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for

Atlantico 3 Project
Columbia, South America

HYBRID COMPUTER SIMULATION OF THE GROUND WATER FLOW FIELD

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Submitted by

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February 1970

Progress Report No. 1
February 13, 1970

ATLANTICO PROJECT 3

Hybrid Computer Simulation of Ground Water Flow Field

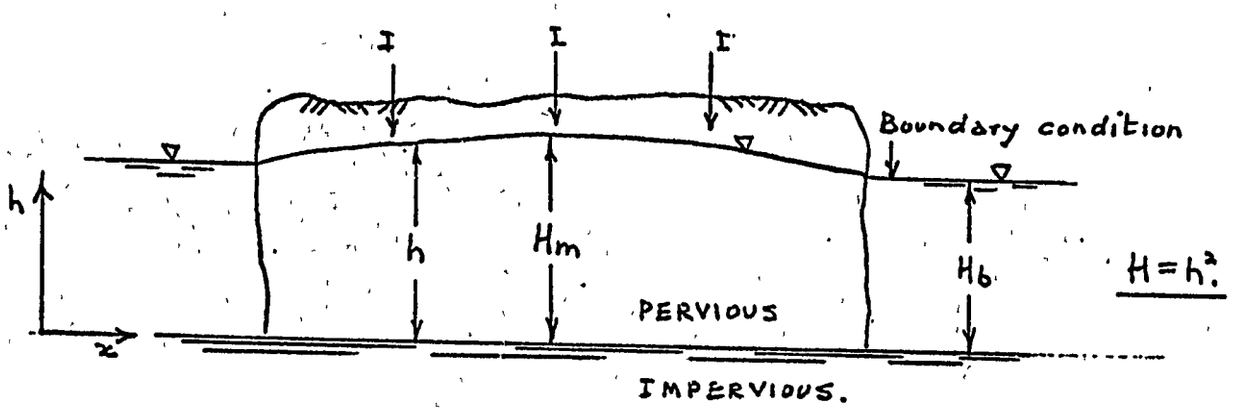
1. Assumptions

   1. Isotropic unconfined aquifer.
   2. Homogeneous porous media.
   3. Flow lines horizontal.
   4. Uniform velocity over depth of flow proportional to the slope of the ground water surface (Darcy's Law).
   5. Compressibility effects neglected.
   6. Present ground water levels assumed steady state.

2. Equations

(A).

$$\frac{\partial^2(H)}{\partial x^2} + \frac{\partial^2(H)}{\partial y^2} \pm \frac{2I}{k} = S/T\,\frac{\partial(H)}{\partial t}$$



h = height of water table above impermeable strata.

x & y = coordinates in plan.

± I = net input or output to groundwater system.

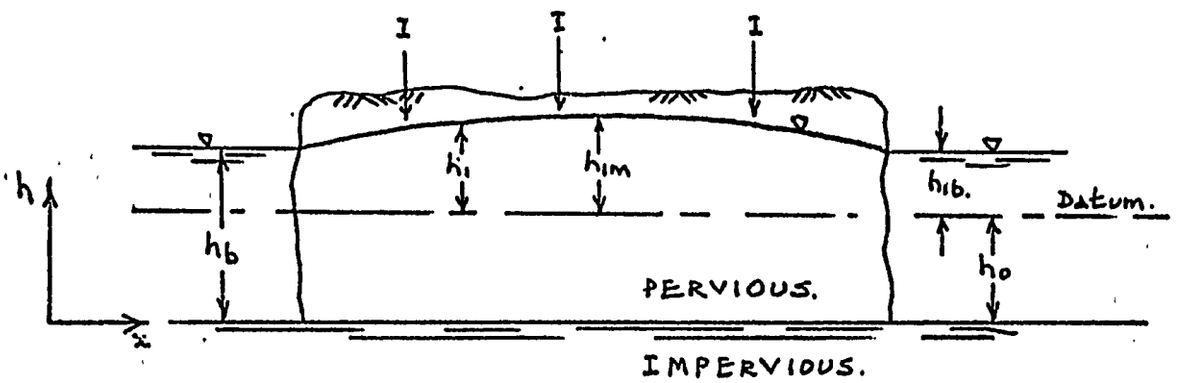
k = permeability (or hydraulic conductivity).

S = storage coefficient

T = transmissivity = k h.

(B). $$\frac{\partial^2 (h_1)}{\partial x^2} + \frac{\partial^2 (h_1)}{\partial y^2} \pm \frac{I}{T} = S/T \frac{\partial h_1}{\partial t}$$

Note:- $\left(\frac{\partial h}{\partial x}\right)^2$ and $\left(\frac{\partial h}{\partial y}\right)^2$ are neglected in above equation



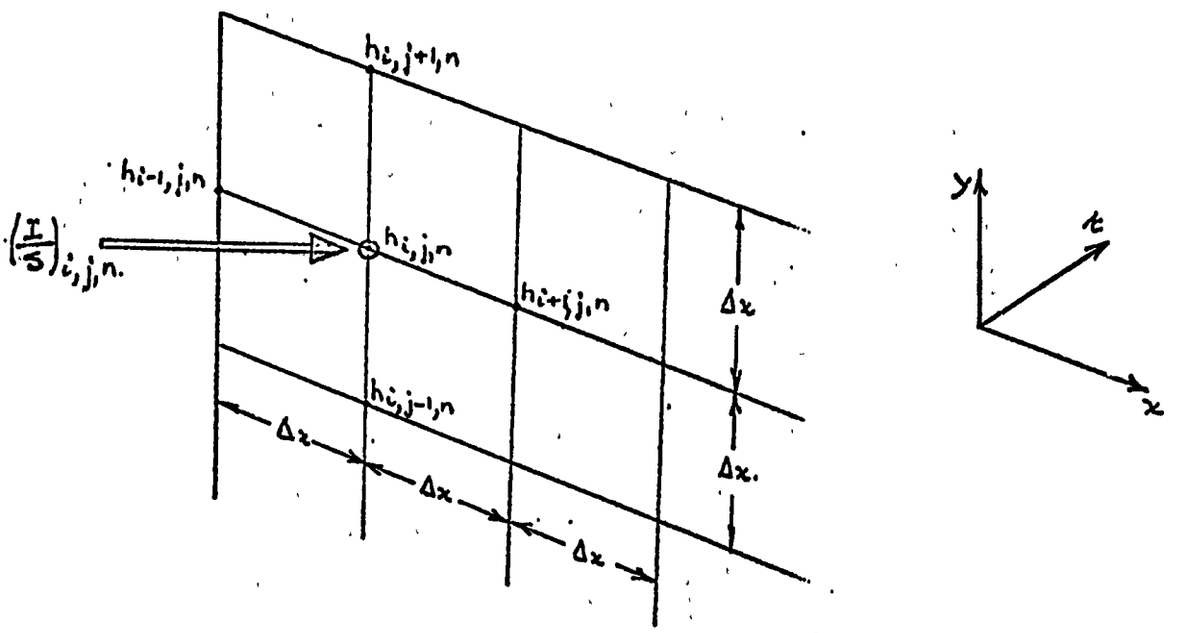
Equation (A) is an exact equation in that no terms are neglected in its derivation. It has the disadvantage however in that there is a loss of accuracy, particularly for deep aquifers, due to analog scaling problems. This difficulty is overcome in Equation (B) by measuring the water table fluctuations from a datum at a fixed height above the impermeable layer. In this way the full dynamic range of the analog computer can be utilized.

3. Hybrid Computer Solution of Equation (B)

By using central finite differences Equation (B) can be expressed in the form:

$$\frac{dh_1}{dt} = \frac{T}{S}\left\{\left[\frac{h_{i-1,j,n} + h_{i+1,j,n} + h_{i,j-1,n} + h_{i,j+1,n} - 4h_{i,j,n}}{(\Delta x)^2}\right] \pm \frac{I}{T}\right\}$$

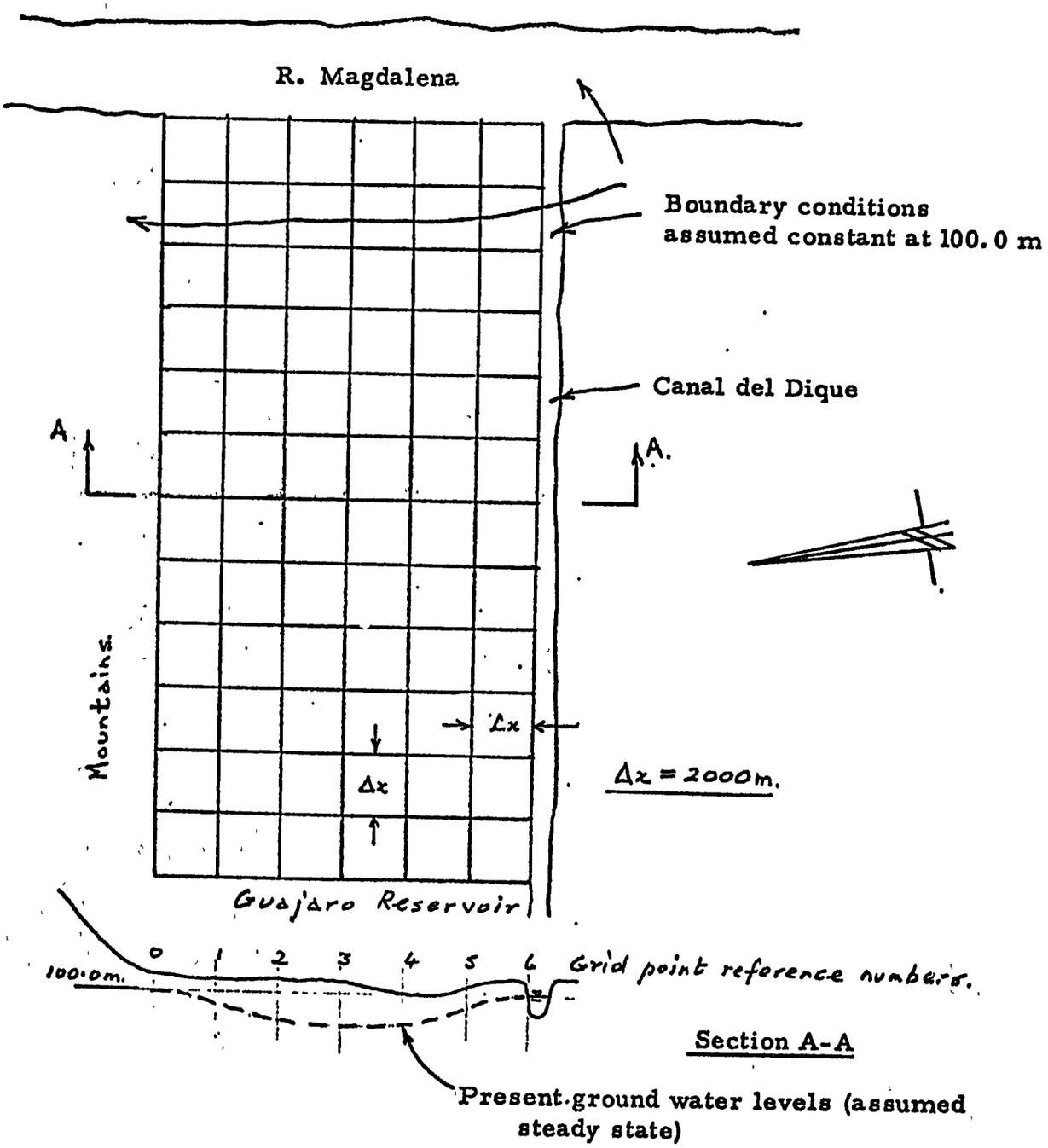
where $h_{i-1,j,n}$ etc. are as shown below



The ground water flow field is represented in plan by a grid network and a solution (h vs. t) is obtained at each grid point with an analog cell sharing technique. The error between successive h vs. t curves at each point is measured and a solution is obtained when this error (Σe^2) becomes less than a given tolerance.

4. Scope of Present Studies

As a first approximation the project area has been represented by a rectangular grid as shown:



Studies have been carried out to investigate the effect on the ground water levels of net constant monthly inputs (deep percolation) or outputs (evapotranspiration) at each grid point. The results for a period of 1 year are shown graphically in Fig. 1 for Section A-A.

These show clearly a linear relationship between I and h (see Fig. 2). The steady state condition was not obtained in all cases and the time to reach steady state will be the subject of further investigation. It is interesting to note that the approximate Equation 2 gives values which closely agree with Equation 1 except where there is a rapid change in the water table levels and the terms $\left(\frac{dh}{dx}\right)^2$ and $\left(\frac{dh}{dy}\right)^2$ become appreciable.

A hybrid program has also been prepared to compute the monthly net input or output at each grid point of the groundwater system. These input/outputs have been computed from the following basic data: precipitation, pan evaporation, assumed irrigation and crop density.

5. Further Work

In the near future the storage capacity of the digital computer will be expanded from 8K to 16K. This will make possible the following refinements to the present model.

a. A larger number of grid points with variable inputs at each node to represent more closely the areal variations in vegetation, etc. In addition a triangular grid layout may be used to give an improved areal representation.

b. Variable boundary conditions.

c. Modeling of groundwater movement within the unsaturated zone.

d. Sensitivity tests will be carried out to investigate the influence of certain parameters and various management alternatives will be studied as detailed on Pages 3 and 4 of the attached statement.

6. Additional Data Requirements

On the basis of simulation tests already conducted, the following additional data would be desirable in order to improve the existing model.

1. Monthly precipitation and pan evaporation for the existing climatological stations. A sufficient number of climatological stations are needed to accurately monitor the precipitation and evaporation within the area.
2. Areal distribution of various crops and vegetation, also root distribution pattern in soil.)
3. Monthly irrigation applications.
4. Values for permeability and storage coefficient from pumping tests on wells.
5. Aquifer thickness.
6. Mean monthly water levels for R. Magdalena and Canal del Dique.

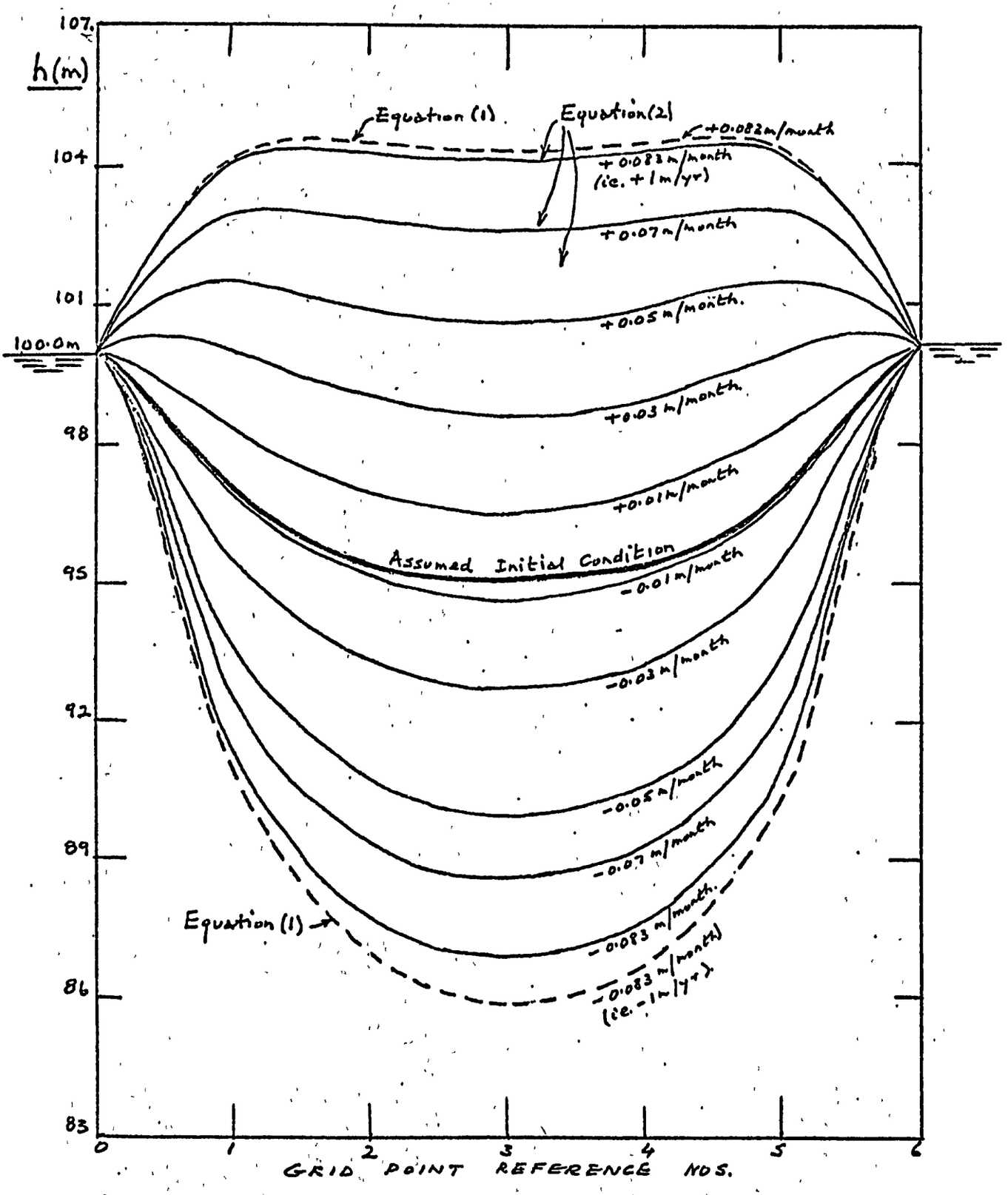


FIG. 1. GROUND WATER LEVELS AT SECTION A-A. FOR VARIOUS VALUES OF I.

ASSUMPTIONS :- $k = 300$ m/month, $S = 0.1$, $h_b = 100$m.

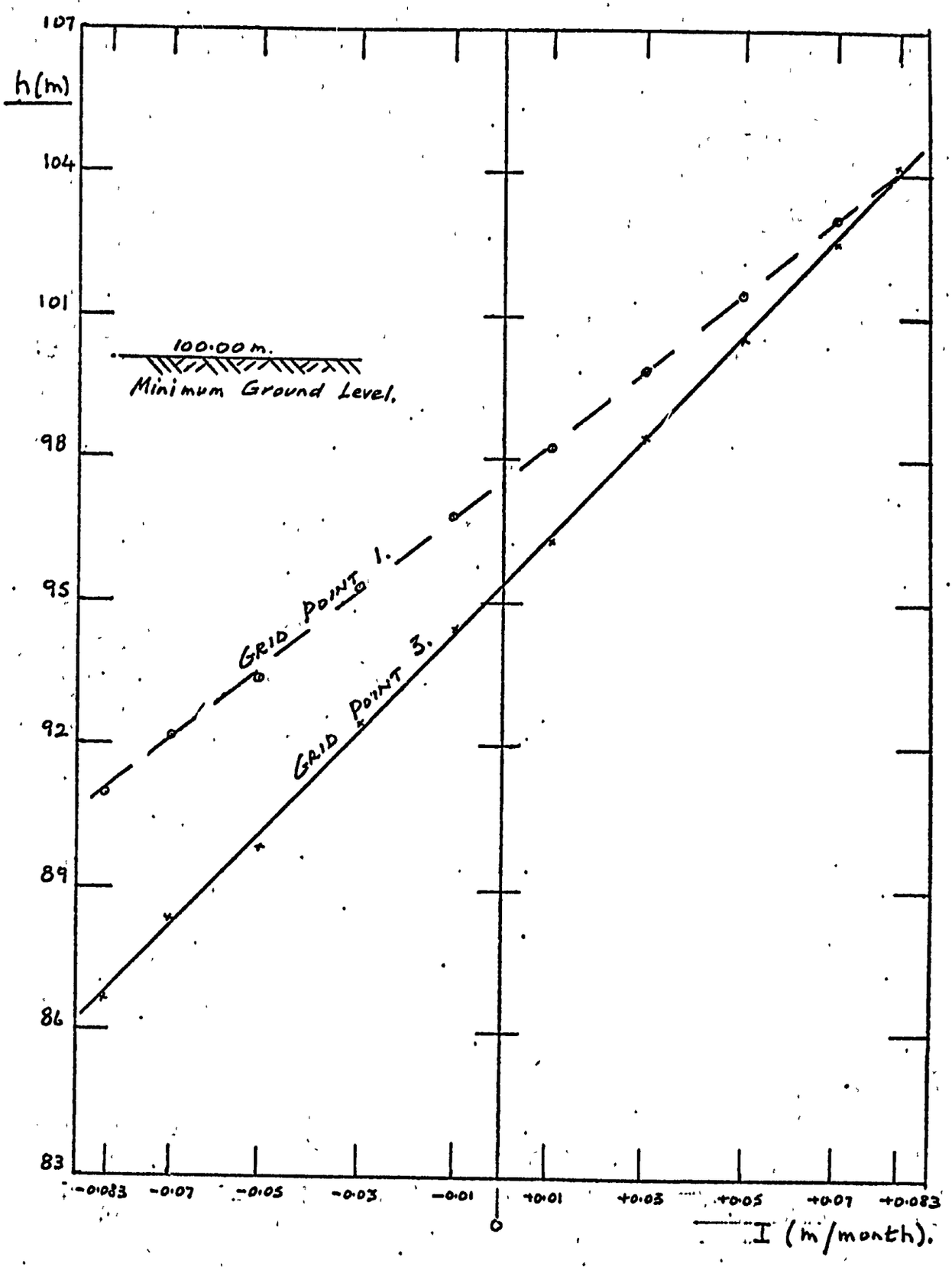


FIG. 2. h. vs. I AT SECTION A-A.

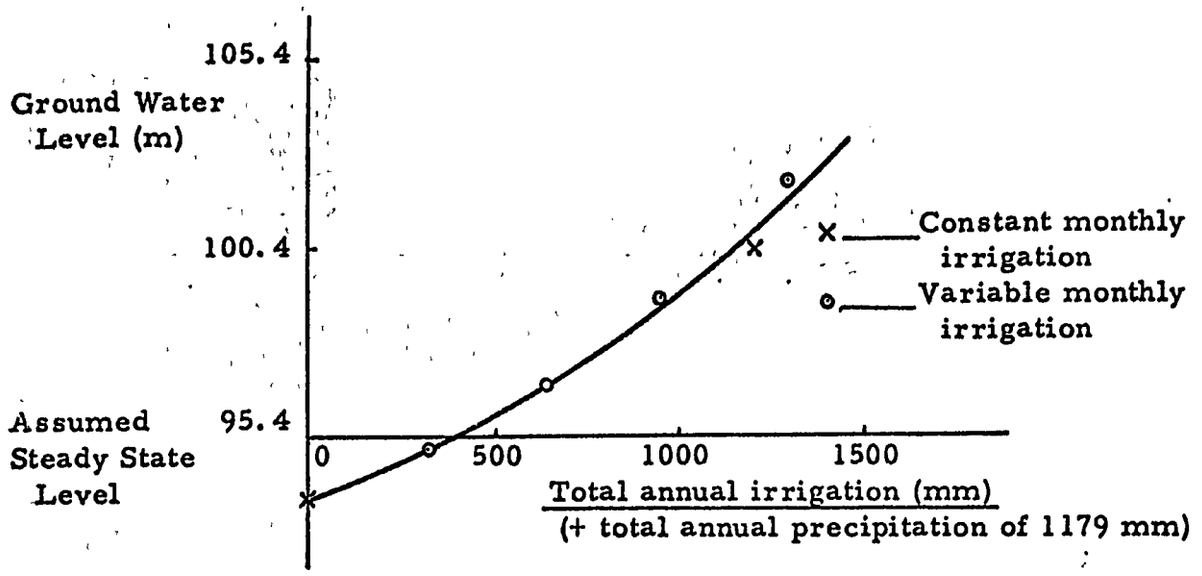


Fig. 3 Variation in Ground Water Levels at Grid Point 3 (Section A-A) from assumed steady state condition of 95.4 m due to various total annual irrigation applications.

Assumptions

1. Native vegetation - 50% of total area.
2. Cultivated crops (combination of cotton and dry beans) 50% of total area.
3. Rooting depth 1.2 m.
4. Evapotranspiration calculated from $ET = K_c EVP \frac{M_s}{M_{es}}$

   Where: K_c = crop coefficient

   EVP = pan evaporation

   M_s = soil moisture content above wilting point

   M_{es} = available soil moisture capacity

5. Native vegetation extract water both from ground water $(0.7\, EVP \frac{M_s}{M_{es}})$ and root zone $((K_c - 0.7)\, EVP \frac{M_s}{M_{es}})$

Sign Convention

For Ground Water System
+ ve = Input to ground water (e.g. infiltration)
- ve = Output from ground water (e.g. evapotranspiration)

Note: These signs are reversed for the tabulated computer output.

The Following is a Typical Hybrid Computer Output

for the Model of the Unsaturated Zone

PT. 1 FMES=240. FIC=120. DDP= .50

THE YEAR OF 1964

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP	FDP (m/month)	Δh(m) (from Fig. 2)
1	7.	187.	.70	.80	0.	100.	65.	116.	65.		
2	3.	194.	.50	.85	0.	97.	67.	113.	67.		
3	0.	239.	.25	.90	0.	109.	83.	111.	83.		
4	85.	206.	.25	.95	0.	101.	72.	141.	72.		
5	59.	187.	.40	1.00	0.	103.	65.	141.	65.		
6	258.	164.	.90	.95	0.	150.	57.	240.	-76.		
7	246.	163.	.60	.90	0.	121.	57.	240.	-92.		
8	88.	162.	.25	.85	0.	89.	56.	240.	29.		
9	138.	131.	.40	.80	0.	79.	45.	240.	-29.		
10	223.	141.	.65	.75	0.	98.	49.	240.	-92.		
11	60.	127.	.90	.70	0.	101.	44.	240.	44.		
12	12.	154.	.90	.75	0.	118.	53.	211.	53.		
					0.				+189.	-.016	-1.7 m

THE YEAR OF 1965

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP
1	7.	187.	.70	.80	50.	131.	65.	211.	65.
2	3.	194.	.50	.85	50.	122.	67.	211.	67.
3	0.	239.	.25	.90	0.	126.	83.	194.	83.
4	85.	206.	.25	.95	0.	115.	72.	210.	72.
5	59.	187.	.40	1.00	0.	122.	65.	210.	65.
6	258.	164.	.90	.95	25.	150.	57.	240.	-101.
7	246.	163.	.60	.90	25.	121.	57.	240.	-117.
8	88.	162.	.25	.85	25.	89.	56.	240.	5.
9	138.	131.	.40	.80	25.	79.	45.	240.	-53.
10	223.	141.	.65	.75	25.	98.	49.	240.	-117.
11	60.	127.	.90	.70	50.	101.	44.	240.	19.
12	12.	154.	.90	.75	50.	126.	53.	240.	53.
					325.				+41.

-.003 -0.4 m

THE YEAR OF 1966

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP
1	7.	187.	.70	.80	100.	139.	65.	240.	58.
2	3.	194.	.50	.85	100.	130.	67.	240.	54.
3	0.	239.	.25	.90	0.	131.	83.	217.	83.
4	85.	206.	.25	.95	0.	120.	72.	228.	72.
5	59.	187.	.40	1.00	0.	127.	65.	228.	65.
6	258.	164.	.90	.95	50.	150.	57.	240.	-125.
7	246.	163.	.60	.90	50.	121.	57.	240.	-142.
8	88.	162.	.25	.85	50.	89.	56.	240.	-18.
9	138.	131.	.40	.80	50.	79.	45.	240.	-77.
10	223.	141.	.65	.75	50.	98.	49.	240.	-142.
11	60.	127.	.90	.70	100.	101.	44.	240.	-28.
12	12.	154.	.90	.75	100.	126.	53.	240.	41.
					650.				-159.

+.013 + 1.3 m

THE YEAR OF 1967

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP	FDP (m/month)	Δh(m) (from Fig. 2)
1	7.	187.	.70	.80	150.	139.	65.	240.	11.		
2	3.	194.	.50	.85	150.	130.	67.	240.	7.		
3	0.	239.	.25	.90	0.	131.	83.	217.	83.		
4	85.	206.	.25	.95	0.	120.	72.	228.	72.		
5	59.	187.	.40	1.00	0.	127.	65.	228.	65.		
6	258.	164.	.90	.95	75.	150.	57.	240.	-150.		
7	246.	163.	.60	.90	75.	121.	57.	240.	-167.		
8	88.	162.	.25	.85	75.	89.	56.	240.	-43.		
9	138.	131.	.40	.80	75.	79.	45.	240.	-102.		
10	223.	141.	.65	.75	75.	98.	49.	240.	-167.		
11	60.	127.	.90	.70	150.	101.	44.	240.	-77.		
12	12.	154.	.90	.75	150.	126.	53.	240.	-6.		
					975.				-474.	+ .039	+ 4.0 m

THE YEAR OF 1968

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP		
1	7.	187.	.70	.80	200.	139.	65.	240.	-36.		
2	3.	194.	.50	.85	200.	130.	67.	240.	-41.		
3	0.	239.	.25	.90	0.	131.	83.	217.	83.		
4	85.	206.	.25	.95	0.	120.	72.	228.	72.		
5	59.	187.	.40	1.00	0.	127.	65.	228.	65.		
6	258.	164.	.90	.95	100.	150.	57.	240.	-175.		
7	246.	163.	.60	.90	100.	121.	57.	240.	-191.		
8	88.	162.	.25	.85	100.	89.	56.	240.	-67.		
9	138.	131.	.40	.80	100.	79.	45.	240.	-127.		
10	223.	141.	.65	.75	100.	98.	49.	240.	-191.		
11	60.	127.	.90	.70	200.	101.	44.	240.	-127.		
12	12.	154.	.90	.75	200.	126.	53.	240.	-54.		
STOP 00000					1300.				-789.	+ 0.66	+ 6.9 m

Δh = Change in ground water level at Grid Pt. 3 (Section A-A) from Initial Condition.
FMES = Available soil moisture storage capacity.
FIC = Initial soil moisture content.
DDP = Density of native vegetation.
PPT = Monthly precipitation.
EVP = Monthly pan evaporation.
CSH = Coefficients for cultivated crops.
CDP = Coefficients for native vegetation.
QIR = Monthly irrigation.
AET = Total evapotranspiration.
DPT = Transpiration by native vegetation.
FMS = Soil moisture content.
FDP = Deep percolation (-) to or transpiration from ground water (+)

Wilting point as datum, field capacity = 240 mm above wilting pt.

PT. 1 FMES=240. FIC=120. DDP= .50

THE YEAR OF 1965

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP	FDP (m/month)	Δh(m) (from Fig. 2)
1	7.	187.	.70	.80	0.	100.	65.	116.	65.		
2	3.	194.	.50	.85	0.	97.	67.	113.	67.		
3	0.	239.	.25	.90	0.	109.	83.	111.	83.		
4	85.	206.	.25	.95	0.	101.	72.	141.	72.		
5	59.	187.	.40	1.00	0.	103.	65.	141.	65.		
6	258.	164.	.90	.95	0.	150.	57.	240.	-76.		
7	246.	163.	.60	.90	0.	121.	57.	240.	-92.		
8	88.	162.	.25	.85	0.	89.	56.	240.	29.		
9	138.	131.	.40	.80	0.	79.	45.	240.	-29.		
10	223.	141.	.65	.75	0.	98.	49.	240.	-93.		
11	60.	127.	.90	.70	0.	101.	44.	240.	44.		
12	12.	154.	.90	.75	0.	118.	53.	211.	53.		
					0.				+188.	-.016	-1.7 m

THE YEAR OF 1966

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP		
1	7.	187.	.70	.80	100.	135.	65.	224.	65.		
2	3.	194.	.50	.85	100.	130.	67.	239.	67.		
3	0.	239.	.25	.90	100.	137.	83.	240.	64.		
4	85.	206.	.25	.95	100.	123.	72.	240.	-31.		
5	59.	187.	.40	1.00	100.	130.	65.	240.	1.		
6	258.	164.	.90	.95	100.	150.	57.	240.	-175.		
7	246.	163.	.60	.90	100.	121.	57.	240.	-191.		
8	88.	162.	.25	.85	100.	89.	56.	240.	-67.		
9	138.	131.	.40	.80	100.	79.	45.	240.	-127.		
10	223.	141.	.65	.75	100.	98.	49.	240.	-192.		
11	60.	127.	.90	.70	100.	101.	44.	240.	-28.		
12	12.	154.	.90	.75	100.	126.	53.	240.	41.		
					1200.				-573.	+ .048	5.0 m

THE YEAR OF 1967

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP		
1	7.	187.	.70	.80	150.	139.	65.	240.	11.		
2	3.	194.	.50	.85	150.	130.	67.	240.	7.		
3	0.	239.	.25	.90	150.	137.	83.	240.	17.		
4	85.	206.	.25	.95	150.	123.	72.	240.	-80.		
5	59.	187.	.40	1.00	150.	130.	65.	240.	-47.		
6	258.	164.	.90	.95	150.	150.	57.	240.	-224.		
7	246.	163.	.60	.90	150.	121.	57.	240.	-241.		
8	88.	162.	.25	.85	150.	89.	56.	240.	-116.		
9	138.	131.	.40	.80	150.	79.	45.	240.	-176.		
10	223.	141.	.65	.75	150.	98.	49.	240.	-241.		
11	60.	127.	.90	.70	150.	101.	44.	240.	-77.		
12	12.	154.	.90	.75	150.	126.	53.	240.	-6.		
					1800.				-1173.	+ .098	10.0 m

THE YEAR OF 1968

MTH	PPT	EVP	CSH	CDP	QIR	AET	DPT	FMS	FDP		
1	7.	187.	.70	.80	200.	139.	65.	240.	-37.		
2	3.	194.	.50	.85	200.	130.	67.	240.	-41.		
3	0.	239.	.25	.90	200.	137.	83.	240.	-32.		
4	85.	206.	.25	.95	200.	123.	72.	240.	-129.		
5	59.	187.	.40	1.00	200.	130.	65.	240.	-97.		
6	258.	164.	.90	.95	200.	150.	57.	240.	-249.		
7	246.	163.	.60	.90	200.	121.	57.	240.	-249.		
8	88.	162.	.25	.85	200.	89.	56.	240.	-166.		
9	138.	131.	.40	.80	200.	79.	45.	240.	-226.		
10	223.	141.	.65	.75	200.	98.	49.	240.	-249.		
11	60.	127.	.90	.70	200.	101.	44.	240.	-127.		
12	12.	154.	.90	.75	200.	126.	53.	240.	-55.		
					2400.				-1657.	+ .138	

STOP 00000

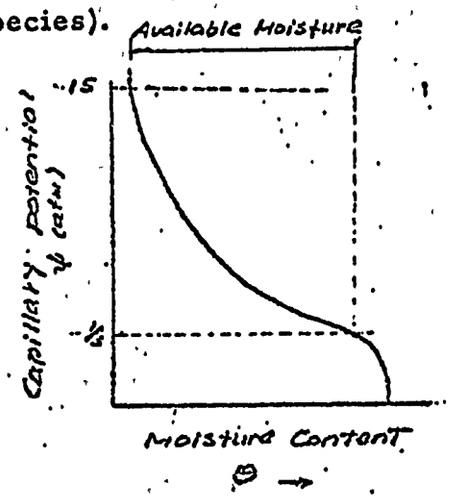
January 27, 1970

Root Zone Model for Atlantico 3 Project - Colombia

Preliminary Assumptions

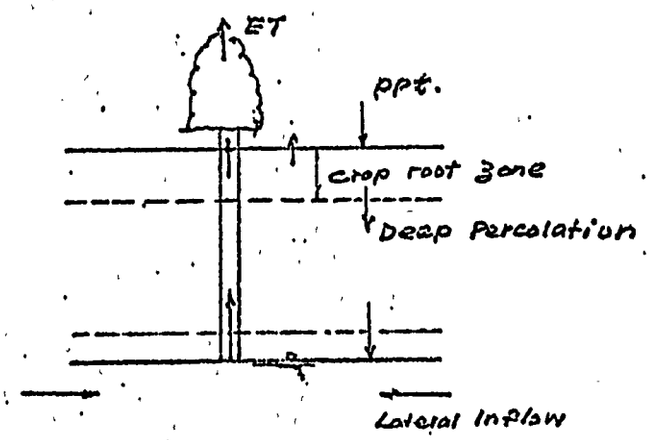
1. Assume average rooting depth for the various crop varieties grown.

2. Estimate available soil moisture storage capacity for each rooting depth (crop species).



3. Assume that deep percolation occurs only when the available capacity is reached for crop species.

4. Assume that the native vegetation extracts most of its water supply from the groundwater basin at PET rate.



5. Assume equilibrium conditions now exist between inflow to the groundwater and extraction by native vegetation on a long term basis. This will be a verification assumption.

6. Alternative to 4.

Native vegetation withdraws from the entire unsaturated zone above the water table making up PET deficits by withdrawals from the groundwater basin (including the capillary fringe). Under this assumption, little, if any, precipitation would likely reach the groundwater table by deep percolation.

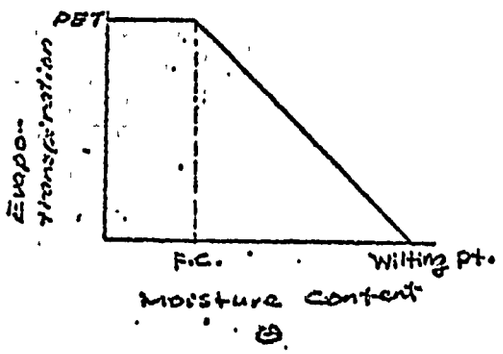
Note: Some information regarding the root distribution of the native vegetation would provide some basis for a decision between assumption (4) and (5). We also have no reasonable means of knowing the actual E.T. rate of the native vegetation. Presumably the water table has been lowered by plant withdrawal either from the capillary fringe or the groundwater basin, as could be the case with phreatophytes. Here again, some knowledge of root distribution would help. However, it appears that in any case water supplies have not been limiting to the native vegetation.

7. Use J.E. Christiansen's equations for computing PET by native vegetation and ET by crops.

a) crop cover coeff. needed for native vegetation and for each cultivated crop variety.

b) growth stage coeff. (seasonal variation) needed for each cultivated crop variety and native vegetation.

c) the effect of available soil moisture level within the root zone upon ET rate needs to be included.



Example:

Clay: available capacity 6"

M_{es} = 4"

Sand: -- 3"

M_{es} -- 2"

$$ET = PET \left(\frac{M_{\theta s}}{M_{es}}\right), \quad (M_{\theta s} \leq M_{es})$$

$$ET = PET, \quad (M_{\theta s} > M_{es})$$

8. Assume the swamp areas to be infiltration sources of a local and steady state nature.

Various Management Alternatives

1. No vegetation on the land surface
   a) No irrigation, only rainfall
   b) Varies water application rates.
2. Only cultivated vegetation under various irrigation rates. The groundwater table would be influenced. When deep percolation occurs, there might also be some influence on the groundwater table by lateral inflow from the

boundaries. Irrigation water in excess of crop ET requirements would likely be desired in order to maintain a salt balance within the root zone. The quality of deep percolation required to maintain the balance is, however, the subject of additional study.

Some native vegetation, e.g., in the low areas, in conjunction with cultivated crops. Under these conditions, some deep percolation, e.g., that required to maintain salt balance would probably be used by the native remaining vegetation. In fact under conditions of no deep percolation, the remaining native vegetation will probably lower the water table even further because much of the rainfall available to the native vegetation would be used by the cultivated crops. One problem that might occur is that under conditions of sufficient deep percolation of irrigation water an increase in salinity within the groundwater basin would probably occur. Increasing salinity levels might eventually adversely affect the native vegetation. This requiring eventually artificial drainage (as opposed to drainage by ET of native vegetation).

High irrigation rates would cause a raising of the water table even with some native vegetation remaining on the area if deep percolation rate exceeded ET rates from the groundwater basin by native vegetation.