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A CONJUNCTIVE WATER MANAGEMENT MODEL FOR METRO MANILA AND LAGUNA LAKE BASINS

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ABSTRACT

This paper presents the objectives and accomplishments of the water resources management modelling project undertaken by NHRC during the period 1990-1993. Presented in particular are the features of the Manila Model or CUWARM (Conjunctive-Use Water Resources Management Model), consisting of a coupled groundwater hydraulic-subsidence model, and including daily, monthly, and annual surface-water models. Discussed in detail are the equations and solutions of the groundwater model, the pre-calibration runs for model tests, and the computational and input-output features of the developed Manila Model. The results of the calibration runs for Metro Manila are presented. Conclusions and recommendations on both modeling and management aspects are given.

(Based on a paper presented in the **Regional Workshop on Management Modelling for Conjunctive Water Use**, sponsored by IDRC-GRC-UPERDFI-NHRC, held on March 16-17, 1993, at the National Engineering Center, U. P. Diliman, Quezon City.)

INTRODUCTION

The research project, entitled "Water Resources Management Model for Metro Manila," has been undertaken over the period 1990-1993 by the National Hydraulic Reserach Center (NHRC) and the U. P. Engineering Research and Development Foundation (UPERDFI), in cooperation with the Geotechnical Research Centre (GRC), McGill University, Canada, and with funding support from the International Development Research Centre (IDRC) of Canada [refs. 3, 4, 5]. The project is intended to provide a planning and management tool to assist government agencies in evaluating the various alternatives in the development and utilization of both surface water and groundwater supply sources to meet the demands of the increasing population. It may also be used in evaluating the need for regulatory measures to protect and conserve the water resources in the region.

The main objective of the study is to develop a Water Resources Management Model for Metro Manila and its environs. (Metro Manila and Laguna Lake Basins), which takes into account both surface water and groundwater resources in the region. Its specific objectives are:

a. to determine the aquifer characteristics underlying Metro Manila and its fringe areas, including extent, hydraulic properties, water quality, and geological nature in its most relevant details;

b. to establish the basin groundwater boundaries and define its properties and yield;

c. to construct the total hydrological cycle which accounts for the conjunctive use of surface water and groundwater resources;

d. to determine actual recharge, its distribution points, and recharge potential;

e. to develop the external surface water module to be added to the basic BUH model in order to make it Manila-specific;

f. to validate and demonstrate the viability of the Manila Model as a water management tool; and

g. to disseminate the research program and its results through workshops and conferences.

In a past completed project, the IDRC of Canada provided support for the development of the Bangkok Urban Hydrogeological (BUH) groundwater model through a project cooperation between McGill University and the Asian Institute of Technology [refs. 1, 6]. This model has been adapted and tested to suit local conditions and requirements in order to create a Manila-specific model.

CUWARM: THE MANILA MODEL

This paper presents the accomplishments under the tasks of development and calibration of the **Manila Model.** A more generic nomenclature was also given to the model: namely, **CUWARM** (Conjunctive-Use WAter Resources Management Model). CUWARM is essentially a coupled groundwater hydraulic-subsidence model, containing additional features of surface water-balance models and interactive input-output routines. Whereas the groundwater model is an annual model, the surface-water models, which are available in different segments or modules, have daily, monthly, and annual time scales. The annual surface-water model is an integral computational module of CUWARM. The daily and monthly watershed and lake surface-water models are separate but accessible programs, used to analyze daily and monthly surface hydrologic series, and to determine the needed driving parameters of the annual surface-water module.

DAILY AND MONTHLY SURFACE WATER MODELS

This section briefly discusses the three (3) surface water models which are **daily baseflow separation, monthly watershed water balance model,** and **monthly Laguna Lake water balance model.** These models consider the accounting of the surface water components such as rainfall, evapotranspiration, soil moisture, and runoff, and compute as one principal output the recharge to groundwater which in turn may partly reappear as river baseflow, and partly, as net recharge to deeper aquifers. The daily and monthly analyses carried out for these hydrologic series also determine hydrologic input parameters for the annual groundwater model.

Baseflow Separation

Baseflow separation is performed on daily streamflow hydrograph data for subbasin river stations, for the purpose of determining the relative amounts of recharge to upper groundwater zones, baseflow derived from them, and total streamflow. Two methods were used:

U. K. Institute of Hydrology Method

This method was applied to provide the **initial baseflow turning points** which define the upper envelope of the baseflow hydrograph.The method requires a baseflow turning point $Q_b(t)$ to satisfy all the following conditions:

$Q_b(t)$= the minimum of every five consecutive daily streamflows, where t is a day in that five-day interval, to be included as turning point provided further that:

$.90\ Q_b(t_2) \leq Q_b(t_1)$, and
$.90\ Q_b(t_2) \leq Q_b(t_3)$

for every possible triples of successive baseflow turning points at times: $t_1 < t_2 < t_3$.

Under this method, some of the turning points may still be too high to equal realistic baseflow, hence there is a need to adjust them downward based on a conceptual baseflow model, as presented below.

NHRC First-Order Linear Baseflow Model

This is a conceptual model which **finalizes the baseflow turning points and estimates** based on fitted values of the exponential recession constant k, and **determines the corresponding rates of recharge R** to upper groundwater storage zones which contribute to baseflow. The model for baseflow Q_b is based on a set of linear equations for continuity and discharge-storage relationship in the upper groundwater storage zones:

$$dS_g / dt = R - Q_b$$

$$Q_b = k\, S_g$$

which have the following solution for any given episode between two successive turning points:

$$Q_b = Q_{bo} \exp(-kt) + R\,[1 - \exp(-kt)]$$

where t = time,
S_g = upper groundwater storage
Q_b = baseflow at time t
Q_{bo} = initial baseflow for a given episode
k = exponential recession constant
R = recharge rate for the episode

The initial and final turning points for an episode interval $(t, t+\delta t)$, together with a value of k, fitted interactively to the dry-season recession flows, would determine the value of R during the episode:

$$R = [Q_b(t+\delta t) - Q_b(t) \exp(-k\, \delta t)]/[1-\exp(-k\, \delta t)]$$

If a non-positive R is obtained, downward adjustment of the initial turning point value is made so that $R = 0$, implying a pure recession episode. If a positive R is obtained, no adjustment is made, implying a recharge episode. This algorithm is applied recursively backward through time over the entire period of analysis. It is expected that the recession constant k is a basic basin property which varies with the size and nature of the surface and subsurface basins.

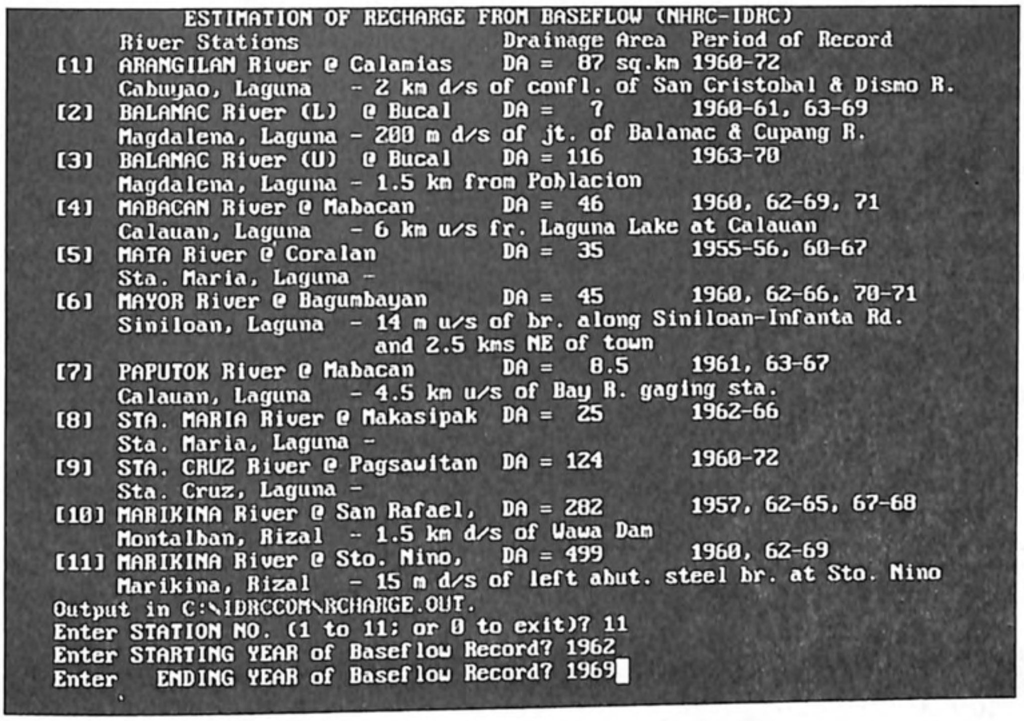
The inputs to the model are:

- choice of river station
- choice of analysis period
- daily total streamflows
- initial baseflow turning points (U.K.I.H.)
- exponential recession coefficient, k (interactively-fitted parameter)

The outputs are:

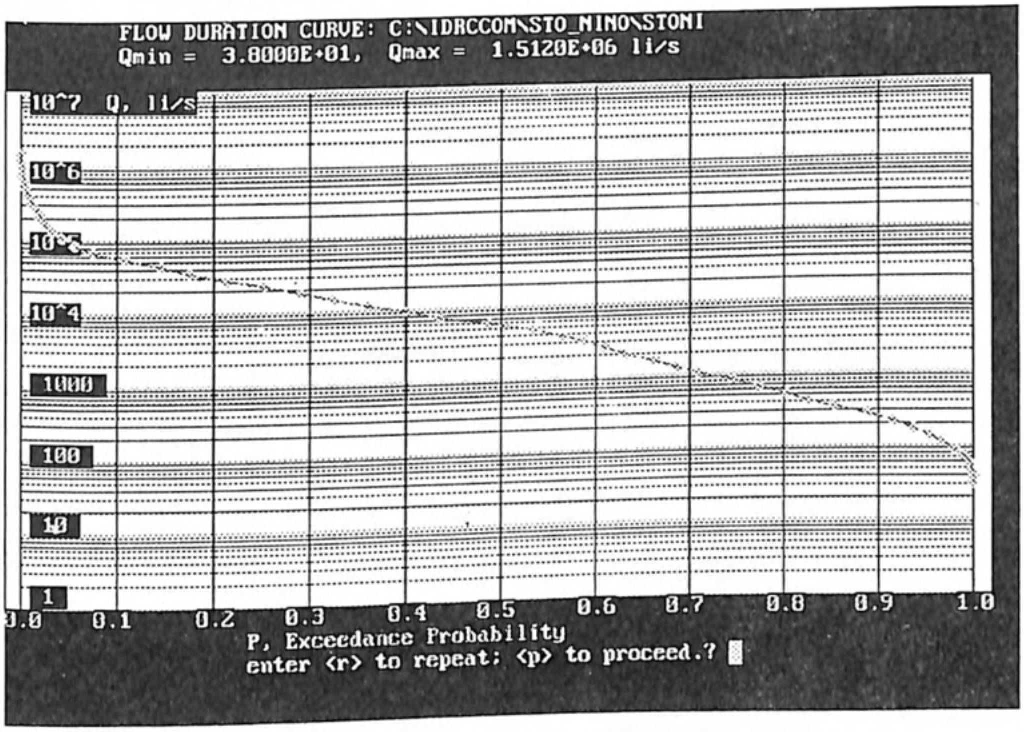
- daily baseflow Q_b
- daily recharge rate R, going to baseflow
- optional flow-duration curves of total flow
  monthly, annual, and period summary

Examples of screen input and screen output of the baseflow separation model are given in Figs. 1, 2, and 3.



```
              ESTIMATION OF RECHARGE FROM BASEFLOW (NHRC-IDRC)
      River Stations                   Drainage Area  Period of Record
 [1]  ARANGILAN River @ Calamias      DA =  87 sq.km 1960-72
      Cabuyao, Laguna   - 2 km d/s of confl. of San Cristobal & Dismo R.
 [2]  BALANAC River (L)  @ Bucal      DA =   7       1960-61, 63-69
      Magdalena, Laguna - 200 m d/s of jt. of Balanac & Cupang R.
 [3]  BALANAC River (U)  @ Bucal      DA = 116       1963-70
      Magdalena, Laguna - 1.5 km from Poblacion
 [4]  MABACAN River @ Mabacan         DA =  46       1960, 62-69, 71
      Calauan, Laguna   - 6 km u/s fr. Laguna Lake at Calauan
 [5]  MATA River @ Coralan            DA =  35       1955-56, 60-67
      Sta. Maria, Laguna -
 [6]  MAYOR River @ Bagumbayan        DA =  45       1960, 62-66, 70-71
      Siniloan, Laguna  - 14 m u/s of br. along Siniloan-Infanta Rd.
                          and 2.5 kms NE of town
 [7]  PAPUTOK River @ Mabacan         DA =   8.5     1961, 63-67
      Calauan, Laguna   - 4.5 km u/s of Bay R. gaging sta.
 [8]  STA. MARIA River @ Makasipak  DA =  25         1962-66
      Sta. Maria, Laguna -
 [9]  STA. CRUZ River @ Pagsawitan  DA = 124         1960-72
      Sta. Cruz, Laguna -
[10]  MARIKINA River @ San Rafael,  DA = 282         1957, 62-65, 67-68
      Montalban, Rizal  - 1.5 km d/s of Wawa Dam
[11]  MARIKINA River @ Sto. Nino,   DA = 499         1960, 62-69
      Marikina, Rizal   - 15 m d/s of left abut. steel br. at Sto. Nino
Output in C:\IDRCCOM\RCHARGE.OUT.
Enter STATION NO. (1 to 11; or 0 to exit)? 11
Enter STARTING YEAR of Baseflow Record? 1962
Enter   ENDING YEAR of Baseflow Record? 1969
```

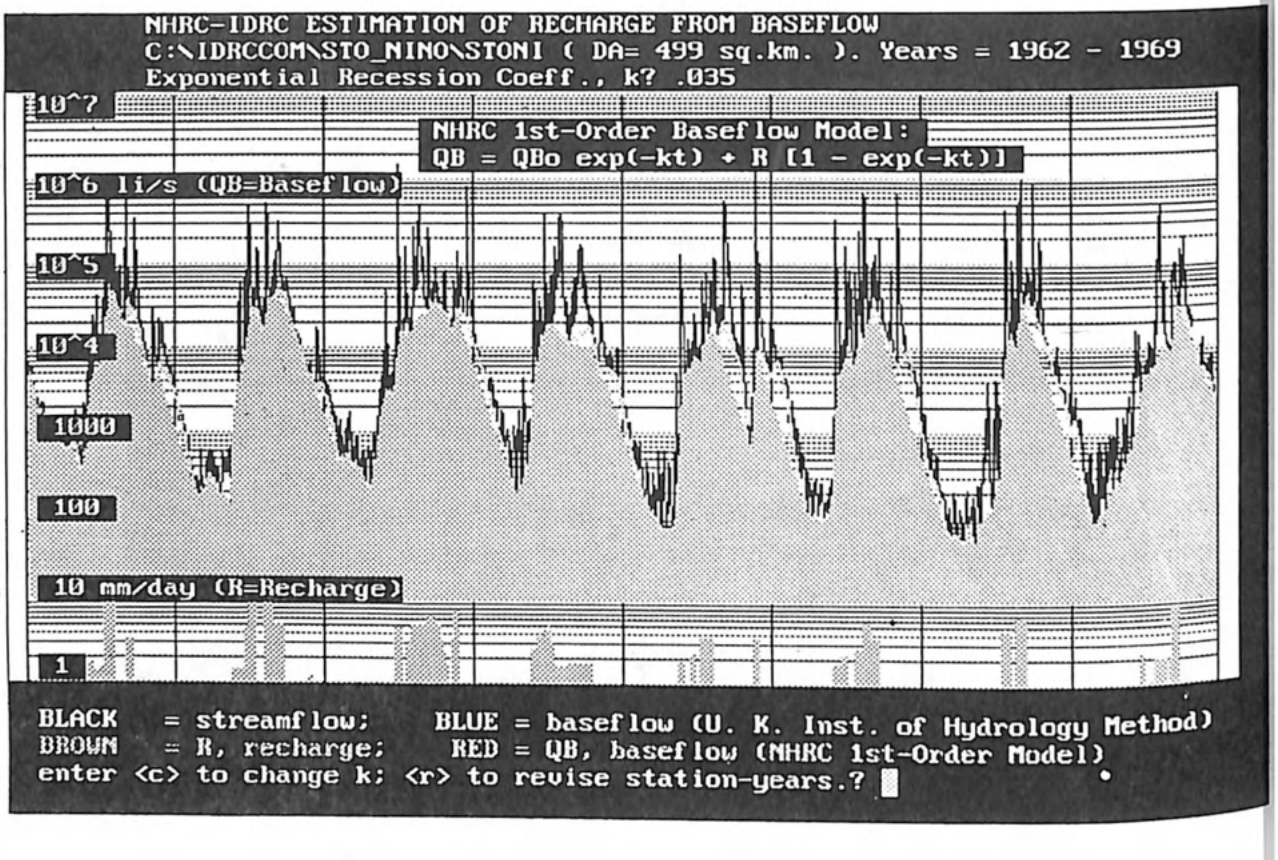
Fig. 1 Baseflow separation - sample screen input



```
     FLOW DURATION CURVE: C:\IDRCCOM\STO_NINO\STONI
     Qmin =  3.8000E+01,  Qmax =  1.5120E+06 li/s
```

```
enter <r> to repeat; <p> to proceed.?
```

Fig. 2 Baseflow separation - sample flow-duration curve



```
NHRC-IDRC ESTIMATION OF RECHARGE FROM BASEFLOW
C:\IDRCCOM\STO_NINO\STONI ( DA= 499 sq.km. ). Years = 1962 - 1969
Exponential Recession Coeff., k? .035
```

```
BLACK   = streamflow;     BLUE = baseflow (U. K. Inst. of Hydrology Method)
BROWN   = R, recharge;     RED = QB, baseflow (NHRC 1st-Order Model)
enter <c> to change k; <r> to revise station-years.? █
```

Fig. 3 **Baseflow separation - sample screen output**

Watershed Water Balance Model

A **water balance model** has been prepared for the purpose of **monthly water balance computations at lumped subbasin scale** for a given period of analysis. The model features are:

a. **Input Hydrologic Series:**

- Choice of subbasin
- Choice of analysis period (within 1949-1990)
- P = monthly rainfall
- PET = monthly potential evapotranspiration, PET

b. **Input Parameters (to be calibrated):**

- S_m = maximum soil moisture storage, derived from soil and land-use/cover types.
- r = ratio of total recharge to excess moisture; for later calibration against groundwater level data.
- f = fraction of recharge going to the upper groundwater zone. The other part (1-f) goes to the lower groundwater zone.

- k = baseflow exponential recession coefficient (from baseflow separation)

c. Choice of Actual ET/Soil Moisture Accounting Methods

This requires the choice of functional relationships for **actual evapotranspiration**, AET, with available precipitation, P, and soil moisture, S(t), for a given potential evapotranspiration, PET; and the consequent change in soil moisture storage, S(t+1):

AET = function of P, PET, and S(t).
S(t+1) = function of P, PET, S(t), and S_m.

The different moisture accounting methods all apply priority of satisfying evapotranspiration and soil moisture deficit requirements ahead of producing excess moisture, which, if available, divides into direct runoff and recharge. The methods differ essentially on the functional types of relationships among the variables. Their output values are also close. The methods are:

Averaging Method (based on Linsley and Franzini):

$$S(t+1) = \text{Max}\ \{0, \text{Min}[\ S_m, S(t)[1-.5\ PET/S_m + P]/[1+.5\ PET/S_m\ ]\}$$

$$AET = PET * .5\ [S(t) + S(t+1)]/S_m$$

$$\text{Excess Moisture} = P - AET - [S(t+1) - S(t)]$$

Crawford Method:

$$AET = \text{Min}\ \{\ PET, S(t) + P, P + [PET - P]*S(t)/S_m\ \}$$

$$S(t+1) = \text{Min}\ \{\ S_m, S(t) + (P - AET)*[1 - m]\ \}$$

where
m = excess moisture ratio

$$= 2*[S(t)/S_m]^2 \text{ for } 0 < S(t)/S_m < .5 \text{ and } P>AET$$

$$= 1 - 2*[1-S(t)/S_m]^2 \quad \text{for } .5 < S(t)/S_m < 1 \text{ and } P>AET$$

$$= 0 \quad \text{for } P<AET$$

$$\text{Excess Moisture} = P - AET - [S(t+1) - S(t)]$$

Exponential Method:

$$S(t+1) = S(t) \exp[-(PET-P)/S_m] \text{ for } P<PET \text{ (exponential)}$$
$$= \text{Min}\ \{\ S_m, S(t) + P, PET\ \} \text{ for } P>PET$$

$$AET = \mathrm{Min}\{ PET, P - [S(t+1) - S(t)] \}$$

$$\text{Excess Moisture} = P - AET - [S(t+1) - S(t)]$$

d. Output Hydrologic Series:

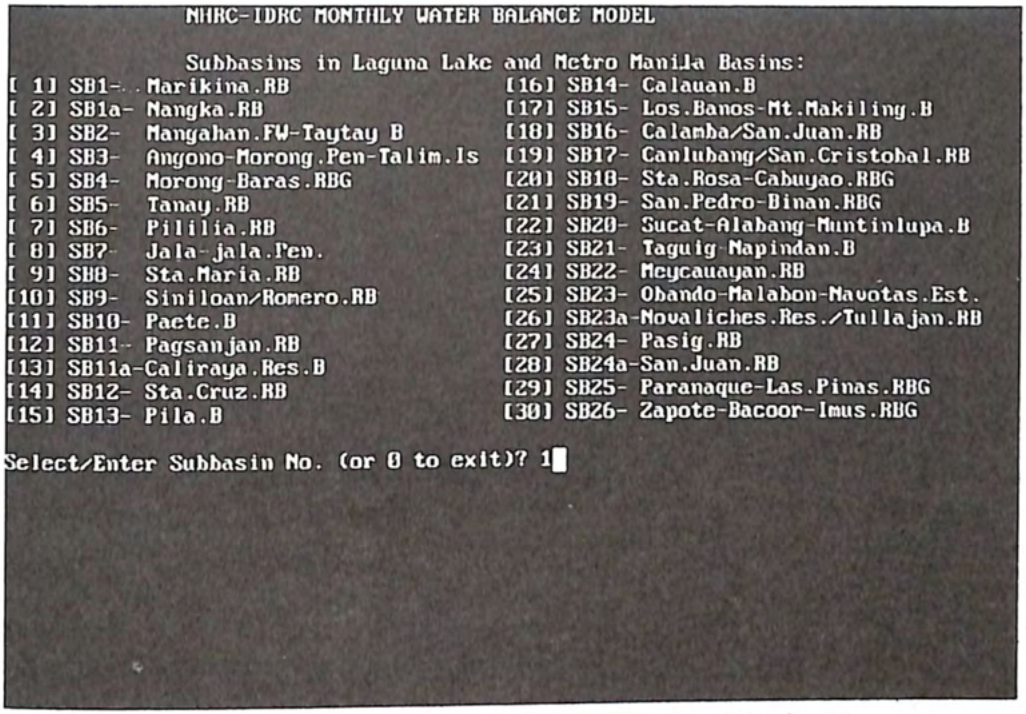
Monthly average, annual, and period summaries of:

- AET = actual evapotranspiration
- $S(t)$ = soil moisture storage
- $f R_g$ = recharge to upper groundwater zone
- $(1-f) R_g$ = recharge to lower groundwater zone
- $S_g(t)$ = upper groundwater storage
- Q_b = baseflow from upper groundwater zone
- Q_d = direct flow
- Q = total flow

computed from the **Water Balance Equations**:

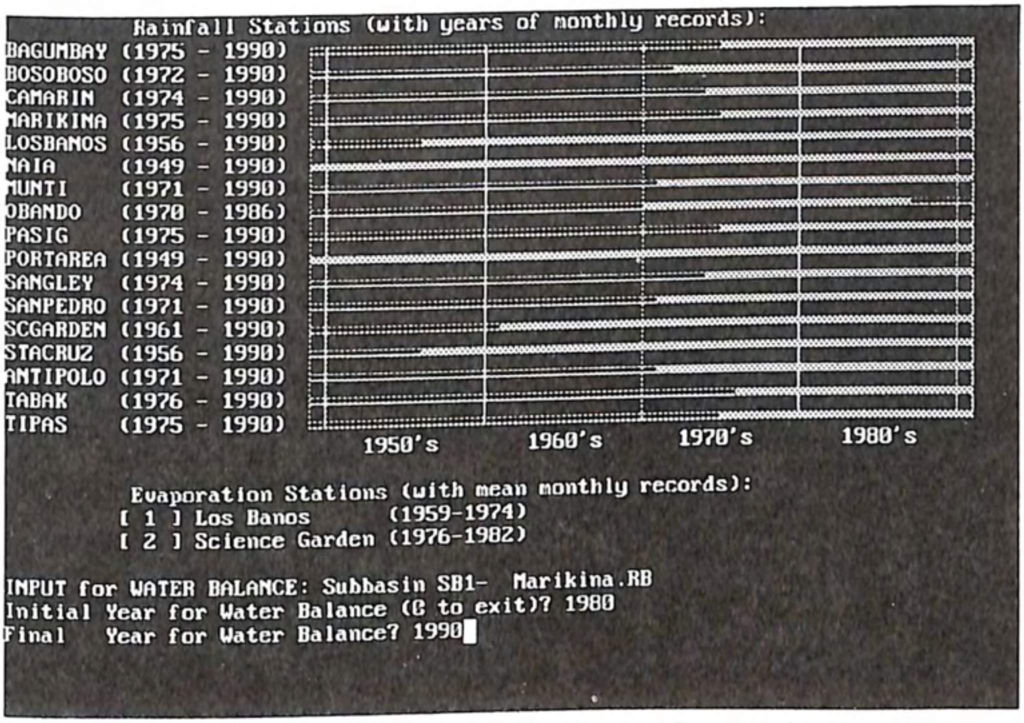
- **Surface Water Balance:**
  $S(t+1) = S(t) + P - AET - R_g - Q_d$
- **Recharge Relation:**
  $R_g = r [P + S(t) - S(t+1) - AET]$
- **Direct Flow Relation:**
  $Q_d = (1-r) [P + S(t) - S(t+1) - AET]$
- **Baseflow Relation:**
  Q_b = (NHRC First-Order Linear Baseflow Model, monthly version)
  = function of $S_g(t)$ and $f R_g$
- **Upper Groundwater Zone Balance:**
  $S_g(t+1) = S_g(t) + f R_g - Q_b$
- **Total Flow Relation:**
  $Q = Q_d + Q_b$

Examples of screen input and screen output of the water balance model are given in Figs. 4, and 5.



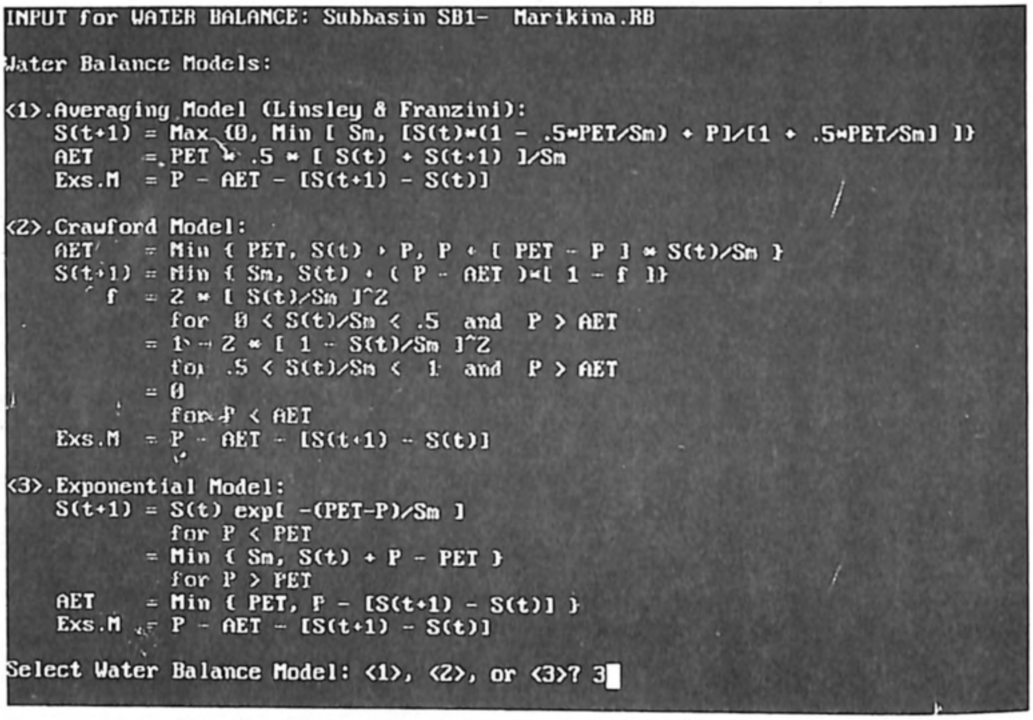
```
                    NHRC-IDRC MONTHLY WATER BALANCE MODEL

                    Subbasins in Laguna Lake and Metro Manila Basins:
[ 1] SB1-   Marikina.RB                        [16] SB14- Calauan.B
[ 2] SB1a-  Mangka.RB                          [17] SB15- Los.Banos-Mt.Makiling.B
[ 3] SB2-   Mangahan.FW-Taytay B               [18] SB16- Calamba/San.Juan.RB
[ 4] SB3-   Angono-Morong.Pen-Talim.Is         [19] SB17- Canlubang/San.Cristobal.RB
[ 5] SB4-   Morong-Baras.RBG                   [20] SB18- Sta.Rosa-Cabuyao.RBG
[ 6] SB5-   Tanay.RB                           [21] SB19- San.Pedro-Binan.RBG
[ 7] SB6-   Pililia.RB                         [22] SB20- Sucat-Alabang-Muntinlupa.B
[ 8] SB7-   Jala-jala.Pen.                     [23] SB21- Taguig-Napindan.B
[ 9] SB8-   Sta.Maria.RB                       [24] SB22- Meycauayan.RB
[10] SB9-   Siniloan/Romero.RB                 [25] SB23- Obando-Malabon-Navotas.Est.
[11] SB10-  Paete.B                            [26] SB23a-Novaliches.Res./Tullajan.RB
[12] SB11-  Pagsanjan.RB                       [27] SB24- Pasig.RB
[13] SB11a-Caliraya.Res.B                      [28] SB24a-San.Juan.RB
[14] SB12-  Sta.Cruz.RB                        [29] SB25- Paranaque-Las.Pinas.RBG
[15] SB13-  Pila.B                             [30] SB26- Zapote-Bacoor-Imus.RBG

Select/Enter Subbasin No. (or 0 to exit)? 1
```

Fig. 4 Watershed water balance - sample screen input
(a) Choice of subbbasin



```
           Rainfall Stations (with years of monthly records):
BAGUMBAY (1975 - 1990)
BOSOBOSO (1972 - 1990)
CAMARIN  (1974 - 1990)
MARIKINA (1975 - 1990)
LOSBANOS (1956 - 1990)
NAIA     (1949 - 1990)
MUNTI    (1971 - 1990)
OBANDO   (1970 - 1986)
PASIG    (1975 - 1990)
PORTAREA (1949 - 1990)
SANGLEY  (1974 - 1990)
SANPEDRO (1971 - 1990)
SCGARDEN (1961 - 1990)
STACRUZ  (1956 - 1990)
ANTIPOLO (1971 - 1990)
TABAK    (1976 - 1990)
TIPAS    (1975 - 1990)
                            1950's      1960's      1970's      1980's

           Evaporation Stations (with mean monthly records):
          [ 1 ] Los Banos        (1959-1974)
          [ 2 ] Science Garden (1976-1982)

INPUT for WATER BALANCE: Subbasin SB1-  Marikina.RB
Initial Year for Water Balance (0 to exit)? 1980
Final   Year for Water Balance? 1990
```

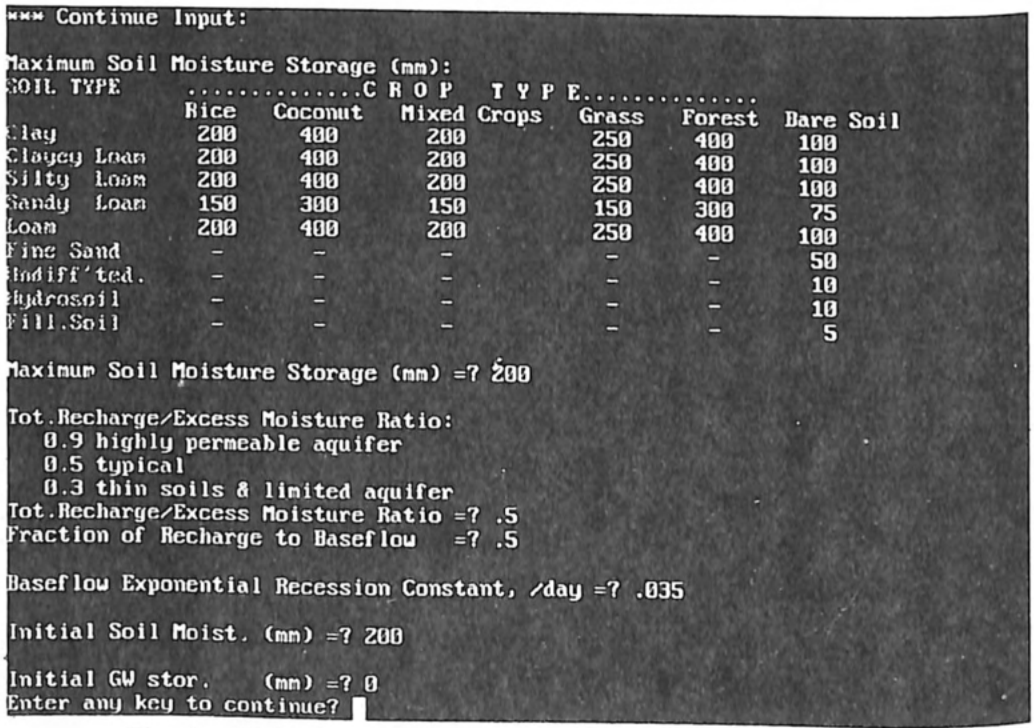
Fig. 4 Watershed water balance - sample screen input
(b) Choice of period of analysis



```
INPUT for WATER BALANCE: Subbasin SB1-  Marikina.RB

Water Balance Models:

<1>.Averaging Model (Linsley & Franzini):
    S(t+1) = Max {0, Min [ Sm, [S(t)*(1 - .5*PET/Sm) + P]/[1 + .5*PET/Sm] ]}
    AET     = PET * .5 * [ S(t) + S(t+1) ]/Sm
    Exs.M   = P - AET - [S(t+1) - S(t)]

<2>.Crawford Model:
    AET     = Min { PET, S(t) + P, P + [ PET - P ] * S(t)/Sm }
    S(t+1) = Min { Sm, S(t) + ( P - AET )*[ 1 - f ]}
       f    = 2 * [ S(t)/Sm ]^2
              for  0 < S(t)/Sm < .5  and  P > AET
            = 1 - 2 * [ 1 - S(t)/Sm ]^2
              for  .5 < S(t)/Sm <  1  and  P > AET
            = 0
              for P < AET
    Exs.M   = P - AET - [S(t+1) - S(t)]

<3>.Exponential Model:
    S(t+1) = S(t) exp[ -(PET-P)/Sm ]
              for P < PET
            = Min { Sm, S(t) + P - PET }
              for P > PET
    AET     = Min { PET, P - [S(t+1) - S(t)] }
    Exs.M   = P - AET - [S(t+1) - S(t)]

Select Water Balance Model: <1>, <2>, or <3>? 3█
```

Fig. 4 Watershed water balance - sample screen input

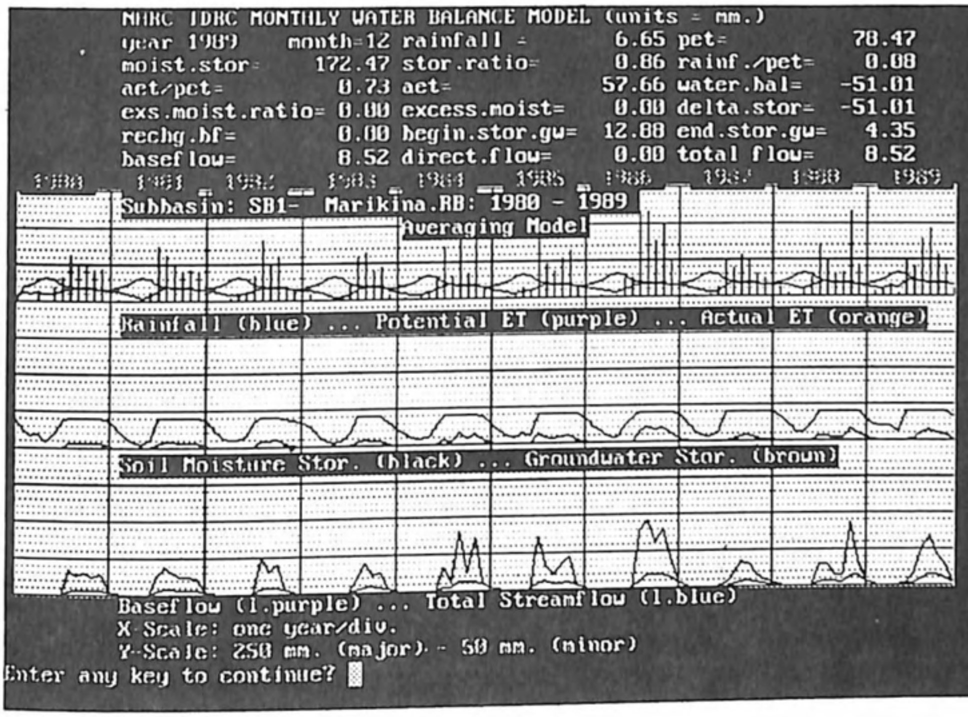
(c) Choice of moisture accounting method



```
*** Continue Input:

Maximum Soil Moisture Storage (mm):
SOIL TYPE       ...............C R O P   T Y P E...............
                Rice   Coconut   Mixed Crops    Grass   Forest   Bare Soil
Clay             200     400       200            250     400      100
Clayey Loam      200     400       200            250     400      100
Silty  Loam      200     400       200            250     400      100
Sandy  Loam      150     300       150            150     300       75
Loam             200     400       200            250     400      100
Fine Sand         -       -         -              -       -        50
Undiff'ted.       -       -         -              -       -        10
Hydrosoil         -       -         -              -       -        10
Fill.Soil         -       -         -              -       -         5

Maximum Soil Moisture Storage (mm) =? 200

Tot.Recharge/Excess Moisture Ratio:
   0.9 highly permeable aquifer
   0.5 typical
   0.3 thin soils & limited aquifer
Tot.Recharge/Excess Moisture Ratio =? .5
Fraction of Recharge to Baseflow   =? .5

Baseflow Exponential Recession Constant, /day =? .035

Initial Soil Moist. (mm) =? 200

Initial GW stor.    (mm) =? 0
Enter any key to continue? █
```

Fig. 4 Watershed water balance (cont'd) - sample screen input

(d) Input of basin properties



```
NHRC IDRC MONTHLY WATER BALANCE MODEL (units = mm.)
year 1989      month=12 rainfall =          6.65 pet=            78.47
moist.stor=      172.47 stor.ratio=         0.86 rainf./pet=      0.08
act/pct=           0.73 act=               57.66 water.bal=     -51.01
exs.moist.ratio=   0.00 excess.moist=       0.00 delta.stor=    -51.01
rechg.bf=          0.00 begin.stor.gw=     12.88 end.stor.gw=     4.35
baseflow=          8.52 direct.flow=        0.00 total flow=      8.52
```

```
X-Scale: one year/div.
Y-Scale: 250 mm. (major) - 50 mm. (minor)
Enter any key to continue?
```

Figure 5 Watershed water balance - sample screen output

Laguna Lake Water Balance Model

A lake water balance model has been prepared for Laguna Lake for the purpose of estimating **monthly net inflows or outflows after evaporation losses**. Utilizing monthly starting values of Laguna Lake gage heights, changes in lake and floodplain stored volumes are computed based on regression equations for lake area-depth and floodplain area-elevation relationships. The net inflow or outflow, Q, during month-t is obtained from the change in lake and floodplain storage volume, S, plus lake evaporation, E:

$$Q(t) = S(t+1) - S(t) + E(t)$$

The computed net inflow or outflow, in algebraic terms, is **interpreted** as the following summation:

(watershed tributary river inflows)
\+ (direct rainfall on the lake)
\+ (discharge from groundwater)
\+ (Mangahan Floodway and Napindan inflow)
(as the case maybe)
\- (recharge to groundwater)
\- (Mangahan Floodway and Napindan reverse flows)
(on the contrary case).

For visual correlation purposes, the plot of monthly lake rainfall is displayed together with those of lake evaporation, lake gage height, and net inflow or outflow. **Coupling** of the lake water balance model with the watershed surface balance and the groundwater models will resolve the separate components in the net lake inflow or outflow values.

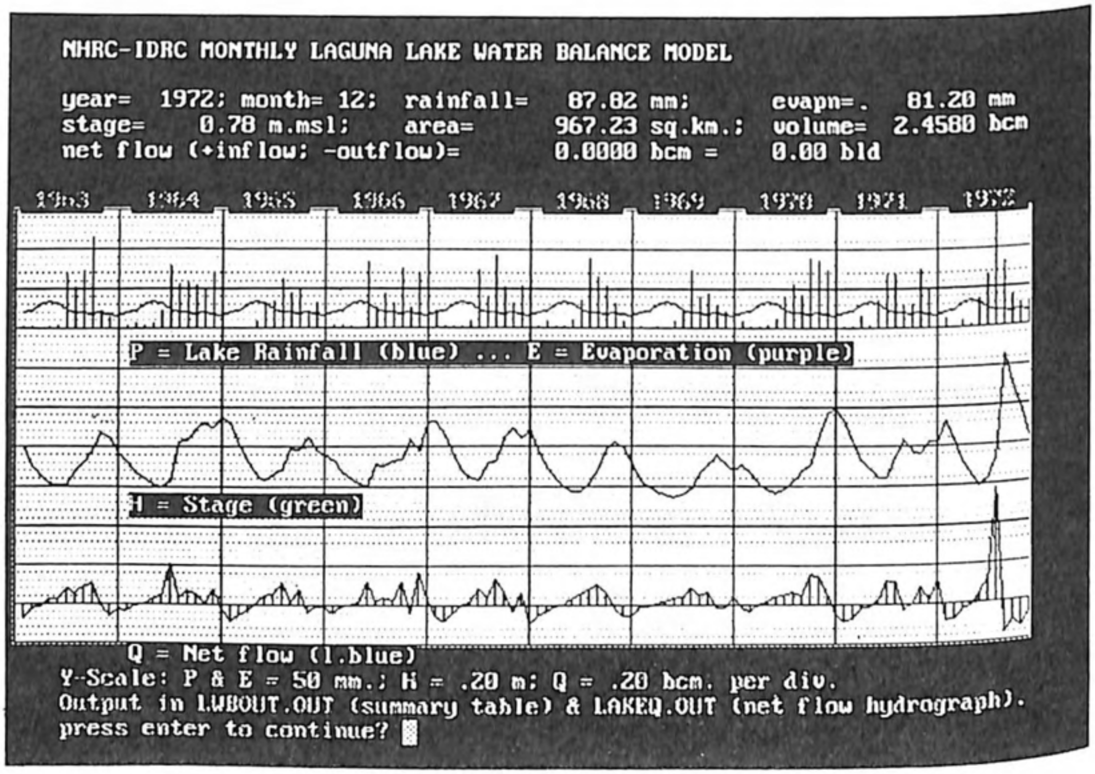
The model features are:

a. **Input Hydrologic Series**
   - Choice of analysis period.
   - Monthly starting lake gage height or stage
   - Monthly rainfall
   - Monthly pan evaporation

b. **Input Parameters**
   - Lake and floodplain area-volume-stage equations, based on depth-area and elevation area regressions, respectively.
   - Gage height, rainfall and evaporation station Thiessen weights

c. **Output Hydrologic Series**
   - Monthly net inflow or outflow

Fig. 6 provides a sample screen output of the Laguna Lake water balance model, computed for the analysis period 1963-1974, which was prior to the construction of the Napindan HCS and Mangahan Floodway. Clearly evident are the regular annual cycles of net inflows during the wet months followed by the net (recession) outflows during the dry season.



```
NHRC-IDRC MONTHLY LAGUNA LAKE WATER BALANCE MODEL

year=  1972; month= 12;  rainfall=   87.82 mm;        evapn=.   81.20 mm
stage=    0.78 m.msl;    area=      967.23 sq.km.;  volume=  2.4580 bcm
net flow (+inflow; -outflow)=       0.0000 bcm =    0.00 bld
```

```
      Q = Net flow (l.blue)
Y-Scale: P & E = 50 mm.; H = .20 m; Q = .20 bcm. per div.
Output in LWBOUT.OUT (summary table) & LAKEQ.OUT (net flow hydrograph).
press enter to continue? ▒
```

Fig. 6 Laguna Lake water balance model (sample screen output)

IDRC COUPLED GROUNDWATER HYDRAULIC-SUBSIDENCE MODEL

This section presents the theory and elements of the IDRC coupled groundwater hydraulic-subsidence model, as originally formulated for the BUH. Both the hydraulic and subsidence submodels are described, together with their assumptions, governing equations and derived solutions. The model, as adapted to the study area, utilizes linear superposition of hydraulic head and subsidence depth. This adaptation is tested by means of pre-calibration runs for the Metro Manila area. After these pre-calibration runs, recommendations are made for implementation in the Manila Model.

Model Assumptions

The basic coupled model consists of **coupling a groundwater hydraulic model and a subsidence model**. The hydraulic model provides the hydraulic presure profile in the aquifer and aquitard layers under pumping conditions, and the subsidence model provides the subsidence arising from hydraulic pressure changes in the aquitard and aquifers. The following basic assumptions are made:

a. A two layer system (aquitard-aquifer) is used to represent the geological system (Fig. 7).

b. Water flow in the aquifer layer is mainly horizontal under pumping withdrawal conditions.

c. Water infiltration from the aquitard layer into the aquifer layer through boundaries between aquifer and aquifer layers under pumping condition is vertical and slow, because of the slow aquitard drainage process.

d. Vertical subsidence characterizes the land deformation.

e. Subsidence is mainly due to consolidation of the aquitards.

f. Darcy's law applies in both aquitard and aquifer layers.

e. With respect to recharge, the aquitard is presumed to show negligible rebound volume change - i.e. subsidence of the aquitard is not reversible.

g. Multi-aquifer communication can be dealt with by introducing a "leakage" percentage factor.

h. Shear stress components in the effective stress tensor are not considered so that the subsidence is taken as a basin average quantity.

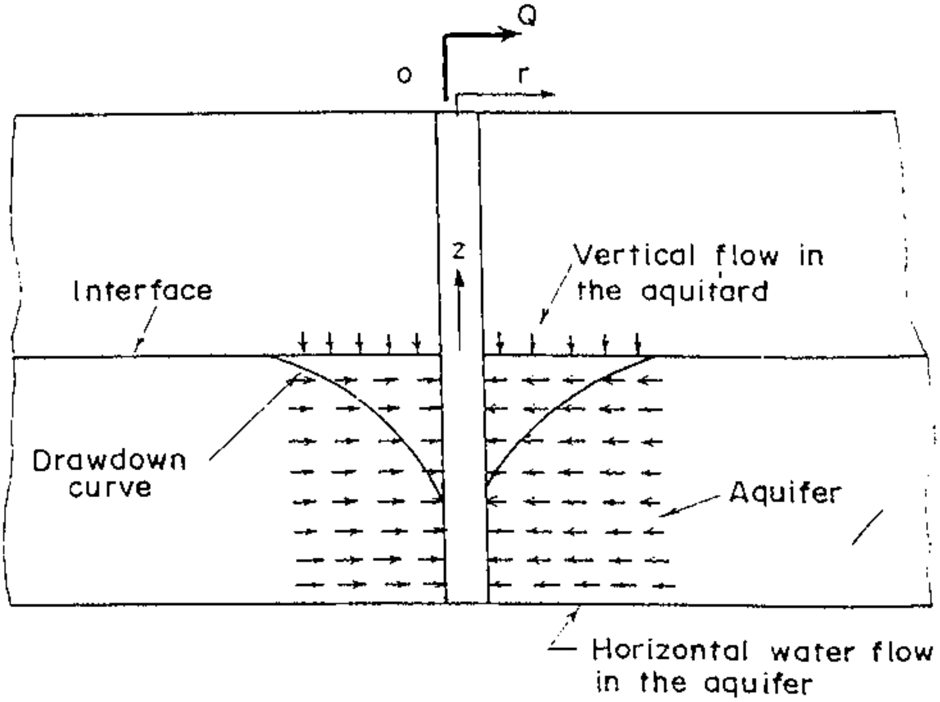


Fig. 7 IDRC model two-layer system

The Hydraulic Submodel

The BUH hydraulic submodel can be mathematically described as follows:

Let r = radial coordinate from a pumping well (meter)
z = vertical coordinate (equal to zero at aquifer-aquitard boundary) (meter)
t = time coordinate (year)
h_s = $h_s(r,t)$ = excess pressure head in the aquifer layer (meter)
h_c = $h_c(r,z,t)$ = excess pressure head in the aquitard layer (meter)

The **aquifer head** h_s, under the asssumption of horizontal flow, satisfies the **combined continuity-Darcy's Law equation in radial coordinates**, coupled with an aquitard drainage term, in the domain ($0 \leq r < \infty$, $0 \leq t < \infty$):

$$m_s\, \delta h_s/\delta t = k_s\, [\delta^2 h_s/\delta r^2 + (1/r)\, \delta h_s/\delta r)] + q$$

where k_s = hydraulic conductivity of the aquifer (m/year)
m_s = compressibility of the aquifer (per meter)
q = $k_c(-\delta h_c/\delta z)|_{z=0}$ = aquitard drainage rate

On the other hand, the **aquitard head** h_c, under the assumption of vertical flow, satisfies the **combined continuity-Darcy's Law equation in vertical coordinates**, in the domain ($0 \leq z < \infty$, $0 \leq t < \infty$):

$$m_c\, \delta h_c/\delta t = k_c\, \delta^2 h_c/\delta z^2$$

where k_c = hydraulic conductivity of the aquitard (m/year)
m_c = compressibility of the aquitard (per meter).

It should be noted that the commonly used parameters, the aquifer and aquitard transmissivities, T_s and T_c, and the storage coefficients, S_s and S_c, respectively, can be related to the above parameters according to:

$$T_s = k_s\, H_s \qquad T_c = k_c\, H_c$$
$$S_s = m_s\, H_s \qquad S_c = m_c\, H_c$$

where H_s = total aquifer thickness (meter)
H_c = total aquitard thickness (meter)

The initial conditions to be satisfied are given as:

$$h_s(r,0) = h_c(r,z,0) = 0$$

which represent initial hydrostatic condition at the time when pumping starts.

The **boundary conditions** which need to be satisfied are as folows:

a. On a well's inner surface,

$Q_m = 2 \pi r_o H_s k_s \delta h_s(r_o,t)/\delta r$
at $r = r_o$, for all t.

where Q_m = pumping rate of the m-th well (cu.m./year).
r_o = radius of the well (meter)
H_s = aquifer thickness (meter)

b. On the aquifer-aquitard interface, the head should be continuous,

$h_c(r,0,t) = h_s(r,t)$
at $z = 0$, for all r and t.

c. On the top of the aquitard under excess pressure head, a nonpermeable boundary condition is assigned, i.e.,

$\delta h_c(r,Z(t),t)/\delta z = 0$
at $z = Z(t)$, for all r and t

where $Z(t)$ = a time-varying vertical front of progressing aquitard head (meter).

d. When r is at infinity,

$h_s(\infty,t) = h_c(\infty,z,t) = 0$
at $r = \infty$, for all z and t.

The Subsidence Submodel

The total **vertical deformation in the aquifer** is given by:

$$W_s(r,t) = m_s H_s \int_o^t \delta h_s/\delta t \, dt$$

while the **total vertical deformation in the aquitard** is given by:

$$W_c(r,t) = m_{cp} \int_o^t \int_o^{H_c} \delta h_c/\delta t \, dz \, dt \qquad \text{for compression}$$

$$W_c(r,t) = m_{ce} \int_o^t \int_o^{H_c} \delta h_c/\delta t \, dz \, dt \qquad \text{for expansion}$$

where
$W_s(r,t)$ = vertical deformation within the aquifer (meter)

$W_c(r,z,t)$ = vertical deformation within the aquitard
m_{cp} = aquitard compresibility for compression
m_{ce} = aquitard compressibility for expansion such that $m_{ce} < m_{cp}$.

The **average compression/subsidence values** for both aquifer and aquitard are defined as:

$$W_s^*(t) = \int_0^{R(t)} 2\pi r\, W_s(r,t)\, dr \,/\, [\pi R(t)^2]$$

$$W_c^*(t) = \int_0^{R(t)} 2\pi r\, W_c(r,t)\, dr \,/\, [\pi R(t)^2]$$

where
$W_s^*(t)$ = average subsidence within the aquifer (meter).
$W_c^*(t)$ = average subsidence within the aquitard (meter).
$R(t)$ = radial front of the progressing head (meter).

The **total average subsidence** $W^*(t)$ is given as:

$$W^*(t) = W_s^*(t) + W_c^*(t)$$

The Trial Function Solutions

Integrated equations were derived from the continuity equations in the flow domains of both aquifer and aquitard, based on assumed **trial functional forms for aquifer and aquitard heads which satisfy the prescribed boundary conditions**. The trial functions for aquifer and aquitard heads consist of **separable time-dependent generalized coordinates and space-dependent quadratic forms** (Fig. 8):

$$h_s(r',t) = -S_1(t)\,[1 - r'/S_2(t)]^2 \quad \text{for } 0 \le r' \le S_2(t)$$
$$= 0 \quad \text{for } r' \ge S_2(t)$$

$$h_c(r',z,t) = h_s(r',t)\,[1 - z/S_3(t)]^2 \quad \text{for } 0 \le z \le S_3(t)$$
$$= 0 \quad \text{for } z \ge S_3(t)$$

where $r' = r - r_0$, and the generalized coordinates $S_1(t)$, $S_2(t)$, and $S_3(t)$ are defined as:

$S_1(t)$ = **head drop or drawdown** at the well (meter).
$S_2(t)$ = **disturbed radial distance from the well** or the so called radius of influence of the well (meter). This is the same as the radial front R(t), introduced in section 8.1b.
$S_3(t)$ = **disturbed vertical distance or front in the aquitard** (meter). This is the same as the vertical front Z(t), introduced in section 8.1b.

The integrated equations are **nonlinear ordinary differential equations in the unknowns $S_1(t)$, $S_2(t)$, and $S_3(t)$**. For constant pumping rates, the approximate but acceptable time-dependent solutions for the case wherein $m_s << m_c$ are:

$$S_1(t) = [Q_m/(4\pi r_o H_s k_s)]\, S_2(t)$$

$$S_2(t) = \{ 72\,(1-n)\, r_o H_s k_s/[3\, m_s H_s + m_c S_3(t)] \}^{1/3}\, t^{1/3}$$

$$S_3(t) = [\, 6\, k_c/m_c\,]^{1/2}\, t^{1/2}$$

wherein the leakage factor, n, has been inserted in the solutions to reflect leakage between neighboring aquifers.

The **average subsidence** is computed from

$$u(t) = W^*(t) = S_1(t)\, \{ 3\, m_s H_s + m_c S_3(t)\}/[\, 18\, (1-n)]$$

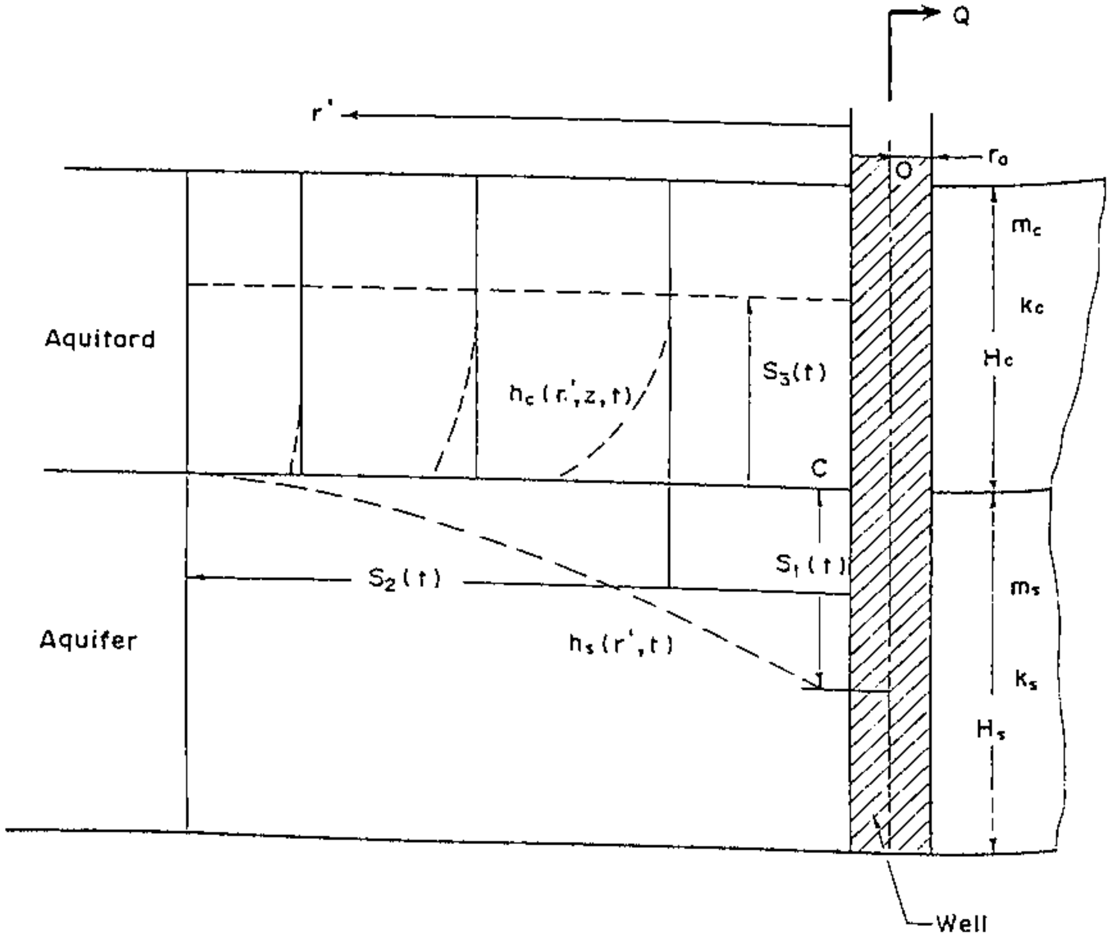


Fig.8 Definition sketch of well trial functions

DEVELOPMENT AND CALIBRATION OF THE MANILA MODEL

A test version of the IDRC Coupled Hydraulic Subsidence Model was initially developed at NHRC. This implements the well trial functions and subsidence equation as defined above. The required input groundwater parameters are thicknesses, permeabilities, and compressibilities of both aquitard and aquifer and the leakage factor. The input well variables are number of wells, well locations, well radii, and pumping rates.

The outputs consist of well drawdown (S_1), aquifer head radial front or radius of influence (S_2), aquitard head vertical front (S_3), and average subsidence height (u) for each well. A new feature in this adaptation is the additional output of grid values of aquifer and aquitard heads, and subsidence, obtained by spatial superposition of the heads and subsidence created by several wells.

The theoretical basis of the spatial superposition scheme is the fact that both aquifer and aquitard heads satisfy linear partial differential equations (the combined continuity-Darcy's Law equations) as well as boundary conditions which are linear in these dependent variables.

The pointwise definition of the subsidence function is also expressed linearly in terms of the heads. Hence, mathematically speaking, subsidence created by several wells can also be linearly superposed together. It is useful to display superposed subdsidence, say as a contour map, to indicate maximum subsidence potential as it varies from place to place.

Based on the foregoing, the following linear superposition scheme is adopted:

Grid Values of Aquifer Heads:

$$h_s(x_i,y_j,t) = \sum_m h_s(r_{ijm}, t) \qquad \text{(summation for all wells)}$$

Grid Values of Aquitard Heads:

$$h_c(x_i,y_j,z_k,t) = \sum_m h_c(r_{ijm}, z_k, t) \qquad \text{(summation for all wells)}$$

Grid Values of Subsidence:

$$W(x_i,y_j,t) = \sum_m W_s(r_{ijm},t) + W_c(r_{ijm},t) \qquad \text{(summation for all wells)}$$

where

r_{ijm} = radial distance of the m-th well from the grid point (x_i,y_j,z_k)

$= [(x_i-x_m)^2 + (y_j-y_m)^2]^{1/2}$

Pre-Calibration Runs for the Metro Manila Area

The test model, as adapted, was initially applied to the portion of the Metro Manila area occupied by the lower-elevation municipalities of Malabon, Navotas, Manila, Pasay, and Las Pinas, which are located mostly on the Manila Bay Alluvium; and by the higher-elevation municipalities of Valenzuela, Caloocan, Quezon City, San Juan, Mandaluyong, Makati and Paranaque, mostly located on the Guadalupe Formation. Using esentially a **basin approach**, the application area was made congruent with the aggrupation of six (6) river subbasins which drain directly to Manila Bay.

Preliminary model input data preparation and model runs were made in order to assess program memory and speed capacity, and to test model consistency and sensitivity relative to input parameter values. The two major aquifer systems in the model application area are the **Manila Bay Alluvium** and the **Guadalupe Formation**. The application area was schematized into 67 nodes (each 0.025 deg. longitude x 0.25 deg. latitude), divided into 14 nodes on the Alluvium and 53 nodes on the Guadalupe Formation.

The estimation of the model parameters, namely permeability and compressibility, was based on **Metro Manila transmissivity and storage coefficeint data**, as well as **generalized rock properties quoted from literature**. The Metro-Manila transmissivity and storage coefficent data were obtained, as a matter of established practice in the country, from **the analysis of both continuous-pumping and recovery well test data**, using Theis and Jacobs methods.

Order-of-magnitude estimates of average formation properties in both aquitard and aquifer can be made out of average rock properties and composition, using averaging techniques with weighting factors equated to the expected volume fractions, x_i, for each rock types with hydraulic properties: permeability K_i, and compressibility m_i:

Aquitard (assumming vertical flow and vertical subsidence of rock types in series):

Permeability = $\Sigma x_i / \Sigma(x_i/K_i)$
(weighted reciprocal mean)

Compressibility = $\Sigma(x_i m_i) / \Sigma x_i$
(weighted arithmetic mean)

Aquifer (assuming horizontal flow and vertical subsidence of rock types in parallel):

Permeability = $\Sigma(x_i K_i) / \Sigma x_i$
(weighted arithmetic mean)

Compressibilty = $\Sigma x_i / \Sigma(x_i/m_i)$
(weighted reciprocal mean)

For this initial modeling exercise, each municipal withdrawal rate was applied at a **single imaginary well**, properly located at the approximate centroid of each municipal array of wells. Instead of assigning typical well radius as required by the BUH model, typical well field radius was instead used for each municipality point.

During model simulation, **well interference by superposition of the trial functions** was allowed to take place for **aquifer heads within the same aquifer** (Guadalupe Formation), and **for aquitard heads within the same aquitard** (Manila Bay Alluvium). This takes place when the circles of influence of two wells intersect.

For this initial modeling exercise, recharge was applied on each node in the guise of **imaginary wells with negative withdrawal rates**. The recharge rates were certain fractions of annual rainfall (obtained from the water balance models) multiplied by the node area, the fractions being dependent on the formation type. The imaginary recharge wells were also subject to well interference. It was decided to model recharge in this manner, instead of using a leakage factor n to represent possible leakage from the surface. Whereas the leakage factor has to be assigned to a particular well, the recharge input as adapted can generally be placed anywhere in the model grid. More importantly, this recharge formulation is the **principal linkage mechanism** between the surface water models and the groundwater model.

The application of higher recharge rates on the exposed Guadalupe Formation was effective in reproducing the high mound of the piezometric surface in the northeastern part of the application area. Significant drawdowns were clearly predicted in municipalities with high pumping rates. Interference among their wells was also depicted by the model.

CUWARM Modelling Schemes

Based on the results of the pre-calibration modeling exercise and the preceding surface-water modeling steps, the following schemes were integrated into the Manila Model:

- **Linear spatial superposition of well trial functions** for head and subsidence was adopted in order to depict interference among wells and recharge points wherever and whenever their radii of influence would intersect.

- Application of **annual withdrawal rates** was spread over several well cells in order to realistically depict the spatial distribution of wells. Each well cell is of submunicipal scale, on the average a lumping of about seven (7) actual neighboring wells each cell.

- On the basis of the results of monthly water balance computations applied to the different subbasins, annual recharge fractions relative to excess of rainfall (after subtraction of evapotranspiration, soil moisture addition, and surface runoff) were derived for varying soil types, land-use/cover and surface geology. **Annual recharge rates** are thereby evaluated and introduced in the guise of recharging wells on a node-by-node basis. Spatial variations of recharge coefficient and annual rainfall were therefore introduced in this manner. Natural mounds of the piezometric surface on such recharge areas were reproduced. This formulation is the **principal linkage mechanism between the surface water models and the groundwater model.**

- An **annual water-balance computation** on a **node-by-node basis** is thus applied, using rainfall, potential evapotranspiration, soil type, land-use/cover, surface geology, presence of lake/se body, and well-cell withdrawal data as inputs. The accounting process has been modeled as **an annual aggregation of the observed and essential seasonal characteristics of the monthly, water-balance components**. The annual surface water-balance equation is as follows:

$$P = AET + DR + BF + RG$$

(neglecting interannual net change in soil moisture storage, which exhibits only an intra-annual seasonal variation.)

where the hydrologic components are computed as follows:

P $= P_d + P_w$ (given data)
= dry-season rainfall + wet-season rainfall
= annual rainfall

PET $= PET_d + PET_w$ (given data)
= dry-season PET + wet-season PET
= annual potential evapotranspiration

AET_d $= \text{Min}\ [PET_d\ ,\ P_d + S_m]$
= dry-season AET
(mainly limited by available soil moisture and low dry-season rainfall)

AET_w $= \text{Min}\ [PET_w\ ,\ P_w - S_m]$
= wet-season AET
(mainly limited by wet-season PET under excess rainfall condition)

S_m = maximum soil moisture storage
(function of soil type and land use/cover)

AET $= AET_d + AET_w$
= dry-season AET + wet-season AET
= annual actual evapotranspiration

DR $= r \cdot [P - AET]$
= annual direct runoff
= runoff coeff.[annual rainfall - annual AET]
(runoff coefficient, r, is a function of soil type and land-use/cover)

$EXSM$ $= P - AET - DR$
= excess moisture after evapotranspiration and direct runoff.

RG $= f \cdot EXSM$
= net recharge to aquifer
= recharge fraction·[excess mmoisture]
(recharge fraction, f, is a function of surface geology and presence of lake/sea body)

BF $= (1-f) \cdot EXSM$
= baseflow

R $= DR + BF$
= total runoff
= direct runoff + baseflow

Q = total annual withdrawal rate

Net Surplus (+)/Mining (-) Rate = RG - Q

- Although the original model was developed for constant withdrawal rates, it was extended to **time-varying withdrawal/recharge rates** by utilizing linear temporal superposition by **discrete convolution of annual incremental withdrawal/recharge rates, δQ_m, with the well trial functions converted to unit-response functions** in order to simulate aquifer heads:

$$h_s(x,y,t) = \underset{m}{\Sigma}\,\underset{t'}{\Sigma}\, \delta Q_m(t-t')\, S_1(t')\, [1-r_m/S_2(t')]^2$$

where the double summation signs imply summing of trial functions over all wells (m) and for all time periods (t').

- An initial version of the model assumes zero heads as **initial conditions**, regardless of actual initial levels of the piezometric surface in the area being modeled. The justification for this scheme is the fact that the zero initial conditions produce only a transient error which decays after a sufficient simulation period has elapsed and, much faster, if withdrawal rates increase with time. The neglect of pre-simulation levels of net withdrawal (including past recharge levels) and corresponding actual initial condition has diminishing effect on future values of simulated head. This can be seen from an error analysis of the trial functions:

$$S_1(t) = [Q_m/(4\pi r_o H_s k_s)]\, S_2(t)$$

$$S_2(t) = \{\, 72\, r_o H_s k_s/[3\, m_s H_s + m_c S_3(t)]\, \}^{1/3}\ t^{1/3}$$

$$S_3(t) = [\, 6\, k_c/m_c\,]^{1/2}\, t^{1/2}$$

Let t = actual time since net withdrawal has started
= $t_i + t_s$
t_i = neglected pre-simulation time
t_s = assumed simulation time
n = fractional power of time in the drawdown function, S_1
= 1/6 (for $m_s << m_c$)
Q_i = pre-simulation net withdrawal rate
δQ = additiomal net withdrawal rate during the simulation period

Following a temporal superposition of the trial functions:

Let $S_1(t)$ = actual drawdown at time t

= proportional to $Q_i (t_i + t_s)^n + \delta Q\, t_s{}^n$

$S_1(t_s)$ = simulated drawdown at time t_s

$= \text{proportional to } (Q_i + \delta Q)\, t_s^{\,n}$

The relative error between actual and simulation drawdown is computed as:

Relative Error $= [S_1(t) - S_1(t_s)]/S_1(t)$

$$= \frac{Q_i (t_i + t_s)^n + \delta Q\, t_s^{\,n} - (Q_i + \delta Q)\, t_s^{\,n}}{Q_i (t_i + t_s)^n + \delta Q\, t_s^{\,n}}$$

$$= [1 - \{t_s/(t_i + t_s)\}^n]/[1 + \delta Q/Q_i \{t_s/(t_i + t_s)\}^n]$$

For typical values of the parameters:
t_i = 10 years (say, 1971-1980)
t_s = 10 years (say, 1981-1990)
$\delta Q/Q_i = .02 \times 10 = .20$ (based on 2% annual growth rate)
Relative Error $= [1 - (.5)^{1/6}]/[1 + .2(.5)^{1/6}]$
$= .109/1.178 = .09 = 9\ \%$ error

In the long run, as both t_s and δQ become larger, the relative error given by the above formula approaches zero.

A later improved version of the adapted model allows the introduction of **arbitrary initial conditions** for the simulation of piezometric heads. This adaptation required the introduction of correction terms in order to take properly into account the influence of withdrawals during both the pre-simulation and simulation periods.

Let $h(t') = S_1(t')\,[1 - r_m/S_2(t')]^2$
= well-cell unit-response function for well cell- m.
t_i = pre-simulation period (since pumping started).
β_m = pre-simulation average annual increment of net withdrawal
$= Q_m(0)/t_i$ (constant)
$= \delta Q_m(0), \delta Q_m(-1), \ldots, \delta Q_m(-t_i + 1)$.

Application of linear superposition and convolution to obtain the head at time, t, results in the following:

$$h_s(x,y,t) = \sum_m \sum_{t'=1}^{t+t_i} \delta Q_m(t-t'+1)\, h(t')$$

$$= \sum_m \Big[\underbrace{\sum_{t'=1}^{t} \delta Q_m(t-t'+1)\, h(t')}_{\text{(simulation period)}} + \underbrace{\sum_{t'=t+1}^{t+t_i} \beta_m\, h(t')}_{\text{(pre-simulation period)}} \Big]$$

The initial condition for head (at t=0) derives from the pre-simulation terms, and is therefore theoretically equal to

$$h_s(x,y,0) = \underbrace{\sum_{m} \sum_{t'=1}^{t_i} \beta_m \, h(t')}_{\text{(pre-simulation period)}}$$

Combining the equation for the initial condition and that for the head at time t gives:

$$h_s(x,y,t) = \underbrace{h_s(x,y,0)}_{\text{(initial condition)}} + \underbrace{\sum_{m} \sum_{t'=1}^{t} \delta Q_m(t-t'+1) \, h(t')}_{\text{(simulation term)}}$$

$$+ \underbrace{\sum_{m} \sum_{t'=1}^{t_i} \beta_m \, \{h(t+t') - h(t')\}}_{\text{(pre-simulation correction term)}}$$

Model Input Data Preparation

The first input steps are the aggrupation and schematization of all deep wells inside the study area into **89 Metro Manila and 91 CALABAR** well **cells**, with spatial resolution of submunicipal scale (one or more barangays or city districts).

Reflected in the 180 well cells are a total of **3265 wells** (43 % of the 7615 well records in the 1992 NWRB well-inventory and water-rights files of private and government wells located in the Metro Manila and CALABAR provinces). The 3265 wells are all inside the basin study area, having drilled depths of at least 50 meters and reported pumpage or discharge data. The 50 meter depth cutoff was made in order to segregate uniform samples of lithologic description for both unconfined and confined conditions.

Another input step is the preparation and implementation of a **well-cell lithology statistical analysis program** in order to characterize each well cell in terms of:

- **Averaged lithologic profiles for major rock types** -

  good aquifer: sand, gravel
  fair aquifer: tuff, sandstone, limestone
  poor aquifer: clay, shale, basalt
  (in volume fractions vs. depth);

- **Averaged lithologic statistics** for a two-layer (aquitard/aquifer) scheme with inferred interface and basement horizons which identify the aquitard and aquifer layers.

After lithologic analysis of all available well logs in the study area, the next step is the assignment of relevant **well cell parameters**, utilizing both topographic, geologic, and lithologic information, transmissivity values from pump tests, and available withdrawal data:

- Well cell centroid coordinates
- Well cell quadrangle coordinates
- Well cell ground elevation
- Well cell hydraulic parameters -
  aquitard permeability, compressibility
  aquifer permebility, compressibility, specific yield
- Annual well-cell withdrawal (MCM/year)
  for Metro Manila - using NWRB water rights and well inventory pumpage/discharge data; MWSS and WELDAPHIL pumpage data.
  for CALABAR provinces - using NCSO projections of population; DPWH-PMO-RWS per capita rural domestic water consumption; and NWRB industrial, commercial, and agricultural withdrawal data.

The last input step is the the assignment of relevant **basin parameters to recharge nodes** over the entire study area. Each node covers a pixel area of 0.025° 'deg. latitude by 0.025° deg. longitude, or roughly 2.7 km. by 2.7 km., and each node is characterized by:

- Annual rainfall (1981-1990)
- Mean annual PET
- Subbasin identifier: subbasin or lake/sea body
- Surface geology type: Q.Alluvium, Q.Volcanics, or C.Impermeable
- Soil and land-use/cover type
- Average ground or lake/sea bottom elevation
- Depth to hydrogeological basement

Manila Model Features and Functions

The Manila Model, or more generically, the conjunctive-use water resources management model **(CUWARM)**, contains the following **features and functions:**

- **Batch input of all model parameters:**
  basin recharge node parameters and well-cell parameters as listed above.

- **Interactive selection of management unit:** one of 56 municipalities, or one of five (5) regional options:
  - Southwest: Cavite, Laguna, Batangas
  - Southeast: Laguna
  - Northeast: Eastern Rizal
  - Northwest: Metro Manila
  - Whole Study Area

- **Automatic derivation of active recharge nodes and well cells** applicable to the selected management unit, with graphic display of well cells and nodes.

- **Diagnostics of recharge nodes** in each subbasin with respect to the occurrence and distribution of surface geology and soil types, with tabular display of drainage areas and node counts of both surface geology and soil types, for each subbasin.

- **Diagnostics of well-cell hydrogeology:**
  - * Hydraulic parameter variation versus surface geology and lake/sea body
  - * Linear trend analysis of aquitard thickness versus location coordinates
  - * Input override options for regional nodal and well-cell hydraulic parameters (for calibration)
  - * Option between an artesian and a water-table aquifer (a parameter choice between confined storage coefficient and unconfined specific yield; and between confined and unconfined subsidence behavior)

- **Interactive graphics display of input parameters and variables:**
  - * Surface geology isomap
  - * Hydrogeology cross-sections (ground, aquifer, basement sections)
  - * Ground or lake/sea bottom elevation isomap
  - * Basement depth isomap
  - * Soil type isomap
  - * Annual rainfall isomap (annual series and average)

- **Interactive annual water balance**
  - * Choice of simulation period
  - * Annual water balance computation on a node-by-node basis using rainfall, PET, soil type, land-use/cover, surface geology and well-cell withdrawal data.
  - * Derivation of net recharge coefficient as a function of surface geology and lake/sea body (for calibration)

- **Computation of hydraulic head and subsidence** by linear superposition and time-convolution of all active well-cell and recharge-node trial functions for the chosen simulation period. There are two computational options based on the selection of aquifer type:

  - * Under the option of an **artesian or confined aquifer beneath an aquitard**, the same input parameter of aquifer compressibilty is utilized both in the evaluation of storage coefficient
    (equal to compressibility x total aquifer thickness, needed for the simulation of head), and in the computation of aquifer subsidence depth due to head changes across its entire thickness. Aquitard permeability and compressibilty are used as in the original model.

  - * Under the option of a water-table or unconfined aquifer beneath an aquitard, the following features were introduced: for purposes of head computation, the storage coefficient is replaced by the input specific yield of the aquifer; while aquifer susbsidence is computed using the aquifer compressibilty and hydraulic head changes applicable to the variable saturated depth, instead of the total thickness of the aquifer. The treatment of aquitard permeability and compressibility is the same as in the original model.

- Interactive graphics display of output variables:
  - Hydraulic head isomap
  - Groundwater flux vector field
  - Subsidence depth isomap

CALIBRATION OF THE MANILA MODEL

The calibration of CUWARM for Metro Manila (i.e., the Manila Model) was performed by fine adjustments of hydraulic parameters, recharge coefficients, and withdrawal rates on the basis of reasonable levels of withdrawal capacity factors (0.5 to 0.67) of well cells. The objective is to reproduce on a regional scale the observed end-of-1990 piezometric levels in Metro Manila as reported by MWSS.

Closer calibration is being done for Metro Manila in view of the availability of 1990 piezometric data in this region. The calibration runs have established the sensitivity of computed hydraulic head to the realistic ranges of the input parameters being used, so much so that reproducing the observed piezometric levels is attainable.

Figures 9 and 10 show **the 1980 and 1990 levels of deep-well withdrawals.**

Figure 11 present the screen output provided by CUWARM for the annual water balance during the calibration period 1982-1990. Figures 12 and 13 provide, respectively, the computed contour maps of the outputs variables: **hydraulic head (or piezometric surface) and subsidence depth**. Figure 14 exhibits a three-dimensional picture of the piezometric surface in Metro Manila.

As expected, the maximum computed drawdowns are occurring in the Metro Manila municipalities tapping the Guadalupe Formation. An interesting result is the computed weak groundwater flux occurring in the aquifer beneath Laguna Lake and Manila Bay, and pointing in the direction of the maximum withdrawal cells. Recharge mounds are also being reproduced in the nodes located at the upper catchments of Cavite and Bulacan, producing weak fluxes towards the withdrawal cells at the lower municipalities.

The results implied by the water balance computations, and also confirmed by the declined piezometric levels given by the calibrated groundwater model, are large drawdowns concentrated at high- withdrawal municipalities, due to a withdrawal rate (235 MCM/year) which exceeds the effective natural rechatge (206 MCM/year average or 5.76% of annual rainfall over the period 1982-1990). These point to a conclusion that groundwater is being mined from the Guadalupe Formation at a rate of 29 MCM/year with a calibrated specific yield of .013. The value of 5.75% of rainfall obtained as recharge is consistent with quoted values reported by Quiazon (1971) and MWSS/SOGREAH (1989). This conclusion applies to the highly urbanized Metro Manila area.

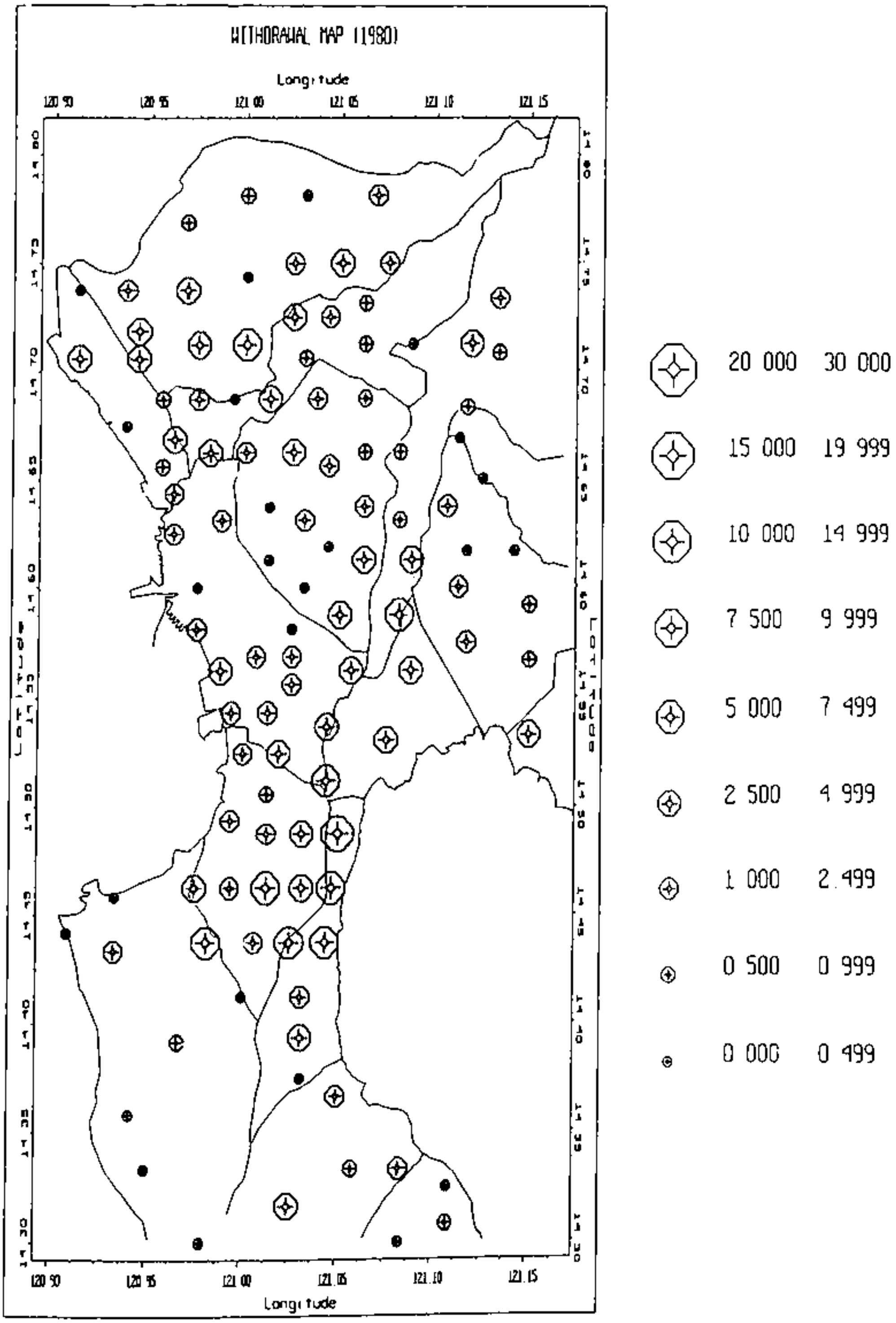


Fig. 9 1980 groundwater withdrawal by well cells (in MCM/year) for Metro Manila

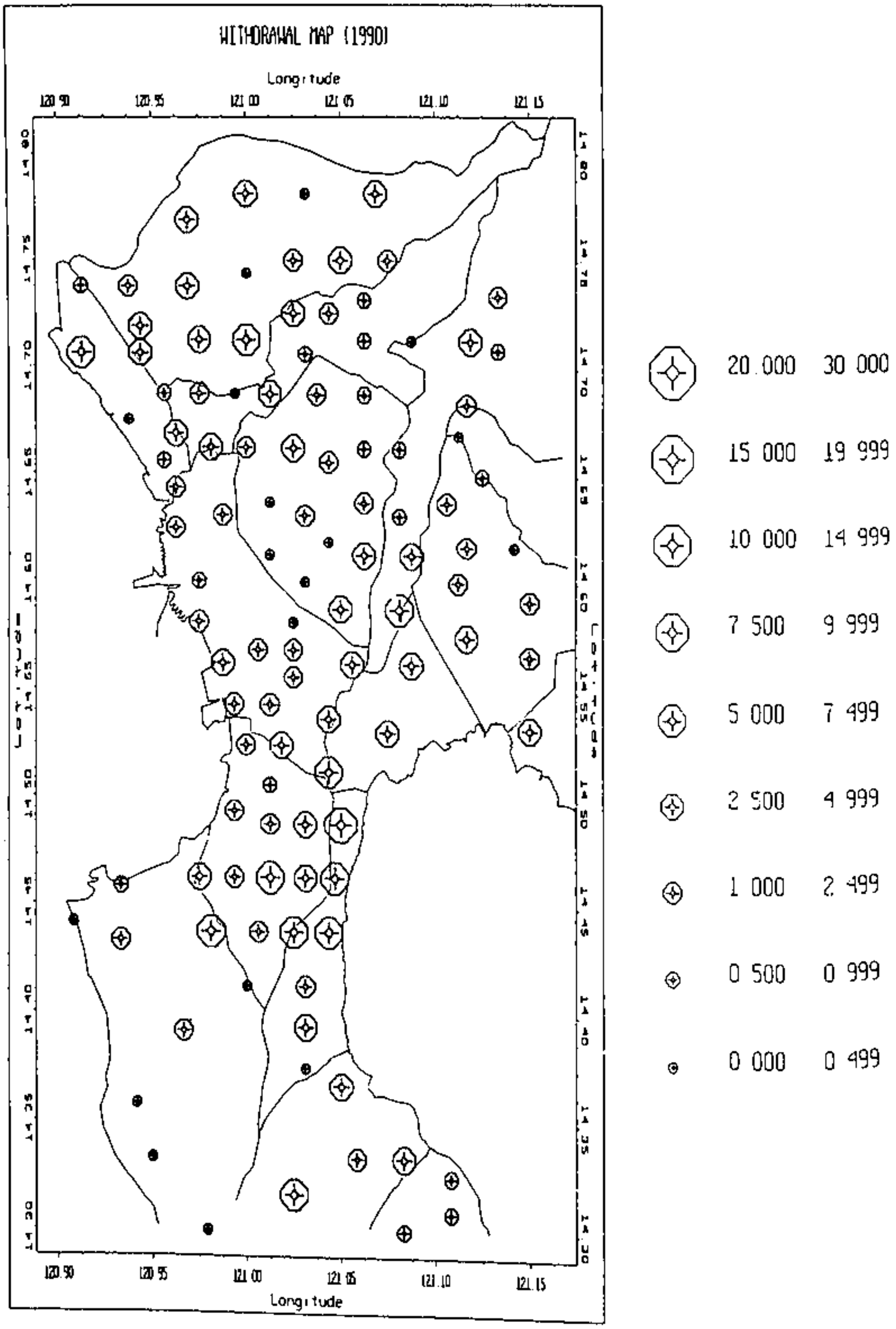
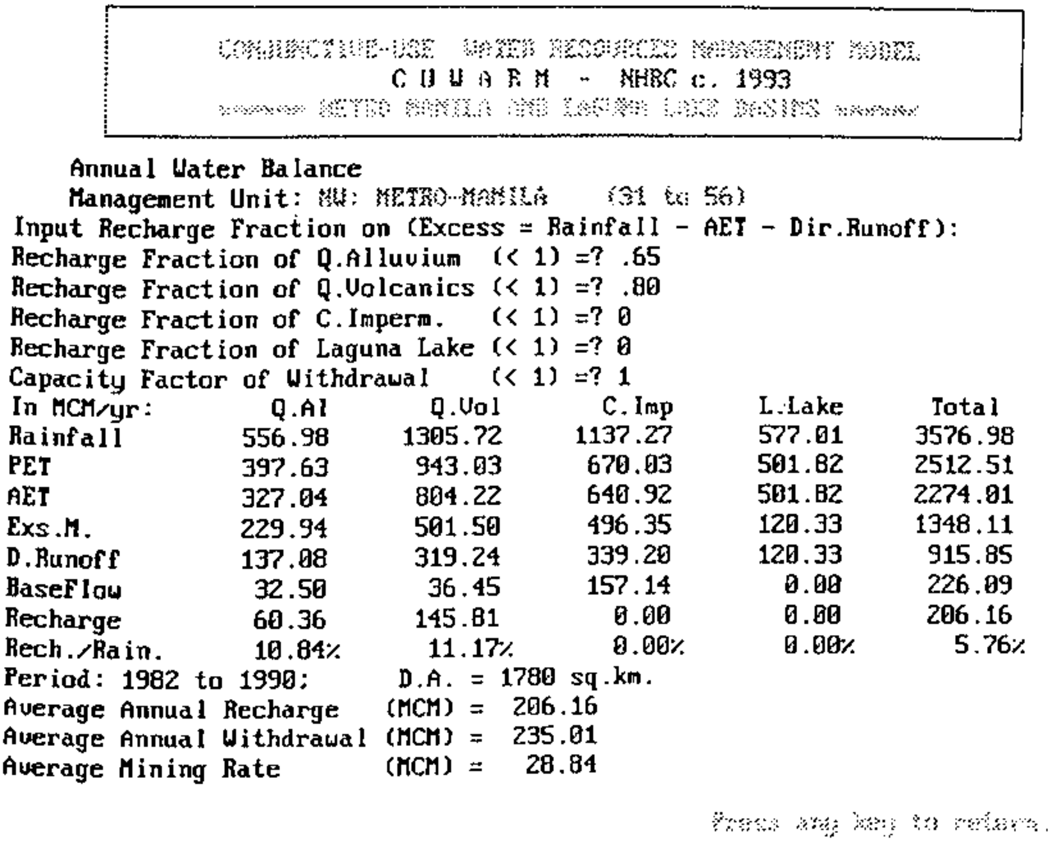


Fig. 10 1990 groundwater withdrawal by well cells (in MCM/year) for Metro Manila



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        CONJUNCTIVE-USE  WATER RESOURCES MANAGEMENT MODEL
                 C U W A R M  -  NHRC c. 1993
        ~~~~~~ METRO MANILA AND LAGUNA LAKE BASINS ~~~~~~

   Annual Water Balance
   Management Unit: MW: METRO-MANILA    (31 to 56)
 Input Recharge Fraction on (Excess = Rainfall - AET - Dir.Runoff):
 Recharge Fraction of Q.Alluvium  (< 1) =? .65
 Recharge Fraction of Q.Volcanics (< 1) =? .80
 Recharge Fraction of C.Imperm.   (< 1) =? 0
 Recharge Fraction of Laguna Lake (< 1) =? 0
 Capacity Factor of Withdrawal    (< 1) =? 1
 In MCM/yr:          Q.Al      Q.Vol       C.Imp       L.Lake      Total
 Rainfall          556.98    1305.72     1137.27      577.01    3576.98
 PET               397.63     943.03      670.03      501.82    2512.51
 AET               327.04     804.22      640.92      501.82    2274.01
 Exs.M.            229.94     501.50      496.35      120.33    1348.11
 D.Runoff          137.08     319.24      339.20      120.33     915.85
 BaseFlow           32.50      36.45      157.14        0.00     226.09
 Recharge           60.36     145.81        0.00        0.00     206.16
 Rech./Rain.        10.84%     11.17%       0.00%       0.00%      5.76%
 Period: 1982 to 1990;      D.A. = 1780 sq.km.
 Average Annual Recharge   (MCM) =  206.16
 Average Annual Withdrawal (MCM) =  235.01
 Average Mining Rate       (MCM) =   28.84

                                                  Press any key to return.
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Fig. 11 Annual water balance for Metro Manila (1982-1990)

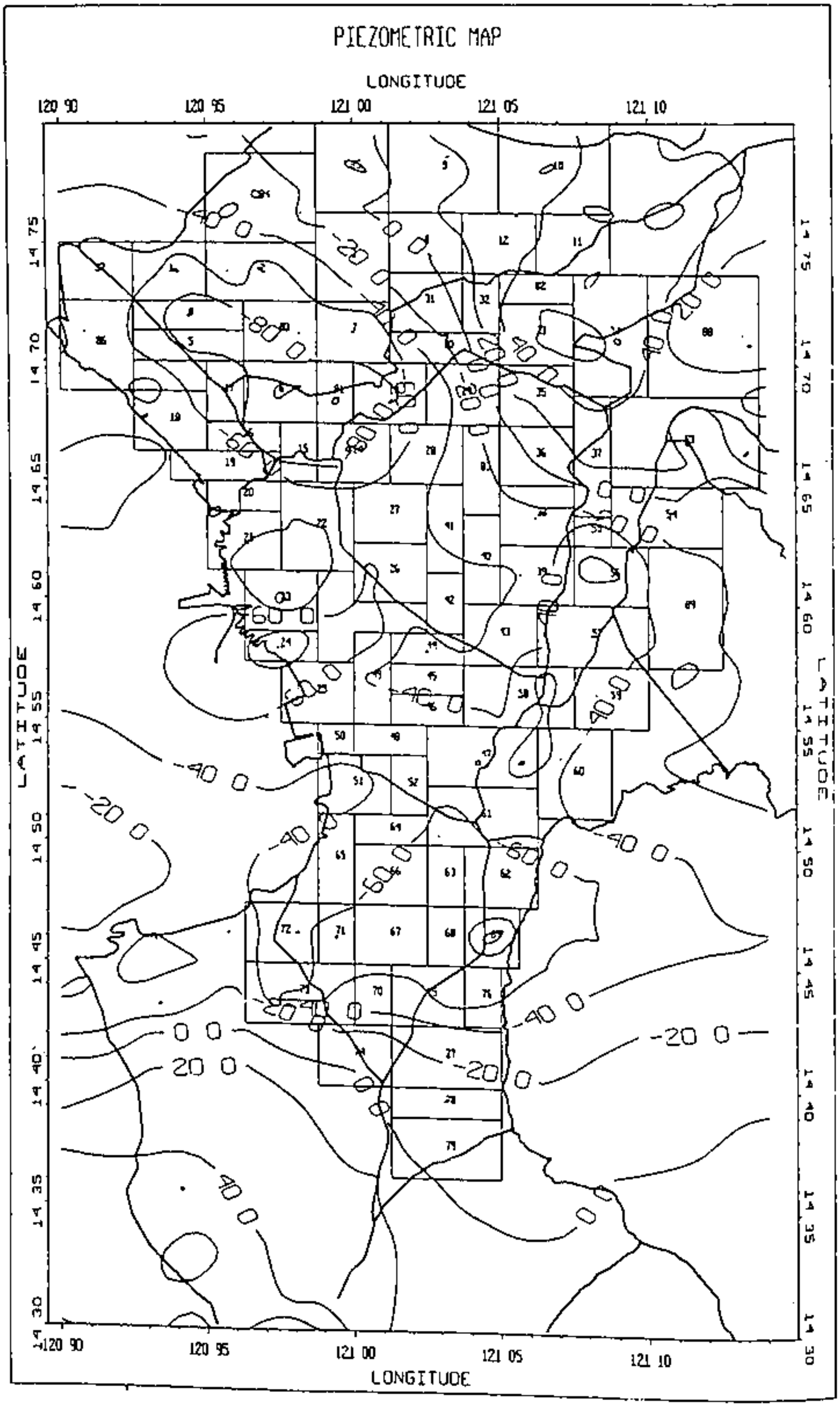

Fig. 12 Computed 1990 piezometric contour map for Metro Manila

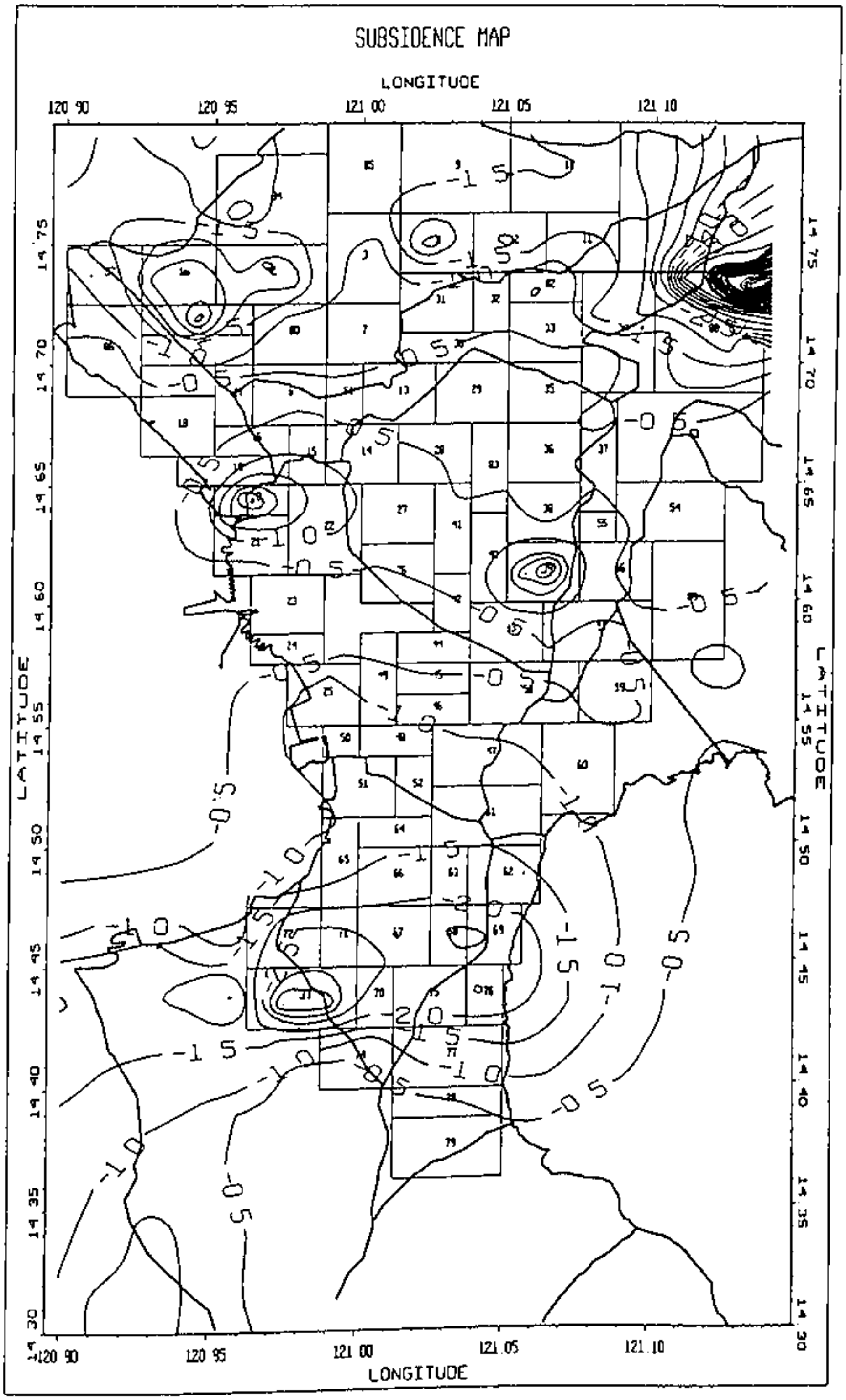

Fig. 13 Computed 1990 subsidence contour map for Metro Manila

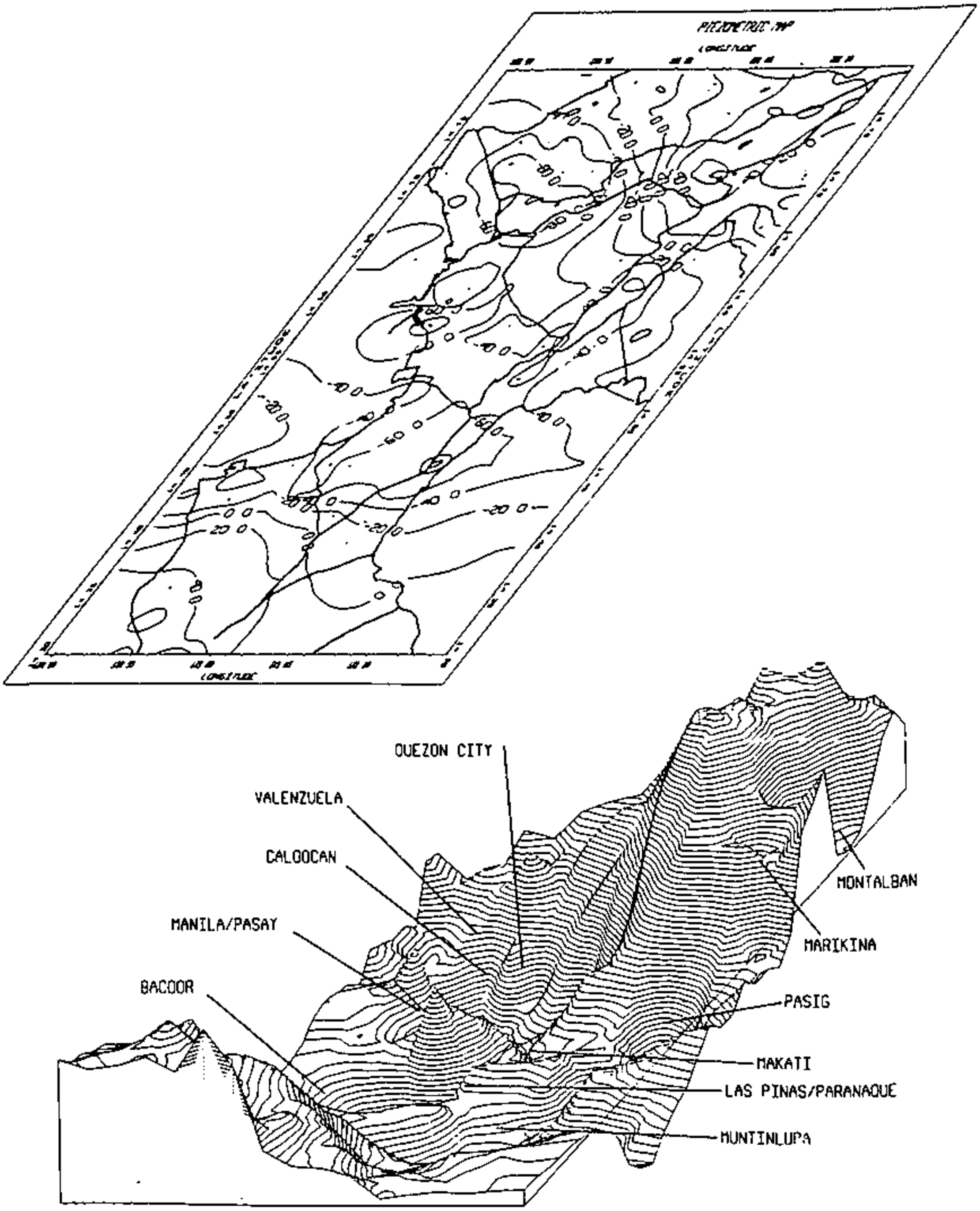

Fig. 14 Three-dimensional view of the computed 1990 piezometric surface for Metro Manila

Despite the fact that there is a large surplus of excess surface water, hydrogeological limitations, such as low aquitard and aquifer permeabilities and very few effective natural recharge areas, pose limits to the net amount of excess water finding entry into the deep aquifer. There is also indirect evidence that portions of infiltrated water may reappear as baseflow in rivers, that is, they flow in transit through shallow alluvial aquifers, return as natural baseflow of rivers being fed by the shallow aquifers, and thus not contribute to net recharge. The bulk of the suplus water is in the form of direct runoff, mainly present as flood flows during the wet season, and a major part of it diverted to the Laguna Lake itself and eventually evaporated or drained to Manila Bay.

MODEL APPLICATIONS TO CALABAR AREA

The extent of calibration done for the Metro Manila area has not been carried out for the Laguna, Cavite, Batangas and eastern Rizal portions of the aquifers. This is due to the absence of 1990 observed piezometric levels in those provinces needed for calibration. In any case, reliable qualitative results regarding drawdown, recharge, and groundwater flux can be simulated using best estimates of model parameters. The hydrogeologic behavior of the entire aquifer beneath Laguna Lake may also be investigated using the model once more calibration data become avilable.

Preliminary runs were made to provide the annual water-balance results for the Southwest (Cavite, Laguna, and Batangas), Southeast (Laguna), and Northeast (Rizal) subregions of the study area, respectively. The recharge fractions utilized are tentative values, based on estimates of hydrological properties not yet subjected to detailed calibration. The results show the large amounts of excess water in the form of direct runoff and baseflow, compared to the relatively low levels of natural groundwater recharge. Although there are still surpluses of recharge over the current wihdrawal rates, these are very small surpluses, easily offset to become mining rates by future increases in withdrawal rates.

The Southwest (Cavite, Laguna, and Batangas) subregion, being more urbanized and industrialized, has a large annual withdrawal rate of. 27.29 MCM/year, compared to the less urbanized Southeast (Laguna) subbregion, the latter with 2.61 MCM/year of annual withdrawal. Their estimated natural recharge rates of 31.80 MCM/year and 23.94 MCM/year, respectively, are similar in magnitudes, yet the wide difference in their surplus rates points to contrasting near-future scenarios. The industrializing Southwest subregion will experience mining rates much sooner, joining the mined corridor already found in Metro Manila. In contrast, the Southeast subregion has more surplus to absorb higher future withdrawal, and shall then have longer time and better opportunity to undertake more rational planning and implementation of water-supply projects.

It may also be mentioned that the limestone aquifers of the Northeast (Rizal) subregion, compared with the alluvial and volcanic aquifers, are quick-response systems identifiable with baseflow behavior, as confirmed by observed dry-season creek flows and waterfalls coming from karst springs. One may therefore say that Eastern Rizal has a unique and promising type of water-supply potential coming from baseflows (60.26 MCM/year), better than the net recharge to its aquifers (8.26 MCM/year). What is significant here is the ratio of baseflow to recharge (more than 7:1), rather than absolute amounts.

CONCLUSIONS AND RECOMMENDATIONS

Based on the modeling and calibration results, the following conclusions and recomendations can be made:

a. The Manila Model or CUWARM, an adaptation of the IDRC coupled groundwater hydraulic-subsidence model, and augmented with a surface-water component, is capable of serving as a planning and management tool for the conjunctive use of both surface water and groundwater resources in the Metro Manila and Laguna Lake Basins.

b. Calibration has been done only for the Metro Manila area, with a clear conclusion of a net groundwater mining rate. Nevertheless, no impediment to using the model for the rest of the study area, such as the less-populated municipalities of the provinces of Rizal, Laguna, and Cavite, is foreseen except the scarcity of basic calibration data. This problem of data, with time, can be solved by a regular and concerted data collection effort by water utilities, natural resource agencies, and local governments.

c. CUWARM accepts as inputs a whole of array of physical parameters and variables for the modeling of both surface water and groundwater flows in the study area. As such, the dependence and sensitivity of the output hydrologic components (especially runoff, recharge, piezometric levels) to inputs of rainfall, evapotranspiration, withdrawal rates, soil type, land-use/cover, basin topography, surface geology, hydrogeology, and presence of lake/sea body, can be appropriately modeled and calibrated.

d. The fact that CUWARM utilizes in explicit manner the input parameters already enumerated, leads to the realization of the importance to be attached to collection, compilation, and validation of natural resource data on water, soil, land, and aquifers. These data, which are normally collected for varied purposes by different agencies, attain sharper definition and requirements of data quality when used for modeling purposes. The importance of basic data to planning and management is made clear and explicit by modeling exercises.

e. With regard to the development and management issue of providing for the future water supply of Metro Manila, a policy recommendation may be stated as follows:

In view, on one hand, of the prevailing groundwater mining rate of the aquifers in the area and, on the other hand, of the large volume of excess water in the form of direct runoff and lake storage, concerned agencies may not discount utilizing the excess surface water within the basin to supply future domestic, municipal, and industrial requirements. Transbasin transfer of surface water (from Angat Reservoir) for water supply has been the major source, and other similar transfers have been considered for future implementation. Transbasin transfer, as a solution, has to be compared with diversion from within the basin itself. The possible, and even complementary, engineering alternatives for the use of the surface water inside the basin are:

- Diversion, treatment, and distribution of Laguna Lake stored water. Treatment technology and storage and conveyance works between suitable diversion sites (such as along the Central or Mid bay of the lake) and population centers are major engineering components of this approach. Policy and institutional issues over priorities among multiple and conflicting uses of the lake water have to be categorized and resolved.

- A truly conjunctive approach, such as artificial recharge of the Guadalupe Formation using the upper Marikina River runoff near Montalban, Rizal, or diverted Laguna Lake water from the Mid Bay itself. This approach will ideally attempt to increase recharge rates beyond the low natural levels, in such a way that current pumping rates may at least be maintained without mining the groundwater.

  The aquifer will be made a water-supply storage and transmission facility, subject to the limitations of hydrology, hydraulics, geology, and hydrogeology. This plan requires a detailed scientific and engineering study of the aquifer sytems in order to ascertain its technical and economic feasibility. Intermediate surface-water storage and conveyance facilities will be needed between points of diversion and recharge. In addition, close management has to be instituted against excessive pumping rates without permits and potential sources of groundwater contamination. A program of allowable withdrawal levels by existing wells consistent with the engineered recharge rates and drawdown limitations must be implemented.

- Utilizing the aquifer as groundwater-supply storage may be preferable over a surface-water storage reservoir across Marikina River with its attendant risk of a dam-break which can suddenly inundate Manila and other low towns. On the other hand, a high dam and a reservoir can serve multi-purposes of flood control and hydropower generation, among other uses.

A second management issue concerns the future water supply of the less-populated municipalities of the Laguna Lake Basin, and the expected rise of water demand due to projected population growth and industrial development of some towns of CALABARZON.

It can be stated that, while at present, there is still a surplus of recharge owing to the low withdrawal rates, this can easily be offset my rapid growth and aggravated by lack of proper water management. Inland surface water in these areas are partly used for run-of-river irrigation, and future use of surface water for water supply will have to compete with irrigation requirements. On a regional scale, there is a foreseeable long-term competition between the CALABARZON towns and Metro Manila over the Laguna Lake water. After all, Laguna and Cavite local governments may assert custody and right over Laguna Lake waters, to which Metro Manila can lay historical if not political claim.

Another conflict which has arisen in the rural towns is the drying up of domestic shallow wells due to excessive drawdown caused by deep-well withdrawals. The overall solution will have to rely on a scientifically planned and closely-managed conjunctive-use program for water-supply and irrigation, respecting both old and new water rights. It may consist of surface water diversion from rivers and lakes, natural recharge from farms, limited shallow-well pumping for rural use, and allowable deep-well pumping for population centers and industrial estates.

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