Yellow Copy - Mrs. "Irrigation Wells"
Carl Robiner
1936
IRRIGATION WELLS

By

Carl Rohwer,
Associate Irrigation Engineer.
Figure 7.- Discharge-drawdown relation of a well in a thin water-bearing formation and one in a thick water-bearing formation or in an artesian stratum.
Figure 24. Turbine test-pump with air lines for measuring drawdown.
Figure 1. Cross-section of a broad valley containing artesian and non-artesian water-bearing formations. ABC is an artesian stratum, and zone between water table GI and impervious stratum is a non-artesian formation.
Figure 2. Vertical cross-section of a typical irrigation well in a non-artesian formation.
Figure 5. Cross-section of water-bearing formations made up of boulders and fine sand.
Figure 5.—Drawdown curves of a single well and a battery of wells.
Figure 6. Cross-section of a driven well with modern drive point and screen.
Figure 4. Typical string of tools used on a standard rig. A regular pattern drilling bit is shown.
Figure 12. Different patterns of bits used on a standard drill rig.
Figure 4: Sand buckets or bailers with different types of valves and a California mud scow.
Figure 45. A modern type of drive clamp.
Figure 1. Hydraulic jack installation for forcing down California stovepipe casing.

End Boards 3" x 8" x 6'-00"

Floor Boards 3" x 8" x 6'-00"

8" x 8" x 8'-00"

Hydraulic Jack

Note: Floor not connected to walls - allow 1" to 2" clearance.
Figure 21. Mill's knife used in perforating stovepipe casing.
Figure 24. Types of bits used with hydraulic-rotary, hollow-rod and jetting equipment.
Figure 28. Air-lift pump installation for developing well by pumping and back washing.
Mr. Paul Ewing,
U. S. Bureau of Agricultural Engineering,
Box 180,
Berkeley, California.

Dear Mr. Ewing:

Enclosed are prints of photographs taken while University of California Farm Well #9 was being drilled by the hydraulic rotary method.

Photo 735-B-36 shows the drill stem (A) being rotated by the turntable (B) which is driven by chain-drive. This drill-stem is hollow and carries ordinarily a fish-tail bit on drilling end. Mud-soup is pumped down through this revolving stem to the bit. The pressure hose (C) connected to the high-pressure side of the mud-pump is shown in the photo. A revolving connection (D) permits rotation of the drill stem. The mud-soup fills the well as it is drilled and carries cuttings upwards to the surface. The mud stream in the ditch in the foreground carries this overflow of soup to the sump on the suction side of the mud pump. So, around and around the mud-soup goes and where it ends only the driller knows. Excess soup is settled out, of course, in the ditch and sump.

Because of its high specific gravity this soup helps prevent caving of material through which the well is drilled. The fine mud is also plastered on the inside of the well by the bit.

Photo 735-B-37 shows the other side of rig surrounded by drillers, vehicles, and experts.

Casing used in rotary-drilled wells is usually tailor-made; i.e., pre-perforated to match what the driller considers water-bearing strata. Photo 735-B-38 shows driller cutting slits in 14-inch O.D. casing with torch. Photo 735-B-39 shows perforated 14 inch casing in foreground wrapped diagonally with #9 wire, 5/8" centers, and spot welded to casing. This #9 wire was covered with #23 gage brass-wire screen, and then wrapped with wire as shown.

Photo 735-B-40 shows casing being dropped into well. The driller butt-welds each section with torch. This practice saves expense and eliminates the collar often used to join screw casing,
Attached is copy of well log. The space between the 22-inch reamed hole and the casing was filled with gravel.

The hydraulic rotary method is widely used in California for drilling wells for irrigation supply although the number of stove-pipe wells sunk with percussion and auger tools, often in combination, greatly exceeds the number of hydraulic wells. Six-inch test holes can be sunk very rapidly if boulders and quicksand are not encountered.

If you want any more information on the hydraulic method, I will be glad to write a longer statement.

Yours truly,

C. V. Givan
Assistant Irrigation Engineer.

CVG:P
Encl

Dr. Veihmeyer stated that hydraulic hole should have been larger than 22" diameter which was drilled because some trouble has resulted from use of this well. Apparently, a portion of gravel stuck between casing and drilled hole at some unknown depth, and then slipped suddenly, causing the formation outside the casing to cave in. Considerable mud was pumped and specific yield of well decreased.
This appendix is added because sometimes confusion exists when someone refers to the auger method as the rotary method. I believe it best to restrict use of word "rotary" to modified form "hydraulic-rotary". An hydraulic-rotary rig is often referred to as a rotary rig by drillers.

Photo 735-B-4 shows stove-pipe casing being forced down by loaded wooden pry. The casing is surrounded by the turn-table which is used to revolve an auger when stiff clay strata are being penetrated. When operating, the auger (shown in left photo 735-B-25) is attached to round hollow drill-stem shown in upright position (leaning to right).

After auger has been withdrawn the clay is under-reamed so that stove-pipe casing will slip easily.
Log of Well No. 9  
Branch of the College of Agriculture  
Davis, California

**Location** - Approximately 1/4 mile south of northwest corner of the University Farm, Davis, California, which is in the northwest corner of Section 16, TRN, Range 2E, MD B and M.

**Driller** - F. H. Eaton, 109 Third Street, Woodland, California.

**Date** - 10-inch test hole started May 20, 1933; finished May 23, 1933. Hydraulic rotary well drilling rig used.

<table>
<thead>
<tr>
<th>Sample Jar number</th>
<th>From Feet</th>
<th>To Feet</th>
<th>Formation encountered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>4</td>
<td>Top soil - clay loam</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>34</td>
<td>Fine sand</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>37</td>
<td>Coarse sand</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>106.5&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>5</td>
<td>106.5&quot;</td>
<td>111</td>
<td>Sand</td>
</tr>
<tr>
<td>6</td>
<td>111</td>
<td>124</td>
<td>Gravel (2 samples)</td>
</tr>
<tr>
<td>7</td>
<td>124</td>
<td>149.6&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>8</td>
<td>149.6&quot;</td>
<td>150.6&quot;</td>
<td>Gravel</td>
</tr>
<tr>
<td>9</td>
<td>150.6&quot;</td>
<td>173.10&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>10</td>
<td>173.10&quot;</td>
<td>176.7&quot;</td>
<td>Gravel</td>
</tr>
<tr>
<td>11</td>
<td>176.7&quot;</td>
<td>182.4&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>12</td>
<td>182.4&quot;</td>
<td>183.10&quot;</td>
<td>Sand (both in one)</td>
</tr>
<tr>
<td>13</td>
<td>183.10&quot;</td>
<td>189.1&quot;</td>
<td>Gravel (3 samples)</td>
</tr>
<tr>
<td>14</td>
<td>189.1&quot;</td>
<td>215.10&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>15</td>
<td>215.10&quot;</td>
<td>234.11&quot;</td>
<td>Gravel and sand</td>
</tr>
<tr>
<td>16</td>
<td>234.11&quot;</td>
<td>235.8&quot;</td>
<td>Yellow clay</td>
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<td>17</td>
<td>235.8&quot;</td>
<td>253.4&quot;</td>
<td>Gravel</td>
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<td>253.4&quot;</td>
<td>269.7&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>19</td>
<td>269.7&quot;</td>
<td>293.11&quot;</td>
<td>Gravel</td>
</tr>
<tr>
<td>20</td>
<td>293.11&quot;</td>
<td>314.2&quot;</td>
<td>Yellow clay</td>
</tr>
<tr>
<td>21</td>
<td>314.2&quot;</td>
<td>327.5&quot;</td>
<td>Blue clay</td>
</tr>
</tbody>
</table>

The test hole was reamed out to a diameter of 22" and to a depth of 288'3". The well was completed on June 8, 1933. The log was obtained by the well driller and Mr. A. Coons.

**Perforations:**
- 112 to 125 feet - 13 slots
- 185 to 190 feet - 5 slots
- 218 to 253 feet - 35 slots
- 268.6" to 288 feet - 19.6" (72.6"")

**Casing:**
- 0 - 130 feet - 16 inch
- 130 - 288 feet - 14 inch

**Screening:**
- 112 - 125 feet - 13 slots
- 185 - 190 feet - 5 slots

**Details of Perforations**
- 14 inch casing
  - Slots - 1/4" x 6" - 16 rows
- 16 inch casing (screened)
  - Slots 1/2" x 6" - 16 rows
Mr. W. W. McLaughlin, Chief,
Division of Irrigation,
P. O. Box 180,
Berkeley, California.

Dear Mr. McLaughlin:

I have your letter of December 17 and the preliminary report on irrigation wells by Mr. Rohwer which accompanied that letter.

I note that only one typewritten copy of the report has been made and, as you suggest, am referring herein to section headings as well as page numbers. I have not attempted to make ordinary editorial corrections in most instances. There are a number of cases where the paper might be improved by such corrections. I think that a very considerable reduction in the total length might be made by eliminating repetition and by changing the style of presentation in some cases.

I note that you ask for suggestions on the question of the territory covered by the bulletin. There are only two places in which I think material might be left out without seriously curtailing the usefulness of the publication. I doubt if it is necessary to describe in quite so much detail the standard drilling equipment and method of drilling. As Mr. Rohwer points out, no farmer should undertake to drill a well for himself but should have it done by a competent driller where the standard methods are required. If it is to be done by an experienced driller, there is no particular object in describing all the methods in detail. As for methods of drilling or constructing wells other than the standard method, I think it is desirable to give the details which Mr. Rohwer has included.

The other material which it seems to me might possibly be left out is the series of tables giving the seasonal and annual duty of water in various locations. Those data are all available in the other bulletin to which Mr. Rohwer refers. On the other hand, as he points out, a farmer would not always have them available and it may be worth while to repeat the information in the present bulletin.

In the following pages I am calling attention to a number of points which I think might be differently handled.
On pages 5 and 6 near the end of the section covering the quantity of water supply, I think it would be desirable to point out that the character of the soil, the type of crop and the method of irrigation are all important factors in determining the necessary capacity of an irrigation pumping plant. For instance, with careful leveling it is entirely possible to use strip borders on tight soil with a much smaller irrigation head than could be used on a very coarse, sandy soil. Again, a much smaller head of water can be used for furrow irrigation than is feasible with flooding methods.

On page 9 in the section on pumping lifts, the statement is made that "the cost of pumping is almost directly proportional to the lift and each additional foot of lift adds that much more to the cost of operation." I think that statement should be very much qualified. With the low head discussed in most of this bulletin the cost of pumping plant will not be increased with increase in head, in fact in some cases a somewhat cheaper plant will be required for a higher head since larger motors can be used. Then, the cost of drilling the well may or may not be related to the head against which water will have to be pumped. The cost of applying water will be the same regardless of the lift. In fact, the only part of the cost which is proportional to the lift is that for energy in the power schedule or that for fuel if an internal combustion engine is used.

On page 11 under the section of the well contract, it would be well to point out that some provision should be made for a minimum depth of drilling or a minimum payment to the driller and that there should be some provision for stopping the work by the owner when he considers the depth of well great enough.

On page 12 in the same section the suggestion is made that the thickness of the gravel envelope should be fixed in the contract. I think that is not a good suggestion. The amount of gravel which can be used in developing a well cannot be told in advance and all the gravel possible should be placed.

In the section on factors affecting flow of ground water in the well, pages 17 and 18, it occurred to me that the discussion of water holding capacity of soils and sand might be abbreviated considerably. It appears to me that a statement as to the relative specific yields of different types of water-bearing formations is about all that is required. It also appears to me that too much stress is laid on the fact that clay soils retain a considerable portion of the total water held in them at saturation as compared with the emphasis on the slowness with which water will pass through a clay soil. The latter is much the more important factor in the undesirability of such soils as water bearing material.
On page 20 in that same section and again on page 26 in the section of hydraulics of wells the statement is made that the velocity of flow of the water in the soil will decrease as the uniformity coefficient increases. I can find no justification for that statement except the general idea that the porosity of a stratum of material of uniform size is ordinarily greater than the porosity of a stratum of material made up of particles of different sizes. On the contrary, Slichter on pages 10 and 11 of "Water Supply Paper 140" points out that if to a body of uniform sand you add a certain amount of sand of a somewhat larger size the transmission constant will increase; whereas if you add a quantity of sand of a considerably larger size, the transmission constant will decrease until a very much greater quantity of the larger size has been added. In other words, as the uniformity coefficient increases the transmission constant might either increase or decrease.

On page 21 in the section on factors affecting the flow of ground water, the statement "the product of the area of the water-bearing layer at right angles to the slope of the water surface and the transmission constant or the coefficient of permeability gives the quantity of water flowing in the area in cubic feet per minute or in gallons per day" is false. Originally the phrase "the slope of the water surface" occurred in this sentence but had been marked out by somebody before the manuscript reached me. Certainly the gradient is a factor there and should be included in the statement.

On page 26a, the page of formulas in the section on the hydraulics of wells, the formula

\[
\frac{Q}{Q_1} = \log \frac{R}{r} - \frac{Q}{Q_1} = \frac{\log e \frac{R}{r}}{\log e \frac{R_1}{r}}
\]

should read

\[
\frac{Q}{Q_1} = \frac{\log e \frac{R}{r}}{\log e \frac{R_1}{r}}
\]

There seems to be no justification for assuming that the zone of influence would remain constant when the diameter and discharge of the well is changed.

As you may remember, I had considerable correspondence and discussion with Dr. Gardner on this question of the effect of diameter on the capacity of wells. Personally I am very much in accord with Mr. Rohwer's general statement that the capacity will increase with the diameter but at a very much slower rate. Dr. Gardner, on the other hand, feels that it is reasonable to assume that the capacity will increase in direct proportion to the diameter.
I do not think that Dr. Gardner would agree to the statement in the section on hydraulics of wells near the bottom of page 28 that "based on the theoretical relation the discharge under ordinary conditions from a two-foot well is only 10 per cent greater than that from a one-foot well."

In the section on well batteries on page 31 the statement is made that "the effect of this arrangement is equivalent to that of having a well with a diameter approximately equal to the diameter of the circle of well." This statement does not agree with the figure 5 taken in connection with the statement occurring a little further down on page 31 as to the effective radius of the well battery. I think the figure is correct.

In the section on dug wells at the bottom of page 36 and top of page 37 the following sentence occurs: "When the material will stand without support while being excavated with spades and shovels and after the men can no longer throw the excavated material out of the hole a windlass or hoist with a bucket and rope is used to remove the excavated material." The use of a windlass or hoist is not at all dependent upon the ability of the walls of the well to stand.

In the section on drilling operations for the standard method on pages 60 and 61 the method of "mudding up" the walls of the well is described. I think it would be well at this point to add a very positive warning that the method may result in so sealing the walls of the well as to reduce its capacity.

I think the fact that a mud skow can be used with the standard rig with very good results in constructing irrigation wells should be brought out. There is no need for a special type of rig to be used when a well is put down with a mud skow and cased with stove-pipe casing. I have seen standard rigs used successfully in both Idaho and Oregon for this purpose.

In the section on the California or stove-pipe method, one advantage of the use of the mud skow should be stressed and that is the fact that samples of the material are brought up much more nearly in their original condition than by any of the other methods. When using the standard method, it is sometimes difficult, if not impossible, to tell whether gravel is consolidated or not. In either case, the material is broken up and into very fine chips and it is hard to say how large the pebbles were and whether they had been cemented together. Where the mud skow is used, the material is brought out in very nearly its original condition. This advantage of the use of the mud skow of course applies whether it is used on a standard rig or on the California type of machine.
In this same section, on page 66, it would be well, I think, to point out that the flap valve should be just as large as possible in the bottom of the mud skow in order that large sized gravel can be brought up without having to be broken up. With a properly made mud skow, material almost as large can be brought out as can be taken out with the ordinary steel bucket through the same sized casing.

On this same page and several other pages, the term "substitute" is used. It is my understanding that that term covers only the particular piece of equipment which has male threads on one end and female threads of a different type on the other end; in other words, an adapter for use when two different types of threads must be brought together. It appears to me that the use of the term is not quite accurate.

In Figure 18, there are shown 14' by 14' by 12 foot timbers under the floor boards. In the particular type of installation shown, I can see no reason for these very heavy joists under the floor. It appears to me that two rather different types of design are indicated, the one where the load from the jack is transmitted to the side walls through diagonal braces and another type of design in which the load is carried by the floor, and in the latter case a very heavy joist under the floor would be necessary.

There appears to be two figures numbered 19.

In the section on perforating casing, on page 72, the statement is made that the Mill’s knife is held in place by a pipe line and that a cable is used for operating the knife. I think these two are reversed. As is shown in Figure 20, the perforator is suspended in the well by a cable and the string of pipe is used for operating the knife.

As I wrote in commenting on Mr. Code’s bulletin a year ago, I still think that the thicknesses recommended in Table 3 for single casings are rather light. As I wrote at the time, they have had considerable trouble in the Harney valley of Oregon with wells cased with single galvanized casing.

In the section on the hydraulic rotary method, page 88, a brief statement is inserted as to the possibility of sealing out the water by reason of the clay wall formed in the well. It seems to me that that danger should be emphasized even more than it has been. I have personally had no experience with that method of drilling, but I should hesitate to recommend its use on account of the danger of forming a wall which would not break down with the ordinary methods of well development.

In the auger method for putting down test holes, on page 95, it is recommended that the auger itself should be welded to a piece of one-half inch pipe. If the holes are to be deep or difficult at
all, a half-inch pipe is not heavy enough for this purpose. I have found it necessary to use three-quarter inch pipe even in the small auger used for drainage investigations.

In the discussion of the gravel envelope or gravel screened well, not sufficient emphasis is placed on the need of having the gravel replace the sand which is pumped out in developing the well. I think that idea should be stressed again in the section on well development. In this same section the statement is made that the gravel screen is from 6 to 12 inches thick. It seems to me rather doubtful whether a definite statement should be made as to the thickness of the gravel envelope. On page 99, in the same section, the statement is made that the amount of gravel required may vary from a few yards to several hundred, which would seem to preclude any very definite thickness of gravel wall.

In the same section, on page 99, the plan of using a double casing and filling the space between the two casings with gravel is suggested. It seems to be very doubtful if that method is of much value. I know that in one case in the Willamette valley a well being installed under Mr. Sloan’s supervision was ruined by that method. If the gravel between the two casings is fine enough to prevent sand coming through, it tends to increase the draw-down. On the other hand, if the gravel is so coarse that the sand does come through, it does not make any particular difference. As I understand it, the chief value of the gravel screen is that it reduces the velocity of flow of the water at the outer circumference of the gravel screen. If the gravel is not permitted to replace the sand which is drawn off during drilling or development, I cannot see that it does a great deal of good.

On page 102 in the section on developing by pumping, it is suggested that a long suction line should be attached to the pump in order to pick up sand from the bottom of the well. On Figure 43 no suction line is indicated. It appears to me it might be better to indicate a long suction pipe on Figure 34.

As noted before, it seems to me it would be desirable to emphasize in this section again the use of a gravel envelope in developing wells in fine sand.

The heading of Table 7 should state at what point or to what area the prices quoted apply.

It seems to me that it would be desirable to bring Tables 5 and 8 together.

In the summary, on page 129, the statement is made that "The discharge is proportional to the draw-down and to the thickness of the water bearing formation and not that the discharge is proportional to the transmission constant." It seems to me that that must be a
typographical error and that Mr. Rohwer meant to say "and also that the discharge is proportional to the transmission constant."

On page 132, in the same section, the statement is made that most wells of this type, referring to wells made with the mud skow method, are from 500 to 1000 feet deep, but many of them are considerably deeper. I wonder if that statement is correct. It is my impression that the depths are not as great as given in the statement.

In conclusion I should like to say that I think the bulletin will fill a need and that it covers the field very well. I believe that when Mr. Rohwer rewrites this, he will find it possible to reduce the length considerably without leaving out any important information.

As I said at the beginning of this letter, I have not attempted to make corrections of the editorial type.

Yours very truly,

M. R. Lewis,
Irrigation Engineer.
February 1, 1936

Mr. W. W. McLaughlin
P. O. Box 180
Berkeley, California

Dear McLaughlin,

I have examined the manuscript by Mr. Rohwer and I am returning it under separate cover by registered mail. I think Mr. Rohwer has done a fine piece of work. He is confronted with the problem of getting into the mind of his readers a large amount of detailed information and in work of the type he is doing this is not an easy task.

I have sent with the manuscript 62 detailed comments in pencil notes most of which are of an editorial nature. The note numbers on my penciled pages correspond to numbers written in blue pencil on the right hand margin of the manuscript. A few of my comments concern rather vital points particularly notes No. 16, 19, 21, 23, and 37. I will be glad to amplify and defend my viewpoint if you or Mr. Rohwer desire that I do so.

My general notes submitted in typewriting are probably self-explanatory. Special attention should be directed to eliminating unnecessary repetition. Doubtless some repetition is essential, but in the present form of the manuscript there is too much.

The illustrations are very good. Knowing the difficulty of presenting technical information in non-technical language, I think the work is well done, and particularly that part on the hydraulics of wells.

Yours very truly,

O. W. Israelsen
Irrigation and Drainage Engineer
December 17, 1935

Mr. Carl Rohwer  
Colorado Agricultural Experiment Station  
Fort Collins, Colorado.

Dear Mr. Rohwer:

I have received the preliminary draft of your report on "Irrigation Wells" and am this day sending it on to Lewis for his suggestions.

Very truly yours,

Division of Irrigation

Enc.

By [signature]
W. W. McLaughlin  
Chief
Mr. Carl Rohwer  
Associate Irrigation Engineer  
Colorado State College  
Fort Collins, Colorado  

Dear Mr. Rohwer:

I have yours of the 20th, and have also received the manuscript from Mr. McLaughlin. It will be a pleasure to read it and I assure you that I will make such suggestions that appeal to me to be worth while.

Yours very truly,

O. W. Israelsen  
Irrigation and Drainage Engineer
U. S. A. C.  
Logan, Utah  
January 24, 1936

Mr. W. W. McLaughlin  
P. O. Box 180  
Berkeley, California

Dear Mr. McLaughlin:

I received the manuscript by Mr. Rohwer on January 21. I will aim to complete it during the week end February 1 and 2 and mail it to you on February 3.

If your needs are very urgent, and it must be returned before February 1, advise me accordingly.

Yours very truly,

O. W. Israelson  
Irrigation and Drainage Engineer

OWI G  
cc to Mr. Rohwer
1. A list of definitions would greatly assist most readers. Many technical terms in the manuscript may be understood by well drillers, but surely farmers are not acquainted with these terms. The list of definitions might be arranged alphabetically and printed in small type. Some of the typical terms for which definitions would seem to be helpful are as follows:

Air-logging
"Bridge" of sand particles, page 103. Define
Consolidated and unconsolidated
Casing "assembled",
Chamfered
Dead men
"Develop" the well. (Stress Power Saving)
Drive point
Drum
Hoist
Percussion tools
Starter
Suction header
Suction limit
Sand Point
"Well Characteristics". Define
Windlass
Windtch

2. Clearness may be increased by using more topical headings. There seems to be urgent need for marginal topic headings to assist readers.

3. Concerning the arrangement of that part of the manuscript from page 34 to 90:

The author says that driven wells are used for irrigation but very little, if at all and that dug wells, pits, and bored wells are all secondary in importance to drilled wells. In view of these facts, it seems it would be advisable to print the material of the drilled wells first. There are 14 typed pages of material under the general heading "Irrigation wells and their construction", preceding the work on drilled wells, all of which is of relatively less importance. I would consider the advantage of discussing drilled wells first to be followed by brief mention of bored wells, dug wells, and large pits and then reference to driven wells in appendix only.

4. Under the general heading "Drilled Wells", one may raise a question as to the advantage of discussing tools and casings in four different places. Of course the object is clear, that is to place each of the four methods, namely: Standard; California or stovepipe; Sand-pump and orange-peel, and hydraulic-rotary as complete units. There is possibility of avoiding repetition by combing into one general paragraph all of the common elements concerning casing, and then considering only the unique features along with each method of construction of wells.
5. In actual procedure the test hole must precede the well drilling. If the present position of the discussion concerning test hole drilling is maintained, that is following the discussion of construction, then it would seem advisable in the discussion which is introductory to construction, to the fact that test hole drilling is discussed in detail further in the bulletin.

6. If the major object of the bulletin is to serve the needs of farmers and well drillers, and not technical professional men, then many of the references may be deleted without loss. Likewise, the formulas on pages 26a and 26b could be deleted.

7. Could the cost data be included as an appendix without loss to the purpose of the bulletin?

8. The summary is very good. Its value would be increased if it were presented immediately following the introduction.

9. A further summary in a table showing in condensed form the condition of water-bearing materials, consolidated or unconsolidated, depth, permeability, etc., to which each of the several methods of well construction, types of casing, etc., are best adapted would serve as a valuable condensed statement of the details in the manuscript.

10. Lists of the reliable companies which make well drilling equipment, used for irrigation wells could be included as an appendix and would be of value.
<table>
<thead>
<tr>
<th>Note</th>
<th>Page</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Should not the introduction include statements such as the following: (a) Ground water has long been used for irrigation. (b) About ___ acres are wholly supplied irrigation from ground water sources and ___ acres get a supplemental supply. (c) Many new irrigation wells are constructed every year and dependable information is essential to economy and success in such construction. (d) The purpose of this bulletin is to make information available to persons interested, notably well drillers, irrigation farmers, engineers, and public officials. It seems to me that the bulletin will be of greater value to drillers than to any other class of readers.</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Table 1 is a &quot;pretty heavy load&quot; for a bulletin of this purpose. It is of value, but cannot the farmer get this information from local sources satisfactorily? Moreover, the nature of the soil to be irrigated will influence so much the seasonal need and the rate of application of the water.</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>Is not 300 g.p.m. too small? I'd like to see this raised to 450 g.p.m. or 1 second-foot?</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>Why not say &quot;some places in the arid regions?&quot; The word most seems a bit extravagant.</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>I would use the word &quot;lift&quot; as previously. See also Table 2.</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>Insert the word &quot;financial.&quot;</td>
</tr>
<tr>
<td>7</td>
<td>10 &amp; 11</td>
<td>This seems to be unnecessary. It is so obvious to all.</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>Repetition of idea in first sentence of paragraph 3, on page 7.</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>Say &quot;These processes.&quot;</td>
</tr>
</tbody>
</table>
This is a broader and better concept than the (static) reservoir ideas in paragraph 3 of page 1. I would adhere to the concept of page 14.

Say "water."

Why not in footnote only. Not really essential.

Is this 65% for a soil in natural condition? If so, please give me reference to source. If on disturbed soil, it has but little if any significance here. There is much misinformation in the literature about the high porosity of fine textured soil. See Fig. 97 of "Irrigation Principles and Practices," page 176.

Repetition. See page 14, opposite note 13.

We may say with equal truth that the flow in soils is very different to the flow in pipes; one is "viscous" — the other "turbulent." Different basic laws apply.

Note: Subject to Mr. Rohwer's approval, I would like to work with him in recasting page 20.

I would use this as footnote only, especially in view of conclusion on top of page 21.

The words through which a pencil line has been drawn must be included to make the statement correct. I do not see why they have been excluded.

Say "continuously." The word "constantly" implies a straight-line change whereas the change is not really linear, as stated later.

In pumping from an artesian aquifer the "water level" lowering may be so slight as to be imperceptible, whereas the lowering of the piezometric surface is a measure of the drawdown.

Why not say the "flow into" a well. Really the "discharge" depends also on the size, speed, and power of the pump.

This statement is likely to convey a wrong idea. Many of the "variables" can be measured with satisfactory accuracy:

(a) The slope is variable.
(b) The cross-section area is variable.
The only thing we cannot measure accurately is the transmission constant. Even this is subject to closer measurement than we have thought. The formulas are rational to a considerable degree. We should, I think, stress the need for more experimental measurements of the conductivity factors, i.e., the transmission constant, hydraulic permeability, etc.

Why not quote the fact that an artesian aquifer in Utah is 100,000 times as permeable as the overlying clay? See Station Bulletin 259, by O. W. Israelsen and W. W. McLaughlin.

Title may well state that the boulders obstruct the flow.

Would "depth of water-bearing sand" be better than "thickness of sand"?

Considering (a) the uncertainty introduced by the assumptions regarding drawdown (10 feet) and radius (600 feet) and (b) the fact that the bulletin is designed for non-technical readers, it seems that the computed percent and reference to Slichter's method contribute very little if anything.

Say "plant" instead of "project."

Delete last four words.

Delete the words "under these circumstances."

Note the repetition of the words "these wells". Can delete same with advantage.

These should be "tied in" with the "many sided polygon" and the "circle" of the previous paragraph. See words underscored.

It appears that all of the description which follows concerns only the loose stave supported by the rigid frame. Is there a specific description of the "fixed stave" type? Does Fig. 7 show it? If so, amplify title.

Say "volume" not "area."

Does the expression "side by side" mean so that one end of each brick is flush with the inside of the curb and the other end with the outside.
<table>
<thead>
<tr>
<th>Note</th>
<th>Page</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>45</td>
<td>This 37 percent applies only for a particular radius of the circle of influence, namely 1,000 feet. It is very close for a 500-foot R, but if R=100 feet the percent is 52. See Turneaure &amp; Russel, 3d Ed., Table 36, page 257, and compare the 6-inch well to the 4-foot one. Also I would refer to this book because it is probably more accessible than Parker. I think the comparison of capacity should be further restricted. See Soil Science paper by Gardner, Israelsen and McLaughlin, page 37 and also equation (H₃) on page 38. For conditions of well penetration there illustrated, which may be &quot;extraordinary&quot; the statement of theoretical relation does not apply to all. The above comments apply also to manuscript at bottom of page 28 and top of page 29, which see.</td>
</tr>
</tbody>
</table>
| 38   | 49   | Compare with "contents:"
Calif. or mud-sew vs. Cal or stave pipe
Sand-bucket method vs. sand pump and orange peel bucket methods. |
| 39   | 52   | Obvious and unnecessary. |
| 40   | 53   | Delete words underscored. |
| 41   | 55   | Are these parts properly classed as "tools?"
Would it be better to change the topic heading to "Tools and Equipment?"
<p>|
| 42   | 57   | Why not make this heading &quot;Auxiliary Tools and Equipment?&quot; Note that tools are described under the heading. |
| 43   | 59   | Much of this is repetition. See Page 54, near bottom. |
| 44   | 63   | Some repetition in a work of this kind is no doubt inevitable, but it seems desirable to strive to reduce as much as possible. See paragraph 2, on page 73, and compare with this paragraph on page 63. |
| 45   | 63-64 | The heading &quot;casing&quot; does not cover this concluding paragraph. Why not introduce a heading like this, &quot;Adaptability of Standard Method?&quot; |</p>
<table>
<thead>
<tr>
<th>Page</th>
<th>Note</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>66</td>
<td>This repetition seems to be unnecessary. See page 52.</td>
</tr>
<tr>
<td>47</td>
<td>67</td>
<td>Undesirable repetition. See page 65. Then, too, page 65 says &quot;most&quot; and page 67 says &quot;every.&quot;</td>
</tr>
<tr>
<td>48</td>
<td>69</td>
<td>Seems that the reference to &quot;Levers&quot; should follow final reference to the Jacks.</td>
</tr>
<tr>
<td>49</td>
<td>69</td>
<td>The description of the &quot;Setting&quot; needs to be amplified. Not clear how the foundation for the hydraulic jacks can resist a force of such magnitude.</td>
</tr>
<tr>
<td>Note</td>
<td>Page</td>
<td>Comment</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>---------</td>
</tr>
<tr>
<td>50</td>
<td>74</td>
<td>This closing paragraph should have a heading. It does not belong under the heading &quot;perforating casing.&quot; Try &quot;California Method Most Used.&quot;</td>
</tr>
<tr>
<td>51</td>
<td>78</td>
<td>Why not place last paragraph of page 78 and all of page 79, and top of 80 under the head &quot;Casing?&quot; It all relates to the forcing of the casing and would properly follow the description of the casing which ends on page 81. Possibly should have a sub-head &quot;Installing Casing.&quot;</td>
</tr>
<tr>
<td>52</td>
<td>82-85</td>
<td>It appears that all of the casing perforations described on these pages are made before the casing is put into the well. Is this right? Are these perforations made by hand or by machine processes? If general distinctions of this kind can be made, it helps a reader.</td>
</tr>
<tr>
<td>53</td>
<td>85</td>
<td>This heading should be &quot;Tools and Equipment.&quot;</td>
</tr>
<tr>
<td>54</td>
<td>87</td>
<td>Why not another heading here. For instance, &quot;Avoiding a Possible Danger.&quot;</td>
</tr>
<tr>
<td>55</td>
<td>87</td>
<td>Insert a heading. &quot;Backwashing&quot; seems to be appropriate.</td>
</tr>
<tr>
<td>56</td>
<td>89</td>
<td>Why not say &quot;The West&quot; instead of the United States. Is the Hyd-Rotary method used for irrigation wells in the East?</td>
</tr>
<tr>
<td>57</td>
<td>95</td>
<td>Might give an approximate depth. I have used them to a depth of 24 feet.</td>
</tr>
<tr>
<td>58</td>
<td>96</td>
<td>Not true if post-hole type soil auger is meant. Can be used in many saturated soils.</td>
</tr>
<tr>
<td>59</td>
<td>101</td>
<td>Insert after yield &quot;at a given drawdown.&quot;</td>
</tr>
<tr>
<td>60</td>
<td>107</td>
<td>Call attention here to Fig. 35.</td>
</tr>
<tr>
<td>61</td>
<td>109</td>
<td>Will this be indicated by a marked reduction in pressure gage reading?</td>
</tr>
<tr>
<td>62</td>
<td>111</td>
<td>The term &quot;Dry Ice&quot; is probably not generally understood. Should be amplified a little.</td>
</tr>
</tbody>
</table>
Mr. Carl Rohwer,
Colo. Agr'l Expt. Sta.,
Fort Collins, Colorado.

Dear Mr. Rohwer:

Enclosed are some comments prepared by Mr. Bloodgood, Mr. Young and me on your manuscript on "Irrigation Wells," which you sent us.

You have compiled some very interesting data on wells. It is regretted that our time is limited, as I would like to spend more time studying the report, but we are in the midst of revising one bulletin and preparing another.

I assume some member of our staff at Berkeley will edit the final draft before publication. Undoubtedly, Mr. A. L. Fellows at Denver would have some valuable suggestions to make if time permitted.

Very truly yours,

Harry F. Blaney,
Irrigation Engineer.

Encl. (3)

P.S. Your report is being returned by registered mail.

P.S. You surely have compiled some valuable information and it most have been a job that took a lot of hard work. Best regards.
Comments by Barry F. Blaney on manuscript "Irrigation Wells," by Carl Rohwer

It is assumed that this manuscript will be published as a technical bulletin; also, that the draft submitted is preliminary and the report will be carefully edited. In a few instances, the report is addressed more to the farmer.

In some parts, such as page 10, the phraseology should be improved, as I doubt whether it would be clear to the average reader.

Footnotes to references are omitted in some instances, such as pages 17, 18, 19, and 21. Perhaps you intend to list them at the end of the text, which is customary in technical bulletins.

I believe it would be well if definitions of some of the more technical terms used in the report were added to the introduction.

Page 2

(a) Typographical error.

Page 6

(b) Modify paragraph. In many sections of Arizona, California and Nevada 300 gallons a minute would be considered a good flow and can be economically handled if a small storage reservoir is provided.

Page 8

(c) Suggest substituting "many" for "most".

Table 2

(d) Headings of columns 1 and 2 should be changed as indicated. Title of table should be more general. Question advisability of including last column, especially for California where 100-foot maximum economic limit of lift is too low.

Page 10

(e) Federal Government may change policy before bulletin is published.

Page 17

(f) Suggest deleting.

(g) No footnote.

Page 47 and Figure 9

(h) The use of large pits as described is exceptional. Suggest either omitting or modifying.
(i) Can you purchase dry ice in most localities as low as 5 cents a lb.?
1. What is a reasonable depth? Here in California, where there is more pumping than any other place, and especially in southern California, the depth is several hundred feet (as high as 640 feet in the Fontana district), and agriculture is dependent on pumped water, having little gravity water. Depends on what portion of the country the economic limit of pumping for irrigation would be.

2. Are wells "constructed", or drilled, excavated, dug, etc.? On page 4 drill is used instead of constructed. Wells should be designed and planned to supply the largest quantity of water at the minimum cost.

2. Use "assist" instead of "help". The purpose of this publication is to present information which might assist those contemplating the installation of a pumping plant as to the better methods and practices used in recognized pumping districts. (As a matter of fact, the above sentence and the one the author uses "to provide information," etc. could just as well be left out of the manuscript.)

4. Instead of using the author's sentence, "For preliminary studies of water requirements exclusive of rainfall, average values may be used." Change to read, "For preliminary studies the average water requirements exclusive of rainfall may be used."

5. Twenty-five percent of 2.5 feet or 30 inches, use 2.5 feet (30 inches).

5. "Since one second-foot of water," instead of "Since one cubic-foot per second."

8. The ground water in most arid regions. Most is too strong a term to use and is not true, use "ground water in some of the arid regions."

8. Instead of using "pumping plants" use "pumping equipment".

9. Not only "low priced agricultural products, however, reduce the economical pumping lift," but the low yields is a big factor in reducing the economical pumping lift.

Data in Table 2 under "area irrigated from wells" are wrong for all of the States.

10. Cannot get the connection of the first 10 lines. "*, then the farmer or backing should determine whether he has sufficient finances (or financial assistance) to go ahead with his proposition."

10. By the time the bulletin is published, I doubt whether it would be possible for anyone to obtain a loan from the Federal Government, as their loaning at the present time is only temporary.

10. Cannot get heads or tails out of the first 10 lines on this page.
11. Too many "shoulds" on this page. Could be rewritten to a better advantage. Many of the references in the footnotes are not indicated in the text of the manuscript.

19. Ground water is never static even in a closed basin, for if the basin is replenished, there is ground-water movement somewhere within the basin.
The rate of flow is more dependent on the pulsating hydro-static pressure on the ground water than any other factor.

20. I think the slope has little to do with the velocity or underground movement of the ground water, and I do not think the underground water movement is similar to flow in pipes.

36. Suction lift is mentioned. It might be well to make a statement what the maximum suction lift would be at sea level and what causes it to vary with different altitudes.
A driven well is well suited for windmill power and the irrigation of small tracts of land such as garden plots, etc.

39. Use "sump" instead of "a pit" should be dug for the pump suction.

47. I think the subject of "Large Pits" could be left out as it is not practical in recognized pumping districts. I have never seen nor heard of such a construction for irrigation purposes.

49. Sometimes water in water-bearing material directly under a stratum of clay or other impervious material is under pressure and when the clay stratum is perforated water will rise into the hole and make a good well.

49. "At the present time most irrigation wells are being put down," etc., use "practically all of the irrigation wells are being put down" etc.
In Figure 14, instead of using "flat valve" use "foot valve" which is a better term. The flap part of the valve is a part of the foot valve. The foot valve is made up of the flap and the cushion upon which it rests.

54. "The flat valve bailer has a flapper valve" which is correct? Are they both the same? The foot valve bailer has a flapper which cannot be opened when the bailer is fitted.
Another word should be substituted for "drillings" for the bailer could not remove the drillings alone. The bailer also removes a larger quantity of water than it does the drilled material.
At your request I have read the greater portion of Mr. Rohwer's manuscript on Irrigation Wells and have made a few notes. Due to the request from the Berkeley office that the bulletin be returned as soon as possible my examination has been hurried and my notes are not as complete as they would have been otherwise.

It appears that the outline of the report has been well thought out, that the different chapters follow each other in a logical sequence, and that the report as a whole will be of considerable aid to the increasing number of farmers who are turning to wells for water for irrigation. It is to be regretted that this report was not available for distribution during and following the drought of 1934.

The report does not state if it is written for a Farmer's Bulletin or a Technical Bulletin. From the many references to the farmer I am assuming that it may be a Farmer's Bulletin. This assumption seems to be supported by the manner of popular writing which has been employed. If this be true the report is probably too long for the ordinary bulletin of this type.

On the other hand the discussion becomes quite technical at times, so much so in fact that an ordinary farmer would have considerable difficulty in understanding portions of the text.

My principal criticism of the report is the rather loose construction employed in much of the text. Unnecessary words and phrases are numerous. Able editing will correct much of this.

Other suggestions are as follows:

Page 2. Give names of authors when referring to Technical Bulletins.
Table 1. This table has been compiled direct from tables in different Irrigation Requirement bulletins which have sub-headings that do not always agree with each other in exact wording. This is permissible in separate bulletins but when the different tables are brought together in a single table a single sub-heading should be used. In this Table two sheets use the sub-heading "Portion of total seasonal ---"; three sheets have "Monthly
percentages of total seasonal ---" and one has "Percentage of total seasonal---". These should be made uniform. Also, one sheet 5, Table 1, the seasonal net irrigation requirement is in feet and tenths while on other sheets it is in feet and hundredths. As this is all one table sheet 5 must conform to the rest of the table and include all months from January to December even though no irrigation is practiced in these months.

Table 2, Col. 1. The acreage given here does not agree with that in Table 36, Irrigation Census of 1930 which are consistently higher. The figures Mr. Rohwer has used are taken from tables used in individual state reports such as California Table 12 which gives "Irrigated area reporting " maintenance and operation but not the total acreage irrigated in the state. The acreage given is correct for the associated maintenance costs but is not the acreage irrigated by wells for the state as indicated by the column heading.

Page 24; Simplify sentence where indicated.

Page 25; "Phenomena" seems to be an unusual use of the word in this case.

Page 48; It is not clear how the reamer can be an extension of the cutting edge at the bottom of the bucket and at the same time be attached to the top of the bucket. Should be clarified.

Page 52, par. 2; The length of stem given here does not agree with that shown in Figure 12. Also, it is called "drill stem" in the text and "Auger stem" in the Figure.

Figure 14, a-d. Is the valve in the California muckcraw a "flat" or a "flap" valve. My experience would indicate that it was a "flap" valve. In the following pages "flap" and "flap" seem to be confused, sometimes one word being used and again the other.

Page 107; The word "education" may be correct though it is new to me. If there is another word which could be substituted it might be easier for the farmer to understand.

Yours very truly,

A. A. Young,
Asst. Irrig. Engr.
Mr. Carl H. Rohwer,
Associate Irrigation Engineer
United States Department of Agriculture
Colorado State College
Fort Collins, Colorado

Dear Mr. Rohwer:

Use the enclosed material on flow of ground water as you please or not at all.

I wish it were possible for me to give it more time but this week is fully taken for a special course to water masters and last week also was very full.

Note that I have omitted reference to the uniformity coefficient. I did this in the thought that you are talking to a non-technical audience and that actual use of these uniformity coefficients will never be made by your readers.

I am glad for the opportunity to endeavor to assist you in preparation of your bulletin. I have always been grateful for your assistance on "Irrigation Principles and Practices". When the bulletin is ready I shall want a dozen copies.

Feel free to write me further if you care to.
Best wishes.

Yours very truly,

C.W. Israelsen

Irrigation and Drainage Engineer

OWI

dk
Groundwater is seldom, if ever, static; it is nearly always moving in some direction. Usually groundwater flows slowly toward a stream, a lake or a swamp where it emerges and becomes surface water. In parts of closed basins the flow may be upward and the groundwater may evaporate from the land surface as it emerges. The velocity of flow depends on two classes of forces which act at the same time, i.e. driving forces and resisting forces. The driving forces are proportional to the loss of energy of the water per pound in each unit distance of flow, and this is usually designated simply loss of "head". The head loss may be reflected in change of position only, as in the flow of groundwater downward under the force of gravity, or it may be reflected in change of pressure only, as in the case of flow through a horizontal soil column, or it may be reflected in a loss of the combined head due to position plus the head due to pressure. It is customary to measure the effect of driving forces by measuring the fall of the water surface in a given distance along the land surface, and for the ordinary case of flow that is nearly parallel to the land surface this method is satisfactory. However, in the case of groundwater flow upward or downward in the soil the method cannot be applied, because it is essential to measure the loss for each unit of distance of actual water flow. The effective driving force is proportional to the ratio of the difference in elevation of the water surface (the pressure on the water surface being constant) to the flow length between any two points considered, and this is known as the hydraulic slope.

Resisting forces are dependent on the size, shape, uniformity and compactness of the soil particles and on the temperature of the water; the influence of temperature, being relatively small, is usually neglected. Largeness in size of soil particles smoothness in shape, uniformity in size, and open
structures all cause but little resistance to water flow, whereas; smallness in size, irregularity in shape, non-uniformity in size and compactness are soil properties which cause great resistance and consequent very low velocities of flow. Indeed, all groundwater flows are at velocities that are very low compared to the velocities of surface water flowing in rivers, canals, and ditches.

Two Kinds of Water Flow

There are two rather distinct kinds of flow of water, i.e. streamline flow, in which water particles move in nearly parallel paths, and turbulent flow in which the particles move in zig-zag irregular directions. Streamline flow is characteristic of very low velocities, whereas with higher velocities such as occur in ordinary canals and ditches the flow is turbulent. All groundwater flow is believed to be streamline. The vital difference in these two kinds of flow is that with streamline flow the loss of energy is proportional to the velocity, whereas with turbulent flow it is proportional to the square of the velocity. For instance, if in groundwater (or streamline) flow, the velocity is doubled, the loss of head per foot of flow length is also doubled, whereas; if the velocity of flow of water in a canal or a pipe is doubled, the loss of head per foot of length is made 4 times as great.

Darcy's Law

The fact that the relation of loss of head to velocity for streamline flow applies to the flow of water in soils was discovered by Darcy in 1856 and is now widely known as Darcy's law. It is considered the fundamental physical law governing the flow of groundwater.
Conductivity Factors

The combined effect of the factors which resist the flow of groundwater is designated a water conductivity factor, and is defined as the capacity of the soil to conduct (or convey) water through unit area of soil under the influence of a given force. The conductivity factor is called the *transmission constant* by some authorities, the *coefficient of permeability* by others. It is defined as the volume of water that will flow in unit time through a column of soil of unit cross section area under the influence of unit hydraulic slope. Fundamentally, the *transmission constant* and the *coefficient of permeability* are identical physical quantities, but the former is usually given in cubic feet per minute, and the latter in gallons per day. Formulas have been derived for computing the magnitudes of these conductivity factors on the basis of the diameter of the soil particles, the compactness of the soil and the temperature etc., but the results are at best only rough approximations when applied to a natural soil.

The computed values have usually been too low, and there is an increasing recognition of the need for determining them experimentally under natural field conditions as a basis for predicting the quantity of flow under pumping.
February 27, 1936

Mr. M. R. Lewis,
Soils Department,
Oregon State Agricultural College,
Corvallis, Oregon.

Dear Mr. Lewis:

There is enclosed a manuscript for the proposed bulletin on "Equipping a Small Irrigation Pumping Plant", by W. E. Codie. This report is for publication by the Colorado Agricultural Experiment Station and they have asked us to review the manuscript and offer any suggestions or criticisms we may have. I would appreciate it if you would go over this manuscript as soon as convenient and return it with your comments to this office that I may send it elsewhere for comment.

Very truly yours,

Division of Irrigation

By

W. W. McLaughlin, Chief

Encl
W6M/sn
ce-Rohwer
January 17, 1936

Mr. Carl Rohwer
Colorado Agricultural Experiment Station
Fort Collins, Colorado.

Dear Mr. Rohwer:

For your consideration I am sending on comments by Messrs. Lewis and Jessup on your manuscript "Irrigation Wells." This manuscript has been sent on to Dr. Israelsen and will then be reviewed further here. In the meantime I wish you would give serious consideration to the suggestions enclosed.

It is evident Mr. Jessup may have a little misconception in that he assumes this bulletin is for the farmers only. It is to be published as a technical bulletin. Later we will prepare a farmers' bulletin either on this subject alone or on the subject of Pumping for Irrigation.

Very truly yours,

Division of Irrigation

Encs.

By W. W. McLaughlin
Chief
Mr. W.W. McLaughlin, Chief,
Division of Irrigation,
Bureau of Agricultural Engineering,
Berkeley, Calif.

Dear Mr. McLaughlin:

I have gone over Mr. Rohwer's report on irrigation wells. He gives a very good description of drilling equipment, methods, casing, etc. If this is regarded as a report on drilling of irrigation wells, then I think that the first part of the report, (prior to "Irrigation Wells and their Construction") should be considerably reduced in scope.

However, I assume that this report is not intended for use by well drillers but rather for the farmer who intends to install a well. In view of this, and also in view of the fact that early in the report the farmer is advised that he will not be able to do the drilling himself and that he should employ a reliable driller and outfit, it seems that somewhat too much space is devoted to certain drilling methods, description of tools, etc.

Trying to look at the report from the standpoint of a farmer the following criticisms are offered:

Water Supply. Quantity

I am about to install a well in the Yakima Valley for an orchard requiring a cover crop and on rather sandy soil. For Yakima I find the water requirement to be 2.6 acre-feet. But is this enough for my conditions? (Note: I think a paragraph or so should be given explaining briefly how requirement might vary from the average figures given in Table 1.)

Pumping Lift. Table 2.

Does "Investment in Pumping Plant per Acre", include cost of well?

What does "Cost of Operation per Acre" include? Does it include interest and depreciation? If not how much should be allowed for this?
Factors Affecting Flow of Ground Water into Wells.

Not interested, (as a farmer), in porosity of packed spheres.

Not interested in definition of "effective size", particularly since it is stated that this is not a satisfactory method of arriving at a transmission constant.

Hydraulics of Wells.

Not much interested in the formulas.

I wonder what should be the diameter of my proposed well? Are small wells apt to fail more quickly and give more trouble than larger ones? Assuming that I have a good water bearing formation and need a big flow, can I get a pump of large capacity into a 1-foot well? Should the diameter of the well be somewhat larger than the diameter of the pump. Is entrance head into small wells as compared with larger ones and important factor?

Driven Wells.

I would like to know a little more about screen sizes in sand points and what mesh to use in different formations.

Dug Wells.

Loose Stave Type. Should the staves be bevelled on the inside? (Note: I never drove staves in a well but I have used them for sheeting in construction of closed drains and in this case they should not be bevelled on the inside.)

Drilled Wells. Standard Method.

I am interested in a brief general description of this method but am not interested in nearly so much detail as to equipment, methods, tools, etc. I am not interested in Figure 15, (Drive Clamp).

I am very much interested in knowing about casings, perforations and strainers. I would like a little more information relative to the relation of size and number of perforations for different types of formations.
California or Stovepipe Method.
Sand-Pump and Orange-Peel Bucket Methods.
Hydraulic-Rotary Method.

In general the same observations apply to these subjects as those made in connection with "Standard Methods" above.

Test Hole Drilling.

I wish that I had a little better idea as to what it might cost me to have my farm tested.

Log of Test Holes.

"Large samples should be taken so that there will be enough material to make a mechanical analysis of the sand and also a percolation test if necessary". Where and how should I get this done? How shall I use the information when I get it? After having drilled test holes how do I decide whether to install a well or not?

Development of Wells.
Testing of Wells.

I wonder what these operations might cost me. Later there appears to be some information on cost per hour or per day but this does not give me much idea as to total cost.

I wonder what special types of screens cost such for example as that shown in Figure 29.

This is the end of my observations from the viewpoint of a farmer. Other suggestions follow.
Factors Affecting Feasibility.

First Paragraph. Both the subject matter and the list of publications given seem to improperly indicate that this report covers such subjects as methods of irrigation and irrigation of various crops.

Quality of Water

It might be well to find out, if possible, whether the water will corrode screens and pumping equipment rapidly and whether incrustations are liable to rapidly form on screens and suction column of pump. Also in some localities the presence of gas in the water reduces pump efficiency.

Pumping Lift.

I may be wrong but it seems to me that the following general statement is open to some question: "Higher heads are also feasible if the water pumped is to be used only as a supplemental supply."

Hydraulics of Wells.

I think that one gets the impression from this report that wells having a diameter greater than about 1-foot have no advantages over larger ones other than a very small increase in capacity. Of course cost demands that the diameter be limited as much as possible, however, larger wells have some other advantages such as less entrance head, less trouble from clogging of screens, perforations, etc.

Dug Wells.

"Theoretically a well 8 feet in diameter has a capacity only 37 percent greater than a well 1 foot in diameter". Does this statement as to theory take into account entrance of water through the bottom of the well as well as the sides. (Dug wells are usually shallow).
I believe that this report says nothing about open-bottom wells, (see our Farmers Bulletin, U.S.D.A. 1404). Landings for casings is an important matter in some California districts. Is the open bottom well a good type? Should the bottom of a well ever be plugged with concrete or supplied with gravel?

This report says nothing about the probable life of wells except to point out the danger of over pumping the supply. How long will casings and screens resist corrosion? How long before incrustations may clog the screens and perforations? Where danger of the latter exists what kind of screens should be used? Which is better under such conditions round holes or long narrow slots? The removal of fine sand with the pumped water may eventually result in severe caving. I appreciate that these questions can not be answered definitely but I think that it should be pointed out that the life of a well is very apt to have some limitations.

So far I have offered nothing much but adverse criticism. However, I think that Mr. Rohwer has put together a very good report on this subject.

The report is being returned herewith by registered mail.

Yours very truly,

L.T. Jessup
Assoc. Drainage Engineer.
IRRIGATION WELLS (1)
by Carl Rohwer

Introduction
The quantity of water available from streams and reservoirs in the
western regions of the West is frequently not sufficient to supply
the needs of the land suitable for irrigation. Where this condition
exists, additional sources of water must be sought. In many areas
large quantities of water are stored beneath the surface of the ground
in layers of saturated sand and gravel. Not all of this water can be
recovered, nor is the water table in all areas close enough to the
surface to be within the economic limit of recovery, but where condi-
tions are favorable the water stored in the soil may be used as the
source of an additional supply for irrigation.

The most feasible method of recovering this water is by pump-
ing from wells, and for this purpose wells capable of supplying large
quantities of water at a reasonable cost are required. Wells of this
type differ materially from those used for domestic purposes, and for
this reason farmers, well drillers and others who are concerned with
the construction of pumping plants for this purpose, should be familiar
with all the factors necessary to obtain a satisfactory well for supply-
ing water for irrigation.

(1) Prepared under the direction of W. W. McLaughlin, Chief of the
Division of Irrigation, Bureau of Agricultural Engineering, and with
the assistance of the members of the staff of the Division of Irrigation,
W. E. Code of the Colorado Experiment Station, and Dr. O. W. Israelsen
of the Utah Experiment Station. The drawings were prepared by Clarence
Tyler, and various agencies supplied information for the report.
IRRIGATION WELLS

by

Carl Rohwer,

Introduction.

An ample supply of water is essential for the success of any irrigation enterprise, but in arid regions the quantity of water available from streams and reservoirs is often not sufficient to provide for the needs of the land. Under these conditions additional sources of supply must be sought.

In many sections of the West the soil is underlain by a stratum of saturated material. In each acre-foot of saturated soil there are approximately 4 acre-inches of water, and as the layer of water-bearing material in some sections is of considerable thickness, it is apparent that there is a large volume of water stored in the soil beneath the surface in these regions. All of this water cannot be recovered nor is the water level in all sections close enough to the surface to be within the economic limit of pumping for irrigation, but in many sections the water is at a reasonable depth and may be used as the source of an additional supply for irrigation.

In order to get the water out of this underground reservoir so that it can be used for irrigation, wells must be constructed capable of supplying large quantities of water at a reasonable cost. Wells of this type differ materially from those for domestic purposes, and for this reason the farmer contemplating the construction
of a pumping plant should familiarize himself with all the factors that would help him to obtain a satisfactory well.

To provide this information is the purpose of this bulletin. Factors Affecting the Feasibility of Pumping Plants.

The construction and operation of a pumping plant for irrigation using water from wells is an expensive undertaking, and before embarking on a project of this sort the farmer should make a careful investigation of the possibilities of success of the enterprise. The principal items which must be given consideration are the legal status of pumping from wells for irrigation, the quantity of water required for the crops to be irrigated, the quantity and quality of water available from the underground source, the economic limit of pumping lift and the contract between the farmer and the well driller. In addition, the farmer should give attention to the fact that his land must be prepared for irrigation, that the soil must be suitable for growing the proposed crops under irrigation, that the climate must be favorable, that accessible markets must be at hand and that facilities for financing the undertaking must be available. Some of these subjects are explained in detail in other publications of the U. S. Department of Agriculture and well drillers, but as the farmer does not always have access to these reports, the essential information necessary to obtain a proper understanding of the problem is given here.

(1) Porter, S.
  Technical Bulletin No. 36, Irrigation Requirements of the Arid and Semi-Arid Lands of the Missouri and Arkansas River Basins.
  (7, 9, 13, 14, 15, 18, 22)

(2) Porter, S.
  Technical Bulletin No. 185, Irrigation Requirements of the Arid and the Semi-Arid Lands of the Southwest.
Legal Status of Pumping from Wells.

Before starting the construction of a well for the purpose of providing water for irrigation, the farmer should investigate the legal status of pumping from wells for irrigation by writing to the official in charge of irrigation in his State. He should find out what procedure should be followed in order to establish a right to pump water. He should find out also whether there are any sanitary restrictions to be complied with in drilling wells or any restrictions in regard to the tapping of artesian formations. Only a few states have clearly defined laws in reference to
pumping from wells for irrigation, but the farmer should, nevertheless, safeguard his right to pump water by complying with all the legal requirements. Where the doctrine of appropriation is in force, the farmer is protected against reduction in the water supply of his well caused by a well or wells being drilled near him at a later date. When, however, the doctrine of correlative use has been adopted, every farmer has a common right to use the underground water in proportion to the needs of his land. When the latter doctrine is in force, the farmer is constantly menaced by the possibility that wells drilled subsequently will cause such a large draft on the ground water that the water level will be permanently lowered. This fact should be given careful consideration when planning to drill a well under these conditions.

The Water Supply

Quantity

The amount of water required to irrigate various crops depends upon the crop, the type and fertility of the soil, the topography, the climate and the method of irrigation. For preliminary studies on water requirements exclusive of rainfall, average values may be used. These average values have been assembled from publications of the U. S. Department of Agriculture(2) and are given in table (2). Technical Bulletins 36, 185, 200 and 379. Irrigation Requirements of the Semi-Arid Lands.

This table shows the net irrigation requirement exclusive of rainfall for the principal irrigated areas in the
Table 1 Monthly and seasonal net irrigation requirements of the various subdivisions of the arid and semiarid regions of the United States.

Pacific Slope

<table>
<thead>
<tr>
<th>Division</th>
<th>Portion of total seasonal net irrigation required in</th>
<th>Seasonal net irrigation requirement per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umpqua, Coquille and lower Rogue River basins</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Upper Rogue</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>River Basin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oregon &amp; Calif.:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klamath Lake and River Basins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pacific slope in northwest-ern Calif.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pit River drainage basin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feather, Yuba, and American River Basins</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Sacramento Valley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sacramento–San Joaquin delta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Francisco Bay Basin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salinas River Basin</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Monthly and seasonal net irrigation requirements of the various subdivisions of the arid and semiarid regions of the United States. (Continued)

<table>
<thead>
<tr>
<th>Division</th>
<th>Seasonal net irrigation requirement per acre, acre-feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calif. (cont.)</td>
<td></td>
</tr>
<tr>
<td>Santa Maria, Santa Clara &amp; Santa Inez River Basins</td>
<td>2</td>
</tr>
<tr>
<td>San Joaquin Valley</td>
<td>--</td>
</tr>
<tr>
<td>Western Slope of the Sierras, east of San Joaquin Valley</td>
<td>--</td>
</tr>
<tr>
<td>Eastern Slope of the Coast Range west of San Joaquin Valley</td>
<td>--</td>
</tr>
<tr>
<td>Antelope &amp; Victor Valleys</td>
<td>--</td>
</tr>
<tr>
<td>Los Angeles, San Gabriel, &amp; lower Santa Ana River Basins</td>
<td>3</td>
</tr>
<tr>
<td>Upper Santa Ana River Valley</td>
<td>2</td>
</tr>
<tr>
<td>San Diego County</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1. Monthly and seasonal net irrigation requirements of the various subdivisions of the arid and semiarid regions of the United States. (Continued)

### Southwest

<table>
<thead>
<tr>
<th>Division</th>
<th>Monthly percentages of total seasonal net irrigation</th>
<th>Seasonal net irrigation requirements per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per-</td>
<td>Per-</td>
</tr>
<tr>
<td></td>
<td>cent</td>
<td>cent</td>
</tr>
<tr>
<td>Imperial Valley, Cal.</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Southern Nevada</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Southwestern Ariz.</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Northwestern Ariz.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Navajo Country in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>northern Ariz.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Southeastern Ariz.</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>San Juan Basin, N.Mex.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Western N. Mex.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Rio Grande Basin, N. Mex.</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Pecos River Ridge, N. Mex.</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Northwestern N. Mex.</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>west Texas</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pecos River Basin, Texas</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>West-central Texas</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Lower Rio Grande Basin, Texas</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Upper Nueces and Colo. River Basin, Texas</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Upper Brazos and Red River Basin, Texas</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Eastern Panhandle, Texas</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Western Panhandle, Texas</td>
<td>--</td>
<td>4</td>
</tr>
<tr>
<td>Panhandle, Okla.</td>
<td>--</td>
<td>6</td>
</tr>
<tr>
<td>Western Okla.</td>
<td>--</td>
<td>8</td>
</tr>
<tr>
<td>San Luis Basin, Colo.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>San Juan Basin, Colo.</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Yampa &amp; White River Basin, Colo.</td>
<td>13</td>
<td>35</td>
</tr>
<tr>
<td>Upper Colo. River Basin, Colo.</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Virgin River Basin, Utah</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>San Juan Basin, Utah</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>Green River Basin, Utah</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Uintah Basin, northeast Utah</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Green River Basin, Wyo.</td>
<td>12</td>
<td>36</td>
</tr>
</tbody>
</table>

(Tech. Bul. 185, U.S.D.A. "Irrigation Requirements of the Arid and Semiarid Lands of the Southwest" Fortier and Young)
Table 1. Monthly and seasonal net irrigation requirements of the various subdivisions of the arid and semiarid regions of the United States.

<table>
<thead>
<tr>
<th>Division</th>
<th>Percentage of total seasonal net irrigation requirements in</th>
<th>Seasonal net irrigation requirements per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per-</td>
<td>Per-</td>
</tr>
<tr>
<td>Snake River Valley in Idaho</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Upper Snake River Valley in Idaho</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Jackson Lake and upper Snake River Basin in Wyoming and Idaho</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>Southwestern Idaho and northern Nevada</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Salmon River Basin in Idaho</td>
<td>--</td>
<td>8</td>
</tr>
<tr>
<td>Northern Idaho</td>
<td>--</td>
<td>11</td>
</tr>
<tr>
<td>Basins of Bitterroot and Missoula Rivers in Montana</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Flathead Lake and River basins in Montana</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Basins of the Owyhee and Malheur Rivers in Oregon</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>Northeastern Oregon</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Lower Basins of the Umatilla, John Day, Deschutes, and Hood Rivers in Oregon</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>Central Oregon</td>
<td>--</td>
<td>11</td>
</tr>
<tr>
<td>Basins of the Yakima and Wenatchee Rivers in Washington</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Southeastern Washington</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Northeastern Washington</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Okanogan River Basin in Washington</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Lower Columbia River Basin in Washington</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>Willamette River Basin in Oregon</td>
<td>--</td>
<td>9</td>
</tr>
<tr>
<td>Puget Sound district in Washington*</td>
<td>--</td>
<td>12</td>
</tr>
</tbody>
</table>

*Not in the Columbia River Basin

### Table 7. Monthly and seasonal net irrigation requirements of the various subdivisions of the arid and semiarid regions of the United States. (Continued)

**Missouri and Arkansas River Basins.**

<table>
<thead>
<tr>
<th>Division</th>
<th>Monthly percentage of total seasonal net irrigation requirements</th>
<th>Seasonal net irrigation requirement per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per- cent</td>
<td>Per- cent</td>
</tr>
<tr>
<td>Northeastern Montana</td>
<td>--</td>
<td>6</td>
</tr>
<tr>
<td>North Central Montana</td>
<td>--</td>
<td>6</td>
</tr>
<tr>
<td>Central Montana</td>
<td>--</td>
<td>3</td>
</tr>
<tr>
<td>Upper Missouri River Basin in Mont.</td>
<td>--</td>
<td>3</td>
</tr>
<tr>
<td>Upper Yellowstone River Basin in Montana</td>
<td>--</td>
<td>4</td>
</tr>
<tr>
<td>Southeastern Montana</td>
<td>--</td>
<td>5</td>
</tr>
<tr>
<td>Big Horn River Basin in Wyoming</td>
<td>--</td>
<td>4</td>
</tr>
<tr>
<td>Yellowstone &amp; Missouri River Basin in Wyoming</td>
<td>--</td>
<td>6</td>
</tr>
<tr>
<td>Upper Platte River Basin in Wyoming</td>
<td>--</td>
<td>3</td>
</tr>
<tr>
<td>Northeastern Colorado</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>North central Colorado</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>South central Colorado</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Southeastern Colorado</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Western Kansas</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Central Nebraska</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Western Nebraska</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Western South Dakota</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Western North Dakota</td>
<td>--</td>
<td>3</td>
</tr>
</tbody>
</table>

* Winter irrigation
** Mainly winter irrigation

(Tech. Bul 36, U.S.D.A. "Irrigation Requirements of the Arid and SemiArid Lands of the Missouri and Arkansas River Basins" Fortier)
The amount of water required to irrigate various crops depends on the crop, the type and fertility of the soil, the topography, the climate and the method of irrigation. In irrigated areas the amount of water required can be determined from the local practice and in newly developed areas the water requirements can be approximated from the amount of water used under similar conditions elsewhere or from the information given in the publications of the United States Department of Agriculture, (8, 9, 10) on irrigation requirements of arid lands. The tables in these bulletins give the net irrigation requirements exclusive of rainfall for the principal irrigated areas in the West and also the percentage of the total requirement which is used each month. These tables show that June and July are usually the months of maximum demand, and that during these months the water required is from three to nine inches or from 20 to 40 percent of the total seasonal requirement. In general, areas having a long growing season have the minimum peak demand and those having a short growing season have the maximum peak demand.

The capacity of the well required for irrigating a given area depends on the rate of maximum demand for water. If for example, a farmer has 80 acres on the Snake River in Idaho on which he proposes to grow general crops, he may, as previously explained, find out from neighboring farmers how much water will be required for his crops during the period of maximum demand, or he may look in the bulletins
referred to in the preceding paragraph and find that the average seasonal irrigation requirement is 2.5 acre-feet, and the month of maximum demand is July during which 25 percent of the seasonal supply will be required.
The figures given in the above example are for average conditions. If there are unusual features, such as growing only one crop, growing two crops simultaneously on the same area, or if the soil is very sandy, then the rate of maximum demand would probably have to be increased.
test and also the percentage of the total requirement which is used each month. By the use of this table it is possible to determine the capacity of a well which would be best suited to the area to be irrigated.

If, for example, a farmer has 80 acres on the Snake River in Idaho on which he proposes to grow general crops, he will find in table I that the average seasonal irrigation requirement is 2.5 acre-feet, and the month of maximum demand is July during which 25 percent of the seasonal supply will be required. Twenty-five percent of 2.5 feet (30 inches) is 7½ inches, the depth of water required per acre in July. For 80 acres this amounts to 80 times 7½ or 600 acre-inches which equals 50 acre-feet. Since one cubic foot per second equals nearly 450 gallons per minute, and since one cubic foot per second flowing for 24 hours equals approximately 2 acre-feet, it will require a flow of one cubic foot per second or 450 gallons per minute for 25 days of 24 hours each to yield 50 acre-feet. A flow of 2 cubic feet per second or 900 gallons per minute will yield 50 acre-feet in 12½ days of 24 hours each or 25 days of 12 hours each. A higher rate of flow, of course, yield the required amount in still less time.

Large pumping plants have the advantage that they have to be operated a shorter time in order to supply the required amount of water, and consequently the labor cost for irrigating is smaller, but large pumping plants cost more than small ones and also cost more to operate. It has been found that the most economical results are obtained, particularly for electric motor driven plants, when the smallest plant is
installed which will supply the required amount of water during the period of maximum demand even though the labor cost of applying the water may be slightly higher.\(^{(3)}\)

(3) Code, W. E., Bulletin No. 350, Colorado Experiment Station, Suggestions Concerning Small Irrigation Pumping Plants.

From the foregoing discussion, it is evident that the flow of 450 gallons per minute, which is about the smallest amount that will supply the required quantity of water for the 80-acre farm within the time limit, should be chosen for the capacity of the plant.

Pumping plants are frequently built to provide a supplemental supply of water, and during periods of drought large numbers of plants of this type are constructed. In case the plant is being designed to provide a supplemental supply, the quantity of water necessary will be the difference between the total requirement and the amount which will be available from the other source.

In some sections the supply of groundwater is sufficient to provide whatever quantity is needed for irrigation crops, but in many areas conditions are not so favorable. In these regions the capacity of the well will determine the size of the plant; the acreage irrigated and the kind of crops grown will have to be adjusted to the water supply from the well. For general farm crops about 300 gallons per minute is the smallest amount that can be economically handled, and where the yield of the well is less than this amount it is doubtful whether a pumping plant will be successful except for small tracts such as orchards or gardens where the furrow or the sprinkler system can be used to apply the
In some sections of California, Arizona, and Nevada, however, 300 gallons per minute would be considered a good flow of water. In cases where it is not possible to get a sufficient supply of water from a single well, it is often possible to obtain the desired amount by using a battery of wells. (See page 30.)

Except in areas where there are a large number of wells, it is impossible to predict the yield of a well with any degree of precision. The best wells are usually found where the water-bearing formation is of considerable thickness and is made up of fairly coarse material free from very fine sand, clay or cementing material. The ground water should be at a relatively shallow depth and should be fed from a dependable source. The most favorable locations for good wells are in the valleys adjacent to streams and on the alluvial cones where streams from mountain areas flow out on the plains. Where irrigated areas are underlain by sand or gravel, the conditions are generally favorable for getting good wells.

When there is doubt as to the possibility of getting a good well, test holes should be put down to locate the water-bearing formation and the character of the water-bearing material. A careful record should be kept of the depth to water and the location and thickness of the various materials penetrated by the test hole. Samples of the water-bearing material removed from the test hole should be saved. From the log of the test hole and the samples of the water-bearing material, it is possible to determine whether a satisfactory well could be drilled at that point. If the conditions are found to be unfavorable for a good well at the first test hole, a new location should be chosen and tested. Several
Some groundwater contains chemicals which corrode metal casing, and some contain sufficient gas in solution to interfere with the operation of pumps.
Test holes should be drilled before abandoning the hope of finding a suitable condition for locating a satisfactory well. The methods of drilling test holes are explained on page 90. When other conditions are the same the well should be located so that the greatest area of the farm can be irrigated with water from the well. Usually, however, the location of the well is determined by the site where the prospects are best for getting a good well.

**Quality**

The ground water in most arid regions contains considerable alkali, and in some places the concentration is so great that the water is injurious to plants and sometimes to the soil also. Strong alkali water has a brackish taste and when evaporated will produce a pronounced white deposit on the sides of a glass tumbler. If there is doubt as to the suitability of the water for irrigation, a sample should be sent to the State Agricultural College or other qualified agency for testing and an opinion as to the suitability of the water for the crops to be irrigated.

**Pumping Lift**

The limit of the lift against which water may be profitably pumped for irrigation varies with the cost of pumping and the value of the crops grown. As greater care is being used in the design of pumping plants and as the efficiency of pumps is being constantly increased and the cost of power reduced, the cost of pumping an acre-foot of water per foot of lift has been reduced; consequently, if other conditions remain the same it will be possible...
to pump profitably against a higher lift than formerly. Higher heads are also feasible, if the water pumped is to be used only as a supplemental supply to provide water in case of shortage. Low priced agricultural products, however, reduce the economical pumping lift. The average lift through which water was being pumped from all sources including streams and lakes in each state in 1930 is given in table together with the estimated economic limit of pumping lift from wells. The area irrigated by pumping from wells in each state, the cost of the pumping plant per acre irrigated and the cost of operation are given also. The average lift shown is less than the estimated economic limit of lift, and although it is possible to operate a pumping plant successfully under favorable conditions against heads equal to the limiting lifts, the farmer contemplating the installation of a pumping plant should not plan to exceed the average lift given in the table unless he is favorably located as to markets, or can grow special crops upon which the cash return is higher than from general crops. Especially fertile soil or a favorable climatic condition, as a 12-month growing season, make it possible to pump successfully against high lifts. The cost of pumping is almost directly proportional to the lift, and each additional foot of lift adds just that much more to the cost of operation. For this reason the farmer should consider carefully the chances of success before going into any project where the lift against which the pump must operate is above the average values given.
<table>
<thead>
<tr>
<th>State</th>
<th>Area Irrigated by Pumping (Acres)</th>
<th>Investment in pumping plant per acre (Dollars)</th>
<th>Cost of operation per acre (Dollars)</th>
<th>Average Lift (Feet)</th>
<th>Economic limit of lift (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona</td>
<td>99,740</td>
<td>58.70</td>
<td>10.76</td>
<td>46</td>
<td>40 to 50</td>
</tr>
<tr>
<td>California</td>
<td>1,358,975</td>
<td>146.04</td>
<td>10.05</td>
<td>53</td>
<td>50 to 100</td>
</tr>
<tr>
<td>Colorado</td>
<td>11,403</td>
<td>30.66</td>
<td>5.38</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Idaho</td>
<td>3,467</td>
<td>19.64</td>
<td>2.30</td>
<td>32</td>
<td>35 to 40</td>
</tr>
<tr>
<td>Kansas</td>
<td>10,954</td>
<td>33.44</td>
<td>3.69</td>
<td>28</td>
<td>50</td>
</tr>
<tr>
<td>Nebraska</td>
<td>22,432</td>
<td>19.95</td>
<td>4.03</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>Nevada</td>
<td>2,075</td>
<td>20.19</td>
<td>4.82</td>
<td>31</td>
<td>50 to 40</td>
</tr>
<tr>
<td>New Mexico</td>
<td>27,586</td>
<td>58.75</td>
<td>6.44</td>
<td>40</td>
<td>40 to 50</td>
</tr>
<tr>
<td>Oregon</td>
<td>3,091</td>
<td>59.08</td>
<td>10.72</td>
<td>27</td>
<td>30 to 100</td>
</tr>
<tr>
<td>Texas</td>
<td>49,053</td>
<td>47.15</td>
<td>8.50</td>
<td>55</td>
<td>60 to 100</td>
</tr>
<tr>
<td>Utah</td>
<td>9,951</td>
<td>54.64</td>
<td>3.58</td>
<td>36</td>
<td>50 to 75</td>
</tr>
<tr>
<td>Washington</td>
<td>18,418</td>
<td>82.24</td>
<td>15.43</td>
<td>59</td>
<td>50 to 80</td>
</tr>
</tbody>
</table>

(1) Data taken from U.S. Census of 1930
(2) Data covers all pumping whether from wells, streams, or reservoirs.
(3) Estimates based on information gathered from members of the Division of Irrigation and other sources.
(4) Investment may include other investment besides that in wells and pumping equipment.
(5) Under special conditions, economic limit of lift may exceed 500 feet in California.
(6) Cost of operation covers cost of power, attendance and repairs.
Col 1 is "Area irrigated by pumping which reported cost of maintenance and operation."

Col 2 is "Investment of enterprise using water pumped from wells" may include other investment bids that in pumping plant."
Consideration should be given also to the plans for financing the undertaking.
Where the pumping plant is being installed to supplement the supply of water for irrigation from some other source, the land is already in shape for applying water, the suitability of the soil and the climate for growing crops under irrigation is known and the market for the crops is established. Under these conditions the feasibility of the project depends primarily on finding a satisfactory supply of ground water. Where, however, the proposed well and pump are to be installed in an area where irrigation has not been practised previously, the farmer must consider each of these items carefully. The land must be prepared for irrigation, ditches must be built, the suitability of the land and the climate for growing crops under irrigation must be investigated and the crops to be grown must be decided upon. Under these conditions the farmer would do well to study what is being done in similar areas elsewhere and to find out from his county agricultural agent or his experiment station whether they consider his project feasible. If they feel that there is a reasonable chance for success, then the farmer should find out whether he will be able to borrow the money to build his plant. Sometimes well drilling companies and pump manufacturers will finance the construction of the plant, but these companies usually prefer to make short time loans. Private individuals and banks will loan money on good security, if, however, the farmer's credit is exhausted he may be able to obtain a loan from the Federal Government if it appears that the pumping plant will assist in the rehabilitation of the farmer. Federal loaning agencies change as conditions change and in order to get information as to
where the application for the loan should be made, the farmer should get in touch with his county agent.

The Well Contract

If after the farmer has made a thorough investigation he has found that conditions are favorable for the construction, financing and successful operation of a pumping plant for irrigation from wells, he must then consider the drilling of the well. Except under very favorable conditions the farmer will not be able to do this work himself. He should get in touch with a reliable well driller and should discuss with the driller, who usually is familiar with local conditions, the possibility of obtaining a well of the required capacity on his farm. Where the underlying formations have not been thoroughly explored, it may be desirable to drill test holes to find out whether the conditions are favorable for getting a good well. In any event the farmer and the well driller should agree as to what is to be done and what the cost is to be. The agreement should be put in writing in the form of a well contract. The well contract should specify the work to be done, the time of starting and completing the work, the equipment to be used and the bid price for the various items. If the farmer is to supply any of the equipment, materials or labor, each item should be included in the contract. If reconditioned casing is to be used in the well, this fact should be designated in the contract. The driller should be required to furnish a bond to guarantee satisfactory completion of the well and to carry liability insurance to protect himself in case of property damage and should carry compensation insurance sufficient...
Is it advisable to be so insistant upon a formal contract? Desirable unquestionably, but not customary in many sections. I do not oppose this recommendation but merely wish to suggest it have further thought. HB 404 may have gone too far.

[Signature] HOS
A guaranteed minimum payment to the driller should be specified in the contract in order to protect the driller, and the maximum depth of well or a provision authorizing the owner to stop the work when he considers the well deep enough should be included in order to protect the owner.
to cover his liability under the workman's compensation act. The principal items concerning the well that should be included in the contract are, the length, diameter and thickness of the starter, if used; the type, material and dimensions of the shoe; the length, diameter and thickness of the casing; the material of which the casing is to be made, whether it is to be black or galvanized and whether it is to be welded or riveted; the size and spacing of the reinforcing bands when large single thickness casing is used; the size and number of the perforations and the method of perforating; the thickness of the gravel envelope, if used; and the size of the gravel; and the method of developing and testing the well. If concrete casing is to be used, the mix of the concrete should be designated. A clause should be included in the contract to the effect that the base of the well must be straight enough so that the type and size of pump which it is planned to use can be inserted in the well and operated successfully. If any changes in plans become necessary after the work has started, the order for the change should be in writing.

In some sections it is the custom for the well driller to contract to drill a well of specified capacity. If many wells have been drilled in the region and the waterbearing formation is, however, to be feasible, but it is obvious that under these circumstances the driller takes all the risk, and in order to protect himself he will bid enough higher to cover the risk. The maximum acceptable drawdown when pumping the specified amount, and the number of hours the well should be pumped at this rate should be designated in this sort of contract. If the drawdown is not specified the required quantity may be
obtained by drawing down the well below the economical limit, and if the time is not specified the well may not hold this capacity when pumped a longer time. These contracts should also have a clause providing a penalty if the well does not come up to the terms of the contract and a bonus if the well exceeds the terms. The penalty or bonus should be computed on the basis of a unit amount for a definite number of gallons of excess or deficiency. The penalty and bonus clause may be included in other forms of well contract to advantage because it provides an incentive for the driller to do better work.

When the well is completed, the driller should be required to furnish the farmer with a complete log of the well showing the depth to water, the location, character and thickness of the different materials encountered in the well, the location of the points where the diameter of the casing was changed and the location of the perforations in the well. This information will be found to be invaluable if at some later date it becomes desirable to reperforate the well or lower the bowls of the pump.

In case any controversies arise the procedure to be followed in settling the dispute should be set forth in the contract. Large well drilling companies have their own contract forms and in case they are used the farmer should read over the provisions of the contract carefully before signing so that he will understand just what the agreement is. Forms for well drilling contracts have been prepared which protect both the driller and the farmer. Information concerning these contracts can be obtained by writing to the Division of Irrigation, Bureau of Agricultural Engineering, Berkeley, California.
Factors Affecting Flow of Ground Water into Wells

The source of supply for irrigation wells is the water that accumulates in the surface layers of the earth as the result of the downward percolation of moisture from rain and snow, the percolation of water applied for irrigation, or spread on porous soil for the increasing 
and the ground-water supply, the seepage of water from streams, canals and reservoirs. All the water that sinks into the soil from these sources is not available for pumping; some of it is evaporated from the surface of the ground while it is still damp; some of it is brought back to the ground surface by capillary action from moist soil and then evaporated; some of it is held in the soil as capillary or hygroscopic water; and some of it is taken up by the roots of growing plants to be either stored in the plant or evaporated from the surface of the leaves. The remaining water moves downward until it reaches a zone of saturation or comes in contact with a layer of water-tight material such as clay or shale. At this point the water starts to spread laterally filling up the pores of the overlying material as it goes.

This process has continued for long periods of time and has, as a result, built up a supply of water which underlies large areas of land surface of the earth. This water, with the exception of that held in closed basins, is all moving toward points where it can escape into a spring, stream or swamp.

In most areas the additions to this water supply and about equal the amount being lost in this manner, as a result
a condition of approximate equilibrium has been reached. In some places, however, the balance has been artificially interfered with as in the case of irrigated areas. Here the water level may still be rising on account of the application of irrigation water or may be lowering on account of excessive pumping.

The water that exists in the zone of saturation is known as ground water, and the upper surface of the zone of saturation or the free water surface is known as the water table. When the water in the zone of saturation is confined between layers of water-tight material the water in contact with the top layer of impervious material is under pressure and consequently there is no water table. When a zone of saturation of this type is tapped the water in the hole will rise above the level of the bottom of the confining layer. This condition gives rise to what are known as artesian basins.

Formerly, only those areas where the water rose above the surface of the ground were considered as artesian basins, but this view is no longer held; now any region where the pressure is sufficient to raise the water above the level of the top of the water-bearing layer is regarded as an artesian basin. Where the ground water is not under pressure, as in the case where the zone of saturation is not confined between layers of impervious material, the water when tapped will not rise above the level of the water table. Regions where this condition exists are known as non-artesian or normal pressure areas.

The conditions which give rise to the two types of areas are shown in figure 1 which represents a section
of broad valley. Here A-B-C is a porous stratum confined between two water-tight layers. The outcrops of these layers are at A and C. The moisture from the rain and snow on the slopes above these points runs into the porous layer until it is saturated with water up to the level A-D. The area between A and D is then an artesian basin because if the water-bearing layer A-B-C is tapped as at E, the water will rise to the level A-D which is above the ground surface A-H-C. If the water-bearing layer A-B-C is tapped at E', the water will rise to the level A-D as before but not above the ground surface A-H-C.

The zone above the water-bearing stratum A-B-C is filled with material washed in by the river H. This material consists of layers of silt, sand and gravel and is quite porous. The water that falls on the valley between the points A and C soaks down into the porous material and keeps it saturated. Seepage from the river H helps also to supply water for raising the ground-water level in the valley. G-H-I represents the water table which in this case is assumed to be level; if the amount of seepage from the river is large the water table will slope downward away from the river, or if, as frequently happens, there is a return flow to the river from the surrounding land then the water table will slope upward away from the river. If the ground water in this area is tapped at any point, as F, the water will not rise above the level of the water table or the line G-H-I. This is a non-artesian area.

The amount of water in a layer of saturated material depends on the thickness and extent of the layer and the porosity
of the material in the layer. Porosity is the measure of the amount of pore space. It is the ratio of the volume of the openings or pores in the material to the total volume of the material and is usually expressed as a percentage. Porosity increases with the fineness of the material and with the angularity of the particles, and is greatest when all the particles are of uniform size. When the particles are well graded in size, the smaller particles fill the spaces between the larger particles, and if the sizes of the different particles are in the proper proportion, each smaller size will just fill the spaces between the larger particles. Under ideal conditions properly graded spheres may be packed so closely that the pore space is only 5 percent whereas spheres of uniform diameter cannot be packed so that the pore space is less than 25 percent regardless of the arrangement nor more than 48 percent if the spheres are symmetrically arranged. The porosity of soils also varies widely, ranging from as low as 20 percent for graded sand to as high as 65 percent for very heavy clay. Water-bearing formations suitable for providing water for irrigation wells usually have porosities ranging from 20 to 40 percent of the total volume of the material.

From the foregoing it is seen that clays have the largest percentage of pore space although it is well known fact that minimum wells in clay yield very little water. The reasons that these wells are not satisfactory even though the clay contains much more water than sand or gravel is
that the clay will not give up the water when the well is pumped. Clay is made up of extremely fine particles, and as a result the pore spaces are extremely small also. These small spaces hold water against the force of gravity by capillarity. This is known as capillary water. In addition a portion of the water is held by molecular attraction. This is known as hygroscopic water. Neither capillary water nor hygroscopic water is given up when a well is pumped. The ratio of the amount of water retained to the volume of the water-bearing material, expressed as a percentage, is known as the specific retention. The moisture held in this manner, that is, the specific retention, may amount to from 5 to 35 percent of the volume of the water-bearing material depending on the distance from the free water and the nature of the water-bearing medium. The lowest percentages are retained by sand and gravel and the highest percentage by clay and clay loam. The percentage of the moisture retained decreases in general as the distance from the free water surface increases.


above values of specific retention are given had a porosity greater than 50 percent so it is evident that if 35 percent may be retained the amount available for pumping for a well in clay is not going to be large.

The amount of water that a definite volume of water-bearing material will yield as distinguished from that which it will retain is called the specific yield. It is expressed as a percentage and is the ratio of the yield from a given volume of water bearing material to the volume of the material. The specific yield varies between 16 and 41 percent of the volume of the water-bearing medium.


It is greatest for sand and gravel and least for clay and clay loam. It has been estimated by Lee that from 15 to 30 percent of the volume of the water-bearing medium represents the water that is available for pumping although actual tests have shown as low as 12 percent to be all that could be obtained.


Groundwater is not static except in closed basins where it cannot escape. It has a definite though slow velocity toward some point such as a stream, lake or swamp where it discharges. The rate of flow depends on the slope or fall of the water surface, on the size, shape, uniformity and compactness of the particles in the medium through which the water is moving and on the temperature of the water. The effect of temperature is
The velocity of water through the pores in saturated soil is directly proportional to the slope of the water table. This relation is known as Darcy's law. The effect of the other factors on the rate of flow is so complicated that it cannot be expressed by a simple law, but it can be determined experimentally.

Footnote

*The term specific water conductivity is also used to designate the water transmitting characteristics of a soil. It is defined as the volume of water that will flow in unit time through a soil column of unit cross-section area due to the driving force per unit mass corresponding to unit potential gradient. This term is not generally used by engineers but it has the advantage that the value of the constant is the same regardless of the system of units adopted.

Israelsen, O. W.: Irrigation Principles and Practices, 422 pages, illus., see pages 200 to 205.
usually disregarded, however, because the temperature of the ground water does not vary through wide limits. The flow of ground water is similar to the flow of water in pipes. In both, the velocity varies with the slope, but in a pipe the velocity varies as the square root of the slope whereas in a water-bearing medium, the velocity is directly proportional to the slope. This relation is known as Darcy's law. It is the fundamental law of flow for ground water. The size, slope and compactness of the particles in the soil determine the resistance to the flow of the water in the pores. The effect is similar to that of the roughness and the hydraulic radius of pipes. The velocity of the water in the soil increases as the effective size of the sand particles increase and decrease as the uniformity coefficient and the compactness increases. The effective size is the size of an equivalent sand made up of uniform particles which would offer the same resistance to flow as the sand being tested. It is a size such that 10 percent of the particles by weight are smaller and 90 percent are larger. The uniformity of a sand is expressed by the uniformity coefficient which is the ratio of the size of sand that has 60 percent smaller to the size of sand that has 10 percent smaller.

The combined effect of these factors is expressed by what is known as the transmission constant or the coefficient of permeability which is the rate at which water will flow through a column of the material of unit section when the slope is unity, or in other words, when the head is equal to the length of the column of material. The coefficient of permeability is given in gallons per day, and the transmission constant is given in.
is given in cubic feet per minute. Formulas have been


derived for computing these constants, but the results obtained have not been satisfactory.

Smith, G.E.P., Arizona Agricultural Experiment Station 64, p. 127, 1910, Ground water supply and irrigation in the Rillito Valley.

The constants computed from the analyses of the materials have usually been too low.

Grover, N. C., U.S.G.S., 596, p. 151

More satisfactory results are obtained when these constants are determined experimentally by observing the rate at which water percolates through the material. The other factors required to compute the quantity of flow are obtained by direct observation. The slope of the water table is found from observations on wells, and the depth and extent of the water-bearing medium are obtained by putting down test holes.

The product of the area of the water bearing layer at right angles to the slope of the water surface, the slope of the water surface and the transmission constant or the coefficient of permeability gives the quantity of water flowing in the area in cubic feet per minute or in gallons per day.

The velocity of flow may also be measured by noting the time it takes a salt solution to move from one well to another in the direction of flow of the ground water.

The salt is introduced in the upper well, and the time of arrival of the solution at the lower well is determined by chemical analyses or by electrical methods. Observations have been made by this method on the velocity of flow of ground water in many sections of the United States. These studies show that the velocity varies from a fraction of a foot to nearly 500 feet per day depending on the slope and the characteristics of the water-bearing material. The ordinary range of velocities, however, is from 1 to 100 feet per day.

The quantity of water flowing in an underground stratum of water is the product of the velocity of the water and the area and porosity of the water-bearing medium. The porosity of the material has to be obtained from tests on samples of the water-bearing medium taken from test holes and the area of the water-bearing material has likewise to be determined from test holes.

The water stored in the ground constitutes an underground reservoir which may be drawn on to supply water for irrigation and other purposes. The volume of water in storage may be determined from the area and depth of the saturated zone and from the porosity of the water-bearing medium. However, the volume of water, which may be withdrawn for use for irrigation or other purposes at any time from a given area by lowering the water table a definite amount, depends on the specific yield of the water-bearing medium rather than the porosity because, as previously explained, much of the water in the zone of saturation is held so firmly in the soil that it cannot be drawn out by pumping.

The water available for pumping is as just given, but the water which may be safely withdrawn each year depends on the
recharge of the area, that is, the rate at which water is being added to the zone of saturation by inflow from other areas, by downward percolation of the moisture from rain and snow falling on the area, by the penetration of water applied for irrigation or spread to increase the water supply down to the zone of saturation, by seepage from streams, or by the combination of any of these sources of supply. In an emergency such as a period of drouth water may be withdrawn at a faster rate than it is supplied, but in the long run the rate of withdrawal can not exceed the rate of recharge or the water table will continue to lower. The disastrous effects of this practice have already been observed in some areas.

The rate at which water may be safely withdrawn from a given area can be determined approximately, but it is a difficult problem; there are so many factors that have to be estimated. The rainfall and the amount of run-off can be measured, but no one can say definitely how much of the water that seeps into the soil is going to be used by plants or lost by evaporation. The same may be said of the water that is applied for irrigation. Furthermore, this inflow from other areas, which is frequently an important source of supply, is difficult to measure accurately on account of the fact that the velocity of the water in the water-bearing medium can not be measured accurately nor can the pore space through which the water is pouring be determined with certainty. Where pumping is being practised, the simplest method of getting information as to the rate at which water may safely be withdrawn from a given area is to measure the lowering of the water table in the wells of the area from time to time. If there is a gradual lowering of the water table extending over a period of years, then the rate at which the water is
being pumped is exceeding the rate of discharge and the lowering of the water table will continue unless the rate of withdrawal is reduced or the rate of recharge is increased. During periods of drought the rate of recharge decreases, and as pumping is usually heavier because of the drought the combination of causes produces a marked lowering of the water table which might be interpreted as indicating a definite overdraft on the area. However, a period of wet years increases the rate of recharge and usually reduces the pumping draft. This condition again establishes the balance between the rate of withdrawal and recharge unless the area is being pumped at too high a rate.

Hydraulics of Wells

When an irrigation well is put down into a layer of water-bearing material and then pumped, the water in the casing is first lowered, and then the water from the saturated material surrounding the casing starts to come into the well. If pumping is continued the water in the well will continue to lower, and the water coming into the well from the saturated material will continue to increase until the water coming into the well will just equal the water being pumped out. The first water drawn into the well comes from the area immediately surrounding the casing. As the pumping continues the supply of water near the well becomes exhausted, and the water has to come from greater and greater distances to supply the pump. The water coming toward the well has to pass through the pores in the sand, and the closer it gets to the well the faster it has to move as the area through which it has to travel is constantly decreasing.
As previously explained, the velocity of water flowing through a water-bearing medium is directly proportional to the slope of the water surface. For this reason the slope increases as the water approaches the well, and the change in the slope is directly proportional to the change in the velocity. For the same reason the slope decreases as the distance from the well increases. The water surface formed, as the result of the continuously increasing downward slope toward the well, is an inverted bell-shaped depression around the well which is known as the cone of depression. The circle formed by the intersection of the outer edge of the cone of depression with the static water level is called the circle of influence, and the area of this circle is called the area of influence. The intersection of the surface of the water in the cone of depression with a vertical plane through the center of the well is a curved line which is known as the drawdown curve. The distance that the water level is lowered by pumping is the drawdown. It is the distance between the water level in the well when being pumped and the static water level or water table. These different features of a well are shown in figure 2, which is a vertical cross-section of a typical well in a non-artesian formation.

The discharge from a well depends on the drawdown, the thickness and nature of the water-bearing stratum, the diameter of the well and the radius of the circle of influence. Formulas have been developed showing the relation between these factors and the discharge for various types of wells, but, owing to the complexity of the phenomena involved and the difficulty of

Lewis, M. R., Transactions American Society of Civil Engineers, Vol. 96, No. 1814, pp. 1194 - 1211
For the type of well shown in figure 2, the discharge formula is

\[ Q = K' \frac{H^2 - h^2}{\log \frac{R}{r}} \]

in which

- \( Q \) = discharge in gallons per day
- \( K' \) = a quantity which depends on the characteristics of the water-bearing material.
- \( H \) = distance in feet of static water level above bottom of water-bearing formations.
- \( h \) = distance in feet of water in well above bottom of water-bearing formation while being pumped.
- \( R \) = radius of circle of influence in feet.
- \( r \) = radius of well in feet.

For an artesian well which penetrates the entire depth of a water-bearing formation, the discharge formula is

\[ Q = 2K't \frac{H - h}{\log \frac{R}{r}} \]

in which \( t \) is the thickness of the water-bearing formation and the other letters have the same significance as before.

If two wells of different diameters are in the same formation and the drawdown is kept the same, then the relation of the discharges of the two wells will be

\[ \frac{Q}{Q'} = \frac{\log \frac{R}{r}}{\log \frac{R}{r}} \]

This relation holds for both types of wells.

The formula

\[ Q = K' \frac{H^2 - h^2}{\log \frac{R}{r}} \]

may be written

\[ Q = K' \frac{(H + h)(H - h)}{\log \frac{R}{r}} \]

if the drawdown is small, then \( H + h \) is approximately equal to \( 2H \), then

\[ Q = 2K' \frac{H(H - h)}{\log \frac{R}{r}} \]

This formula shows that in wells of this type, the discharge is proportional to the quantity \( K' \), the depth of water \( H \), the
drawdown $H - h$ and $\frac{1}{\log \frac{R}{r}}$.

The formula for the artesian well shows that the discharge is proportional to the quantity $K'$, the thickness of the artesian formation, the drawdown and $\frac{1}{\log \frac{R}{r}}$.

Turneraur and Russel, Public Water Supplies, 1908, pages 278 to 286.
An artesian water-bearing formation in Utah was found to be 100,000 times as permeable as the overlying clay.
determining accurately the values of the variables in the formulas, the well discharges computed by these formulas have not been satisfactory. These formulas, however, show certain fundamental relations which are of value in studying wells.

All the formulas show that the discharge from a well is directly proportional to the transmission constant of the material in the water-bearing stratum. As previously explained, the value of the transmission constant increases as the coarseness and porosity of the water-bearing material increase and decreases as the compactness and the uniformity coefficient increase. The transmission constant moves through wide ranges, the value for coarse sand being 4000 times as great as that for fine sand.


It is apparent therefore, that it is important to have the water-bearing medium as coarse as possible and also free from fine material such as silt or clay because it is the fine material that fills the pores between the large particles and retards the flow of water.

Farmers frequently assume that the water-bearing medium is satisfactory simply because it contains quite a few boulders the size of baseballs or larger. If there were no fine particles, these boulders would be an indication of an excellent well, usually, however, the spaces around these boulders are completely filled with graded sand, and the result is that the boulders obstruct the flow. This is clearly shown in figure 2, which is a section of such material taken at right angles to the direction of flow of the water. It is obvious that the water cannot flow through the large rocks, and as a result, the water is retarded more than it would be if all the space were filled by
the smaller particles. If, however, there were no fine particles filling the space around the large rocks there would be large unobstructed passages for the water.

In wells where the casing penetrates the full depth of the water-bearing stratum, the capacity is directly proportional to the thickness of this stratum if the drawdown and other conditions remain the same. It may also be said that the deeper the well is driven into a water-bearing stratum the greater will be the discharge for a given drawdown. This fact is frequently lost sight of when wells are being put down. Where the water-bearing formations are quite thick there is a tendency to limit the depth of wells on account of the cost. It is true that increasing the depth increases the cost, but this additional cost is usually balanced by the saving in cost of operation resulting from the decreased drawdown.

In wells which penetrate deep into water-bearing formations of considerable thickness the capacity is directly proportional to the drawdown so long as the drawdown is small in comparison with the depth of water in the well. If the drawdown is large then the discharge of the well does not mount as rapidly as the drawdown increases. If the depth of water in the well is small the yield per foot of drawdown will decrease as the drawdown increases. The decrease in yield is due to the fact that as the drawdown increases the depth of sand through which the water enters the well is decreasing. In other words, the effect of the increased drawdown is counteracted by the effect of the decreased thickness of sand through which the water can enter the well. In artesian wells the yield is directly proportional to the drawdown as long as the drawdown is less than the artesian pressure.
The relation of the discharge to the drawdown for the different conditions is shown in figure A. The curves shown are plotted from actual data from representative wells. The discharge from the well in the shallow water-bearing medium increases 100 gallons per minute when the drawdown is increased from 2 feet to 3 feet, whereas, it increases only 50 gallons per minute when the drawdown increased from 10 feet to 11 feet. It is apparent from these figures, that when the limit of the drawdown is being approached, the increase in yield is being obtained at the expense of a disproportionate increase in the drawdown. This fact should be kept in mind by the farmer when he is deciding how much water he is going to pump from his well. For the same conditions in the artesian well or the well drilled deep into a thick water-bearing formation, the increase in discharge is 100 gallons per minute whether the drawdown is increased from 2 feet to 3 feet or from 8 feet to 9 feet. In this case the yield may be increased without causing a disproportionate increase in the drawdown.

Consideration of the theoretical relation of the various factors that affect the discharge from wells leads to the conclusion that the discharge (from a well) increases as the diameter increases but not in the same proportion. Based on the theoretical relation the discharge under ordinary conditions from a 2-foot well is only 10 percent greater than that from a 1-foot well, and the discharge from a 4-foot well is only 21 percent greater than that from a 1-foot well. According to a theoretical study made abroad, the discharge from a 24-inch well is only 8 percent greater than that from a 12-inch well.

Zeitschrift des Vereines deutscher Ingenieure, Feb. 1930
Experiments made on two wells in Colorado under practically identical conditions show, however, that the discharge from a 2-foot well is 25 percent greater than that from a 1-foot well. If the discharge is kept constant then the drawdown will decrease in about the same ratio as the discharge increases when the drawdown is constant. The change in the drawdown caused by increasing the diameter of the well is shown graphically in figure 2. When the diameter of the well is increased from 2r to 2r', the level of the water in the well changes from EF to E'F' if the loss of head caused by the resistance of the casing to the flow of the water through it is neglected. The drawdown is reduced from H - h to H - h'. Actually, however, the drawdown curve for the large well does not coincide with the curve for the small well, as shown in figure 2.

From the foregoing discussion it is seen that doubling the diameter of a 1-foot well increases the discharge of the well somewhere between 50 and 25 percent, whereas doubling the depth of penetration of the well into the water-bearing medium increases the discharge by approximately 100 percent. If the discharge were kept constant the drawdown would be cut in half. This fact should be given careful consideration when putting down a well.
Footnote.

* The practical limit of suction lift for pumps is 22 feet at sea level, 17 feet at 5000 feet elevation and 14 feet at 10,000 feet elevation. Siphons will operate if these lifts are exceeded but they will probably require frequent priming on account of the accumulation of air from the water or from small holes in the pipe.
Battery Wells

In many sections the depth of water-bearing material is small. In these areas it is impossible to increase the capacity of the well by deepening because wells in these regions are usually drilled through the water-bearing formation. Where additional capacity or a smaller drawdown for a given capacity is desired under these conditions a battery of wells is installed. This is a group of wells arranged in a line or in a circle and connected either by siphons to a central well in which the pump is installed or by a suction header to the pump which is located in a pit at a central point. When the latter arrangement is used each well is attached to the suction line, but when siphons are used they discharge into the central well. When siphons are used the central well has to be large enough to accommodate the drop pipes of the siphons as well as the suction pipe of the pump. For this reason the central well is usually made a larger diameter than the other wells. When a suction header is employed all the wells are usually made the same diameter. The wells in battery systems are made smaller in diameter than when single wells are used except, of course, the central well in siphon systems.

The battery system is particularly adapted to conditions where the water table is relatively close to the ground surface because the suction header or the siphon pipes have to be close enough to the water surface so that the drawdown in the wells will not exceed the suction limit. If the water table is at a considerable distance below the ground surface, tunnels or very deep trenches will be necessary to keep the drawdown of the wells within the suction limit. The construction cost under these conditions is likely to be prohibitive.
The method of locating the wells on the circumference of a circle is best suited to conditions where the water-bearing medium contains clay or considerable fine sand which does not give up water readily. The effect of this arrangement is equivalent to that of having a well with a diameter approximately equal to the diameter of the circle of wells. This is clearly shown in figure 5 which is a vertical section through a battery of wells.

$E'F'$ is the position of the water surface if all the water is pumped from a single well, and $AEFB$ is the drawdown curve. $E''F'$ is the level of the water when the same amount of water is being pumped from the battery of wells. The intersection of the line $E''F'$ with the drawdown curve $AEFB$ at $E''F''$ locates two points which determine the radius $Re$ of the single well which is the equivalent of the battery of wells with the radius $Ra$ because the drawdown of this well is the same as that of the battery of wells.

Satisfactory results have been obtained by putting down 4 small wells in the bottom of a pit 10 feet in diameter, but in general better results will be obtained if the diameter of the circle is made considerably larger, probably from 50 to 100 feet would be about right for most conditions. From 4 to 7 wells, depending on the diameter of the circle, are all that are necessary in the closer battery. If they are spaced together there will be considerable interference between wells. (see page 2)

The method of placing the wells of the battery in a line is satisfactory whether the water-bearing stratum is fine sand or coarse gravel. This arrangement is used most when the ground water has a definite movement in one direction, and in this case the wells are placed in a line at right angles to the direction of flow of the water. By this method a large portion of the flow
through a given section may be intercepted.

The spacing of the wells in a battery arranged in a line will depend on the diameter and the depth of the individual wells and the nature of the water-bearing medium. On account of their cost deep wells should be spaced at greater intervals than shallow wells, but wells in tight materials should be placed closer together than those in open formations. Small-diameter wells should be placed closer together than large wells. For shallow wells of the type used for irrigation the spacing should be from 30 to 75 feet.  

Code, W. E., Colorado Experiment Station Bulletin 415, Construction of Irrigation Wells in Colorado.  

The interference of the wells with each other will be less when the greater spacing is used, but the cost of installing the wells will be greater on account of the longer connecting pipe lines and trenches.

**Interference of Wells**

The amount of interference between wells in a battery depends on the diameter, depth, spacing and number of the wells, the drawdown and the nature of the water-bearing material. This subject has been investigated theoretically by Slichter, and has been studied experimentally in Kansas by pumping a group of four wells singly and in groups. The wells were 24 inches in diameter and from 35 to 38 feet deep. The distance between the wells was 56, 92 and 73 feet. The depth to water was 4 feet.
The water-bearing medium was fairly coarse sand and the casing, which was of concrete was driven into the impervious layer below the sand. When these wells were pumped as a group, the average yield per well was 74 percent of the average yield of the wells when pumped separately. When these wells were pumped in pairs the average yield per well compared to the average yield of the wells when pumped separately showed the following reductions:

Distance between wells | Reduction in yield
-----------------------|---------------------
56 feet                | 14.2 percent        
75 "                   | 8.7 "               
92 "                   | 7.5 "               
148 "                  | 5.3 "               
221 "                  | None 17             

The computed reductions in yield based on Slichter's formula are also shown in the table.

In making the computations it was assumed that the drawdown was 10 feet and that the radius of influence was 600 feet. Comparison of the results shows that the theoretical reduction in yield was considerably greater than that observed experimentally, but regardless of these differences the results indicate that under the conditions of the test there was no particular advantage in spacing the wells further than from 50 to 75 feet apart. It should, however, be kept in mind that if there were more than 2 wells in the battery, the interference would be greater and the spacing would have to be greater.
irrigation wells and Their Construction

The well is the most important part of a pumping plant. Upon it depends to a large extent the success or failure of the project. Pumps, motors and engines have all been perfected until they are highly dependable and efficient, but in order to have a successful pumping plant it is essential that the well be satisfactory also. It is impossible to get a good well when conditions are not favorable, but even when conditions are favorable it is necessary to choose the proper type of well and method of construction in order to get the most satisfactory results under the existing conditions.

The types of wells most commonly used to obtain water from underground sources are driven wells, dug wells, bored wells and drilled wells. This classification is on the basis of the method of construction. There are other methods of classifying wells, but this is satisfactory and convenient. Of these different types of wells, the drilled wells are the most important from the standpoint of irrigation as the number of wells constructed by this method exceeds all the others taken together. There are, however, special conditions where other methods should be used and for this reason must be given consideration.

Driven Wells

A driven well is one that consists of a pipe and sand point which is forced into the water-bearing material by driving with a wooden maul, drop hammer or other suitable means. As the driving proceeds additional lengths of pipe are added until the desired depth is reached. A driving cap should be used to protect the end of the pipe while it is being driven. Turning the pipe with a wrench makes driving easier. In order to keep clay from clogging the screen of the
sand point while being driven it is frequently desirable to drill through formations of this sort with an auger. Driven wells are usually from 1½ to 3 inches in diameter, and standard weight water pipe, either black or galvanized, with screw couplings is used as casing. The sand point, also called a drive point, consists of a forged steel or cast iron point which is attached to a piece of perforated pipe. The perforated pipe is wrapped with a layer of fine mesh screen and then covered with a sheet of brass perforated with small round holes. The perforated brass jacket protects the fine mesh screen against injury while the sand point is being driven. Several different screen sizes suitable for different types of water-bearing formations are available. Sand points may be obtained in a variety of lengths to suit the thickness of the water-bearing formation and the quantity of water required. A typical installation of a driven well with sand points of this type is shown in figure 6.

A new type of drive point has recently been perfected consisting of spirally wound brass strips which are spaced so that they form a continuous slot of any desired width. These slots are narrower on the outside than on the inside and consequently do not clog easily with sand. These drive points also are made in various lengths.

Driven wells have long been used to supply water for domestic purposes, and batteries of these wells connected by a suction header to a single pump have recently been used to lower the water table over considerable areas in construction work. The yield from a single (one of these wells) is rather small, but the aggregate yield from a large number of these wells would be sufficient to provide water for irrigation. Although there is no record of the use of driven wells for irrigation purposes, it is believed that a battery of these wells would have sufficient merit to warrant...
a trial when conditions are favorable.

This type of installation is best suited to conditions where the water-bearing formation is free from large gravel and boulders which might injure the screen on the sand point, and where the water table is not more than 10 or 15 feet below the ground surface, because the pipe connecting the wells has to be near the water level in order to get sufficient drawdown in the wells to obtain the desired quantity of water without exceeding the suction limit. Although driven wells can be used in thick water-bearing formations, other types of wells would be more effective under these circumstances, but in formations of limited thickness the driven wells would probably give the best results. The yield from thin layers of water-bearing material is slight, and consequently small wells are well adapted to this condition. The cost of these wells is small, and have the further advantage that they can be put down by the farmer with little difficulty.

Dug Wells

The first irrigation wells were large open pits excavated by hand and lined with wood, brick, stone or special types of curbs. These wells were usually shallow and from 6 to 10 feet in diameter although sometimes larger. These wells seldom penetrated very deeply into the water-bearing formation and were frequently failures because of this reason. Many of these wells had to be abandoned before they were completed because of the difficulties encountered in sinking these wells to the desired depth.

Dug wells are sometimes made rectangular or square in shape, but usually because of their greater strength and the ease in sinking them the many sided polygon or the circle is the shape chosen for the well. When the material will stand without support while being
excavated with spades and shovels and after the men can no longer throw the excavated material out of the hole, a windless or hoist with a bucket and rope is used to remove the excavated material. Windlasses are usually operated by hand with a crank at each end of the drum; a horse or a truck is used to furnish the power when a hoist is employed to raise the excavated material from the well.

As soon as the water table is reached or the walls of the pit begin to cave, the curb should be started in the well. Many different types of curbs have been used, but the commonest forms are the wood-stave and the ring type. The latter type consists of rings of brick, flat stones, concrete blocks or cylindrical concrete sections which usually are laid on some form of shoe. The wood-stave curbs are made with either loose or fixed staves. In case the loose-stave type is used several rigid frames are built which are enough smaller than the pit so that the staves may be placed in a vertical position on the outside of these frames and still leave sufficient room to feed in gravel between the staves and the wall of the pit. The staves should be beveled on the bottom from the inside and placed close enough together so that the sand and gravel will be kept from coming through, but so the least possible obstruction will be offered to the passage of the water than necessary.

The staves are made from 8 to 16 feet long depending on the depth to water and are usually 2 or 3 inches thick. As the excavating proceeds the staves are driven down one by one with a sledge or a wooden maul. The rigid frames hold the staves in place, and the beveled edge forces out the bottom of the stave as it is driven downward. The rigid frames should also be
driven down occasionally so that the lowest frame will always be near the lower end of the staves otherwise the weight of the material back of the staves will force them inward. The upper ends of the staves should be chamfered on the sides and then wrapped with three turns of number 10 soft steel wire to keep them from splitting while being driven down.

As soon as the sinking of the well has proceeded until the excavation is about a foot below the water table, it will be necessary to install a pump to keep down the water so that the men will not be hampere in excavating the material from the bottom of the pit. A turbine pump is best suited for the work if electric power is available because it does not require priming and no belts are necessary. The pump sinks down of its own accord as the excavating proceeds. Satisfactory results may also be obtained with a vertical centrifugal pump. As these pumps are usually belt driven, the pulley on the pump shaft will have to be reset frequently as the well gets deeper. A split pulley should be used for this purpose. A horizontal centrifugal may be used for pumping the water out of the well, but in this case the pump must always be kept within 15 or 20 feet of the water surface so as not to exceed the suction lift. A gate valve should be provided on the discharge of a horizontal pump for the purpose of regulating the discharge so that it will not exceed the flow into the well. A foot valve in the suction pipe will also be desirable as it will eliminate the necessity for priming each time the pump is shut off. Sinking pumps should be equipped with a substantial screw on the suction pipe to keep coarse gravel and rocks out of the pump. This screen should have a large area of openings and should preferably be as short as possible so that the pump will keep the water in the well at a low level. Long screws are not suited
for this purpose. In order to keep the water in the well as low as possible a pit should be dug for the pump suction. This pit should be kept a foot or two deeper than the well if possible.

Sinking pumps are subjected to severe service on account of the amount of sand and gravel pumped, and for this reason new pumps should not be used for this work.

When the first set of staves has been driven down as far as possible, a second curb is built inside the first and in the same manner. This curb will reduce the size of the well considerably, and if a deep well is planned, which might require several curbs, the diameter of the well should be made large enough in the beginning so that the necessary number of curbs may be installed without reducing the well diameter too much.

Considerable difficulty is frequently encountered in sinking wells by this method, because the pressure on the curb increases as the depth of the well increases, and when the water is removed from the well the pressure on the curb increases still more. This makes driving difficult. Furthermore the weight of the material back of the curb and the velocity of the water under the ends of the staves causes the sand and gravel to wash into the well. If this continues a cavity will be formed back of the curb which will ultimately cave in and either crush the curb or distort it. To overcome this difficulty gravel should be fed down on the outside of the curb from the top to keep these cavities filled. If this precaution is not taken a large area around the well frequently begins to sink down. This is very likely to happen if a layer of fine sand is encountered which is difficult to keep from running under the bottom of the staves. Sometimes as much as a foot or more of sand and fine
Gravel will come into the well at one time. This is known as heaving and usually occurs while the well is being pumped and after being allowed to fill with water. It is frequently impossible to sink the curb under these conditions, and the well has to be abandoned. If it is possible to drive the staves down into the sand a considerable distance ahead of the excavation, it may be possible to keep the sand from coming in, otherwise a different method will have to be adopted for sinking the well if it must be driven deeper.

Another type of curb which is frequently used in dug wells, in fact it is the type most often found, consists of a cylindrical tube made of vertical timbers securely attached to a series of rigid frames in the shape of rings which are built up out of several layers of 2-inch lumber cut to form a circle. These rings are made with lapping joints and are spiked or bolted together. The rings should be spaced about 4 feet apart in the curb, and the top ring should be attached to the vertical timbers in such a manner that it will be able to support the weight of the load required to sink the casing. The bottom edges of the timbers should be beveled from the inside to form a cutting edge. The timbers should be spaced so that slits from 1/4-to 1/2-inch wide, depending on the coarseness of the water-bearing material, are left between them. This curb is placed in the excavated pit when water is reached or when the walls of the pit start to cave. When the curb is in place tiers of bricks are built up on the rings on the inside of the curb until the curb is level with bricks. When the top of the curb sinks beneath the surface of the ground, the layers of bricks are covered up beyond the timber curb. The bricks provide the
weight that forces the curb downward. Above the curb they are frequently laid in a continuous spiral to avoid fitting the bricks on each ring, but a stronger curb will result if each ring of bricks is laid separately with the last brick cut to fit the space. Care should be taken to keep the brick curb in as nearly perfect a circle as possible because of the increased strength in this form. When the well is completed the bricks inside the wooden portion of the curb may be removed for use elsewhere. Concrete blocks are sometimes used in place of brick for loading the curb.

The excavation of the pit near the curb should proceed carefully in order that the curb may settle uniformly. If more material is removed from one side of the pit than the other the curb may get out of plumb. This makes further sinking difficult. The curb should be weighted with enough bricks so that it will sink down as the material is removed from the pit. If the curb fails to move downward and the excavation of the pit is continued, there is danger that a cave-in may occur, or if the curb starts down suddenly it may become distorted when it strikes the bottom of the well. If the curb gets out of plumb it is sometimes possible to straighten it by doing most of the excavating on the side of the curb that is not sinking as rapidly as it should. This side should also be loaded more heavily.

When this type of curb is used the water is removed from the well by the same methods as previously explained, and as the excavation proceeds gravel should be fed around the outside of the curb to replace the material washed out. If the well is carried to bed rock, care should be taken to see that the bottom of the curb
is everywhere in contact with the bed rock or there is danger that considerable quantities of sand and gravel may come into the well when it is pumped. If the curb is stopped in clay the excavation should be carried a foot or two into the clay so there will be no possibility of sand coming in under the bottom of the curb. If, however, the well is not carried down to a layer of impervious material the well should be backfilled with about 2 feet of coarse gravel to keep the sand from coming in under the curb. When the well is backfilled a pit should be made for the suction pipe of the pump to protect the pump from sucking air when the well is being drawn down to the limit. An oil drum with the head cut out and the sides punched full of holes makes a suitable lining for this pit.

Under favorable conditions this type of curb has been sunk 50 feet into the water-bearing formation, but under ordinary conditions 25 feet is about the limit when the hole has to be kept unwatered and the digging is done by hand. Some of the difficulties encountered in sinking this type of curb may be eliminated by carrying on the excavation without unwatering the well. In this case the material is removed from the well with a sand bucket or an orange-peel bucket which is operated by a well drilling rig or any equipment that has a hoist on it. Much better results are obtained by this method of sinking the curb because the water in the well reduces the pressures on the curb and also tends to keep the sand from running into the well. If no boulders or layers of clay are encountered, this method works very satisfactorily.

Still another method of constructing dug wells consists of sinking a brick, concrete blocks, monolithic concrete or
large metal casing which also acts as the strainer. When bricks or concrete blocks are used for the curb a strong shoe must be made upon which the curb is built. This shoe must be strong enough to support the curb and to resist distortion. It is usually made of layers of planks similar to the rings used in the wooden curbs but much heavier. Sometimes a metal shoe is used. When the curb is made in this manner the inside corners of the bricks or blocks should be broken off to provide passage for the water into the well. The bricks should be laid flat. A single row is all that is required for small wells, but for large wells two rows should be used and these should be tied together every four or five tiers by a row of bricks laid side by side.

Monolithic concrete curbs are built in rings three or four feet high as the well increases in depth and as the curb sinks down additional rings are added. These rings are usually reinforced, and the individual rings are tied together by the vertical steel which is left protruding from the top of the ring when it is poured. Inside and outside forms should be used in order to obtain a smooth curb which will sink easily. The portion of the curb in the water below the limit of drawdown should be perforated. The perforations are usually made by casting short pieces of 1-inch pipe, tubes or pieces of garden hose in the curb. The holes in these tubes should be plugged with clay before placing in the concrete and should be cleaned out after the forms are removed. Several tubes should be placed in each square foot of area of the curb.

The large metal curbs are generally made of used material. The bottom of the curb should be strengthened by a steel ring
consisting of a heavy flat bar on an angle, and if the curb is not very rigid additional stiffening rings should be added at intervals throughout the length of the curb. The curb should be perforated below the limit of drawdown by punching it full of holes from the inside, by cutting slots with an acetylene torch, or by drilling holes from 3/8 to 1/2 inch in diameter. Best results will be obtained if the perforations are made before the curb is placed in the well. If the curb does not sink readily it may be loaded on the inside with brick, but in that case an angle iron ring should be used instead of a flat bar for the stiffening ring at the bottom of the curb because a bracket has to be provided to support the tiers of brick.

These wells are generally excavated by hand with spades and shovels, but a sand bucket or an orange-peel bucket with a power hoist may be used when no boulders, layers of clay, hardpan or other consolidated material are encountered. When hand methods are used the water has to be kept down in the well, and to do this some type of pump must be installed and operated as previously explained. Gravel should be fed around the outside of the curb as the excavation proceeds. When a monolithic concrete curb is being installed, a very coarse gravel should be used to keep the sand from coming through the perforations which are usually made large in this type of casing. The bottoms of the wells should be finished in the same manner as previously described. Under favorable conditions, bricks or concrete block curb wells can be driven from 15 to 20 feet into the water-bearing material. Greater penetration can be attained with monolithic concrete or large metal casing.

Large-diameter wells, such as dug wells for providing water for irrigation, are best suited to conditions where the water table
is near the surface and where the thickness of the water-bearing formation is small. The large area of strainer permits the water to enter the well with a minimum loss of head and also reduces the velocity of the water entering the well through the perforations. As a result the tendency for the water to wash sand into the well is reduced. There is a general impression that large wells have a much greater capacity than small ones for the same drawdown. Actually the advantage of the large wells in this respect is not nearly as great as is usually believed. Theoretically under ordinary conditions a well 8 feet in diameter has a capacity only 37 percent greater than a well 1 foot in diameter.

Parker, Philip A. Morley, The Control of Water, 1913, p. 264.

Under actual conditions the yield from the 8-foot well will probably be somewhat greater than this because the loss of head through the strainer will be less for the 8-foot well than for the 1-foot well. These large wells are much more expensive to construct than the smaller wells, and it is doubtful whether the increase in capacity is sufficient to justify the construction of a large well under these circumstances. They do, however, have the additional advantage that the pump and motor or engine may be installed in the well near the water table thereby making it possible to use a horizontal centrifugal pump where otherwise a deep well turbine pump would have been installed at a much greater cost. Although gasoline engines are frequently installed in large wells, the practice is a dangerous one owing to the possibility that gasoline fumes might accumulate in the well and explode when conditions were favorable. There is danger also from carbon monoxide poisoning.
The large open well is the type that the farmer most often attempts to put down when he tries his hand at well digging, because no special equipment is required. All he needs is a spade or shovel, two large buckets and some form of hoist to bring up the excavated material. Actually, however, this is one of the most difficult types of wells, and very often the farmer finds himself in difficulty about the time the casing has penetrated 2 or 3 feet of the water-bearing formation. The usual difficulties are that the casing gets out of plumb or collapses, the sand and gravel gave into the well under the curb faster than they can be removed, the pump will not take care of the water or the curb refuses to go down. As the result of these misfortunes the well is frequently abandoned and a well digger is called. He usually finds a large area caved in around the well, the casing out of plumb and partially collapsed and several discarded pumps. If the well is not in too bad a condition a good well driller can sink a smaller casing to the desired depth inside the first. If, however, the area around the well has sunk down to a considerable depth and the casing is much out of plumb or badly collapsed it will probably be cheaper to start a new well. More satisfactory results would be obtained if the farmer would dig the well down to the water table and then hire an experienced well driller to complete the well.
Large Pits

Large open pits excavated with a dragline or a steam-shovel are sometimes built to supply water for irrigation. These pits are from 50 to 250 feet long and are of varying width, the maximum being about 50 feet. These pits are excavated as deeply as possible into the water-bearing formation, but on account of the tendency of the sand and gravel to run into the pit owing to the constant agitation of the water by the excavating machinery the maximum depth of the pit below the water table seldom exceeds 8 or 10 feet. When pumping from the pit is started the pit gets shallower rapidly because the velocity of the water through the water-bearing medium carries sand into the pit, and because the removal of the water pressure on the inside of the pit causes the banks to slough. The material excavated from the pit forms large spoil banks which are very unsightly and the area required for the pit and the spoil banks takes up valuable space. The sloughing of the banks makes it difficult to obtain a firm foundation for the pump. When the water-bearing material is quite fine, the large filtration area coupled with the considerable storage capacity of the pit should make it possible to get a satisfactory pumping plant under these conditions, but the results obtained are usually poor because the small depth of water in the pit makes it impossible to get sufficient drawdown to force a large quantity of water through the fine sand into the pit. Better results would probably be obtained if a deep narrow trench were made so that a perforated pipe, laid horizontally and connected with a pump sump could be placed in the bottom of the trench at a considerable distance below the water table, and then...
covered with coarse gravel. Although a well of this sort would have very little storage capacity it would probably yield more water than the large pit because it would be possible to draw the water in the well down to a greater depth than before.

Bored Wells

Augers are sometimes used to put down irrigation wells to the point where unconsolidated water-bearing material is encountered. These wells are called bored wells, and the augers used to construct them are similar to post-hole augers, but they are much larger and are more substantially made. They consist of a cylindrical steel bucket with a cutting edge along a slot in the bottom. The bucket is filled by turning with a power driven rotating mechanism. The turning motion is imparted to the auger through a square stem which slides down through a hole of similar size in the rotating mechanism as the well gets deeper. A hoist is required to lower the auger into the well and to raise it when the bucket is filled. After the auger has been brought to the surface the material excavated is removed by opening a door in the side of the bucket. The augers are made in different sizes and when it is desired to make a hole larger than the size of the auger a reamer is used which consists of an extension of the cutting edge. This cutter is attached to the top of the bucket in such a manner that the material excavated when enlarging the hole is carried into the bucket at the top. Holes up to 32 inches in diameter and sometimes larger are made by this method.

Augers work most satisfactorily where the walls of the holes do not cave. Casing may be used, but it is difficult to force the casing down because the rotating mechanism
in the way. As soon as unconsolidated water-bearing material is encountered other methods have to be adopted for completing the well. Augers may be used, however, to cut through layers of clay which sometimes occur in the water-bearing formation.

When conditions are favorable rapid progress can be made with this type of equipment. From 5 to 10 feet can be excavated per hour in shallow holes, but the rate decreases when the holes get deeper. Where equipment for boring wells is available and the material to be excavated does not contain boulders or large roots, this method is very useful.

**Drilled Wells**

Wells sunk by means of percussion drills, rotary drills, water jets or modifications of these tools are called drilled wells. At the present time most irrigation wells are being put down by one or another of these drilling processes. The methods used in drilling the wells with the different tools are known as the standard method, the California or mud-scow method, the sand-bucket method, the hydraulic-roto method, the jetting method and the hollow-rod or self-cleaning method. The material in the well being drilled by these methods is loosened by being broken up by the percussion of the drill, by being cut by the rotating bit, by being eroded by the action of a water jet or by a combination of these processes.
The standard method 

incorporates

many basic 

operations 

in well drilling 

and in 

several other 

methods as 

would 

be expected. 

The 

standard method of 

drilling is 

described 

in detail in the 

report.
Drilled Wells

Wells put down by means of percussion drills, rotary drills, water jets, or modifications of these tools are known as drilled wells. The methods used in drilling wells are classified as the standard method, the California or stovepipe method, the sand-pump or orange-peel bucket method, the hydraulic rotary method, the jetting method and the hollow rod or self-chaining method. At the present time most irrigation wells are being put down by one or another of these methods.

Standard Method *

Wells put down by the standard method are drilled with a standard rig and percussion tools in conjunction with a bailer which is used to remove the drillings from the hole. This method is adapted to drilling deep holes in consolidated material, such as rock, and is sometimes used in shallow holes when drilling through boulder formations. Holes from 2 inches to 24 inches and more in diameter can be drilled by this method, but most irrigation wells are from 12 to 24 inches in diameter. The principle upon which the drilling is accomplished when using standard tools is the breaking of the rock by the impact of a bit with a relatively sharp chisel edge which is lifted and dropped at regular intervals, and which is at the same time slowly turned by hand so that the edge of the bit will strike on a different line at each successive blow. If the tools are sharpened properly and are turned carefully, the bit will cut a round hole.

Tools and Equipment
method of drilling wells. The latter is sometimes called the self-cleaning method.

**Standard Method**

Wells sunk by the standard method are drilled with standard percussion tools in conjunction with a bailer which is used to remove the drillings from the hole. This method is used in drilling deep holes in consolidated material such as rock and is sometime used in shallow formations. Holes from 2 inches to 24 inches in diameter can be drilled by this method, but most irrigation wells are from 12 to 24 inches in diameter.

The equipment used in sinking a well with standard tools consist essentially of a string of tools, a bailer and a drill rig. The drill rig used in putting down irrigation wells is usually of the portable type in which the derrick, engine, hoists and drilling mechanism are built as a unit and mounted on wheels so that the rig can easily be moved from one location to another. Rigs were formerly moved by attaching them to a truck, but many of the newer rigs are made so that they may be mounted on the bed of a truck, and some of the heavier rigs are provided with crawler-type tread mountings.

The principal upon which the drilling is accomplished when using standard tools is the breaking of the rock by the impact of a bit with a relatively sharp chisel edge which is lifted and dropped by the drill rig at regular intervals and which is at the same time slowly turned by hand so that the edge of the bit will strike on a different line at each successive blow. If the tools are sharpened properly and turned carefully the bit will cut a round hole.
A complete string of standard tools is made up of a drill bit, a stem, a set of jars, a sinker and a rope socket. It may weigh as much as 5000 pounds. The tools are subjected to very hard service in drilling wells, and in order to withstand this service special steels must be used in their manufacture. The tools are joined together by screw joints of the box and pin type. These joints have a pronounced taper which can be made up so tightly that even the constant jarring of drilling will not loosen them. Special wrenches which fit the squared sections of the tools at the joints are used to tighten the joints.

The bit is the most important part of the string of tools. It does the actual drilling and consists of the cutting edge, the body, the wrench square, the shank and the pin. Different shapes of bits are made for different purposes. Some of the different forms are shown in figure 13. The regular drill bit (figure 12a) is the type generally used in drilling rock. The Mother Hubbard bit (figure 13b), which is similar to the regular bit except it has square shoulders instead of rounded shoulders, is used where the mud from drilling shale builds up on the sides of the hole because the sharp shoulders ream out the hole easily. The California pattern bit (figure 13c) has long sloping shoulders and is used in drilling large holes in hard formations and where the drilling is carried on ahead of the casing. The sloping shoulders do not catch on the bottom of the casing when the tools are being withdrawn. Spudding bits (figure 13d) are short and thin and are used in starting holes in soft formations. Star pattern bits (figure 13e) have two cutting edges at right angles to each other.
They are used for drilling in fissured and tilted rock because the additional cutting edges tend to keep the hole round and straight. Various special types of drills, not shown, are made for the purpose of performing particular functions, such as reaming, undercutting, or straightening the hole.

The drill stem (see figure 12) consists of a round steel bar which is connected to the drill bit by a box and pin joint as previously explained. The purpose of the stem is to add weight and length to the drill so that it will cut rapidly and will make a straight hole. Stems vary from 6 feet to 30 feet in length and from 2½ inches to 6 inches in diameter. The weight varies with the diameter and length of the stem, the maximum being about 3000 pounds.

The jars (see figure 13) consist of a pair of narrow steel links with a box joint on the lower end for attaching them to the drill stem and a pin joint on the upper end for attaching the rope socket or the sinker bar if one is used. The purpose of the jars is to provide a means for giving an upward blow to the tools in case there is a tendency for them to stick in the hole. They have very little effect on the downward blow struck by the bit when drilling. Jars are also used on fishing tools, and in this case the stem is frequently attached above the jars so as to give a harder blow to the tools. The stroke of jars varies, depending on the nature of the work being done; the heavier the blow required, the longer the stroke. For light work, such as drilling, the stroke, from 6 to 8 inches, but where a blow of maximum force is necessary, jars with as much as 36-inch stroke are provided.

The sinker bar, now seldom used, is similar to the drill
stem in shape except that it is shorter. It was attached to the upper end of the jars to give additional length and weight to the tools without increasing the weight on the bit while drilling. The additional weight causes the tools to fall faster, but when the drills struck the force of the blow from the sinker bar was dissipated by the opening of the jars.

Rope sockets (see figure ) are for the purpose of attaching the rope to the string of tools. They are made both with and without a swivel joint although at the present time the swivel type socket is generally used when drilling with a wire rope. Wire cables are held in the socket by pouring melted zinc or babbit around the unraveled end of the cable after it has been threaded through the neck of the socket.

Manila ropes are held by rivets driven through the neck of the socket after the end of the rope has been tightly wrapped with twine and forced into the socket.

The drilling tools are suspended by either a wire or a manila cable. Manila cables are more elastic and cause less shock to the rig when drilling, but they wear out very rapidly, and for this reason wire ropes are more generally used at the present time. Manila ropes are still used by some drillers in starting holes because the lack of elasticity in wire rope is particularly noticeable when drilling with a short cable as is the case when starting a hole. Wire cables used in drilling vary in size from 1/2 inch to 1 inch in diameter. The largest sizes of cables are used only when drilling deep holes with heavy tools.

In drilling a hole the best results are not obtained when the bit is allowed to strike the rock with the full weight of the tools. Experienced drillers operate with a tight cable so that the bit will strike the rock with a quick blow that is
obtained by stretching the cable a little. On large rigs a temper screw is used to feed out the cable, so that the bit will strike the rock with a blow of maximum cutting power, but on small rigs the adjustment of the length of the cable is made by winding or unwinding the cable from the reel on the drilling rig.

When a standard rig is used the drillings are removed from the well by means of a bailer or vacuum sand bucket. See figure 14. A bailer consists of a section of pipe generally from 8 to 20 feet long with a valve in the bottom and a bail at the top for attaching the drilling cable or the sand line which ever is used. The diameter of the bailer is determined by the size of the hole being drilled, plenty of clearance being allowed so that the bailer will fall freely. Bailers are equipped with flat valves, dart valves or bayonet valves. The purpose of these valves is to allow the drillings to enter the bailer and to keep them from running out after they have been caught in the bailer. The flat valve bailer has a flapper valve which cannot be opened when the bailer is filled. This type has to be emptied by turning it up on end and allowing the drillings to run out of the top. Bailers with dart valves are emptied by striking the dart attached to the valve on something solid which will force the valve open and allow the drillings to run out. Bailers with the bayonet type valve have the valve mechanism in a hinged portion of the pipe which is relieved by opening a latch. The drillings then run out through the open end of the pipe. The bailer is filled with drillings by allowing it to fall rapidly to the bottom of the hole.
As the bailer approaches the bottom the mixture of water and drillings enters through the valve in the bottom of the bailer and when the bailer is raised the valve closes. Usually several trips up and down are required to fill the bailer.

The vacuum sand pump is similar to a bailer except that it is equipped with a piston for the purpose of drawing the drillings into the bailer. The piston is attached to the hoisting cable, and when the sand pump reaches the bottom of the hole the piston sinks to the bottom of the bailer. Some types have loose-fitting pistons, but the best types have a valve in the piston so that the water flows through the valve in the bottom of the bailer. The weight of the sand pump holds it down on the bottom of the hole while the piston is being raised, and for this reason this type is more effective than the ordinary bailer in clearing out the hole.

The standard portable rig consists essentially of a mast, a two or three line hoist, a walking beam and an engine mounted on a frame so that it can be transported from place to place easily. The mast is a built-up section of wood or steel with sheaves at the top for the sand line and the drilling line. The mast is made long enough so that the longest string of tools or section of pipe can be hoisted out of the hole, the minimum height being about 30 feet. The mast is made so that it may be folded up and carried on the top of the rig when the equipment is being moved from place to place. The sheave for the drilling line is usually mounted on springs or rubber to take up some of the slack when drilling is in progress. The hoists consist of power operated reels large enough to hold sufficient cable for drilling the deepest holes of which the rig is capable. The reels are driven by
friction pulleys or by positive drives such as gears or chains. When a positive drive is used a clutch has to be provided for each reel to throw the mechanism in and out of gear. The sand line reel is smaller than the drilling reel and usually operates at a higher speed. The drilling line reel has to have sufficient power to hoist the tools and the cable out of the hole and to operate fishing tools and other equipment. Also long strings of casing have to be raised or lowered frequently by the drilling line hoist. If an additional hoist is required to operate special equipment a separate reel is provided. All the reels are equipped with powerful brakes capable of stopping or holding them at anytime. In addition the drilling reel is equipped with a hand operated slow-motion drive for the purpose of raising or lowering the cable a small amount while drilling. This device takes the place of the temper screw. The walking beam is a heavy hinged arm with a sheave at one end through which the drilling line passes. A pitman which is operated by a crank driven by the engine is attached to the walking beam near the sheave end. As the crank rotates the walking beam moves up and down. The sheave at the end of the walking beam also moves up and down and as a result raises and lowers the drilling line. Since the end of the line on the reel is held fixed by the brake the tools which are attached to the other end of the line rise and fall. This is the motion that causes the drill to operate. The length of the stroke depends on the radius of the crank arm which may be varied by changing the setting of the crankpin. The experienced driller adjusts the length of the stroke and the number of strokes to the minute to suit the work. When the equipment is adjusted properly the drilling
proceeds at a maximum rate with a minimum amount of vibration and jerking. Steam engines were formerly used to operate portable well drilling rigs, but at the present time gasoline engines are used almost exclusively. Single cylinder engines are used on small rigs, but on the larger rigs where more power is needed 4- and 6-cylinder engines are used because they are lighter and more flexible. A belt drive is usually employed to transmit the power from the engine to the walking beam and the hoists. For small rigs a seven- or eight-horsepower engine is all that is necessary to operate the rig but for large rigs from 20 to 40 horsepower engines depending upon the size of the rig are required.

Auxiliary Equipment

In addition to the equipment described already, a large number of accessories, such as, drive clamps, drive heads, casing rings and slips, jacks, casing elevators, tool wrenches, tool wrench tighteners, pipe wrenches, and some of the common types of fishing tools, are required also when using the standard method of drilling wells. Drive clamps are used for the purpose of forcing the well casing by the drive clamps. Drive clamps are made of a pair of square forged steel bars each of which contains a V-shaped notch which fits the corner of the wrench square. The bars are held together at each end by a large bolt. Drive heads are used to protect the ends of the pipe when pounding down the pipes with drive clamps. Drive heads consists of heavy forged steel rings which fit on the end of the pipe and take the blows of the drive clamp. Casing rings and slips are used when casing which has become fastened in the hole is being pulled. The casing rings are made of cast steel and are fitted with tapered steel jaws which fit between
the ring and the casing. When the ring is lifted the jaws are forced into the casing. Either hydraulic or screw jacks are placed under the ring to start the casing. As soon as the casing has been lifted far enough by the jacks so that it moves freely then the drilling cable is attached, and the remainder of the pulling is done with the drilling line hoist. The drilling line is fastened to the casing by what is known as a casing elevator which consists of a circular clamp with an eye on each side which fits under the top coupling of the pipe. A large link is welded in each eye on the clamp, and the hoisting cable is attached to these links. Special wrenches, about 4 feet long, are required to tighten the joints in the string of tools. These members are made of forged steel with one end in the shape of a hook which fits snugly on the wrench squared on the tools. The wrenches come in pairs, and the joints are tightened by pulling the ends of the wrenches together with a bar and chain tightener or by sledging. Sometimes a special jack which travels on a circular track is used to operate the wrenches. This type is used mostly on the larger tools. A pair of large size chain-pipe wrenches should be included for use in screwing and unscrewing pipe joints.

Drilling Operations

Wells with sufficient capacity to supply water for irrigation are usually found only in unconsolidated material, but layers of rocks or beds of boulders are sometimes encountered in these formations, and under these conditions the standard method of drilling wells is used. The method was developed for drilling in solid rock, but it is also the best
method for drilling in boulders. When using the standard method for putting down irrigation wells the drilling, as previously explained, is done by raising the tools by means of the walking beam and then allowing them to drop so that the bit strikes the material in the bottom of the hole. The tools make from 25 to 50 strokes per minute and by turning the drilling cable back and forth, the bit rotates also and in so doing makes a round hole. As the hole grows deeper more and more cable is let out so that the tools will always be striking the bottom of the hole with blows of maximum cutting power. If no water is encountered in the well, water is added from time to time. This mixes with the drillings and forms a paste which does not reduce the force of the blows of the bit nearly so much as the dry material. Too much water in the hole, however, interferes with the progress of the drilling because of the buoyant effect of the water on the string of tools and the friction of the cable in the water. Casing is usually required when drilling in unconsolidated material and if blank casing is used, it cuts off the flow of water into the well sufficiently so that it does not interfere with the drilling.

When the bit has cut four or five feet into the rock or other material the tools are withdrawn and the drillings are cleaned out of the hole with a bailer or sand pump. The bailer or sand pump is let down to the bottom of the hole on the sandline which is lighter and operates more rapidly than the drilling cable. When the bottom is reached the sand line is run up and down a few times for a short distance so that as much material as possible will be forced into the bailer or sand bucket. The material caught is then hoisted to the surface and dumped. Several trips are usually required
to clear the drillings out of the hole. When the hole is
clean, the tools are lowered to the bottom of the hole and
drilling is resumed. If the drilling is being done in a
dry hole water has to be added to replace that taken out while
cleaning the hole.

Each time the string of tools is withdrawn the bit is
inspected to see whether it is too dull to drill rapidly or
worn too small to cut a full size hole. If so the bit is
replaced with a newly sharpened one. The joints in the
string of tools are inspected also to see whether any of them
have worked loose. Each joint is marked with a chisel cut
across the joint, and all that is necessary to see if the
joint has unscrewed is to note whether the parts of the cut are
in alignment. If any joint has loosened it is again tightened
by means of the tool wrenches.

In hard rock unless much water is encountered the hole
is not cased, but in soft material casing is used to keep the
hole open. As the drilling progresses the casing is driven
down by means of the tools and the drive clamp. It is
customary to keep the end of the pipe near the bottom of the
hole so as to avoid the danger of the hole caving in, and in
some materials the casing is forced ahead of the tools. When
layers of quicksand are encountered difficulty in driving
casing is usually encountered, and unless the casing is
forced through the layer, the sand will keep running into
the well when bailing or sand pumping is attempted. Under
these circumstances it is usually customary to dump clay
into the well and then to mix this material with the quicksand
by churning with the tools. This forces the clay out of the
casing into the quicksand surrounding the casing and forms
a barrier through which the sand cannot come. The casing
The casing is then driven as far as possible, and after bailing out the hole, more clay is added which is mixed with the sand by churning with the tools. This procedure is repeated until the casing is driven through the layer of quicksand. Progress by this method is slow, and if it is anticipated that a large amount of quicksand will be encountered some other method such as the rotary method, which will be described later, should be adopted for drilling the well or that portion where the layers of quicksand are located.

Casing

Wells drilled by the standard method are cased either with standard pipe or well casing. Light casing cannot be used satisfactorily because it does not withstand driving with the tools and drive clamps successfully nor is it strong enough to resist the wear of the tools against the sides of the casing while drilling is in progress. For ordinary work where heavy driving is not required well casing is ordinarily used. It is lighter in weight than standard pipe and also cheaper. It is made with either screw and socket joints or inserted joints. Casing having screw and socket joints is threaded on both ends and the joints are made up by screwing the ends of the pipe into a coupling. Inserted joint casing is made with one end of the pipe threaded on the outside and the other end, which has been expanded slightly, threaded on the inside. This type of joint will not stand much driving. When it is anticipated that hard driving will be necessary to force the casing down, standard pipe is used. This pipe comes in three weights - standard, extra strong and double extra strong. These
pipes are threaded on both ends and the joints are made by screwing the ends of the pipes into sleeve couplings. For heavy driving the couplings are made so that the pipe can be screwed into the coupling until the ends of the pipe butt together; in this way the threads on the pipes are protected to some extent when hard driving is necessary because the ends of the pipe bear part of the load.

The sizes of standard pipe refer to the inside diameter, extra strong and double extra strong pipe, however, have the same outside diameter as standard pipe, the additional thickness being obtained by making the inside diameter smaller and consequently the same fittings may be used on these heavy weight pipes as on standard pipe. The size of well casing, however, is based on the outside diameter. The threads on well casing also differ from those on standard pipe, the threads being finer because the well casing is thinner than standard pipe. Fittings for standard pipe will not fit well casing. The farmer should keep these differences in mind and when ordering pipe should specify the kind of pipe desired and if ordering fittings should indicate whether they are for standard pipe or for well casing.

A drive shoe should always be used when driving either standard pipe or well casing. The shoe is made of forged steel and is either screwed or welded to the bottom of the first section of pipe. The shoe has a beveled edge for cutting and is made strong enough to withstand heavy driving without failure or distortion.

In shallow irrigation wells the hole is sometimes cased with standard pipe or well casing while the well is being drilled, and when the well is completed a string of light
weight riveted pipe which has already been perforated is installed in the hole inside the casing after which the heavy outside casing is pulled out for use elsewhere. If the well is in fine material screened gravel may be placed in the space between the inside and outside casing while the outside casing is being pulled. The gravel will act as a strainer and keep the fine sand from coming into the well.

Casing used in irrigation wells has to be perforated where it passes through water-bearing formations in order to let the water into the well. Some casing is perforated before it is put into the well, but in most instances the casing is perforated in place after the well is completed. The perforations consist of slots. The size and number of the slots depends on the nature of the formation and on the water supply. The perforations are usually placed in rings with one slot for every inch the pipe is in diameter. The slots in perforated pipe are either punched in or cut with an oxyacetylene torch. Casing in place in the well is perforated by means of a Mills knife or a similar type of perforator. These devices will be described in connection with California Steel Pipe method of putting down wells. Screens or strainers of the type used in wells for domestic water supplies are seldom employed in irrigation wells. Strainers with sufficient capacity to supply water for irrigation would be too expensive to use on an irrigation well.

The standard percussion tool method of drilling wells may be used under a variety of conditions, but it is most useful in drilling in hard rock, fissured formations, and in boulders. Although the standard portable well rig is designed primarily for drilling with percussion tools, with slight changes it may be used for drilling wells by other methods.
when drilling in formations of a variable nature it is customary to change from one method to another depending on the nature of the material encountered. For these conditions, the standard portable rig is particularly well suited. The standard method of well drilling is not, however, adapted for use by the farmer in drilling his own well. The use of this method requires that an experienced well driller be on the work or the outcome is almost certain to be unsuccessful. For this reason the farmer whose well will penetrate formations requiring the use of this method should take special pains to secure the services of an experienced and successful driller.
The California or Stovepipe Method

The California or stovepipe method of drilling wells is an adaptation of the standard method. Percussion tools are used, but instead of standard tools and a bailer, a tool known as a mudscow is used which combines the functions of the drill and the bailer. This method was developed in California for drilling large relatively deep wells in unconsolidated material such as clay, sand, gravel and boulders, to supply water for irrigation. This method is not suitable for drilling in hard consolidated materials, but the equipment used in the California method may be used to operate standard percussion tools, and most well drillers are equipped with standard tools as well as a mudscow. Then if a layer of hard material is encountered, the mudscow is replaced by a string of tools and drilling is continued by the standard method until the hole is driven through the hard layer.

The equipment used in sinking a well by the California method consists of a mudscow, a set of hydraulic jacks and a California rig. The mudscow loosens and breaks up the material in the hole, and at the same time it acts as a bailer for removing the drillings from the well. The hydraulic jacks force down the well casing, and the drilling rig operates the mudscow and drives the pump for the hydraulic jacks. The mudscow is raised and dropped in the same manner as a standard string of tools and the drilling is done by the impact of the cutting edge of the mudscow. California rigs are portable but are much heavier than the standard portable rigs and are consequently much more expensive to move.
The string of tools used on a California rig consists of the mudscow, a pin and tongue sub, fishing jars, a box and tongue sub and a rope socket. The mudscow is made from a section of heavy pipe and is equipped with a flat valve having a large opening so that it will not be clogged easily by clay balls or small rocks while drilling. A heavy shoe of special steel is welded to one end of the pipe, and a pair of ears is formed on the other end by cutting away a part of the pipe or by riveting or welding a pair of straps on the inside of the pipe. The ears are drilled for a large size pin which fits the hole in the pin together and tongue sub and forms a knuckle joint between the mudscow and the jars. This joint makes it possible to tip the mudscow up on end to dump it. For drilling in clay a special type of mudscow is used which has a cutting edge welded across the bottom of the shoe. This cuts the clay into small chunks so that they will not get caught in the valve at the bottom of the mudscow. A special type of mudscow is used also for under reaming. It has a deflector plate just above the shoe and an outlet for the water through the side of the pipe opposite the deflector. When the mudscow drops through the water the deflector plate forces the shoe against the side of the hole, and as a result increases the diameter of the well.

Fishing jars having a stroke from 18 to 36 inches are used when drilling with the mudscow. The jars are used for the purpose of striking an upward blow to loosen the mudscow in case it becomes fast in the hole or tends to stick as when drilling in clay or shale. The jars are connected
to the mud-scows by means of a substitute or sub. which has a tongue with a hole in it at one end and a pin at the other end. The jars are attached to the rope socket by a box and tongue sub. The rope sockets are similar to those used on standard tools except that for light work a wing socket is sometimes used. The end of this socket is split so that the wings may be sprung apart for inserting the rope. After the rope is inserted the wings are united together by pointed rivets which are driven through the rope. For convenience in disconnecting the rope from the tools, jaw sockets are sometimes used as the removal of the pin, which passes through the jaws and the tongue of the substitute, is all that is necessary to disconnect the line.

A string of standard tools which is used to drill through layers of consolidated material is part of the equipment of every California outfit. The bit used for this work is called a spudding bit, and is shorter in length and lighter in section than a standard bit. The size of the bit depends on the diameter of the hole being drilled.

The California well rig consists of a mast, a hoist capable of operating two or more lines, a pressure pump, an engine and a walking beam. The principal difference between a standard rig and a California rig is that the walking beam on the California rig is at the top of the mast instead of in the body of the rig. The walking beam is about 10 feet long and is made either of wood or steel. It is pivoted near the center on a spring mounted support which takes some of the jar off the rig and the cable while drilling. The front end of the walking beam carries the
crown pulley and the sand-line pulley. The rear end of the walking beam is attached by tail rods to the crank which gives the walking beam its reciprocating motion. Tail rods are usually made of heavy pipe, but wood is sometimes used. Some rigs are equipped with a cable between the crank and the rear end of the walking beam instead of a steel or wood rod.

The mast on the California rig is about 36 feet high and is made heavier than the mast on a standard portable rig in order to take care of the additional load imposed by the operation of the walking beam. It is usually made of timber in the form of an A-frame and is braced by two diagonal struts attached to the top of the mast and the frame of the rig. Lateral stability is obtained by the use of guy wires. The frame of the rig is made very strong to carry the weight of the hoisting machinery, the engine and the pressure pump as well as the load from the walking beam on the mast. The rig is equipped with 4 wheels which are usually removed and replaced by heavy sills when the rig is being set in position preparatory to drilling. Steam power was originally used on California rigs, but at present most outfits use gasoline engines. The hoisting equipment is similar to that used on a standard rig.

The pumps for supplying pressure to the hydraulic jacks which are used to force the casing down are located on the side of the drill rig. These pumps are of the double acting type and are very substantially made as they develop pressures up to 4000 pounds per square inch.
Hydraulic jacks have barrels from 3½ to 6 feet in length and from 4 to 8 inches in diameter depending upon the length of the sections of casing and the force required to drive the casing. These jacks have to be built strong enough to withstand the maximum pressure developed by the pumps. The jacks are double acting so that they may be used either to force the casing down or to pull it out in case the well has to be abandoned. The jacks are set in a vertical position close to the casing in the manner shown in figure 18. The setting of the jacks is very important because the pull on the foundation may amount to several hundred tons. Either two or four jacks are used. Levers loaded with sand bags are sometimes used to force the casing down when drilling shallow wells. A heavy steel cap with two or four lugs on the sides, for attaching the jacks, is placed on top of the casing to keep from crushing it when the force is applied by the jacks. This cap has to be removed each time a new section of casing is added as the drilling progresses. This is conveniently done by passing a wire-rope sling through the link of the jars and then attaching the loops to the lugs on the cap. When the mudscow or the standard tools are withdrawn from the well, the heavy cap is lifted also. When the tools are replaced in the well, the cap drops until it reaches the top of the casing. The sling is then released by unhooking the loops on the sling from the lugs. Sometimes the mudscow is so large that it will not go through the hole in the casing cap. In that case it is necessary to lift the cap in the manner just described every time the mudscow is withdrawn from the well to be dumped. The heavy cap assists in dumping the mudscow by causing the top of the bucket to drop lower than
the bottom of the bucket when it is lowered over a frame which acts as a fulcrum for the bucket.

Stovepipe Casing or Double-Well Casing

The type of casing used in the California or stovepipe method of drilling wells is unique. It is made up of inside and outside sections which telescope into each other and form a casing of two thicknesses of metal with joint in the middle of each section. The sections are made usually with vertical single riveted joints, the inside sections having the rivets countersunk on the outside and the outside sections having the rivets countersunk on the inside. Sometimes the sections are made by welding the vertical joints. In that case the beads formed by welding have to be ground off on the surfaces which will be in contact when the sections are forced together. The sections are made so that they fit together closely, and considerable force has to be applied to drive the sections together.

The ends of the sections will butt together evenly and squarely and not slip by each other when they are forced together. After each section is added it is dinted with a special pick for the purpose of keeping the sections from slipping apart in the well. Sometimes the sections are riveted or welded together to keep them from coming apart. The latter method should be used in case it is anticipated that the casing may have to be pulled.

Stovepipe casing is made of what is known as hard-red steel. The thickness used varies with the nature of the formations and with the depth and diameter of the well, 8- or 10-gage being used in deep wells when hard driving is required, and 16-gage in shallow wells of smaller size.
small diameter. Stovepipe casing is made in all diameters from 4 to 36 inches but the 16-inch size is the one most commonly used. Stovepipe casing is made in 24-, 36- and 48-inch sections depending on the size of the pipe and the gage of the material.

The first section of casing used when starting a well, is assembled before being placed in the well. This section, called the starter, usually consists of from 9 to 20 feet of 2, 3-or 4-ply casing which is riveted or welded together and attached to a heavy drive shoe. The length and thickness of the starter depends on the depth of the well and the nature of the material into which the hole is to be driven. The drive shoes are made of steel and are recessed on the inside so that when they are attached to the starter sections the joints will be flush on the inside and the bottom of the casing will butt against the shoulder in the shoe. Drive shoes, or well rings, as they are sometimes called, are made in various sizes where it is anticipated that difficulty will be encountered in forcing or driving the casing down, heavy shoes some of them as much as 1½ inches in thickness are attached to the starter. Where driving is especially difficult forged steel shoes are sometimes used. In some cases no starter is employed, the sections of casing being placed directly on the shoe. This method, however, is usually not satisfactory because it is difficult to keep the well straight and plumb without the starter sections.

Single thickness casing with telescope joints or with butt joints and bands is sometimes used in shallow wells. This type of casing...
cannot be used successfully when heavy driving is required because the casing will crumple when subjected to pressure from the jacks or other driving device. Well casing and standard pipe are used also for casing when drilling by the California method. The drive shoe is screwed, riveted or welded on the bottom of the casing. This casing will stand heavy driving, but ordinarily it is too expensive for use unless it can be purchased secondhand. This type of casing will stand long periods of drilling with standard tools without injury, and has the added advantage that it can be pulled and be used over again if necessary.

Perforating Casing.

The casing used in wells drilled by the California or stovepipe method is usually perforated in place although more satisfactory results can usually be obtained when the casing is perforated before it is placed in the well. Various methods of perforating the casing are used, but the Mill's knife which cuts rings of slots in the pipe at the points desired is most generally used and has been found to be quite satisfactory. The Mill's knife consists of a frame which carries the perforating knife, a string of pipe for holding the perforator rigidly in place, and a cable for pulling the lever which forces the knife through the casing. This device has an indicator on the pipe which shows where the perforations are being made. The star perforator is also used to some extent. This is one of the objections to the star perforator. It makes the perforations by means of 4 star-shaped cutters held in a frame which is forced down by means of a special
Finally those positions of the core should be performed which are opposite under.

The location of the core formations is obtained from the well log which is determined by the sample.

Material brought up by the mud screen, when soluble samples are obtained, is another because the mudscan pride up the material in the hole as soon do up is broken loose and consequently the nature of the formations can be more accurately determined.
The star perforator does not have an indicator to show where the slots are being made. A hammer on the end of a drill stem. Casing is also perforated by ripping long slots in it with a device called a ripper. These long slots weaken the casing and may cause it to collapse. The Mill's knife starts at the bottom of the well and works toward the top. The other devices start at the top and work down. If there is much sand coming into the well as the result of perforating the casing, the accumulation of sand in the bottom of the well will interfere with the operation of these devices which have to be driven downward because the sand has to be removed before the perforator can be forced to the bottom of the well. Another type of perforator, which was developed more recently, is operated by hydraulic pressure through pistons which cut shutter-shaped perforations in the casing. Like the Mill's knife, the position of this perforator device can be accurately controlled and very satisfactory results are claimed for the device.

The number and size of the perforations required in a well cannot be accurately determined. There should be enough perforations so that the water can enter the well without unnecessary loss in head, and not enough perforations to weaken the casing seriously. Slots from 3 to 6 inches apart around the circumference of the casing and from 6 inches to 1 foot apart along the axis of the casing have been found to give satisfactory results under most conditions.

When the casing is perforated before it is installed in the well, a different type of perforation is used than when the casing is perforated in place. Both the inside and the outside section of pipe have to be perforated,
The heavy equipment necessary and the special knowledge required makes the California method unsatisfactory for use by the farmer. Wells drilled by this method and experienced and for this reason the farmer should obtain the services of an experienced and competent well driller rather than to attempt to do the work himself.
and in order to have the two sets of holes coincide when the sections are forced together one of the sections is perforated with slots and the other with round holes. When the casing is assembled the lines of slots and holes are made to coincide and then when the sections of casing are forced together the round holes will come under the slots even though the joint does not come together exactly in the center of the sections because the length of the slots is so much greater than the diameter of the round holes. By using casing perforated before it is installed, the condition of the perforations is definitely known, and there is no possibility of having casing insufficiently perforated as frequently happens when the casing is perforated in the well.

Adaptability of California Method

Most irrigation wells in use at the present time were drilled by the California or stovepipe method. This situation is not entirely the result of the superiority of this method for drilling wells under all conditions, but is caused by the fact that over 80 percent of all irrigation wells in the United States are in California where conditions are favorable for the use of this method. Where relatively deep wells have to be drilled in unconsolidated material the California method has demonstrated its superiority by the large number of successful wells drilled by this method which are in operation in California and neighboring states. When the conditions such that shallow wells only can be obtained, other methods of drilling will be found to be more economical to use and just as satisfactory.
Sand-Pump and Orange-Peel Bucket Drilling Methods.

When the water-bearing formations are at a shallower depth and are not covered by a layer of consolidated material nor interspersed by layers of clay, boulders or rocks, drilling by means of some type of sand pump or orange-peel bucket is an effective means of putting down irrigation wells. When this method is used, an open pit is usually dug by hand or bored with an earth auger down to the water level or to sand in case it is encountered before the water table is reached. Some type of sectional casing is then installed and from then on the well is put down by removing the material from the hole by means of some type of sand bailer or an orange-peel bucket operated by a portable well-drilling rig, an engine-driven hoist and tripod or derrick or any other means available. Trucks, tractors, automobiles or teams of horses hitched to a wire cable or manila rope, which is run through the crown pulley on a tripod set over the well and attached to the bailer of sand bucket, have been used in place of the portable well-drilling rig or engine hoist to operate the equipment. In fact, many successful wells have been put down by these simple means.

As the excavation of the well proceeds the casing is forced down by levers, by weights placed in special boxes hung around the top of the casing or on a platform on top of the casing, by a powerful winch attached to deadmen on each side of the well or by hydraulic jacks although the last method is seldom used.

If a layer of clay is encountered in the water-bearing formation, it is usually possible to cut through it with the bailer or the orange-peel bucket but it is slow process. Under these circumstances
it is usually customary to bore through the layer of clay with an earth auger or to chop it up with a sharp cutting edge welded across the bottom of the bailer. The hole cut by these means is usually smaller than the diameter of the casing. This frequently stops the progress of the casing, and in order to proceed with the construction of the well it is necessary to set a new string of casing inside the first which will go through the hole cut in the clay.

The bailers used when drilling wells by this method are similar to those employed when removing drillings from wells drilled by means of standard tools except that they are usually shorter in length, because it is not necessary to bring up such a large load each time as in the case in deep wells where the time required to hoist the bailer is important. Both plain sand buckets and vacuum-or piston-type bailers are used depending on the preference of the driller. It is believed, however, that faster drilling would result if the piston type of bucket was more generally used. The ordinary sand buckets are operated on the drilling line of the rig and are churned up and down until the bucket is filled. Piston buckets are operated on the sand line or the drilling line, whichever most nearly meets the conditions as to the power required to hoist the bucket. The piston bucket is filled after being lowered to the bottom of the well by pulling up the piston as rapidly as possible without lifting the bucket off the bottom of the well. For best results the bucket should be drawn down while the piston is being pulled up. Three or four trips of the piston are usually required to fill
the bucket. Where sand is encountered above the water table, it is necessary to supply water as neither the common bailer nor the piston bucket will work in a dry hole.

The orange-peel bucket will operate equally well in dry or wet sand. It consists of four segments hinged on the top edge and arranged so that when the segments are pulled together they form a hemispherical bucket. Each segment of the bucket is similar in shape to a half a quadrant cut from the skin of an orange, hence the name. The orange-peel bucket is usually operated by two lines, one attached to the frame of the bucket and one to the mechanism which closes the bucket. When the bucket is lowered, the line to the closing mechanism is kept loose so that the bucket will stand open. When the bucket strikes the bottom of the well, the line on the former is released and the line to the closing mechanism is tightened by the hoist on the rig. This closes the bucket and causes the segments to bite into the sand, thereby filling the bucket. The bucket is then hoisted by the same line. To dump, the line to the frame of the bucket is tightened, and the line to the closing mechanism released. This permits the segments to open and drop their load of sand.

The orange-peel bucket can be operated by means of a single line attached to the closing mechanism, if necessary, as is the case when only a single drum hoist, a truck or similar equipment is available for operating the equipment. To do this, a short auxiliary line 4 feet long with a FOOT at one end is attached to the hoisting cable about 3 feet above the bucket. When lowering
the bucket the hook is attached to the frame; this takes the pull off of the closing mechanism and allows the bucket to open. When the bucket strikes the bottom of the well the auxiliary line slackens and unhooks. This permits the hoisting line to function, closing the bucket when the bucket is pulled up. To dump the bucket a short rod with a hook at one end, which is attached to the derrick, is hooked into the frame of the bucket. Then when the hoisting line is slacked off, the pull on the casing mechanism is released, and the bucket opens and drops its load of sand.

Some orange-peel buckets are equipped with a heavy ball weight which slides on a rod attached to the frame. When this type of bucket is used, the line ordinarily attached to the frame of the bucket is attached to the ball, and when the bucket is dropped into the well the ball will drive the points of the bucket into the sand by dropping down onto the frame when the line becomes slack. The ball or hammer type of orange-peel bucket is especially effective when digging in clay or hard sand.

The most common method of forcing the casing down is by loading a wood platform on top of the casing with the material excavated from the well. This method works satisfactorily, but it has the disadvantage that it is necessary to unload the platform each time a section of casing is added. An improvement on the method is to hang containers for the sand from the top of the casing. When it is necessary to add another section of casing the sand-filled containers are removed by attaching them to the hoisting line. When the section of casing has been added, the sand-filled containers are again hung on the casing. The containers should not be too large as they are too difficult to handle. Old oil drums make satisfactory containers. A
method, sometimes used when sinking large casings, is to dump the excavated material back into the casing on a floor built in the bottom of the casing. A hole just large enough for the bailer and is left in the floor, an auxiliary casing is set in this hole to keep out the material dumped back into the hole. As the depth of hole increases the depth and weight of material forcing the casing down increases. When the well is completed the material in the large casing is taken out with the bailer or a sand pump. This method has been found to be quite satisfactory for sinking these large casings in sand formations, but it cannot be used successfully if layers of clay or consolidated material are encountered because these materials cannot be excavated by this method.

Levers or pries are often used to force down the casing. These levers are made of a pair of beams from 16 to 24 feet long braced together so as to form a rigid unit with space enough between the beams to allow the casing to pass between them. One end of the lever is placed under the frame of the rig or attached to deadmen buried near the well as a fulcrum. The other end of the lever is loaded with sand or other material in a box at this point. The pull-down ears or pull-down head on the casing is attached to the lever by a pair of elbows or similar means at a point near the fulcrum. With this equipment it is possible to exert a force of several tons on the casing which is ample for most conditions.

Another method of forcing the casing down is to use a ratchet which has a very small drum operated by a long lever and ratchets. The winch is firmly anchored to deadmen buried near the well. The cables from the winch are run over pulleys attached to the pull-down head on top of the casing and then back to the frame of the winch. By turning the drum with the lever the cables are
Table 2

Recommended Minimum Well-Casing Thickness for Shallow Wells

<table>
<thead>
<tr>
<th>Depth of Well in Feet</th>
<th>Diameter of Well Casing in Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 10 12 14 16 18 20 24 26 30 36+ 42* 48*</td>
</tr>
<tr>
<td>20</td>
<td>16 16 16 16 16 16 14 14 12 10 16 16</td>
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<td>60</td>
<td>16 16 14 14 14 12 12 10 12 10 14</td>
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<td>70</td>
<td>16 14 14 14 12 12 10 10 12 10 14</td>
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<td>80</td>
<td>14 14 14 14 12 12 10 10 10 10 12</td>
</tr>
<tr>
<td>90</td>
<td>14 14 14 14 12 12 10 10 10 10 12</td>
</tr>
<tr>
<td>100</td>
<td>14 14 14 14 12 12 10 10 10 10 10</td>
</tr>
</tbody>
</table>

* Reinforcing bands of following sizes placed on outside of casing at top and bottom and also at joints on diameters greater than 30 inches: 1 x ⅛ inch on 8- and 10-inch wells, 1⅛ x 3/8 inch on 12- to 18-inch wells, 2 x 3/8 inch on 20-inch wells, 3 x 3/8 inch on 24- to 36-inch wells and 3 x ⅛ inch on 42- and 48-inch wells.
If the casing stops going down, it can usually be started again by allowing the hauler or avenger peel mandlet to fall into the well from the top of the derrick. The joint caused by the tennis equipment sinking the water surface is supposed to break the casing loose. If the casing gets caught on a rock the normal procedure is to shatter the rock with dynamite but before doing this it is necessary to understand the casing for enough so that it will not be injured by the explosion.
tightened and the casing is forced down. This is a simple method of forcing the casing down, but more time is required to set up the apparatus than is necessary when the other methods are used because pits have to be dug to bury the deadmen.

### Casing

Several different types of casing are used at the present time in wells put down by means of bailers or orange-peel buckets. Of these the riveted casing composed of rolled sheets of either black or galvanized iron is in most economic use. The vertical joints in the sections are lap riveted and the joints between the sections are either to lap riveted or butt riveted. This casing is made in sections from 2 to 6 feet and from 6 to 48 inches in diameter. The thickness of the material used depends on the depth of the well and the diameter of the casing. The gages recommended for various depths and diameters are given in table 2. Large casing of this type is usually reinforced by bands at the joints in addition to being made of heavier material. This type of casing is comparatively cheap, it is easy to install and may be purchased from local dealers. If the casing is galvanized it will last a long time in ordinary soils.

Another type of casing used in wells excavated in this manner consists of concrete rings which are made with tongue and groove joints or have vertical holes in them through which rods or cables are strung which hold the casing together. Tie-plates which extend across the joints and are bolted to the adjoining sections are sometimes used to hold the sections together. These rings are usually built on the ground, but they are sometimes cast in the well, section by section as the well is excavated.
This type of casing is generally used in the larger sizes of wells. The thickness of the walls of the rings is from 4 to 6 inches. Concrete casing can be used under most conditions where metal casing is satisfactory and in addition can be used where the soil or the water corrodes metal. Certain waters cause deposits to form on concrete, where this occurs metal casing gives better results than concrete casing.

Wood casing is sometimes used in the larger wells of this type. The casing is built in sections and consists of wood staves which are either held in shape by metal hoops or by circular frames built up of planks. Wood casing is usually made with the staves flatwise, but it is also made with the staves on edge. The latter method makes the stronger casing. Wood casing is not satisfactory where it is alternately wet and dry, and for this reason it should not be used above the low water line. Brick or concrete curbs should be used above the water line. They also provide additional weight for forcing the casing down.
Perforations

Shallow wells require a large area of perforations per unit length of strainer to let the water in because the depth of water in the well is small, and consequently only a short length of strainer can be used. In order to get the water through the strainer without an unduly large loss of head, a large area of perforations has to be provided. Metal casing is well adapted for getting a large area of perforations in a short length of strainer. The slots can be placed close together, and unless the sand is too fine the size of the perforations can be made large enough to permit the water to enter freely. Perforations in metal casing are made with various shapes, but the chisel type of perforation (see figure 25) is the most common. It consists of a slot cut through the casing from the inside by means of a chisel punch. This leaves the opening larger on the inside, and this fact helps to keep the holes from clogging with sand because each particle of sand that passes through the narrow outside portion of the slot will go on through because the width of the slot is greater on the inside. Chisel type perforations are made from 1/16 to 3/16 inch in width are usually about 1 inch long and are spaced from 3/4 to 1 1/2 inches apart.

The width of the perforations is determined by the depth of penetration of the punch. There are minor variations in the shapes of the perforations made by this method, but the essential features are the same. One type for which important advantages are claimed is made with a punch with round ends. Perforations made by this method have rounded ends which strengthen the casing at this point. These types of perforated casing are relatively cheap and
Another form of perforation of this type consists of raised strips, (see figure 27,) with the holes for the entrance of the water at the sides of the strips. These perforations are made by a punch which cuts the strips and then pushes them out the amount necessary to give the size of opening desired at the sides. Still another type of metal casing has the perforations in the form of horizontal louvres, (see figure 27,) having the opening on the bottom. It is claimed that sand does not enter the perforations in this casing readily because the opening is protected by the hood over it. This is the type of perforation used in heavy gauge casing. Still another form of perforation used in metal casing is the crowfoot type, (see figure 27,) except that the strips are cut in a pattern roughly resembling a crow’s foot. These various forms of perforations are usually made in flat sheets and afterwards rolled to form the casing.

A type of perforated casing sometimes used in fine materials is similar to a sand point except that it is much larger. It consists of a standard pipe or well casing which has been drilled full of 5/8 inch holes and then covered by a layer of 12 or 14 mesh brass screen. This brass screen is protected by a sheather of galvanized iron hardware cloth having a quarter inch mesh. This casing is expensive, but it is effective in keeping out fine sand. Special provision has to be made for installing this casing because it cannot stand driving without injuring the fine mesh screen. This strainer is usually set in a blank casing which has
previously been sunk to the desired depth in the water-bearing formation. The blank casing is then pulled, and the space between the casing and the strainer filled with suitable gravel. This type of casing is also used in wells put down by the hydraulic rotary method without the use of blank casing. This method is described later.

The perforations in concrete casing are in the form of slots cast in the rings by inserting wood or metal wedges which are subsequently knocked out. Figure 31 shows a patented concrete casing having vertical slots which are connected to passageways in the concrete. A much greater area of perforations is obtained by this method than is usually found in concrete casing. The latter form of concrete casing is used most extensively in city wells for domestic water supplies because the higher first cost of this casing is not such an important item in the entire cost of city water supply.

The perforations or openings in wood casing are made by laying the staves so that there are vertical spaces between them. These spaces are usually wider on the outside than on the inside but sometimes the edges of the staves are placed in such a manner that the slots are narrowest on the outside. The width of the slots can be varied to suit the size of the sand in the water-bearing formation but in doing this consideration should be given to the fact that the lumber will swell some in the water and this should be taken care of by making the slots a little wider, then when the wood swells the openings will not close.
Adaptable in the Sand-pump or Orange-peel bucket Method

Former using the Sand-pump or orange-
peel bucket method have in many instances
obtained successful wells. They should not however
attempt to put down wells by the method of layers
of claystone to be penetrated, under these conditions
an experienced well driller should be hired
to do the work.
Hydraulic Rotary Method

The hydraulic rotary method of drilling wells has been in use for many years in drilling test holes and wells for domestic water supplies. It has also been employed extensively in drilling oil wells, but until recently it was not used for drilling irrigation wells. The hydraulic rotary method is especially adapted to drilling irrigation wells up to 18 inches in diameter in unconsolidated materials by using a reamer, even larger wells can be put down by this method. It is an effective method where layers of clay are encountered which frequently cause considerable delay when using a bailer or an orange-peel bucket for putting down the well. The hydraulic rotary method is one of the fastest methods of drilling wells. Wells drilled by the hydraulic rotary process are put down by means of a rotating bit through which a mixture of clay and water is forced at high pressure. The bit is attached to a hollow drill stem through which the clay and water mixture is pumped. The material in the hole is loosened by the rotation of the bit and by the action of the high pressure jets from the bit, and the loosened material is carried to the surface by the mixture of clay and water as it flows upward. Some of the clay in the mixture deposits on the sides of the hole, and the rubbing of the drill stem on the deposit forms a clay lining which in sandy formations prevents the material from caving. No casing is ordinarily used while drilling the hole, the clay lining forming a wall sufficiently strong to keep the material from caving. Wells several hundred feet deep have been drilled by this method in unconsolidated formations without casing. The drill used in this method is known as the fishtail type. It has a
hollow shank and an orifice on each side for the jet. The bit is attached to a drill stem consisting of heavy pipe which is turned by means of a rotating table through which the drill stem can slide as the hole deepens. A swivel hose connection with pressure hose connects the drill stem with the double acting plunger pump which forces the mud into the drill stem. The rigs used for rotary hydraulic drilling are of several types, but all of them have a rotating table, a pair of double acting plunger pumps, a hoist and an engine. This is all the equipment some drillers use except a derrick built over the well. Most rigs, however, have standard drilling equipment in addition to the special attachments necessary for rotary drilling. This makes it possible to drill with standard tools or to use the rotary bit for percussion drilling in case a layer of hard material is encountered in the well. Duplicate pumps and swivel hose connections are usually provided so that there need be no delay caused by repairing one of the pumps or necessary nor by changing the hose connection when putting on another length of pipe on the drill.

After the mixture of water and clay with its load of drillings reaches the surface, it is run into a sump through a channel long enough to permit the sand and chips in the drillings to be deposited before they reach the sump. From the sump the mixture of clay and water is taken into the pump through a suction hose and again forced down the drill stem and out through the openings in the bit. From time to time more clay has to be added to the water to take care of the material lost in mudding up the sides of the hole. Water also has to be added from time to time.
It is claimed that there is danger when using the hydraulic rotary method, that the driller may pass a water-bearing formation without noticing it because after the water is sealed off by the deposit of clay there is no way of telling whether the formation contained water or not. There are, however, certain indications which guide the driller, and if he is experienced in water-well work he will know whether he is drilling through a water-bearing formation or not. In the first place, layers of sand below the water table usually contain water, and in the second place, the pressure on the mud pump usually drops when a water-bearing formation is encountered because in the mud mixture escapes more rapidly in a water-bearing formation than in an impervious layer. The escape of the water causes the pressure on the mud pump to drop, and as most pumps are equipped with pressure gages, the driller has a good indication that he is passing through a water-bearing formation. If the water in the formation is under considerable pressure, the change in pressure may be too small to be detected on the gage. For this reason best results are obtained by this method when the log of the formations and the location of the water-bearing strata in the area are known from previous tests.

When the hole is drilled to the depth desired, the drill is withdrawn and the casing with perforations opposite the water-bearing formations is lowered into the hole. The well should then be back-washed to remove the clay which has deposited on the wall of the hole and sealed the water-bearing layers. This is done by lowering the drill to the bottom of the well and then forcing clear water through the bit by means of the pressure pump. A collar, which just fits the casing, is attached to the drill stem just above the bit so that the water will be forced out of the
casing and against the mud wall of the well. Plunging the drill with the attached collar rapidly up and down in the casing opposite the area being washed is very effective in loosening the clay deposit. As soon as the clay is washed away in one portion of the well, the equipment is raised so that a new area will be exposed to the action of the water. In order to concentrate the flow of water from the pump in a limited area, two diaphragms or collars, one above and one below the jets, are sometimes used. By reducing the distance between the diaphragms, the area being washed at one time can be reduced to any desired limit. The clay washed off the wall of the hole mixes with the water pumped in and is carried to the surface on the outside of the casing. While the washing is in progress, screened gravel, usually pea size, is slowly shovelled into the space between the casing and the wall of the well to form a gravel screen to replace the clay washed out and to fill any cavities developed by the drilling process. As soon as possible after the washing process is completed, the well should be pumped in order to take out any clay remaining in the gravel or the surrounding sand before it has a chance to settle and seal the pores in the material surrounding this strainer.

There is some uncertainty as to whether it is possible to wash the clay out of the water-bearing strata after they have once been sealed by this method of drilling, and for this reason where the water-bearing formation is reached the hydraulic rotary process is often discontinued, and the hole is completed by sinking the strainer means by the use of a bailer. This eliminates the possibility of clogging the water-bearing formation with clay. Where the water-bearing material is fine, pea-gravel should be fed outside the strainer as the hole is deepened in order to
A well covering which is joined together by threaded couplings or welded joints is used also.
replace material pumped out and for the purpose of providing a gravel screen or envelope for the well.

Casing

The casing used in wells put down by the hydraulic rotary process varies in different parts of the United States. In some areas the California stovepipe or double casing is used. The sections of casing have to be welded or riveted together because the casing is set after the hole is completed. This casing is usually assembled in 20-foot sections at the factory, and these sections are joined together when they are lowered into the well. In other areas riveted sheet metal casing of only one thickness is used. This type of casing is made with telescope joints or butt joints and, like the stovepipe casing, is built in sections about 20 feet long at the factory. The sections are joined together when they are placed in the well. Heavy gage materials are used in making the casing for wells put down by this process. Light weight galvanized casing, such as used in shallow wells put down by means of bailers or orange-peel buckets, is seldom used. Sometimes one kind of casing is used above the water-bearing formation and another for the perforated portion in the zone from which the water is to be drawn.

When perforated casing is installed in wells put down by this process, the factory perforated type is generally used. The log of the well is known before the casing is set so there is no point in using casing that has to be perforated after it is in place. The type of perforation most often used in stovepipe casing consists of round holes and slots arranged in rows so that the line of holes which are put into the inside casing and slots which are punched in the outside casing will coincide when the inside and outside sections of casing are forced
Applicability of the Hydraulic-Rotary Method

The construction of intubation wells by the hydraulic-rotary process requires special machinery and familiarity on the part of the drillers. With this method in drilling, the method is most suitable for use by farmers. Because the skill required in getting an accurate log of the material passed through and in working the log from the well is considerable. It is important that great care be exercised in choosing a driller qualified to do the work.
together. Single thickness casing is made with chisel-punch,
horizontal-louver, crowfoot or other special shape perforations.
Well casing perforated with slots cut with an ordinary punch
made the hydraulic rotary method, are the same as those used in wells
put down by other methods in similar materials. In very
fine material special types of strainers must be used. The
strainer consisting of standard pipe or well casing bored full
of 5/8 inch holes and then wrapped with 12- or 14-mesh brass wire
screen and 1/4 inch-mesh hardware cloth has been used successfully.
Another strainer used under these conditions is made by wrapping
a trapezoidal-shaped brass band around a perforated pipe similar
to that just described. The width of the slots formed is
determined by the spacing of the bands. The width of the
slots is fixed permanently by punching lugs on the bands after
they are wound around the perforated pipe. The bands are
wound on the pipe so that the upper portion of the band is on the
outside. This makes the slots wider on the inside than on the
outside and helps to keep the sand particles from clogging the
perforations. This screen works very satisfactorily in fine
sand, but it is more expensive than the other types.

Test Hole Drilling

Test Hole Drilling

Sand Bucket Method

The purpose of drilling test holes before putting down irrigation
wells is to determine the location of the water table, the quality
of the water and the nature and location of the various formations
encountered in order that it may be possible to decide whether conditions are
favorable for obtaining a satisfactory irrigation well at the
point. The most common method of putting down test holes is by
means of a sand bucket or bailer. This is also the most satisfactory
method where conditions are favorable for its use. This method
is used most successfully in sandy formation, but in conjunction
with a soil auger it may be used also in testing...
formations which contain layers of clay. It cannot be used in consolidated materials or formations which contain boulders: by the use of this method accurate samples of the material encountered are obtained, and the location of the different strata are definitely determined. The method of putting down test holes with a bailer or sand bucket is the same as that used when drilling an irrigation well by this method except that the hole is smaller and that a smaller bailer is used. Standard pipe or light weight riveted pipe with screw joints is used in the test hole and is pulled and used over again as soon as the test is completed. Any well drilling rig with a hoist can be used for putting down a test hole with a bailer or sand bucket. in fact many of the test holes put down by this method are made by hand. All that is necessary is a tripod with pulley, a sand bucket and a rope. Two men can easily handle a 4-inch sand bucket such as is used for the work. The sand-bucket method of putting down test holes is very satisfactory both from the standpoint of cost and from the standpoint of accuracy of the results obtained. The use of this method is recommended where conditions are favorable and the necessary equipment is available.

Where consolidated materials or layers of boulders are known to exist in the underlying formations, a standard portable rig and drop tools are used for drilling test holes. In hard materials test holes are usually made either 4 or 6 inches in diameter. For holes of these diameters light tools having a 4- or a 6-inch drill bit are used, and a light rig is all that is required, although heavier equipment is frequently used because it is available. Drilling is done in the same manner
as previously described when using this method in putting down irrigation wells. The material in the hole is loosened by percussion of the drill bit, and it is then removed with a bailer or sand pump. This makes it possible to take accurate samples and to locate the different strata definitely. The test holes are capped with standard pipe or well casing is used in the test holes. Light weight casing such as riveted pipe cannot be used as it will not stand the driving necessary to force the casing down nor the wear of the tools against the casing while drilling. The standard tool method of Drilling test holes is rather slow and is quite expensive, but it is the only satisfactory method of drilling test holes in consolidated materials and in boulders.

Hydraulic Rotary Method

The hydraulic rotary method is often used for drilling test holes. It can only be used in drilling in unconsolidated materials, but under these conditions it is the fastest method there is for putting down test holes. Unfortunately the results obtained by this method are not so satisfactory as those obtained by the methods previously explained. Owing to the fact that clay is added to the water used in drilling it is difficult to determine whether the formations encountered contain clay, and furthermore, the fact that the drillings are carried to the surface continuously by the flow of the clay and water mixture makes it impossible to determine accurately the depth from which the drillings caught at the surface are coming. Approximate results can be obtained very cheaply by the hydraulic process, but many drillers do not consider the information obtained sufficiently accurate for determining the possibilities of an area for producing successful irrigation wells. Test holes drilled by this method are
usually small, a two-inch bit on a 1 1/4-inch pipe frequently being used. The hole drilled is slightly larger than the bit. A light weight hydraulic rotary rig is made for this type of work. It can be moved easily and requires much less power to operate it than the larger rigs. With a rig of this sort as much as a hundred feet of hole can easily be put down in a day. No casing is required, but the hole should be kept full of water or there is danger that the material will cave and cause the loss of the hole.

A method similar to the hydraulic rotary method is sometimes used for drilling test holes. It is known as the jetting method. The equipment used is operated by hand and consists of a jetting bit, drill pipe, a swivel-hose connection, a force pump and a derrick. The material is loosened by the force of the jet of water from the bit and is carried upward by the velocity of the water as it flows to the surface. The drill pipe is turned by hand with a pipe wrench to assist in the drilling and to keep the hole straight. Holes from 2 to 4 inches in diameter are usually put down. Casing, consisting of standard pipe, is driven down into the hole by a hand-operated drive weight as fast as the hole is jetted down. This method is very fast, but it has the same objection as the hydraulic rotary method as far as the accuracy of the results obtained is concerned. Also, it cannot be used in consolidated material or boulders, but by lifting it and dropping the drill pipe and bit, it is possible to drill through layers of hardpan or shale.
A method which is used in drilling domestic wells and in prospecting for coal and other minerals is sometimes used also for drilling test holes for water. It is known as the hydraulic, hollow-rod or self-cleaning method. The equipment necessary consists of a hollow-drill bit with valve, a drill pipe, a swivel-base connection and some means for lifting and dropping the drill pipe. The spudding mechanism on a standard portable rig is frequently used, but the cat-head on a hoist may be used by putting two or three turns of the hoisting line around it and lifting and dropping the drill by alternately tightening and loosening the rope on the cat-head. When the hollow-rod method is being used to drill a test hole, water is poured into the hole being drilled, instead of being forced through the drill pipe as is the case when the jetting process is used. The reciprocating motion of the drill forces the water and the drillings through the center of the drill and up the drill pipe. The valve in the drill bit prevents the water from running back once it has entered the drill pipe. Auxiliary valves in the drill pipe reduce the shock on the valve in the drill bit by supporting part of the water column. The drill pipe is turned slowly by hand by means of a wrench in order to make the drill bit strike in a different place each time it drops. Casing, consisting of standard pipe is used in unconsolidated materials for the purpose of keeping the wall of the well from caving and the water in the hole from seeping away. Drive clamps are attached to the drill pipe, and the casing is then driven in the same manner as that used when drilling with standard percussion tools. Both the drilling and the driving operations put a severe strain on the drill pipe, and for this reason heavy pipe with special couplings is used. When the hollow-rod or self-cleaning method is being used, the strokes of the drill must be carefully timed so that there will be...
more or less continuous upward movement of the water through the drill pipe. The hollow-rod method is an improvement over the jetting process and the hydraulic rotary process in that it can be used for drilling through hardpan and soft rock. Furthermore, the water bearing strata can be definitely located and the samples obtained are more satisfactory because the material removed from the hole comes up through the drill pipe where it cannot be contaminated.

Auger Method

A preliminary test of the possibilities of an area for supplying water from wells for irrigation is often desirable. If the water table is not too deep, the farmer can make the test himself by means of an auger and a long steel rod. A post-hole auger may be used for shallow holes. No casing is required. An old 1½-inch or 2-inch wood auger makes a more satisfactory auger for this work when deeper holes have to be bored. The lips of the auger should be filed off if they have not already been worn away, and the shank should be welded to a piece of 2½-inch pipe threaded for pipe couplings. A handle for turning the auger may be made from a tee and two 1½-inch lengths of pipe threaded on one end. Enough 4-foot sections of pipe with couplings should be provided to make a hole of sufficient depth to reach the water-bearing formation. Care should be exercised in boring the hole so as not to fill the auger too full before attempting to pull it or it may become fast in the hole. As the joints in the pipe are all screw couplings, it is not possible to back the auger out without the danger of unscrewing the pipe in the hole. If the auger becomes fast in the hole, an automobile jack set under a pipe wrench on the pipe will be found useful for loosening the auger. Sometimes the material encountered is so dry that it will not remain in the auger while it is being pulled. This situation may be corrected by pouring a small
Post-lake augers of the bucket type can be operated in wet sand and gravel. If the material is saturated, progress is slow because the sand and gravel wash the hole from the side.
amount of water into the hole from time to time. When the water-bearing formation is reached, the auger can no longer be used because it will not hold wet sand or gravel. Further testing of the formation should be done with the steel rod which is forced down into the sand and gravel until it reaches bed rock or strikes a boulder. The rod should be forced down several times to make sure that bed rock has actually been reached. If possible, several holes should be bored in the neighborhood to determine the extent of the water-bearing formation and to check the data obtained from the first hole. The results of these tests should not be taken as final; they show merely the depth to water and the thickness of the water-bearing formations. They do not show the nature of the material. If, from these tests, the conditions look favorable for obtaining an irrigation well in the area, a test hole should be put down by one of the methods previously described preferably with a sand bucket, in order to get samples of the water-bearing material.

Log of Test Holes.

When drilling test holes a careful record should be kept of the thickness and location of the various formations encountered and of the depth to water. In addition representative samples, weighing five or ten pounds should be taken of the water-bearing formations. Care should be taken to see that these samples are not contaminated by clay or other fine material from adjacent formations. Large samples should be taken so that there will be enough material to make a mechanical analysis of the sand and also a percolation test if necessary.
The samples should be placed in cloth bags, two or three, in jars for safe keeping and each sample should be labeled so as to show the location of the well and the depth of which the sample was taken.

From the thickness of the layer of gravel and the samples, the experienced well driller can make a fairly good estimate as to the possibility of obtaining a desirable well. Furthermore, if the well is in a territory with which he is familiar, the former should not attempt to pour on the samples himself. A sample of the sample will be of assistance to the derrick manufacturer in determining the size of perforation which should be used in the well.
The thickness of the layer is normally from 6 to 12 inches thick. Probably much quartz where the cooling passes through a bed of fine sand which has the control through the permeability in the cooling, and much less where the cooling passes through a larger layer.
Gravel-Envelope or Gravel-Screen Wells

The gravel envelope or gravel screen used in irrigation wells is an auxiliary strainer which has been developed in recent years for the purpose of keeping fine sand from coming into the well and of reducing the resistance to the flow of the water through the material surrounding the well. It also fills the cavities that occur. The gravel envelope consists of a layer of screened gravel from 6 to 12 inches in thickness which surrounds the casing.

There are two methods of making gravel envelope wells. In one method the gravel is placed around the casing after the hole for the well is completed. In the other method the gravel envelope is put in at the same time the well is being drilled. When the first method is used either a blank casing is sunk to the desired depth or a hole is put down by the hydraulic rotary process in which a clay lining is built up on the inside of the hole. After the hole is completed, the casing, with the perforations located so that they will come opposite the water-bearing formations, is lowered into the well. In wells with blank casing, gravel is then filled into the space between the blank casing and the perforated pipe. As the filling proceeds the blank casing is withdrawn. When a gravel envelope is used in connection with a well drilled by the hydraulic rotary process, the gravel is added after the perforated casing has been installed and while the clay deposit is being washed from the walls of the well. The gravel fills the space between the casing and the sides of the hole and keeps the wall of the well from caving when the clay lining has been washed off.

When the gravel envelope is put in at the same time the
well is being drilled, the usual practice in shallow wells is to excavate the well, down to the level of the water, somewhat larger in diameter than the casing which is to be used. The casing is set in this hole, and the space between the casing and the sides of the hole is then filled with gravel. As the sinking of the well proceeds some sand is pulled into the well through the perforations and under the bottom of the casing. This material is replaced by the gravel which works down as the casing sinks, and as the level of the gravel around the casing is lowered more gravel is added. Another method, which is used when drilling deep wells where the water table is at a considerable distance below the surface, is to drill several holes near the well at such an angle that they will intersect the bore of the well at about the water surface. Then as the drilling proceeds gravel is fed into these holes, and as the sand around the casing flows into the well it is replaced by gravel which comes down through the holes around the well. Either method of getting the gravel to the water level is satisfactory, although the first method is used most often.

Gravel envelopes are used on wells put down by means of a bailer or sand pump, on wells drilled with standard tools, and on wells drilled with a mud-scov or by the hydraulic rotary process. The amount of gravel required varies from a few yards to several hundred depending on the volume of the formations penetrated. In drilling through some fine sand formations a large amount of sand is carried into the well. When a gravel envelope is used, the material taken out is replaced by
gravel, and the danger of a cave-in which might cause the failure of
the well is avoided.

A gravel envelope provides a continuous passage for the water from
one water-bearing formation to another, and if it should happen that
the casing opposite one of these strata was not perforated, the water
from the formation would flow down through the gravel screen to the
perforated portion of the pipe at a lower point, or if the water in
the formation was at a higher pressure than the water in the well at
the level of the formation, the water would flow upward through the
gravel screen.

The use of excessive quantities of gravel may indicate that the cas-
ing is not being forced down rapidly enough thereby permitting a large
amount of sand and gravel to come into the well under the casing. If
this condition is permitted to continue some of the water bearing
formations may become distorted and even shut off completely by over-
lying beds of clay. For this reason the casing should be forced down
more rapidly when this condition exists.

The blank casing, sometimes put down in making gravel-envelope wells,
may be left in place if the water-bearing formations are fine or if
there is danger of caving. In the event the casing is left in the
well, it is perforated in place opposite the water-bearing formations.
The inner casing is perforated before it is put into the well. The
space between the inner and outer casing is then filled with screened
gravel. This method of construction is more expensive than when a
single string of perforated casing is used, but the use of this
method provides another safeguard against the danger of caving, the
possible failure of the well and injury to the pump.

In making gravel-screen wells the type of gravel used should be
given careful consideration. The principal purpose of the gravel
screen is to keep fine sand from coming into the well and to provide
an easy passage for the water as it approaches the strainer. If the
water-bearing material is coarse gravel, no great advantage will
probably result from the installation of a gravel screen because the
fine material will be washed out of the coarse gravel by
pumping, and the coarse gravel will be left which makes just as effective a screen as any which may be produced by adding gravel. Screened pea-gravel has been found to be most satisfactory for the conditions usually encountered. Mixtures of gravel of various sizes are unsatisfactory because the smaller particles fill the spaces between the larger particles and cut down the pore space. This increases the resistance to the passage of the water, and it is possible that a mixed-gravel screen in a well in fairly good gravel might cut down the capacity of the well rather than increase it. The greater the diameter of the gravel screen the more effective it is in keeping back fine sand because the velocity of the water through the sand decreases as the distance from the strainer increases on account of the greater area of the section through which it must pass. The velocity decreases at about the same rate as the diameter increases, and since the weight of particles which can be carried along by the current varies as the sixth power of the velocity; it is obvious that cutting the velocity in half will reduce materially the weight of the particles of sand which can be moved, actually they would weigh only one-sixth as much. It is evident, from the foregoing, that if the diameter of the sand screen were increased sufficiently, the velocity could be reduced to a point where it would no longer wash out the sand regardless how fine it was.
Development of wells

The purpose of developing wells is primarily to increase the yield, or in other words, to reduce the drawdown when pumping a definite quantity of water. This result is accomplished by washing the fine sand, silt and clay out of the water-bearing formation in the area immediately surrounding the strainer. The removal of these fine materials opens up the channels through which the water enters the well, and as a result reduces the resistance to the flow. Because of this fact the maximum yield of the well will be increased as well as the yield per foot of drawdown, and, incidentally, in doing this the flow of sand into the well is stopped or at least temporarily reduced.

The development of irrigation wells in many sections has not been given the attention which it should. The situation is partly due to the fact that both the farmer and the driller are anxious to get the well completed, and as a result this important part of the work is neglected or only indifferently done. The farmer and driller should both realize that in order to get the best well possible it is just as important to develop the well properly as it is to use the best methods in drilling it. The yield of a well per foot of drawdown has been more than doubled by thorough development, and although such a marked improvement cannot be obtained in every instance.

Bulletin 112, University of Arizona, "The Stovepipe or California Method of Well Drilling as Practiced in Arizona" by H. C. Schwalen, page 146.
Developing by Pumping

There are several methods of developing irrigation wells, each of which has its advantages and disadvantages. Of these methods, developing by pumping is the simplest. It is not as effective as some of the other methods, but it yields very satisfactory results. This process is sometimes known as "rawhiding" the well. The only equipment necessary to develop a well by this process is a pump, preferably a turbine with sufficient capacity to handle the estimated discharge from the well. The pump should be equipped with a regulating valve for controlling the discharge. If electrically driven, a valve is not necessary on engine-driven plants because the discharge of the pump can be controlled by throttling or accelerating the engine. The larger the pump is, the better.

A long suction line should be attached to the pump so that the pump will pick up from the bottom of the well, the sand carried in by the process of development. A new pump should not be used because the large quantity of sand which must be pumped would cause considerable wear and might seriously reduce the efficiency of the pump. The pump used to develop the well can also be used to test the well.

Before starting the developing process, the well should be pumped slowly at first and gradually at higher and higher rates. At each rate the pumping should be continued until no more sand comes. This procedure should be continued until the maximum capacity of the pump or well is reached. After pumping has started, the pump should not be shut down until this preliminary pumping is completed because there is danger that the sand may clog the well or lock the pump if the sand is not kept moving. The pump should not be
started at maximum capacity because there is a tendency for
the sand particles to bridge if the water from the formation
is drawn at too high a rate at the start.

After pumping has continued at the maximum rate until the
water begins to clear, the pump should be shut down until all
the water in the pump has drained back into the well, and until
the water table has come back approximately to normal. This
procedure builds up a head in the well and forces water out
through the perforations into the sand, thereby clearing the
perforations of sand particles and stirring up the material
around the strainer. As soon as the water level in the well
has built up the desired amount, the pump is

The time required to develop a well by this process varies
through wide limits. Sometimes only a few hours are required,
but usually at least a day is necessary. When no more sand
is brought in, the work is complete so far as this method
is concerned. If it is thought desirable to continue the
development of the well, some other method will have to be adopted.

Developing by Surging.

One of the most effective methods of developing wells is
by surging. There are several methods of doing this, but the
principle of the different methods is the same. The essential
feature is the rapid up and down movement of a plunger in the
well opposite the perforations in the strainer. Raising the
plunger draws water and fine materials into the well, and
lowering the plunger forces water out through the perforations and into the material surrounding the strainer. This reversal bridge of flow overcomes the tendency of the sand to and brings in much more fine material than when the flow is always toward the well. The action is more violent and consequently more effective than when the developing is done with a pump.

One of the most common methods of developing wells by surging is by means of a mud-scow. This method is well adapted to wells drilled by the California method because the rig and the mud-scow necessary for doing the work are available at the site when drilling of the well is completed. The mud-scow used for the surging should have sufficient clearance so that it will move freely in the strainer. A close fit is not required because the slippage caused by the clearance between the mud-scow and the strainer is small in proportion to the total volume of water moved. The mud-scow is attached to the drilling line and is given an up and down movement by the walking beam. A long stroke is used, and the speed is adjusted until there is no slack in the cable on the down stroke. The usual practice is to start surging at the top of the perforated portion of the casing and then to gradually work down by ++xxx out more cable. The sand, drawn in by the surging forces, accumulates in the bottom of the well and has to be bailed out from time to time. The driller can tell by the action of the mud-scow whether the hole is full of sand or not. In order to obtain the most effective results, the valve in the mud-scow should be kept closed. This is done by filling the mud-scow with gravel or by placing a stick between the valve and the bail of the mud-scow. A heavy mud-scow should be used so that it will force the water out of the well rapidly on the down stroke.
The mudcow is operated in this manner until no more sand comes into the well. Two or three days are usually required to develop a well by this method. Less time is ordinarily required to develop shallow wells than deep ones.

A sand pump or bailer can also be used for the purpose of developing wells. The bailer is loaded with sand to give it more weight; it is operated on the drilling line and is given the up and down movement by being attached to the spudding mechanism on the rig. If the rig does not have this equipment, the bailer can be run up and down by means of one of the hoists on the rig. This method, however, is not so satisfactory because the sand line hoist is usually too light and the drilling line hoist too slow to get the best results.

Another method of surging a well is to use a surge block. The surge block consists of a circular wood disc several inches in thickness which is attached to a metal stem for the purpose of guiding the plunger and giving it additional weight. The circular disc should not fit tightly in the casing because the block would not drop rapidly enough on the down stroke, nor would it be possible to raise the block fast enough on the upstroke with the power of an ordinary rig to obtain the best results. When a surge block is used to develop a well cased with light weight riveted pipe, there is danger that the surge block will tear the casing. In order to eliminate this danger, the disc should be wrapped with rubber belting or covered with an old truck tire. The surge block can be operated by the drilling line on a California or a standard rig. A long stroke should be used, and the speed should be adjusted so that the cable will not become too slack on the downstroke. Some drillers prefer surge
blocks equipped with valves so that there will be very little obstruction to the movement of the surge block on the downstroke. This permits faster spudding action and makes possible a faster suction stroke. The action of the surge block is similar to that of the mudscow. The usual practice is to begin at the top of the perforated section of the casing and to work down. The sand drawn in through the perforations accumulates on the bottom of the well and has to be bailed out from time to time. Wells put down by means of a bailer, mudscow or orange-peel bucket receive considerable development as a result of a similar action of these tools while the well is being drilled. The time required to develop a well with a surge block is about the same as that required when using a mudscow. When no more sand comes in, the surging should be discontinued. The well should then be pumped at the maximum rate for several days. This opens up the water-bearing formation in the area which cannot be reached by the surging process.
Developing with Air

Irrigation wells are sometimes developed by means of compressed air, when an air compressor is available and when conditions are favorable for the use of air. This method is best suited to wells of relatively small diameter in which there is a considerable depth of water in proportion to the total depth of the well. Compressed air is used either to pump the water from the well or to surge the water in the well. Sometimes a combination of the two methods is used. Either method requires an air compressor of ample capacity capable of developing a pressure of from 100 to 150 pounds per square inch and a motor or engine with sufficient power to operate the compressor. The power available should not be less than that necessary to pump the well at its maximum capacity. The use of compressed air, as a means of pumping a well to develop it, is limited to wells in which the depth of water exceeds 25 percent of the total depth of the well. When this method is used, an eduction pipe for discharging the water is lowered into the well to within two feet of the bottom. The air line is placed inside the eduction pipe and should extend to within one or two feet of the bottom of the eduction pipe. Sometimes the eduction pipe is dispensed, the well casing being used to discharge the water, but this practice is not recommended on account of the inefficient use of air under these circumstances. For irrigation wells of ordinary size, that is, having a capacity of not to exceed 1000 gallons per minute, a 6- or 8-inch eduction pipe and a 2-inch air line should be used. This is a simple air-lift installation, and the principle of operation is the same. The well is
pumped by turning air into the air line, and the rate of
pumping is varied by changing the rate at which the air is
turned into the line. Pumping should be intermittent in
order to permit the water to build up in the well to the
static level from time to time. If the compressor has a
pressure tank, it should be pumped up to capacity while
the water is rising in the well, and this large volume of
air should be released suddenly in the bottom of the well
through the air line. This large volume of air causes
the water in the well to rush upward through the eduction
pipe and the space between the eduction pipe and the casing.
The inertia of the column of water causes it to resist the
sudden movement and as a result some of the water is forced
out through the perforations and into the water-bearing
formation. The reversed flow of the water loosens more
fine material and when pumping is resumed this is washed
turning out. In order to obtain the best results when
the large volume of air into the well, the air line should
be lowered until it extends below the eduction pipe. If
the strainer in the well is long the eduction pipe and
air line should be raised, and the process repeated when sand
is no longer being brought in at the original position.

Developing wells with an air lift pump is very effective
where a large amount of sand is being brought in. There
are no moving parts in the pump so it cannot be injured
by the sand. If this process does not develop the well
sufficiently, the eduction pipe and air line should be
removed, and the well should be surged with a mud-scow or
surge block as previously explained. After the well has
been thoroughly surged the air equipment should be reinstalled,
and development should be continued by pumping until no more
An soon as the air starts to escape, the fire refuses to engage with us longer.
Another method of developing wells by means of air is known as backwashing. When this method is used, the water in the well is forced out through the perforations by means of the pressure of the air on the water. This process cannot be used unless the water in the well stands at a considerable height above the perforated portion of the casing. When this method is used, the top of the casing is sealed with an air-tight cap through which the air line extends. The air line is equipped with a three-way valve so that the pressure in the well can be released at any time. When air is turned into the air line, the water in the well is forced out through the strainer until the air begins to escape through the perforations. At this time the air should be shut off and the pressure in the well released by opening the three-way valve because there is danger of air logging the water-bearing formation if the air is allowed to escape through the perforations. A pressure gage on the air line is very desirable in order to know definitely when the pressure has built up high enough to force air through the perforations in the strainer. When the pressure is released, the water will flow back into the well through the perforations and bring in fine sand from the area surrounding the strainer. This process is repeated until no more sand is brought in. The cap is then removed and the accumulated sand bailed out. If a large amount of sand is coming into the well it should be removed before too great a depth has built up in the well. A large volume of air is lost each time the pressure is released. This loss can be eliminated to a large extent by putting an air-tight plug in the well at the water surface rather than by
capping the casing at the ground surface.

A continuation of the backwashing and pumping method of developing wells by means of air is more effective than either of the methods used separately. When the combination method is used, the eduction pipe is run through the air-tight cap on the well. The air line is inserted in the eduction pipe as before, and a separate air line with an air cock is run through the cap. The eduction pipe is carried into the well to a point a foot or two above the top of the strainer. When the well is being back washed, the water cannot be forced below the strainer with the possible danger of air logging the strata because the air will escape through the eduction pipe. The same effect could be obtained by installing a pressure gage and shutting off the air when the gage indicated that the water had been forced down to the top of the strainer. To develop the well the air cock is opened and air is turned into the air line in the eduction pipe. This pumps water out of the well and washes some of the fine material out of the water-bearing formation. The well is pumped in this manner until the water is forced below the strainer and the water allowed to return to its original level. The air cock is then closed, and air turned into the other line thereby building up the pressure in the well and forcing out the water through the perforations until the water drops to the level of the bottom of the eduction pipe.

When the air begins to escape through this pipe, this process is repeated several times, and then the air is turned into the eduction pipe again, and the well pumped until the water clears. The process of alternately pumping and back washing is then continued until no more sand comes into the well. Most of the sand that is washed into the well is carried out by the pump, but when the
developing is completed the well should be sounded, and, if there is any sand remaining in the well, it should be pumped out dry by lowering the ejection pipe to the top of the sand. When the developing process is completed, the well should be pumped at the maximum rate for several days to open up the pores in the area outside the influence of pumping or backwashing with air. Developing wells by this process is a rapid and fairly effective way to accomplish the desired results. In combination with the surging method, they are capable of developing a well to its full capacity.

**Developing with Dry Ice.**

Developing with dry ice has been tried with considerable success under some conditions but in general the cost is too great. Dry ice costs about 5 cents per pound, and as a large quantity of dry ice is required to develop a well, the cost of the ice alone is an important item. The process is similar to the backwashing method. The well is capped, and the dry ice is introduced through a valve in the cap. Fifty pounds is a suitable charge for an ordinary well. As soon as the dry ice hits the water, it begins to evaporate rapidly and build up the pressure in the well. This forces the water out through the perforations. The pressure is then released by opening the valve, and the water comes back into the well. If all the dry ice has not evaporated, the pressure can be built up again by closing the valve, if not, more dry ice will have to be added. The rate of evaporation of the dry ice depends on the size of the pieces, and the smaller they are the faster they evaporate. The best size to use for a particular well must be determined by trial. The evaporation of the dry ice should...
build up the pressure in the well rapidly so as to force the water out through the perforations at a high velocity, but should not evaporate so quickly that much of the gas is lost before the valve can be closed.
Testing of Wells

After the well has been developed and pumped at the maximum rate possible with the equipment available, long enough to establish equilibrium between the discharge and the drawdown, the well should be thoroughly tested in order to determine its characteristics. The choice of the type of pump and the determination of the economical yield of the well and the horsepower required to operate the plant will depend to a large extent on the results of the test. In the past, many farmers purchased pumping plants without having had their wells tested, and as a result some of the plants were later found to be unsatisfactory because the capacity of the well was not sufficient to supply the pump or the drawdown was so great that pumping was uneconomical. Many of these plants had to be replaced at a considerable financial loss to the farmer. In view of these facts, every well should be tested even though the characteristics of nearby wells are definitely lower because wells only a few hundred yards apart often differ widely in yield.

The information which should be obtained in a well test is the location of the static water level and the yield and depth to water when the well is being pumped at different rates. From these data the drawdown, the yield and the specific capacity, that is, the yield per foot of drawdown, can be computed. When testing deep wells in which the water-bearing formations are of great thickness or in which the water in the formations is under pressure, it is not necessary to pump the well at its maximum rate in order to determine the
characteristics of the well because the yield of the well is almost directly proportional to the drawdown, that is, if a drawdown of 5 feet yields 500 gallons per minute, a drawdown of 10 feet will yield approximately 1000 gallons per minute. This statement is not true in general, for shallow wells, and for this reason the test of these wells should preferably be carried on until the maximum capacity of the well is reached. If the well was developed by pumping, the equipment used for developing the well can be used for making the well tests. If other methods were used to develop the well, a pump will have to be installed to make the tests.

Before starting the test on a well, the depth to the static water level should be measured. The well should then be pumped at the maximum rate possible for a sufficient time for the drawdown and the discharge to become constant. When a condition of equilibrium is reached, the discharge of the pump should be measured and the depth to water noted. The difference between this depth and the depth to the static water level is the drawdown. The pumping rate should then be reduced until the drawdown is about 1/5 less than it was before. Pumping should be continued at this rate until the drawdown becomes constant when the discharge and the drawdown should be measured again. The discharge should then be reduced until the discharge is 2/5 less than the maximum drawdown. This process should be repeated until the elevation of the surface of the water in the well is back to its original value.

From these data a curve is plotted showing the relation between the drawdown and the discharge. Figure 4-
shows a typical discharge-drawdown curve for a deep well in an artesian formation and for a shallow well not flowing under pressure. The curve for the deep well is a straight line, whereas the curve for the shallow well bends upward. This means that the discharge per foot of drawdown from the deep well is constant, and that the discharge per foot of drawdown from the shallow well is constantly decreasing. It is evident from this fact that the higher the rate at which the shallow well is pumped the smaller will be the discharge per foot of drawdown. This fact is the reason why it is uneconomical to pump a well of this type at its maximum capacity. Under ordinary conditions it will be found most economical to pump shallow wells at a rate which does not make the drawdown exceed one half the depth of the water in the well. Deep wells usually are not drawn down to the same extent as shallow wells, but the limitation is not the reduction in discharge per foot of drawdown; it is the increase in the lift which restricts depth to which the well should be pumped.

The measurement of the discharge when testing a well should be carefully made. Either a weir, Parshall measuring flume, orifice plate or other suitable device may be used. The methods of making measurements with a weir or Parshall measuring flume are described in U.S.D.A. Farmers' Bulletin 1663, "Measuring Water in Irrigation Channels", by R. L. Parshall. Orifice plates which screw on the end of the discharge pipe of the pump provide one of the simplest means of measuring the discharge from a well. However, unless standard plates are used for which discharge tables have been prepared, each orifice
plate should be calibrate by comparing the measurements made with the orifice plate with those made by some standard measuring device.

Where the discharge from the pump is into a pipeline, the devices previously mentioned cannot be used. Under these circumstances the discharge measurement can be made by installing a thin orifice plate in the line or by timing the flow of color or salt through a known length of the pipe. The thin orifice plate differs from the orifice plate on the end of the discharge pipe in that it is a submerged flow orifice and requires the measurement of two heads to determine the discharge. It is important that these heads be measured at the same points that were used when the orifice was calibrated. When the color or salt velocity method is used to measure the discharge, the inside diameter of the pipe, the length and the time of transit of the salt or color must be accurately determined.

If there is any deposit or encrustation in the pipe, this method should not be used as it is impossible to determine the area of the pipe accurately. The reach of pipe used for measuring the velocity should not be less than 100 feet in length. Whichever method of measuring the yield from the well is used, it is desirable to make several determinations of each discharge in order to eliminate errors and minimize the effect of minor fluctuations in the flow.

The depth to water in shallow wells can be measured accurately without difficulty, but special equipment must generally be used to determine the location of the water surface in deep wells. A tape and weighted float is all that is necessary to measure the depth to water in a shallow
The tape is lowered until the float strikes the water. The reading of the tape at the ground surface, corrected for the distance from the end of the tape to the water line on the float, is the desired depth. This method cannot be used on deep wells because the length of tape required is so heavy that it is difficult to determine when the float hits the water, and usually there is not enough clearance between the pump bowls and the casing to let the float pass. Some deep wells are equipped with air lines of known lengths and pressure gages. The pressure in feet of water required to force all the water out of the air line subtracted from the length of the air line gives the depth to water. If the gage is calibrated in pounds, the gage reading can be converted into pressure in feet of water by multiplying the reading in pounds per square inch by 2.31. If the gage is calibrated in inches of mercury, the conversion can be made by multiplying by 1.13. The air line should extend about 10 feet below the limit of the drawdown, but it should not end within 5 feet of the suction inlet of the pump because of the disturbed flow near this point. Another method of measuring the depth to water in deep wells is to use an electric sounder. There are of several types, but the essential feature of all of them is the electric contact made when the sounder device strikes the water surface. One of the simplest and best of these devices consists of an insulated wire weighted at the lower end by a flexible lead sheath. The lower end of the wire is bare, but it is shielded from spray or from contact with the casing or the pump column by an insulated sleeve. The other end of the wire is attached
ringer to a telephone bell, or to a telephone head-set and battery. A lead is run from one of the terminals of the battery or bell ringer to the pump column or to the casing. Then when the bare end of the wire strikes the water surface, the circuit will be completed, and it will be possible to hear when the contact is made by the ringing of the bell when turning the crank or by the click in the head-set. The depth to water is determined by measuring the length of cable in the well. A two-wire cable with a small electric light bulb in the circuit operated by a storage battery also be used. This sounder contains a small float which rises and breaks the electric circuit when it sinks into the water. The light burns until the circuit is broken by the sounder sinking into the water. This device has the advantage that it is possible to tell instantly whether the circuit is in order by noting whether the light is burning.
Cost of Construction of Wells

The cost of constructing wells varies with the size and depth of the well, the method of drilling, the nature of the material encountered, the locality, the kind of casing used, the method of perforating the casing and the time spent in developing and testing the well. It is possible to assign limits to the cost of these various items, but the values given should be used merely as guides for making a preliminary estimate of the cost of a well, the actual cost will be determined by the contract made with the well driller for the particular well and the cost of casing at the time the well is being drilled. The following data on the cost of well drilling and well casing are based on prices prevailing in 1935 and cover only the states in the arid sections of the west.

California

In California most wells are drilled by the California or mud-scow method and are cased with double stovepipe casing. The hydraulic rotary method is used in some sections and in that case the stovepipe casing is built up into sections 20 to 30 feet long and installed after the well is drilled. The materials encountered in the California wells vary from fine sand to hard rock and the drilling price varies accordingly. The range of prices for drilling wells by the mud-scow method and the price of stovepipe casing and well rings in California are given in table 10. The lowest prices are for drilling in sandy formations where no difficulty is experienced in putting down wells and the highest prices are for drilling where beds of boulders are encountered or where the well is largely in hard rock. The prices for drilling are for a minimum depth of hole, ordinarily 100 feet. If the well is shallower than this a charge for
moving the rig to the site of the well is usually made. This charge should not exceed $50.00. There is frequently a maximum limit also to the depth to which the driller will go for the quoted price. This limit varies from 150 to 500 feet. If the well exceeds the maximum depth there is frequently an additional charge per foot which increases as the depth increases. The prices given include the cost of installing and perforating the casing but do not include the casing nor developing and testing the well. The cost of developing and testing wells varies between 20 and 50 dollars per day depending on the size of the equipment required. If the well is gravel packed the price does not include the gravel.

The quotations on casing are factory prices. In order to obtain the price delivered at the well, the freight from the nearest factory to the site should be added. Casing carries a high freight rate on account of its bulk and for this reason the farmer may find it economical to haul his casing from the factory if he has a truck. Built-up sections of stovepipe casing cost about 10 percent more than plain casing and 2-ply starter sections cost about 25 percent more than plain casing. Three-ply starters cost about twice as much as plain casing. Casing perforated at the factory costs 10 cents per foot additional for each inch of diameter for 10 gage casing, 5 cents additional for 12 gage and 2 cents additional for 14 and 16 gage. The quotations on well rings in table 3 are for welded rings of average weight. Forged rings are higher.
Irrigation wells in Oregon are mostly of the open-pit type, but there are also some drilled wells. The pit wells are from 5 to 8 feet square and are from 10 to 20 feet deep. These wells have wooden casing consisting of 2-inch lagging supported by wooden frames. The cost of digging these wells is about $1.00 per foot for each foot in width and the cost of the curb is from $2.00 to $4.00 per foot of depth depending on the size. Most drilled wells in Oregon are put down with percussion tools and are cased with standard casing. The depths vary from 50 to 400 feet but most irrigation wells are less than 150 feet deep. The average cost of drilling wells of this type is as follows: 6-inch, $1.75; 8-inch, $3.25; 10-inch, $4.75; 12-inch, $6.75; 14-inch, $9.00; and 16-inch, $11.50. The prices are for drilling only. The cost of standard well casing is given in table 4. The prices for drilling are for ordinary conditions, for drilling in rock or in boulders, the prices are about 50 percent higher.

Washington

Hand excavated, pit-type irrigation wells are used also in some sections in Washington. Some of these wells are 150 feet deep. The pits are usually 5 or 6 feet square and above the water table they are curbed with 3-inch planks set horizontally. Metal casing, 5 feet in diameter, perforated with round holes is sunk into the water-bearing formation. The cost of a well of this type including the wood curb and the metal casing is about $20.00 per foot. There are also many drilled wells used to supply water for irrigation. These wells are mostly of small diameter and are cased with standard well casing. The average cost of drilling these wells is about the same as
given for Oregon. The cost of developing, perforating and testing is $3.50 per hour.

Idaho

Most irrigation wells in Idaho are drilled with standard tools. The wells vary in diameter from 8 to 36 inches and from 30 to 150 feet in depth. Nearly all wells are cased but in some lava-rock formations no casing is necessary. Standard screw casing is used in the 8- and 10-inch wells, welded casing 3/16 inch thick is used in the 12- to 30-inch wells and 1/4-inch thick is used in the 36-inch wells. Two-ply stovepipe casing is sometimes used in 14- and 18-inch wells. Some of the casing is perforated before installing and some is perforated in place. About one-half the number of wells is gravel treated. The average cost of drilling wells is from $1.00 to $2.00 per foot for wells from 4 to 6 inches in diameter; from $1.50 to $2.50 for 8-inch wells; from $2.50 to $3.00 for 10-inch wells; and from $3.00 to $5.00 for 12-inch wells. The cost of drilling the larger wells is $6.00 for the 14-inch size; $7.00 for the 18-inch size; $8.00 for the 24-inch size; $9.00 for 30-inch size; and $10.00 for the 36-inch size. The cost of standard well casing is given in Table 4. The price for drilling includes the installation of the casing but does not include developing and testing. The prices are for wells not over 400 feet deep in ordinary valley fill. For additional depth between 400 and 800 feet the cost of drilling should be increased 25 percent. For drilling in hard lava the price per foot should be doubled. The cost of perforating the casing in place averages about $50.00 and the cost of development about $100.00. If a gravel envelope is used, the gravel will cost from $1.50 to $3.00 per cubic yard and from 10 to 100
cubic yards may be required. The quotations on welded casing and riveted casing at Boise are:

- 3/8 inch wall 3.20 per foot for 5/8 inch average
- 2.4 inches in diameter 4.20 per foot for 5/8 inch average
- 8.0 inches in diameter 6.00 per foot for 1/4 inch average
- 3/8 inches in diameter

Nevada

Irrigation by pumping from wells is not practiced extensively in Nevada, but there are some irrigation wells in the Truckee-Carson district and also in the southern part of the state. In the Truckee-Carson district gravel packed wells are being put down at the present time. These wells are 10 inches or more in diameter and are seldom more than 250 feet deep. They are cased with stovepipe casing which may be either perforated in place or before insertion. The hydraulic rotary method is used in drilling these wells. The wells in the southern part of the state are frequently under artesian pressure and vary in depth from 300 to 1000 feet. These wells are drilled with standard tools or with a combination of standard tools and hydraulic equipment. The diameter of these wells is 8 inches or less. Crew casing is used and it is perforated in place opposite the water bearing strata with a knife perforator. The cost of drilling the gravel packed wells including the cost of the casing varies between \$5.00 and \$10.00 per foot depending on the size of the well and the conditions encountered in the area. The wells in the artesian area are much cheaper to construct, the range of prices being from \$1.50 to \$2.00 per foot. The price does not include the cost of the casing which may be estimated from the prices given in table A.
Utah

The most common type of irrigation well in Utah is a hand excavated pit well having either a brick or a concrete curb. These wells are from 4 to 8 feet in diameter and are from 35 to 100 feet in depth. A 10- or 12-inch perforated casing is sunk in the bottom of some of these pits for the purpose of increasing the yield from the well. The cost of digging these pits cannot be determined very definitely because most of them are dug by the farmers themselves but it is estimated that the total cost of these large wells including the curb is about $2.50 per foot per foot of diameter. Some irrigation wells in Utah are drilled with standard tools. The prevailing price per foot for drilling wells is as follows: $1.25 for 4-inch wells, $2.00 to $3.00 for 6-inch wells, $3.00 for 8-inch wells and $4.00 for 10- and 12-inch wells. In silt formations the price for 4-inch wells may be as low as $.60 per foot and $2.75 per foot for 12-inch wells.

Arizona.

Irrigation by pumping has been practiced successfully in Arizona for many years. The original wells were of the shallow pit type and were excavated by hand, but at present most of the wells are being put down by the California or stovepipe method although standard tools are frequently used in combination with the California mudsow equipment. The diameters of wells used for irrigation purposes vary between 16 and 30 inches but most wells are between 15 and 20 inches in diameter. The depths vary between 150 and 350 feet. Double stovepipe casing which is perforated in place opposite the water-bearing formation is used in the wells. The wells
are not gravel packed. The cost of drilling wells in Arizona is given in table __. The prices given include perforating but do not include developing or testing. Developing with a mudscow costs $3.00 per hour. Two or three days are usually required to do the work properly. The price of casing and well rings or drive shoes at Phoenix, Arizona, is given in table 5.

New Mexico.

Although only a small area of New Mexico is irrigated by pumping from wells there is at present considerable interest in providing water for irrigation by this method. Most of the wells being drilled are of small diameter and are from 50 to 100 feet in depth. Galvanized iron casing is used in the wells. Some of the wells are constructed by digging a pit from 25 to 35 feet deep and then drilling a 12-inch hole to the desired depth. Other wells are constructed by drilling a 12-inch hole the entire depth. The cost of drilling the first type of wells is about $1.50 per foot. The other wells are slightly cheaper to construct, the average cost for drilling being about $1.25 per foot. Galvanized iron casing for these wells costs about $1.00 per foot.

Colorado, Kansas and Nebraska.

In Colorado, Kansas and Nebraska irrigation by pumping from wells is practiced for the purpose of providing a water supply for irrigating crops or for the purpose of supplementing the supply of water from natural sources or from other kinds of irrigation systems. Most of these wells are in gravel formations and are relatively shallow, very few of the wells being over 100 feet deep. Most of these wells are from
12 to 48 inches in diameter and are drilled by means of bailers or orange-peel buckets. Sometimes an earth auger is used to start the wells and to drill through beds of clay. Standard tools are used when beds of boulders or layers of rock are encountered. Some of the deeper wells in Kansas are drilled by the hydraulic rotary process. These wells are cased almost exclusively with galvanized iron casing which is made both plain and perforated. There are several types of perforations used, but the chisel-type slot is the most common. Most of these wells are gravel packed. Large wells from 6 to 10 feet in diameter are occasionally found. Most of these wells are excavated by hand but some of them are put down by special methods such as described on page [79]. These large wells are rarely more than 30 feet in depth but there is one 8-foot well in Nebraska that is 70 feet deep. Wood, brick or concrete casing is used in these large wells. The approximate cost of drilling wells from 6- to 48 inches in diameter in Colorado and the price of galvanized iron casing at Denver, Colorado are given in table 6.A115.

*Bulletin 415, Colorado Experiment Station, "Construction of Irrigation Wells in Colorado" by W.E. Code.

The drilling costs do not include the cost of developing or testing but do include the installation of the casing. Similar prices prevail in Kansas and Nebraska. The quotations on casing are for ordinary galvanized iron, the prices for rust-resistant steel casing are higher. The cost of excavating and casing large wells in Colorado is about $2.00 per foot, per foot of diameter. Pumping the water from the well while it is being dug is not included. Large wells excavated by the special
process previously referred to cost $2.50 per foot including the cost of the casing. This process is used principally in Nebraska. On account of the many uncertainties in connection with drilling wells by the hydraulic rotary method which is used in Kansas, drilling is usually contracted on a day basis.

Texas

Less than one percent of the land area of Texas is irrigated and of this area only about 10 percent is irrigated from wells. The water in many of the irrigation wells is under artesian pressure and some of them flowed originally, but the heavy draft on the water-bearing formations caused by irrigation has reduced the pressure in most areas until all the wells have to be pumped. The irrigation wells in Texas vary in depth between 100 and 2000 feet. Nearly all of the wells are of small diameter; the range being from 4 to 14 inches. The wells are put down by means of hydraulic rotary drills and standard tools, but the hydraulic rotary method is used most often. Most of the wells are cased throughout the entire depth with standard well casing, some, however, which are bored in rock are cased only partially. Special strainers are used where the water-bearing formations are very fine. The cost of drilling varies between $1.75 and $2.00 per foot depending on the diameter of the well, and the depth and the character of the material encountered. The price of well casing and standard pipe is given in tables 4 and 7.

Other Areas

Irrigation by pumping from wells is practiced to a limited extent in several other arid states but the areas irrigated are so small that it was not thought advisable to include cost data for these states.
SUMMARY

The principal items which should be given consideration before beginning the construction of a pumping plant for water for supplying irrigation are, the legal status of pumping for irrigation, the quantity of water required for the crops to be irrigated, the quality and quantity of water available from the underground source, the economic limit of pumping lift and the cost of pumping, the well contract, the preparation of the land for irrigation, the suitability of the climate and the soil for growing crops under irrigation, the accessibility of markets, and the facilities for financing the undertaking.

The source of supply for irrigation wells is the water that is stored in the soil in saturated strata of sand and gravel. The quantity of water that can be drawn from this underground source depends on the thickness and extent of the water-bearing formation, the character of the material in the formation, and the rate at which the supply of water in the formation is being replenished.

The rate at which groundwater moves in a water-bearing formation depends on the slope of the water table, the size and shape, uniformity and compactness of the particles of sand and gravel, and on the temperature of the water. The formulas which have been developed for determining the rate of flow have not proved satisfactory because of the difficulty in evaluating the effect of the different factors. The most satisfactory results are obtained when the rates of flow are determined by direct measurements.

The capacity of an irrigation well depends on the
radius of the well, and of the circle of influence, the
type of strainer, the drawdown and the depth and character
of the water-bearing formation. The theoretical relation
of these factors to the discharge has been determined and
expressed by a formula, but the observed capacities of wells
have not agreed very closely with those determined from
the theoretical formulas. This condition is probably
cau sed by the fact that the factors involved cannot be
determined accurately.

Although these formulas do not give satisfactory results
when used to compute the discharge from a well, they can
be used to determine the relative effect of the various
factors that influence the discharge. The formulas
show that increasing the diameter of a well does not increase
the discharge in the same proportion, that if the drawdown
was not too great, the discharge is proportional to the
drawdown and to the thickness of the water-bearing formation,
and that the discharge is proportional to the
transmission constant.

Batteries of wells should be used where the required
quantity of water cannot be obtained from a single well.

The mutual interference of wells in a battery reduces
the capacity of each well, but the interference is not
important if the wells are spaced from 50 to 100 feet apart.
Deep wells should be spaced at greater intervals because
of their greater cost.

Wells used for irrigation purposes are classified according
to their method of construction as driven wells, dug
wells, bored wells and drilled wells.

Driven wells are rarely used for providing water for
irrigation because of their capacity is limited to flows of
Batteries of driven wells may provide sufficient water for irrigation. These wells consist of drive points and screens which are attached to a pipe and then driven down into the water-bearing formation.

Dug wells are open pits usually circular and from 4 to 8 feet in diameter which are excavated by hand and cased with wood, brick, stone, concrete or metal curbs which frequently also act as the strainer. The yield of these wells depends largely on the depth they penetrate into the water-bearing formation; the better wells producing from 500 to 1500 gallons per minute. The most satisfactory results are generally obtained if the well is excavated to water by hand and then finished by sinking the well strainer with a bailer or orange-peel bucket. Farmers frequently attempt to put down this type of well themselves but often without success because they have difficulty in getting the casing down deep enough into the water-bearing formation.

Large open pits which are excavated with teams and scrapers or a dragline are also used as irrigation wells. This type of well is often unsatisfactory because the limit of drawdown is usually so small that not enough water is drawn into the well to supply the desired quantity. Wells yielding 1000 gallons per minute are rare.

Shallow wells in clay formations underlain with gravel are frequently bored down to the water-bearing formation with an earth auger. The strainer is then sunk into the gravel
by means of a sand bucket or bailer. The yield of wells put down in this manner depends on the water-bearing medium. These wells frequently produce from 500 to 1500 gallons per minute.

Wells sunk by means of percussion drills, rotating drills, water jets or combinations of these tools are known as drilled wells. The methods used in sinking wells by means of these tools are known as the standard method, the California or mud-scow method, the hydraulic rotary method, the sand-bucket and orange-peel bucket method, the jetting method and the hollow-rod or self-cleaning method.

The standard method of sinking wells is used principally in drilling in hard rock or boulder formations. The material in the hole is broken up by the percussion of a heavy drill which is raised and lowered at regular intervals by the drill rig. The drillings are removed from the hole by means of a sand bucket or bailer. Holes can be drilled to great depths by this method. The diameters of the wells vary from 6 to 24 inches, but smaller holes are sometimes put down for test purposes. Both standard and well casing and double stovepipe casing are used in these wells, and the casing is usually perforated in place. When the water-bearing formation is suitable, very good wells are obtained by this method. The capacities range from several hundred gallons per minute to several thousand.

The California or mud-scow method is similar to the standard method except that the solid tools and the bailer are replaced by the mud-scow which serves both purposes.
The method is best suited for drilling fairly deep wells in unconsolidated material. The diameters of the wells put down with mud scows range from 4 to 30 inches, but the usual diameters are from 16 to 20 inches. Most wells of this type are from 500 to 1000 feet deep but many of them are considerably deeper. These wells are cased with double stovepipe casing which is forced down by means of hydraulic jacks. The casing is usually perforated in place, but some perforated casing is used particularly in the shallower wells. The yield from these wells varies through wide limits. In good formations wells producing four or five thousand gallons per minute are sometimes obtained, but many wells do not produce more than 500 gallons per minute.

The sand-bucket or the orange-peel bucket method of drilling wells is frequently used when the water-bearing formations are at shallow depths in unconsolidated material free from layers of rock or beds of boulders. These wells are usually from 12 to 48 inches in diameter and are rarely more than 100 feet deep. The material is removed from the well by means of a sand bucket or orange-peel bucket which is operated by a portable well rig or a simple hoist. These wells are usually cased with lightweight riveted metal casing which is perforated before being placed in the well and is forced down by levers or weights. Concrete casing, in the form of pre-cast rings or a monolithic shell, is sometimes used. These wells ordinarily yield from 500 to 1000 gallons per minute although occasional wells have higher yields. If the yield falls below 500 gallons per minute, two or more wells are usually put down.

The hydraulic rotary process which utilizes a rotating bit for loosening the material in the well and a
stream of water heavily charged with clay for washing out the drillings and strengthening the walls of the hole, is especially adapted to drilling irrigation wells in unconsolidated material. This process is particularly effective in drilling through layers of clay which frequently retard the progress when other methods are used. Wells up to 18 inches in diameter and several hundred feet deep are easily put down by this method, and, if a reamer is used, a still larger hole can be drilled successfully. The wells drilled by the hydraulic rotary method are cased with double stovepipe casing which has been built up in sections or with well casing. Perforating is usually done before the casing is installed. The yield from these wells is similar to that from wells put down by the California method. It is sometimes claimed that the yield from water-bearing formations is permanently reduced by the deposit of clay from the jetting water when this method is used. The truth of this statement cannot be definitely established, but it is known that this is one of the fastest and cheapest methods for putting down irrigation wells.

Test holes should be put down for the purpose of deciding whether conditions are favorable for digging an irrigation well. Soil augers, sand buckets, standard tools, hydraulic rotary tools are all used in drilling test wells.

The auger, sand-bucket, standard tools and hydraulic rotary methods are used in the same manner as when drilling irrigation wells, the principal difference being that a smaller hole is put down. Each of these methods, except...
the hydraulic rotary process, will supply the material for an accurate well log.

The jetting process is not used for drilling irrigation wells but it is one of the fastest methods of drilling test holes in unconsolidated material and is especially effective in clay. The information obtained by the jetting process is not very reliable because the materials from the different formations are mixed together as they are carried to the surface by the stream of water used in the process.

The self-cleaning or hollow-rod method can be used in harder materials than the jetting process and it also supplies more accurate information about each formation because the materials from different strata are not mixed together while they are carried to the surface by the flow of the water in the drill stem.

Gravel envelopes or gravel screens should be used on wells in fine sand and silty gravel for the purpose of reducing the resistance to the flow of the water toward the well. Fairly coarse gravel of a uniform size should be used for the screens. If the water-bearing formation is coarse, it is doubtful if the yield of the well will be increased by a gravel screen.

After an irrigation well is completed, it should be developed by working out the fine particles in the water-bearing medium around the strainer. The washing is accomplished by pumping the well at different rates with a centrifugal pump, by a turbine pump, by agitating the water with a surge block or by mud-scows, surging or pumping with air or by a combination of these processes.
Every well should be tested in order to determine its capacity and to provide the information necessary to choose the proper size of pump and motor for the plant. The test should consist of the measurement of the discharge and the drawdown when pumping at several different rates. Pumping should continue at each rate until conditions become stable.

The cost of constructing irrigation wells depends on the diameter and depth of the well, the drilling process used, the nature of the material encountered in the well, the locality, the kind of casing, the length of casing requiring perforating and the time spent in developing and testing the well. Data on the average cost of putting down wells by the various methods are given, but they should be used only for estimating purposes because the exact cost of the well will be determined by the conditions existing at the time the contract is being made.
### Table 3

The range of prices for drilling wells in California by the California or mudscow method and the price of casing and well rings at the factory. *

<table>
<thead>
<tr>
<th>Diameter (inches)</th>
<th>Cost of drilling per foot (dollars)</th>
<th>Cost of double well casing per foot (dollars)</th>
</tr>
</thead>
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<td>0.65 to 1.50</td>
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<tr>
<td>8</td>
<td>0.75 to 2.00</td>
<td>1.02 to 1.22</td>
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<td>22</td>
<td>3.25 to 5.00</td>
<td>2.50 to 3.00</td>
</tr>
<tr>
<td>24</td>
<td>3.75 to 5.50</td>
<td>2.71 to 3.26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size (dollars)</th>
<th>Cost (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6x3/4</td>
<td>10.00</td>
</tr>
<tr>
<td>8x3/4</td>
<td>17.50</td>
</tr>
<tr>
<td>8x3/4</td>
<td>19.00</td>
</tr>
<tr>
<td>8x1</td>
<td>30.00</td>
</tr>
<tr>
<td>10x1</td>
<td>34.00</td>
</tr>
<tr>
<td>10x1</td>
<td>37.00</td>
</tr>
<tr>
<td>10x1 1/2</td>
<td>59.00</td>
</tr>
<tr>
<td>10x1 1/2</td>
<td>73.00</td>
</tr>
<tr>
<td>12x1</td>
<td>85.00</td>
</tr>
<tr>
<td>12x1</td>
<td>90.00</td>
</tr>
</tbody>
</table>

* Factories are located in all large towns in the area irrigated by pumping.

** The quotations and dimensions are for rings of average size, heavier or lighter rings would be correspondingly higher or lower in price.
Table 4. Approximate cost per foot of standard black well casing with couplings in less than carload lots in 1935 and pertinent data on weights and dimensions.

<table>
<thead>
<tr>
<th>Size*</th>
<th>Price** per Foot (1)</th>
<th>Weight*** per Foot (3)</th>
<th>Diameter (4)</th>
<th>Thickness (7)</th>
<th>Threads per inch (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inches</td>
<td>pounds</td>
<td>Outside (5)</td>
<td>Inside (6)</td>
<td>Outside (8)</td>
</tr>
<tr>
<td>3 3/4</td>
<td>0.385</td>
<td>5.65</td>
<td>4.00</td>
<td>3.732</td>
<td>0.134</td>
</tr>
<tr>
<td>4 3/4</td>
<td>0.525</td>
<td>8.00</td>
<td>5.00</td>
<td>4.696</td>
<td>5.521</td>
</tr>
<tr>
<td>5 5/8</td>
<td>0.660</td>
<td>10.50</td>
<td>6.00</td>
<td>5.672</td>
<td>6.664</td>
</tr>
<tr>
<td>6 5/8</td>
<td>0.782</td>
<td>13.00</td>
<td>7.00</td>
<td>6.652</td>
<td>7.692</td>
</tr>
<tr>
<td>7 5/8</td>
<td>0.920</td>
<td>16.00</td>
<td>8.00</td>
<td>7.628</td>
<td>8.788</td>
</tr>
<tr>
<td>8 5/8</td>
<td>1.14</td>
<td>19.00</td>
<td>9.00</td>
<td>8.608</td>
<td>9.788</td>
</tr>
<tr>
<td>9 5/8</td>
<td>1.42</td>
<td>22.75</td>
<td>10.00</td>
<td>9.582</td>
<td>10.911</td>
</tr>
<tr>
<td>10 5/8</td>
<td>1.67</td>
<td>26.75</td>
<td>11.00</td>
<td>10.552</td>
<td>11.911</td>
</tr>
<tr>
<td>11 5/8</td>
<td>1.97</td>
<td>31.50</td>
<td>12.00</td>
<td>11.514</td>
<td>12.911</td>
</tr>
<tr>
<td>12 1/2</td>
<td>2.35</td>
<td>36.50</td>
<td>13.00</td>
<td>12.462</td>
<td>14.025</td>
</tr>
<tr>
<td>13 1/2</td>
<td>2.81</td>
<td>42.00</td>
<td>14.00</td>
<td>13.448</td>
<td>15.139</td>
</tr>
<tr>
<td>14 1/2</td>
<td>3.26</td>
<td>47.50</td>
<td>15.00</td>
<td>14.418</td>
<td>16.263</td>
</tr>
<tr>
<td>15 1/2</td>
<td>3.75</td>
<td>52.50</td>
<td>16.00</td>
<td>15.396</td>
<td>17.283</td>
</tr>
</tbody>
</table>

* Inside diameter. Also frequently designated according to outside diameter as O.D. pipe.

** These prices apply to all the major cities in the West.

*** To obtain local price add freight from nearest warehouse to local freight station.

*** Weight includes couplings.
Table 5  The average cost of drilling wells by the California or mudscow method in Arizona and the price of stovepipe casing and well rings at Phoenix, Arizona.

<table>
<thead>
<tr>
<th>Diameter (inches)</th>
<th>Cost of drilling per foot*</th>
<th>Cost of double well casing per ft.</th>
<th>Well Rings**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>16 gage</td>
<td>14 gage</td>
</tr>
<tr>
<td>6</td>
<td>1.50</td>
<td>0.82</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>1.75</td>
<td>1.00</td>
<td>1.20</td>
</tr>
<tr>
<td>10</td>
<td>1.85</td>
<td>1.19</td>
<td>1.43</td>
</tr>
<tr>
<td>12</td>
<td>2.50</td>
<td>1.39</td>
<td>1.67</td>
</tr>
<tr>
<td>14</td>
<td>2.65</td>
<td>1.59</td>
<td>1.91</td>
</tr>
<tr>
<td>16</td>
<td>2.75</td>
<td>1.60</td>
<td>2.16</td>
</tr>
<tr>
<td>18</td>
<td>3.00</td>
<td>2.02</td>
<td>2.40</td>
</tr>
<tr>
<td>20</td>
<td>3.25</td>
<td>2.23</td>
<td>2.89</td>
</tr>
<tr>
<td>22</td>
<td>3.35</td>
<td>2.46</td>
<td>2.95</td>
</tr>
<tr>
<td>24</td>
<td>3.50</td>
<td>2.66</td>
<td>3.20</td>
</tr>
<tr>
<td>26</td>
<td>3.75</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

* Prices are for drilling wells under average conditions. The cost of perforating is included but the cost of developing is not.

**The quotations and dimensions are for rings of average size; heavier or lighter rings would be correspondingly higher or lower in price.
Table 6 — Approximate Cost per Foot of Well Drilling and Riveted Galvanized Steel Well Casing.

<table>
<thead>
<tr>
<th>Size (Inches)</th>
<th>Drilling Cost 16 gage</th>
<th></th>
<th>Drilling Cost 14 gage</th>
<th></th>
<th>Drilling Cost 12 gage</th>
<th></th>
<th>Drilling Cost 10 gage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6*</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.50</td>
<td>0.85</td>
<td>1.05</td>
<td>1.05</td>
<td>1.45</td>
<td>1.85</td>
<td>1.85</td>
<td>2.35</td>
</tr>
<tr>
<td>14</td>
<td>3.25</td>
<td>1.00</td>
<td>1.20</td>
<td>1.50</td>
<td>1.70</td>
<td>2.10</td>
<td>2.10</td>
<td>2.65</td>
</tr>
<tr>
<td>16</td>
<td>3.75</td>
<td>1.10</td>
<td>1.40</td>
<td>1.75</td>
<td>1.90</td>
<td>2.35</td>
<td>2.40</td>
<td>3.00</td>
</tr>
<tr>
<td>18</td>
<td>4.50</td>
<td>1.25</td>
<td>1.55</td>
<td>1.95</td>
<td>2.10</td>
<td>2.65</td>
<td>2.70</td>
<td>3.35</td>
</tr>
<tr>
<td>24</td>
<td>6.50</td>
<td>1.65</td>
<td>2.05</td>
<td>2.50</td>
<td>2.80</td>
<td>3.50</td>
<td>3.50</td>
<td>4.40</td>
</tr>
<tr>
<td>30</td>
<td>7.50</td>
<td>1.90</td>
<td>2.35</td>
<td>2.90</td>
<td>3.15</td>
<td>3.95</td>
<td>4.00</td>
<td>4.95</td>
</tr>
<tr>
<td>36</td>
<td>8.50</td>
<td>2.25</td>
<td>2.80</td>
<td>3.50</td>
<td>3.85</td>
<td>4.75</td>
<td>4.80</td>
<td>6.00</td>
</tr>
<tr>
<td>48</td>
<td>10.00</td>
<td>3.00</td>
<td>3.75</td>
<td>4.65</td>
<td>5.05</td>
<td>6.30</td>
<td>6.60</td>
<td>8.20</td>
</tr>
</tbody>
</table>

* Test hole. For more than one, a reduction in price is usually made.

Iron bands required at each joint and at top and bottom for values below heavy line. The approximate cost of these bands, welded and drilled is 10 cents per pound.
## Table 1. Approximate cost per foot of standard black pipe with couplings in less than carload lots in 1935 and pertinent data on weights and dimensions.

<table>
<thead>
<tr>
<th>Size* (inches)</th>
<th>Price** (per Foot)</th>
<th>Weight*** (per Foot)</th>
<th>Diameter</th>
<th>Thickness</th>
<th>Threads per Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outside Pipe</td>
<td>Inside Pipe</td>
<td>Outside Coupling</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>10.889</td>
<td>4.500</td>
<td>4.026</td>
<td>5.091</td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>14.610</td>
<td>5.563</td>
<td>5.047</td>
<td>6.296</td>
</tr>
<tr>
<td>6</td>
<td>1.05</td>
<td>19.185</td>
<td>6.625</td>
<td>6.065</td>
<td>7.358</td>
</tr>
<tr>
<td>7</td>
<td>1.34</td>
<td>23.769</td>
<td>7.625</td>
<td>7.023</td>
<td>8.358</td>
</tr>
<tr>
<td>8</td>
<td>1.46</td>
<td>25.000</td>
<td>8.625</td>
<td>8.071</td>
<td>9.420</td>
</tr>
<tr>
<td>9</td>
<td>2.00</td>
<td>34.188</td>
<td>9.625</td>
<td>8.941</td>
<td>10.420</td>
</tr>
<tr>
<td>10</td>
<td>1.88</td>
<td>32.000</td>
<td>10.750</td>
<td>10.192</td>
<td>11.721</td>
</tr>
<tr>
<td>11</td>
<td>2.75</td>
<td>46.247</td>
<td>11.750</td>
<td>11.000</td>
<td>12.721</td>
</tr>
<tr>
<td>12</td>
<td>2.70</td>
<td>45.000</td>
<td>12.750</td>
<td>12.090</td>
<td>12.958</td>
</tr>
</tbody>
</table>

*Normal inside diameter

These prices apply to all the major cities in the West.

**To obtain local price add freight from nearest warehouse to local freight station.

***Weight includes couplings.
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