the water applied in irrigation passes downward past the root zones and, like the seepage from the canals and reservoirs, joins the same groundwater body to become return flow farther down the valley.

Cities and towns also divert the waters necessary for the domestic, commercial and industrial users served by the municipalities. In most cases these waters are transmitted to the localities of use by closed pipelines from which there is practically no loss. However, after usage within the city or town, the unconsumed water is returned to the adjacent stream at some point below the municipality.

The total quantity of water diverted from a stream at the headworks of any canal or reservoir intake is commonly referred to as "gross diversion." From the preceding discussion, it is clear that there is a vast difference between "gross diversions" within the South Platte Valley and the "consumptive use" of water by crops, vegetation, commercial, industrial, animal and human uses to which it is applied.

Each year since its formation in 1937, the Northern Colorado Water Conservancy District has obtained the officially measured stream flows and diversions from the records of the State Engineer and the Water Commissioners of the seven administrative districts comprising the Conservancy District portion of the South Platte Valley. Analyses of the records by the District staff and by J. M. Dille, District Consultant, reveal a number of interesting facts concerning the efficiency of water supply usage within the Conservancy District area.

First, taking the South Platte River from Kersey upstream to Ft. Lupton, together with the principal tributary valleys of the Poudre, Big Thompson, St. Vrain and Boulder Creek, the stream flow records show that this upper, fan-shaped area of the South Platte Valley received a water supply averaging 820,000 acre-feet per year during the 20-year period from 1939 to 1958. Over the same period of record irrigation canals, reservoirs, town and city systems annually diverted an average of 756,500 acre-feet. Ignoring the municipal diversions, since they amount to less than 3% of the
total, the "gross diversions" from the upper South Platte amount to less than 1.6 acre-feet per year for each of the 485,000 acres of irrigated land within that area.

The inflow of water supply and the gross diversions are compared in the following tabulation.

<table>
<thead>
<tr>
<th>Upper So. Platte Valley Area</th>
<th>A.F. Inflow at Head of Area</th>
<th>A.F. of Gross Diversion</th>
<th>Acres Irrigated</th>
<th>Gross Diversion A. F./Acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poudre Valley</td>
<td>273,235</td>
<td>323,470</td>
<td>216,630</td>
<td>1.49</td>
</tr>
<tr>
<td>Big Thompson</td>
<td>119,616</td>
<td>137,225</td>
<td>92,315</td>
<td>1.49</td>
</tr>
<tr>
<td>St. Vrain</td>
<td>89,716</td>
<td>81,360</td>
<td>80,960</td>
<td>1.05</td>
</tr>
<tr>
<td>Boulder Creek</td>
<td>62,822</td>
<td>51,660</td>
<td>17,960</td>
<td>1.15</td>
</tr>
<tr>
<td>So. Platte - Ft. Lupton</td>
<td>271,192</td>
<td>156,130</td>
<td>18,100</td>
<td>3.24</td>
</tr>
<tr>
<td>To Kersey</td>
<td></td>
<td></td>
<td>185,095</td>
<td>1.56</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>819,580</td>
<td>758,155</td>
<td>185,095</td>
<td></td>
</tr>
</tbody>
</table>

Thus, the upper area of the South Platte diverts for application to all purposes an average of more than 92% of the water supply entering the area. If the total water diverted were wholly consumed in its application to various uses, the stream measuring station at Kersey would record nothing more than the difference between the average inflows of 320,000 acre-feet and the diversions of 756,000 acre-feet, or 64,000 acre-feet. However, the Kersey gage shows a 1939-1958 average annual stream flow of 509,000 acre-feet. Obviously, all but the 64,000 acre-feet or an average of 645,000 acre-feet represents the return flow to the South Platte of the unconsumed waters which are diverted and put to beneficial use upstream.

A similar pattern is repeated in the Morgan County portion of the Valley between the gaging stations at Kersey and Belzoe. From the 20 year average stream flow of 509,000 acre-feet measured at Kersey, there were 122,500 acre-feet annually diverted from the stream and applied to use in Morgan County on an irrigated area of 130,000
acres. Hence, the gross diversions amount to 3.25 acre-feet per acre of irrigated land. In applying these diversions to use, the area between Kersey and Balzac diverts 83% of the water supply which passes the Kersey gage. Therefore, if the diversions were consumed, the remaining flow at Balzac would only amount to 86,400 acre-feet annually. Actually, however, the average flow of the South Platte at Balzac, corrected for reservoir diversions immediately above the gage, amounts to 390,000 acre-feet per year. Again, this means that return of unconsumed water from the area of use in Morgan County accounts for all of the Balzac flow except the 86,400 acre-feet undiverted within that area. Thus, the return flow to the river between the Kersey and Balzac measuring stations averages 303,600 acre-feet annually.

Another repetition of the use pattern again occurs in the lower valley area between Balzac and the Nebraska line near Julesburg. As in the upper river sections, the Logan and Sedgwick County areas of the Valley received, as available inflow, the water measured at Balzac gaging station plus the diversions to North Sterling and Fort Pratt Reservoirs which are taken from the river above the gage. As already noted, the 1939-1958 average of these inflows amounted to 390,000 acre-feet. Over the same period of record, gross diversions to the lands of the lower valley area averaged 338,500 acre-feet or 87% of the inflow received. Diverted waters are applied to 105,000 acres of irrigated land, or an application of 3.22 acre-feet per acre annually. Again, if all the diverted water were consumed, only the difference between average inflows of 390,000 acre-feet and diversions of 338,500 acre-feet would be measurable at Julesburg. The 20-year average flow at the Julesburg gage, however, amounted to 319,000 acre-feet per year. Thus, in addition to 51,500 acre-feet undiverted from the inflows, another 267,500 acre-feet appears at the gage as return flow from the use areas upstream.

In summary, the gross diversions to all canals, reservoirs and municipal systems in the Conservancy District portion of the South Platte Valley amount to more than
1,500,000 acre-feet per year. In addition, there are some 6,000 to 7,000 irrigation wells within the same area which withdraw, "divert" or at least make use of waters from the same underground body of return flows as they move back toward the stream beds. Although the records are incomplete, the entities which supply electric energy for pumping purposes have estimated that at least 500,000 acre-feet are annually pumped for irrigation of lands in Weld, Morgan, Logan and Sedgwick County portions of the South Platte Valley. In effect, then, the water users of the area are, by one method or another, diverting and applying to beneficial use an average of slightly more than 2,000,000 acre-feet per year by the use and re-use of an original inflow of only 850,000 acre-feet.

It is most fortunate, of course, that the physical make-up of the South Platte basin is such that the inflow of water supply can be utilized 2.5 times within the State of Colorado and further, in fulfillment of an interstate compact obligation, pass on to Nebraska a quantity of water which is nearly 40% of the annual inflow itself.
Quantitative ground-water management.

(1) Two new laws relating to ground-water. Extracts.

(2) Many people affected. We now face the task of carrying out these mandates, and we will need means of quantitatively assessing the effects of ground-water movements.

(3) It is the purpose of this presentation to describe methods and procedures to accomplish these assessments. Idealizing to be used. Basis of development. Need for tests. Daum's comment. Reason for confusion.

Surface water methods inadequate. Flow measurement, point of diversion, ground-water reservoir, Water quantities, Aquifer properties, Tables, Charts.

(4) Well interference

\[ y = \frac{Q}{2\pi K D} \int_{0}^{r} \frac{e^{-u^2/4D}}{u} \, du \]

(5) Case of a well near a stream. Drawdown. Table in monograph 31.

Example.

(6) Stream depletion due to a well. - Charts. Rate & volume basis.

\[ \frac{Q}{Q_0} = 1 - \frac{2}{\pi} \int_{0}^{x_1} e^{-u^2/4D} \, du = 1 - E\left(\frac{x_1}{14Dt}\right) \]

Example. Curves for wells at various distances.

(7) Pattern of stream depletion. Effect of a barrier

Geologic maps

(8) Pumping since 1930.

Uniform distribution idealization.

Maasland's concept.

Chart. Evaluation for South Platte.

(9) Seasonal variation - Charts.

Application to South Platte.

(10) Check - Summary.
Summary.

(a) We can assess the effects of ground-water movements quantitatively.

(b) The assessment can be based upon tables and charts.

(c) Either quick approximations or detailed assessments can be made.

(d) The accuracy can be comparable to what is accepted for surface water.

(e) Need for tests.
1. Section through a pumped well - notation
2. Page from W.S.P. 1378 - Aquifer constants
3. Table for computing drawdowns due to a well
4. Probability integral table
5. Stream depletion - rate basis
6. Stream depletion - volume basis
7. Distribution of depletion
8. Depletion vs distance from stream
9. Depletion - effect of a barrier
10. Geologic map - Denver to Greeley
11. Geologic map - Greeley area
12. Geologic map - Ft. Morgan area
13. Geologic map - Sterling area
14. Maasland's idealization
15. Depletion due to pumping since 1930
16. Seasonal depletion - Amplitude chart
17. Seasonal depletion - Lag chart
18. Mesilla Valley
19. Patrick Hurley's correlation
20. Check of pump formula
21. Part remaining curves
22. Section across the South Platte area
23. Part remaining curves
(1) The following figures for power consumption by pumps in the South Platte Valley are obtained from Code's Bulletin 500-s on Water table fluctuations.

<table>
<thead>
<tr>
<th>Year</th>
<th>$10^6$ KWH</th>
<th>Year</th>
<th>$10^6$ KWH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930</td>
<td>1.70</td>
<td>1951</td>
<td>35.6</td>
</tr>
<tr>
<td>1</td>
<td>2.10</td>
<td>2</td>
<td>50.9</td>
</tr>
<tr>
<td>2</td>
<td>2.10</td>
<td>3</td>
<td>52.2</td>
</tr>
<tr>
<td>3</td>
<td>1.73</td>
<td>4</td>
<td>85.4</td>
</tr>
<tr>
<td>4</td>
<td>3.81</td>
<td>5</td>
<td>79.0</td>
</tr>
<tr>
<td>5</td>
<td>3.56</td>
<td>6</td>
<td>96.90</td>
</tr>
<tr>
<td>6</td>
<td>5.65</td>
<td>1957</td>
<td>47.40</td>
</tr>
<tr>
<td>7</td>
<td>7.82</td>
<td>1958</td>
<td>48.98</td>
</tr>
<tr>
<td>8</td>
<td>5.21</td>
<td>59</td>
<td>67.77</td>
</tr>
<tr>
<td>9</td>
<td>11.60</td>
<td>1960</td>
<td>83.71</td>
</tr>
<tr>
<td>1940</td>
<td>15.20</td>
<td>61</td>
<td>57.67</td>
</tr>
<tr>
<td>1</td>
<td>10.50</td>
<td>62</td>
<td>73.62</td>
</tr>
<tr>
<td>2</td>
<td>7.65</td>
<td>63</td>
<td>108.20</td>
</tr>
<tr>
<td>3</td>
<td>12.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>16.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>14.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>25.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>18.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>28.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>23.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td>39.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With the aquifer properties $K = 0.00384$ ft/sec, $D = 66.6$ ft, $V = 0.171$, $\alpha = 1.50$ ft/sec, $KD = 0.255$ ft²/sec. Estimate the depletion of flow in the South Platte river at the end of the year 1963 on the basis that the pumps are at an average distance of one mile from the river, 71 percent are electrically driven, 30 percent are along the main stream, 50 percent of the water pumped returns to the water table and that 100 Kilowatt hours (KWH) are required to pump one acre foot of water.
Problem 1

Well being pumped at the rate of 140 ft³/sec
\[ \alpha = 1.55 \text{ ft}^2 \text{ sec} \quad K_0 = 0.270 \text{ ft}^2 \text{ sec} \quad V = 0.174 \text{ ft} \]

Complete drawdown at a distance of 2640 ft (2 mile) after the well has been pumped for 3 months.

Solution

3 months is \( 2628000 \) \( \text{sec} \) = \( 7884000 \) \( \text{sec} \).

\[ \frac{144t}{V} = V \quad (44052) (7884) (70)^2 = 6991 \]

\[ \frac{1}{44t} = \frac{2640}{6991} = 0.378 \quad K_0 = 6.20 \]

\[ \frac{Q}{24t} = \frac{140}{(0.270)(0.270)} = 0.8253 \]

From table, \( R \left( \frac{144t}{V} \right) = 0.75322 \)

Then

\[ Y = (0.8253)(0.75322) = 0.622 \text{ feet} \]

\[ (0.8253)(1.03612) = 0.855 \text{ ft}^3 \text{ for 6 months} \]

Problem 2

Suppose an above well is 1 mile from a river. How much depletion will it cause after it has been pumped 6 months?

Solution

\[ \frac{Q}{Q_0} = 1 - \frac{2}{144} \int_0^t e^{-u^2} du = 1 - \Phi \left( \frac{\sqrt{t}}{144t} \right) \]

\[ 144t = V(44052)(7884) = 9887. \text{ Since} \]

6 months is \( 15768000 \) \( \text{sec} \).

Then

\[ \frac{Q}{Q_0} = 1 - 0.54987 = 0.45013 \] (From chart about 0.45)

Then the amount of stream depletion is

\[ Q = (140)(0.45013) = 0.630 \text{ ft}^3 \text{ per sec} \]
Problem 3.

Some well at A. 2.
Estimate total depletion for the 6 months period.
From the Volume bases chart.

\[
\frac{\Delta V}{\Delta t} = 0.534 \quad \text{feet}^3/\text{yr}
\]

\[
\frac{\Delta V}{\Delta t} = 0.25
\]

The total depletion is

\[
(1.4) (15,768,000) = 506,700 \text{ acre-feet}
\]

Check \((1.4)(60)(6) = 506,700 \text{ acre-feet} \approx \text{early estimate.}

Then the total stream depletion would have been

\[
(506,700)(0.25) = 126,700 \text{ acre-feet}
\]

---

Problem 4.

Strategy:
Estimate the depletion of the South Platte between Denver and the state line due to all of the pumping which has been done since pumping began in 1930.
Assume the valley is 4 miles wide with the stream in the center. Data on pumping comes from recent electrical plans. Consumers.

Distance

\[
K = 0.00384 \quad \text{miles} \quad v = 66.6 \quad \text{feet} \quad K_0 = 0.255 \quad \text{feet}^2/\text{yr}
\]

\[
K = \frac{K_0}{v} = 150 \quad \text{feet}^2/\text{yr}
\]

Distance

\[
L = 21120 \text{ ft} \quad (4 \text{ miles})
\]

71 percent of pumps are electrically driven.
50 percent are doing the main stream.
100,000 is a sufficient base to store 1 acre-foot.
One-third of water pumped is consumed.

Solution:

From Meklelands chart

1 year is 3,536,000 seconds = 1

\[
\frac{\Delta V}{\Delta t} = \frac{(160)(3,536,000)}{21120} = \frac{47304000}{4446054400} = 0.1060
\]

\[
\Delta V = \frac{L^2}{2} = \frac{21120^2}{2} = 2243760
\]

<table>
<thead>
<tr>
<th>Year</th>
<th>( \Delta V )</th>
<th>( L^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000</td>
<td>21120</td>
</tr>
<tr>
<td>1</td>
<td>0.0160</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td>0.0329</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>0.0514</td>
<td>0.96</td>
</tr>
<tr>
<td>4</td>
<td>0.0694</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>0.0830</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Construction of chart.

Depletion to end of 1963.
Estimated at 4149,000.
Example 5

Estimate the seasonal variation of pump depletion of the Platte of the South Platte.

Solution

Since the chart represents the fluctuation of the nearest available data as a matter of judgment, the average of the last four years preceding 1963 is used.

<table>
<thead>
<tr>
<th>Year</th>
<th>$10^6$ KWH</th>
<th>Average</th>
<th>Equivalent Rate of 4/5 is Consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>83.71</td>
<td>$rac{323.20}{4}$</td>
<td>$(80.8 \times 10^6)$ KWH/yr</td>
</tr>
<tr>
<td>61</td>
<td>57.67</td>
<td>$(80.8 \times 10^6) \times 0.80$</td>
<td>$\frac{646.4 \times 10^6}{164212} = 4196.6$</td>
</tr>
<tr>
<td>62</td>
<td>75.62</td>
<td>$(80.8 \times 10^6) \times 0.71$</td>
<td>$(728 \times 0.71 \times 3) = 4196.6$</td>
</tr>
<tr>
<td>63</td>
<td>108.20</td>
<td>$\frac{323.20}{4}$</td>
<td>$\frac{4196.6}{21120} = 0.651$</td>
</tr>
<tr>
<td>Total</td>
<td>323.20</td>
<td>$\frac{323.20}{4}$</td>
<td>$\frac{4196.6}{21120} = 0.651$</td>
</tr>
</tbody>
</table>

Take the width $L$ to be valley at 4 miles $= 21120$ ft.

$$\frac{L}{R} = 150 \frac{\text{ft}}{\text{sec}}$$

$$\frac{\sqrt{4L^2}}{2} = \sqrt{4 \times 21120 \times 1536000} = 13775 \frac{\text{ft}}{21120} = 0.651$$

From the chart,

$$\frac{R}{R_0} = 0.765$$

$$\log \frac{R}{R_0} = 0.126$$

The seasonal changes is to first approximation (Trend line applied as a wave case)

$$(419.6 \times 0.265) = 111.2 \text{ ft}$$

$$(419.6 \times 0.265) = 111.2 \text{ ft}$$

The result is combined with the pending 10 problem. The present depletion varies from a 3 to 4 ft.

$$442 + 111 = 553 \text{ ft}$$

in September

$$442 - 111 = 331 \text{ ft}$$

in March

Parabolic pattern of irrigation for 6 months.

$$442 + 0.519 \times 419.6 = 660 \text{ ft}$$

$$442 - 0.361 \times 419.6 = 316 \text{ ft}$$
Depletion of a stream by a pumped well. (Rate basis)

\( Q \) flow of well.

Notation (consistent units):

- \( K \) permeability
- \( t \) time
- \( D \) saturated depth
- \( V \) voids
- \( \frac{x}{\sqrt{4KDt}} \) stream depletion

\( K, D, V, t \) are constants in the context of groundwater flow and depletion.
Depletion of a stream by a pumped well (Volume basis).

Notation: (Consistent units)

\[ \alpha = \frac{K}{V} \]

- \( K \): permeability
- \( t \): time
- \( D \): Saturated depth
- \( Q \): flow of well
- \( V \): voids
- \( q \): stream depletion

\[ \left( \frac{Q}{V} \right) \left( \frac{1}{\sqrt{4 \pi kt}} \right) \]
Stream depletion due to a well.

(Ultimate configuration)

Stream

Well

Q: Flow of well.

Q: Flow per unit length of bank of the stream.

\( \chi_1 \): Distance of well from the stream.

\( \pi = 3.14159 + \)

\( \frac{\Delta x_1}{Q} \)

0.87

0.79

0.70

0.60

0.50

0.40

0.30

0.25

0.20

0.15

0.10

0.05

0.00

-5

-4

-3

-2

-1

0

1

2

3

4

(\( \frac{z}{\chi_1} \))

5
Drain flow due to a continuous infiltration.

Notation:
- $i$: infiltration rate (ft/sec)
- $K$: permeability (ft/sec)
- $q_2$: flow to both drains (ft$^2$/sec)
- $t$: time (sec)
- $V$: voids (dimensionless)
- $\alpha = \frac{Kd}{V}$: drainable depth (ft)

Equation:

\[
\frac{q_2}{iL} = 1 - \sum_{n=1}^{\infty} \frac{\alpha n^2 \pi^2 n}{n^2}
\]

$h << d$
South Platte River

River depletion due
to pumping in the Valley
of the South Platte
Pumping uniformly distributed
over the area.

Aquifer properties:

\[ K = 0.00384 \text{ ft/sec} \]
\[ D = 66.6 \text{ ft} \]
\[ V = 0.171 \]
\[ a = 1.50 \text{ ft}^2/\text{sec} \]
\[ kD = 0.255 \text{ ft}^2/\text{sec} \]

\[ L = 2.120 \text{ ft} \] (4 miles valley width with river in center)

71% Electrically driven
80% Are along the main stream.

100 KWH are required to pump
one acre foot.

0.667 of water pumped returns
to the water table.

Area by planimeter 42.60 in²

Planimeter reads 9.99 in² on 10.00 in²

One square inch represents 2 KWH/Yr (10)

Pump depletion:
\[ \frac{(42.60)(2)(10)^6(0.90)(0.385)}{(100)(0.71)} \]
\[ = 520000 \text{ A.F.} \text{ Year} \]

This is equivalent to:
\[ \frac{520000}{724} = 442 \text{ ft}^3/\text{sec} \]

The equivalent of 1,148,800 A.F. Yr (Gildersleeve)

15
\[ \frac{1148800}{724} = 1614 \text{ ft}^3/\text{sec} \]

0.0 Power used for 50 pumping.

100. \(10^6\) KWH/Yr
\[
\frac{q_2}{q_{2,0}} = \left( \frac{H_2L/V}{H_2L/V} \right)^{1.6}
\]

Amplitude chart

\[
q_2 = \frac{H_2L/V}{T} \sum_{n=1,3,5}^{\infty} \frac{b}{m} \sin bt \left( 1 + \frac{b^2}{m^2} \right)
\]

\[
p = \frac{2\pi}{T}
\]

\[
m = \alpha n^2 \pi^2
\]

\[
\frac{b}{m} = \left( \frac{L^2}{\alpha TL} \right) \frac{2}{\pi n^2}
\]

Reg. 9-2-4
Lag chart

Cosine curve

Assumed irrigation pattern

Idealized valley cross section

Water table

Permeability, K

Ground surface

Voids, V

L

H₀

Idealized valley cross section
Notation:
- \( q \): pumping rate (ft/sec)
- \( \delta \): drawdown (ft)
- \( t \): time (sec)
- \( V \): drainable voids (dimensionless)

Drawdown \( \delta \) at the corner of a rectangular area due to uniformly distributed pumping at the rate \( q \).
Part remaining

\[ p = \frac{S_{hax}}{HL} \]

\[ \alpha = \frac{K_D}{V} \]

Drainable depth, \( H \).
Height of water table above drain, \( h \).
Time, \( t \).

Part of drainable volume remaining.

Note: (Consistent units)

Permeability, \( K \), Voids, \( V \).

FIG. 8