope of this course. Such methods result from a carefully studied balance of engineering feasibility and rigid economics.

The other field lies in the economic use of water on the plantation itself. Each unit of water delivered to a plantation ditch should be so distributed that maximum returns, in terms of dollars, should accrue to the plantation. And in this distribution lies the field of the irrigation agronomist.
His problem is complicated by the fact that maximum production per acre is not his aim. He must distribute water in such a way that the dollar return from the entire plantation should be as great as possible. And the basis for this distribution is not as yet well understood.

In general, the irrigation engineer works from known principles of engineering and economics. The modern irrigation agriculturist, especially on Hawaiian plantations, is a research worker. He must discover principles as well as apply them. He should possess some knowledge of plant physiology; he must be resourceful; he must be capable of accurate instrumental manipulation and be familiar with methods of interpretation. And above all he should enter into his work with an open mind.

Soil Moisture Control

If the principles of Lesson IV can be applied to the production of sugar cane, it might be assumed that the distribution of irrigation water could best be based upon detailed studies of the actual soil moisture content in the individual fields. If this policy is adopted, irrigation might be so timed that the soil moisture content in each field is kept between the maximum water holding capacity and the wilting point, the details of such intensive sampling for moisture content forming a perfect soil moisture history for the field. Except for the questionable time of maturing, we have some evidence, mainly from other crops, that such a distribution would result in maximum production and that any departures from the program would either result in waste of water or in an unescapable loss of growing time.
Such a plan of irrigation control is in use in many high producing irrigated areas. In southern California, commercial firms undertake to advise with respect to dates and abundance of irrigation, this advice being based upon intensive soil sampling and the determination of the controlling soil moisture constants. The policy is, of course, used in the irrigation control of many orchards under irrigation experimentation.

This control requires a high degree of care and judgment for satisfactory results. If the soil in question were ideally uniform and carried a uniform root concentration, the problem would become relatively simple. For in such a case one soil sample, for soil moisture determination, would be as reliable as many. And the soil moisture history of a large area might be accurately determined by single samples taken, from time to time, at the most convenient point.

It is well known that no soils are sufficiently uniform to permit such treatment. Local areas may differ widely in water holding capacity, the required frequency of irrigation being consequently variable at different points in the field. The required number of samples per acre increases greatly as the inherent soil variability increases, and the care required in sampling increases in the same ratio. Another factor which might confuse this sort of control is the variability in root concentration which may be expected in row crops, especially when such rows are as widely spaced as in cane. Samples taken from the bottoms of lines where the concentration of feeding roots might be expected to be relatively low would not be a fair indication of average moisture content in the field, for the rate of soil
moisture depletion there would be relatively slow; and an irrigation schedule based upon such sampling would be faulty.

Theoretically such irrigation control is ideal, although in practice many considerations require such refinements and detail that the cost may be out of line with the benefits. On uniform soils, especially when the basin method of irrigation is used and when economic considerations justify it, this method of irrigation control seems to have great promise. Some of the commercial firms operating upon this principle take all their samples from a small part of the area in which they are interested. They assume that the results of such sampling will be consistent and indicative of conditions under the larger piece. They seem to prefer a relatively accurate record of a small area than the results from widespread sampling which can be interpreted only with difficulty, if at all.

Veihmeyer refines this practice still more and samples at each tree in an orchard. Samples are taken within one foot of permanent stakes driven under the skirts of the trees in the sampled blocks. Successive samplings are distributed in such a way around these stakes and at such short distances from them that each may be unaffected by the hole remaining from the previous sampling and the observed moisture content be indicative of that in a very small area. Even with this refinement inconsistencies often appear, these being attributed to minor variations in soil type within the closely limited zones of sampling.

However, such irrigation control is rapidly becoming
popular where economic conditions justify it.

**Interval Control**

Irrigation control based upon observations of the effect of varying irrigation intervals upon the cane's growth is more popular in Hawaii than the more detailed methods involved in soil-moisture control. No assumptions from plant physiology are required, nor is soil sampling equipment necessary for irrigation control based upon interval test. Here sugar cane, in test plots, is irrigated at varying intervals, the best results as measured in the rate of cane growth and by observation being applied to the larger fields. It is purely empirical. Although simple in conception and inexpensive in operation, this plan gives valuable results under commercial conditions. Moreover, some of the best results obtained from this method find considerable substantiation in the argument of plant and water relations discussed in Lesson IV.

**Irrigation Research**

As has been indicated, problems in irrigation research cover a wide field. Many pure sciences contribute methods of use in their attack and soil physicists, chemists and plant physiologists are constantly discovering new principles which are directly applicable by the research worker in irrigation.

Perhaps the most valuable bit or research work with an unstudied crop lies in determining the water requirement of that crop. For this ratio when determined under normal growing conditions is the only possible common denominator by which
relative efficiencies of irrigation distribution can be gaged.

In general, this problem requires the attention of an investigational agency. The equipment is heavy and costly. The work is confining and attendance charges are correspondingly heavy. This work with respect to sugar cane is being done at Waipio and if environmental conditions here can be assumed as comparable to those over the entire coastal area from Red Hill to Ewa on Oahu, the results may be applicable to a considerable part of the cane producing area on that island. The results from Waipio will presumably prove unreliable in other districts, where environmental factors make for a more or less rapid transpiration rate and the factor of water used to sugar produce must necessarily be adjusted or redetermined for other conditions.

Other problems of research in irrigation immediately suggest themselves. The field is particularly wide in a study of soil and moisture relations in view of the peculiar characteristics of these highly colloidal soils. Such problems as the reliability of the moisture equivalent in the determination of the maximum waterholding capacity, the wilting coefficient together with its relation to the moisture equivalent and capilllary phenomena are all fertile and almost untouched fields for research in Hawaii. And progress must be made in all of them before commercial irrigation in the islands can be put under definite rational control.

**Plantation Investigation**

However, such problems are highly abstract. Although each finding may be considered as a real contribution, it may not be of much practical value when considered alone. Moreover,
the equipment and detail involved puts such studies rather outside the scope of the agricultural departments of commercial plantations unless special circumstances exist.

Such departments may find an adequate field in more practical phases of the same general problem of the economic use of existing water resources. In many places a study of an elimination of seepage losses in transmission promises greater return in terms of dollars to a plantation than any of the more theoretical studies listed above, while in others equitable distribution in conditions of difficult topography forms a challenge worthy of great skill and resourcefulness. Distribution immediately suggests overhead sprinkling. As has been suggested there is a field here not only for the investigator but also for the inventor.