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شوال 1429ھ

Ministry of Higher
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University of Babylon
College of Engineering
Civil Eng. Department

LOWERING THE WATER TABLE IN ANCIENT BABYLON

A Thesis

Submitted to the College of Engineering
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By

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B.Sc.2004

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شوال 1429 هـ

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

اللَّهُ نُورُ السَّمَوَاتِ وَالْأَرْضِ مِثْلُ نُورِهِ كَمَشْكُوتٍ فِيهَا مِصْبَاحُ الْمِصْبَاحِ
فِي نِزْجَاةِ النِّزْجَاةِ كَأَنَّهَا كَوْكَبٌ دَرِيٌّ يُوقَدُ مِنْ شَجَرَةٍ
مُبَارَكَةٍ زَيْتُونَةٍ لَّا شَرْقِيَّةٍ وَلَا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ
تَمْسَسْهُ نَارُ نُورٍ عَلَى نُورٍ يَهْدِي اللَّهُ لِنُورِهِ مَنْ يَشَاءُ وَيَضْرِبُ اللَّهُ الْأَمْثَالَ
لِلنَّاسِ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيمٌ

صَدَقَ اللَّهُ الْعَظِيمُ

سورة النور، الآية (35)

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

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سورة النور، الآية (35)

ABSTRACT

Shallow groundwater level in the archeological site of Babylon, which is 22.79 km², prevents further archeological investigations as well as causes serious damages to some of the old buildings. The depth of groundwater in this area varies from 0.5 to 4m depending on distance from Shatt Al Hilla and season.

The purpose of the present study is to simulate the groundwater flow in Babylon using two different mathematical models. The first one is the GMS model while the second is a new numerical one.

In this study, different numbers of wells assumed at different locations penetrating the whole 28 m thick upper unconfined aquifer are considered in the GMS program. Hence, it is found that the optimum number of wells located at a specific site far enough from the old buildings is 15 well. When these wells discharge at a rate of 17 ℓ/s each for a period of 360 days, the water table will be lowered by 1-10 m, but the same results obtained in the numerical model when using 18 wells (3 wells added) at a rate of 20 ℓ/s for a duration of 720 days.

The problem of the suggested pumped water disposal is also studied. Chemical analysis of groundwater in the study area shows that the properties of this water does not vary from the water of Shat Al Hilla. Therefore, it is concluded that the pumped water can be discharged into Shatt Al Hilla.

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Rand Sami

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APPENDICES

Appendix - A –

```
REM Finite Difference Flow Model to Simulate the Ground Water Flow
REM in Old Babylon City
INPUT "Enter Time Period of Simulation in Days"; TP
PRINT "Enter Number of Time Steps through the Period of Simulation "
PRINT "This Number Should be Greater Than Zero "
INPUT ; NS
IF NS > 0 THEN 5
PRINT "NS should be greater than zero, the program will be stopped "
GOTO 170
5 INPUT "Enter Number of Wells That Supposed to be "; NW
INPUT "Enter Number of Iterations"; NI
PRINT " Enter Maximum Difference Between the Observed and Simulated "
PRINT "Heads in the Phreatic Layer"
INPUT ; ER1
PRINT " Enter Maximum Difference Between the Observed and Simulated"
PRINT "Heads in the Lower layer "
INPUT ; ER3
INPUT " Enter Maximnm Number of intervales for a well"; MNP
INPUT " Enter Number of Rows"; R
INPUT " Enter Number of Columns"; C
DIM HO1F(R, C), HO3F(R, C )
DIM HS1(R, C), HS3(R, C), HO1(R, C), HO3(R, C), DY(R), DX(C), TX1(R, C)
DIM TY1(R, C), TX3(R, C), TY3(R, C), GSL(R, C), X(R, C), Y(R, C), S(R, C)
DIM EFFE(R, C), Qnet(R, C), BL1(R, C), LCM(R, C), LCB(R, C), WL(R, C),
awb(R, C)
DIM perm(R, C), trans(R, C), Teb(R, C), Beb(R, C), Wx(NW), Wy(NW)
DIM NP(NW), TI(NW, MNP), TF(NW, MNP), Qqw(NW, MNP), F(R), G(R),
Qw(R, C )
OPEN "HO1.dat" FOR INPUT AS #1
OPEN "HO3.dat" FOR INPUT AS #2
OPEN "GSLT.dat" FOR INPUT AS #3
OPEN "S.dat" FOR INPUT AS #4
OPEN "EFFE.dat" FOR INPUT AS #5
OPEN "Qnet.dat" FOR INPUT AS #6
OPEN "BL1.dat" FOR INPUT AS #7
OPEN "LCM.dat" FOR INPUT AS #8
OPEN "river1.dat" FOR INPUT AS #9
OPEN "perm.dat" FOR INPUT AS #12
OPEN "trans.dat" FOR INPUT AS #13
OPEN "HS1.dat" FOR OUTPUT AS #18
OPEN "HS3.dat" FOR OUTPUT AS #19
FOR I = 1 TO R
DY(I) = 100
NEXT
FOR J = 1 TO C
DX(J) = 100
NEXT
```

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FOR I = 1 TO R
FOR J = 1 TO C
INPUT #1, X(I, J), Y(I, J), HO1F(I, J)
INPUT #2, X(I, J), Y(I, J), HO3F(I, J)
INPUT #3, X(I, J), Y(I, J), GSL(I, J)
INPUT #4, X(I, J), Y(I, J), S(I, J)
INPUT #5, X(I, J), Y(I, J), EFFE(I, J)
INPUT #6, X(I, J), Y(I, J), Qnet(I, J)
Qnet(I, J) = Qnet(I, J) / (DX(J) * DY(I))
INPUT #7, X(I, J), Y(I, J), BL1(I, J)
IF GSL(I, J) = 0 THEN 10
IF GSL(I, J) > BL1(I, J) THEN 10
PRINT " Ground Surface Level is Below or Equal "
PRINT " to the Top Elevation of the phreatic Layer "
PRINT " Check the Entered Data "
PRINT " the Program Will Be Stopped "
PRINT "I="; I, "J="; J
GOTO 170
10 INPUT #8, X(I, J), Y(I, J), LCM(I, J)
INPUT #9, Teb(I, J), Beb(I, J), LCB(I, J), WL(I, J), awb(I, J)
INPUT #12, X(I, J), Y(I, J), perm(I, J)
INPUT #13, X(I, J), Y(I, J), trans(I, J)
IF Teb(I, J) = 0 THEN 15
IF Teb(I, J) > Beb(I, J) THEN 15
PRINT " Top Elevation of the Bed of Surface Water Body "
PRINT " is Less or Equal to the Bottom Elevation "
PRINT " Check the Entered Data "
PRINT " the Program Will Be Stopped "
PRINT "I="; I, "J="; J
GOTO 170
15 NEXT
NEXT
IF NW = 0 THEN 20
FOR I = 1 TO NW
L = 0
PRINT "Enter number of pumping intervales for the well"; I
INPUT ; NP(I)
PRINT " Enter number of cell in X direction that the well"; I
PRINT " is supposed to be "
INPUT ; Wx(I)
PRINT " Enter number of cell in y direction that the well"; I
PRINT " is supposed to be "
INPUT ; Wy(I)
FOR J = 1 TO NP(I)
PRINT "Entre Initial Time of Pumping Interval"; J
PRINT " for the well"; I
INPUT ; TI(I, J)
PRINT "Entre Final Time of Pumping Interval"; J
PRINT " for the well"; I
INPUT ; TF(I, J)

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PRINT "Enter the Discharge of Well"; I
PRINT "for the Interval"; J
INPUT ; Qqw(I, J)
Qqw(I, J) = Qqw(I, J) / (DY(Wy(I)) * DX(Wx(I)))
Td = TF(I, J) - Tl(I, J)
L = L + Td
NEXT
NEXT
IF L <= TP THEN 20
PRINT " There is an Error in pumping interval data "
PRINT " the program will be stoped "
GOTO 170
REM Calculations of Internodal Transmissivity and Permeability
REM and Area Adjustment
20 FOR I = 1 TO R
FOR J = 1 TO C
LCB(I, J) = LCB(I, J) * awb(I, J) / (DX(J) * DY(I))
NEXT
NEXT
FOR I = 1 TO R - 1
FOR J = 1 TO C - 1
Z1 = perm(I, J) + perm(I, J + 1)
Z2 = perm(I, J) + perm(I + 1, J)
Z3 = trans(I, J) + trans(I, J + 1)
Z4 = trans(I, J) + trans(I + 1, J)
IF Z1 = 0 THEN TX1(I, J) = 0: GOTO 25
TX1(I, J) = perm(I, J) * perm(I, J + 1) * 2 / (perm(I, J) + perm(I, J + 1))
25 IF Z2 = 0 THEN TY1(I, J) = 0: GOTO 30
TY1(I, J) = perm(I, J) * perm(I + 1, J) * 2 / (perm(I, J) + perm(I + 1, J))
30 IF Z3 = 0 THEN TX3(I, J) = 0: GOTO 40
TX3(I, J) = trans(I, J) * trans(I, J + 1) * 2 / (trans(I, J) + trans(I, J))
40 IF Z4 = 0 THEN TY3(I, J) = 0: GOTO 50
TY3(I, J) = trans(I, J) * trans(I + 1, J) * 2 / (trans(I, J) + trans(I + 1))
50 NEXT
NEXT
FOR I = 1 TO R
FOR J = 1 TO C
HS1(I, J) = HO1F(I, J)
HS3(I, J) = HO3F(I, J)
NEXT
NEXT
FOR I = 1 TO R - 1
FOR J = 1 TO C - 1
TX1(I, J) = TX1(I, J) / (.5 * (DX(J) + DX(J + 1)))
TY1(I, J) = TY1(I, J) / (.5 * (DY(I) + DY(I + 1)))
TX3(I, J) = TX3(I, J) / (.5 * (DX(J) + DX(J + 1)))
TY3(I, J) = TY3(I, J) / (.5 * (DY(I) + DY(I + 1)))
NEXT
NEXT
DTIME = TP / NS

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IF NW = 0 THEN 90
FOR I = 1 TO NW
FOR J = 1 TO NP(I)
DE = TF(I, J) - TI(I, J)
IF DE > Td THEN 60
Td = DE
60 NEXT
NEXT
IF Td > 0 THEN 65
PRINT "minimum interval should be greater than zero"
PRINT " check the input data "
PRINT "the program will be stopped "
GOTO 170
65 IF DTIME <= Td THEN 90
NS = 0
70 NS = NS + 1
DTIME = TP / NS
IF DTIME <= Td THEN 80
GOTO 70
80 PRINT "Number of Time Steps is Adjusted to"; NS
PRINT "Time Step is Adjusted to be Less or Equal"
PRINT " to minimum pumping interval"; DTIME
90 TIME = 0
FOR IK = 1 TO NS
FOR I = 1 TO R
FOR J = 1 TO C
HO1(I, J) = HS1(I, J)
HO3(I, J) = HS3(I, J)
NEXT
NEXT
TIME = TIME + DTIME
IT = 0
95 CE1 = 0
CE3 = 0
IT = IT + 1
REM Phreatic layer Column Calculations
FOR J = 2 TO C - 1
m = (IT / 2)
IF m = INT(m) THEN J = C - J + 1
FOR I = 2 TO R - 1
IF HS1(I, J) = 0 THEN 96
IF HS1(I, J) <= BL1(I, J) THEN
AM1 = .01
AM2 = .01
AM3 = .01
AM4 = .01
ELSE
96 DH = HS1(I, J) - BL1(I, J)
AM1 = SQR(ABS((HS1(I - 1, J) - BL1(I - 1, J)) * DH))
AM2 = SQR(ABS((HS1(I, J + 1) - BL1(I, J + 1)) * DH))

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AM3 = SQR(ABS((HS1(I + 1, J) - BL1(I + 1, J)) * DH))
AM4 = SQR(ABS((HS1(I, J - 1) - BL1(I, J - 1)) * DH))
END IF
Qw(I, J) = 0
IF NW = 0 THEN 99
FOR mm = 1 TO NW
IF Wy(mm) <> I THEN 98
IF Wx(mm) <> J THEN 98
FOR kk = 1 TO NP(mm)
IF Tl(mm, kk) > TIME THEN 97
IF Tf(mm, kk) < TIME THEN 97
Qw(I, J) = Qw(I, J) + Qqw(mm, kk)
97 NEXT
98 NEXT
99 A = -TY1(I - 1, J) * AM1 / DY(I)
Cc = -TY1(I, J) * AM3 / DY(I)
IF HS1(I, J) > BeB(I, J) THEN
QR1 = LCB(I, J)
QR2 = LCB(I, J) * WL(I, J)
ELSE
QR1 = 0
QR2 = LCB(I, J) * WL(I, J) - LCB(I, J) * TeB(I, J)
END IF
b1 = TY1(I - 1, J) * AM1 / DY(I) + TX1(I, J) * AM2 / DX(J) + TY1(I, J) *
AM3/DY(I)
b2 = TX1(I, J - 1) * AM4 / DX(J) + EFFE(I, J) / DTIME + LCM(I, J) + QR1
b = b1 + b2
d1 = Qw(I, J) + HS1(I, J + 1) * TX1(I, J) * AM2 / DX(J) + HS1(I, J - 1)*TX1(I,J-
1)*AM4/DX(J)
d2 = Qnet(I, J) + HO1(I, J) * EFFE(I, J) / DTIME + LCM(I, J) * HS3(I, J)+QR2
d = d1 + d2
F(1) = 0
F(R - 1) = 0
G(1) = 0
G(R - 1) = 0
w = b - A * F(I - 1)
IF w = 0 THEN
F(I) = 0
G(I) = HS1(I, J)
ELSE
F(I) = Cc / w
G(I) = (d - A * G(I - 1)) / w
END IF
NEXT
HF = ABS(HS1(R - 1, J) - G(R - 1))
IF HF > CE1 THEN CE1 = HF
HS1(R - 1, J) = G(R - 1)
FOR v = R - 2 TO 2 STEP -1
HA = G(v) - F(v) * HS1(v + 1, J)
HF = ABS(HA - HS1(v, J))

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IF HF > CE1 THEN CE1 = HF
HS1(v, J) = HA
NEXT
NEXT
FOR I = 1 TO R
FOR J = 1 TO C
CHECK = HS1(I, J) - GSL(I, J)
IF CHECK > .1 THEN
PRINT " water table at the following printed nodes is greater than"
PRINT " the ground surface levelmor than 10 cm.This is not agree with the"
PRINT " assumption in construction this model. The program will be stopped"
PRINT "I="; I, "J="; J
PRINT "HS1="; HS1(I, J), "GSL="; GSL(I, J)
GOTO 170
ELSE
END IF
NEXT
NEXT
REM Lower Layer Column Calculations
FOR J = 2 TO C - 1
m = (IT / 2)
IF m = INT(m) THEN J = C - J + 1
FOR I = 2 TO R - 1
Qw(I, J) = 0
IF NW = 0 THEN 120
FOR mm = 1 TO NW
IF Wy(mm) <> I THEN 110
IF Wx(mm) <> J THEN 110
FOR kk = 1 TO NP(mm)
IF TI(mm, kk) > TIME THEN 100
IF TF(mm, kk) < TIME THEN 100
Qw(I, J) = Qw(I, J) + Qqw(mm, kk)
100 NEXT
110 NEXT
120 A = -TY3(I - 1, J) / DY(I)
Cc = -TY3(I, J) / DY(I)
b1 = TX3(I, J) / DX(J) + TX3(I, J - 1) / DX(J) + TY3(I, J) / DY(I)
b2 = TY3(I - 1, J) / DY(I) + LCM(I, J) + S(I, J) / DTIME
b = b1 + b2
d1 = Qw(I, J) + HO3(I, J) * S(I, J) / DTIME + LCM(I, J) * HS1(I, J)
d2 = HS3(I, J - 1) * TX3(I, J - 1) / DX(J) + HS3(I, J + 1) * TX3(I, J) / D
d = d1 + d2
F(1) = 0
F(R - 1) = 0
G(1) = 0
G(R - 1) = 0
w = b - A * F(I - 1)
IF w = 0 THEN
F(I) = 0
G(I) = HS3(I, J)

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ELSE
F(I) = Cc / w
G(I) = (d - A * G(I - 1)) / w
END IF
NEXT
NEXT
HF = ABS(HS3(R - 1, J) - G(R - 1))
IF HF > CE3 THEN CE3 = HF
HS3(R - 1, J) = G(R - 1)
FOR v = R - 2 TO 2 STEP -1
HA = G(v) - F(v) * HS3(v + 1, J)
HF = ABS(HA - HS3(v, J))
IF HF > CE3 THEN CE3 = HF
HS3(v, J) = HA
NEXT
NEXT
REM Pheratic Layer Raw Calculations
FOR I = 2 TO R - 1
m = (IT / 2)
IF m = INT(m) THEN I = R - I + 1
FOR J = 2 TO C - 1
IF HS1(I, J) = 0 THEN 125
IF HS1(I, J) <= BL1(I, J) THEN
AM1 = .01
AM2 = .01
AM3 = .01
AM4 = .01
ELSE
125 DH = HS1(I, J) - BL1(I, J)
AM1 = SQR(ABS((HS1(I - 1, J) - BL1(I - 1, J)) * DH))
AM2 = SQR(ABS((HS1(I, J + 1) - BL1(I, J + 1)) * DH))
AM3 = SQR(ABS((HS1(I + 1, J) - BL1(I + 1, J)) * DH))
AM4 = SQR(ABS((HS1(I, J - 1) - BL1(I, J - 1)) * DH))
END IF
Qw(I, J) = 0
IF NW = 0 THEN 128
FOR mm = 1 TO NW
IF Wy(mm) <> I THEN 127
IF Wx(mm) <> J THEN 127
FOR kk = 1 TO NP(mm)
IF TI(mm, kk) > TIME THEN 126
IF TF(mm, kk) < TIME THEN 126
Qw(I, J) = Qw(I, J) + Qqw(mm, kk)
126 NEXT
127 NEXT
128 A = -TX1(I, J - 1) * AM4 / DX(J)
Cc = -TX1(I, J) * AM2 / DX(J)
IF HS1(I, J) > Beb(I, J) THEN
QR1 = LCB(I, J)
QR2 = LCB(I, J) * WL(I, J)
ELSE

```

```

QR1 = 0
QR2 = LCB(I, J) * WL(I, J) - LCB(I, J) * Teb(I, J)
END IF
b1 = TY1(I - 1, J) * AM1 / DY(I) + TX1(I, J) * AM2 / DX(J) + TY1(I, J) *
AM3/DY(I)
b2 = TX1(I, J - 1) * AM4 / DX(J) + LCM(I, J) + EFFE(I, J) / DTIME + QR1
b = b1 + b2
d1 = Qw(I, J) + Qnet(I, J) + HO1(I, J) * EFFE(I, J) / DTIME + LCM(I,
J)*HS3(I,J)+QR2
d2 = HS1(I - 1, J) * TY1(I - 1, J) * AM1 / DY(I) + HS1(I + 1, J) * TY1(I ,
J)*AM3/DY(I)
d = d1 + d2
F(1) = 0
F(C - 1) = 0
G(1) = 0
G(C - 1) = 0
w = b - A * F(J - 1)
IF w = 0 THEN
F(J) = 0
G(J) = HS1(I, J)
ELSE
F(J) = Cc / w
G(J) = (d - A * G(J - 1)) / w
END IF
NEXT
NEXT
HF = ABS(HS1(I, C - 1) - G(C - 1))
IF HF > CE1 THEN CE1 = HF
HS1(I, C - 1) = G(C - 1)
FOR v = C - 2 TO 2 STEP -1
HA = G(v) - F(v) * HS1(I, v + 1)
HF = ABS(HS1(I, v) - HA)
IF HF > CE1 THEN CE1 = HF
HS1(I, v) = HA
NEXT
NEXT
FOR I = 1 TO R
FOR J = 1 TO C
CHECK = HS1(I, J) - GSL(I, J)
IF CHECK > .1 THEN
PRINT " water table at the following printed nodes is greater than "
PRINT " the ground surface level more than 10 cm.This is not agree with th
PRINT " assumption in construction this model. The program will be stopped
PRINT "I="; I, "J="; J
PRINT "HS1="; HS1(I, J), "GSL="; GSL(I, J)
GOTO 170
ELSE
END IF
NEXT
NEXT
NEXT
REM Lower Layer Raw Calculations

```

```

FOR I = 2 TO R - 1
m = (IT / 2)
IF m = INT(m) THEN I = R - I + 1
FOR J = 2 TO C - 1
Qw(I, J) = 0
IF NW = 0 THEN 150
FOR mm = 1 TO NW
IF Wy(mm) <> I THEN 140
IF Wx(mm) <> J THEN 140
FOR kk = 1 TO NP(mm)
IF Tl(mm, kk) > TIME THEN 130
IF Tf(mm, kk) <= TIME THEN 130
Qw(I, J) = Qw(I, J) + Qqw(mm, kk)
130 NEXT
140 NEXT
150 A = -TX3(I, J - 1) / DX(J)
Cc = -TX3(I, J) / DX(J)
b1 = TY3(I - 1, J) / DY(I) + TX3(I, J) / DX(J) + TY3(I, J) / DY(I)
b2 = TX3(I, J - 1) / DX(J) + LCM(I, J) + S(I, J) / DTIME
b = b1 + b2
d1 = Qw(I, J) + HO3(I, J) * S(I, J) / DTIME + LCM(I, J) * HS1(I, J)
d2 = HS3(I - 1, J) * TY3(I - 1, J) / DY(I) + HS3(I + 1, J) * TY3(I, J) / D
d = d1 + d2
F(1) = 0
F(C - 1) = 0
G(1) = 0
G(C - 1) = 0
w = b - A * F(J - 1)
IF w = 0 THEN
F(J) = 0
G(J) = HS3(I, J)
ELSE
F(J) = Cc / w
G(J) = (d - A * G(J - 1)) / w
END IF
NEXT
HF = ABS(HS3(I, C - 1) - G(C - 1))
IF HF > CE3 THEN CE3 = HF
HS3(I, C - 1) = G(C - 1)
FOR v = C - 2 TO 2 STEP -1
HA = G(v) - F(v) * HS3(I, v + 1)
HF = ABS(HS3(I, v) - HA)
IF HF > CE3 THEN CE3 = HF
HS3(I, v) = HA
NEXT
NEXT
PRINT " Number of Iteration ="; IT
PRINT "Maximume Difference Between the"
PRINT "Heads in the Pheratic Layer="; CE1
PRINT "Maximume Difference Between the "

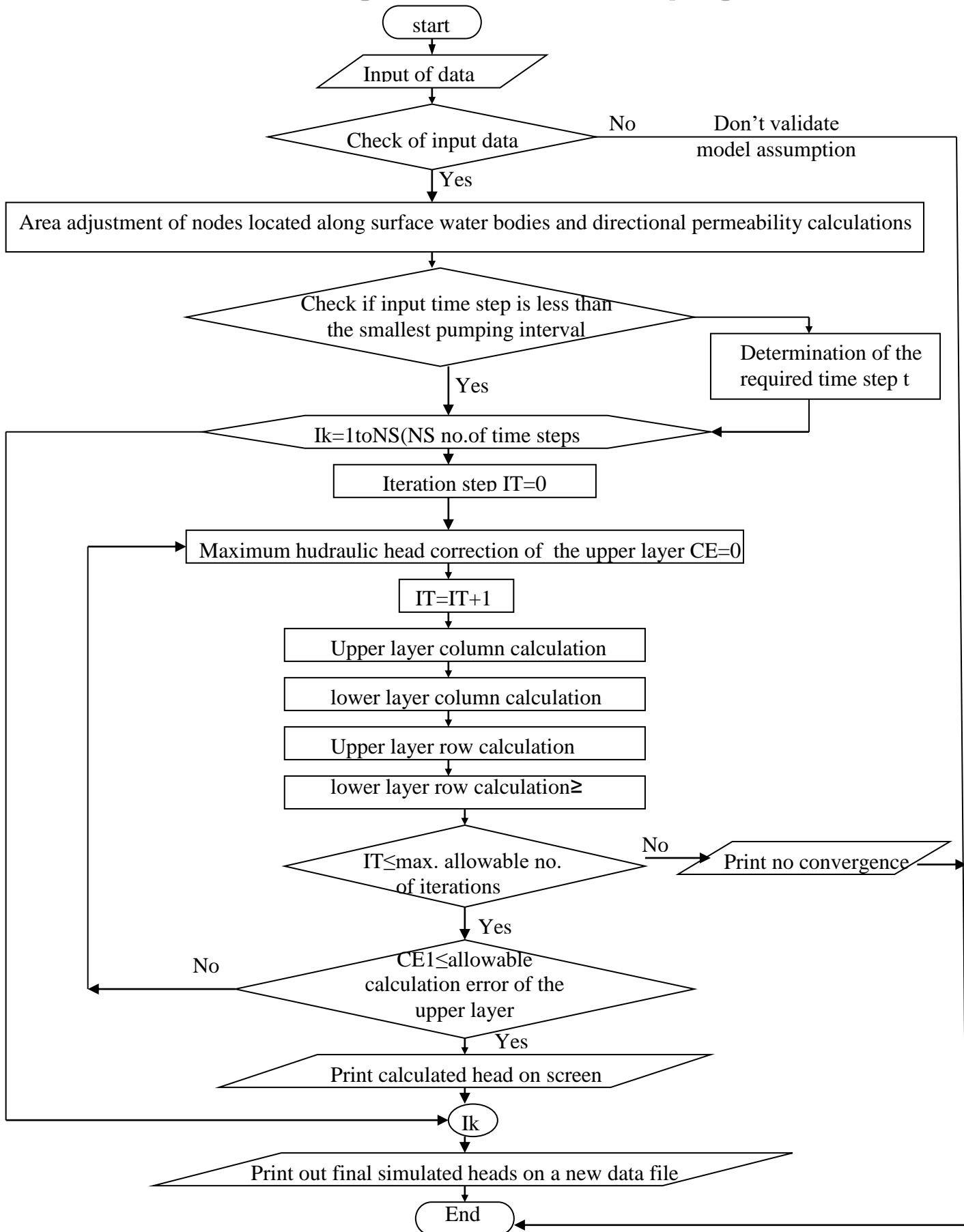
```

```

PRINT "Heads in the lower Layer="; CE3
PRINT "Time Step Number="; IK
PRINT "Time in Days="; TIME
IF IT <= NI THEN 160
PRINT " No Convergence "
GOTO 170
160 IF CE1 > ER1 THEN 95
IF CE3 > ER3 THEN 95
FOR I = 1 TO R
FOR J = 1 TO C
PRINT #18, X(I, J), Y(I, J), HS1(I, J)
PRINT #19, X(I, J), Y(I, J), HS3(I, J)
NEXT
NEXT
sum1 = 0
sum2 = 0
sum3 = 0
sum4 = 0
FOR I = 1 TO R
FOR J = 1 TO C
sum1 = sum1 + Qnet(I, J) * DX(J) * DY(I)
df = HS1(I, J) - HS3(I, J)
sum2 = sum2 + (df * LCM(I, J) * DX(J) * DY(I))
sum3 = sum3 + (HS1(I, J) - HO1F(I, J)) ^ 2
sum4 = sum4 + (HS3(I, J) - HO3F(I, J)) ^ 2
NEXT
NEXT
RMSE1 = (sum3) ^ .5 / (R * C)
RMSE3 = (sum4) ^ .5 / (R * C)
PRINT " Total Recharge="; sum1
PRINT "Amount of Leakage to the Lower Layer="; sum2
PRINT "Root Mean Square Error for the Upper Layer="; RMSE1
PRINT "Root Mean Square Error for the Lower Layer="; RMSE3
NEXT
170 END

```

Flowchart describing the outlines of the program



Appendix (B)

Calculation of the Conductance

Three of the attribute types listed above, general head, rivers, and drains, include a conductance parameter, this study uses the river attribute. *MODFLOW* uses the conductance to determine the amount of water that flows in or out of the model due to river stresses. The way the conductance term should be entered depends on whether the feature object is a polygon, arc or point. The arc is represent the river in this study. The conductance of arcs, as in this thesis specified as rivers, is calculated as follows, before explaining this fully, a short review of what conductance represents is appropriate. Darcy's law states (Environmental Modeling Research Laboratory, 1999).:

$$Q = k \cdot i \cdot A \dots\dots\dots (1B)$$

where

Q: is the flow rate (L³/T).

k: is the hydraulic conductivity (L/T).

i: represents the hydraulic gradient(unitless).

A: represents the gross cross-sectional area of flow (L²).

Darcy's law can also be expressed as:

$$Q = k \cdot \frac{\Delta H}{L} \cdot A \dots\dots\dots (2B)$$

where

ΔH : represents the head loss (L).

L: represents the length of flow (L).

Since the unknown on the right side is the head, it is convenient to group all of the other terms together and call them conductance:

$$Q = C \cdot \Delta H \dots\dots\dots (3B)$$

This results in the following general definition for conductance:

$$C = \frac{k}{L} \cdot A \dots\dots\dots (4B)$$

This may be represented more specifically in the following form.

$$C = \frac{k}{t} \cdot l \cdot w \dots\dots\dots (5B)$$

Where t represents the thickness of the material in the direction of flow, and $l \cdot w$ represents the cross-sectional area perpendicular to the flow direction.

In the case of a river boundary condition, the conductance is defined in *MODFLOW* as the hydraulic conductivity of the river bed materials divided by the thickness (length of travel based on vertical flow) of the river, multiplied by the area (width times the length) of the river. The last term, area, is the hardest parameter to determine by hand. Also, each of these terms is very cumbersome to calculate on a cell-by-cell basis. Fortunately, *GMS* can automatically calculate the lengths of arcs and areas of polygons. Therefore, when a conductance is entered for an arc, it should be entered in terms of conductance per unit length. For example, in the case of rivers, conductance should be entered as:

$$C_{arc} = \frac{k/t \cdot l \cdot w}{L} = k/t \cdot w \dots\dots\dots (6B)$$

Where t is the thickness of the material and w is the width of the material along the length of the arc. When *GMS* applies the boundary condition from the arc to the grid cell, it automatically multiplies the entered value of conductance by the length of the arc that intersects the cell to create a true conductance value.

CERTIFICATION

We certify that we have read this thesis, titled "*Lowering the Water Table in Ancient Babylon*", and as examining committee examined the student *Rand Sami Kamel* in its contents and in what is connected with it, and that in our opinion it meets the standard of thesis for the Degree of Master of Science in Civil Engineering (Water Resources).

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ABBREVIATIONS

<i>symbol</i>	<i>Meaning</i>
GDGSMI	General Directorate Geological Survey and Mineral Investigations.
FCSDIP	Al-Furat Center of Studies and Design of Irrigation Projects.
RMSE	Root Mean Square Error.
S_t	Total drawdown at a certain point in the area, (L).
Q	Rate of discharge at the specific pumping well, (L^3/T).
K	Hydraulic conductivity of the aquifer, (L/T).
R	Radius of influence of the pumped well, (L).
r	Distance between any point at the pumped well, (L).
H	Total head of the aquifer, (L).
x	Distance along the flow path, (L).
L	Length of the flow path, (L).
$h_{i,j}(t)$ & $h_{i,j}(t+\Delta t)$	Hydraulic heads of the upper aquifer at time (t), and (t+Δt), respectively of a nodal cell (i,j), (L).
Q_w	Represent the discharge or recharge flow from the pumping wells, (L^3/T).
$\varepsilon_{i,j}$	Specific yield of the upper aquifer at a nodal cell (i,j), (unitless).
$\Delta x_{i,j}$ & $\Delta y_{i,j}$	x and y dimensions, respectively of a nodal cell (i,j), (L).
$lr_{i,j}$	Leakage coefficient of surface water body bed at a nodal cell (i,j), L/T.
$kr_{i,j}$	Vertical permeability of surface water body bed at a nodal cell (i,j), L/T.
$dr_{i,j}$	Thickness of surface water body bed at a nodal cell (i,j), L.
$hr_{i,j}$	Water level of surface water body at a nodal cell (i,j), L/T.
$br_{i,j}$	Top level of surface water body bed at a nodal cell (i,j), L.
$b_{i,j}$	Bottom level at a nodal cell (i,j), L.
$h^s_{i,j}$	Simulation head at raw i, column j (L).
$h^o_{i,j}$	Observed head at raw i, column j (L).
r and c	Number of raws and columns, respectively.

rc	Number of cells within the modeled region.
w	Unit weight of water in kg/m^3 .
η	Efficiency of the set.
d	diameter of pipe, (L).
f	Coefficient of friction assumed as 0.006.
l	length of pipe, (L).
v	velocity through casing pipe, (L/T).

REFERENCES

- Al-Furat Center For studies and designs of Irrigation Projects(FCSDIP), 1989, "Lowering of groundwater level in Babylon city", Unpublished Report, Baghdad Iraq.
- Anderson, M.P. and Woessner, W.W., 1992, "Applied groundwater modeling simulation of flow and vertical transport", Academic Press, Inc. San Diego.
- ASTM, 1992, *Standard Guide for Evaluating Mathematical Models for the Environmental Fate of Chemicals*, E 978-92, American Society for Testing and Materials, West Conshohocken, PA. <http://www.astm.org>.
- Ayers, R.S. and Westcott, D.W., 1985, "Water quality for agriculture" FAO irrigation and drainage paper, 29 rev., Rome 174p.
- Banat, K.M. and Al-Rawi, Y.T. 1986, "Hydrochemistry, clay minerals and carbonates of the Euphrates river", Iraqi, J. Sci., Vol.27, pp.347-362.
- Bear, J. and Verruijt, A., 1987, "Modelling groundwater flow and pollution", D.Reidal Publisheg Co., Dordrecht, The Netherlands.
- Boonstra, J. and De Ridder, N.A., 1981, "Numerical modeling of groundwater basins", International Institute for land Reclamation and Improvement (ILRI), publication 29, Wageningen, The Netherlands.

- Boonstra, J. 1989. SATEM: Selected Aquifer Test Evaluation Methods: A Microcomputer Program. ILRI Publication 48, Wageningen, 80 p.
- Butler, S.S., 1957. Engineering Hydrology. Prentice Hall, Englewood Cliffs, N. J., 356p.
- Carey, M., Erskine, A., Heatcote, J. and McMahon, A. (2001), *Guide of Good Practice for the Development of Conceptual Models and the Selection and Application of Mathematical Models of Contaminant Transport Processes in the Subsurface*, National Groundwater & Contaminated Centre report NC/99/38/2, Environment Agency, Bristol.
- Carrera, J., and S.P. Neuman, 1986, *Estimation of Aquifer Parameters Under Transient and Steady State conditions, I. Maximum Likelihood Method Incorporating Prior Information*: Water Resour. Res., 22, 2, 799-210.
- Cooley, R.L., 1971, *A Finite Difference Method for Unsteady Flow in Variable Saturated Process Media: Application to a Single Well Pumping Test*: Water Resources Research, 8, 4, 1046-1050.
- Cynthia Ardito, C.G.W.P., David Jordan, P.E., Marsh Lavenue, PhD., Greg Ruskauff, C.G.W.P., PHg.,2001, *Requirement for Defensible Ground Water Modeling*: INTERA Incorporated.
- Encyclopedia Britannica, 2002, "Babylon, History of Babylonia", Google Earth.

- Environmental Modeling Research Laboratory, (1999), *Groundwater Modeling System – GMS Reference Manual*, Birmingham Young University, Birmingham.
- General Directorate of Geological Survey and Mineral Investigation, (GDGSMI), 1979, " The possibility of lowering under groundwater in Babylon", Technical report, Baghdad.
- GeoTrans, Inc., Roswell, GA ,2001,Groundwater Modeling for the Southern Sector of A/M Area (U), Westinghouse Savannah River Company LLC Savannah River Site.
- Harbaugh, A.W., and McDonald, M.G., 1996a, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.
- Harbaugh, A.W., and McDonald, M.G., 1996b, Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-486, 220 p.
- Harbaugh, A.W., 2005, *MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process*, U.S. Geological Survey Techniques and Methods 6–A16, Book 6, Chapter 16, Reston, Virginia.
- Hassan Al-Khateeb, 2001, "Problem of Shallow Groundwater level in the centre of Karballa City: Evaluation and

Simulation", Ph.D thesis, College of Engineering, Al-Mustansiriyah University.

- Herweijer, J.C., 1996, *Constraining Uncertainty of Groundwater Flow and Transport Models Using Pumping Tests, in Calibration and Reliability in Groundwater Modeling*: IAHS Publ., 237, 473-482.
- Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.
- Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 210 p.
- <http://www.scisoftware.com>, 2004.
- Ibtisam R. Kareem, 2005, "Lowering Groundwater Levels in the Ancient City of Babylon", Ph.D. thesis, University of Technology.
- Kennecott Utah Copper Corporation (KUCC), 2002, " Final Design for Remedial Action at South Facilities Groundwater", Southwestern Jordan Valley, Utah.
- Kinzelbach, W., 1986,"Groundwater modelling: an introduction with sample program in basic", Development in

water science, Ei-Sevier Science publishing Co., Inc., New York, 333p.

- Konikow, L.F., 1996. Use of numerical models to simulate groundwater flow and transport. U.S. Geological Survey, Reston, Virginia, USA.
- Konikow, L.F., Bredehoeft, J.D., 1978. Computer Model of Two-Dimensional Solute Transport and Dispersion. In: Ground Water Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 7, Ch. C2: 90 pp.
- Kuiper, L.K., 1987, Computer program for solving groundwater flow equations by the preconditioned conjugate gradient method: U.S. Geological Survey Water-Resources Investigations Report 87-4091, 34 p.
- Lachassagne, P.E. Ledoux, and G. de Marsily, 1989, *Evaluation of Hydrological Parameters in Heterogeneous Porous Media, in Groundwater Management: Quantity and Quality*: IAHS Publ., 188, 3-18.
- Leake, S.A., and Prudic, D.E., 1991, *Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model*: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A2, 68 p.
- Leebe, L., and W. De Breuck, 1995, *Validation of an Inverse Numerical Model for Interpretation of Pumping Tests and a Steady of the Factors Influencing Accuracy of Results*: Journal of Hydrology, 172, 61-85.

- McDonald, M.G. and Harbough, A.W.,1984, " A modular Three Dimensional finite difference groundwater Flow Model", U.S. Geol. Survey, Scientific Publication Co., Washington, D.C., (quoted by Mayer and Miller, 1988).
- McDonald, M. G., and Harbaugh, A. W. 1988. "A Modular Three-Dimensional Finite Difference Ground- Water Flow Model," U.S. Geological Survey.
- McWhorter, D.B. and Sunada, D.K. , 1977,"Ground-water hydrology and hydraulics", water Resources Publications, Colorado,290p.
- Meier, P.M., Carrera, A. Medina, and L. Vives, 1997, *Inverse Geostatistical Modeling of Groundwater Flow Within a Shear-Zone in Granite: Proceedings of IAMG 1997, the Third Annual Conference of the International Association for Mathematical Geology, Int. Cent. Of Numer. Method in Eng., vol. 2,. 755-76.*
- Meier, P.M., Carrera, X. Sanchez-Vila, 1998, *An Evaluation of Jacob's Method for the Interpretation of Pumping Tests in Heterogenous Formations: Water Resour. Res., 34, 5, 1011-1025.*
- Nuclear Regulatory Commission 1992; sited by U.S. Army Corps of Engineers, 1999, "Engineering and Design groundwater Hydrology", Washington, DC 20414-1000 EM 1110-1421.
- Perry M. Jones, 2005, " Simulated Effects of Water-Level Changes in the Mississippi River and Pokegama Reservoir on

Ground-Water Levels, Grand Rapids Area, Minnesota" U.S. Geological Survey Scientific Investigation Report 2005-5139.

- Pinder, G.F., and J.D. Bredehoeft, 1968, Application of the Digital Computer for Aquifer Evaluation, *Water Resources Research*, Vol. 4, pp. 1069-1093.
- Prickett, T.A., 1975, "Modelling techniques for groundwater evaluation", in *Advance in Hydroscience* chow, V.T., (ed), Academic Press, New York.
- Prickett, T.A., Naymik, T.G., Lonquist, C.G., 1981. A "Random-Walk" Solute Transport Model for Selected Groundwater Quality Evaluations. Ill. State Water Survey Bulletin 65: 103 pp.
- Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.
- Rasheeduddin, M., Yazicigil, H., and Al-Layal, R.I., 1989, "Numerical modeling of muliaquifer system in Eastern Saudi Arabia", *J.of Hydrology*, Vol. 107, No.1, 193-222.
- Reilly, T.E., Plummer, L.N., Phillips, P.J., Busenberg, E., 1994. The use of simulation and multiple environmental tracers to quantify groundwater flow in a shallow aquifer. *Water Resources Res.* 30 (2): 421-433.
- Remson, I., Hornberger, G.M., Molz, F.J., 1971. *Numerical Methods in Subsurface Hydrology*. Wiley, New York: 389 pp.

- Rushton, K.R. and Redshaw, S.C., 1979,"*Seepage and Groundwater flow*", John Wiley and Sons, 339p.
- Sanford, W.E., Konikow, L.F., 1985. A Two-Constituent Solute-Transport Model for Ground Water Having Variable Density, U.S. Geol. Survey Water-Res. Inv. Rept. 85-4279: 88pp.
- Sharll S. S., 1986, "Engineering of Drainage and Irrigation", Baghdad University.
- Todd, Ph.D. 1959,"Ground water Hydrology", Wiley International Edition, New York.
- Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional groundwater flow: U.S. Geological Survey Open-File Report 75-438, 32 p.
- Trescott, P.C., and Larson, S.P., 1976, Supplement to Open-File Report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.
- Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, " Finite Difference model for aquifer simulation in two dimensions with results of numerical experiments", U.S. Geol. Survey Techniques of Water Resources Investigations, Book 7, Chapter C1.
- U.S. Army Corps of Engineers, 1999, "Engineering and Design groundwater Hydrology", Washington, DC 20414-1000 EM 1110-1421.

- U.S. Department of Defense, 1998, Groundwater modeling system, user's manual: Brigham Young University.
- U.S. Department of Energy. 1991. "Description of Codes and Models to be Used in Risk Assessment," DOE/RL-91-44, prepared for the U.S. Department of Energy, Richland Office, Richland, WA.
- U.S. Environmental Protection Agency. 1993. "Compilation of Ground-Water Models," EPA/600/R- 93/118, prepared for the Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, OK.
- U.S. Department of the interior, 1985, "Groundwater Manual", Government Printing Office, Denver, 480P.
- Wang, H., 1982, "Introduction to Groundwater Modelling: Finite Difference and Finite Element Methods",Freeman and Company, 237p.
- W. D. Welsh, 2006, "Great Artesian Basin transient groundwater model",Bureau of Rural sciences, <http://www.brs.gov.au>.
- Zheng, C., 1990. MT3D: A Modular Three-Dimensional Transport Model. S.S. Papadopoulos and Associates, Inc., Bethesda, MD.

الخلاصة

تعتبر مشكلة المياه الجوفية تحدي كبير لعملية التحري والتنقيب في مدينة بابل القديمة, والتي مساحتها 22.79 كم². ان عمق الماء الجوفي في تلك المنطقة تراوح بين 0,5 الى 4 متر اعتمادا على البعد من شط الحلة و موسم الأمطار مما تسبب اضرار في بعض الأبنية القديمة.

ان الغرض من هذه الدراسة وضع تقييم و محاكاة لهذه المشكلة باستخدام نموذجين رياضيين مختلفين. الأول هو موديل لبرنامج حاسوب مسمى GMS بينما الثاني موديل رياضي جديد, تم حل معادلاته بلغة البيسك.

تمت دراسة اعداد مختلفة من الآبار وفي مواقع مختلفة بعمق 28 متر والذي هو سمك الحشرج الأول الغير محصور. حيث وجد ان اقل عدد من الآبار موزعة في مناطق مختلفة بعيدة عن منطقة الآثار هو 15 بئر و بمعدل تصريف 17 لتر/ثا و لمدة 360 يوم, ادى الى تخفيض منسوب المياه الجوفية بمقدار 1-10 متر في برنامج الـ GMS, لكن نفس النتيجة تم الحصول عليها في الموديل الرياضي عند استخدام 18 بئر (3 آبار أضيفت) وبمعدل تصريف 20 لتر/ثانية ولمدة 720 يوم.

ان مشكلة تصريف الماء المسحوب من الآبار كذلك تمت دراستها. حيث بين التحليل الكيميائي للمياه الجوفية ان لها خواص لا تختلف عن مياه شط الحلة. لذلك يتم اعادتها اليه.

CHAPTER ONE

INTRODUCTION

1.1 General

Babylon, Akkadians word means "the gate of God(s)", was the capital of the land of Babylonia, the ancient empire that existed in the Near East in Southern Mesopotamia between the Tigris and Euphrates Rivers (modern Al Hilla, Iraq), as shown in figure (1.1). Babylon was a city in Mesopotamia, the ruins of which can be found in present-day Babil Province, Iraq, about 50 miles south of Baghdad. Babylon is the Greek variant of Akkadian. Babylonia was a long, narrow country bordered on the north by Assyria, on the east by Elam, on the south and west by the Arabian Desert, and on the southeast by the Arab Gulf. The Hanging Gardens of Babylon were one of the Seven Wonders of the Ancient World. (Encyclopedia Britannica, 2002, Google Earth).

Groundwater has been an important water resource throughout the ages. Old dug wells can be found along the wades of the Middle East, the cradle of civilization, groundwater today is a major source of water supply for domestic, agricultural, and industrial uses.

However, shallow groundwater level badly affects buildings and other constructions. Engineering characteristics of building materials are usually deteriorated when submerged in groundwater.

When groundwater flows under certain circumstances, hydraulic gradient and soil conditions cause soil erosion leading to piping

which causes considerable subsidence and building differential settlements. The present study deals with a problem of shallow groundwater level in the ancient Babylon city in which the high groundwater is considered as a source of problems which affect the buildings of the ancient remnants of the city, so its need to solve this problem.

One of the suggested options to lower the level of groundwater is by pumping wells, provided that the wells are far enough from the remnants to avoid unwanted damage to it. The pumping should not be more than 17 ℓ/s to avoid sudden settlement that may lead to damaging the buildings of this historical city.

1.2 Physical Characteristics of the Study Area

Investigations about the study area done by both the General Directorate Geological Survey and Mineral Investigations (GDGSMI) in 1979, and by Al-Furat Center of Studies and Design of Irrigation Projects (FCSDIP) in 1989, may be summarized as follows:

Geology

Geological works were carried out by the GDGSMI, with dense hand and auger holes, also core drilling was set to determine the vertical and horizontal changes in the recent sediments, their type and composition. The area is covered by flood plain and Aeolian sediments of quaternary age. The presence of the Babylonian outer wall played an important role in the manner of sedimentation, the outer wall had acted as an embankment and protected the inner area

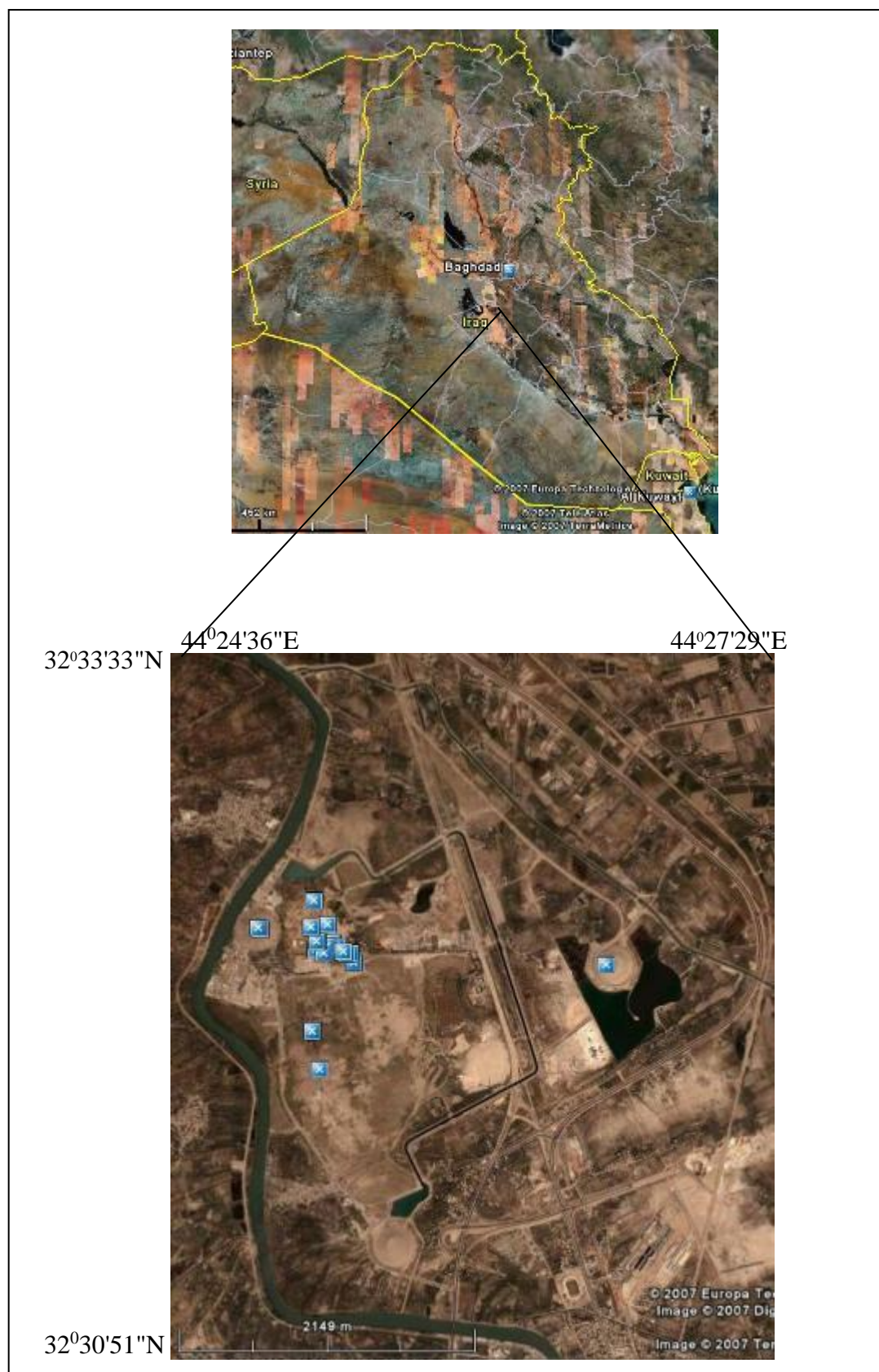


Fig.(1.1) Location of Babylon City

from the flood, this causes the difference in deposition in the areas outside the wall and inside it. The drilling proves that the depth of the Babylonian outer wall is about 15 m, and the depth of the remnants is about 25 m. the first meter of these sediments generally shows homogeneity and consists mainly of silty clay and sand of local artificial channels. The western part of the area consists mainly of flood plain sediments of Shat Al-Hilla (GDGSMI, 1979).

The second meter of sediment proved some differences between the deposition outside the outer wall and inside it. The area outside the wall is composed of sandy deposits, while the area within the wall is composed mainly of silty clay. Mineralogically, the sand and silt fraction consist of quartz, feldspar, carbonate minerals (calcite, dolomite), chert and a variety of heavy minerals. The clay fraction is characterized by clay minerals including montmorillonite, chlorite, kaolinite and illite. Both the carbonate fraction and the clay minerals seem to be of detrital origin (Banat and Al-Rawi, 1986).

Hydrogeologic conditions and aquifer Hydraulic properties

To study the Hydrogeological conditions of the study area, the GDGSMI stated constructed contour map for the ground water level as shown in figure (1.2). This figure shows that the groundwater is highly affected by the Shat Al-Hilla and Babylon canal, and the flow was directed from the two rivers toward Babylon old city, so the main source of groundwater in Babylon City can be considered as a surface water derived from both rivers (GDGSMI, 1979). The depth of groundwater varies from 0.5-4m in the central part of the

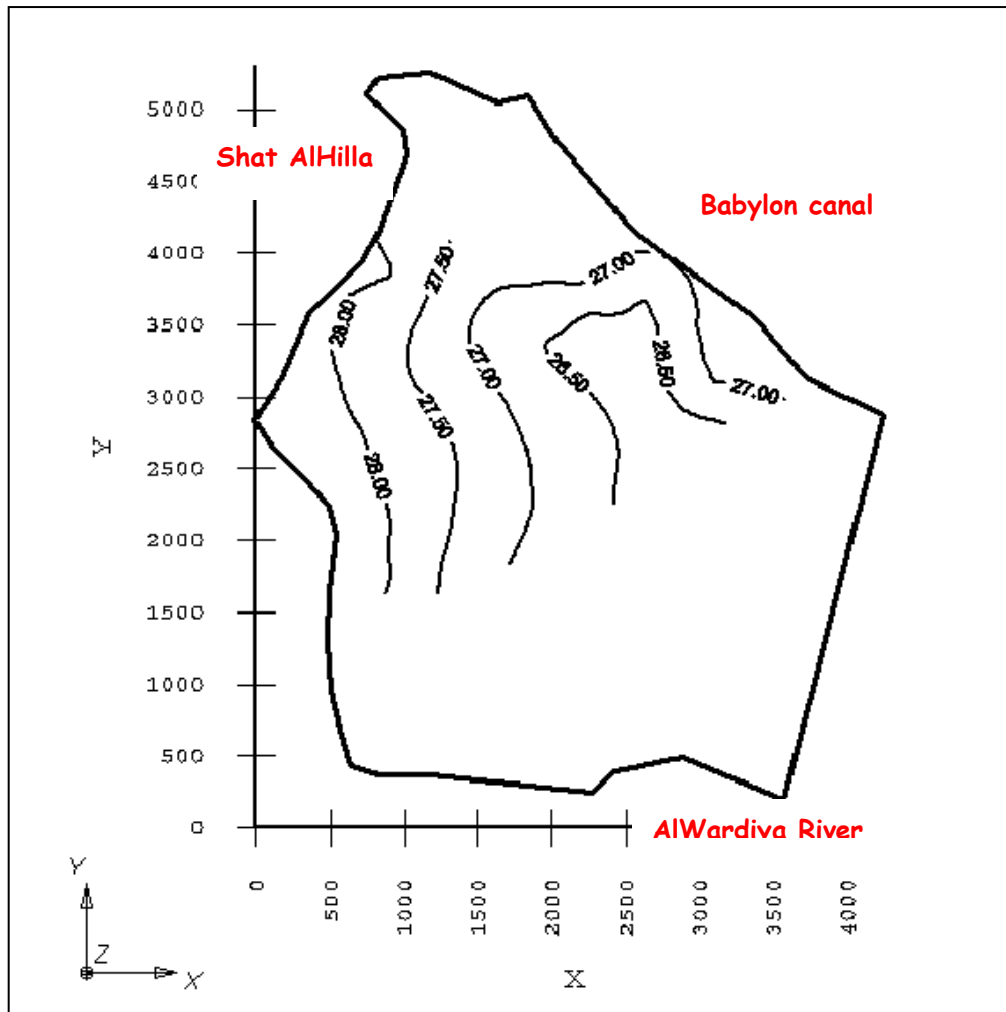


Fig. (1.2) groundwater contour map (GDGSMI, 1979)

Babylonian city, but nowadays the water level is raising more than 2m, it is believed that this is due to the impounding of groundwater level in the area. The groundwater discharges in many depressions creating salt lakes (FDSDIP, 1979).

The result of drilling shows that the upper 10 meters of the area consist of large amount of bricks and silty clay especially in the central part of the city. From (10-28m) a fine sand layer, which is considered as the first water table aquifer (unconfined aquifer). From (28-30m) a layer of brown clay which acts as an impermeable layer. Overlaying by a layer of medium sand from (30-45m), and it can be

considered as a second aquifer (GDGSMI,1979), these details can be shown in figure (1.3).

The hydraulic properties of the penetrated aquifer vary between the strip parallel to Shat Al-Hilla and the area behind it, (the area inside the Babylonian outer wall) (FDSDIP, 1979).

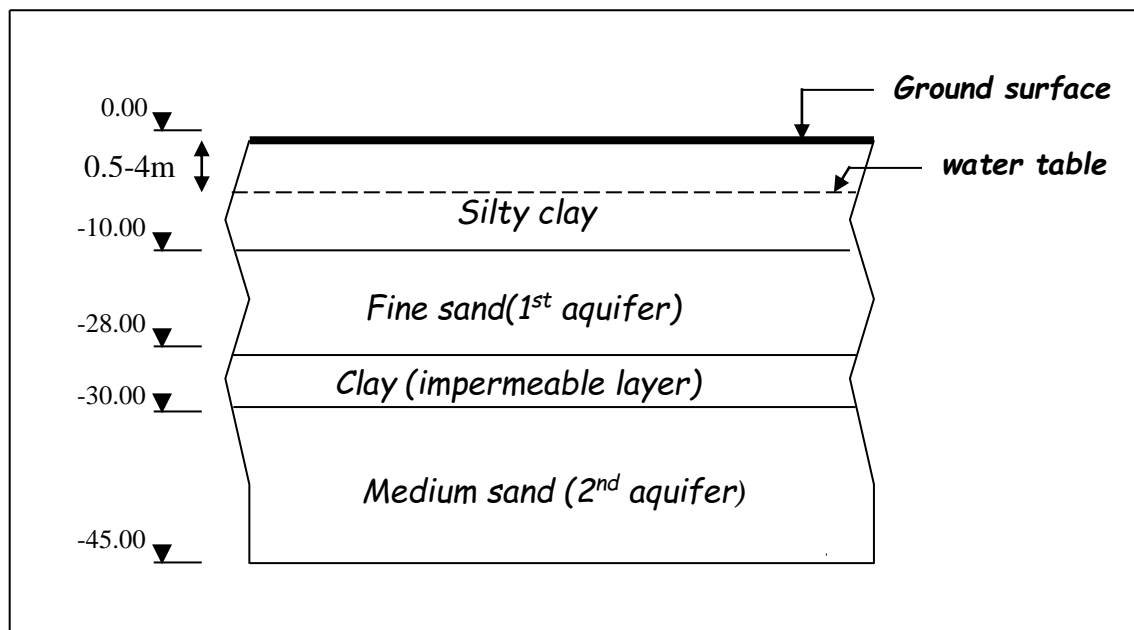


Fig.(1.3)Properties of soil in the study area.

The transmissivity of Shat Al Hilla strip is about 350 m²/day, and the specific yield varies from 0.01-0.1, the specific capacity of the wells is about 1-5 ℓ/sec/m. The area behind Shatt Al Hilla has a transmissivity about 150 m²/day, the specific yield is about 0.01-0.001 and the specific capacity of the wells varies from 0.3-1 ℓ/sec/m.

Climatic Conditions

Meteorological data of Hilla Meteorological Station have been used to evaluate the climatological characteristics of the area. As shown in table (1.1) the monthly average meteorological elements at Hilla station was recorded. These elements are temperature, sunshine, relative humidity, wind, rainfall and evaporation. The average annual temperature is 23.08 C°. The maximum monthly average temperature is 34.64 C° in July, while the minimum is 10.1 C° in January. The fluctuation between day and night temperatures is appreciable in Winter as well as in Summer regarding the sunshine with maximum duration occurring at June. The minimum monthly average duration is in December.

Table (1.1) Monthly average meteorological elements at Hilla station for the period(1976- 1996).

Month	Mean Temp.°C	Sunshine hr.	Relative Humidity%	Wind Speed m/sec	Rainfall mm	Evaporation mm
Jan.	10.1	6.41	73	1.45	24.17	49.68
Feb.	12.6	7.29	63.47	1.92	19.03	72.99
Mar.	16.8	7.92	56.14	2.35	20.09	131.37
Apr.	22.97	8.8	47.53	2.06	12.77	190.87
May	28.73	9.49	37.69	2.24	1.26	278.49
Jun.	32.46	11.99	31.88	2.63	Nil	339.54
Jul.	34.64	11.96	31.2	3.01	Nil	363.73
Aug.	33.8	11.46	33.73	2.35	Nil	324.55
Sep.	31.09	10.13	37.79	1.68	Nil	243.18
Oct.	25	8.52	48.29	1.39	5.03	159.86
Nov.	16.97	7.29	61.57	1.39	15.16	82.17
Dec.	11.81	6.28	73.07	1.51	13.21	51.28

Chemistry of Groundwater

Many samples were taken from different sites of the area, and were chemically analyzed to examine the groundwater source that exists in the study area, and its suitability for agriculture, domestic, and drinking purposes. The results of chemical analysis showed that the groundwater in Babylon city is similar to Shat Al Hilla water as well as to Babylon canal water, which may conclude that those two rivers could be the main sources to high level of groundwater in the area.

According to Food and Agriculture Organization (Ayers and Westcott, FAO, 1985), the groundwater in the study area is suitable for agriculture.

The results of chemical analyses can be seen in Table (4.2).

1.3 Objectives of this study:

The purpose of this study is to predict the water table elevation after dewatering in Babylon city by using pumping wells. This is accomplished by using the following two different computer models:

- A. Application of GMS program to the study area.
- B. Constructing and applying a new numerical model.

1.4 Layout of thesis:

The present study consist from the following:

1. ***Chapter one'' Introduction''***: contain the introduction about Babylon city, the problem of shallow groundwater table, the physical characteristics of the study area that were gained by the previous studies about this area and objectives of this study.
2. ***Chapter two'' Literature review and previous study''***: consist of the literature review that worked about the same problem but in another site, and the previous studies on Babylon city.
3. ***Chapter three'' Theoretical work''***: this chapter describes the GMS model and the numerical model, and how they work.
4. ***Chapter four'' Application of the models and the results''***: This chapter will review the application of both models (GMS model and numerical model), and the simulation was performed using the two dimensional finite difference flow model which constructed by using all input data that are possibly needed and the output of both models with their comparison and discussion.
5. ***Chapter five'' Conclusions and recommendations''*** : this chapter contain the conclusions of this work, and the recommendations to the researchers that will work about the same area.

CHAPTER TWO

LITERATURE REVIEW AND PREVIOUS STUDIES

2.1 Literature Review

Numerical models grew out of the limitations associated with analytical models. Numerical models, whose use began in the 1960s, are solved by using numerical analysis techniques. They became easier to apply in the 1980s because of the increased computational speed of computers. Since then, numerical models have continued to be used in the practice of hydrology. They require numerous, repetitive calculations and use a gridding process to divide the aquifer into regularly-shaped portions. Through this gridding process, important spatial features controlling the hydrologic system can be incorporated. Numerical models that simulate ground water impacts caused by a pumping well originate back to 1968 when **Pinder and Bredehoeft, (1968)** presented an axisymmetric numerical model designed for well-test interpretation. Since that time, there have been numerous numerical modeling efforts focused on well-test interpretation, pumping impacts and the impact of heterogeneity upon the uncertainty of the interpreted results (e.g., **Cooley, 1971; Lachassagne et al., 1989; Herweijer, 1996; and Meier et al., 1998**). Applications to actual field test data have led to the development of inverse methods to automatically interpret well-

test drawdowns. Examples may be found in **Carrera and Neuman (1986)**, **Lebbe and De Breuck, (1995)**, and **Meier et al, (1997)**.

A good review of the development in the analysis of groundwater flow by means of numerical models, for the period in the late sixties and early seventies, were given by **Remson et al.,(1971)**, **Prickett, (1975)**, **Konikow and Bredehoeft, (1978)**, **Sanford and Konikow, (1985)**, **Prickett et al, (1981)**, and **Zheng, (1990)**.

McWhorter and Sunada, (1977) constructed a two-dimensional groundwater model, which may be used for analyzing of the areal distribution of heads in either confined or unconfined aquifers. The model was based upon the fully implicit central difference scheme using Gauss elimination procedure.

Rushton and Redshaw, (1979) demonstrated the use of analogy and digital computer methods in the solution of both two- and three-dimensional problems in both steady and transient simulations. Regional groundwater flow, external and internal boundary effects and analysis of pumping test were described in details with computer programs.

Hassan Al-khateeb, (2001) conducted a study dealing with evaluating and simulating the problem of shallow groundwater level in the center of Karbala city. The study area is about 3.2 km² and comprises the two holy shrines of Al-Hussain and Al- Abbas. He simulated this problem by constructing three mathematical flow models, two of which are analytical, the third model is a two-dimensional finite difference flow model to simulate the hydraulic conditions of the system modeled and to simulate the dewatering of the shrines. He stated that the simulation by the numerical finite

difference flow model shows that the dewatering of the shrines can be carried out by the vertical drainage rather than the subsurface drainage of the analytical model.

A modular three dimensional finite difference flow model called MODFLOW, Prior to the development of MODFLOW, the two- and three-dimensional finite-difference models described by **Trescott, (1975), Trescott and Larson, (1976), and Trescott, Pinder, and Larson, (1976)** were used extensively by the U.S. Geological Survey (USGS) and others for the computer simulation of ground-water flow. The first version of MODFLOW was the result of the need to consolidate all the commonly used simulation capabilities into a single code that was easy to understand, use, and modify. This first version was developed between the spring of 1981 and the winter of 1983. That model code was originally called the USGS Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, but the model became known as MODFLOW several years later. This model was developed using the Fortran 66 computer language.

Revised documentation was released in the report series Techniques of Water Resources Investigations (TWRI) (**McDonald and Harbaugh, 1988**). The program was largely the same as the 1984 version, but small changes were made to make the code conform to Fortran 77 rather than Fortran 66. This version of MODFLOW is called MODFLOW-88.

By the early 1990, MODFLOW had become the most widely used ground-water flow model both within and outside the USGS. Many additions had been made to expand MODFLOW's

capabilities. For example, more elaborate representation of the relation between streams and an aquifer was developed (**Prudic, 1989**). **Leake and Prudic, (1991)** developed a package to represent subsidence. Two preconditioned conjugate-gradient packages were developed (**Kuiper, 1987; Hill, 1990**). An overall update to MODFLOW, called MODFLOW-96, was published (**Harbaugh and McDonald, 1996a and 1996b**). MODFLOW-96 was a relatively minor update primarily to improve ease of use, this version of MODFLOW was used in this study.

To facilitate the incorporation of related equations into MODFLOW, an expansion of the modular design was required. The result, which became MODFLOW-2000, was the addition of “Process,” which is defined as parts of the code that solve a major equation or set of related equations. The part of the code that solves the ground-water flow equation became the Ground-Water Flow (GWF) Process. MODFLOW-2005 is similar in design to MODFLOW-2000. The expanded concept of processes continues as in MODFLOW-2000. The primary change in MODFLOW-2005 is the incorporation of a different approach for managing internal data. Fortran modules are used to declare data that can be shared among subroutines. This allows data to be shared without using subroutine arguments. As a result of using Fortran modules, a change in terminology for MODFLOW has been made. MODFLOW subroutines were originally called modules in a generic sense. The generic term module has been eliminated and replaced by the term subroutine (Harbaugh, 2005).

Reilly, et al., 1994 combined the application of environmental tracers and deterministic numerical modelling to analyses and estimate recharge rates, flow rates, flow paths, and mixing properties of a shallow groundwater system near Locust Grove, in eastern Maryland, U.S.A. A two-dimensional cross-sectional model was developed for the simulation of processes occurring along this flow line. The MODFLOW model was used to simulate groundwater flow and advective transport.

The Groundwater Modeling studies for **Kennecott Utah Copper Corporation (KUCC)**, 1998, Southwestern Jordan Valley (SWJV) flow and transport modeling have been an on-going effort beginning with the South Facilities Remedial Investigation and Feasibility Study (RI/FS) in 1998. As is typical for a complex groundwater-modeling program, the modeling objective has continued to be refined, and knowledge of the system and the questions to be addressed evolve. Model was converted from the current KUCC expanded regional model using the Groundwater Modeling System (GMS) software GMS was selected as upgrade software for its pre- and post-processing functionality and its compatibility with the previous KUCC models using MODFLOW (groundwater flow modeling). The current KUCC model has been incorporated into GMS using two approaches. The first was a direct import of the KUCC expanded regional model data using the GMS import features. In essence, the model remains identical (with the exception of a few manual changes that GMS required as per differences in how the Processing MODFOLW software and GMS software each handle information). This first step allowed for the model to be run

with both software packages, allowing for direct comparisons. The second modeling approach in GMS involves the creation of a conceptual model in GMS using the KUCC model data. Steady-state calibration comparisons with the GMS conceptual model were performed. The process of steady-state calibration primarily focused on achieving results in line with those of the previous model's calibration to provide a useful benchmark for further simulations. The shallow unconfined aquifer could only be analyzed by evaluating the groundwater flow along the Jordan River.

Cynthia, C.G.W.P., and etal, 2001 built a three-dimensional numerical flow model using the MODFLOW code to evaluate the effects of pumping on a water resource over 10 miles away from a development site in New Mexico, the three dimensional geologic model was constructed within GMS, then converted into standard MODFLOW format.

Perry M. Jones ,2005, constructed a calibrated steady-state, finite-difference, ground-water flow model to simulate a system of three glaciofluvial aquifers, defined as the upper, middle, and lower aquifers, in an area of about 114 m² surrounding the city of Grand Rapids in north-central Minnesota. This model was constructed as part of a 5-year cooperative study between the United State Geological Survey (USGS) and the Minnesota Department of Health (MDH) to simulate ground-water-flow conditions in aquifers. The calibrated model will be used by Minnesota Department of Health (MDH) and communities in the Grand Rapids area in the development of wellhead protection plans for their water supplies. The model was calibrated through comparison of simulated ground-

water levels to measured static water levels in 351 wells, and comparison of simulated base-flow rates to estimated base-flow rates for reaches of the Mississippi and Prairie Rivers. The USGS flow model, MODFLOW, was used to simulate ground-water flow conditions in the Grand Rapids area.

W. D. Welsh, 2006, constructed a transient MODFLOW model of the Great Artesian Basin (GAB) was requested by the GAB Technical Working Group. The Great Artesian Basin (GAB) is a Mesozoic groundwater basin covering parts of Queensland, New South Wales (NSW), South Australia (SA) and the Northern Territory (NT) west of the Great Dividing Range. It is a valuable source of fresh water in a generally arid inland environment. To simplify the model, and because of a lack of data in other aquifers, only the shallowest artesian aquifer is modelled. The plan was to build on the existing steady state model, called GABFLOW (Welsh 2000), increasing its utility by adding a temporal component to water level predictions. The model is constructed as a single confined layer. Cells over the basin are 5 km x 5 km, giving a model grid with 359 rows and 369 columns and more than 60,000 active cells. The model was used to predict water level recoveries from some bore rehabilitation scenarios. For each scenario the recovery is the difference between ‘before’ and ‘after’ model results. The model is run under MODFLOW-2000 as distributed with version 4.0 of Groundwater Modeling System (GMS) software.

2.2 Previous Studies on Babylon Groundwater problem

Three previous studies were conducted to describe and discuss the geological, hydrological, and hydrogeological aspect of the ancient Babylon city. The aim of all these studies was to solve the problem of shallow groundwater level in old Babylon city. The first study was done by the General Directorate of Geological Survey and Mineral Investigation (GDGSMI) in 1979. The second study was done by Al-Furat Center of Studies and Design of Irrigation Projects (FCSDIP) in 1989, the third was made by Ibtisam R. Karim, (2005) to the university of Technology.

Presentation and discussion of these studies is given below.

2.2.1 The study of (GDGSMI)

The General Directorate of Geological Survey and Mineral Investigation (GDGSMI) in 1979 carried out the first work on the ancient Babylon city according to a request made by the State Organization for Antiques to study the possibility of lowering the ground water level, as groundwater affects all the old Babylonian remnants and, consequently, obstructed the work of the archiologist.

The aim of the study was to obtain information about the surface geology, lithology, and the hydrogeological conditions of the area.

The geological works were done by drilling 97 auger holes, with a distance vary between 50-200m, with ranging depth between 1.5-3m. From measuring water level in all auger holes, groundwater contour map was constructed, as shown in figure (1.2).

To determine the aquifer hydraulic parameters, two groups of pumping test were constructed in this study. One in the central part

of the old Babylon city and the other one near Shat Al Hilla. The first group consists of a one pumping well and three piezometers, the second one consists of five boreholes near Shat Al Hilla. Average values of hydraulic parameters (T,Sy) for the first group are $T=350\text{m}^2/\text{d}$, $S_y=7.9*10^{-2}$, and $T=266\text{ m}^2/\text{d}$, $S_y=5*10^{-2}$ for the second group.

Where:

Specific yield S_y : is the ratio of the water that will drain from a saturated rock owing to the force of gravity to the total volume of the media. *Specific retention S_r* is defined as the ratio of the volume of water that a unit of media can retain against the attraction of gravity to the total volume of the media. The porosity of a rock is equal to the sum of the specific yield and specific retention of the media. For most practical applications in sands and gravels, the value of effective porosity can be considered equivalent to specific yield. In clays, there is a much greater surface area and corresponding adhesion of water molecules.

Transmissivity T : is a measure of the amount of water that can be transmitted horizontally through a unit width by the fully saturated thickness of an aquifer under a hydraulic gradient equal to 1. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer and is given by:

$$T = Kb$$

where,

K = hydraulic conductivity [LT⁻¹]

b = saturated thickness of the aquifer [L]

Since transmissivity depends on hydraulic conductivity and saturated thickness, its value will differ at different locations within aquifers comprised of heterogeneous material, bounded by sloping confining beds, or under unconfined conditions where the saturated thickness

will vary with the water table.

During a multiple pumping test, was carried out by the GDGSMI in three boreholes. The drawdown was calculated by using the Hydrodynamic method and applying ForchHaimer equation.

$$S_i = H - \sqrt{H^2 - \frac{1}{\pi k} (Q_1 \ln \frac{R_1}{r_1} + Q_2 \ln \frac{R_2}{r_2} + \dots + Q_n \ln \frac{R_n}{r_n})} \dots\dots\dots(2.1)$$

Where;

S_i : Total drawdown at a certain point in the area, (L).

Q : Rate of discharge at the specific pumping well, (L^3/T).

k : Hydraulic conductivity of the aquifer, (L/T).

R : Radius of influence of the pumped well, (L).

r : Distance between any point at the pumped well, (L).

H : Total head of the aquifer, (L).

The process of pumping was carried out for only one day in this study because of the continuous shutdown of electricity. The rate of pumping was 9 ℓ/s . The GDGSMI had found the total drawdown as 5.72 m at the center of the city and decreased gradually as the distance increased further from the boreholes until the effect of pumping reached the recharge boundaries (i.e. Shat Al Hilla) where the drawdown would be equal to zero. The GDGSMI found from chemical analysis that the groundwater in the study area derived

from Shat Al Hilla which participates in rising the groundwater level about(4-5)m.

2.2.2 The study of (FCSDIP)

Al-Furat Center of Studies and Design of Irrigation Projects conducted a study during 1989 to evaluate and suggest a suitable well field design for Babylon city. The study was based on the previous work of the GDGSMI. The hydraulic properties of the aquifer were calculated from the pumping test analysis, and found to be varying between the strip parallel to Shat Al Hilla, and the area behind it. The transmissivity and the specific yield of Shat Al Hilla strip were found as 350 m²/d and 0.007 respectively, the area behind the river has a transmissivity of 150 m²/d and a specific yield about 0.005.

The water balance equations were used to evaluate the amount of groundwater recharge, which was found to be 280 ℓ/sec. This amount of groundwater was suggested to withdrawal in two wells field design. The first design was carried out for 30 bore holes, located on a ring following the tourist canal and parallel to Shat Al Hilla. Penetrates at a 25 m depth, 14 of which have a pumping rate equal to 12 ℓ/sec, and the other 16 boreholes have a pumping rate equal to 7 ℓ/sec.

The total drawdown was calculated using hydrodynamic equation, maximum drawdown was found to be 6 m at the center of Babylon city and decreased toward the recharge boundaries.

The disposal of pumped water assumed at this study gone to Shat Al Hilla and to the tourist canal according to the locations of boreholes.

This study considers Shat Al Hilla and Babylon canal as the main source of recharge.

The alternative design for the vertical drainage including a new well field design consists of 21 wells distributed on the parameter of the area. The discharge rate of the pumping wells ranged between 2-15 ℓ/sec, spaced between 200-400 m. This method provides a slower dewatering rate and hence a slower settlement rate to avoid the damage of the city structures. This method depends on the Equivalent Interceptor Drain and Water Balance equations. Drawdown contour map was produced by using the following equation,(Hantush.1964)

$$h = \sqrt{h_1^2 - (h_1^2 - h_2^2) \frac{x}{L}} \dots \dots \dots (2.2)$$

Where

h : hydraulic head at the desired point, (L).

h_1 and h_2 : hydraulic heads at the boundaries, (L).

x : distance along the flow path, (L).

L : length of the flow path, (L).

For reaching to steady state condition, this method recommended 500 days as a minimum.

The analysis of the vertical drainage in the study area in both GDGSMI and FCSDIP studies used the analytical solution only, while the numerical models are more reliable and were accurate approach to analyze and solve the dewatering problems.

2.2.3 Ibtisam R. Karim's study

The last study was done by Ibtisam R. Karim in 2005. Two models were considered in this study; one is numerical and the other is analytical. The numerical model uses the finite difference technique based on the continuity hypothesis and Darcy's law. The analytical model is theoretically based on the Hantush Analysis of interfering drainage wells with a superposition and Image principles.

Numerical simulation is conducted with the aid of a computer program called Ground Water Modeling System (GMS) to simulate the steady and unsteady states of flow. Ibtisam proved that the water level at the study area can be lowered to about 16 m from its present level after the steady state condition is reached within a period of 250 days from start of pumping.

She considered a ring of wells system surrounding the old Babylon city. A well field contains (45 wells) distributed in the study area, as shown in figure (2.1). Each well is assumed to penetrate a depth of 45 m, and discharge at a rate of 17 ℓ /sec.

The analytical simulation was carried out by a simple computer program. Ibtisam found that the numerical model was more accurate than the analytical one, but the latter requires less effort and time and the results of lowering the ground water of the two models was different. Comparison of results numerical solutions with the analytical solutions showed reasonable agreements between the two models during the early time of pumping.

Ibtisam reported that Shat Al Hilla is the main source of recharge.

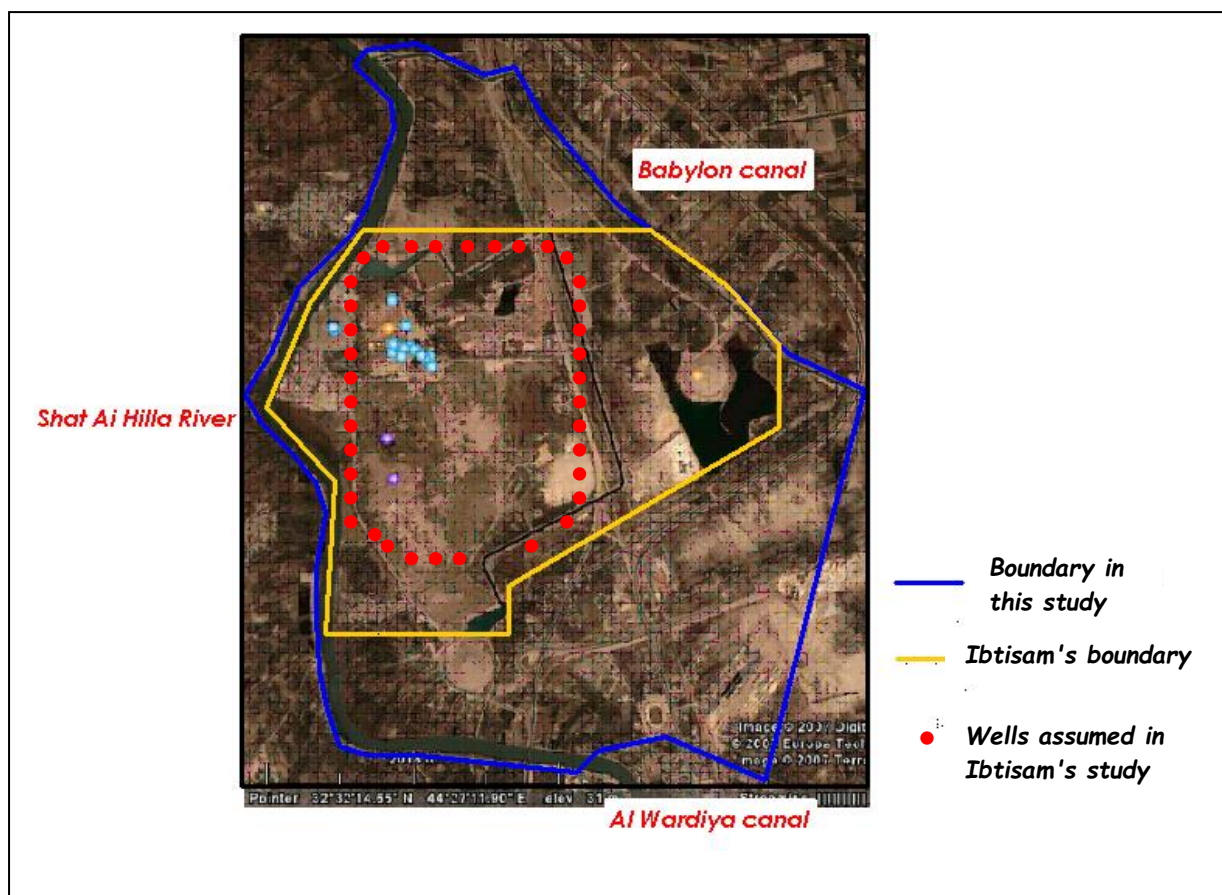


Fig. (2.1) Boundary and locations of the 45 wells in Ibtisam's study.

The analysis of Ibtisam study can be documented in the following:

- A ring of wells was considered in Ibtisam's study regardless of the presence of remnants, as shown in figure (2.1). Ibtisam's study concluded from that the drawdown after dewatering by 45 wells discharging water at a rate of 17 l/sec, for a duration of 250 days was 16 m, in the center of the city, which is too much in comparison with that given by the GDGSMI and FCSDIP, where obtaining the drawdown is no more than 6 m only. This may lead to excessive lowering of the water level and risk of settlement that will may damage the historical buildings.

- Ibtisam's study considered that Shat Al Hilla is the main source of recharge regardless of Babylon canal, while the last one should be considered as the second source of shallow groundwater level in the area, (FCSDIP, 1989).
- The 45 m depth of the wells in Ibtisam's study involve both the two aquifers. The discharging water from the second aquifer has no much effect on lowering the ground water level in the first aquifer, because the presence of 2m clay layer will work as an impermeable layer, (GDGSMI, 1979).
- The boundary condition of Ibtisam's study that surrounded the area is shown in figure (2.1), where the three lakes shown in figure (4.3), are considered incorrectly as a boundary because they are too small to be considered as a boundary.

CHAPTER THREE

THEORETICAL WORK

3.1 Introduction:

This chapter describes what models are and how they work. It deals with two numerical models, uses the finite difference technique based on the Continuity Hypothesis and Darcy's law. The first solution with aid of computer program is called GMS "Groundwater Modeling System", and the second is with aid of a Quick-basic program.

3.2 Definitions of the model;

A groundwater model is a replica of some real-world groundwater system.(U.S. Army Corps of Engineers, 1999). The International Groundwater Modeling Center defines a model as "a non-unique, simplified, mathematical description of an existing groundwater system, coded in a programming language, together with a quantification of the groundwater system, the code simulates in the form of boundary conditions, system parameters, and system stresses" (U.S. Environmental Protection Agency (USEPA) 1993). "A model is a simplified description of a physical system" (U.S. Department of Energy 1991). A groundwater flow model is an application of a mathematical model to represent a site-specific flow system" (ASTM

1992). “A mathematical model is a replica of some real world object or system” (Nuclear Regulatory Commission 1992).

3.3 Principles of Groundwater Modeling

Groundwater modeling can be used to simulate the flow and transport processes in an aquifer. A groundwater model can be used in an interpretative sense to gain insight into the head distribution and the flow pattern within a watershed. It can also be used to assess different scenarios that may occur in the future or to assess and better understand processes that have already occurred. With the comprehensible visualization, complex situations can be described effectively. A model is an abstraction of the reality in order to aid the understanding of and/or predict the outcomes of the real system (Carey, Erskine, Heatcote and McMahon, 2001). The more detailed and complex the model is, the better it may represent the real situation. It is however practically impossible to perfectly represent all natural processes included, and consequently all groundwater models are simplifications of real situations. (Anderson and Woessner, 1992).

Groundwater models simulate the hydraulic head and flows, and can be either physical or mathematical. A physical model can be the study of groundwater flow through a sand column, while a mathematical model simulates the processes through a partial differential equation with the hydraulic head as the variable parameter. The model can be steady state, representing conditions where the inflows and outflows to the model are constant with time. For time variant or transient models, initial conditions must also be specified. The model can solve the differential equation analytically or numerically. Analytical solutions can only be obtained for very simple or simplified problems. Numerical models, on the other hand,

can be used for more complex problems, and are typically solved using powerful computers. (Anderson and Woessner, 1992).

3.4 Conceptual model

A conceptual model is a simplified representation of reality with a focus on the geology and hydrogeology. The conceptual model, is a three-dimensional representation of the groundwater flow and transport system based on all available, geologic, hydrogeologic, and geochemical data for the site. The first step in any modeling effort is the development of the conceptual model. A complete conceptual model will include, geologic and topographic maps of the site, cross sections depicting the site geology/hydrogeology, a description of the physical and chemical parameters associated with the aquifer(s), contaminant concentration and distribution maps. The purpose of the conceptual model is the integration of the available data into a coherent representation of the flow system to be modeled. The conceptual model is used to aid in model selection, model construction, and interpretation of model results.

The purpose of a conceptual model is to organize field data and to consider how these data can be translated into a physical or mathematical model. It is hence one of the first steps in the modeling process. The key processes controlling the flow, transport and fate of the groundwater are identified (Carey et al., 2001).

Construction of a conceptual model includes the definition of the basin boundaries, aquifers and non-aquifers, recharge and discharge sources and the hydrochemical pattern. When natural phenomena are represented, a number of simplifications and assumptions have to be

made, which should be thoroughly explained and justified (Anderson and Woessner, 1992).

3.5 Groundwater Modeling

3.5.1 Groundwater Modeling System (GMS)

Groundwater Modelling System (GMS v2.0) is the most advanced, powerful, and comprehensive groundwater modelling package available. The program was developed under the direction of the U.S. Army Corps of Engineers and involves support from the Department of Defence, the Department of Energy, and the Environment Protection Agency. GMS provides complete support for the USGS MODFLOW 3D finite difference. Tools are provided for site characterisation, model conceptualisation, mesh and grid generation, geostatistics, telescopic model refinement, automated model calibration, and output post-processing. Several groundwater modeling data types are represented, including TINS (The *TIN Module* is used for surface modeling. TINs are formed by connecting a set of XYZ points (scattered or gridded) with edges to form a network of triangles. The surface is assumed to vary in a linear fashion across each triangle. TINs can be used to represent the surface of a geologic unit or the surface defined by a mathematical function. TINs can be displayed in oblique view with hidden surfaces removed. Elevations or other values associated with TINs can be displayed with color fringes or contours. TINs can be used in the construction of solid models and 3D finite element meshes)

, boreholes, 2D mesh, 2D grid, 2D scatter points, 3D mesh, 3D grid, 3D scatter points, and solids. The program allows common information to be shared among different data types and groundwater models.

3.5.1.1 GMS modules

The *Groundwater Modeling System* (GMS) is a modeling environment used for groundwater simulations. It contains a graphical interface and a number of different analysis codes, including MODFLOW and others. GMS provides tools that allow the user to characterize the study area, conceptualize the model and generate the inputs for the various models in the system. It also performs the calculations and interpolations needed to visualize the result. GMS is divided into ten modules each of which handles different data types. The modules used in this study are the *Map module*, and the *3D grid module*. These are described below. (Environmental Modeling Research Laboratory, 1999)

3.5.1.1.1 Map module

The *Map module* contains the tools needed to construct a conceptual model in GMS. It is used to manipulate Feature objects such as images and drawings. The most important Feature objects of the modeled area are represented as points, Arcs (lines) and polygons, each corresponding to features such as wells, rivers and lakes. These objects are saved as coverages (Feature objects can be grouped together into coverages). Each coverage represents a particular set of data. For example, one coverage can be used to define recharge zones, and another coverage can be used to define

zones of hydraulic conductivity. A coverage can be of the type sources/sinks, areal, layer or observation, depending on the assigned parameters. In the sources/sinks coverage all objects contributing to the recharge and discharge of groundwater, including the model boundaries, are specified. This includes rivers, lakes, ponds and wells. The set of defined coverages represents the conceptual model, and can later be used to generate MODFLOW solution.

3.5.1.1.2 3D grid module

In the *3D-grid module* a three dimensional grid is created. This grid is later used for 3D interpolation, iso-surface generation, cross-sections and finite difference modeling. The flow and transport modelling interfaces are provided in the 3D-grid module, including the MODFLOW interfaces. (Environmental Modeling Research Laboratory, 1999,& U.S. Department of Defense, 1998).

3.5.1.2 MODFLOW

3.5.1.2.1 Introduction;

A graphical interface to the groundwater model MODFLOW is provided in GMS. MODFLOW is a computer program that simulated three dimensional groundwater flow through a porous medium by using a finite-difference method (Mc Donald and Harbaugh,1988). MODFLOW is a 3D, cell-centered, finite difference, saturated model developed by the United State Geological Survey, and can perform both steady state and transient analyses and has a wide variety of boundary conditions and input options.

MODFLOW is one of the world's most used programs for groundwater modeling. *MODFLOW* can be used for unconfined, confined and combination aquifers and for both two and three dimensional flow. As it focuses on the saturated zone, processes taking place at the surface and in the unsaturated zone are not represented (<http://www.scisoftware.com>, 2004). In this study, the setting of parameters such as recharge represents these processes. *MODFLOW* can be used for both steady state and transient problems.

GMS supports *MODFLOW* as a pre and post-processor. The input data for it are generated by GMS and saved to a set of files. These files are then read by *MODFLOW*, when it is executed. It can be executed with a GMS menu command or from the DOS or UNIX command line. The output from *MODFLOW* is then imported to GMS for post-processing (U.S. Department of Defense, 1998).

The partial differential equation (3.1) describing the groundwater flow is solved numerically for each discrete cell in the defined grid.

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \dots\dots(3.1)$$

Equation (3.1) solved in *MODFLOW* is a combination of the three-dimensional Darcy's law and the mass balance equation. where hydraulic head, h (m), is the dependent variable (hydraulic head). The hydraulic conductivity is represented here in the three coordinate directions (x, y and z) by K_{xx} , K_{yy} and K_{zz} (m/day). S_s is the specific storage (dimensionless) and W (1/day) represents the general source/sink term per volume of aquifer. If W is positive, water is leaving the system and if it is negative water is entering the

system. The t (days) stands for time. If the problem is steady-state, there is no time-variant parameter and the right side of the equation vanishes. The result of a MODFLOW simulation is typically illustrated as contours or iso-lines representing the groundwater surface (Anderson, and Woessner, 1992)

3.5.1.2.2 MODFLOW Related Codes

Many computer codes have been developed to be used with MODFLOW. The codes are often called package, models or sometimes simply programs. Each hydrologic capability, such as leakage to rivers, recharge, and evapotranspiration, that is included within the groundwater flow equation is a separate to package. Because there are many methods for solving the simultaneous equations resulting from the finite-difference methods, each solution method is a package.

The Preconditioned Conjugate Gradient (PCG2 of Hilla,1990) and Strongly Implicit Procedure (SIP) are examples of solution methods implemented as packages in MODFLOW.

Two approaches can be used to construct a MODFLOW simulation in GMS; the grid approach and the conceptual model approach, The grid approach involves working directly with the 3D grid and applying sources/sinks and other model parameters on a cell by cell basis. The conceptual model approach involves using the GIS tools in the *Map* module to develop a conceptual model of the site being modeled. The data in the conceptual model are then copied to the grid. In most cases, the conceptual model approach is more efficient than the grid approach. However, the grid approach is

useful for very simple problems or academic exercises where cell by cell editing is necessary, in this study the conceptual model approach were used.

3.5.1.2.3 Constructing a MODFLOW Conceptual Model in GMS Program

The first step in creating a conceptual model of this site is to create points, arcs and polygons that represent hydrologic features at the site. These points, arcs and polygons are assigned types that correspond to the feature they represent. The resulting source/sink coverage is shown in figure (3.1). Other coverages, defining such things as Recharge Zones and Hydraulic Conductivity Zones, are also defined.

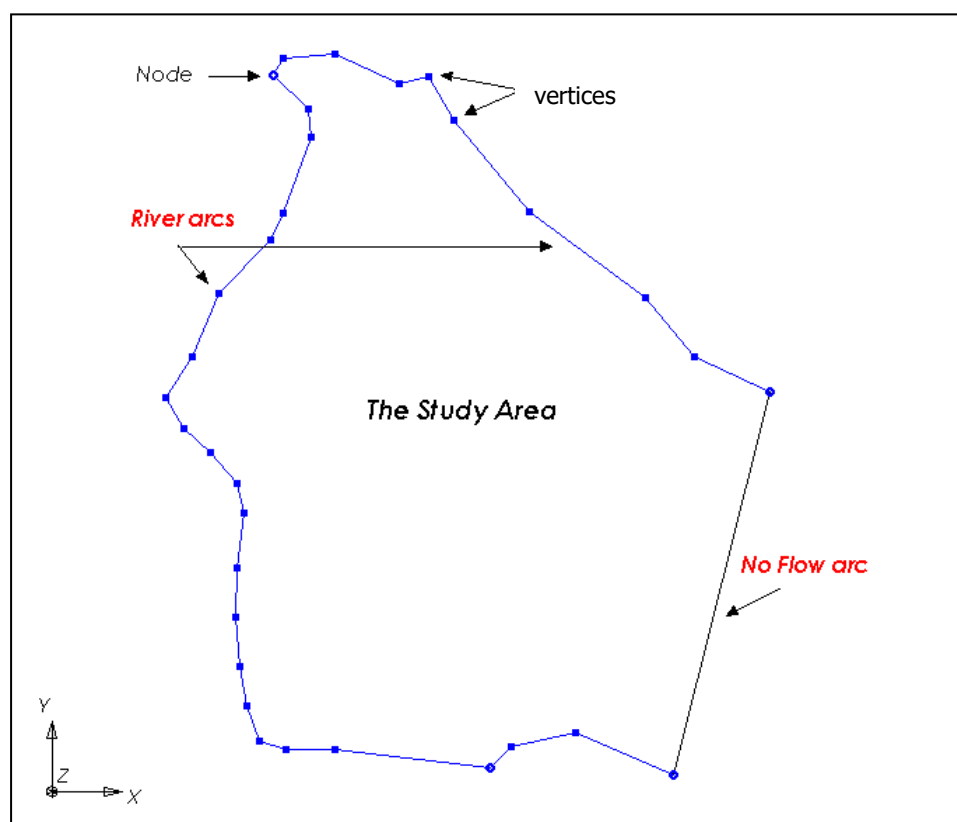


Fig. (3.1) Resulting Source/Sink coverage for the study area from the GMS program.

Groundwater modeling system (GMS) problems are typically solved according to the following steps:

1. Develop a conceptual model.

The first step, the development of a conceptual model, is often the most important step in the modeling process. A conceptual model is a simplified representation of the site to be modeled.

Several steps are involved in setting up a conceptual model and converting the conceptual model to a numerical model. These steps are listed here to provide a summary of the overall process. The steps are as follows:

- a. Create a coverage defining the local sources/sinks in the model, as shown in figure (3.1). The most effective way to do this is with the aid of a background image. A digital image in the form of a TIFF file representing a scanned map or an aerial photo of the site can be imported and displayed in the background using the image tools. Once the image is displayed, feature objects defining the model boundary, rivers, lakes, and specified head boundaries can be created on top of the background image.
- b. Create coverages defining areal attributes such as recharge zones.
- c. Create coverages defining layer attributes such as hydraulic conductivity.
- d. Use the *Grid Frame* command to place an outline of the numerical grid on the conceptual model. The frame is placed so that it just surrounds the conceptual model. The frame can

be rotated if necessary if the major axis of the model is at an angle.

e. Use the *Map -> 3D Grid* command to automatically generate a grid. The location of the grid is controlled by the *Grid Frame* and the density of the grid is automatically adjusted around user-specified points (typically wells).

f. Define the active region of the grid using the *Activate Cells in Coverage* command. This automatically activates all of the cells

within the boundary of the conceptual model and inactivates all cells outside the boundary.

g. Initialize the *MODFLOW* data by selecting the *Basic Package* command in the *MODFLOW* menu in the *3D Grid* module and selecting the *New* button in the *Basic Package* dialog. Turn on the packages required in the simulation and define the stress periods if the simulation is transient. Define a set of starting heads. Go to the *BCF Package* dialog and define the layer type for each of the layers in the grid, where, The block centered flow *BCF* package computes the conductances between each of the grid cells and sets up the finite difference equations for the cell to cell flow. The input to this package includes layer types and cell attributes such as storage coefficients and transmissivity.

g. Select the *Map -> MODFLOW* command to automatically assign the *MODFLOW* boundary conditions, stresses, and material properties to the appropriate cells in the grid.

2. *Create a numerical grid.*

Model grids discretize the continuous natural system into segments (i.e. cells elements, blocks) that allow numerical solutions to be calculated. The grid should be superimposed on a map of the area to be modeled. Grid boundaries should be located consistent to the conceptual model and following the guide lines discussed in the boundary conditions.

3. Assign model parameters and boundary conditions to the grid.

Boundary conditions are constraints imposed on the model grid that express the nature of the physical boundaries of the aquifer being modeled. Boundary conditions have great influence on the computation of flow velocities and heads within the model area.

4. Calibrate the model.

Calibration is the process of adjusting model inputs to achieve a desired of correspondence between the model simulations and the natural groundwater flow system. A flow model is considered calibrated when it can reproduce, to an acceptable degree, the hydraulic heads, and groundwater fluxes of the natural system being modeled. In other words, calibration methods solve a problem inversely by iteratively adjusting the unknowns (hydraulic conductivities, certain boundary fluxes, etc.) until the solution matches the known (usually the hydraulic heads).

5. Make predictions.

Means suggesting the solution that needed to solve the problem, for example wells as in the present study (U.S. Army Corps of Engineers, 1999).

3.5.2 Numerical Model

3.5.2.1 Numerical Model Approach

The phenomena to be considered and basic equations of flow for all aquifer types are obtained from two basic principles:

- Continuity and
- Darcy's Law.

while continuity demands the consideration of water mass, Darcy's Law states that in an isotropic porous medium the specific flow rate is proportional to the negative head gradient. In horizontally two-dimensional groundwater flow this is written as:

$$v_x = -k_f \frac{\partial h}{\partial x}, v_y = -k_f \frac{\partial h}{\partial y}$$

The proportionally constant k_f is called permeability.

Difference method

a-Discretization: numerical method requires discretization in time and space. The different method replaces the partial differential equation of flow by a set of difference equations in discretized space and time. The aquifer of the model system is considered to be unconfined aquifer, as a one layer. The aquifer is first divided up into a rectangular grid. The distances in x- and y-direction, Δx and Δy respectively. The center of a cell is called a node, as shown in figure (3.2).

Time is discretized into time levels $t_0, t_1, t_2 \dots$ separated by time intervals of length Δt .

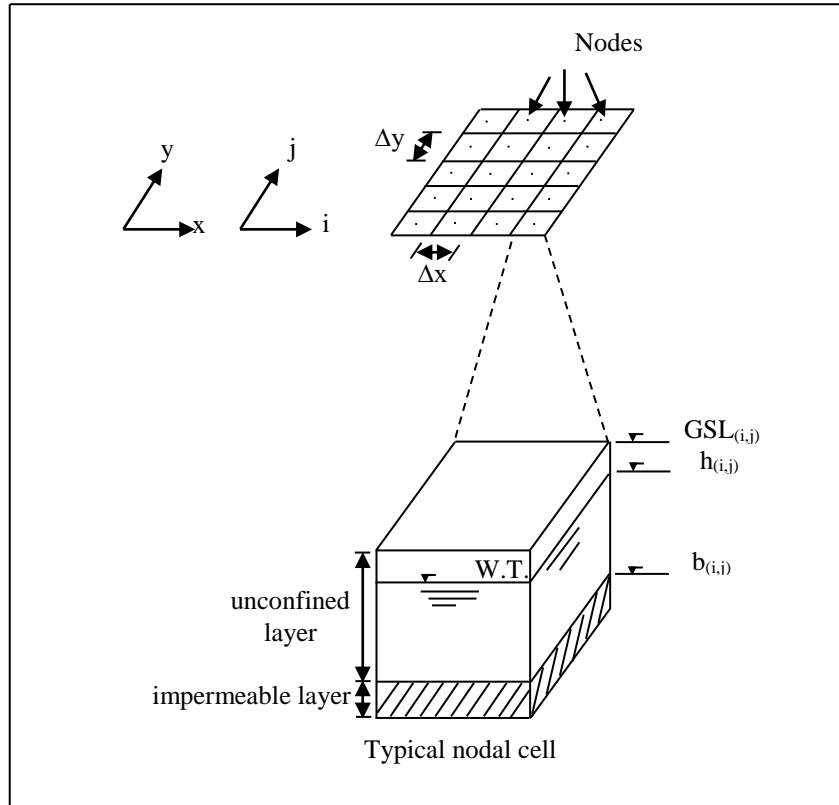


Fig. (3.2) Distribution of the System simulated by the 3D grid model.

Solving the flow equation numerically means that, starting from an initial piezometer head distribution at time t_0 on the discrete nodes of the modeled region, compute head at those nodes for later discrete time level t_1, t_2, \dots in time steps Δt .

b-Water balance

By applying continuity and Darcy's Law to every cell, over a time interval of length (Δt) , assuming that flow will occur only between the cell and its four direct neighbor cells, the water balance of the cell shown in figure (3.3) is represented by considering four in (out) flows from (to) the four neighbors Q_1, Q_2, Q_3 and Q_4 and possibly a discharge or recharge to (from) the surface Q_{SF}, Q_W , it can

be assumed that signs of inflows (enter the cell) are positive, and vice versa, assuming that the flow (Q_w) is an outflow and the others are inflows, so the continuity equation can be written as:

$$[Q_{1i,j}(t+\Delta t) + Q_{2i,j}(t+\Delta t) + Q_{3i,j}(t+\Delta t) + Q_{4i,j}(t+\Delta t) + Q_{SF_{i,j}}(t+\Delta t) - Q_{W_{i,j}}(t+\Delta t)] \Delta t = [h_{i,j}(t+\Delta t) - h_{i,j}(t)] \varepsilon_{i,j} \Delta x_{i,j} \Delta y_{i,j} \dots\dots\dots(3.2)$$

Where;

$h_{i,j}(t)$ and $h_{i,j}(t+\Delta t)$: hydraulic heads of the upper aquifer at time (t), and ($t+\Delta t$), respectively of a nodal cell (i,j), (L).

Q_w : represent the discharge or recharge flow from the pumping wells, (L^3/T).

$\varepsilon_{i,j}$: specific yield of the upper aquifer at a nodal cell (i,j), (unitless).

$\Delta x_{i,j}$ and $\Delta y_{i,j}$: x and y dimensions, respectively of a nodal cell (i,j), (L).

Others; are as previously defined.

The signs of the flows $Q_{1i,j}$, $Q_{2i,j}$, $Q_{3i,j}$, $Q_{4i,j}$, $Q_{W_{i,j}}$, and $Q_{SF_{i,j}}$, in Eq. (3.2) are automatically corrected throughout model application. They depend on hydraulic head conditions in and around the cell under consideration. Eq. (3.2) can be applied to a time level ($t+\Delta t$) which is contained in the interval ($t,t+\Delta t$). When dividing both sides by Δt , Eq. (3.2) becomes:

$$Q_{1i,j}(t+\Delta t) + Q_{2i,j}(t+\Delta t) + Q_{3i,j}(t+\Delta t) + Q_{4i,j}(t+\Delta t) - Q_{W_{i,j}}(t+\Delta t) + Q_{SF_{i,j}}(t+\Delta t) = \frac{h_{i,j}(t+\Delta t) - h_{i,j}(t)}{\Delta t} \varepsilon_{i,j} * \Delta x_{i,j} * \Delta y_{i,j} \dots\dots\dots(3.3)$$

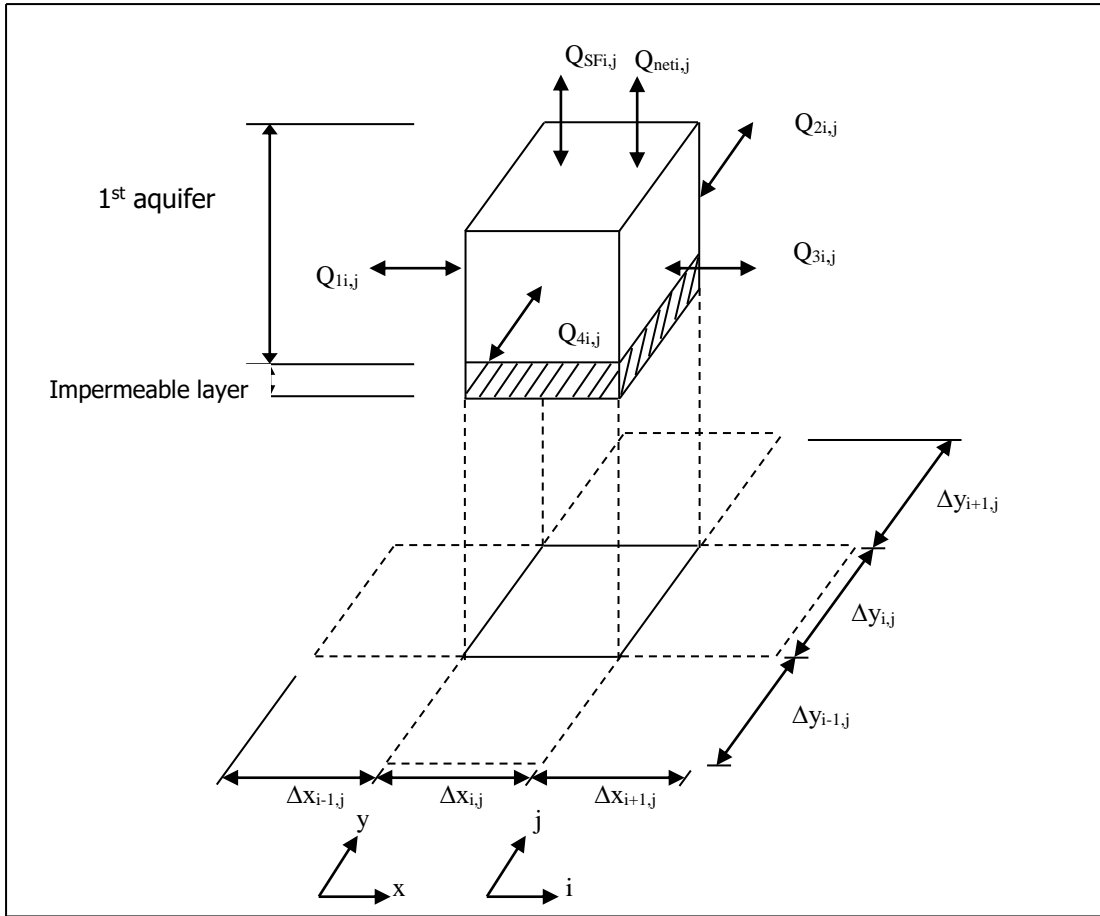


Fig. (3.3) Water Balances around one nodal cell.

c-Infiltration in surface water bodies

The leakage principles can be used to introduce infiltration from or to surface water bodies ($Q_{SF i,j}$). The head difference governing the leakage is the difference between groundwater table ($h_{i,j}$) and the water surface elevation of the surface water body ($h_{r i,j}$) as long as the groundwater table does not drop below the river bottom ($b_{r i,j}$), as shown in figure (3.4), the flow can be determined as:, (kinzelbach, 1986).

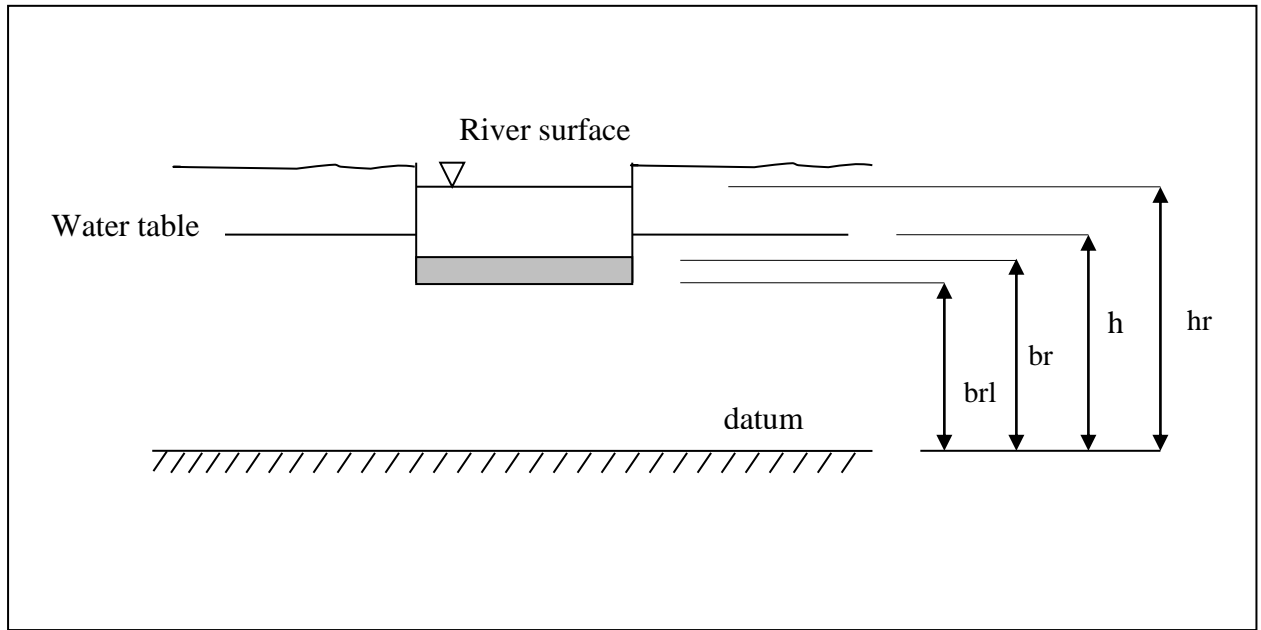


Fig.(3.4) Infiltration from surface water bodies.

$$Q_{SF_{i,j}} = lr_{i,j} (hr_{i,j} - h_{i,j}) \Delta x_{i,j} * \Delta y_{i,j} \quad \dots(3.4a)$$

In which:

$$lr_{i,j} = \frac{kr_{i,j}}{dr_{i,j}}$$

Where:

$lr_{i,j}$: leakage coefficient of surface water body bed at a nodal cell (i,j), L/T.

$kr_{i,j}$: Vertical permeability of surface water body bed at a nodal cell (i,j), L/T.

$dr_{i,j}$: Thickness of surface water body bed at a nodal cell (i,j), L.

$hr_{i,j}$: Water level of surface water body at a nodal cell (i,j), L/T.

$h_{i,j}$: Hydraulic head of the layer (WT) at a nodal cell (i,j), L/T.

$\Delta x_{i,j}$ and $\Delta y_{i,j}$: previously defined.

If the groundwater table ($h_{i,j}$) drops below the river bottom ($br_{i,j}$) or the two elevations are equal, figure (3.3), the flow becomes independent from the groundwater table. The governing head difference is then the head of the surface water body ($br_{i,j}$) with respect to the river bottom.

$$Q_{SFi,j} = lr_{i,j} (h_{i,j} - br_{i,j}) \Delta x_{i,j} * \Delta y_{i,j} \quad (3.4b)$$

Where:

$br_{i,j}$: Top level of surface water body bed at a nodal cell (i,j), L.

Others, as previously defined.

Back to figure (3.3), again with Darcy`s law, the four lateral flows ($Q1_{i,j}$, $Q2_{i,j}$, $Q3_{i,j}$, and $Q4_{i,j}$) can be obtained as follows:

$$Q1_{i,j} = (T1)_{avg} \frac{h_{i-1,j} - h_{i,j}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})} \Delta y_{i,j} \quad \dots(3.5a)$$

$$Q2_{i,j} = (T2)_{avg} \frac{h_{i,j+1} - h_{i,j}}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})} \Delta x_{i,j} \quad \dots(3.5b)$$

$$Q3_{i,j} = (T3)_{avg} \frac{h_{i+1,j} - h_{i,j}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})} \Delta y_{i,j} \quad \dots(3.5c)$$

$$Q4_{i,j} = (T4)_{avg} \frac{h_{i,j-1} - h_{i,j}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})} \Delta x_{i,j} \quad \dots(3.5d)$$

Where ; (T1)avg, (T2)avg, (T3)avg, and (T4)avg are spatial average values of aquifer local transmissivities between a node (i,j) and its four direct neighboring nodes (i-1,j), (i,j+1), (i+1,j), and (i,j-1), respectively.

3.5.2.2 Inter-nodal and directional transmissivities (average transmissivities):

Using average transmissivities (inter-nodal transmissivities) rather than local ones belonging to that (Boonstra and Ridder, 1981), in a realistic regional model, grid size may be anything from some meters to some hundreds of meters. From pumping tests only local values of transmissivity may be found. A correct description of flow between nodes must, thus, be interpolated. To obtain the needed averages (inter-nodal transmissivity) between nodes, arithmetic means may be applied as:

$$T_{1avg} = (T_{i-1,j} + T_{i,j})/2 \quad \dots(3.6)$$

Where $T_{i-1,j}$ and $T_{i,j}$ are local values of transmissivities around nodes (i-1,j) and (i,j), respectively.

The harmonic mean is superior to the arithmetic means used above, as it reflects the fact that two transmissivities arranged in series are equivalent to two parallel resistances. Therefore, they added harmonically as:

$$T_{1avg} = 2(T_{i-1,j} * T_{i,j}) / (T_{i-1,j} + T_{i,j}) \quad \dots(3.7a)$$

The harmonic average, has the advantages of allowing to incorporate impervious boundaries in a simple way later.

Consequence to equation (3.7a), the other three transmissivities can formulated as:

$$T_{2avg} = 2(T_{i,j+1} * T_{i,j}) / (T_{i,j+1} + T_{i,j}) \quad \dots(3.7b)$$

$$T_{3avg} = 2(T_{i+1,j} * T_{i,j}) / (T_{i+1,j} + T_{i,j}) \quad \dots(3.7c)$$

$$T_{4avg} = 2(T_{i,j-1} * T_{i,j}) / (T_{i,j-1} + T_{i,j}) \quad \dots(3.7d)$$

For simplicity, each node of the grid assigned two average transmissivity values $(T_{x_{i,j}})$ and $(T_{y_{i,j}})$ in x and y direction, respectively. $(T_{x_{i,j}})$ is the transmissivity between node (i,j) and its next neighbor node in positive x direction, $(i,j+1)$, and $(T_{y_{i,j}})$ is the transmissivity between node (i,j) and its next neighbor node in positive y direction $(i+1, j)$, figure (3.5). The four transmissivities between node (i,j) and its four next neighbors are expressed as (replaced by):

$$T1_{avg} \rightarrow (T_{x_{i-1,j}})$$

$$T2_{avg} \rightarrow (T_{y_{i,j}})$$

$$T3_{avg} \rightarrow (T_{x_{i,j}})$$

$$T4_{avg} \rightarrow (T_{y_{i,j-1}})$$

Average transmissivities, according to this assignment system, may be called (directional) or (inter-nodal) transmissivities (kinzelbach, 1986). It will be followed hence forward.

Transmissivity depends on the head of the layer, which coincides with the ground water level. Considering figure (3.2), local transmissivity $T_{i,j}$ may be defined by:

$$T_{i,j} = kp_{i,j} (h_{i,j} - b_{i,j}) \dots\dots\dots(3.8)$$

Where:

$kp_{i,j}$: Local permeability of the layer at a nodal cell (i,j) , L/T.

$h_{i,j}$: Hydraulic head of the aquifer at a nodal cell (i,j) , L.

$b_{i,j}$:bottom level at a nodal cell (i,j) , L.

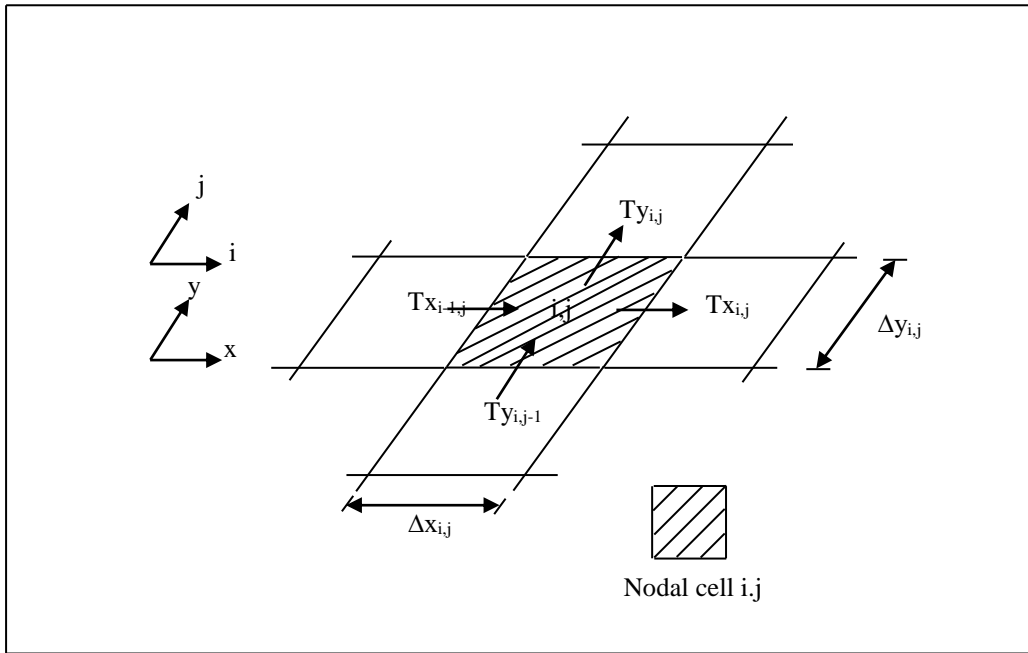


Fig. (3.5) Directional (Internodal) Transmissivity Considered by The 3D-grid Finite Difference Flow Model.

The directional transmissivities can be obtained by taking a harmonic means in analogy to equations (3.7a,b). There is, however, another way of formulating $(T_{x_{i,j}})$ and $(T_{y_{i,j}})$ which is preferable from a calculational point of view. This formulation obtains $(T_{x_{i,j}})$ and $(T_{y_{i,j}})$ by multiplying harmonic average of permeabilities with geometric averages of saturated thickness a long the x and y direction, respectively (Butler, 1957; Bear and Verruijt, 1987):

And,

$$T_{x_{i,j}} = kpx_{i,j} \sqrt{(h_{i+1,j} - b_{i+1,j})(h_{i,j} - b_{i,j})} \quad \dots\dots(3.9a)$$

$$T_{y_{i,j}} = kpy_{i,j} \sqrt{(h_{i,j+1} - b_{i,j+1})(h_{i,j} - b_{i,j})} \quad \dots\dots(3.9b)$$

In which:

$$Kpx_{i,j} = 2(kp_{i,j} * kp_{i+1,j}) / (kp_{i,j} + kp_{i+1,j}) \quad \dots\dots\dots(3.10a)$$

And,

$$K_{py_{i,j}} = 2(k_{p_{i,j}} * k_{p_{i,j+1}}) / (k_{p_{i,j}} + k_{p_{i,j+1}}) \dots\dots\dots(3.10b)$$

Where:

$k_{p_{i,j}}$, $k_{p_{i,j+1}}$, and $k_{p_{i+1,j}}$ are local permeability of the upper layer at cells (i,j), (i,j+1), and (i+1,j), respectively, L/T.

$K_{px_{i,j}}$ and $K_{py_{i,j}}$ are harmonically averaged permeabilities between nodes (i,j) and (i,j+1), and nodes (i,j) and (i+1,j), respectively, L/T.

h and b as previously defined.

Equation (3.5 a-b) can be written using the directional transmissivity concept as:

$$Q1_{i,j} = T_{x_{i-1,j}} \frac{h_{i-1,j} - h_{i,j}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})} \Delta y_{i,j} \dots\dots(3.11a)$$

$$Q2_{i,j} = T_{y_{i,j}} \frac{h_{i,j+1} - h_{i,j}}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})} \Delta x_{i,j} \dots\dots(3-11b)$$

$$Q3_{i,j} = T_{x_{i,j}} \frac{h_{i+1,j} - h_{i,j}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})} \Delta y_{i,j} \dots\dots(3-11c)$$

$$Q4_{i,j} = T_{y_{i,j-1}} \frac{h_{i,j-1} - h_{i,j}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})} \Delta x_{i,j} \dots\dots(3-11d)$$

Substituting Eqs. (3.4a or b), and (3.11a-d) into Eq. (3.3), two equation can be obtained for two conditions as follows:

$$T_{x_{i-1,j}} \frac{h_{i-1,j}(t + \Delta t) - h_{i,j}(t + \Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})} \Delta y_{i,j} + T_{y_{i,j}} \frac{h_{i,j+1}(t + \Delta t) - h_{i,j}(t + \Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})} \Delta x_{i,j} +$$

$$Tx_{i,j} \frac{h_{i+1,j}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})} \Delta y_{i,j} + Ty_{i,j-1} \frac{h_{i,j-1}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})} \Delta x_{i,j}$$

$$-Q_{wi,j}(t+\Delta t) + lr_{i,j}(hr_{i,j} - h_{i,j})(t+\Delta t) \Delta x_{i,j} \Delta y_{i,j} =$$

$$\frac{h_{i,j}(t+\Delta t) - h_{i,j}(t)}{\Delta t} \varepsilon_{i,j} * \Delta x_{i,j} * \Delta y_{i,j} \dots\dots\dots(3.12a)$$

Provided $h_{i,j}(t+\Delta t) > br_{i,j}$, (see Eq. (3.4a)), and:

$$Tx_{i-1,j} \frac{h_{i-1,j}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})} \Delta y_{i,j} + Ty_{i,j} \frac{h_{i,j+1}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})} \Delta x_{i,j} +$$

$$Tx_{i,j} \frac{h_{i+1,j}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})} \Delta y_{i,j} + Ty_{i,j-1} \frac{h_{i,j-1}(t+\Delta t) - h_{i,j}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})} \Delta x_{i,j}$$

$$-Q_{wi,j}(t+\Delta t) + lr_{i,j}(hr_{i,j} - br_{i,j})(t+\Delta t) \Delta x_{i,j} \Delta y_{i,j} =$$

$$\frac{h_{i,j}(t+\Delta t) - h_{i,j}(t)}{\Delta t} \varepsilon_{i,j} * \Delta x_{i,j} * \Delta y_{i,j} \dots\dots\dots(3.12b)$$

Provided that $h_{i,j}(t+\Delta t) \leq br_{i,j}$.

Dividing both sides of the above two Eq. (3.12a and b) by $\Delta x_{i,j} * \Delta y_{i,j}$ and rearranging, they can be formed as:

$$\begin{aligned} & \frac{Tx_{i-1,j}(t+\Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j}) \Delta x_{i,j}} h_{i-1,j} + \frac{Ty_{i,j}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j}) \Delta y_{i,j}} h_{i+1,j} \\ & + \frac{Tx_{i,j}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j}) \Delta x_{i,j}} h_{i+1,j} + \frac{Ty_{i,j-1}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j}) \Delta y_{i,j}} h_{i,j-1} \\ & + h_{i,j} \left[-\frac{Tx_{i-1,j}(t+\Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j}) \Delta x_{i,j}} - \frac{Ty_{i,j}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j}) \Delta y_{i,j}} - \right. \end{aligned}$$

$$\begin{aligned}
 & -\frac{T_{x_{i,j}}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_{y_{i,j+1}}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} - \left[r_{i,j} - \frac{\varepsilon_{i,j}}{\Delta t} \right] = \\
 & -\frac{h_{i,j}(t) * \varepsilon_{i,j}}{\Delta t} - \frac{Q_{w_{i,j}}(t+\Delta t)}{\Delta x_{i,j} * \Delta y_{i,j}} - \left[r_{i,j} * hr_{i,j}(t+\Delta t) \right] \dots(3.13 a)
 \end{aligned}$$

Provided that $h_{i,j}(t+\Delta t) > brl_{i,j}$ and;

$$\begin{aligned}
 & \frac{T_{x_{i-1,j}}(t+\Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} h_{i-1,j} + \frac{T_{y_{i,j}}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i+1,j} \\
 & + \frac{T_{x_{i,j}}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} h_{i+1,j} + \frac{T_{y_{i,j+1}}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i,j-1} \\
 & + h_{i,j} \left[-\frac{T_{x_{i-1,j}}(t+\Delta t)}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_{y_{i,j}}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \right. \\
 & \left. -\frac{T_{x_{i,j}}(t+\Delta t)}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_{y_{i,j+1}}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{\varepsilon_{i,j}}{\Delta t} \right] = \\
 & -\frac{h_{i,j}(t) * \varepsilon_{i,j}}{\Delta t} - \frac{Q_{w_{i,j}}(t+\Delta t)}{\Delta x_{i,j} * \Delta y_{i,j}} - \left[r_{i,j} (hr_{i,j} - br_{i,j})(t+\Delta t) \right] \dots(3.13 b)
 \end{aligned}$$

Provided that $h_{i,j}(t+\Delta t) \leq brl_{i,j}$.

The two last equations (3.13a and b) may be described as two-dimensional finite difference flow equations in a discretized (no horizontal plane and time) form for the aquifer.

Transmissivity terms of Eqs. (3.13a and b) depend on hydraulic heads (h), (Eqs (3.9a and b)). Therefore, Eqs. (3.13a and b) are nonlinear to $h(t+\Delta t)$. In order to linearize them, iteration is required. This is made by replacing the unknown $h_{i,j}(t+\Delta t)$ in the transmissivities (Eqs.(3.7 a-d)) by an approximation. In the first iteration step, the approximation is $h_{i,j}(t)$. Then the resulting linear

equation system is solved by any of the iterative implicit procedures yielding a solution value for $h_{i,j}(t+\Delta t)$. By introducing this solution as the needed approximate value for the second iteration continues till the desired convergence is reached. The convergence means that difference between compute $h_{i,j}(t+\Delta t)$ of the successive iterations (of one time step) being somewhat acceptable as small value. Undoubtedly, the constants $Q_{w_{i,j}}$, $l_{r_{i,j}}$, $kp_{i,j}$, $\epsilon_{i,j}$, $brl_{i,j}$, $br_{i,j}$, $\Delta x_{i,j}$ and $\Delta y_{i,j}$ which are all spatial but not temporal variables should be known too.

As explained above, to solve Eqs. (3.13a and b) an Iterative Implicit Procedure for $h_{i,j}(t+\Delta t)$ may be used. In the present model, the Iterative Alternating Direction Implicit procedure(IADI) is adopted.

3.5.2.2 Solving the two Equations

The solution of equations (3.13a and b) is accomplished using the Iterative Alternating Direction Implicit (IADI) procedure, assuming that the system grid figure (3.2) consists of (NY)rows, and (NX) columns. Accordingly, there are (NY*NX) nodes contained by the grid. There are NX nodal equations of nodes in row (j), but also NX heads of the left and NX heads of the right are in neighboring columns. Bringing all heads from neighboring rows to the right-hand side of the equation. Consider Eqs. (3.13a and b):

For $i = 1$ to NX

When $h_{i,j}(t+\Delta t) > brl_{i,j}$

$$\frac{T_{x_{i-1,j}}(t+\Delta t) * h_{i-1,j}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} + h_{i,j}(t+\Delta t) \left[\frac{-T_{x_{i-1,j}}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \right]$$

$$\begin{aligned}
 & \frac{T_{y_{i,j}}}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{T_{x_{i,j}}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_{y_{i,j-1}}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \\
 & -lr_{i,j} - \frac{\varepsilon_{i,j}}{\Delta t} + \frac{T_{x_{i,j}}(t+\Delta t)*h_{i+1,j}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} = -\frac{Q_{w_{i,j}}(t+\Delta t)}{\Delta x_{i,j}*\Delta y_{i,j}} - \frac{h_{i,j}(t)*\varepsilon_{i,j}}{\Delta t} \\
 & -lr_{i,j} * hr_{i,j}(t+\Delta t) - \frac{T_{y_{i,j}}(t+\Delta t)*h_{i,j+1}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} \\
 & - \frac{T_{y_{i,j-1}}(t+\Delta t)*h_{i,j-1}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \quad \dots(3.14a)
 \end{aligned}$$

For i=1 to NX

when $h_{i,j}(t+\Delta t) \leq brl_{i,j}$

$$\begin{aligned}
 & \frac{T_{x_{i-1,j}}(t+\Delta t)*h_{i-1,j}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} + h_{i,j}(t+\Delta t) \left[\frac{-T_{x_{i-1,j}}}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \right. \\
 & \frac{T_{y_{i,j+1}}}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{T_{x_{i,j}}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_{y_{i,j-1}}}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \\
 & \left. - \frac{\varepsilon_{i,j}}{\Delta t} \right] + \frac{T_{x_{i+1,j}}(t+\Delta t)*h_{i+1,j}}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} = -\frac{Q_{w_{i,j}}(t+\Delta t)}{\Delta x_{i,j}*\Delta y_{i,j}} - \frac{h_{i,j}(t)*\varepsilon_{i,j}}{\Delta t} \\
 & -lr_{i,j}(hr_{i,j} - br_{i,j})(t+\Delta t) - \frac{T_{y_{i,j+1}}*h_{i,j+1}(t+\Delta t)}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} \\
 & - \frac{T_{y_{i,j-1}}*h_{i,j-1}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \quad \dots(3.14b)
 \end{aligned}$$

For j=1 to NY

When $h_{i,j}(t+\Delta t) > brl_{i,j}$

$$\begin{aligned}
 & \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i,j-1}(t + \Delta t) + h_{i,j}(t + \Delta t) \left[\frac{-T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \right. \\
 & \frac{T_y}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \left. \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \right] \\
 & - l_{i,j} \left[\frac{\varepsilon}{\Delta t} + \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i,j-1}(t + \Delta t) - \frac{Q_{w_{i,j}}(t + \Delta t)}{\Delta x_{i,j} * \Delta y_{i,j}} - \frac{h_{i,j}(t) * \varepsilon}{\Delta t} \right. \\
 & \left. - l_{i,j} * h_{i,j}(t + \Delta t) - \frac{T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} h_{i-1,j}(t + \Delta t) \right. \\
 & \left. - \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta y_{i,j}} h_{i+1,j}(t + \Delta t) \right] \dots(3.15a)
 \end{aligned}$$

For j=1 to NY

when $h_{i,j}(t + \Delta t) \leq br_{i,j}$

$$\begin{aligned}
 & \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i,j-1}(t + \Delta t) + h_{i,j}(t + \Delta t) \left[\frac{-T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \right. \\
 & \frac{T_y}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \left. \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} \right] \\
 & - \frac{\varepsilon}{\Delta t} + \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} h_{i,j-1}(t + \Delta t) - \frac{Q_{w_{i,j}}(t + \Delta t)}{\Delta x_{i,j} * \Delta y_{i,j}} - \frac{h_{i,j}(t) * \varepsilon}{\Delta t} \\
 & - l_{i,j} (h_{i,j} - br_{i,j})(t + \Delta t) - \frac{T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} h_{i-1,j}(t + \Delta t) \\
 & - \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta y_{i,j}} h_{i+1,j}(t + \Delta t) \dots(3.15b)
 \end{aligned}$$

If all piezometer head that appear on the right –hand sides of equations (3.14a and b) and (3.15a and b) are known either by an

estimate or a previous calculation, then all equations can be solved, so system of equation can be formed as:

By considering Eq.(3.15a) for solving and the other Eq.(3.15b) is the same:

For $i = 1$ to NX

$$A_i h_{i-1,j}(t+\Delta t) + B_i h_{i,j}(t+\Delta t) + C_i h_{i+1,j}(t+\Delta t) = D_i \quad \dots\dots\dots(3.16a)$$

For $j=1$ to NY

$$A_j h_{i,j-1}(t+\Delta t) + B_j h_{i,j}(t+\Delta t) + C_j h_{i,j+1}(t+\Delta t) = D_j \quad \dots\dots(3.16b)$$

In which;

Provided that $h_{i,j}(t+\Delta t) > br_{i,j}$

$$A_i = \frac{T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}}$$

$$A_j = \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}}$$

$$B_i = B_j = \frac{-T_x}{0.5(\Delta x_{i-1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_y}{0.5(\Delta y_{i,j+1} + \Delta y_{i,j})\Delta y_{i,j}} - \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}} - \frac{T_y}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}} - lr_{i,j} - \frac{\epsilon_{i,j}}{\Delta t}$$

$$C_i = \frac{T_x}{0.5(\Delta x_{i+1,j} + \Delta x_{i,j})\Delta x_{i,j}}$$

$$C_j = \frac{T_y h_{i,j+1}(t+\Delta t)}{0.5(\Delta y_{i,j-1} + \Delta y_{i,j})\Delta y_{i,j}}$$

$$D_i = -\frac{Q_{w_{i,j}}(t+\Delta t)}{\Delta x_{i,j} * \Delta y_{i,j}} - \frac{h_{i,j}(t) * \epsilon_{i,j}}{\Delta t} - lr_{i,j} hr_{i,j}(t+\Delta t) -$$

3.6 Boundary Conditions

The boundary conditions of the differential equation represent either a dependent variable (head) or the derivative of the dependent variable (flux) at the model boundaries. There are three types of boundary conditions for groundwater flow models:

- boundary conditions of the first kind (Dirichlet type) prescribe the head value. In a modelled domain there should be at least one point that constitutes a first-kind boundary. This is necessary to guarantee the uniqueness of the solution. Otherwise it can only be determined up to a constant.
- boundary conditions of the second kind (Neumann type) specify the boundary flux, which means the head gradient normal to the boundary. A special case of this type of boundary is the impervious boundary where the flux is zero. If streamlines form boundaries of the modelled domain they are treated as impervious boundaries. Wells can be viewed as inner boundaries of the second kind by cutting out a circle around the well and specifying the flow across the circle.
- boundary conditions of the third kind (semipervious boundary, mixed boundary conditions) specify a linear combination of head and flux at a boundary. They are used at semipervious (leakage) boundaries (Kinzelbach, 1986).

The boundaries can be physical or hydraulic. Physical boundaries can be for example impermeable rock, lakes or waterways. Examples of hydraulic boundaries are water divides or flow lines (Anderson and Woessner, 1992).

The boundary conditions of this study is explained in details in ch.4, sec. 4.3.

CHAPTER FOUR

APPLICATION OF THE MODELS AND THE RESULTS

4.1 General

This chapter will review the application of both models (GMS model and numerical model), and the simulation was performed using the two dimensional finite difference flow model which constructed by using all input data that are possibly needed and the output of both models with their comparison and discussion.

The simulation includes both the steady and unsteady state (transient). The priority was given to the steady state simulation, because its easier for calibration on one hand, and to apply its results in the transient state simulation on the other hand.

4.2 Discretization of the model's grid

The study area was divided into uniform square grid comprising (53) rows and (43) columns, making a total (2279) cells and covering the area of approximately (22.8 km²). All the cells have uniform lateral dimensions of (100m) along rows and columns ($\Delta x = \Delta y = 100\text{m}$), figure (4.1) shows the designed finite difference grid.

The numerical model in the study area is considered as a single unconfined layer. All cells outside the boundary of the study area were treated as inactive cells, the internal cells were considered variable head cells.

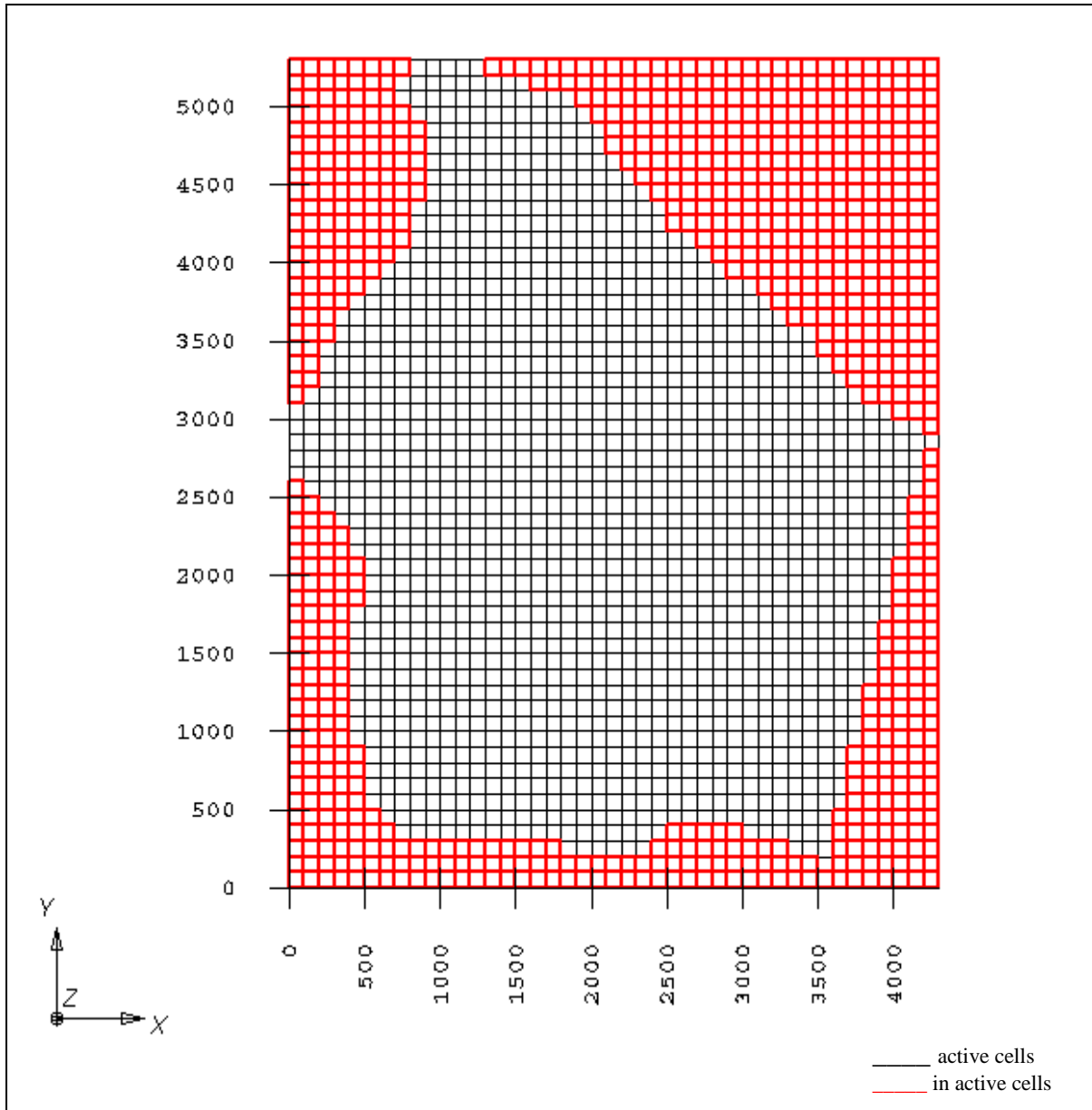


Fig. (4.1) Grid design for the study area.

4.3 Model Boundaries

The map of Babylon city shown in figure (4.2) shows the boundary of the study area, where Shat Al Hilla forms the west and southwestern boundaries of the study area, therefore it was considered as a head dependent boundary allowing inflow to the model region as proportional to head difference between the water surface in the river

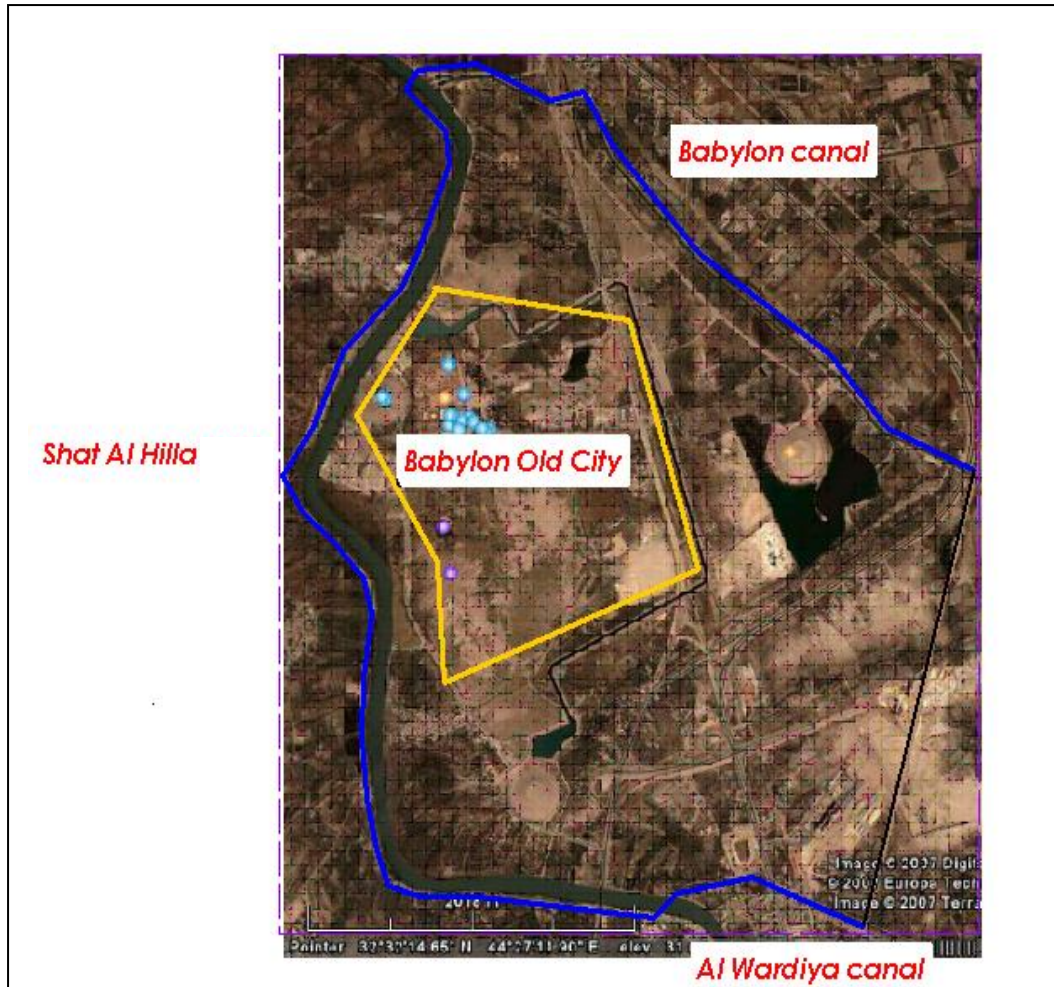


Fig. (4.2) Aerial photo map of Babylon Old City.

and the water table.

The north and the northeastern and part of the east of the study area bounded by Babylon canal, so it is considered as a head dependent boundary too. From the south bounded by Al Wardiya canal, which is considered as a head dependent boundary too. The residual part from the east (the black line in the map) may be considered as no flow boundary, since the flow across this boundary is actually very small resulting in continuous accumulation of groundwater in the study area.

While Ibtisam's study area bounded by Shat Al Hilla from the western end, while the northwestern, southwestern and southeastern

parts bounded by the artificial lakes, as shown in figure (4.3). She considered these lakes as constant head cells. The analysis from that, these lakes are too small to be considered as constant head. So, the boundaries in Ibtisam's study are different from those taken in the present study.

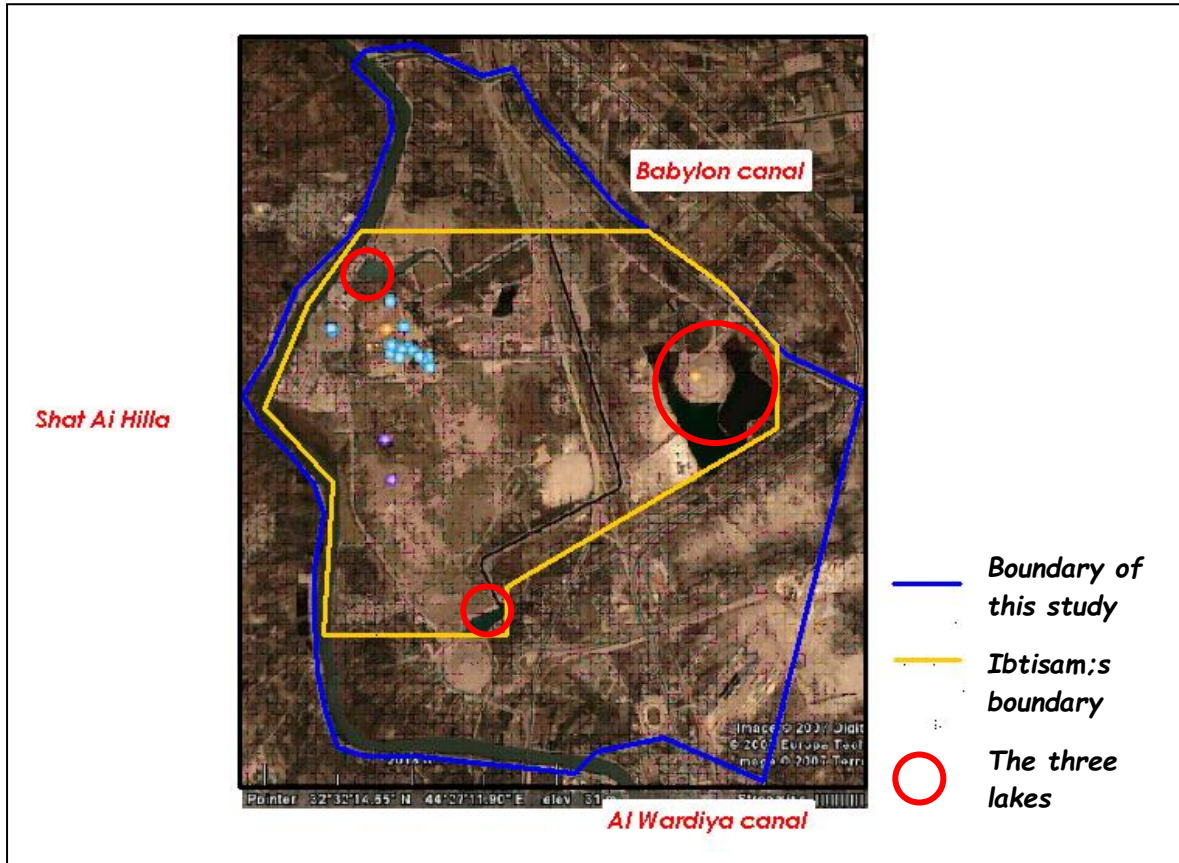


Fig.(4.3) Illustration of the difference between the boundaries of this study and Ibtisam's study (2005).

4.4 Initial conditions and input data

Initial conditions referring to the values of the dependent variables are defined at the beginning of the simulation. For steady state models, initial condition needs only approximately match the natural system because the solution for each dependent node can be found

eventually through repeated iteration (U. S. Army Corps of Engineers, 1999), i.e. calibration.

In the steady state simulation, the initial condition is the head distribution at initial time ($t=0$), the initial heads are considered as the initial conditions for the steady state calibration.

Because of lack of data, some of the data that are necessary for simulating the model should be estimated. The initial estimates of the average permeability values were within the range of (2.5-17.5 m/day) for the system of one unconfined layer, while the effective porosity was estimated to be (0.2) in sand soils (U. S. department of the interior, 1985).

Bottom elevation and ground surface level is given as a constant average level of 15m, and 33m respectively.

Leakage coefficient of the rivers bed is taken as constant average values of 3.5/day, 7/day, and 14/day for Shat Al Hilla, Babylon canal, and Al Wardiya canal respectively. These values are found when dividing an average permeability value of 7 m/day (assumed) for Shat Al Hilla, Babylon canal, and Al Wardiya canal, on an average bed thickness of 2m, 1m, 0.5m (assumed) for Shat Al Hilla, Babylon canal, and Al Wardiya canal respectively.

Distribution of recharge from precipitation, as illustrated is 110mm, of the study area is $460\text{m}^3/\text{day}$, therefore, local recharge rate per each nodal cell (of 22.79 km^2 area) is $(3.68 \cdot 10^{-5}\text{ m/day})$.

Conductance for each of the rivers is calculated and found (180/day, 35/day, 15/day) for Shat Al Hilla, Babylon canal, and Al Wardiya canal respectively. The method of calculation the values of conductance can be found in appendix (B).

The table below shows the initial values and the input data that used in this study.

Table (4.1) Values of initial conditions and input data

Data	Values
<i>permeability</i>	2.5-17.5 m/day
<i>effective porosity</i>	0.2
<i>Bottom elevation</i>	15m
<i>ground surface level</i>	33m
<i>Leakage coefficient</i>	3.5/day for Shat Al Hilla
	7/day for Babylon canal
	14/day for Al Wardiya canal.
<i>Recharge</i>	3.68*10 ⁻⁵ m/day
<i>Conductance of rivers</i>	180/day for Shat Al Hilla
	35/day for Babylon canal
	15/day for Al Wardiya canal.

4.5 Calibration of the GMS Model

The final flow and transport model of the study area is the culmination of a calibration process that was used to increase model reliability (GeoTrans, 2001). Calibration is the process of adjusting model inputs to achieve a desired degree of correspondence between the model simulations and the natural groundwater flow system. A flow model is considered calibrated when it can reproduce, to an acceptable degree, the hydraulic heads and groundwater fluxes of the

natural system being modeled. This is accomplished by finding a set of values for the boundary conditions, aquifer properties, and stresses that result in computed heads and fluxes matching their natural counterparts at target locations (U. S. Army Corps of Engineers, 1999).

In the calibration process, the model results are compared to observed field data. Input parameters and boundary conditions are adjusted until the model results agree with the field observations within a pre-established range of error (Anderson and Woessner, 1992).

The need to calibrate the model originates from the uncertainty in parameter values due to the number of assumptions and simplifications made in the conceptual and mathematical models (Carey et al., 2001).

For GMS model the calibration of the present study is accomplished through a trail and error adjustment of the model's input data (average permeability, model boundaries, and conductance of the rivers) to modify the model's output to be with a good match obtained between computed (simulated) and observed heads.

A steady state calibration was used in the present study because of it's easiness to calibrate and its results can be applied in the transient state simulation. The data chosen for the calibration were the water table level during 1979 (GDGSMI,1979), figure (1.2).

Agreement between observed and computed (simulated) water levels was obtained after several iterations. Graphical comparison of observed and computed water table elevations is presented as figure (4.4) which indicates that similarity is satisfactory since exact match

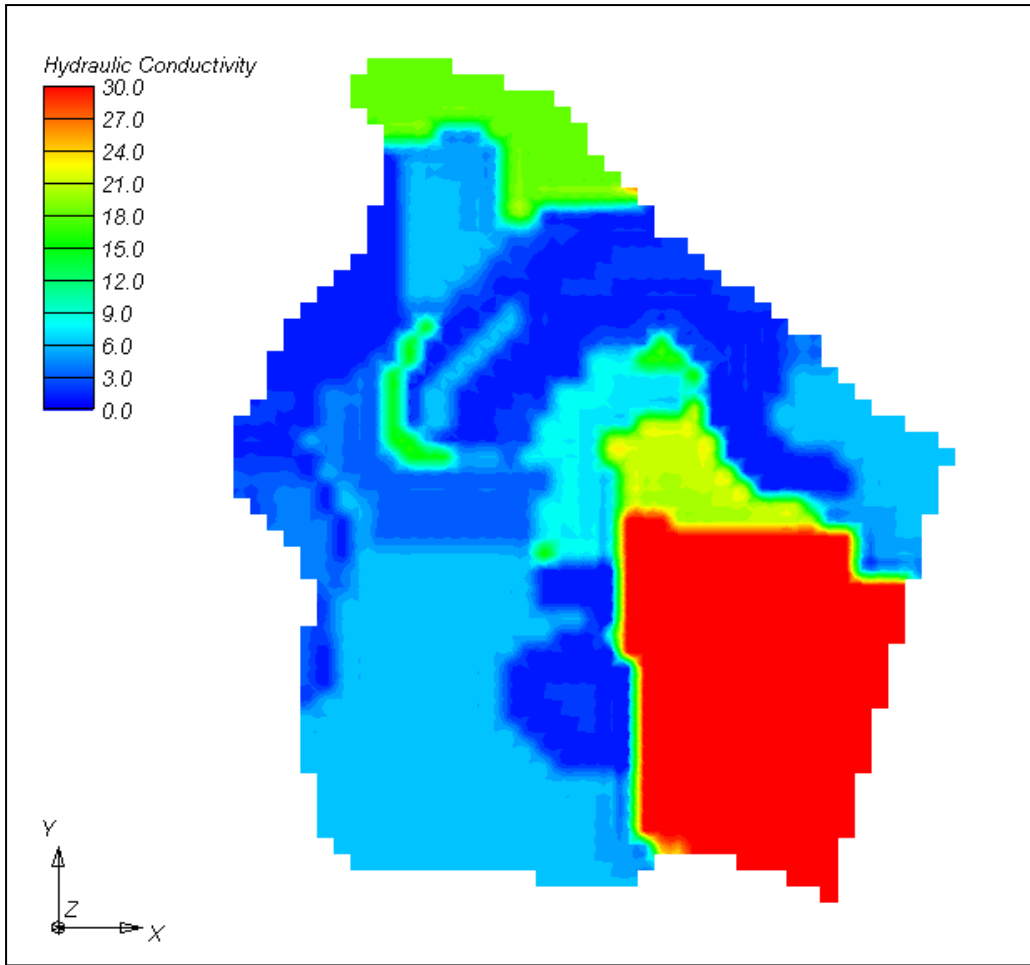


Fig.(4.5) permeability after calibration.

performance using the following equation, (Rasheeduddin, et al, 1989):

$$RMSE = \frac{\sqrt{\sum_{i=1}^r \sum_{j=1}^c (h^o_{i,j} - h^s_{i,j})^2}}{rc} \dots\dots\dots(4-1)$$

Where;

$h^s_{i,j}$: Simulation head at raw i, column j (L).

$h^o_{i,j}$: observed head at raw i, column j (L).

r and c : Number of rows and columns, respectively.

rc : Number of cells within the modeled region.

The RMSE for the GMS model is 1.53 which is less than 10% from maximum value of the head in the studied area (Konikow, 1996). Where maximum value of head equal to about 29 and 10% of it equal to 2.9 that it mean the RMSE of 1.53 is less than 2.9, so the calibration process is succeed..

At the end of the calibration process, the model should be ready for use to simulate the transient (unsteady) state condition, where the simulated head after calibration used as starting heads to simulate the transient (unsteady) state condition.

4.6 Transient state simulation for GMS model

Transient state simulation is done for GMS model only. This simulation is done by using pumping wells. Many different numbers of wells that are suggested to reach a good results in dewatering the groundwater level in the study area to keep it's ruins from damaging.

Several iterations were done for reaching good results with minimum number of wells. Trials of variable numbers of wells were selected in different sites, assumed to be far away from the old buildings.

After many iterations the best results obtained by using 15 wells distributed close to Shat Al Hilla river and Babylon canal as shown in figure (4.6), which are the main source of recharge, (GDGSMI,1979).

The rate of discharge from each well 17ℓ/s obtained by many trails to get the best rate of discharge from the wells to met the required drawdown \approx 5m that advised by the GDGSMI(1979).

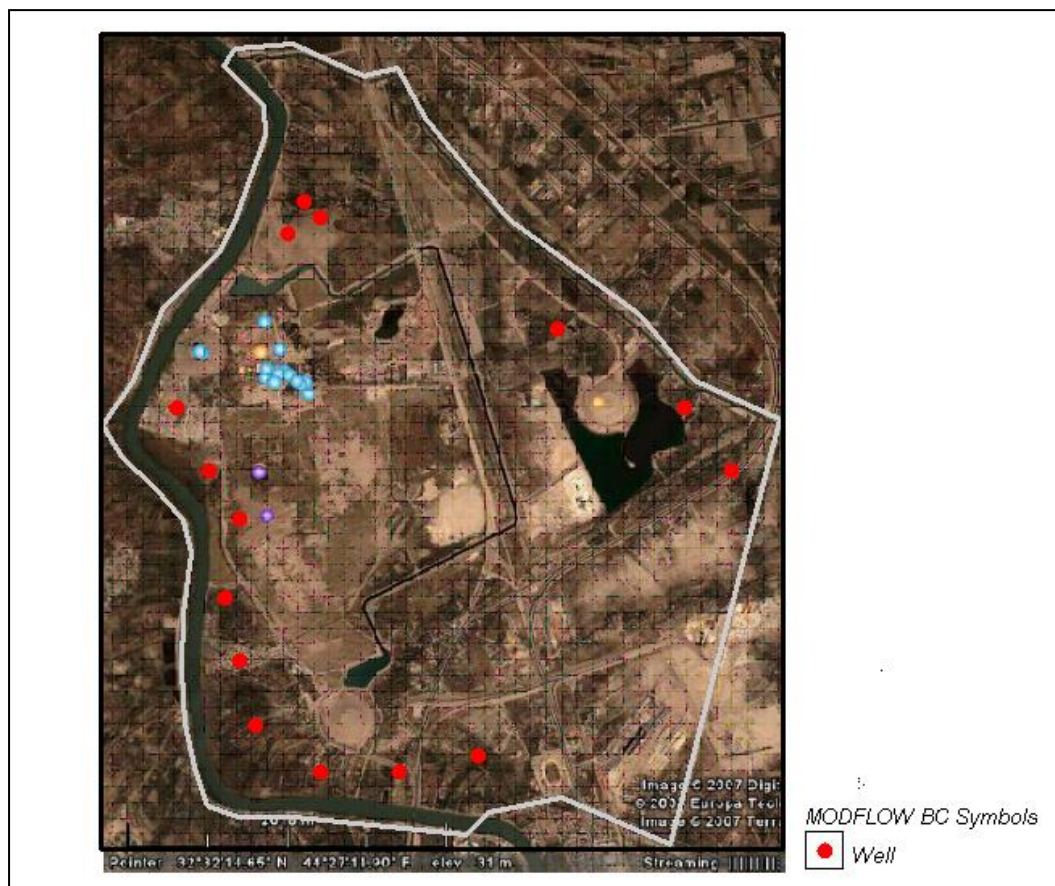


Fig.(4.6) Locations of the 15 wells.

After dewatering from the pumping wells with a rate of 17 ℓ/s with different duration of pumping of 30, 100, 200, 360 days, the results are shown in figures (4.7), (4.8), (4.9), (4.10) respectively.

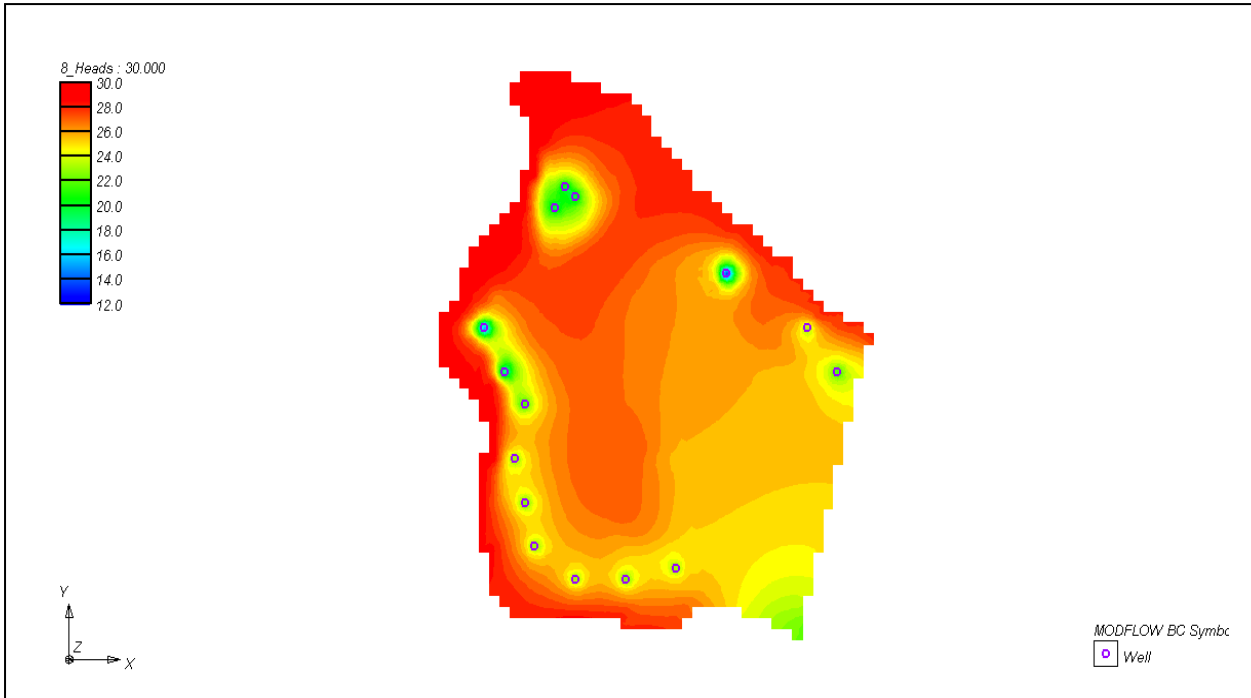


Fig.(4.7) Simulation of water table elevation after 30 days of pumping 15 wells.

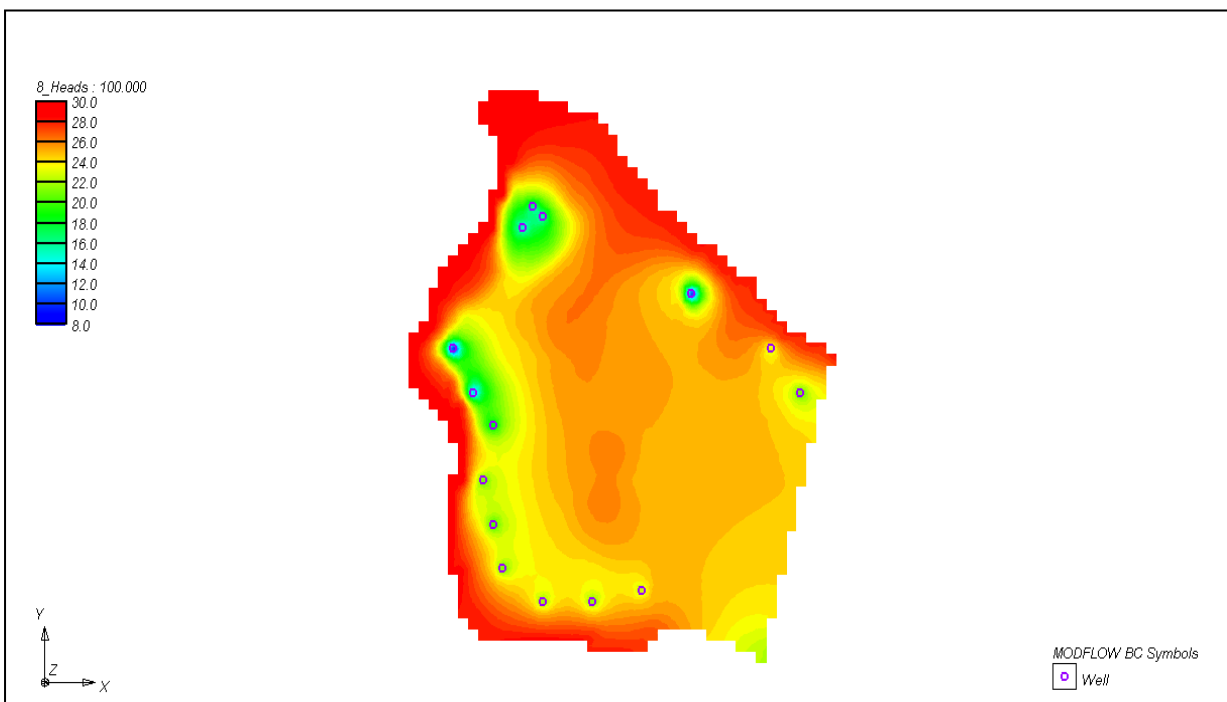


Fig.(4.8) Simulation of water table elevation after 100 days of pumping 15 wells.

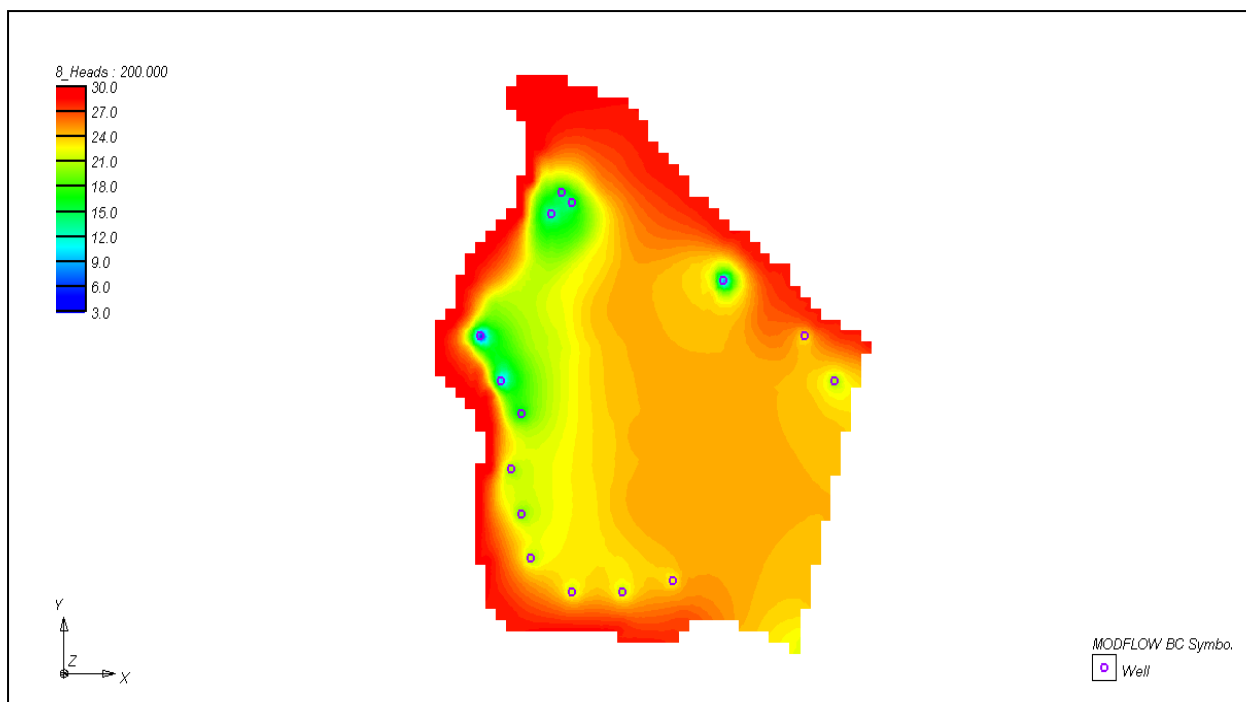


Fig.(4.9) Simulation of water table elevation after 200 days of pumping 15 wells.

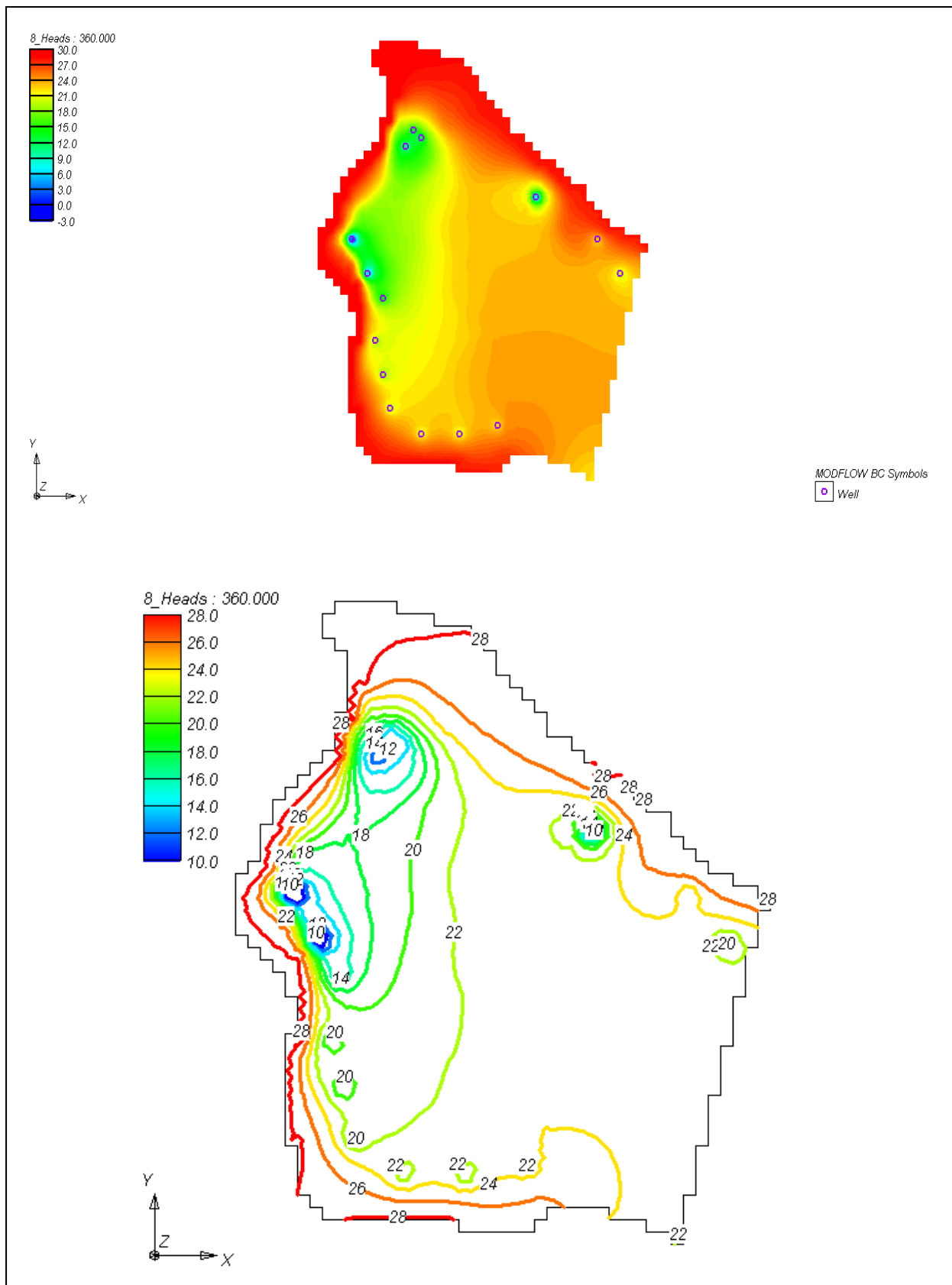


Fig.(4.10) Simulation of water table elevation after 360 days of pumping 15 wells.

The drawdown after 360 days from pumping ranged between 5-12m as shown in figure (4.11)

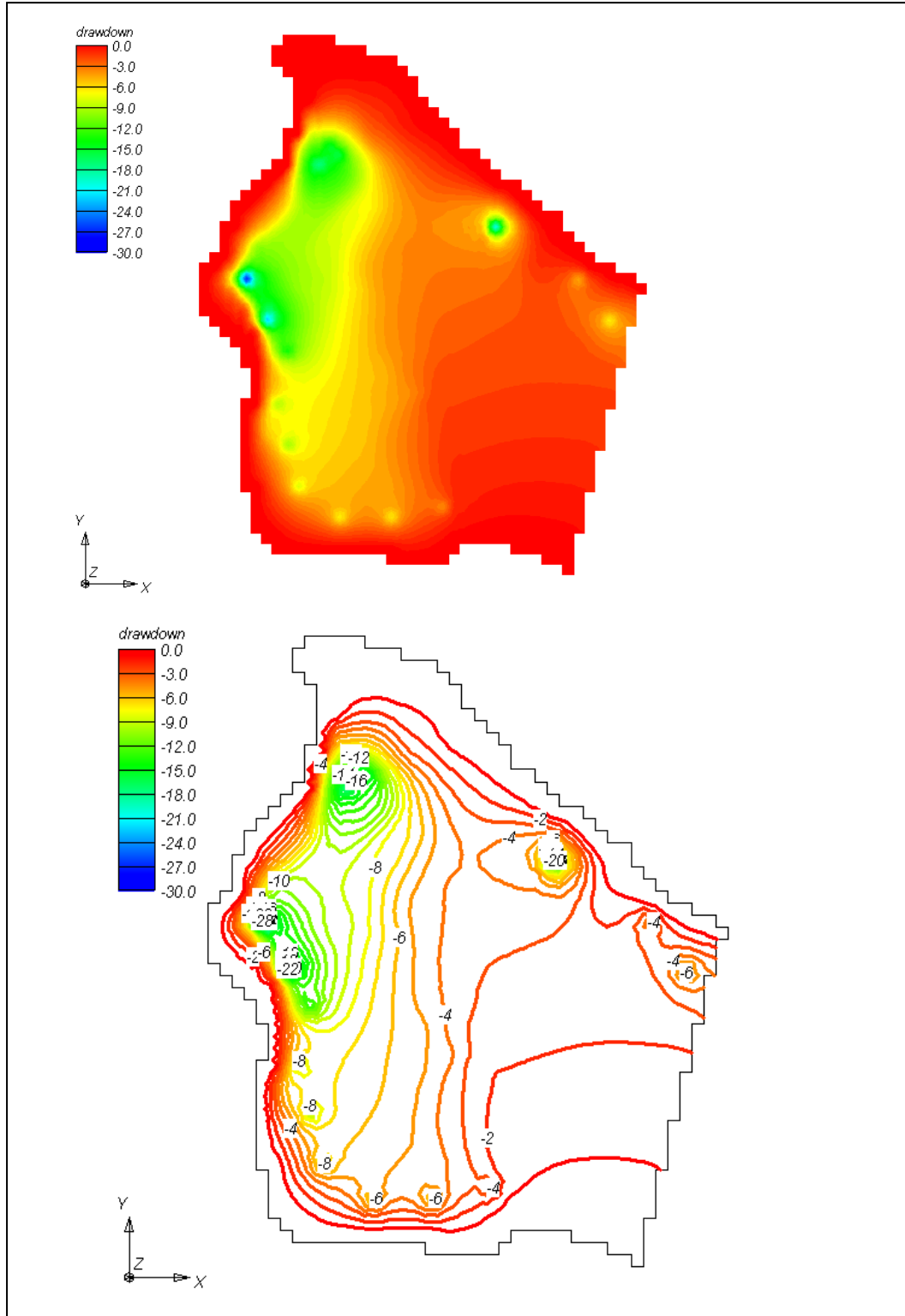


Fig.(4.11) Simulation of the drawdown of the water table after 360 days of pumping the 15 wells.

Several trials with consideration less number of the wells were performed. The first trial contains (12) wells as shown in figure (4.12), the results after pumping the 12 wells at a rate 17ℓ/s can be shown in figures (4.13), (4.14), (4.15) after 100, 200, 360 days from pumping respectively.

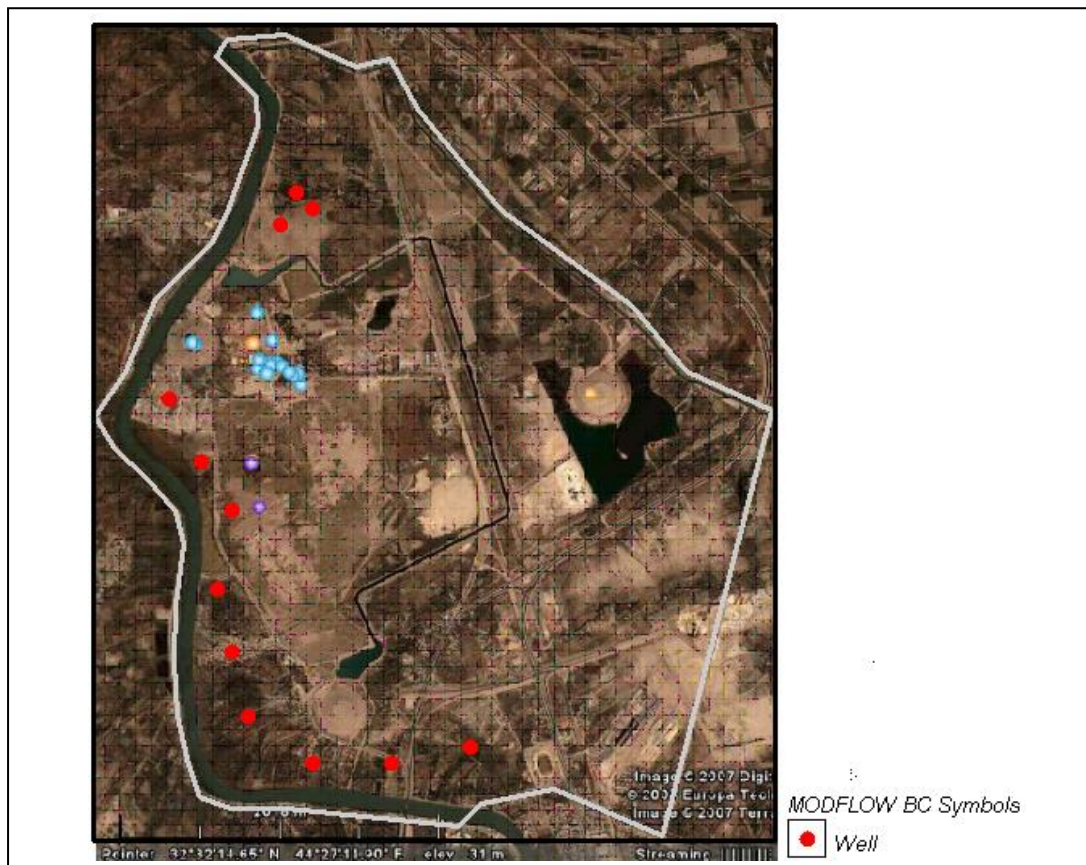


Fig.(4.12) Locations of the 12 wells.

The drawdown of this trail after 360 days from pumping can be shown in figure (4.16).

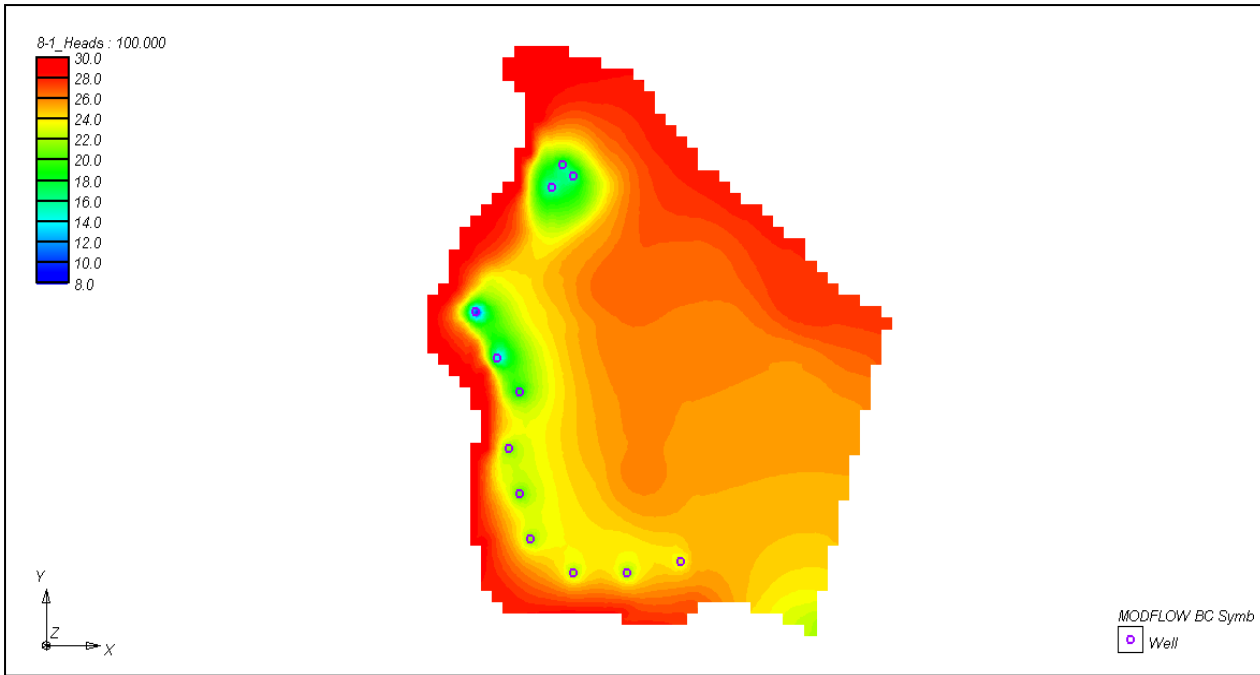


Fig.(4.13) Simulation of water table elevation after 100 days of pumping 12 wells.

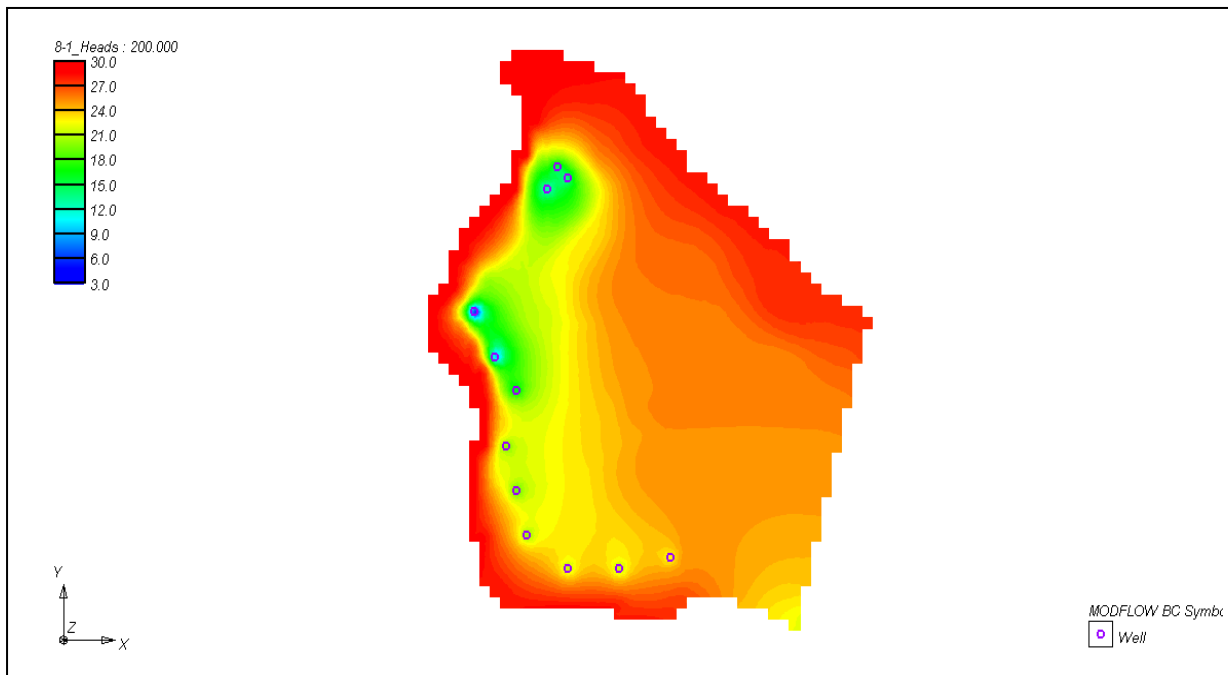


Fig.(4.14) Simulation of water table elevation after 200 days of pumping 12 wells.

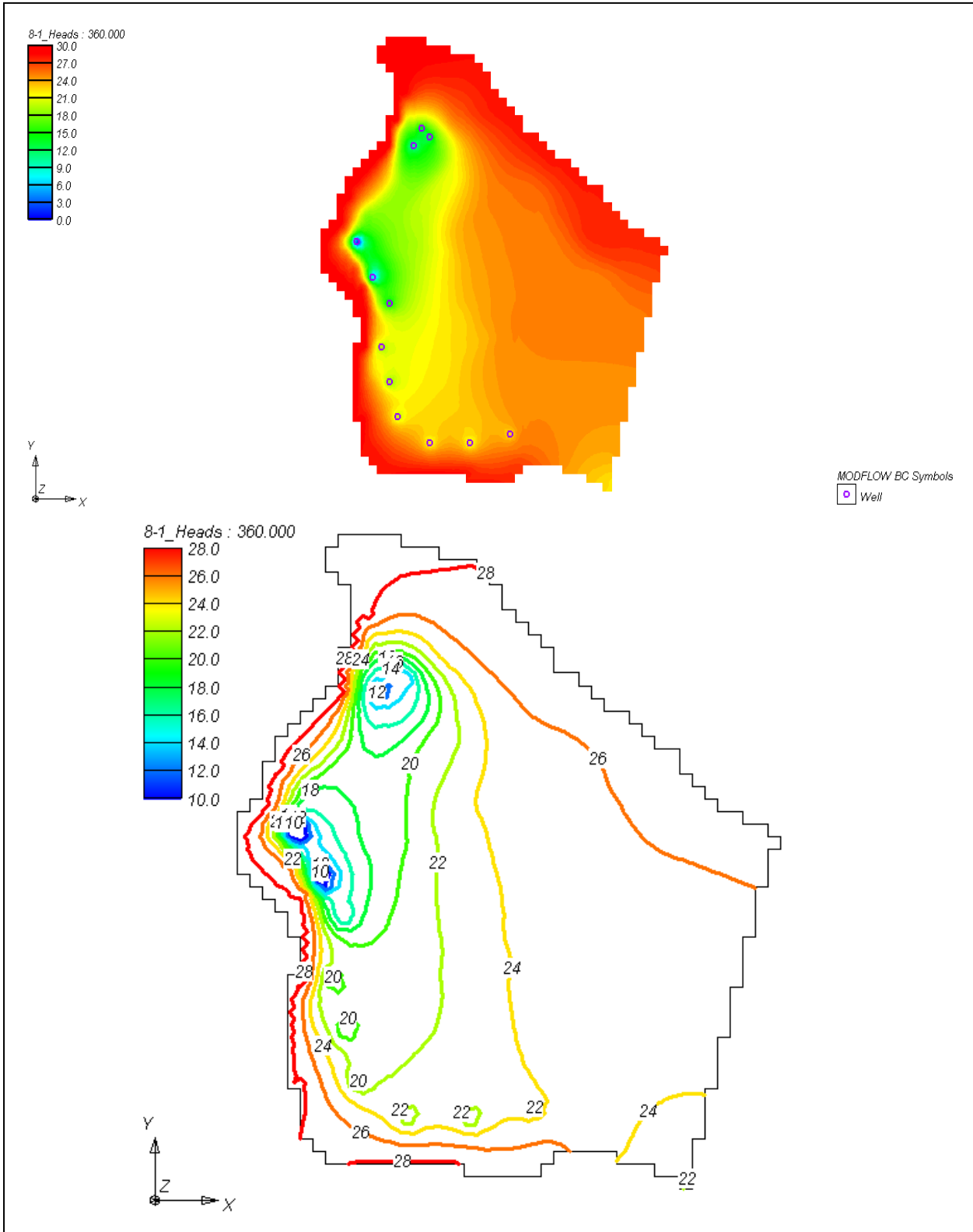


Fig.(4.15) Simulation of water table elevation after 360 days of pumping 12 wells.

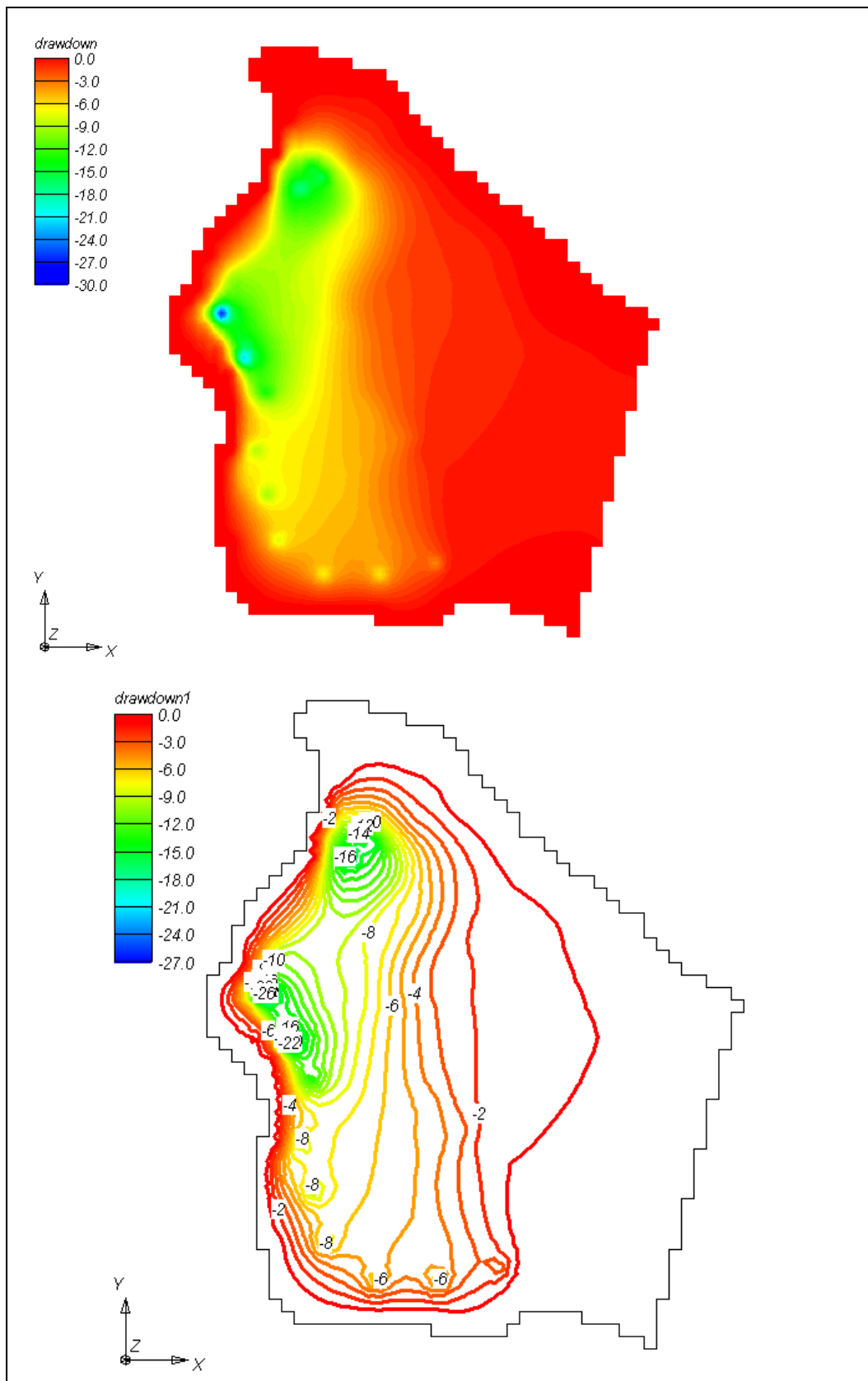


Fig.(4.16) Simulation of the drawdown of the water table after 360 days of pumping the 12 wells.

Another trial with (9) wells as shown in figure (4.17). The results of this trial after pumping from the ninth wells are shown in figures (4.18), (4.19), (4.20) after 100, 200, 360 days from pumping respectively.

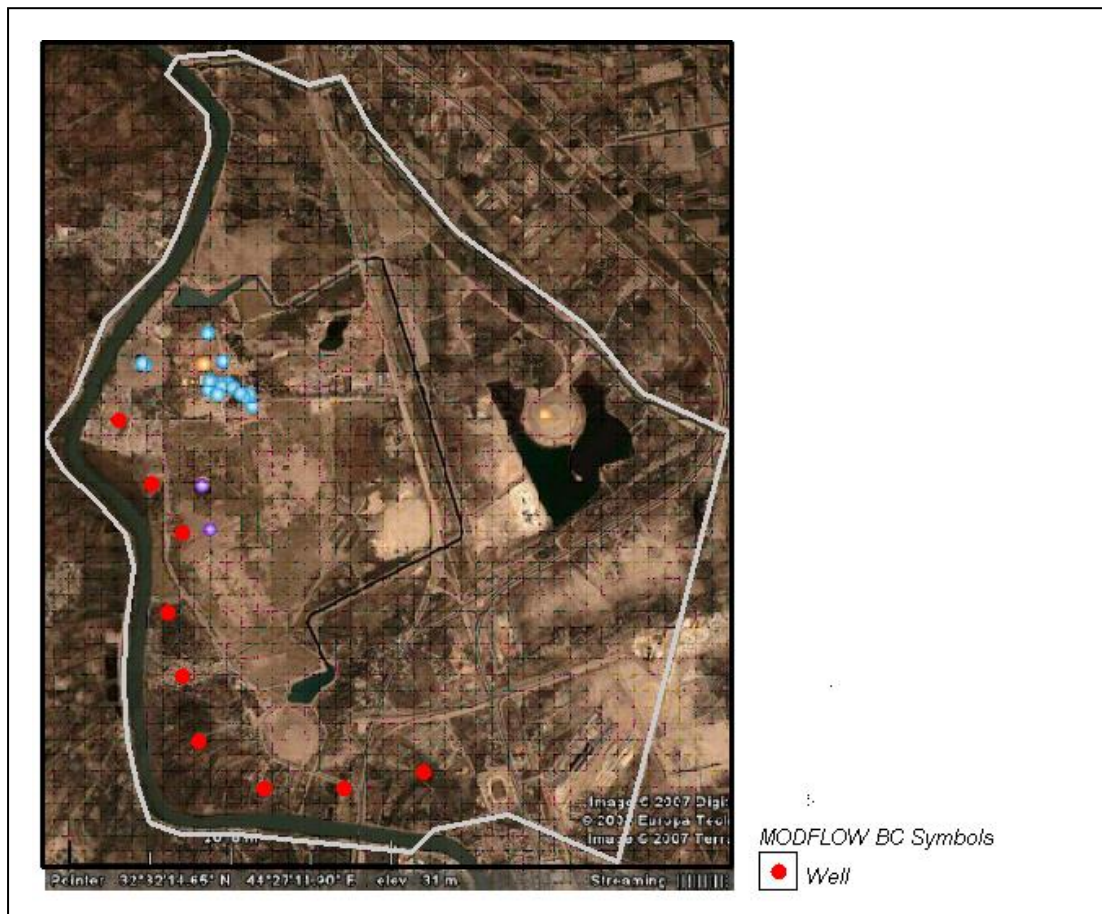


Fig.(4.17) Location of 9 wells.

The drawdown with this trial after 360 days of pumping can be shown in figure.(4.21).

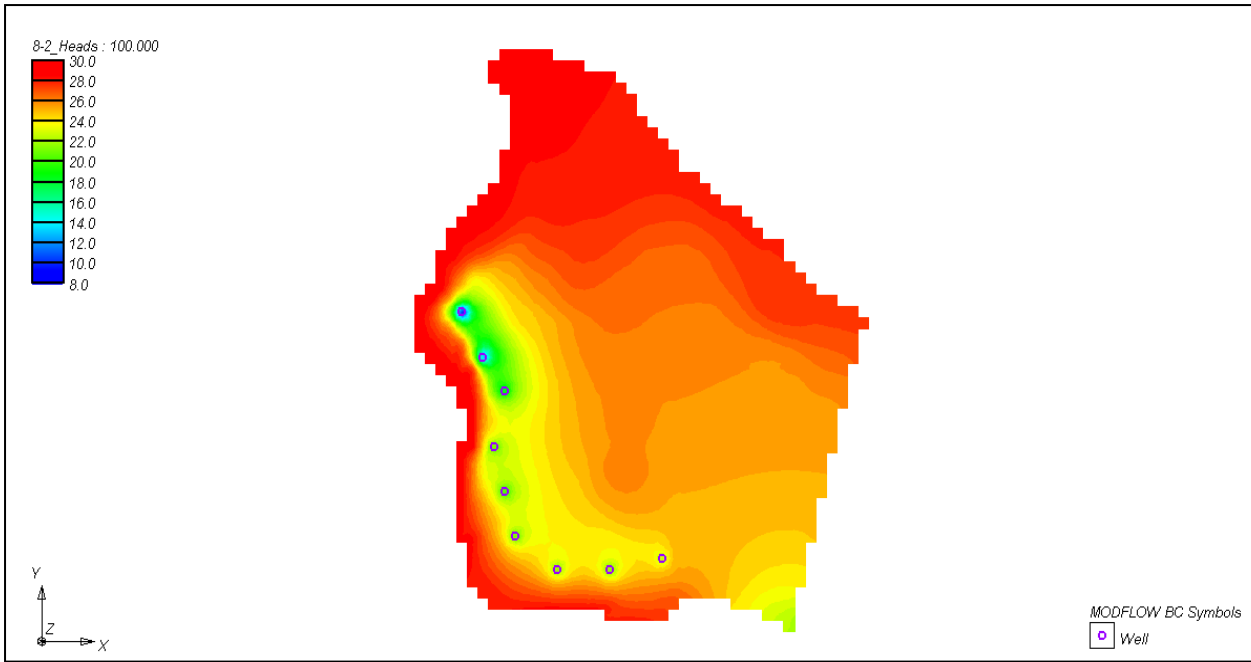


Fig.(4.18) Simulation of water table elevation after 100 days of pumping 9 wells.

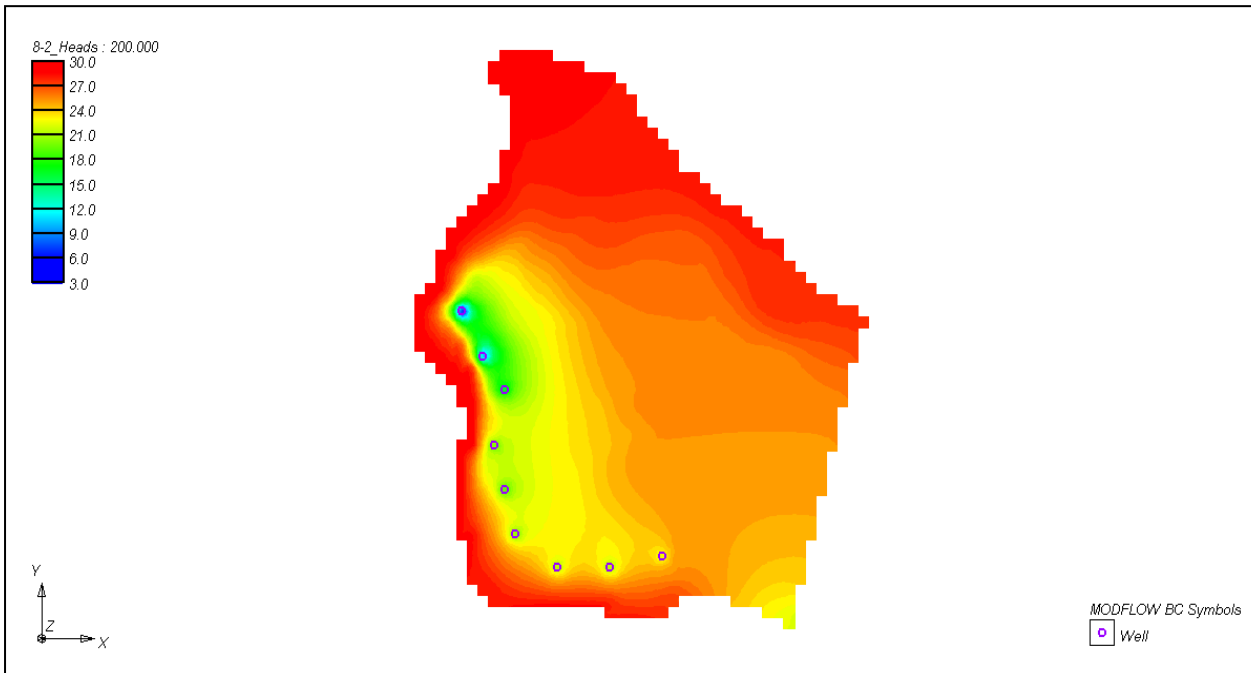


Fig.(4.19) Simulation of water table elevation after 200 days of pumping 9 wells.

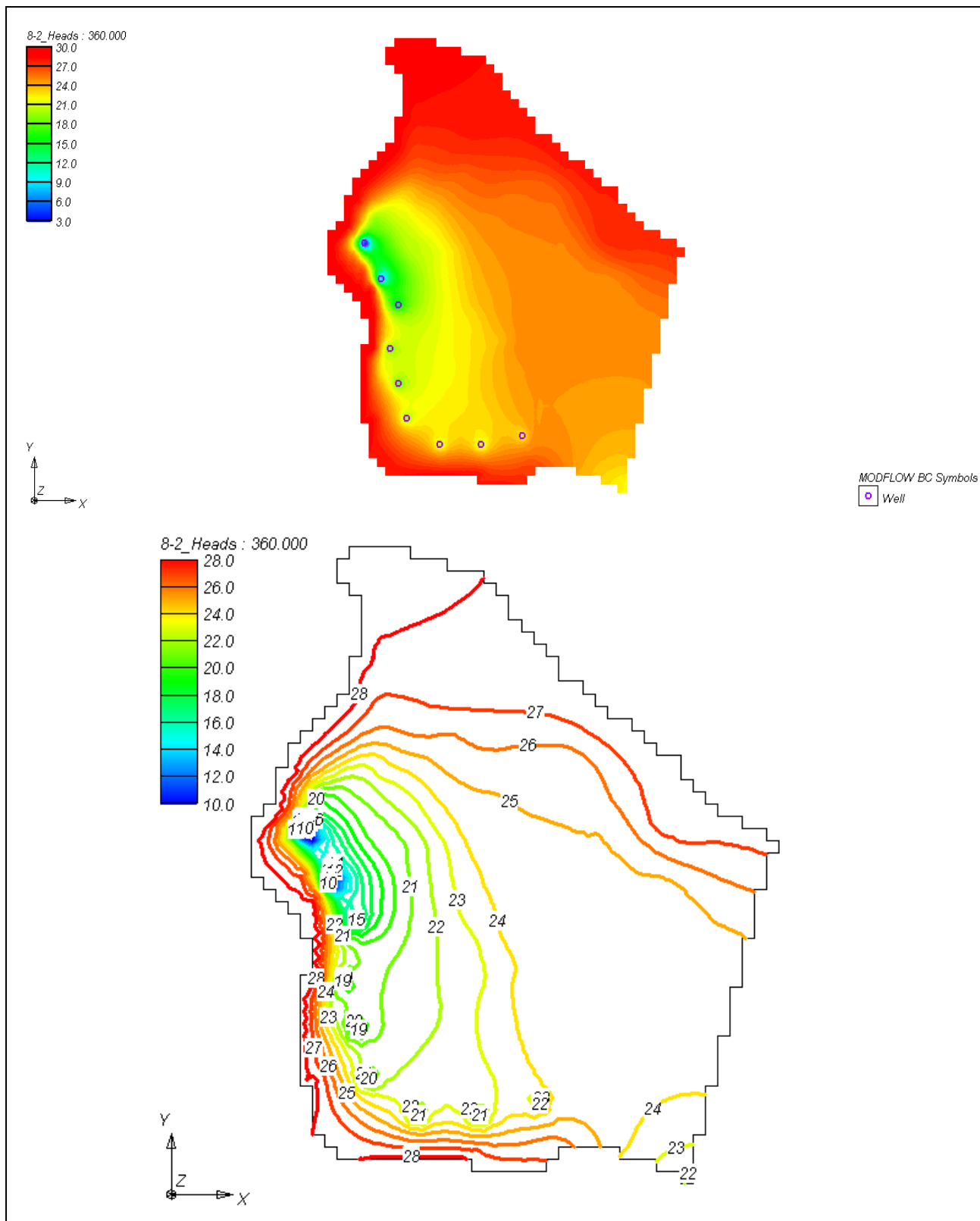


Fig.(4.20) Simulation of water table elevation after 360 days of pumping 9 wells.

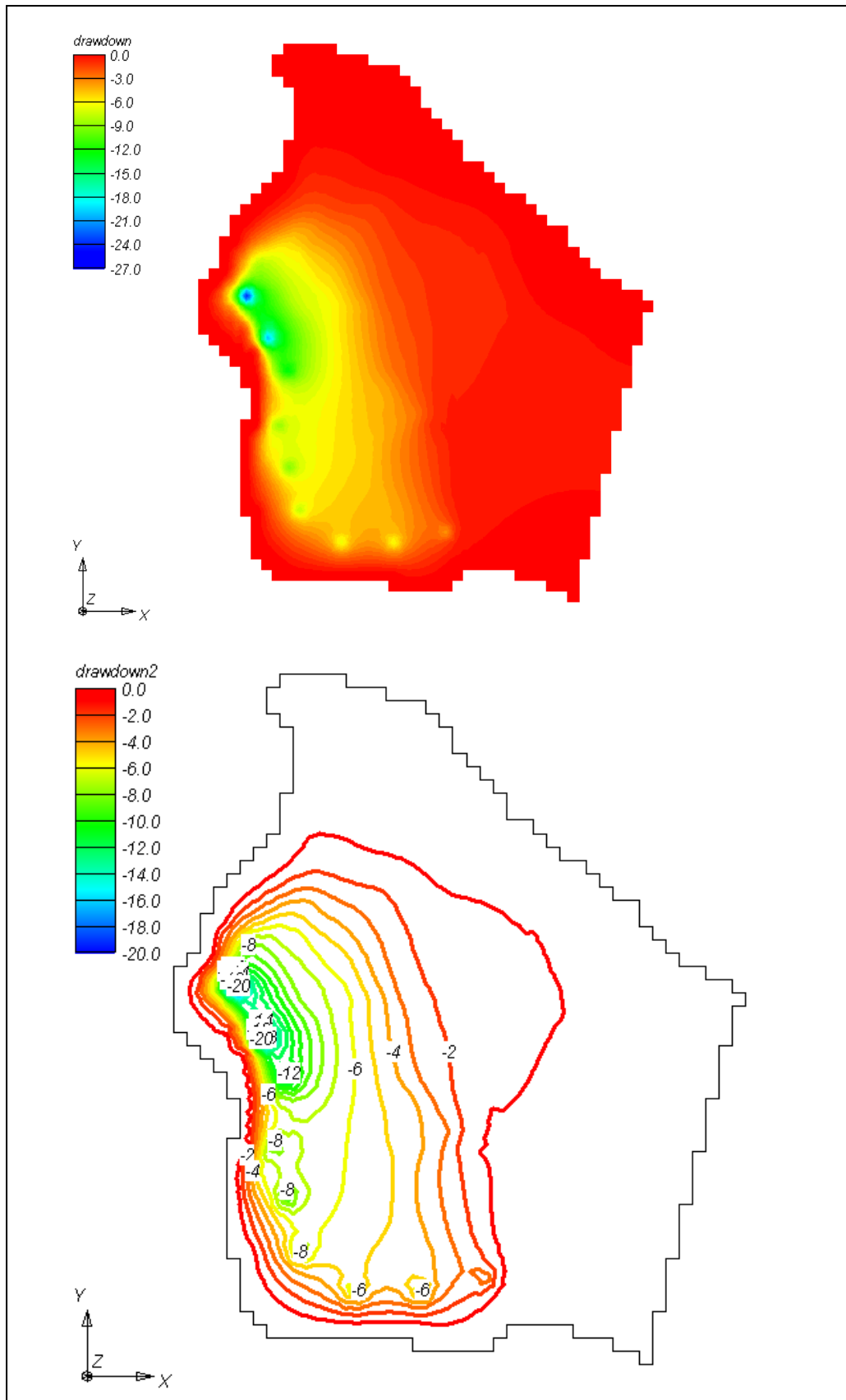


Fig.(4.21) Simulation of the drawdown of the water table after 360 days of pumping the 9 wells.

4.7 Calibration of Numerical Model

The calibration process for the numerical (mathematical) model is achieved by trial and error procedure. Where average permeability, ground surface level and bottom elevation are adjusted after each simulation run until a good match is obtained between the observed and computed (simulated) heads for the unconfined aquifer.

At first a steady state calibration process is followed to permit the adjustment of the permeability, ground surface level and bottom elevation. The data chosen for the calibration were the water table elevation during 1979 (GDGSMI,1979), figure (1.2).

After several iterations, a good agreement between the observed and simulated water levels are obtained. This agreement can be shown in figure (4.22). The closeness of fit between measured and simulated heads is evaluated for each calibration run using the Root Mean Square Error (RMSE). The RMSE is employed to achieve the least difference between the observed and computed head and to summarize the calibration performance. The RMSE value of the first run is 3.45×10^{-2} cm, in the last run it is reduced to 3.04×10^{-2} cm, that it mean the percent of reduction in RMSE are 88%. That it mean the steady state calibration was made a good agreement between the observed and simulated heads.

After finishing the calibration process for the numerical model, the results indicate that the appropriate value of permeability for the aquifer can be shown in figure (4.5) and the ground surface level is 32m.

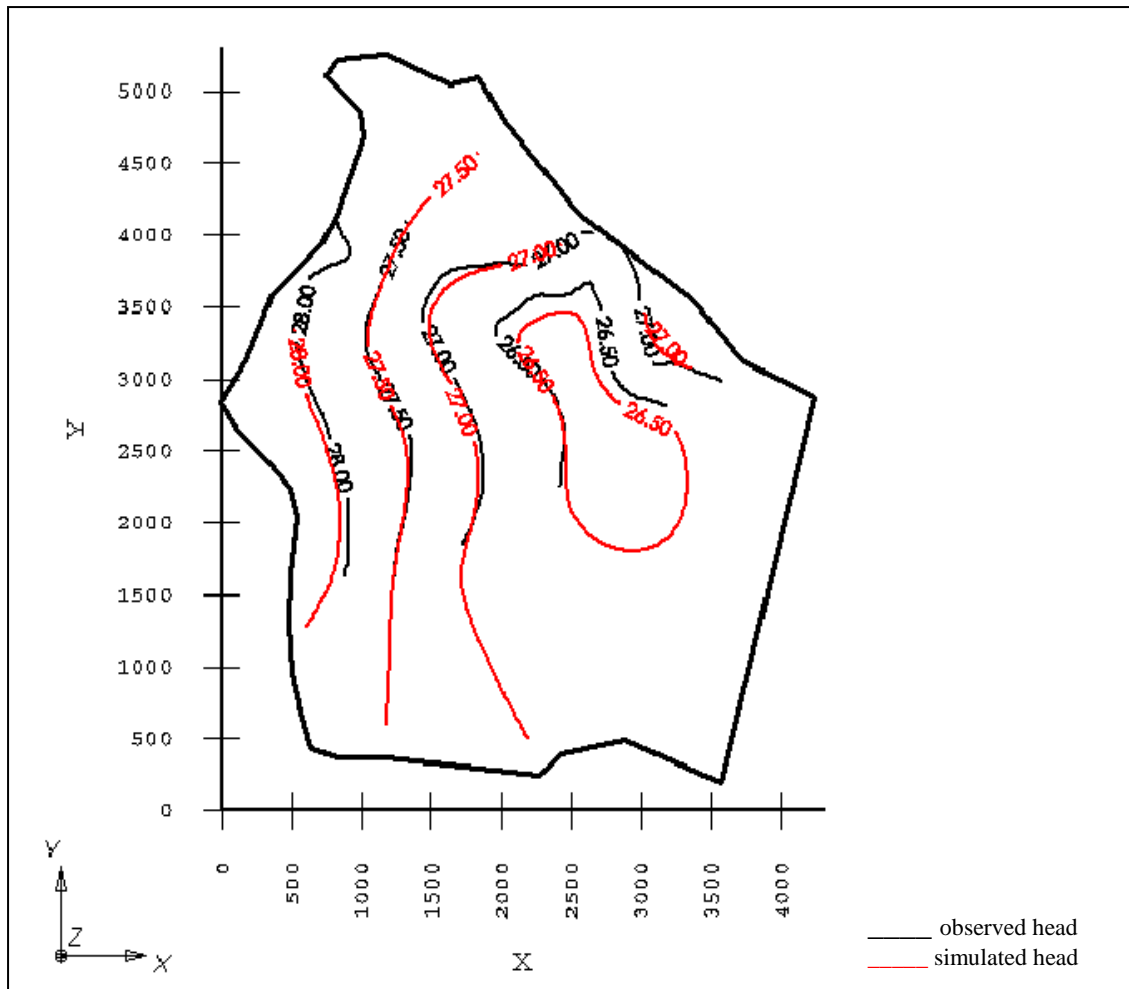


Fig. (4.22) Comparison between observed and simulated head for Numerical model.

4.8 Transient state simulation for Numerical model

Transient state simulation is done for Numerical model by using the 15 pumping wells.

After many iterations, the best results obtained by using 15 wells distributed as in the GMS model in figure (4.6), the results after 360 days of pumping at a rate 17ℓ/sec, as shown in figure (4.23) and the drawdown can be shown in figure (4.24).

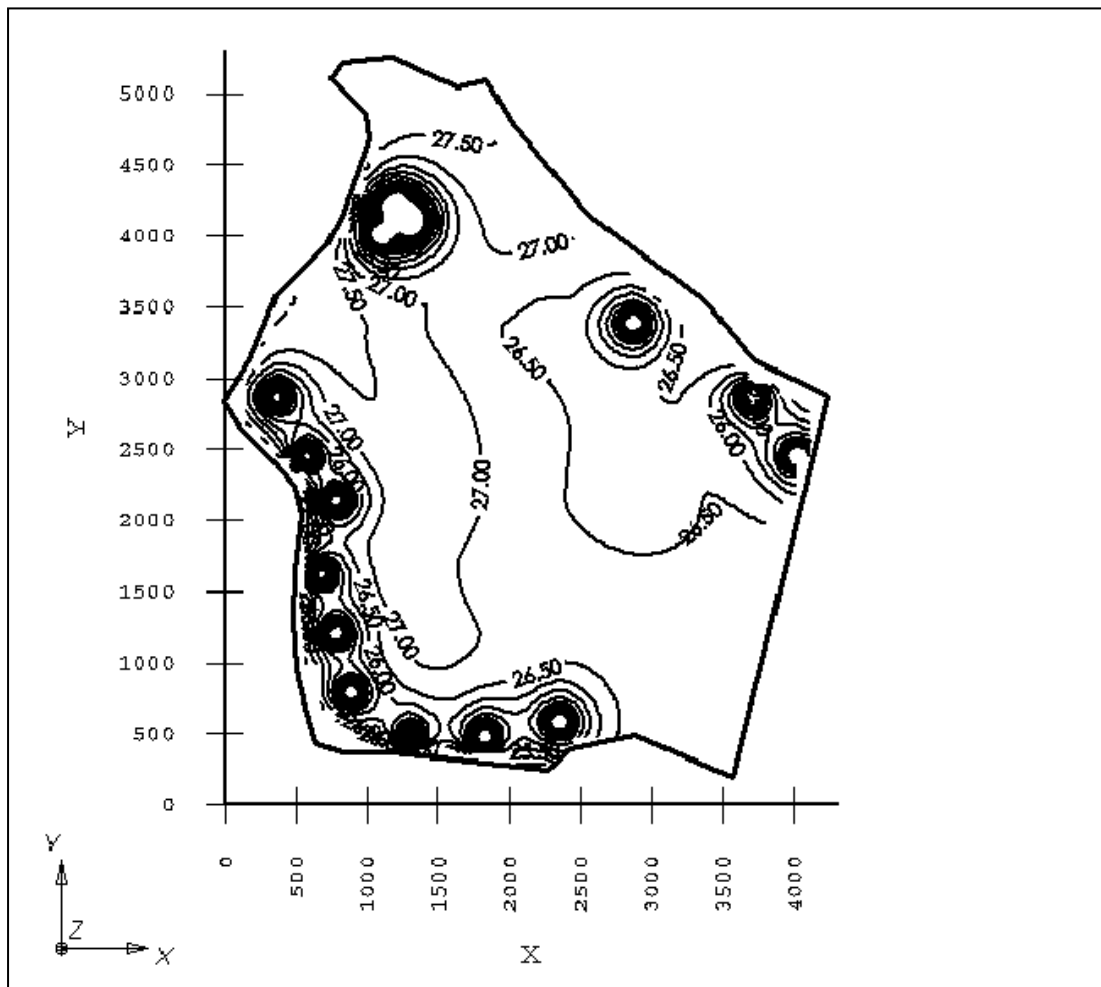


Fig.(4.23) Simulation of water table elevation after 360 days of pumping the 15 wells for the numerical model.

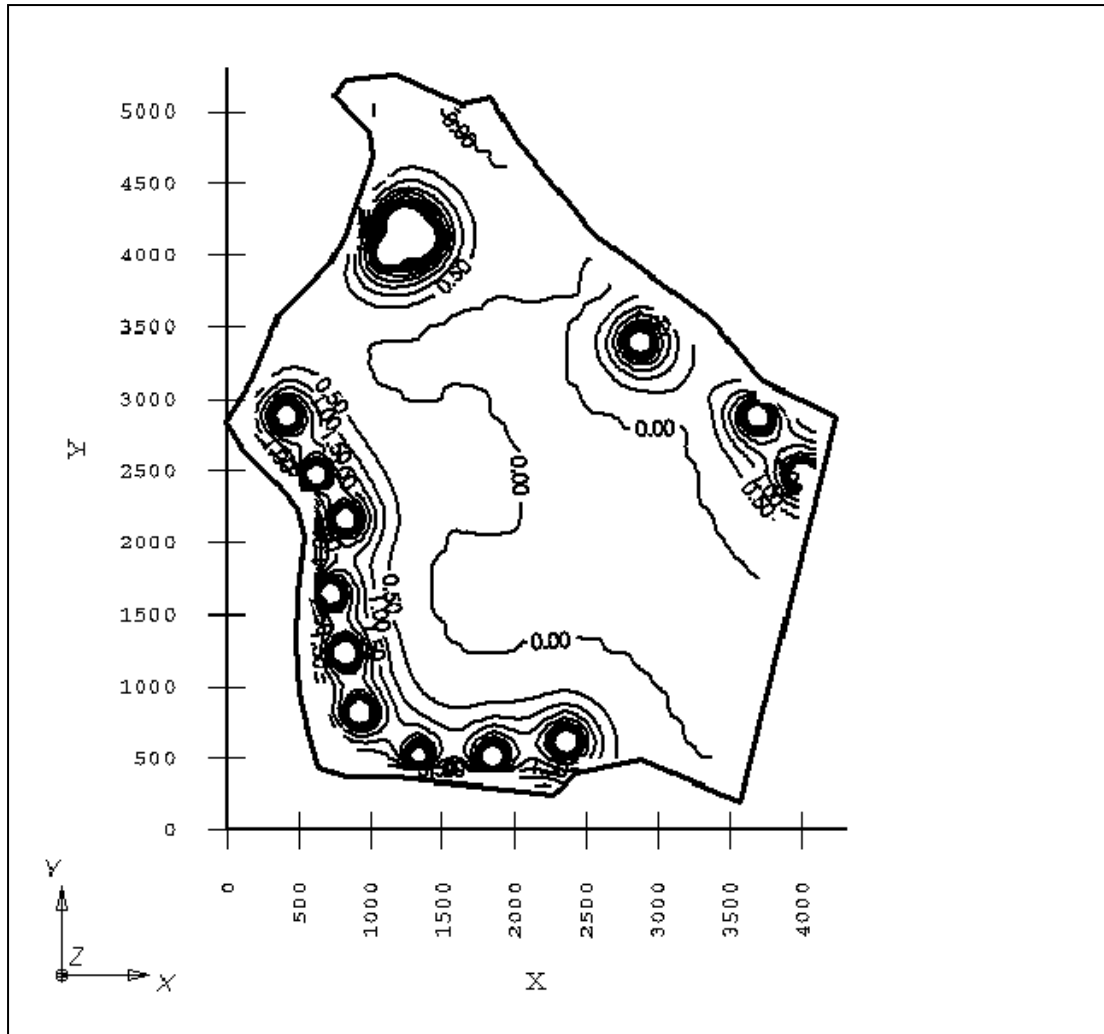


Fig. (4.24) Simulation of the drawdown of the water table after 360 days of pumping the 15 wells for the numerical model.

The results obtained from the numerical model ranged between 10-0 m from the boundaries near the rivers towards the center of the city.

4.9 Pumped-Water Disposal

As mentioned in section (1.2) the chemical analysis of the discharged water from the study area was revealed by General Directorate Geological Survey and Mineral Investigation (GDGSMI) during 1979 and Al-Furat Center of Studies and Design of Irrigation

Projects (FCSDIP) during 1989 similar to Shat Al Hilla water, so the discharging water from the pumping wells can be returned it to Shat Al Hilla by pipes or by open channel. The results of chemical analyses can be seen in table (4.2).

Table (4.2) Chemical analyses of the water samples

Site No.	Depth (m)	Cations (ppm)			Anions (ppm)			T.H* (ppm)	T.D.S** (ppm)	ph	S.A.R***
		Na ⁺	Ca ⁺²	Mg ⁺²	Cr ⁻	SO ₄ ⁻	HCO ₃ ⁻				
1	15	181	325	68	188	520	206	1091	1620	7.5	3.2
2	26	55	40	27	64	43	244	221	489	8.5	2.3
3	25	45	65	22	75	118	165	253	1289	7.9	1.5
4	22	598	160	205	352	660	437	1241	1870	7.3	11.7
5	35	253	56	83	212	500	305	480	1409	7.95	7
Average		226	129	81	178	368	271	657	1335	7.83	5

*Total Hardness.

**Total dissolved solid.

***Sodium Adsorption Ratio.

4.10 Comparison between the two models

Comparison between the GMS model and the mathematical model was done in this study. The results indicated that the two models were clearly different, as shown in figure (4.25) and figure (4.26).

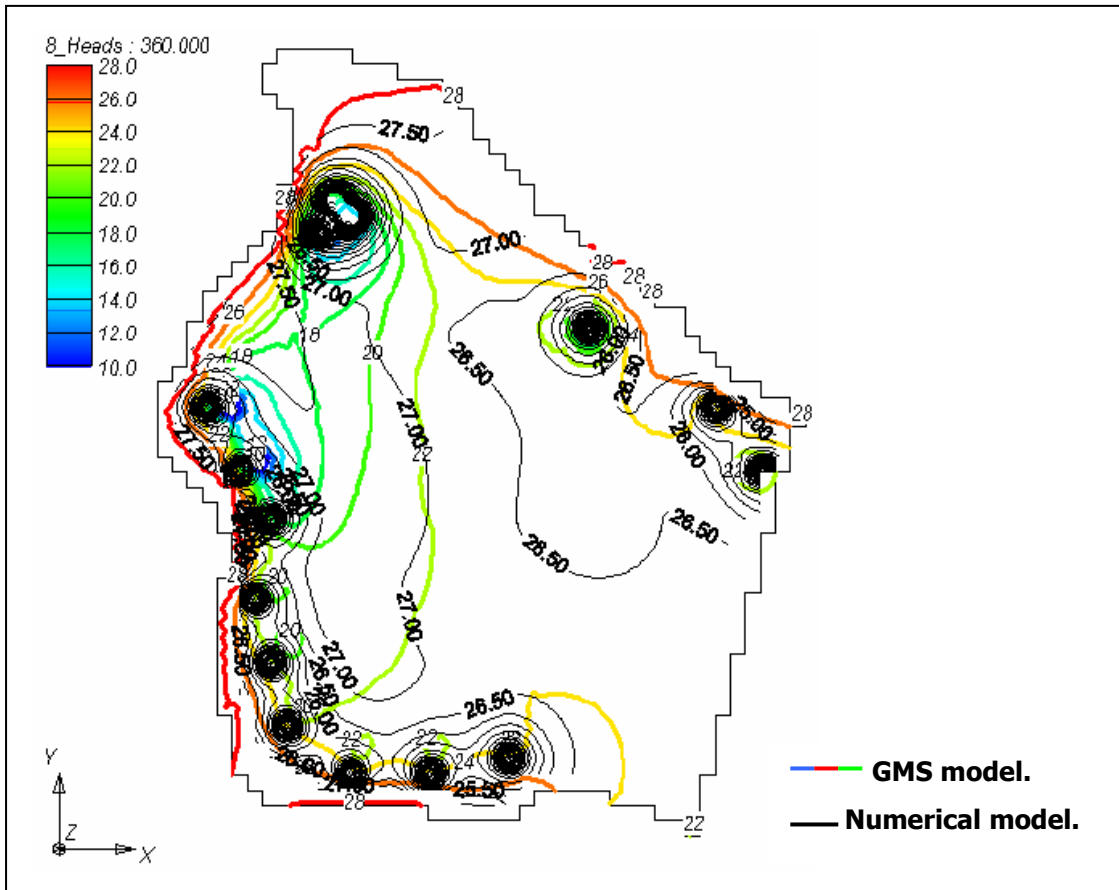


Fig. (4.25) water table elevations contour map for the GMS model and Numerical model after 360 days from pumping the 15 wells.

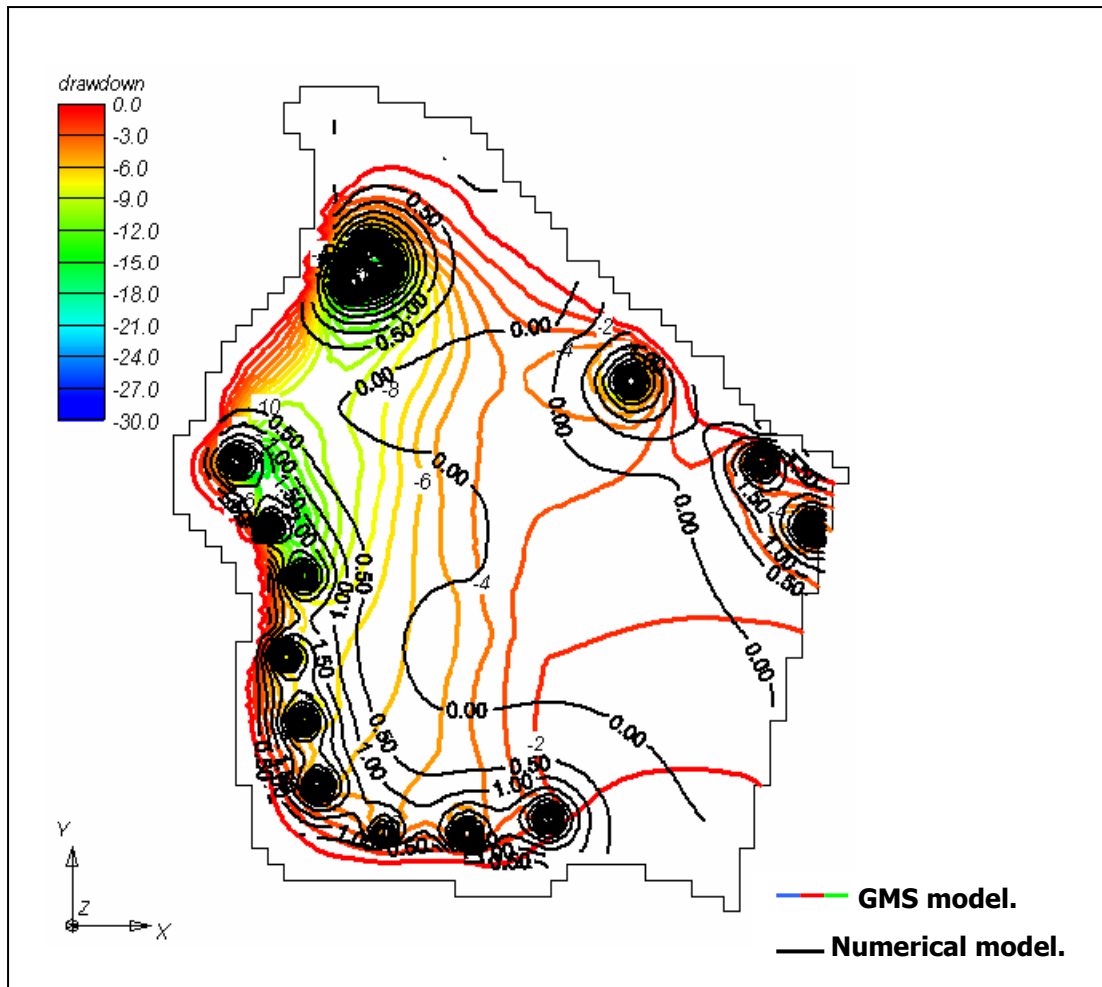


Fig. (4.26) Drawdown contour map for the GMS model and Numerical model after 360 days from pumping the 15 wells.

The difference of the results for the two models may belong to the mathematical methods used in solving the equations in the numerical model are differ from that used in the GMS program.

The RMSE for the GMS model was 1.53, while for the mathematical model was 0.0994, so the later is more accurate in calibration process. Although the RMSE for the mathematical model is less than the GMS model, the drawdown in the GMS is more than that in the mathematical model at the same input data. So, trails for

increasing the number of wells, rate of discharge and duration of pumping from the wells in the mathematical model were done.

After these trails, a drawdown 1-10 m was done as shown in figure (4.27) by using 18 wells, as shown in figure (4.28), with a rate of 20 ℓ/s , for 720 days duration of pumping for each well. The three wells added are away from the old buildings of Babylon city.

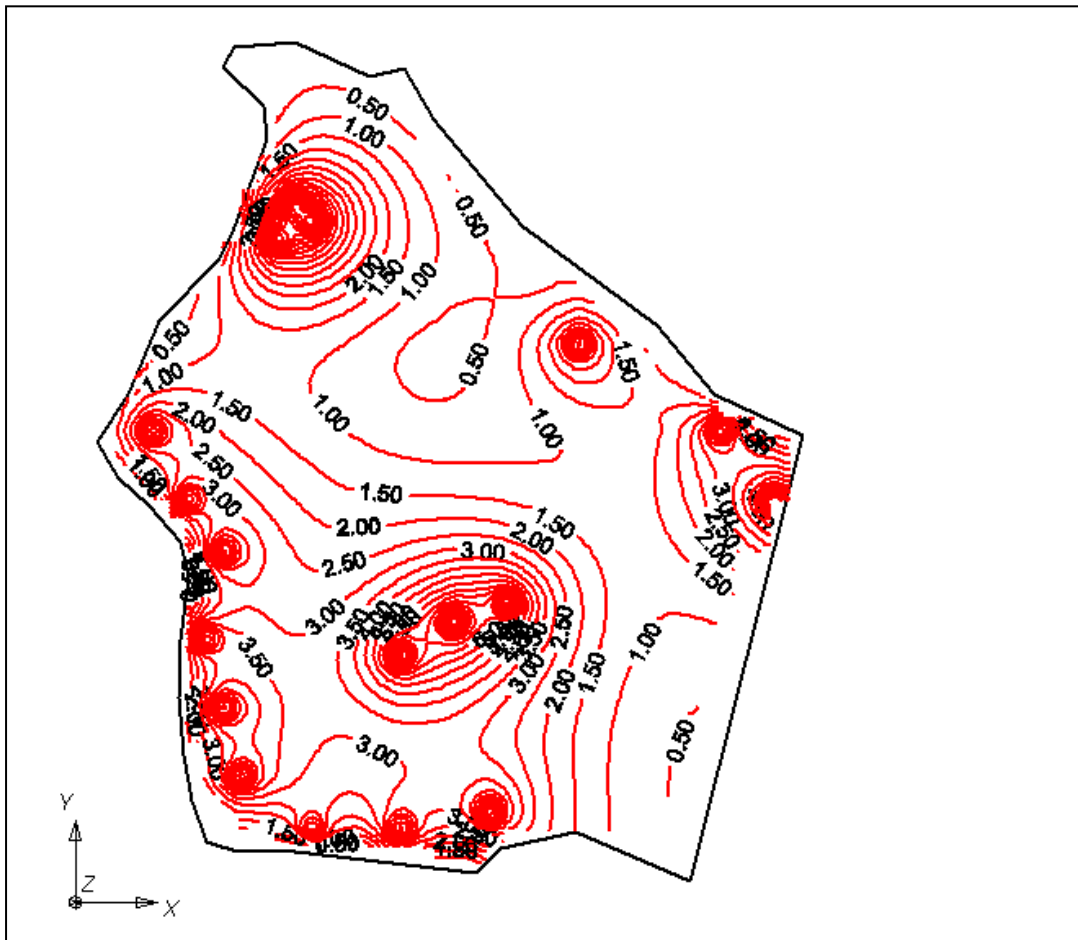


Fig. (4.27) Drawdown contour map for the Numerical model after 720 days from pumping the 18 wells.

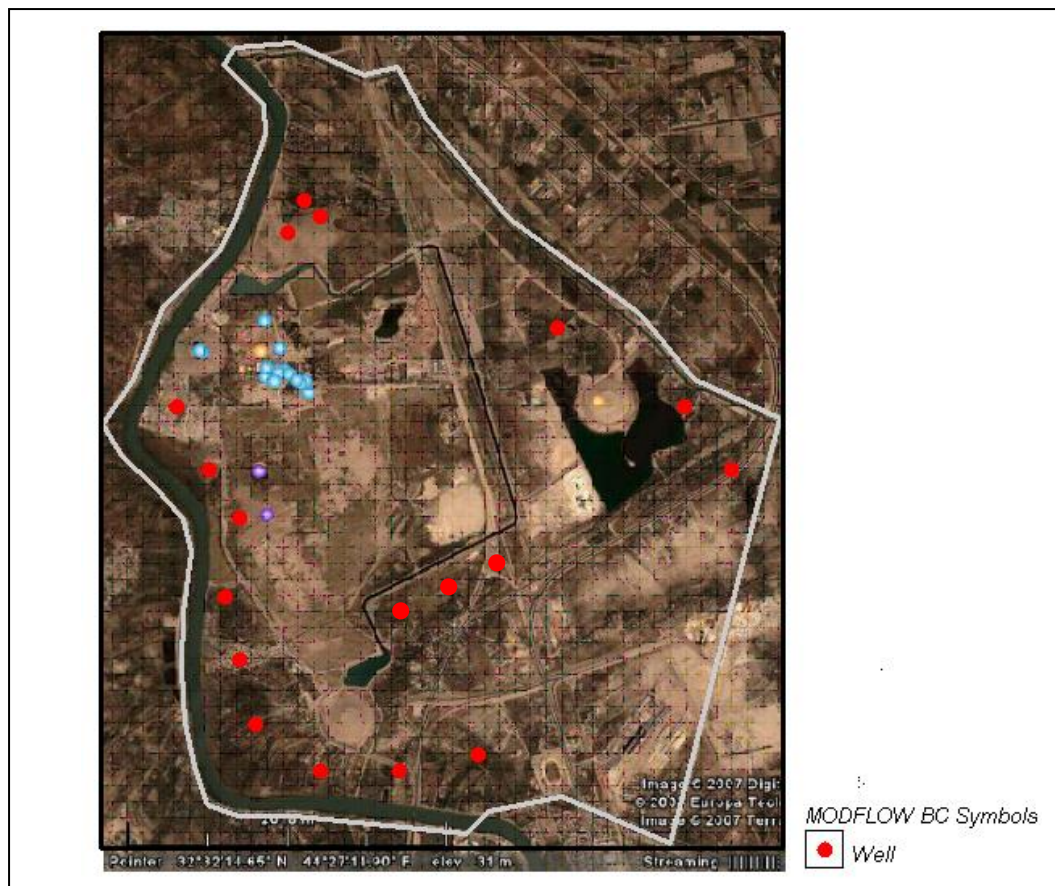


Fig.(4.28) Locations of the 18 wells.

4.11 Well Design

Well design is the process of specifying the physical materials and dimensions for a well. A well design needs the following considerations (Sharell, 1986):

1. The discharge that will be pumped from the well.
2. Geological Sketch at the site of the well explains the elevations of the layers and the permeability of each layer, figure (4.29).
3. Elevation of groundwater.

Diameter of casing pipe:

The production casing is the lower section of blind pipe between the bottom of the pump housing and the top of the aquifer (Boonstra, 1989).

The diameter of the well casing should be chosen to meet the following requirements (Todd, 1959):

1. The casing diameter shall be of two nominal size larger than the bowl size of the pump. This is necessary to accommodate the vertical turbine pump so that no binding occurs, and head losses are reduced. This would also allow adequate clearance for a submersible pump.
2. The open area of a screen increases with the diameter of the screen. Thus the intake section of the well may govern the desirable casing pipe diameter for good hydraulic efficiency. Hence, the casing diameter suitable for (17ℓ/s) discharge is 20 cm, as shown in Table (4.3).

Table (4.3) Optimum diameter of screens (Todd, 1959)

<i>Discharge of well liters/min</i>	<i>Optimum diameter of screen for k in cm/sec</i>		
	0.04	0.09	0.16
2400	15	18	22
4800	20	25	30
7200	23	28	33
9600	26	30	35

Depth of wells:

The drilled wells were penetrated the fully unconfined aquifer with a depth about 28m, which is compatible with the thickness of the first aquifer that considered in the GDGSMI in 1979.

Length and diameter of screen

Important properties of the screen are that it prevents sand and fine material from entering the well during pumping, has a large percentage of open area to minimize the head loss and entrance velocity, supports the wall of the well against collapse, and is resistant to chemical and physical corrosion by the pumped water.

PVC and fiberglass screens are lighter and more resistant to corrosion by chemically aggressive water, but have a lower collapse strength than steel screens and casings. The selection of the screen slot size depends on the type of aquifer and the use of a gravel pack. The screen slot size must be selected to ensure that most of the finer materials in the formation around the borehole are transported to the screen and removed from the well by bailing and pumping during the well-development period immediately after the borehole has been constructed and the screen and casing have been installed (Boonstra, 1989).

The optimum length of well screen depends upon the coefficient of permeability of the aquifer, available drawdown and optimum screen entrance velocity.

After a deep well has been drilled, groundwater enters directly into the uncased well. The casing must either contain perforations or be replacing by a well screen. Other sections of the well should contain blank casing and be sealed by puddle clay or cement grout to prevent

vertical water movement along the exterior of the casing. Well screen are particularly advantageous in sandy aquifers as here the screen opening can be selected to filter a specified fraction of the sand.

In case of unconfined aquifer (as in this study), optimum yield is obtained by screening bottom 0.6m of aquifer. The diameter of a screen is selected so as to ensure that the entrance velocity of water does not exceed the permissible velocity. The minimum length of screen should be worked out with entrance velocity of 3cm/sec. For the optimum diameter of screen, assuming 20% slot area. To determine the length of the strainer in unconfined aquifers (Todd,1959):

$$\text{Aquifer thickness} = 28-4=24\text{m.}$$

$$\text{Optimum screen length } (h_w) = 1/3 * 24 = 8\text{m.}$$

(bottom 1/3 to be screened).

Leaving a depth of 0.6m both at the top and bottom of screen.

$$\pi \times A \times v = Q$$

$$\pi \times 0.15 \times 0.20 \times 8 \times v = 0.017 \times 60$$

$$v = 1.35 \text{ m/min} = 2.254 \text{ cm/sec} < 3 \text{ cm/sec.}$$

Since screen entrance velocity is within admissible limit, the well assembly is o.k.

The strainer is generally constructed of a wire screen wrapped around a slotted or perforated tube the wire screen prevents sand particles from entering the tube well.

The optimum diameter of well screen can be determined depends on the discharge ($Q=17\ell/s$) and the permeability ($k=15 \text{ m/day}$ as a range). Hence, the diameter of screen is 15cm (Todd, 1959).

Design of gravel pack:

The effect of gravel-packed wells is to ensure that the zone around the well screen is made more permeable by removing some formation material and replacing it with specially graded material. This relatively narrow zone separates the screen from the formation material and increases the effective hydraulic diameter of the well. Gravel pack material should ideally be clean, rounded, siliceous sands or gravels; carbonate material, shale particles, or soluble material such as gypsum should not exceed 5% of the total. Gravel pack material should be well sorted to assure good porosity and hydraulic conductivity of these materials around the screen (Boonstra, 1989).

First a large bore is drilled, and shingle or gravel of suitable size is filled in the annular space within the bore and pipe to prevent the sand entering the tube well.

The gravel increases the effective well diameter, acts as a strainer to keep fine material out of the well, and protects the casing from caving of surrounding formations. In an aquifer containing a large proportion of fine sand, a gravel screen is a necessity to avoid a sand-pumping well.

The design of gravel pack requires determination of its gradation and thickness. The gravel pack is placed around the screen pipe by a thickness not less than 7.5 cm (Sharell, 1986).

The size of gravel that is used (4mm) in case of fine sand (as in this study) is filled in the annular space within the bore and pipe to prevent the sand entering the tube well. A thickness of gravel pack 15-20 cm is considered adequate.

Horse Power of motor:

Horse power of motor is given by:

$$H.P = \frac{w.Q.H}{75\eta}$$

w : unit weight of water in kg/m^3 .

Q : discharge to be delivered, (L^3/T).

H : the total head against which the motor has to operate, (L).

η : efficiency of the set.

H = maximum depth of water table below ground level + maximum depression head + velocity head + losses.

$$\text{Velocity through casing pipe} = \frac{0.017}{\frac{\pi}{4} \times (0.15)^2} = 0.962 \text{ m/sec.}$$

$$\text{Velocity head} = \frac{v^2}{2g} = \frac{(0.962)^2}{2 \times 9.81} = 0.04713\text{m}$$

$$\text{Loss of head due to friction in pipe } (h_f) = \frac{4flv^2}{2gd}$$

f : coefficient of friction assumed as 0.006.

l : length of pipe, (L).

v : velocity through casing pipe, (L/T).

d : diameter of pipe, (L).

$$h_f = \frac{4 \times 0.006 \times 28 \times 0.962^2}{2 \times 9.81 \times 0.15} = 0.211\text{m.}$$

$$\text{total head} = 4 + 24 + 0.04713 + 0.211 = 28.26\text{m.}$$

$$\text{H.P. required} = \frac{1000 \times 0.017 \times 28.27}{75 \times 0.65} = 9.85 \text{ say } 10 \text{ H.P.}$$

A sketch of well assembly and other accessories is given in figure (4.29).

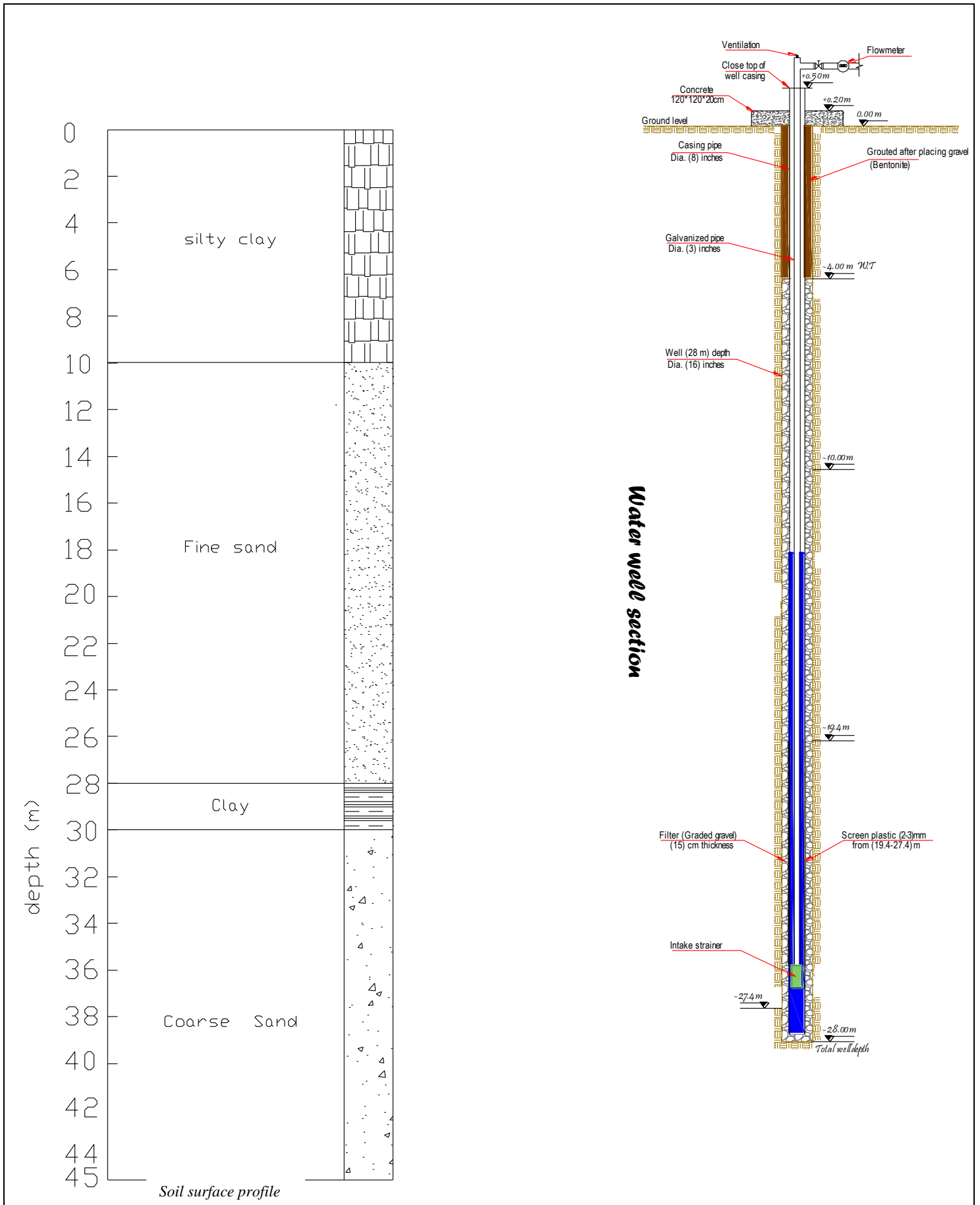


Fig. (4.29) Well Assembly and other accessories.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It can be concluded from this study the following :

1. By the application of GMS program to the study area, the result is a drawdown of 1-10 m using 15 wells distributed away from the buildings of the old Babylon city. This result is compatible to the recommended value by GDGSMI 1979.
2. The GMS program is a useful tool to investigate the effectiveness of each method in dewatering and suitable to any study area before starting the process.
3. The GMS program is easy to use in solution of groundwater flow problems.
4. The results of the numerical model that is applied to the study area differ from that results obtained by GMS program. This may be due to the mathematical methods that is used in solving the equations in the numerical model which is different from that used in the GMS program.
5. The value of drawdown in the numerical model ranged between 0-10 m, when the input values are the same with those used by the GMS model i.e. 15 wells with a duration of

360 days. But a drawdown of 1-10 m obtained by using 18 wells with a duration of 720 days, at a rate of 20ℓ/s.

5.2 Recommendations

The present study concludes that Shat Al Hilla and Babylon canal are the main sources of recharge, so the measures to decrease or prevent this problem are as follows:

1. Shifting the course of Shat Al Hilla away from the area. This solution results in a beneficial effect, but it is associated with difficulty because it needs high economic efforts.
2. Lining the side of these rivers that close to the area by cement and rock or any impermeable lining to prevent water from reaching the area.
3. Future studies that deal with the water table at this city, can develop or make a modification on the numerical model to make it more reliable to use in a wide boundary conditions, for example, putting a drainage along Shat Al Hilla and Babylon canal, or increase the numbers of wells to increase the quantity of water that can be pumped.
4. Further studies as field work by drilling the supposed wells and observations wells to have a new contour map for the elevation of the water table, permeability test and topographic leveling of the study area, and all these data compared with the two models that considered in this study(GMS & numerical model).