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DEPARTMENT OF
WATER RESOURCES

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BEFORE DEPARTMENT OF WATER RESOURCES

STATE OF IDAHO

IN THE MATTER OF DISTRIBUTION OF WATER TO WATER RIGHT NOS. 36-02551 & 36-07694 (RANGEN, INC.)	Docket No. CM-DC-2011-004 **THIRD AFFIDAVIT OF CHARLES M. BRENDECKE**

STATE OF COLORADO)
: ss
County of Boulder)

Charles M. Brendecke, being first duly sworn under oath deposes and states as follows:

1. I am employed by AMEC, 1002 Walnut, Suite 200, Boulder, Colorado 80302. I am a Licensed Professional Engineer in Idaho, Colorado, Wyoming and Oklahoma. I have a Bachelor of Science degree in Civil Engineering from the University of Colorado, and Master of Science and Doctor of Philosophy Degrees and Civil Engineer from Stanford University.

2. As evidenced in prior pleadings, I have been retained by IGWA to provide expert reports, testimony and technical assistance in this delivery call regarding the hydrogeology of the ESPA, the ESPAM, among other technical and scientific matters.

3. I am competent to testify in this matter.

4. Attached hereto as **Exhibit A** is a true and correct copy of *Qanats in the Old World: Horizontal Wells in the New* by C. K. Pearse, which I obtained from

journals.uair.arizona.edu Reference: Journal of Range Management 26(5), September 1973.

5. Attached hereto as **Exhibit B** is *Qanat Systems* in Iran, by P. Beaumont, B.A., Ph.D., which I obtained from iahs.info/hsj/161/161004.pdf Reference: Bulletin of the International Association of Scientific Hydrology, XVI, 1. 3/1971.

6. Attached hereto as **Exhibit C** is a true and correct copy of an article titled *Flow to horizontal drains in isotropic unconfined aquifers* by Samani, Kompani-Zare, Seyyedian, and Barry, which I obtained from www.sciencedirect.com/science/article/pii/S0022169405004841 Reference: Journal of Hydrology Volume 324, Issues 1-4, 15 June 2006, pages 178-194.

7. Attached hereto as **Exhibit D** is a true and correct copy of the SRBA Partial Decree for Rangen Water Right No. 36-02551.

8. Attached hereto as **Exhibit E** is a true and correct copy of the SRBA Partial Decree for Rangen Water Right No. 36-07694.

9. Attached hereto as **Exhibit F** is a map depicting the decreed point of diversion for Water Right Nos. 36-02551 and 36-07694. I am familiar with the area depicted on the map attached hereto as **Exhibit F**, having visited in person on June 19, 2012, and evaluated water sources in the area in conjunction with preparing my reports submitted previously in this case.

FURTHER YOUR AFFIANT SAYETH NAUGHT.

DATED this 22 day of March, 2013.

CHARLES M. BRENDECKE

SUBSCRIBED AND SWORN TO before me this 22ND day of March, 2013.

NOTARY PUBLIC FOR COLORADO
Residing at: 1002 WALNUT ST #300 BOULDER CO 80302
My Commission Expires 02/13/2016

CERTIFICATE OF SERVICE

I hereby certify that on this 22nd day of March, 2013, I caused to be served a true and correct copy of the foregoing **Third Affidavit of Charles M. Brendecke**, upon the following by the method indicated:

Signature of person serving form

Original and one copy: Director, Gary Spackman Idaho Department of Water Resources PO Box 83720 Boise, ID 83720-0098 Deborah.Gibson@idwr.idaho.gov Kimi.white@idwr.idaho.gov	☒ U.S. Mail/Postage Prepaid ☐ Facsimile ☐ Overnight Mail ☐ Hand Delivery ☒ E-mail
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EXHIBIT A

Fig. 2. *Sun baked clay collars used to line sandy parts of the qanat tunnel at Estahard. These indicate the size of the shaft.*

Qanats in the Old World: Horizontal Wells in the New

C. KENNETH PEARSE

Highlight: *Horizontal wells make use of the principle of the qanat developed in Persia about 2,500 years ago and still widely used there and in other arid regions of the world. The driven horizontal well offers several important advantages over the hand dug qanat especially for livestock watering places.*

Horizontal wells as a source of livestock water are a recent development in the southwestern United States (Welchert and Freeman, 1973). They should have an important place on arid and semiarid ranges throughout the western part of North America and elsewhere.

The basic concept of the horizontal well or qanat originated in Persia some 2,500 years ago. The expansion of the Persian Empire, beginning in the fifth centruy B.C., carried the idea from the Indus to the Nile and into Afganistan and China. Then the Islamic conquest extended the qanat to Cyprus, West Africa, Spain, and the Canary Islands. Similar structures are found in Mexico, Peru, and Chile, perhaps brought by the Spaniards, but perhaps an independent discovery by pre-Columbian New World people.

The author is a consultant, 634-D Avenida Sevilla, Laguna Hills, California.

Manuscript received December 1, 1972.

Numerous publications have described the origin, development, spread, construction, and use of "qanats," "karez," "foggaras," or "galerias" as they are variously called in different parts of the old and new worlds. These have been well summarized by English (1968).

Fig. 1. *Method of digging mother well and cleaning qanats at Estahard, Iran.*

In Persia qanats made possible and served as the basis for agricultural and livestock development and even now constitute the most important source of water supply for most rural as well as metropolitan areas in modern Iran. From one third to one half of the irrigated area of the country is watered by qanats, and most of the major cities rely on qanats for domestic water.

Qanats are ingeniously but laboriously constructed by hand digging. The site selected is usually an alluvial fan near the top of which a mother well is dug to the water table (Fig. 1). Then a tunnel, large enough to admit a man, is dug from the lower end of the fan so as to connect with the mother well on a very gentle slope. Where the tunnel passes through sand, sunbaked clay collars are used to form a lining (Fig. 2). Vertical shafts are constructed at intervals of 50 to 100 meters to provide ventilation for the workers, dispose of spoil, and provide access for maintenance (Fig. 3, 4). This results in a chain of spoil piles stretching across the arid slopes that is especially striking when viewed from the air. Some

Fig. 3. *Opening of ventilation and access shaft of a qanat at Estahard. Other shafts are indicated by spoil piles in the background.*

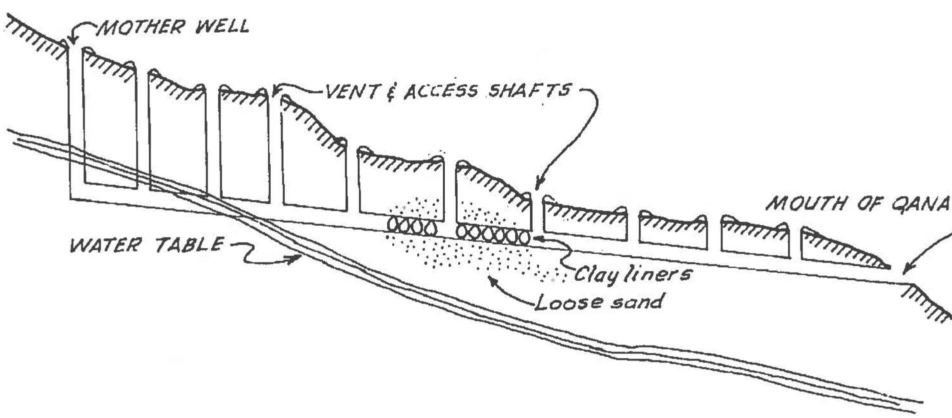

Fig. 4. *Schematic cross section of alluvial fan showing construction of a typical qanat.*

qanats extend for only a few kilometers but the length of many exceeds ten kilometers and some exceed 50 kilometers. The depth of the mother well is usually at least 50 meters and in some qanats is more than 300 meters.

Qanats are expensive to build. Skilled workers are required and the work is hazardous. The average cost is probably more than $10,000 per kilometer, but where much sand is encountered and lining is necessary much greater expenditures are made. Annual maintenance is also expensive, and extensive repairs are frequently made necessary by floods, earthquakes, and other major disasters. Another serious drawback of qanats is their inefficient use and waste of water. Although they do not seriously lower the water table, the flow is more or less constant throughout the year, and during the nonirrigating season tremendous quantities of water go unused.

Deep wells are being driven throughout the area where qanats have been important. Cost of development and maintenance are less and the rate of withdrawal can be controlled. However, deep wells almost always significantly lower the water table, and this can and does have serious social, economic, and political repercussions. The cost of pumping, which is nil in the case of qanats, is considerable.

Horizontal wells as described by Welchert and Freeman (1973) seem to offer opportunities to overcome the shortcomings and to retain the advantages of qanats. There are doubtless many situations throughout arid and semiarid regions where driven horizontal wells are adapted. Their location will be somewhat limited by the terrain and the nature of the water table, and the horizontal drilling method of construction may make it impractical to achieve the lengths as well as water yields of hand dug qanats. These limitations should have little effect on their value for livestock water. Stockmen and land administering agencies should give serious consideration to making more use of them.

Literature Cited

English, Paul Ward. 1968. The origin and spread of qanats in the Old World. Proc. Amer. Philosophical Soc. 112; 170-181.

Welchert, W. T., and Barry N. Freeman. 1973. Horizontal wells. J. Range Manage. 26:253-260.

EXHIBIT B

THE ORIGIN AND SPREAD OF QANATS IN THE OLD WORLD

PAUL WARD ENGLISH

Associate Professor of Geography, Assistant Director, Middle East Center, University of Texas

INTRODUCTION

Subterranean tunnel-wells (*qanats*) are extremely important in the history of irrigation and human settlement in the arid lands of the Old World.[1] Apparently originating in pre-Achaemenid Persia, tunnel-wells spread to Egypt, the Levant, and Arabia in Achaemenid times (550–331 B.C.). The Arabs carried *qanats* across North Africa into Spain and Cyprus; they are also found in Central Asia, western China, and on a more limited scale in dry regions of Latin America. In modern times, more than twenty terms are used to identify these horizontal wells; the Arabic word *qanāt* meaning "lance" or "conduit" is used in Iran, the Persian term *kārīz* is used in Afghanistan, while in Syria, Palestine, and North Africa *fuqarā* (pronounced foggara) is the most common term. In all of these regions, tunnel-wells are still being constructed in the traditional manner, and many settlements depend on them for irrigation and domestic water. Where used, *qanats* have strongly influenced village socio-economic organization and patterns of ownership and tenure.

THE NATURE OF QANATS

Qanats are gently sloping tunnels dug nearly horizontally into an alluvial fan until the water table is pierced. Once constructed, ground water filters into the channel, runs down its gentle slope, and emerges at the surface as a stream (fig. 1). In excavating these tunnels, diggers must have air and tunnel spoil must be removed, so the tunnels are connected to the surface with a series of vertical shafts spaced every 50 to 150 meters along its course. The tops of these shafts are rimmed by piles of excavated dirt to form a "chain-of-wells" on the surface, a distinctive feature of the arid landscapes of *qanat*-watered regions (figs. 2, 3). This system of water supply is widely used in the deserts of the Old World for several reasons. First, unlike other traditional irrigation devices such as the counterpoised sweep (*shaduf*), the Persian wheel (*dulab*), and the noria (*na'urah*), *qanats* require no power source other than gravity to maintain flow.[2] Second, water can be moved substantial distances in these subterranean conduits with minimal evaporation losses and little danger of pollution. Finally, the flow of water in *qanats* is proportionate to the available supply in the aquifer, and, if properly maintained, these infiltration channels provide a dependable supply of water for centuries.

Qanats vary considerably in size. Those in mountainous areas are usually short, shallow tunnels only tens of meters long and several deep, which draw surface water from small patches of alluvium. Others are major engineering feats such as those which supply water to the Iranian cities of Kirman, Yazd, and Birjand. At Kirman, *qanats* extend more than 50 kilometers southward to penetrate the water table at the base of the Kuhi Jupar (fig. 4).[3] Literally thousands of vertical shafts, the deepest 100 to 125 meters, dot the Kirman Plain marking the courses of an unknown number of galleries which carry water to the city (fig. 2). Yazd is watered by some 70 *qanats*, 30 to 45 kilometers in length, with mother wells (that shaft furthest from the point where water emerges

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[1] Field work for this study was supported by the Foreign Field Research Program of the National Academy of Sciences—National Research Council. Michael E. Bonine drew figures 1 and 4.

General articles on tunnel-wells include: George B. Cressey, "Qanats, Karez, and Foggaras," *"Geographical Review* **48** (1958): pp. 27–44; Carl Troll, "Qanat-Bewässerung in der Alten und Neuen Welt," *Mitteilungen der Österreichischen Geographischen Gesellschaft* **105** (1963): pp. 313–330; Johannes Humlum, "Underjordiske Vandingskanaler: Kareze, Qanat, Foggara," *Kultergeografi* **16** (1965): pp. 81–132; Hans E. Wulff, *The Traditional Crafts of Persia* (Cambridge and London, 1966), pp. 249–256; "The Qanats of Iran," *Scientific American* **218** (1968): pp. 94–105.

[2] Jørgen Laessøe, "Reflexions on Modern and Ancient Oriental Water Works," *Journal of Cuneiform Studies* **7** (1953): pp. 5–26; Charles Singer, ed., *A History of Technology* (5 v., Oxford, 1954) **1**: pp. 531–535; A Molenaar, *Water Lifting Devices for Irrigation,* FAO Agricultural Development Paper **60** (Rome, 1956).

[3] Philip H. T. Beckett, "Qanats around Kirman," *Journal of the Royal Central Asian Society* **40** (1953): pp. 47–58; Paul Ward English, *City and Village in Iran* (Madison, 1966), pp. 135–140.

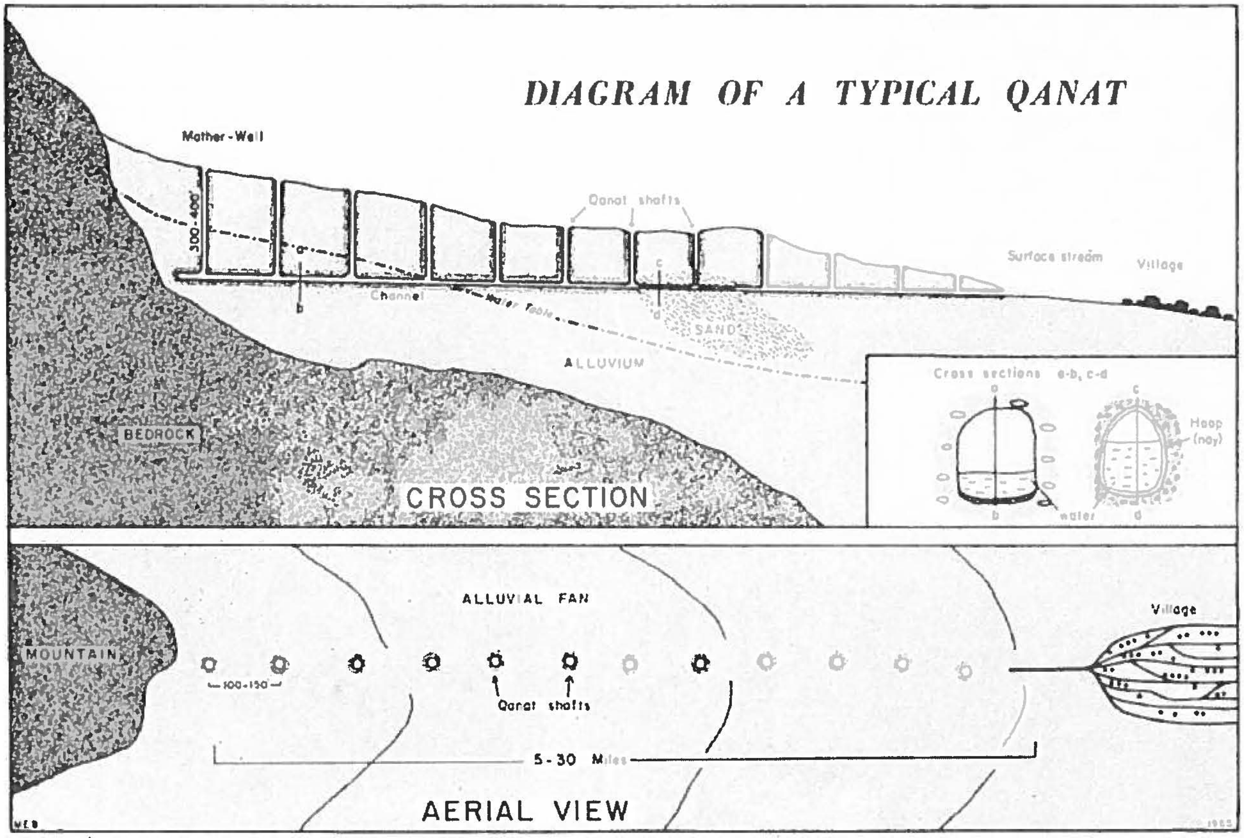

FIG. 1. Diagram of a typical *qanat.* Profile, cross sections, and aerial view illustrating the varying dimensions of a tunnel-well.

at the surface) 50 to 125 meters deep.[4] The deepest reported *qanat* is located at the village of Gunabad near Birjand.[5] Though only 27 kilometers long, its mother well lies at a depth of more than 300 meters.

QANAT CONSTRUCTION

Most *qanats* in Iran are constructed by a class of professional diggers (*muqannis*) who inherited this task from the slaves and captives of the Achaemenid and Sassanian kings. These men form a community of traveling artisans, migrating from place to place as floods destroy *qanats* in one area or a lowered water table demands that *qanat* tunnels be lengthened in another. The tools of the *muqanni* are primitive: a broad-bladed pick, a shovel, and a small oil lamp. His profession is well paid but hazardous. The *muqanni* must work with water flowing around him, ventilation is poor, and the chances of cave-ins are great. Today, *qanats* are still being built by these *muqannis* and the techniques of construction have changed little.

Site selection is the first step in the construction of a *qanat.* Local slope conditions, ground-water supplies, and the proposed location of the new settlement determine this decision. These factors are weighed by an expert, usually one of the older, more famous *muqannis,* who decides where a trial well should be dug. Favorable sites often lie near the mouth of a wadi, but where the water table is deep and the *qanat* long, the general topographic setting and variations in vegetation are used as indexes of the likely location of underground water supplies.

After the expert has chosen the site, a vertical shaft deep enough to penetrate the permanent water table is dug. The *muqanni* must be certain that this well has penetrated the permanent water table or has struck a constant flow of ground water on an impermeable stratum. If there is doubt concerning the water supply's permanence, more test holes are dug to determine the extent of the aquifer and the depth of the water table. When a trial well has sufficient water, it becomes the starting

[4] British Admiralty, *Persia,* Geographical Handbook Series **BR525** (London, 1945), p. 541.

[5] E. Noel, "Qanats," *Journal of the Royal Central Asian Society* **31** (1944): p. 192.

FIG. 2. Aerial photograph (1:18,750) illustrating the "chain-of-wells" effect of *qanats* located south of the city of Kirman, Iran. Note *qanat* entering gardens in upper right.

point for the construction of a *qanat*. This shaft will be called the mother well (*madari chah*) of the *qanat*, though the term is misleading because water is not removed from the ground at this point. The length of the *qanat* is measured from the mother well to the point where water surfaces. The depth of the mother well may vary from ten to several hundred meters.

The *muqanni* next establishes the alignment and grade of the *qanat* and this is the most difficult

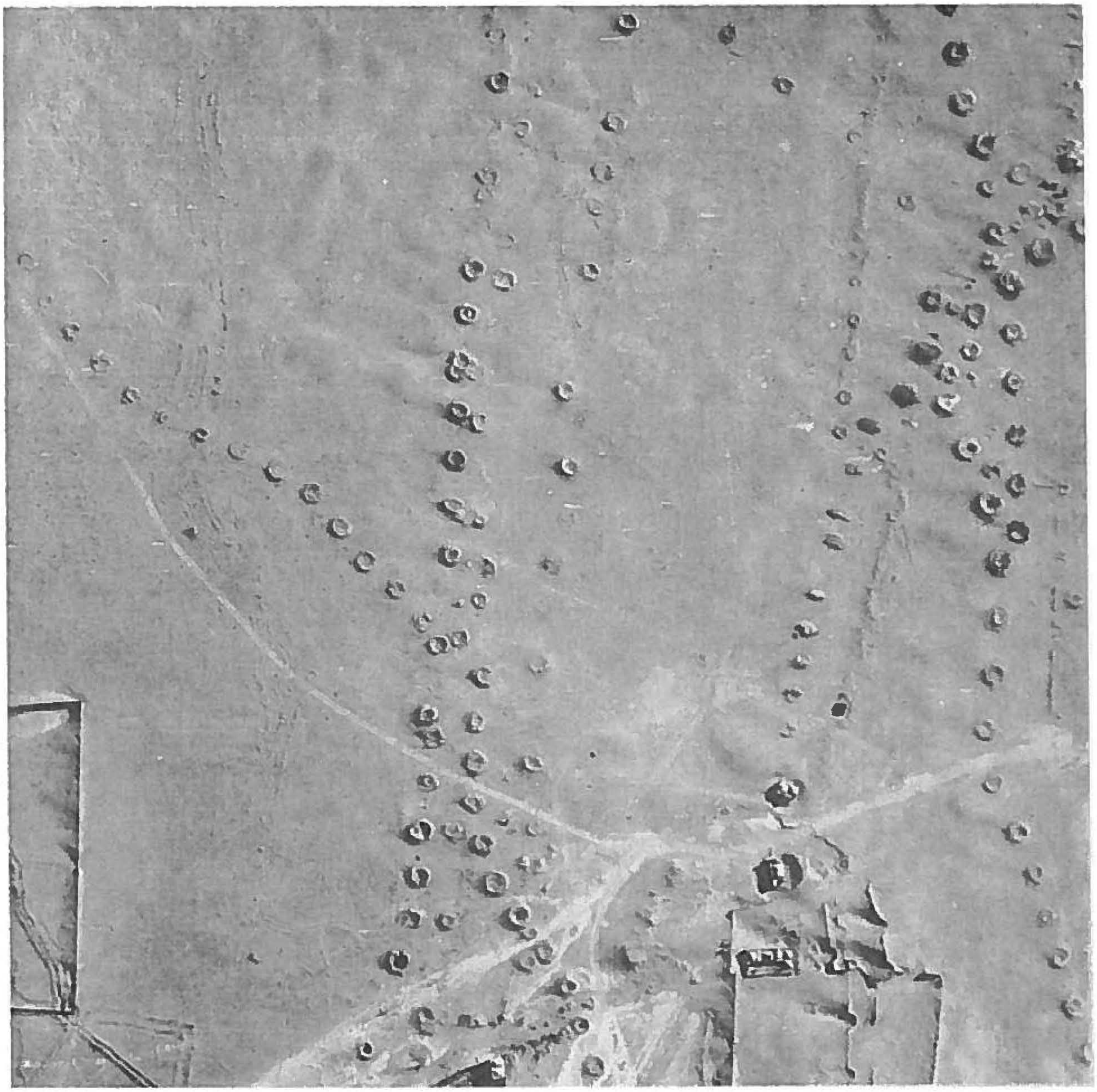

FIG. 3. Detailed aerial photograph (1:3,000) of *qanats* at the southern margin of the city of Kirman, Iran. Note their passage through abandoned fields in the lower center.

engineering task in the entire operation.[6] The *qanat* is aligned so that a gently sloping tunnel from the water-filled base of the mother well will surface *above* the irrigated fields of the settlement. If the tunnel emerges far from the settlement, water will flow on the surface in an open channel to the houses and fields. In such cases, evaporation and seepage become major problems, as at Turbat-i Haidari in eastern Iran where only one-quarter of the *qanat* water actually reaches the fields.[7] If the gradient of the tunnel is too steep, water rushing down the tunnel will erode the walls and soon destroy it. The maximum gradient in a short *qanat* is approximately 1:1,000 or 1:1,500; in a long *qanat* the tunnel is nearly horizontal. Using a string as a level, a skilled *muqanni* can

[6] This process was not observed in the field. It is described in: *ibid.*, pp. 196–197; Philip H. T. Beckett, *op. cit.* 40 (1953): pp. 48–49; Hans E. Wulff, *op. cit.* (1966), pp. 252–253.

[7] F. H. Kochs K. G., *Rural Development Plan, South Khorassan: Preliminary Study* (Tehran, 1959), p. 29.

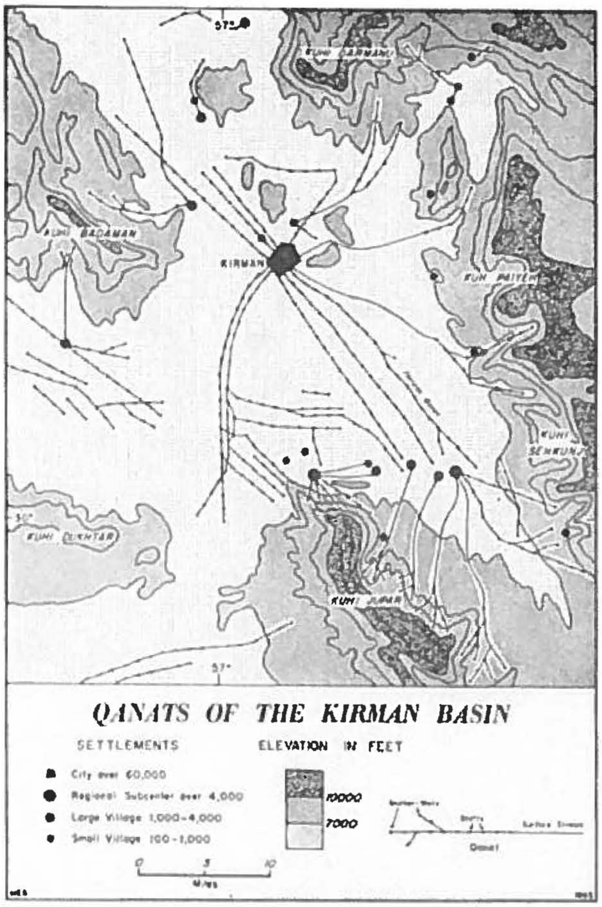

FIG. 4. *Qanats* of the Kirman Basin. The radial pattern of tunnel-wells around the city of Kirman, Iran, is repeated in many cities of the Old World.

establish such a grade, even when the tunnel passes beneath several kilometers of rough terrain.

Actual construction of the tunnel begins after the alignment and grade of the *qanat* have been determined. Work starts in the dry section of the *qanat* at the downslope end. The tunnel is dug back toward the mother well, with vertical shafts connecting the tunnel to the surface every 50 to 100 meters. In some cases, the vertical shafts are dug first and the tunnel is constructed to connect the bottoms of the shafts.

A team headed by a *muqanni* collaborates in the construction of a *qanat*. With a small pick and shovel, he excavates a tunnel roughly a meter wide and 1.5 meters high. An apprentice packs the dirt into a rubber bucket, and two laborers at the surface haul the dirt up the shaft by turning a windlass. If the *qanat* tunnel lies at a depth of more than 100 meters, a second windlass is set in a niche half way down the vertical shaft and the dirt is transferred from one bucket to another at this point.

The major problems in constructing a *qanat* occur when the tunnel enters the water-bearing section, where many *muqannis* are drowned or suffocated each year. In some cases the shafts fill with water before having reached the proper depth and the *muqanni* must dig upward beneath this pool and avoid the rush of water when a breakthrough is made. If the tunnel passes through an area of soft sand, clay hoops are inserted in the tunnel to prevent collapse (fig. 1). Where ventilation is poor, extra vertical shafts are dug to prevent suffocation. Every *muqanni* carries a castor oil lamp; when the air no longer keeps its flame lit, he leaves the tunnel and another shaft is built. In Yazd, where the *qanats* are very deep, vertical shafts are built on either side of the tunnel. A lamp is placed at the bottom of one shaft to create an updraft which draws air down the other shaft and improves ventilation.[8] Sometimes twin *qanats* are built side-by-side, enabling the *muqanni* to move from one to the other.

The time required to build a *qanat* varies with the capital of the owner, underground soil and water conditions, the amount of water desired, and the skill of the *muqanni*. Two new *qanats* recently built at the villages of Javadieh and Hujatabad south of Kirman can be used as examples. The Hujatabad *qanat* is only one kilometer long, with a mother well 45 meters deep, but it was under construction for twenty-seven years because of three changes in ownership. Construction on the Javadieh *qanat* began in 1941 and one team of *qanat*-diggers worked daily for seventeen years to bring water to the surface. In 1958, when small amounts of water began to flow, the owner hired a second team to work at night. Now the Javadieh *qanat* is 3 kilometers long; its tunnel bifurcates and has two mother wells at 50 and 55 meters respectively. Most of the tunnel had to be lined with clay hoops because of loose sand. It cost $33,000 to build this *qanat* and it now irrigates about one-half acre of land every twenty-four hours.

On this basis, *qanats* cost about $10,000 per kilometer to build. The Javadieh *qanat* cost more, $11,000 per kilometer, because the tunnel was lined. The expense of this relatively short *qanat* indicates the monumental costs of constructing a new long *qanat*. Such a one to Kirman, 40

[8] The diagram illustrating this device in E. Noel, *op. cit.* 31 (1944): p. 198 has been printed upside down.

kilometers long with a mother well 90 meters deep, cost approximately $213,000 when completed in 1950. Because of inflation and higher wages, the capital costs of constructing this *qanat* today would be about $387,000.

THE DISTRIBUTION AND DIFFUSION OF QANATS

Qanat technology apparently originated in the highlands of western Iran, northern Iraq, and eastern Turkey some 2,500 years ago, possibly in connection with early mining ventures in that region.[9] Laessøe has argued that *qanats* supported a flourishing civilization near Lake Reza'iyeh (Urmia) which was destroyed by Sargon II in his eighth campaign in 714 B.C., but unfortunately this information is based on a badly damaged tablet.[10] It is certain, however, that later Assyrian cities, particularly those on the Tigris River, relied on *qanats* for their drinking water. One *qanat* built during this period bears the inscription of Sargon's successor, Sennacherib (705–681 B.C.); this conduit, some 20 kilometers long with shafts spaced every 45 meters, still carries water to the city of Arbil.[11] The capital city of the Medes, Ecbatana (modern Hamadan), was also watered by *qanats* in the seventh century B.C.[12] and Darius' capital at Istakhr may also have used this water supply system.[13]

The core area of *qanats* then lies in the realm of the Persians whose language is rich in words relating to *qanat* technology and where *qanats* are very old, very numerous, and construction techniques are fully developed. *Qanat* technology was widely applied on the Iranian Plateau by Parthian times [14] on the numerous piedmont alluvial plains, where near horizontal tunnels can intersect sloping water tables, which provide an ideal setting for *qanat* construction. In modern times, most of the major cities in Iran including Tabriz, Qazvin, Saveh, Tehran, Yazd, and Kirman rely on *qanats* for domestic and irrigation water and chains of wells radiate outward from each of them (fig. 4). It is estimated that nearly 15 million acres of cultivated land, one-third to one-half of the irrigated area of Iran, are watered by some 37,500 *qanats* of which an estimated 21,000 are in fully operating order and 16,500 are used but need repair.[15] Their aggregate length has been placed at more than 160,000 kilometers; their total discharge at 20,000 cubic meters per second.[16] The Nishapur Plain near Mashhad alone is reputed to have "12,000 springs fed by 12,000 *qanats*." [17] Though these figures are suspect, having never been verified by field work, there is no doubt that *qanats* are the major source of irrigation water in Iran.

The first diffusion of *qanats* out of this core area occurred in the Achaemenid period when the Persians established an empire extending from the Indus to the Nile. To the west, the Persians car-

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[9] A supposition based on (1) the early evidence for *qanats* in this region, (2) the fact that *qanats* differ little from the horizontally driven adits of early miners, and (3) Armenia's reputation as one of the oldest mining and metallurgical centers in the Middle East.

[10] Jørgen Laessøe, "The Irrigation System at Ulhu, 8th Century B.C.," *Journal of Cuneiform Studies* **5** (1951): pp. 21–32; R. J. Forbes, *Studies in Ancient Technology* (6 v., Leiden, 1955–1958) **1**: p. 153 *ff.* The precise location of this irrigation system has been identified as modern Ula (Ulagh) at the northwest end of Lake Reza'iyeh by Edwin M. Wright, "The Eighth Campaign of Sargon II of Assyria (714 B.C.)," *Journal of Near Eastern Studies* **2** (1943): pp. 173–186.

[11] W. A. MacFadyen, "The Early History of Water-Supply: Discussion," *Geographical Journal* **99** (1942): pp. 195–196; Charles Singer, ed., *op. cit.* **1** (1954): pp. 533–534; R. J. Forbes, *op. cit.* **2** (1955–1958): pp. 21–22.

[12] Henri Goblot, "Dans l'ancien Iran, les techniques de l'eau et la grande histoire," *Annales: économies-sociétés-civilisations* **18** (1963): p. 510.

[13] E. Merlicek, "Aus Irans Kulturvergangenheit: Wasserwirtschaft und Kultur in ihren Zusammenhängen und gegenseitigen Beziehungen," *Deutsch Wasserwirtschaft* **36** (1941): pp. 301 *ff.*; Carl Troll, *op. cit.* **105** (1963): p. 314.

[14] An important passage from Polybius (*Historiae*, X. 28) states that *qanats* were widespread in Persian territory early in Parthian times (248 B.C.–A.D. 224). Stein's archaeological evidence supports this statement. Aurel Stein, "Archaeological Reconnaissances in Southern Persia," *Geographical Journal* **83** (1934): pp. 122–124, 132. Other early writers who discuss *qanats* include the Greek geographer Megasthenes [quoted in R. J. Forbes, *op. cit.* **1** (1955–1958): p. 153] and the Roman architect and engineer Pollio Vitruvius (*De Architectura*, VIII. 6.3.)

[15] Farhad Ghahraman, *The Right of Use and Economics of Irrigation Water in Iran* (Ann Arbor, 1958), pp. 44–45; Henri Goblot, "Le Problème de l'eau en Iran," *Orient* **23** (1962): p. 50. Other discussions of *qanats* in Iran include: B. Fisher, "Irrigation Systems of Persia," *Geographical Review* **18** (1928): pp. 302–306; Fritz Hartung, "Wasserwirtschaft in Iran," *Der Kulturtechniker* **39** (1935): pp. 78–85, 175–192; Gholam-Resa Kuros. *Irans Kampf um Wasser* (Berlin, 1943); Hans E. Wulff, *op. cit.* **218** (1968): pp. 94–105.

[16] This figure was originally suggested by E. Noel, *op. cit.* **31** (1944): p. 191 and is repeated in George B. Cressey, *op. cit.* **48** (1958): p. 39 and R. N. Gupta, *Iran: An Economic Survey* (New Delhi, 1947), p. 46.

[17] Clifford E. Bosworth, *The Ghaznavids: Their Empire in Afghanistan and Eastern Iran, A.D. 944–1040* (Edinburgh, 1963), pp. 155–157; George B. Cressey, *op. cit.* **48** (1958): p. 38.

ried *qanat* technology across the Fertile Crescent to the shores of the Mediterranean and southward to Egypt and Saudi Arabia. In the Iraqi foothills of the Zagros, *qanats* water the cities of Kirkuk and Arbil.[18] Deeper in the foothills, the city of Sulaymaniyah receives its entire water supply from tunnel-wells.[19] In Palestine and Syria, *qanats* are found in the Jordan Valley, in the Qalamun region of eastern Syria, near Palmyra, and northeast of Aleppo.[20] Recently, several *qanats* have been uncovered in the Wadi Arava south of the Dead Sea at the oases of Ein Dafieh, Yotvata, and Ein Zureib; the Ein Dafieh *qanats* empty into a reservoir used in Persian and later Roman times.[21] In Syria accurate dating is a problem because some *qanats* are ancient, others were constructed in the Byzantine period, and a few are recently built. At the village of Michrife-Qatna, which occupies the site of an old Hittite fortress 18 kilometers northeast of Homs, a *qanat*-like canal apparently supplied water to the town very early.[22] The more elaborate Byzantine *qanat* systems at Moufaggar, Amsareddi, and Qadeym (ancient Acadama) are Roman or repaired Persian constructions.[23] *Qanats* on the Selemiya Plain, however, have been built and renovated by the Ismailis who settled this region in the 1870's.[24]

In Egypt *qanats* built during the Persian occupation (525–332 B.C.) are found in the Kharga Oasis and at Matruh.[25] Beadnell measured one of these tunnel-wells, which at Kharga are dug into soft sandstones, and found 150 shafts on a line 3,200 meters long; he estimated that 4,875 cubic meters (about 11,000 tons) of rock had been removed from that tunnel and its shafts alone.[26] Agricultural colonies in the early 1900's cleared some of the ancient Kharga *qanats*, which had been choked with debris for more than a millennium, and they still supplement surface water supplies today.[27] At Matruh *qanats* were driven beneath consolidated sand dunes into limestone and were closed with cement caps.[28] *Qanat* construction in solid rock is rare elsewhere in the Old World.

The Persians also introduced *qanats* into Arabia in the fifth century B.C. and they are still used in the Hijaz, in the mountains of Yemen, along the Hadhramaut, in Oman, and at the Al Kharj oasis southeast of Riyadh and the Al Qatif oasis north of Dhahran.[29] Underground conduits are found in the Wadi Fatima west of Mecca and similar channels carry water to this holy city from Ain Zobeida to the southeast. *Qanats* also carry water to several quarters in Medina from a spring at Ain Zarqa south of the city.[30] The mountains west of San'a have *qanats* as do some districts in the central highlands of Najd. *Qanats* are most numerous in Oman where they are called *aflaj*; in Yemen and the Hadhramaut they are called *felledj*. At Al Kharj the *qanats* are specifically attributed to

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[18] C. E. N. Bromehead, "The Early History of Water-Supply," *Geographical Journal* **99** (1942): pp. 195–196. See also: F. Krenkow, "The Construction of Subterranean Water Supplies during the Abbaside Caliphate," *Transactions of the Glasgow University Oriental Society* **13** (1951): pp. 23–32.

[19] W. A. MacFadyen, *Water Supplies in Iraq*, Iraq Geological Publications **1** (Baghdad, 1938).

[20] Nelson Glueck, "Some Ancient Towns in the Plains of Moab," *Bulletin of the American Schools of Oriental Research* **91** (1943): pp. 9–10; B. Aisenstein, "The 'Kahrez', an Ancient System of Artificial Springs," *Journal of the Association of Engineers and Architects in Palestine* **8** (1947): pp. 2–3; A. Reifenberg, *The Struggle between the Desert and the Sown* (Jerusalem, 1955), pp. 53–54.

[21] M. Evanari, L. Shanan, N. H. Tadmor, and Y. Aharoni, "Ancient Agriculture in the Negev," *Science* **133** (1961): pp. 979–997.

[22] Mesnil du Buisson, *La Site archéologique de Michrife-Qatna* (Paris, 1935), p. 53, pl. XI.

[23] A. Poidebard, *La Trace de Rome dans le désert de Syrie.—Le limes de Trajan à la conquête arabe.—Recherches aériennes (1925–1932)*, Bibliothèque archéologique et historique **18** (Paris, 1934); R. Mouterde and A. Poidebard, *Le Limes de Chalcis*, Bibliothèque archéologique et historique **38** (2 v., Paris, 1945) **2**: plans 2–4.

[24] Norman N. Lewis, "Malaria, Irrigation, and Soil Erosion in Central Syria," *Geographical Review* **39** (1949): p. 286.

[25] A. T. Olmstead, *History of the Persian Empire* (Phoenix ed., Chicago, 1948), p. 224.

[26] H. J. L. Beadnell, *An Egyptian Oasis: An Account of the Oasis of Kharga in the Libyan Desert, with special reference to its History, Physical Geography, and Water-Supply* (London, 1909), p. 171; "Remarks on the Prehistoric Geography and Underground Waters of Kharga Oasis," *Geographical Journal* **81** (1933): pp. 128–139.

[27] G. W. Murray, "Water from the Desert: Some Ancient Egyptian Achievements," *Geographical Journal* **121** (1955): pp. 171–181.

[28] G. F. Walpole, *An Ancient Subterranean Aqueduct West of Matruh*, Survey of Egypt **42** (Cairo, 1932).

[29] George B. Cressey, *op. cit.*, **48** (1958): pp. 42–43; Carl Troll, *op. cit.* **105** (1963): p. 318; Johannes Humlum, *op. cit.* **16** (1965): p. 102.

[30] British Admiralty, *Western Arabia and the Red Sea*, Geographical Handbook Series **BR 527** (London, 1946), pp. 33–34.

Persian workmanship, as the name of a nearby ridge, Firzan, attests.[31]

East of Iran, *qanats* are used in Afghanistan, Central Asia, and Chinese Turkestan (Sinkiang). Here, *qanats* are called by their Persian term (*kariz*) rather than the Arabic *qanat*, yet whether this technology spread eastward during the Achaemenid diffusion or at some later period is uncertain. In Afghanistan *qanats* are a major source of irrigation water in the south and southeast, especially around the city of Qandahar.[32] In Pakistani Baluchistan, approximately two-thirds of the water in the city of Quetta is supplied by *qanats*, which also irrigate some 90,000 acres of land in the vicinity.[33] *Qanats* were apparently used in western China as early as the second century B.C., yet Huntington claims that they were not used in the Turfan Basin, which has one of the most extensive *qanat* systems in the world, until the eighteenth century.[34] In modern times approximately 40 per cent of the people in this region depend for water on *qanats* dug by imported Turki laborers.[35]

In a second major diffusion, *qanat* technology spread with Islam and the Arabs across North Africa into Spain, Cyprus, and the Canary Islands in the seventh and eighth centuries A.D. In North Africa *qanats* (here called *fuqarā*) are widely distributed, though having been built and maintained by Negro slave specialists, new constructions are rare.[36] In Libya they are found in the Kufra oases and in the Fezzan, particularly at Ghadames.[37] In Tunisia *qanats* have been reported north of the Chott Djerid[38] and in Algeria, on the borders of the Tademait Plateau in the Touat and Tidikelt districts south of the Great Western Erg.[39] In Morocco *qanats* are called *khettara* or *rhettara* and are used on the northern slopes of the Atlas, particularly around the city of Marrakech,[40] and south of the Atlas in the Tafilalt.[41] It is in these last three regions, in the Tademait district of southern Algeria, near Marrakech, and in the Tafilalt of Morocco, that *qanats* reach their greatest development outside the Persian core area.

Qanats were introduced into the Touat and Tidikelt districts of Algeria several centuries before the Arab conquest by Jews or Judaized Berbers fleeing from Cyrenaica during Trajan's persecution in A.D. 118.[42] These refugees were the first Jewish colonists in the Tademait region, establishing their capital at Tamentit south of Adrar.[43] Having absorbed the fundamentals of *qanat* technology during their long stay in Persian territory, first in Palestine and later in Cyrenaica, these Jews introduced *qanats* into the Western Sahara. In this region today, more than 1,500 kilometers of *qanat* tunnels can be found.[44] Near Aoulef al

[31] D. G. Hogarth, "Some Recent Arabian Explorations," *Geographical Review* **11** (1921): p. 336; Douglas D. Crary, "Recent Agricultural Developments in Saudi Arabia," *Geographical Review* **41** (1951): p. 368. The importance of *qanat* irrigation to the existence of settlement in this region is a dramatic theme in the novel by Hammond Innes, *The Doomed Oasis* (New York, 1960).

[32] Johannes Humlum, "L'Agriculture par irrigation en Afghanistan," *Comptes rendus, Congrès International de Géographie, Lisbon, 1949,* **3** (1951): pp. 318–328.

[33] C. W. Carlston, "Irrigation Practices in the Quetta-Pishin District of Baluchistan, Pakistan," *Annals of the Association of American Geographers* **43** (1953): p. 160.

[34] Huntington's evidence, which was based on local interviews, is given negative support by the lack of any references in Chinese sources to *qanats* in the Turfan Basin down to T'ang times and even later. Ellsworth Huntington, *The Pulse of Asia* (New York, 1907), pp. 310, 317; Aurel Stein, "Note on a Map of the Turfan Basin," *Geographical Journal* **82** (1933): pp. 236–246.

[35] L. Wawrzyn Golab, "A Study of Irrigation in East Turkestan," *Anthropos* **46** (1951): pp. 187–199.

[36] Though Pond has recently described the construction of a new *qanat* at Aoulef al Arab in southern Algeria. Alonzo W. Pond, *The Desert World* (New York, 1962), pp. 173–176.

[37] James R. Jones, *Brief Resumé of Ground Water Conditions in Libya,* (Benghazi, 1960), p. 20; personal communication, March 16, 1964.

[38] Marcel Solignac, "Recherches sur les installations hydrauliques de Kairouan et les steppes tunisiennes du VIIe au XIe siècle," *Annales de l'institut d'études orientales* **10** (1952): pp. 1–9; J. Despois, *La Tunisie, ses régions* (Paris, 1961), pp. 60–61.

[39] Cne. Lô, "Les Foggaras du Tidikelt," *Travaux de l'institut des recherches sahariennes* **10** (1953): pp. 139–181; **11** (1954): pp. 49–79; Lt. Voinot, "Le Tidikelt: étude sur le géographie, l'histoire, et les mœurs du pays," *Bulletin de la société de géographie et d'archéologie d'Oran* **29** (1909): pp. 185–216, 311–366, 419–480.

[40] Pierre Troussu, "Les Rétharas de Marrakech," *France-Maroc* **3** (1919): pp. 246–249; P. Fénélon, *"L'irrigation dans le Haouz de Marrakech," Bulletin de l'association de géographes français* **18** (1941): pp. 63–70.

[41] Jean Margat, "Les Recherches hydrogéologiques et l'exploitation des eaux souterraines au Tafilalt," *Mines et géologie* (Rabat) **4** (1958): pp. 43–68; "Les Ressources en eau des palmeraies du Tafilalt," *Bulletin économique et social du Maroc* **22** (1958): pp. 5–24.

[42] Lloyd C. Briggs, *Tribes of the Sahara* (Cambridge, Mass., 1960), pp. 11–12.

[43] Cressey estimates that there are now 40 kilometers of *qanat* tunnels in Tamentit with mother wells 60–75 meters deep. George B. Cressey, *op. cit.* **48** (1958): p. 44.

[44] Estimates vary. Gerster, for example, states that there are about 3,000 kilometers of tunnels on the borders of the Tademait with a total yield of 600 gallons per second. Georg Gerster, *Sahara* (New York, 1961), p. 74.

Arab, forty *qanats* now produce about 7,000 gallons of water per minute to support some 8,000 people scattered over 31,000 square kilometers.[45] At the oasis of In Salah, the upkeep of existing *qanats* alone cost the administration more than 115,000 working days each year.[46]

Qanats were first built in Marrakech in the eleventh century A.D. during the reign of the Almoravides.[47] Today some 85 *qanat* systems are found on the Haouz plain, 40 of which are functioning and carry water to the city.[48] Most of these systems are rather short; the largest lie to the south of the city, are 4–5 kilometers long, and reach a maximum depth of 70 meters. In the Tafilalt, *qanats* are most numerous in the oases of Tadrha, Ferkla, Jorf, and Siffa south and west of Ksar es Souk. Margat found 273 *qanats* in this region, 145 in good condition, providing 1,100 liters of water per second to irrigate some 850 hectares of palm groves.[49]

Qanat technology spread into Europe with Arab culture; they were used marginally in the Spanish province of Catalonia and at Madrid [50] and are still a major source of water in Cyprus and the Canary Islands. Recently, abandoned *qanats* were discovered in Central Europe, in Bavaria and Bohemia, though when or how *qanats* spread into that region is unknown.[51] In Cyprus the total flow from all *qanats* amounted to 9.25 billion gallons in 1950 with an additional capacity of 1.85 billion gallons then under construction.[52] In the Canary Islands, Tenerife and Gran Canaria are literally dotted with *gálerias,* as *qanats* are called here and in Latin America.[53] Until recently, it was assumed that the New World *qanats* which are found in Mexico at Parrás, Canyon Huasteca, Tecamenchalco, and Tehuacán and in the Atacama regions of Peru and Chile at Nazca and Pica were introduced into the Americas by the Spaniards. It appears, however, that the *qanat* systems of the Atacama region may predate the Spanish entry into the New World; thus *qanats* have become an additional item in the continuing pre-Columbian trans-Pacific diffusion controversy.[54]

SOME SOCIO-ECONOMIC CONSIDERATIONS

Qanats are expensive to build and expensive to maintain, but their distribution in the dry lands of the Northern Hemisphere is nearly circumglobal, because for centuries *qanats* have been the most economic means of water supply in regions where water is the critical scarcity. Most *qanats* were built by powerful political rulers and in countries like Iran each leader was evaluated on the basis of the number of *qanats* (and mosques) constructed during his reign. The *qanat* was built of local materials; slaves were given the task of constructing them and maintenance was solved by a corvée. In recent times, however, deep wells which have several advantages over *qanats* have been introduced into *qanat*-watered regions. Deep wells are not limited by slope or soil conditions and can be placed at locations convenient in terms of transportation, market, or other considerations; they draw water from the permanent aquifer thereby eliminating seasonal variations in flow. Nor is water wasted when demand falls short of supply.[55] But altering or replacing the *qanat* system with deep wells requires major adjustments in social patterns, customs, and laws that have developed around this water-supply system; thus a conflict between these two technologies is developing.

[45] Lloyd C. Briggs, *op. cit.* (1960): p. 11. Production figures for individual *qanats* can be found in: André Cornet, "Essai sur l'hydrogéologie du Grand Erg Occidental et des régions limitrophes: les foggaras," *Travaux de l'institut des recherches sahariennes* **8** (1951): pp. 84–104.

[46] Georg Gerster, *op. cit.* (1961), p. 76.

[47] Pond states that the first *qanat* was built at Marrakech by Ubaid Allah ibn Yamus in 1078 A.D. Alonzo W. Pond, *op. cit.* (1962), pp. 175–176.

[48] George S. Colin, "La Noria marocaine et les machines hydrauliques dans le monde arabe," *Hespéris* **14** (1932): pp. 38–39; Jeanne-Marie Poupart, "Les Problèmes de l'eau à Marrakech," *Les Cahiers d'Outre-Mer* **2** (1949): pp. 38–53.

[49] Jean Margat, *op. cit., Mines et géologie* (Rabat) **4** (1958): p. 48.

[50] J. Oliver Asín, *Historia del nombre Madrid* (Madrid, 1959), pl. XVII and map.

[51] Helmut Klaubert, "Qanats in an Area of Bavaria—Bohemia," *Geographical Review* **57** (1967): pp. 203–212.

[52] George B. Cressey, *op. cit.* **48** (1958): p. 42. For details see: C. Raeburn, *Water Supply in Cyprus* (2nd ed., Nicosia, 1945).

[53] There were 305 *qanats* on Tenerife in 1960. See map in: Johannes Humlum, *op. cit.* **16** (1965): p. 107.

[54] Karl Kaerger, *Landwirtschaft und Kolonisation im Spanischen Amerika* (2 v., Leipsig, 1901) **2**: pp. 251–254; J. Simon, "Oasenkultur in der chilenischen Wüste Atacama," *Tropenpflanzer* **11** (1907): pp. 387–392; H. Kinzl, "Die künstliche Bewässerung in Peru," *Zeitschrift für Erdkunde* **12** (1944): pp. 98–110; Carl Troll, *op. cit.* **105** (1963): pp. 321–329; Johannes Humlum, *op. cit.* **16** (1965): pp. 108–113.

[55] A comparison of the economics of *qanats* versus deep wells can be found in: Overseas Consultants, *Report on the Seven Year Development Plan for the Plan Organization of the Imperial Government of Iran* (3 v., New York, 1949) **3**: pp. 149–151, 191–192.

After *qanats* came into widespread use in the Muslim World, a body of custom and law (*sharī'a*) developed to regulate the water-supply system. The earliest known codification of this law is the *Kitābi Qanī* or *Book of Qanats* which was in existence in the eleventh century.[56] Its original purpose was to protect *qanat* owners in a risky but essential investment in permanent agricultural settlement. The law of *harim* ("borders"), for example, gave the owner protection over territory surrounding his *qanat* and prohibited the sinking of new mother wells within one kilometer of existing *qanats*. As a result, large areas in the vicinity of cities like Tehran, Kirman, Sulaymaniyah, and Qandahar, where the density of tunnel-wells is high (figs. 2, 4), are closed to new settlement thereby stabilizing agricultural acreage in regions with growing populations.[57] *Qanat* owners in these cities are suspicious of deep wells and decreased flow in any *qanat* leads to immediate accusations that the nearest deep well has drained the water table.

These difficulties are compounded by the pervasive influence of *qanat* utilization on the structure and social patterning of settlements, specifically on (1) the structural organization of the settlement around this water-supply system and (2) the fragmentation of *qanat* ownership among the population. In small towns and villages watered by *qanats*, the stream runs the length of the settlement passing by or through each household compound before irrigating the grain fields downslope. Within these settlements, the location of each household with respect to the watercourse determines the quality and quantity of its water supply, and, as a result, reflects the social and economic status of its occupants. The prosperous houses of the elite are located in the upper sections where water is clean and plentiful; the poorer households of sharecroppers and laborers are located downstream where the volume of water is less and it has been polluted by use.[58] In many cases, the *qanat* enters the settlement at the house or garden of the most powerful local landlord.[59] In larger towns, this social gradient along water-supply lines is often obscured by historical development and the maze of twisting distribution channels whose every diversion is a vestige of some past business transaction, marriage, or inheritance. In short, the social patterns of many *qanat*-watered settlements are oriented to water supply and alterations in one system involve changes in the other.

Further, the ownership of *qanats* is widely diffused throughout the population, for although *qanats* are built by wealthy individuals, the constant need for repairs caused by their sensitivity to natural and social disruptions leads to rapid fragmentation in ownership. Many *qanats* have as many as two or three hundred owners and the water of some *qanats* is divided into 10,000 or more time shares. In some cases, the system of dividing water goes back hundreds of years. The current division of water at Ardistan in central Iran, for example, dates back to the thirteenth century when Hulagu Khan (the grandson of Genghis Khan) ordered that water be divided into twenty-one shares with each allotted to a certain quarter.[60] For several *qanats* in Kirman this process of fragmentation has progressed so far that the smallest owner has rights to only thirty seconds of water once every twelve days. Frequently, a water bailiff is appointed to administer the distribution of *qanat* water in time and space and it is he who settles the numberless disputes arising from its intricacies.

The *qanat* system, which once revolutionized settlement patterns in the dry lands of the Old World, is now a conservative force supporting the maintenance of existing settlement patterns and social and economic conditions. They have become through custom and law an organizing principle of traditional preindustrial society and resist change and retard new developments in its fabric. It seems likely, therefore, that *qanats* will continue to play a major role in the future economic development of settlement and irrigation in these desert regions and that they will not pass quickly into history.

SUMMARY

Horizontal wells or *qanats* were discovered in the vicinity of Armenia more than 2,500 years ago and rapidly spread to become one of the most

[56] A special assembly was convened in Khurasan in the ninth century by 'Abdullah ibn Tahir to write this book of laws on *qanats*, because in the other books on law (*fiqh*) and in the Traditions of the Prophet *qanats* are not mentioned. Ann K. S. Lambton, *Landlord and Peasant in Persia* (London, 1953), p. 217.

[57] For the case of Kirman see discussion in: Paul Ward English, *op. cit.* (1966), pp. 33, 103–104.

[58] In some cases this difference in volume can be as much as 40 per cent of the total, which severely limits the amount and kind of cash crops that poorer farmers living in the lower sections of a settlement can grow.

[59] Also noted in: George B. Cressey, *op. cit.* **48** (1958): p. 29.

[60] Ann K. S. Lambton, *op. cit.* (1953), p. 218.

important methods of dry-land irrigation in the Old World. In parts of Iran, Afghanistan, Algeria, and Morocco, this ingenious device has made human settlement possible in distinctly marginal areas. Modern technology threatens to replace the *qanat* with the more efficient deep wells, but the extent to which social and economic patterns have become enmeshed with this water-supply system will make the transition difficult.

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EXHIBIT C

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Flow to horizontal drains in isotropic unconfined aquifers

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Abstract

The Laplace-transform solution for the problem of flow to horizontal drains in an anisotropic unconfined aquifer is derived. The solution for the constant flux horizontal-well by Zhan and Zlotnik [Zhan, H., Zlotnik, V.A., 2002. Groundwater flow to a horizontal and slanted well in an unconfined aquifer. Water Resour. Res. 38(7), 13-1–13-11.] is modified to obtain the solution for a constant head horizontal drain. The Laplace-transform solution is converted to the real time domain, and type curves for the drawdown around and the discharge to a horizontal drain are computed. The solution is verified by a numerical simulation. The type curves and derivative type curves of the drains are compared with type curves for horizontal wells. The sensitivity of type curves on piezometer location, specific storage, horizontal drain elevation, aquifer delay index and drain length is tested. These type curves can be used for interpretation of drainage data.

Keywords: Horizontal drain; Analytical solution; Laplace-transform solution; Type curve

1. Introduction

In ancient times, groundwater was supplied from horizontal wells known as qanats. Typically, a gently sloping tunnel dug through alluvial material led water by gravity from beneath the water table at its upper end to a ground surface outlet and irrigation canal at its lower end. Vertical shafts dug at closely spaced intervals provided access to the tunnel. Qanats are still used today, e.g. in Iran 22,000 qanats supply 75% of all water used in the country (Todd and Mays, 2005).

Subsurface conditions often preclude groundwater development by vertical wells, e.g. aquifers that are thin, poorly permeable, or underlain by permafrost or saline water. In other circumstances, where groundwater is to be derived primarily from infiltration of stream flow, a horizontal-well system may be advantageous. Also, for collecting the recharge water or contaminants from an aquifer, horizontal wells or drains are more efficient. Because of the gravitational control, discharge from qanats or horizontal drains is proportional to the aquifer head and in equilibrium with it. It makes qanats more suited to sustainable water exploitation compared with pumped vertical wells. Horizontal drains are broadly

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Notation

a	dimensionless radius of spherical/horizontal drain cross-section (r_w/d)
d	aquifer thickness (L)
h	hydraulic head (L)
h_D	dimensionless hydraulic head
h_0	initial hydraulic head (L)
h_{0D}	dimensionless initial hydraulic head
K_0	modified Bessel function of second kind and order zero
K	hydraulic conductivity ($L\,T^{-1}$)
L	drain length (L)
L_D	dimensionless drain length defined as $L_D = L/d$
p	Laplace-transform parameter
Q	point-source discharge ($L^3\,T^{-1}$)
Q_D	dimensionless point-source discharge
Q_{sD}	dimensionless total discharge to spherical constant head drain, Eq. (9)
Q_{DH}	dimensionless total discharge to horizontal, cylindrical, constant head drain, Eq. (12)
Q_{DHI}	dimensionless total discharge to horizontal, infinite, constant head drain, Eq. (14)
r_w	spherical drain radius, or radius of horizontal/slanted cylindrical drain cross-section (L)
s	drawdown (L)
s_c	arbitrary constant drawdown
s_{cD}	dimensionless arbitrary constant drawdown.
s_D	dimensionless drawdown
s'_D	dimensionless drawdown in the Laplace domain, Eq. (7)
s_{sD}	dimensionless drawdown around constant head spherical drain, Eq. (8)
s_{DTH}	dimensionless drawdown around horizontal drain, Eq. (10)
s_{DH}	dimensionless drawdown around constant head horizontal drain, Eq. (11)
s_{DHI}	dimensionless drawdown around constant head, infinite length horizontal drain, Eq. (13)
S_s	specific storativity (L^{-1})
S_y	specific yield
t	time (T)
t_D	dimensionless time defined in Eq. (6)
x	off-center coordinate along the drain axis (L)
x_D	dimensionless x defined in Eq. (6)
x^*_D	fixed head point position (Rosa and Carvalho, 1989) $x^*_D = 0.68L_D/2$
x_0, y_0, z_0	coordinates of the point-source (L)
x_{0D}, y_{0D}, z_{0D}	dimensionless coordinates of the point-source
y	horizontal coordinate perpendicular to the drain axis (L)
y_D	dimensionless horizontal coordinate perpendicular to the drain axis defined in Eq. (6)
z	vertical coordinate (L)
z_D	dimensionless vertical coordinate defined in Eq. (6)
z_w	distance from the midpoint of the horizontal or slanted drain to the bottom boundary (L)
z_{wD}	dimensionless z_w defined in Eq. (6)
δ	Dirac delta function (L^{-1})
α_1	delay index (Moench, 1995) (T^{-1})
η	$=\alpha_1(S_y d/K)$
σ	$=S_s d/S_y$

used in draining water from agricultural land and for lowering groundwater levels in urban regions.

Zhan (1999); Zhan and Cao (2000) have investigated capture times of horizontal wells, where the capture time is defined as the time a fluid particle takes to move from a given location to the well. Zhan et al. (2001); Zhan and Zlotnik (2002) provide a method that solves directly the problem of flow to horizontal and slanted wells in anisotropic confined and unconfined aquifers. This method solves the point-source problem first, and then integrates the point-source solution along the well axis to obtain the horizontal or slanted well solution.

Tile horizontal drains are commonly used in agriculture. Flow to these drains has been investigated extensively (Kirkham, 1958; Sneyd and Hosking, 1976; Prasad et al., 1981; Hazenberg and Panu, 1991; Gjerde and Tyvand, 1992; Schafer, 1996), typically for axisymmetric flow, and closed form solutions have been derived. Hazenberg and Panu (1991) present a solution for non-axisymmetric flow for an infinitely deep aquifer and with an infinitely long tile drain. Their solution predicts flow in a restricted cylindrical region around the drain.

For solving the flow to a tile drain in an unconfined aquifer, many investigators assume that the water table intersects the drain. However, important field evidence (Talsma and Haskew, 1959; Schwab et al., 1981) shows that this assumption is not necessarily valid. Khan and Rushton (1996a–c) and Gjerde and Tyvand (1992) separate the external boundary of the water table from the internal boundary of the tile drain. They present numerical methods for representing the time-varying water table.

In this paper, the analytical solution for three-dimensional unsteady flow to horizontal drains will be derived in an isotropic unconfined aquifer in the Laplace domain. Derivation of the solution is similar to the Zhan et al. (2001); Zhan and Zlotnik (2002) approaches, where the point-source problem is solved first, then the point-source solution is integrated along the horizontal-well axis to obtain the horizontal-well solution.

A drain is a horizontal-well, which on its periphery the head or drawdown is uniform and steady. Many investigators present solutions for predicting flow around a constant or uniform head vertical well (Cassiani and Kabala, 1998; Hemker, 1999; Chang and Chen, 2003). For making the head constant along the drain the distribution of the flow along the drain and its change during time must be numerically determined, which is time consuming. For making the problem simple, in this paper we propose to simulate the drain by a uniform flux well, so that the total flow rate to the drain be equal to the total flow to the uniform flux well. Rosa and Carvalho (1989) present a solution for simulation of finite length uniform head horizontal-well by a uniform flux well with the same dimensions and total flow rate. Rosa and Carvalho (1989) conclude that for these wells, the hydraulic head on their periphery in distance about 0.68 of the half well length from its centre, is similar. On the other hand, for keeping the head constant at a certain point on the well periphery, the method presented by Carslaw and Jaeger (1959, p. 335) is utilized. The same approach has been employed by Hantush (1964, p. 309) for keeping the head constant on the periphery of a well in a non-leaky aquifer. Using this method and Rosa and Carvalho's suggestion (1989), we modify the Zhan and Zlotnik (2002) solution for a horizontal-well in an unconfined aquifer to obtain the Laplace domain solution for a horizontal drain. The credibility of Rosa and Carvalho (1989) method for prediction of the total flow to a drain is also verified.

Based on the analytical solutions, we provide two computer programs for calculating the drawdown and discharge to horizontal drains in the Laplace domain and numerically convert the results to the real time domain. Finally, the sensitivity of the solution to some of the drain and aquifer parameters are tested by calculating the type curves for different parameter sets.

2. Flow to a spherical drain

We assume a horizontal unconfined aquifer of infinite extent and constant saturated thickness. The aquifer is bounded by the water table at the top and the aquifer bottom boundary is impermeable. The Cartesian coordinate system shown in Fig. 1 is used. The base of the aquifer is at $z=0$. We assume an isotropic and homogeneous aquifer. A spherical drain with radius r_w (centre located at $x=0$, $y=0$ and $z=z_w$) is considered (Fig. 1(a)). The pressure on the surface of the spherical drain must be considered to be atmospheric (Gjerde and Tyvand, 1992) over the surface. We chose the dimensionless head on the spherical drain surface equal to $z_{wD}+a$, so the drawdown on the drain surface will be $h_{0D}-(z_{wD}+a)=s_{cD}$.

For simulation of spherical drain we use constant flux point sink and keep the hydraulic head constant on its surface by utilising Carslaw and Jaeger (1959, p. 335) method. This method assumes temperature constant and is equal to V/p (in Laplace domain) on the surface of infinite length circular cylinder with radius a, by dividing the constant flux solution of the problem ($K_0(qr)$) by the solution for point with $r=a$, ($K_0(qa)$), and multiply the result by V/p. By using this method the solution for all points will be normalized based on the solution of point located at $r=a$. For the case presented by Carslaw and Jaeger (1959),

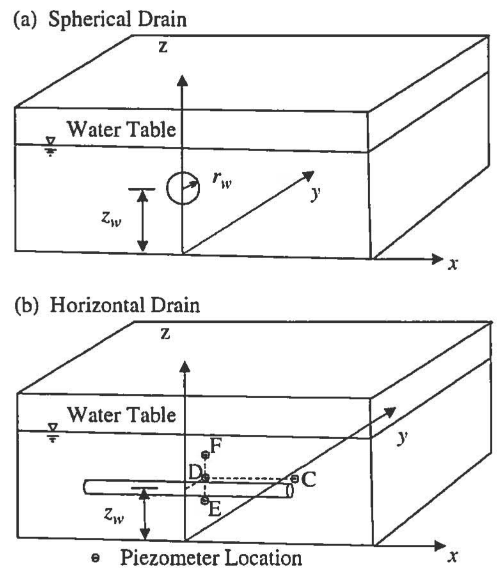

Fig. 1. Schematic diagram of a (a) spherical, (b) horizontal drains in an unconfined aquifer, showing the coordinate systems used, and the piezometers C, D, E and F locations around a horizontal drain with $L_D=2$ and $z_{wD}=0.5$.

the iso-temperature surfaces around the linear source are exactly cylindrical. Keeping the temperature constant at a point on one of those cylindrical iso-temperature surfaces, will result in constant temperature on entire surface during the time.

In simulation of a spherical drain by a point sink, if the drain radius is small relative to the aquifer thickness and if the drain is located not very close to the upper and lower aquifer boundaries, the equipotential surfaces close to the sink will be spherical during the time (Hooghoudt, 1940). In this case, utilising Carslaw and Jaeger (1959) method will create spherical constant head surface around the drain centre.

It is assumed that the drawdown of the water table during drainage is negligible relative to the aquifer saturated thickness and hence that the problem can be linearised (Dagan, 1967; Neuman, 1972, 1974; Hunt and Massmann, 2000; Khan and Rushton, 1996a). This assumption is thought to be reasonable since drainage is driven by gravity alone, and so is relatively low. The effect of water table drawdown on the solution is considered for both instantaneous (Boulton, 1954; Neuman, 1972, 1974) and delayed response drainage (Boulton, 1954; Moench, 1996).

2.1. Constant flux point sink solution in Laplace domain

The governing equation for flow in a homogeneous three-dimensional anisotropic medium near a point sink with discharge Q in an anisotropic confined aquifer is given by Zhan et al. (2001) as:

$$K\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right)+K\frac{\partial^2 h}{\partial z^2} = S_s\frac{\partial h}{\partial t}+Q\delta(x-x_0)\delta(y-y_0)\delta(z-z_0) \quad (1)$$

Initial and boundary conditions used in the solution to Eq. (1) are

$$h(x,y,z,t=0)=h_0, \quad (2)$$

$$\partial h(x,y,z=0,t)/\partial z=0 \quad (3)$$

and

$$h(x=\pm\infty,y,z,t)=h(x,y=\pm\infty,z,t)=h_0.$$

For the delayed drainage, the boundary condition on the water table is as follows (Moench, 1996)

$$K\partial h(x,y,z=d,t)/\partial z=-\alpha_1 S_y\int_0^t \frac{\partial h}{\partial t'}e^{-\alpha_1(t-t')}dt' \quad (5)$$

where h is the hydraulic head (L); K is the isotropic hydraulic conductivity (L T^{-1}); S_s is the specific storativity (L^{-1}); t is time (T); Q is the pumping rate ($L^3 T^{-1}$) (positive for pumping and negative for injection); δ is the Dirac delta function (L^{-1}); h_0 is the initial hydraulic head (L); S_y is specific yield; α_1 (T^{-1}) is an empirical constant (Moench, 1996); d is the aquifer thickness (L) and (x_0, y_0, z_0) is the source location. Note that Eq. (5) has a physical basis as a model for the response due to the capillary zone above the water table (Li et al., 1997).

Similar to Zhan et al. (2001) the problem is non-dimensionalised using

$$s_D=\frac{s}{d},\quad s_{cD}=\frac{s_c}{d},\quad t_D=\frac{K}{S_s d^2}t,$$
$$x_D=\frac{x}{d},\quad y_D=\frac{y}{d},\quad z_D=\frac{z}{d}, \quad (6)$$
$$Q_D=\frac{Q}{Kd^2}$$

where s_c is an arbitrary constant drawdown, s_D, s_{cD}, t_D, x_D, y_D, z_D and Q_D are the dimensionless counterparts of s, s_c, t, x, y, z and Q, respectively. Laplace-transform solution to this problem from Zhan and Zlotnik (2002) for the constant flux point sink is as follows

$$s'_D(x_D, y_D, z_D, p) = \frac{Q_D}{p}\sum_{n=0}^{\infty}\frac{1}{2\pi}\frac{4\omega_n}{2\omega_n + \sin(2\omega_n)} \times \cos(\omega_n z_{wD})\cos(\omega_n z_D) \times K_0[\sqrt{\omega_n^2 + p}(x_D^2 + y_D^2)^{1/2}] \quad (7)$$

where ω_n are the roots of $\omega_n \tan(\omega_n) = p/(p/\eta + \sigma)$ and $z_{wD} = z_w/d$. The solution of Eq. (7) is for a point sink with dimensionless discharge of Q_D, which gives the drawdown in terms of x_D, y_D, z_D and p in the Laplace domain.

2.2. Constant head spherical drain solution in Laplace domain

As mentioned in Section 2, the pressure on the surface of the spherical drain must be atmospheric over the surface, and the drawdown on the drain surface will be s_{cD}. To achieve a constant dimensionless drawdown s_{cD} at a point at the dimensionless distance $a = r_w/d$ from the centre of the drain, we must have constant head s_{cD}/p at that point in the Laplace domain. So, we normalise Eq. (7) by factor s'_D $(0, a, z_{wD}, p) = s_{cD}/p$ following Carslaw and Jaeger (1959):

$$s_{sD}(x_D, y_D, z_D, p) = \frac{s_{cD}}{p}\frac{s'_D(x_D, y_D, z_D, p)}{s'_D(0, a, z_{wD}, p)} = \frac{s_{cD}}{p}\frac{\sum_{n=0}^{\infty}\frac{1}{2\pi}\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos(\omega_n z_{wD})\cos(\omega_n z_D)K_0[\sqrt{\omega_n^2 + p}(x_D^2 + y_D^2)^{1/2}]}{\sum_{n=0}^{\infty}\frac{1}{2\pi}\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos^2(\omega_n z_{wD})K_0(a\sqrt{\omega_n^2 + p})} \quad (8)$$

As it can be seen from Eq. (8) the drawdown around a constant head/drawdown spherical sink is independent of Q_D. Because of the small dimension of the drain relative to the aquifer thickness, the flow close to the drain is radial and as mentioned in Section 2 the isopotential surfaces around it are nearly spherical (Hooghoudt, 1940; Dagan, 1964). At a radius a from the centre of the drain, a constant head condition is approximately satisfied, so the same head will be achieved in all points that are the same distance from the drain centre. This situation thus satisfies the boundary condition of the spherical drain with constant head.

From Eqs. (7) and (8), the dimensionless discharge for a constant head spherical drain with dimensionless radius a in the Laplace domain is:

$$Q_{sD}(p) = \frac{s_{cD}}{\sum_{n=0}^{\infty}\frac{1}{2\pi}\frac{4\omega_n}{2\omega_n + \sin(2\omega_n)}\cos^2(\omega_n z_{wD})K_0(a\sqrt{\omega_n^2 + p})} \quad (9)$$

The above equation shows that over time (increasing t or decreasing p) the discharge will decay. This occurs due to the reduction in the difference between the head in the drain and in the adjacent aquifer with time.

3. Head distribution along the horizontal drain

Horizontal drains can be simulated by superposition of point sinks along the direction of the drain axis. It is assumed that the cylindrical drain with radius a extended along x-axis centred at $x = 0$, $y = 0$ and $z = z_w$ (Fig. 1(b)). It is also assumed that the drain is a full open channel under atmospheric pressure (Gjerde and Tyvand, 1992) and that the drain is able to take away all the incoming water flux. In this condition, the drain can be considered as a constant head internal boundary (Khan and Rushton, 1996a) with dimensionless head $z_{wD} + a$ along its surface (Fig. 1(b)). Integrating Eq. (16) along drain axis and applying Carslaw and Jaeger (1959), an approximate solution for the constant head horizontal drain is derived.

In the case of infinite length horizontal drain applying Carslaw and Jaeger (1959) method will result in exact solution. For the case of infinite length line sink the same number of point sinks affects every point on the cylindrical surface around its axis; hence, the superposed effect of these point sinks from each side of that point is equal. As mentioned in Section 2, the radius of the drain is assumed considerably smaller than the aquifer extension and the drain is located not very close to the aquifer lower and upper boundaries. So, the isopotential surface around the drain will be perfectly cylindrical. Therefore, by using Carslaw and Jaeger (1959) method and keeping the head constant in one point on the surface of an infinite length drain the head on the drain surface will be constant and the solution for uniform and constant head drain will be achieved.

For simulation of a constant and uniform head finite length drain it seems that the best way is utilising the solution for uniform head finite length horizontal-well and then normalising the solution by Carslaw and Jaeger (1959) method. Many investigators present the solutions for keeping the head uniform or constant along the vertical well surface (Cassiani and Kabala, 1998; Hemker, 1999; Chang and Chen, 2003). Rosa and Carvalho (1989) present a solution for simulation of uniform-head finite-length horizontal wells. In their solution, the discharge distribution along the well axis by which the head is kept uniform on the well surface is derived.

Rosa and Carvalho (1989) stated that during early times a uniform head finite length well acts as a uniform flux finite length well with the same dimensions. And during the transient and late times, a uniform-head and a uniform-flux well with the same dimensions and total discharge, yield similar head response in a certain point along the well surface. This point is located at distance, 0.68 of the half well length from centre of the wells along their axis (Rosa and Carvalho, 1989, p. 563). They name this dimensionless distance as x_D^*. In other words, the total discharge to a uniform flux and a uniform head well with the same dimensions is equal when the head on their surface and at $x_D^* = 0.68$ from their centres are equal. Therefore, each uniform flux well has an equivalent uniform head well that the total discharge to it is equal to the total discharge of the uniform flux well at any time.

Here, the main goal is derivation of the total discharge to the drain. Therefore, we use the above suggestion and predict the total discharge to a finite length drain by utilising the solution of the uniform flux well by Zhan and Zlotnik (2002). For this, we select a uniform flux well with the same dimensions as the drain. Then, the solution is normalised by keeping the head constant at $x_D^* = 0.68$ on the periphery of the uniform flux well. As will be discussed in Section 5, by keeping the head constant at $x_D^* = 0.68$ and following Rosa and Carvalho (1989) suggestion, the total discharge to this well at any time will be equal to the total discharge to a drain with the same dimensions.

It must be noted that using uniform flux finite length well for simulating horizontal drain will not result in uniform head on the cylindrical surface around the drain. The error produced by utilising uniform flux well for simulation of a uniform head well in finite length condition is small (less than few percent) if the well length-to-radius ratio satisfies $L_D/a > 20$–40 (Hayashi et al., 1987; Haitjema and Kraemer, 1988; Cole and Zlotnik, 1994; Ruud and Kabala, 1997). More importantly, this error rapidly decays with distance from the well (Luther and Haitjema, 2000). Numerical solutions for a horizontal-well (Zhan and Zlotnik, 2002) also show that the discrepancy between the uniform flux and uniform head results is $<10\%$ when the distance between a measured point to a well end is 5 times the well diameter, and decreases quickly to insignificant level ($<1\%$) for larger distances. The error produced by utilising normalised uniform flux well for simulating a finite length drain is therefore the same as the error produced by utilising uniform flux well for simulating a uniform head well because the ratio between normalised uniform flux and uniform flux solution is equal to the ratio between the drain and uniform head well at any time.

4. Horizontal cylindrical drain solution in the Laplace domain

Based on the discussion presented in Section 3 regarding the simulation of flow to finite length horizontal drains, the point sink solution (s_D', Eq. (7)) with a constant dimensionless discharge of Q_D is integrated along the horizontal-well axis in order to determine the solution of uniform flux horizontal-well. The result was obtained by Zhan and Zlotnik (2002, Eq. (23))

$$s_{\mathrm{DTH}}(x_{\mathrm{D}},y_{\mathrm{D}},z_{\mathrm{D}},p)=\frac{1}{L_{\mathrm{D}}}\sum_{n=0}^{\infty}\int_{-L_{\mathrm{D}}/2}^{L_{\mathrm{D}}/2}\frac{1}{2\pi}\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos(\omega_n z_{\mathrm{wD}})\cos(\omega_n z_{\mathrm{D}})\times\frac{Q_{\mathrm{D}}}{p}K_0\{[(x_{\mathrm{D}}-x'_{\mathrm{D}})^2+y_{\mathrm{D}}^2]^{1/2}\sqrt{\omega_n^2+p}\}\mathrm{d}x'_{\mathrm{D}} \quad (10)$$

where $s_{\mathrm{DTH}}(x_{\mathrm{D}}, y_{\mathrm{D}}, z_{\mathrm{D}}, p)$ is the dimensionless drawdown induced by a horizontal uniform flux well with a total dimensionless discharge of Q_{D}. L_{D} is the dimensionless well screen length defined as $L_{\mathrm{D}}=L/d$.

We keep the drawdown constant $s_{\mathrm{cD}}=h_{0\mathrm{D}}-(z_{\mathrm{wD}}+a)$ in a point located on the surface of the drain and at a distance $x_{\mathrm{D}}=0.68\times L_{\mathrm{D}}/2$ (Rosa and Carvalho, 1989) from the drain centre along x_{D} axis $[0.34L_{\mathrm{D}}, a, z_{\mathrm{wD}}, p]$. As discussed, by applying the Carslaw and Jaeger (1959) method to Eq. (10), the solution for finite length constant head drain is derived

$$s_{\mathrm{DH}}(x_{\mathrm{D}},y_{\mathrm{D}},z_{\mathrm{D}},p)=\frac{s_{\mathrm{cD}}}{p}\frac{s_{\mathrm{DTH}}(x_{\mathrm{D}},y_{\mathrm{D}},z_{\mathrm{D}},p)}{s_{\mathrm{DTH}}(0.34L_{\mathrm{D}},a,z_{\mathrm{wD}},p)}=\frac{s_{\mathrm{cD}}}{p}\times\frac{\sum_{n=0}^{\infty}\int_{-L_{\mathrm{D}}/2}^{L_{\mathrm{D}}/2}\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos(\omega_n z_{\mathrm{wD}})\cos(\omega_n z_{\mathrm{D}})K_0\{[(x_{\mathrm{D}}-x'_{\mathrm{D}})^2+y_{\mathrm{D}}^2]^{1/2}\sqrt{\omega_n^2+p}\}\mathrm{d}x'_{\mathrm{D}}}{\sum_{n=0}^{\infty}\int_{-L_{\mathrm{D}}/2}^{L_{\mathrm{D}}/2}\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos^2(\omega_n z_{\mathrm{wD}})K_0\{[(0.34L_{\mathrm{D}}-x'_{\mathrm{D}})^2+a^2]^{1/2}\sqrt{\omega_n^2+p}\}\mathrm{d}x'_{\mathrm{D}}} \quad (11)$$

where x'_{D} is the dimensionless coordinate along the horizontal drain axis with respect to the drain centre ($x'_{\mathrm{D}}>0$ if $x_{\mathrm{D}}>0$ and $x'_{\mathrm{D}}<0$ if $x_{\mathrm{D}}<0$). By comparing Eqs. (11) and (7), the total dimensionless discharge of the horizontal drain in the Laplace domain is derived as:

$$Q_{\mathrm{DH}}(p)=\frac{L_{\mathrm{D}}s_{\mathrm{cD}}}{\sum_{n=0}^{\infty}\int_{-L_{\mathrm{D}}/2}^{L_{\mathrm{D}}/2}\frac{1}{2\pi}\times\frac{4\omega_n}{2\omega_n+\sin(2\omega_n)}\cos^2(\omega_n z_{\mathrm{wD}})K_0\{[(0.34L_{\mathrm{D}}-x'_{\mathrm{D}})^2+a^2]^{1/2}\sqrt{\omega_n^2+p}\}\mathrm{d}x'_{\mathrm{D}}} \quad (12)$$

If the horizontal drain is much longer than the aquifer thickness ($L_{\mathrm{D}}\to\infty$) a simplification of Eq. (11) is possible that results in the exact solution for infinite length constant head drain:

$$s_{\mathrm{DHI}}(y_{\mathrm{D}},z_{\mathrm{D}},p)=\frac{s_{\mathrm{cD}}}{p}\times\frac{\sum_{n=0}^{\infty}\frac{2\omega_n}{2\omega_n+\sin(2\omega_n)}\frac{1}{\sqrt{\omega_n^2+p}}\cos(\omega_n z_{\mathrm{wD}})\cos(\omega_n z_{\mathrm{D}})\exp(-\sqrt{\omega_n^2+p}|y_{\mathrm{D}}|)}{\sum_{n=0}^{\infty}\frac{2\omega_n}{2\omega_n+\sin(2\omega_n)}\frac{1}{\sqrt{\omega_n^2+p}}\cos^2(\omega_n z_{\mathrm{wD}})\exp(-\sqrt{\omega_n^2+p}|a|)} \quad (13)$$

Using the identity $\int_0^{\infty}K_0(\omega_n\sqrt{x^2+u^2})\mathrm{d}x=\pi/2\omega_n \exp(-\omega_w u)$ (Gradshteyn and Ryzhik, 1994, p. 727), the discharge per unit length of the infinite length drain can be extracted from Eq. (13) as discussed above:

$$Q_{\mathrm{DHI}}(p)=\frac{s_{\mathrm{cD}}}{\sum_{n=0}^{\infty}\frac{2\omega_n}{2\omega_n+\sin(2\omega_n)}\frac{1}{\sqrt{\omega_n^2+p}}\cos^2(\omega_n z_{\mathrm{wD}})\exp(-\sqrt{\omega_n^2+p}|a|)} \quad (14)$$

In Eqs. (12) and (14), the discharge to the horizontal drain is proportional to the reciprocal of the Laplace domain parameter (p).

To invert the derived equations to the real time domain the Stehfest (1970) algorithm is used. Following Moench (1995) we set the accuracy of the computations to 17 decimal points, the number of terms in series to 17 and the Stehfest parameter (Stehfest, 1970, p. 80) to 12 with 13 decimal points accuracy. Higher accuracy increases the run time and in some cases causes erroneous and oscillatory results. The programs HDD and HDQ compute drawdown at any point around the drain and calculate discharge to the drain at any given time by employing the coordinate systems shown in Fig. 1. Also, they can generate dimensionless drawdown and discharge type curves or the derivative type curve for any observation point.

5. Numerical verification of the analytical solutions

To verify the accuracy of the derived solution and to check the credibility of Rosa and Carvalho suggestion in simulation of a drain by a uniform flux well, a cylindrical, horizontal drain is simulated numerically by MODFLOW 2000 (Harbaugh et al., 2000). And the flux distribution along the drain is investigated.

5.1. The flow distribution along the horizontal drain

For determining the flow distribution at the point sinks extended along a drain axis, a constant head drain is simulated numerically by MODFLOW 2000 (Harbaugh et al., 2000). A drain with $r_w=0.305$ m, and $L=61$ m located in an aquifer with saturated thickness, d, of 30.5 m, $K=1.53\times10^{-6}$m s^{-1}, $S_y=0.2$ and $S_s=6.6\times10^{-6}$m^{-1} is considered. For making the drain cylindrical the cells with 0.005 m dimensions are considered. In this model the drain simulated by about 22,000 constant head cells. The lateral extension of the aquifer is considered to be infinite. Flow rate to the drain along its axis is determined by measuring the hydraulic gradient in the cell next to the drain periphery. For determining the flow rate accurately, the cell dimension of 0.001 m is considered for the cells next to the drain periphery. To improve the model efficiency, the cell dimensions are gradually enlarged through getting far from the drain by an expansion factor of 1.44 (Barrash and Dougherty, 1997). The length of drain cells, along its axis and at its ends are 0.001 m and gradually increase toward the midpoint of the drain by extension factor of 1.44. For three periods of 0.18, 16.74 and 855.02 days, the flow rate distribution along the drain is determined. For each period, the average flow rate is determined and distribution of flow rate ratio is plotted versus relative length from the drain centre, in percent (Fig. 2(a)). The flow rate is the discharge rate per unit length of the drain and the flow rate ratio is the ratio between the flow rate into the drain from 0.001 m of its length divided by the average drain flow rate. As can be seen from this figure, along about 90% of the drain length the flow rate ratio is about 0.8–1.2 at all times. And along the last 10% of the drain length this ratio is in range of 1.2–8. For the selected times, the flow rate ratio along the drain is plotted versus the ratio of incremental discharge to the total discharge in percent (Fig. 2(b)). Fig. 2(b) indicates that for all treated times more than about 90% of the total discharge to the drain belongs to those parts of the drain which has flow rate ratio of

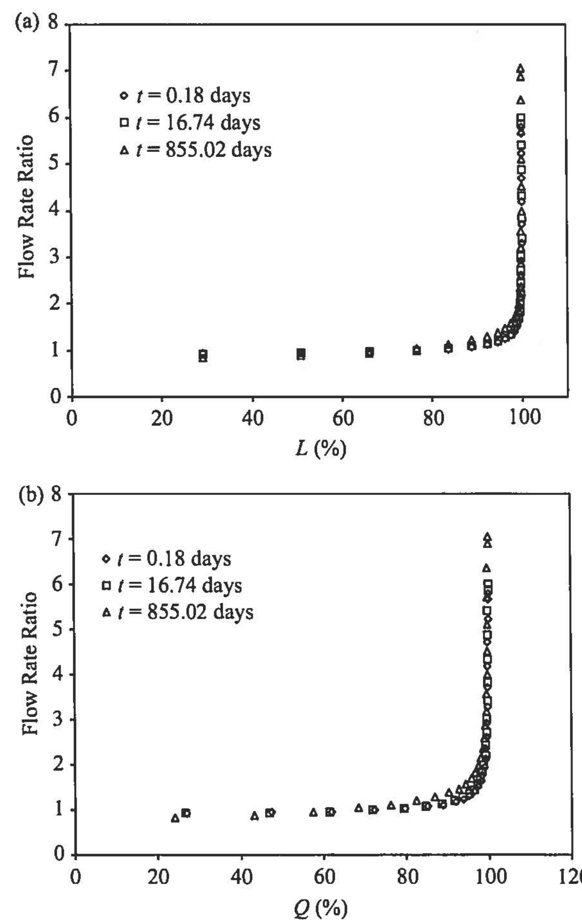

Fig. 2. Variation of flow rate ratio versus (a) relative distance from the drain centre and (b) incremental discharge in percent for three different periods.

0.8–1.2. It means, along 90% of the drain length, the flow rate is almost uniform and it can simply be simulated by a uniform flux line sink with an error less than 10%. As discussed in previous sections, here the main goal is derivation of the total discharge to the drain. The total flow rate to the drain can simply be derived by simulation of the drain by a uniform flux line sink. The question here is, how much must the flow rate to a uniform flux line sink be, in order to act as a drain?

5.2. The Head distribution along the uniform flux line sink

Consider an ideal uniform flux line sink, which has the same total discharge as a drain with equal dimensions, in any time. The average flow rate along the drain is equal to the flow rate along this ideal sink in each selected time period. As can be seen in Fig. 2(a), the flow rate along the central part of the uniform flux line sink is more than the flow rate at the same point on the equivalent drain. And also, the flow rate near the ends of the sink is less than that of the drain. Therefore, it is expected that the head along the periphery of the uniform flux line sink is not uniform, and the hydraulic head in central part of its periphery is lower than that of the drain. Also, the hydraulic head near the ends of the uniform flux line sink is higher than that of the drain. It implies that at all times in some points on the periphery of this ideal uniform flux line sink the hydraulic head is equal to the head at the same points on the drain periphery. We name these points 'fixed head points' or 'equal head points'. In Fig. 3, for the uniform flux line sink and its equivalent drain, one isopotential line is drawn schematically. The two isopotential lines intersect each other at four 'equal head point' located between the centre and the ends of the drain. The head in these four points is steady or fixed during the time at both the drain and the sink. May be the location of these points on the drain or sink periphery changes during the time. But the head at 'fixed head points' are steady and constant.

5.3. Simulation of a drain by a uniform flux line sink

Based on the above discussion, it is implied that in order to predict the total flow to a drain and its simulation by a uniform flux horizontal-well, the head

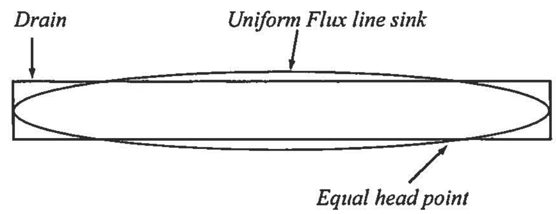

Fig. 3. Schematic isopotential line around a drain and a uniform flux line sink with the same total discharge.

on the periphery of uniform flux sink at a 'fixed head point' position must be kept constant by using Carslaw and Jaeger (1959) method. The question here is that, where must be the location of 'fixed head point' along the line sink by which the best approximation for the total discharge to the drain is obtained. Another question is that, does the position of 'fixed head point' change with time?

5.3.1. Infinite length horizontal drain

As mentioned in Section 3, for the case of infinite length horizontal drain applying Carslaw and Jaeger (1959) method will result in exact solution. For infinite length drain, the isopotential surface around its equivalent uniform flux sink will be perfectly cylindrical. Therefore, by using Carslaw and Jaeger (1959) method and keeping the head constant in one point on the periphery of an infinite length uniform flux sink, the head on all points of its surface will be constant and the exact solution for uniform and constant head drain will be achieved. In other word, at infinite number of 'fixed head points' that cover entire surface of uniform flux line sink the hydraulic head on the sink is steady and equal to the head on the periphery of the drain. And it is not important where the selected location for the 'fixed head point' is.

5.3.2 . Finite length horizontal drain

Rosa and Carvalho (1989) compared the head on the periphery of a uniform flux and a uniform head well with the same total discharge. As mentioned in Section 3, they stated that a uniform-head and a uniform-flux well with the same dimensions and total discharge yield the same pressure response in a certain point along the well surface. This point is located at distance, x_D^*, of 0.68 of the half well length from the well centre along their axis (Rosa and

Carvalho, 1989, p. 563). The suggested x_D^* of Rosa and Carvalho (1989) is an 'equal head point' and is comparable with 'fixed head point' on the drain. The difference is that at x_D^* the head in uniform head and uniform flux well are equal but not constant during the time. But in 'fixed head point' the head in the uniform flux line sink and the drain is equal and constant during the time.

In order to find the location of 'fixed head point' on the uniform flux sink it seems logical to simulate the drain by a uniform flux sink numerically and to find the location of 'fixed head point' by comparing the head on the drain and the sink. But in numerical simulation of drain in Section 5.1, it is obtained that the total flow to the drain in 0.18, 16.74 and 855.02 days periods are 0.00196, 0.00175 and 0.000897 m^3/s and is non-linearly decreased during the time. Therefore, simulating a drain by a uniform flux line sink along which the total flow is continuously changing during the time is complex and time consuming.

In order to find the location of 'fixed head point' during the time we used Fig. 2(a). This figure shows that for keeping the head constant along the drain periphery the flow rate ratio along the drain is increased toward its ends. A sudden change in flow rate can be seen close to the end of the drain in an interval of about 5% of the half-length. This sudden change in flow rate keeps the head constant on the drain periphery near its ends by compensating the lack of line sink in other side of the drain ends. This compensating effect is limited to about 5% of the drain half-length close to its ends. It implies that a point on the periphery of a drain is mainly affected by the point sinks located at a distance of about $\pm 5\%$ of half-length from the point. On the other hand, Eq. (7) shows that the drawdown induced by a point sink at a close by point depends on the distance and discharge rate to the sink (Q_D). Therefore, the resultant drawdown in a specific point from two point sinks located at equal distance from the point will be kept constant if the average flow rate to the sinks remains constant. And so, if the flux rate along the line sink changes linearly and its average remains constant, then the resultant drawdown in a point located at equal distance from the line sink ends will remain constant too. Therefore, the effect of such a line sink on a point located at equal distance from its ends is the same as the effect of a uniform flux line sink whose average flow rate is equal to the flux rate in the midpoint of the line sink. Now, if the flux rate along the line sink located in an interval of $\pm 5\%$ from a point on the periphery of the drain, changes almost linearly, then the induced resultant drawdown at the point is the same as the induced drawdown by a uniform flux line sink with the same average flow rate. The average flow rate is then equal to the flow rate of the point sink located at the middle of the line sink. Also, the head at the point on the periphery of the line sink will be almost the same as the head at a point on the periphery of a uniform flux line sink if the flux rate at the closest point to these points along the line sinks is the same. As can be seen in Fig. 2(a), in the inner part of the drain, along 0–85% of the drain length the flow rate changes almost linearly. Therefore, in the point along the drain axis on which the flow rate ratio is one, the head on the closest point to this point sink on the drain periphery is almost equal to the head on the periphery of a uniform flux sink whose flow rate is equal to the average flow rate of the drain. Therefore, the point with flow rate ratio equal to one on the drain, can be treated as optimum 'fixed head point' position.

Fig. 2(a) shows that the flow rate ratio at $x_D =$ 0.786, 0.771 and 0.673 is equal to one for 0.18, 16.74 and 855.02 days periods, respectively. Therefore, the optimum 'fixed head point' position changes from 0.786 to 0.673 during early to late stages. It shows that the optimum position converges to $x_D^* = 0.68$ of Rosa and Carvalho (1989) during the time.

There is an approximation in determining the optimal position of 'fixed head point' by the above described method, because it is assumed that an interval of $\pm$ 5% around a point is the most effective on the head and the flux rate distribution along the drain axis in this interval is linear.

To clear the problem further and showing the effect of variation in 'fixed head point' position on the total discharge to a uniform flux line sink, the total discharge rate to a sink for different ' fixed head point ' position is calculated. For this, a horizontal uniform flux line sink is considered with the same conditions assumed for simulation of a drain in the beginning of Section 5. The 'fixed head points' were fixed on the sink periphery at $z_D = 0.5$, $y_D = 0.01$ and x_D from 0 to 1 with 0.1 interval. The total discharge rates to the sink were calculated by use of the

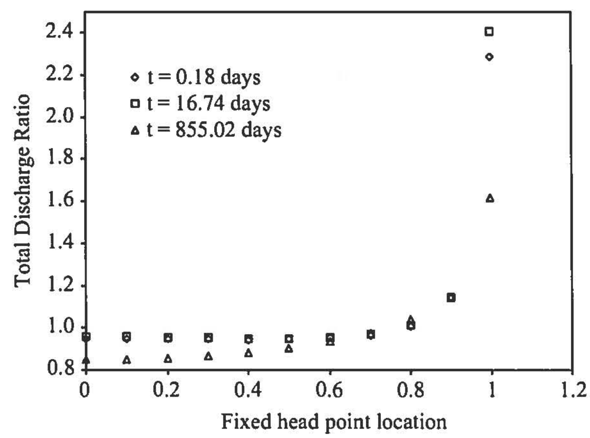

Fig. 4. Total discharge ratio to a uniform flux line sink versus 'fixed head point' location, for three different periods.

analytical method presented in Section 4 (Eq. (12)). Variation of the total discharge versus fixed point location for 0.18, 16.74 and 855.02 days periods are plotted in Fig. 4.

In plotting Fig. 4, the total discharge to the line sink when the 'fixed head point' is in its optimum position is assumed as reference total discharge for that period. In this figure, the horizontal axis, x_D, is the location of 'fixed head point' and the vertical axis is the total discharge ratio. The total discharge ratio is defined as the total discharge to the sink divided by the reference total discharge for that period. Fig. 4 shows that as the position of the 'fixed head point' moves toward the ends of the line sink the total discharge ratio is increased rapidly to about 2.4 and when it moves toward the centre of the sink, the total discharge ratio is decreased gradually to about 0.84. The figure also shows that for 0.18, 16.74 days periods, change in 'fixed head point' position from 0.85 to 0.6 will decrease the total discharge ratio about 5%. It means that the maximum error in estimation of the total discharge of the drain will be less than 5% if the location of 'fixed head point' changes from $x_D=0.6$ to 0.85. Therefore, if the optimum position of 'fixed head point' is assumed fixed at 0.68 during the time then the error in prediction of total discharge will be less than 5% in early times and approach zero at late times. Therefore, Rosa and Carvalho (1989) suggestion used in our solution is quiet acceptable.

6. Derivative type curves of the drawdown

To compare the constant flux horizontal wells solution with the constant head horizontal drains solution and to differentiate various components of flow into the drains, type curves and derivative type curves are computed.

Semilog type curve plots of the dimensionless drawdown s_D (s_{DH}, s_{DHI}, Eqs. (11) and (13)) versus t_D are given in Fig. 5(a). The log–log derivative type curve plots the derivative of dimensionless drawdown over the logarithm of the dimensionless time $ds_D/d\ln t_D$ as a function of t_D (Fig. 5(b)).

The default scenario and parameter values used in these examples are: a horizontal 61 m long drain in an unconfined aquifer with $d=30.5$ m, $K_h=K_z=1.53\times$

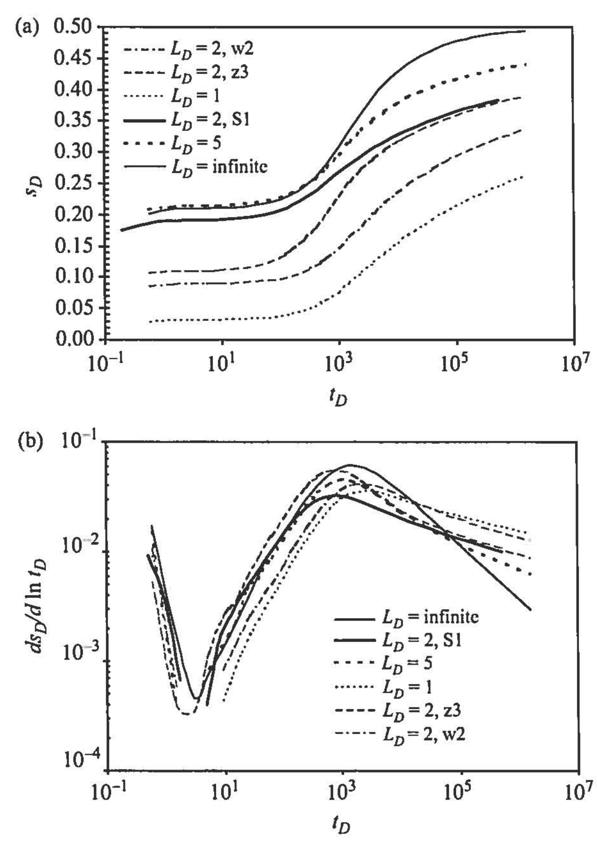

Fig. 5. The type curves (a) and derivative type curves (b) of the cylindrical drain for the case of infinite length, $L_D=1$, 2 and 5, $\sigma=0.003$ (*S1*), $\gamma=20°$ dimensionless drain elevation of 0.25 (w2) and the dimensionless piezometer depth of 0.75 (z3). The other parameters for all the curves are as default.

10^{-6} m s^{-1}, S_y=0.2, σ=0.001 or S_s=6.6×10^{-6}. The initial head of the aquifer is 100.5 m and its bottom is at 70 m elevation. The drain axis is located at z=15.25 m from the bottom of aquifer. The drain is cylindrical with radius $r_w = a \times d = 0.305$ m. Hereafter, for all the cases, only changes in the parameter values will be mentioned.

The type curves of the horizontal drains in the unconfined aquifer have three parts (Fig. 5(a)), as do the type curves of the horizontal wells (constant flux) in an unconfined aquifer (Neuman, 1974). The first part is of very short duration. The drawdown increases with time and the discharge water is supplied from elastic storage, the amount of which is quantified by S_s. In the second part, the drawdown is constant with time. Simply, because the water table drawdown is compensated by the delayed yield. The dominant component is vertical especially near the water table. The third part is characterised by increasing drawdown with time, during which the rate of water discharge is controlled by S_y. Horizontal flow is dominant in this period.

The derivative type curves have two diagnostic parts. The first part is a deep depression that coincides with the horizontal part of the type curve. In the second part, the derivative type curve shows a linear descending trend with a constant slope (Fig. 5(b)). As can be seen in Fig. 5(b), the drains with a certain length have the same slope at late time. The longer the drain length, the steeper the late part of the curve will be. The descending slope in the late part of the constant flux well derivative type curves indicates aquifer recharge (Neuman, 1974). Here, the descending slope in the late part is due to decay of discharge over time.

7. Type curve sensitivity of horizontal drains

Characteristics of the type curves are evaluated through a sensitivity analysis. For the analysis, the following values are set for the aquifer and drain dimensionless parameters: aquifer thickness = 1; drain length $L_D = 2$, $\sigma = 0.001$; delay index $\alpha = 10^9$; well axis $z_{wD} = 0.5$ and $z_D = 0.5$. The effect of each parameter on the type curves is evaluated. For almost all cases the piezometer is located at $x_D = 1$ and $y_D = 0.21$ and the dimensionless drain radius is considered to be 0.01. This is because we want that the distance between the measured point to the drain end be more than 10 times the drain diameter and the discrepancy between the uniform flux and uniform head results be less than 10% (Zhan and Zlotnik, 2002).

7.1. Case 1.Type curves of different piezometer locations

This case tests the sensitivity of the type curves on different monitoring points (piezometers). The piezometers are selected at points C, D, E and F as shown in Fig. 1(b). Points D, E, F are located at $x_D = 0$, $y_D = 0.21$ with elevations, z_D, of 0.5, 0.25 and 0.75, respectively. The point C is at $x_D = 1$, $y_D = 0.21$ and $z_D = 0.5$. Fig. 6 shows the type curves for the different piezometer locations. Points C and D have the same elevation, but less drawdown is observed at point C, because this point is not affected by the total length of the drain. The drawdown at point E near the bottom of the aquifer is larger than at point F near the top of the aquifer at early times, due to the greater recharge near the water table. But, at late time the flow tends to be mainly radial and horizontal and the drawdown at different depths converges to the same amount.

7.2. Case 2.Type curves for different σ

This case tests the sensitivity of type curves for the aquifer with different σ values. Fig. 7 shows the dimensional type curves for σ=0.003, 0.001 and

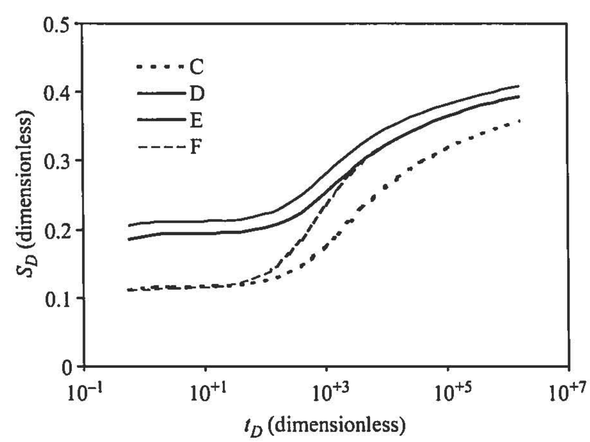

Fig. 6. Type curves for the comparison of the drawdown (Eq. (11)) in piezometer C, D, E and F around a horizontal drain.

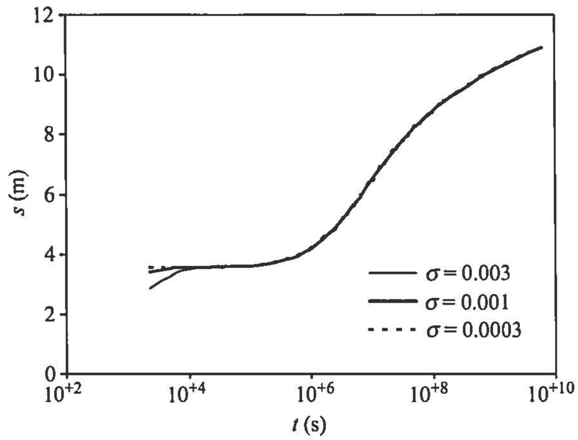

Fig. 7. Drawdown (Eq. (11)) versus time for a horizontal drain with $\sigma=0.003$, 0.001 and 0.0003.

0.0003. A piezometer is located at $x_D=1$, $y_D=0.21$ and $z_D=0.5$ for the three cases. The curves are identical except for the early times when a high value of σ causes less drawdown, indicating the contribution of S_s in controlling discharge to the drain. The drawdown is independent of σ at intermediate and late times. This reflects the gravitational flow to the drain during this period.

7.3. Case 3.Type curves for different delay index

This case tests the sensitivity of type curves for different values of the delay index (α_1). Fig. 8 shows the type curves for $\alpha_1=10^9$, 10^{-2} and 10^{-4}. A piezometer is located at $x_D=1$, $y_D=0.21$ and $z_D=0.5$

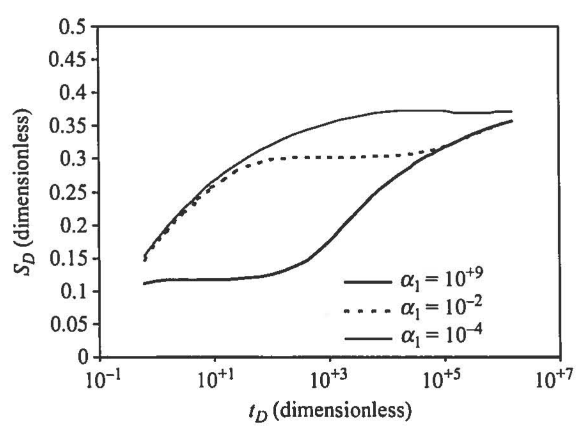

Fig. 8. Type curves (Eq. (11)) for the comparison of different aquifer delay index (α_1) of 10^9, 10^{-2} and 10^{-4}.

for each cases. The curves show that, for the case of instantaneous lowering of water table ($\alpha_1=10^9$), drawdown is least for intermediate times. Decreasing the delay index or increasing the delay time increases the intermediate time drawdown. For $\alpha=10^{-4}$ the drawdown is the largest of the three cases.

7.4. Case 4.Type curves with different drain elevations

This case tests the sensitivity of the type curves for different drain elevations. Fig. 9 shows the type curves for the dimensionless drain elevation of 0.5, 0.25 and 0.75. A piezometers is located at $x_D=1$, $y_D=0.21$ and $z_D=0.5$ for the three cases. The curves show that most drawdown occurs for the well near the bottom of the aquifer ($D_E=0.25$), with the least for the well close to the water table ($D_E=0.75$). That is because the well near the bottom of the aquifer has the maximum constant drawdown. So, the lower elevation drain induces more drawdown to the aquifer. The curves in Fig. 9 also show that at the late time the drawdown around the drain is about linearly and inversely proportional to the drain elevation but in the intermediate time change in drawdown induced by change in drain elevation is less for lower elevation drains. It seems that in intermediate time this proportionality is reduced by decreasing the elevation of the drain.

For the above drain elevations, the type curves of the dimensionless discharge Q_D (Q_{DH}, Q_{DHI}) are also

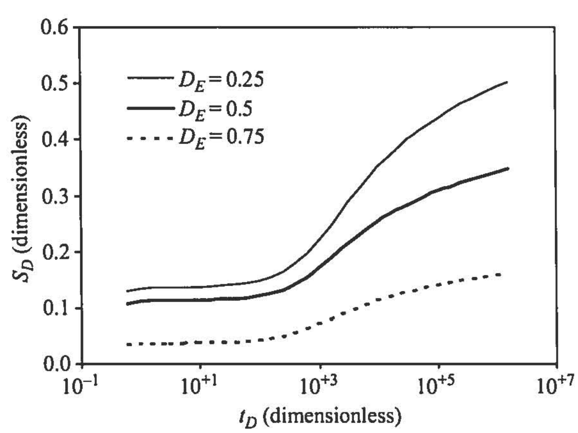

Fig. 9. Type curves of the horizontal drain (Eq. (11)) for different drain elevations, D_E, of 0.5, 0.25 and 0.75 for the piezometer located at $x_D=1$, $z_D=0.5$ and $y_D=0.21$.

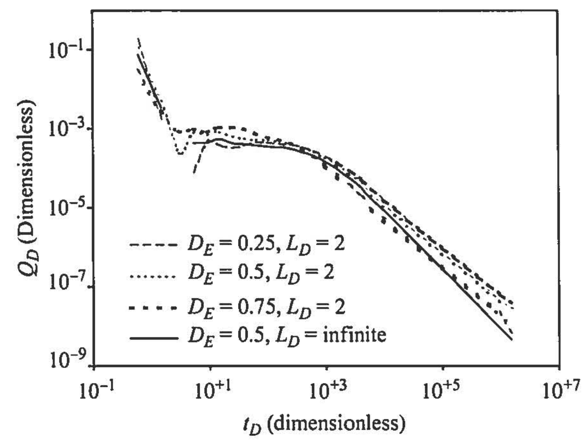

Fig. 10. The discharge (Eqs. (12) and (14)) type curve for different drain elevations, D_E, of 0.5, 0.25 and 0.75.

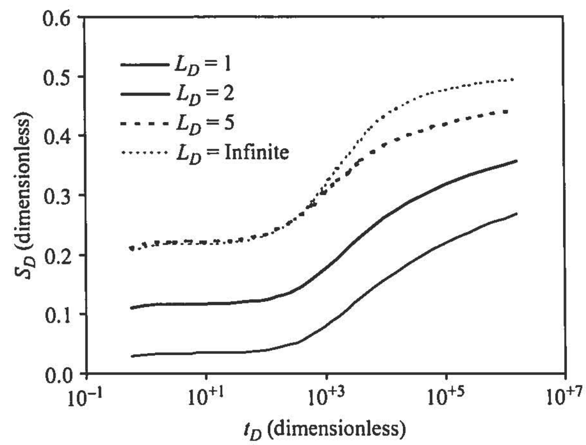

Fig. 11. Type curves of the horizontal drain for different dimensionless drain length, L_D, of 2, 1, 5 and infinite (Eqs. (11) and (13)) for the piezometer located at $x_D=1$, $z_D=0.5$ and $y_D=0.21$.

drawn (Fig. 10). The discharge curves show three distinct parts. Early time shows a steep descending slope. A horizontal part is evident for intermediate time and a descending part with lower slope for late time. The curves also show that for lower elevation drains the discharge is more than that of higher elevation drains especially at late time. The decreasing trend of discharge at late time is due to reduction of difference between the head in the drain and surrounding aquifer during the time.

7.5. Case 5.Type curves with different drain length

This case tests the sensitivity of type curves for the different drain lengths. Fig. 11 shows the type curves for dimensionless drain lengths of 1, 2 and 5, as well as for an infinitely long drain. The piezometer is located at $x_D=1$, $y_D=0.21$ and $z_D=0.5$ for the three finite cases and $y_D=0.21$ and $z_D=0.5$ for infinite case. The curves show that longer drains result in more drawdown. The infinite length drain has more drawdown at late time relative to the drain of length 5. At early and intermediate times they have equal drawdown. This is because at early times the piezometer does measure any effect of distant points along the drains. So, in early times, the flow in both cases is not radial and vertical recharge is dominant. At late times, the flow regime to the drain with $L_D=5$ is mainly radial, but to the infinitely long drain it is two-dimensional and its type curve (Fig. 11) shows greater drawdown.

For determining the effect of drain length on discharge, the discharge curves for infinite length and $L_D=2$ are drawn (Fig. 10). It must be noted that for the $L_D=2$ drain, the dimensionless total discharge is shown, while for the infinite length drain, the discharge per unit length is shown. The curves show that the total discharge increases with increasing drain length. And they also show that the longer drain has steeper slope in its discharge curve at the late time.

8. Summary and conclusion

A method is proposed to directly evaluate discharge from horizontal drains in water-table aquifers. The solution for the horizontal constant flux well (Zhan and Zlotnik, 2002) is modified and then normalised by using Carslaw and Jaeger (1959) method to obtain the solution for a constant head horizontal drain. By the numerical simulation of a constant head drain, we found that for predicting the total flow rate to the drain by use of a uniform flux well, one can use Rosa and Carvalho (1989) suggestion and select a point at 0.68 of the well half-length from its centre and keep the head steady on that point by use of Carslaw and Jaeger (1959) method. The solution in terms of the drawdown and discharge is written in the Laplace domain (Eqs. (11)–

(14)). For the case of infinite length drain, the proposed method results in an exact solution for determining the drawdown around and the total discharge to the drain. In the case of finite length drain, this method will result in less than 5% error in prediction of total flow to the drain.

The proposed solution is simpler than the method currently existed for simulating a constant or uniform head vertical wells (Cassiani and Kabala, 1998; Hemker, 1999; Chang and Chen, 2003). It also has some advantages relative to the solution presented for horizontal drain (Gjerde and Tyvand, 1992). For instance, the proposed method is a semi-analytical solution in which the delay yield and specific storage of the aquifer is considered and also it can be used for finite length drains and infinite extent aquifers.

The computer programs, HDD and HDQ, generate drawdown and discharge type curves for horizontal drains in the real time domain. HDD program numerically evaluates Eqs. (11) and (13) while HDQ program evaluates Eqs. (12) and (14), both using Maple®. These programs can generate the type curves for drawdown at any monitoring point, and so can generate the type curves for discharge to the drain at any given time.

The drawdown type curve and its derivative have also been investigated. In all curves, the early time response is short and consists of two main parts. At intermediate times, the type curve and the derivative type curve are the same as those for constant flux horizontal wells; both cases show a steady drawdown period. This period in the derivative type curve is shown by a deep depression in the curve. At late times, the drawdown type curve has an increasing trend but the derivative type curve as expected shows a descending trend with constant slope. This constant descending slope depends on the drain length and its slope increases with increasing drain length. The descending part of the late time period in the derivative type curve shows an apparent recharge. This apparent recharge is because of reducing discharge to the drain over time.

The sensitivity of the drawdown type curves with respect to piezometer location, parameter σ and aquifer delay index, drain length and elevation was tested. The sensitivity of discharge type curves with respect to drain elevation was also investigated. In general the following results were also achieved:

- In finite length drains, the drawdown depends on the distance to the midpoint of the drain rather than the distance to the drain axis (Fig. 6). As a result, in contrast to all times the prevailing flow is radial toward the midpoint of the drain. Note that in horizontal wells the flow is radial only at late times.
- At intermediate times, the vertical flow is dominated near the water table, in the points located above the drain axis. The vertical flow and recharging effect of falling water table are limited to the region above the drain axis. This causes considerable difference between the drawdown above and below the drain axis. The drawdown below the drain axis is more than that of above the drain axis. But in late times, the drawdown above and below the drain axis converges to the same amount (Fig. 6). It means that at late times the flow tends to be supplied from far distance rather than from falling water table.
- To investigate the drawdown curve sensitivity relative to σ (or $S_s d/S_y$) parameter, the aquifer with high delay index is considered (Fig. 7). Whit the high delay index, the water supply from S_s and S_y both are instantaneous and comparable. For high delay index, the drawdown around the drain is insensitive to σ parameter during the intermediate and late times.
- The drawdown around a drain is inversely proportional to the drain elevation (Fig. 9). At the late time this proportionality is almost linear, but at intermediate times for shallow drains the change in drawdown per unit change in drain elevation is more than that of deep drains. It means that the drain with lower elevation shows a delay in lowering the head in the aquifer in intermediate times. In dewatering projects it is important to know about the length of the intermediate time.
- The total discharge to the drain is inversely proportional to the drain elevation (Fig. 10). This is because, by decreasing the drain elevation the difference between the head at the drain and surrounding aquifer will increase. Also the discharge rate to the drain decreases during the time, which is because of decrease in the head in the surrounding aquifer and decrease in the difference between the head in the drain and the surrounding aquifer during the time.

- For the late times, longer drains induce greater drawdown every where in the aquifer (Fig. 11). But in intermediate times the drawdown is proportional to the drain length and approaches a steady condition at a certain length. It must be noted that at late time the sensitivity of drawdown around the drain relative to the drain length will gradually decrease with increasing the drain length.
- The drains with equal length have a certain constant descending slope in the late time part of their derivative curve. The descending slope in the late times is steeper for longer drains. The slope of the derivative type curve may be helpful in determining the unknown length of natural or artificial drains. In practical problems where the rate of change in drawdown is important, one can determine the optimum drain length. Also, for prediction of drawdown in long times the constant slope of the derivative type curve at the late time can be helpful.

In general, the behaviour of the drain in intermediate and late times are quiet different. For dewatering projects by use of horizontal drains, in a low permeable and thick aquifer, in which the length of intermediate time is considerably long, the behaviour of the drain in intermediate time as considered above is of prompt importance.

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EXHIBIT D

IN THE DISTRICT COURT OF THE FIFTH JUDICIAL DISTRICT OF THE
STATE OF IDAHO, IN AND FOR THE COUNTY OF TWIN FALLS

In Re SRBA	)	PARTIAL DECREE PURSUANT TO
	)	I.R.C.P. 54(b) FOR
Case No. 39576	)	
	)	Water Right 36-02551

NAME & ADDRESS: RANGEN INC
PO BOX 706
BUHL ID 83316

SOURCE: MARTIN-CURREN TUNNEL TRIBUTARY: BILLINGSLEY CREEK

QUANTITY: 48.54 CFS

THE QUANTITY OF WATER UNDER THIS RIGHT FOR DOMESTIC USE SHALL NOT EXCEED 13,000 GALLONS PER DAY.
THIS RIGHT AND RIGHT NO. 36-15501 ARE LIMITED TO A TOTAL COMBINED FACILITY VOLUME OF 123,272 CU. FT.

PRIORITY DATE: 07/13/1962

POINT OF DIVERSION: T07S R14E S32 SESWNW Within GOODING County

PURPOSE AND PERIOD OF USE:

PURPOSE OF USE	PERIOD OF USE	QUANTITY
FISH PROPAGATION	01-01 12-31	48.54 CFS
DOMESTIC 3 HOMES AND 2 OFFICES	01-01 12-31	0.1 CFS

PLACE OF USE:

FISH PROPAGATION Within GOODING County
T07S R14E S31 SENE
S32 SWNW

DOMESTIC Within GOODING County
T07S R14E S31 SENE
S32 SWNW

OTHER PROVISIONS NECESSARY FOR DEFINITION OR ADMINISTRATION OF THIS WATER RIGHT:

THE QUANTITY OF WATER DECREED FOR THIS WATER RIGHT FOR DOMESTIC USE IS NOT A DETERMINATION OF HISTORICAL BENEFICIAL USE.

RULE 54(b) CERTIFICATE

With respect to the issues determined by the above judgment or order, it is hereby CERTIFIED, in accordance with Rule 54(b), I.R.C.P., that the court has determined that there is no just reason for delay of the entry of a final judgment and that the court has and does hereby direct that the above judgment or order shall be a final judgment upon which execution may issue and an appeal may be taken as provided by the Idaho Appellate Rules.

DANIEL C. HURLBUTT, JR.
PRESIDING JUDGE
Snake River Basin Adjudication

EXHIBIT E

IN THE DISTRICT COURT OF THE FIFTH JUDICIAL DISTRICT OF THE
STATE OF IDAHO, IN AND FOR THE COUNTY OF TWIN FALLS

In Re SRBA	)	PARTIAL DECREE PURSUANT TO I.R.C.P. 54(b) FOR	1997 DEC 30 AM 9:46
Case No. 39576	)	Water Right 36-07694	DISTRICT COURT - SRBA TWIN FALLS CO., IDAHO
	)		FILED

NAME & ADDRESS: RANGEN INC
PO BOX 706
BUHL ID 83316

SOURCE: MARTIN-CURREN TUNNEL TRIBUTARY: BILLINGSLEY CREEK

QUANTITY: 26.00 CFS

FACILITY VOLUME=287,640 CU. FT.

PRIORITY DATE: 04/12/1977

POINT OF DIVERSION: T07S R14E S32 SESWNW Within GOODING County

PURPOSE AND PERIOD OF USE:	PURPOSE OF USE	PERIOD OF USE	QUANTITY
	FISH PROPAGATION	01-01 12-31	26.00 CFS

PLACE OF USE: FISH PROPAGATION Within GOODING County
T07S R14E S31 SENE
S32 SWNW

RULE 54(b) CERTIFICATE

With respect to the issues determined by the above judgment or order, it is hereby CERTIFIED, in accordance with Rule 54(b), I.R.C.P., that the court has determined that there is no just reason for delay of the entry of a final judgment and that the court has and does hereby direct that the above judgment or order shall be a final judgment upon which execution may issue and an appeal may be taken as provided by the Idaho Appellate Rules.

DANIEL C. HURLBUTT, JR.
PRESIDING JUDGE
Snake River Basin Adjudication

EXHIBIT F

Exhibit F: Point of Diversion for Water Right 36-02551 & 36-07694

0 | 1,100 | 2,200 Feet

Curren Tunnel outlet 36-2551
spring discharges
SWNW quarter sec
T07S R14E Sec32

N

amec

Map compiled 3/2013; intended for planning purposes only
Data Sources: NAIP 2011 imagery, New Int'l Mortgage Bank v. Idaho Power, In Equity No. 1602 (D. Idaho March 22, 1932)