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Electronic Analog Computer Simulation of the Paez-Pedraza Region of Venezuela

J. Paul Riley
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Kousoum S. Sakhan

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ELECTRONIC ANALOG COMPUTER SIMULATION
OF THE PÆEZ-PEDRAZA REGION
OF VENEZUELA

by

J. Paul Riley
V. V. Dhruva Narayana
Kousoum S. Sakhan

The work reported by this project completion report was supported primarily with funds provided by Corporación de Los Andes, Government of Venezuela.

Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah

February 1969
ABSTRACT

ELECTRONIC ANALOG COMPUTER
SIMULATION OF THE PAEZ-PEDRAZA
REGION OF VENEZUELA

Recently governments and universities in many South American countries have shown considerable interest in a planned and orderly development of available water resources. A case in point is the preliminary study reported in which the problem is approached by utilizing a general mathematical model of the hydrologic system. Specifically, the study involves simulation by means of an electronic analog computer of the hydrology of the Paez-Pedraza region of south western Venezuela. The various processes within the model are linked by the continuity-of-mass principle, which requires a hydrologic balance at all points. The analog computer is ideally suited to the solution of the time-dependent differential equations of the model, and to the trial and error process required during testing and verification.

Despite restrictions imposed by data limitations, a satisfactory model based on a monthly time increment is proposed. The model is applied for (a) estimating runoff from ungaged subbasins, (b) testing the sensitivity of the system to certain parameters and processes, and (c) providing insight into data requirements within the region. In addition, the study provides a basis for evaluating the feasibility of conducting further and more detailed investigations of the Paez-Pedraza and other areas of Venezuela. Several recommendations for additional research are presented.

Riley, J. Paul, Narayana, V. V. Dhruva, and Sakhan, Kousoum S.
ELECTRONIC ANALOG COMPUTER SIMULATION OF THE PAEZ-PEDRAZA REGION OF VENEZUELA.

KEYWORDS--*surface runoff/ *hydrologic models/ *hydrologic simulation/ *tropical hydrology/ *electronic analog computer/ runoff/ precipitation/ *water resource planning and development/ watershed studies/ evapotranspiration/ *hydrologic relationships/ *runoff synthesis/ flood control/ soil moisture.
ACKNOWLEDGMENTS

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J. Paul Riley
V. V. Dhruva Narayana
Kousoum S. Sakhan
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>COMPUTER SIMULATION OF HYDROLOGIC SYSTEMS</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Computer Classification</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Analog computers</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Digital computers</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Hybrid computers</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Review of Past Work</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Digital computer models</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Analog computer models</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Concepts of a Hydrologic Model</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Requirements</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Hydrologic balance</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Time and space considerations</td>
<td>17</td>
</tr>
<tr>
<td>III</td>
<td>DEVELOPMENT OF THE PAEZ-PEDRAZA REGION MODEL</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Description of the Study Area</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Hydrologic Model</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Evapotranspiration</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Watershed storage</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Surface storage</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Retention storage</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Detention storage</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Subsurface storage</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Soil moisture storage</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Groundwater storage</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Runoff and flow routing</td>
<td>32</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Computer Model</td>
<td>34</td>
</tr>
<tr>
<td>Testing and Verification of the Model</td>
<td>36</td>
</tr>
<tr>
<td>Model assumptions</td>
<td>36</td>
</tr>
<tr>
<td>Adjustable parameters</td>
<td>37</td>
</tr>
<tr>
<td>Verification procedure</td>
<td>37</td>
</tr>
<tr>
<td>CHAPTER IV, RESULTS</td>
<td>39</td>
</tr>
<tr>
<td>Sensitivity Analysis</td>
<td>39</td>
</tr>
<tr>
<td>Precipitation input</td>
<td>39</td>
</tr>
<tr>
<td>Soil moisture characteristics</td>
<td>42</td>
</tr>
<tr>
<td>Average maximum infiltration value</td>
<td>42</td>
</tr>
<tr>
<td>Groundwater delay</td>
<td>42</td>
</tr>
<tr>
<td>Simulated and Gaged Outflow</td>
<td>46</td>
</tr>
<tr>
<td>Paguey subbasin</td>
<td>46</td>
</tr>
<tr>
<td>Total basin</td>
<td>54</td>
</tr>
<tr>
<td>CHAPTER V, LIMITATIONS AND CONCLUSIONS</td>
<td>58</td>
</tr>
<tr>
<td>Limitations</td>
<td>58</td>
</tr>
<tr>
<td>Precipitation and runoff data</td>
<td>58</td>
</tr>
<tr>
<td>Model parameters</td>
<td>59</td>
</tr>
<tr>
<td>Total basin outflow</td>
<td>59</td>
</tr>
<tr>
<td>Conclusions</td>
<td>59</td>
</tr>
<tr>
<td>CHAPTER VI, SUMMARY AND RECOMMENDATIONS</td>
<td>62</td>
</tr>
<tr>
<td>Summary</td>
<td>62</td>
</tr>
<tr>
<td>Recommendations</td>
<td>64</td>
</tr>
<tr>
<td>Basic hydrologic data</td>
<td>64</td>
</tr>
<tr>
<td>Flood studies</td>
<td>65</td>
</tr>
<tr>
<td>Sediment studies</td>
<td>66</td>
</tr>
<tr>
<td>Water quality studies</td>
<td>66</td>
</tr>
<tr>
<td>Land and water management studies</td>
<td>66</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Table/Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SELECTED REFERENCES</td>
<td>68</td>
</tr>
<tr>
<td>APPENDIX, Sources of Data Used</td>
<td>70</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET&lt;sub&gt;r&lt;/sub&gt;</td>
<td>evapotranspiration rate</td>
</tr>
<tr>
<td>ET&lt;sub&gt;cr&lt;/sub&gt;</td>
<td>potential evapotranspiration rate or evapotranspiration capacity</td>
</tr>
<tr>
<td>F&lt;sub&gt;r&lt;/sub&gt;</td>
<td>infiltration rate</td>
</tr>
<tr>
<td>F&lt;sub&gt;cr&lt;/sub&gt;</td>
<td>infiltration capacity or maximum infiltration rate</td>
</tr>
<tr>
<td>F&lt;sub&gt;c&lt;/sub&gt;</td>
<td>the limiting or threshold rate of surface water supply at which surface runoff begins to occur</td>
</tr>
<tr>
<td>G&lt;sub&gt;r&lt;/sub&gt;</td>
<td>deep percolation rate to the groundwater basin (inflow to storage)</td>
</tr>
<tr>
<td>G&lt;sub&gt;rs&lt;/sub&gt;</td>
<td>saturated rates of deep percolation losses</td>
</tr>
<tr>
<td>G&lt;sub&gt;ru&lt;/sub&gt;</td>
<td>unsaturated rates of deep percolation losses</td>
</tr>
<tr>
<td>G&lt;sub&gt;s&lt;/sub&gt;</td>
<td>quantity of water stored within the groundwater basin</td>
</tr>
<tr>
<td>k&lt;sub&gt;b&lt;/sub&gt;</td>
<td>a constant in a base flow equation</td>
</tr>
<tr>
<td>k&lt;sub&gt;g&lt;/sub&gt;</td>
<td>constant of proportionality depending upon the porosity of the soil, and applied in an equation for deep percolation rate</td>
</tr>
<tr>
<td>k&lt;sub&gt;h&lt;/sub&gt;</td>
<td>saturated hydraulic conductivity of the soil</td>
</tr>
<tr>
<td>k&lt;sub&gt;u&lt;/sub&gt;</td>
<td>unsaturated hydraulic conductivity of the soil</td>
</tr>
<tr>
<td>k&lt;sub&gt;sr&lt;/sub&gt;</td>
<td>portion of surface water delayed</td>
</tr>
<tr>
<td>M&lt;sub&gt;s&lt;/sub&gt;(t)</td>
<td>quantity of water stored within the root zone and available for plant use at any time, t</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS (Continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s(0)$</td>
<td>quantity of water stored within the root zone and available for plant use at time, $t$, equal to zero</td>
</tr>
<tr>
<td>$M_{cs}$</td>
<td>root zone storage capacity of water available to plants</td>
</tr>
<tr>
<td>$M_{es}$</td>
<td>limiting root zone available moisture content below which the actual evapotranspiration rate becomes less than the potential rate</td>
</tr>
<tr>
<td>$N_r$</td>
<td>interflow rate (inflow to storage)</td>
</tr>
<tr>
<td>$P$</td>
<td>precipitation rate</td>
</tr>
<tr>
<td>$P_{A}$</td>
<td>mean annual precipitation for the ungaged subbasin A</td>
</tr>
<tr>
<td>$P_{B}$</td>
<td>mean annual precipitation for the gaged subbasin B</td>
</tr>
<tr>
<td>$p_{A}$</td>
<td>monthly precipitation for ungaged subbasin A</td>
</tr>
<tr>
<td>$p_{B}$</td>
<td>monthly precipitation for gaged subbasin B</td>
</tr>
<tr>
<td>$P_{gr}$</td>
<td>precipitation through fall rate, including stemflow</td>
</tr>
<tr>
<td>$Q_{rb}$</td>
<td>rate of flow from the groundwater basin into an effluent channel within a watershed</td>
</tr>
<tr>
<td>$Q_{rs}$</td>
<td>rate of total surface discharge from a watershed, including interflow</td>
</tr>
<tr>
<td>$Q_{rt}$</td>
<td>rate of total discharge from a watershed</td>
</tr>
<tr>
<td>$S_r$</td>
<td>rate at which water is available for surface runoff within a watershed (inflow to surface detention storage)</td>
</tr>
<tr>
<td>$t_o$</td>
<td>time at the beginning of the storm event</td>
</tr>
</tbody>
</table>
Even with costly "analog-type" displays and controls which are now available on a limited basis, the pure digital approach to simulation still lacks the flexibility of the man-in-the-loop and hands-on type of simulation capability available in the more economical analog approach.

Hybrid computers

As more sophisticated approaches to the solution of engineering problems are developed, it becomes necessary to employ both analog and digital computation techniques to effect a realistic and economical solution. According to Anderson (1968), during the past five years, it has become increasingly evident that the existing all-analog simulation laboratories were growing less able to provide adequate simulation fidelity in fast-time and real-time studies. This situation has resulted from a marked trend towards incorporating digital components and subsystems in the models to be simulated. As a result, many of the major simulation laboratories have converted to hybrid facilities by re-equipping them with linked digital-analog systems. This computer marriage has resulted in the hybrid computer—a computer with both analog and digital capabilities. Hybrid computing facilities similar to those currently being installed at the Utah Water Research Laboratory are shown by Fig. 2.2.

Since its initial development, computer hybridization has undergone steady improvement. The increase in band width, speed, and dynamic accuracy of the analog components, along with the development of high-speed switching devices (both analog and digital) has allowed the
The console of the digital unit.

A view of the analog unit showing the servo-set pots, digital voltmeter, and program board.

Fig. 2.2. Hybrid computer equipment similar to that currently being installed at the Utah Water Research Laboratory.
When the model is properly verified so that it accurately simulates a particular system, input and individual model parameters can be varied; and the effects of these changes can be observed at any point in the system. The general research philosophy involved in the development of a simulation model of a dynamic system, such as a hydrologic unit, is shown by the flow diagram of Fig. 2.3.

Hydrologic balance

A dynamic system consists of three basic components, namely the medium or media acted upon, a set of constraints, and an energy supply or driving forces. In a hydrologic system water in any one of its three physical states is the medium of interest. The constraints are applied by the physical nature of the hydrologic basin, and the driving forces are supplied by both direct solar energy and gravity and capillary potential fields. The various functions and operations of the different parts of the system are interrelated by the concepts of continuity of mass and momentum. Unless relatively high velocities are encountered, such as in channel flow, the effects of momentum are negligible, so that for many hydrologic models continuity of mass is the only link between the various processes within the system.

Continuity of mass is expressed by the general equation:

\[ \text{Input} = \text{Output} \pm \text{Change in Storage} \]
Fig. 2.3 Development process of a hydrologic model
A hydrologic balance is the application of this equation in order to achieve an accounting of physical hydrologic measurements within a particular unit. Through this means and the application of appropriate translation or routing functions, it is possible to predict the movement of water within a system in terms of its occurrence in space and time.

The concept of the hydrologic balance is pictured by the block diagram of Fig. 2.4. The inputs to the system are precipitation and surface and groundwater inflow, while the output quantity is divided among surface outflow, groundwater outflow, and evapotranspiration. As water passes through this system, storage changes occur on the land surface, in the soil moisture zone, in the groundwater zone, and in the stream channels. These changes occur rapidly in surface locations and more slowly in the subsurface zones.

**Time and space considerations**

Practical data limitations and problem constraints require that increments of time and space be considered by a model design. Data, such as temperature and precipitation readings, are usually available as point measurements in terms of time and space, and integration in both dimensions is usually most easily accomplished by the method of finite increments.

The complexity of a model designed to represent a hydrologic system largely depends upon the magnitudes of the time and spatial increments utilized in the model. In particular, when large increments
Other related phenomena, such as sediment transport, water quality, and economics, were considered to be beyond the scope of the investigation.

A flow chart of the hydrologic model adopted for the study is shown by Fig. 3.2.

The basic components of the system are listed below.

(1) Inflow--The basic input to the watershed is precipitation, and throughout the remainder of this chapter input will be discussed in terms of precipitation only. However, as indicated by Fig. 3.2, the model also provides for both surface and subsurface inflows from adjacent areas. These flows then represent outflows (or parts thereof) from the adjacent and higher runoff areas.

(2) Storage--Storage occurs on both the surface and subsurface of the watershed. Flows to and from storage are affected by the rates of infiltration, deep percolation, and interflow. Abstractions from evapotranspiration occur in every phase of the dynamic system.

(3) Outflow--This parameter includes both surface and subsurface outflows from the watershed at specific points.

The details of these three different phases of the system are discussed in the following paragraphs.
Fig. 3.2  Hydrologic flow diagram for the Paez - Pedraza region of Venezuela.
Precipitation

Precipitation represents the basic input to the hydrologic system. In this regard, the general nature of the storm, latitude and elevation of the basin, and orographic effects are all important. In order to account for spatial variations of both precipitation and watershed characteristics within the study area, the drainage basin was divided into 18 subbasins (Fig. 3.1). Because spatial changes within each subbasin are relatively small, integration of the hydrologic processes with respect to this variable is thus facilitated.

The value of precipitation to be input to the model for any time period is an average value in terms of both time and space. Average values of precipitation over a given area and for any time period can be computed by several methods. Where precipitation data are available from several gages within the area, it is possible to plot isohyetal maps for each time interval and to estimate from the map the average depth of precipitation over the watershed during each period of time. This method is considered to be very reliable because it can take into account such factors as elevation, aspect, and location. However, if only a few precipitation gages are located within the area, as is the case with the subbasins of the Paez-Pedraza area, the isohyetal method cannot be applied. In such cases, the Theissen's weighting procedure is useful. Under this procedure, the precipitation stations are connected by straight lines on a map. Perpendicular bisectors of these connecting lines form polygons around each station. The sides of each polygon are
the boundaries of the effective area assumed for each station. This technique is reasonably reliable if the subbasin demarcation is based on a consideration of topographic and other watershed characteristics.

For watersheds which contain no precipitation gages, rainfall must be estimated by other techniques. With the Paez-Pedraza area, the mean annual isohyetal maps and the recorded runoff for each month for some of the subbasins are available. The weighted monthly precipitation within an ungaged subbasin is determined from the following data from a gaged subbasin with nearly identical hydrologic properties:

(1) Weighted precipitation for each month.

(2) The mean annual precipitation determined from the isohyetal map.

Under this procedure, it is assumed that the ratio of the weighted precipitation for each month to the mean annual precipitation for both the gaged and ungaged subbasins are equal. For example, if $p_A$ and $P_A$ are a particular monthly and mean annual precipitation for the ungaged subbasin A and $p_B$ and $P_B$ are those for the gaged subbasins, B, then:

$$\frac{p_A}{P_A} = \frac{p_B}{P_B}$$

or

$$p_A = \frac{p_B}{P_B} \cdot P_A$$

. . . . . . . . . . . . . . . . . . . . . . . 3.1
in which

\[ P_B \]

is available from the records

and

\[ P_A \text{ and } P_B \]

are estimated from the mean annual isohyetal map.

**Evapotranspiration**

Evapotranspiration is the process whereby precipitation returns to the atmosphere through the process of evaporation from water bodies, soil, and other surfaces, and through transpiration by plants. While various techniques are available for estimating the actual evapotranspiration from a basin (Riley et al., 1966), the following expressions have been adopted in this model for determining evapotranspiration

\[ \text{ET} = 0.8 \left( M < M(t) \right. \]

Grassi (1968) observed that potential evapotranspiration rate \( \text{ET}_{cr} \) in the study area is approximately 0.7 times the evaporation rate from the standard U.S. Weather Bureau class A-pan.

**Watershed storage**

Some of the precipitation falling on a watershed is intercepted by the vegetative cover. The intercepted precipitation is then returned to the atmosphere through evaporation. The magnitude of the interception loss is dependent largely upon the type and density of forest canopy and
the relative extent of the forested land within the area. In the present model, this parameter is included as part of the evapotranspiration occurring from the watershed. As already indicated, precipitation reaching the ground represents the basic input to the watershed storage system, both surface and subsurface.

Surface storage

The surface storage of a watershed consists of two components:

(1) permanent or retention storage and (2) temporary or detention storage.

Retention storage. The retention or depression storage consists of the water retained in puddles, ditches, and other depressions in the soil surface. Outflow from this form of storage occurs either as direct evaporation or infiltration into the soil where the moisture is subject to use by the plants. In this model where large amounts of time are involved, water retained temporarily in depression storage is assumed to be a part of the evapotranspiration loss from the area and thus is not considered separately.

Detention storage. Water held in temporary storage on the land surface in the form of sheet flow falls into this category. The effects of detention storage are further discussed under the heading "Runoff and flow routing."
Subsurface storage

This form of storage consists of two basic categories, namely soil moisture storage which contains water usually available to plants, and the deeper groundwater reservoir on the watershed.

**Soil moisture storage.** Inflow to the soil occurs by the process of infiltration from the surface. Outflow is represented by the phenomena of evapotranspiration, deep percolation to groundwater storage, and interflow which contributes to the surface runoff. The soil moisture storage at any time, \( t \), in this model is represented by the expression:

\[
M_s(t) = \int (F_r - ET_r - G_r - N_R) \, dt \quad \ldots \ldots \ldots \ldots 3.4
\]

Of the four phenomena represented on the right side of the above expression, evapotranspiration has already been discussed and details of the remaining are presented in the following paragraphs.

Infiltration is the passage of water through the soil surface into the soil. In this model, the infiltration process is assumed to occur at rates represented by the following expressions:

\[
F_r = P_r, (P_r < F_c) \quad \ldots \ldots \ldots \ldots \ldots 3.5
\]

\[
F_r = F_c, (P_r \geq F_c) \quad \ldots \ldots \ldots \ldots \ldots 3.6
\]

Deep percolation is defined as the movement of water through the soil from the soil moisture storage (plant root zone) to the under-
lying groundwater storage basin. Rates at which deep percolation takes place are estimated by the following expressions:

\[ G_{rs} = f(k_h) \quad \ldots \quad 3.7 \]
\[ G_{ru} = f(k_u, \theta) \quad \ldots \quad 3.8 \]

in which \( G_{rs} \) and \( G_{ru} \) are the saturated and unsaturated rates of deep percolation losses respectively.

\[ k_h = \text{saturated hydraulic conductivity of the soil} \]
\[ k_u = \text{unsaturated hydraulic conductivity of the soil} \]
\[ \theta = \text{soil moisture content} \]

Equations 3.7 and 3.8 are approximated by the empirical expression.

\[ G_r = -k_g M_s(t), \quad (0 \leq M_s(t) \leq M_{cs}) \quad \ldots \quad 3.9 \]

The negative sign in the above expression signifies that it is outflow from soil moisture storage. \( k_g \) is a constant of proportionality, depending upon the porosity of the soil. \( M_s(t) \) is given by the expression 3.4. At field capacity \( M_s(t) = M_{cs} \). Assuming that deep percolation is only in the vertical direction Riley et al. (1967) derived the following:

\[ k_g = k_h/M_{cs} \quad \ldots \quad 3.10 \]
Interflow is defined as that portion of the outflow from soil moisture storage which does not enter the groundwater basin but moves laterally through the upper and more porous portions of the soil profile to the stream channel. This lateral outflow is assumed to take place only when soil moisture storage is saturated. The interflow rate is given by the following expressions:

\[
N_r = 0, \quad (M_s < M_{cs}) \quad \ldots \ldots \ldots \ldots \quad 3.11
\]

\[
N_r = F_r - G_r - ET_{cr}, \quad (M_s = M_s) \quad \ldots \ldots \ldots \ldots \quad 3.12
\]

These two expressions can be combined in the following manner:

\[
N_r = F_r - k_g M_{cs} - ET_{cr} \quad \ldots \ldots \ldots \ldots \quad 3.13
\]

The total interflow quantity which is available during a time period, \( t_n \), is given by:

\[
\int_{t_{cr}}^{t_n} N_r \, dt = \int_{t_{cr}}^{t_n} (F_r - k_g M_{cs} - ET_{cr}) \, dt \quad \ldots \ldots \quad 3.14
\]

in which \( t_{cr} \) represents the time at which \( M_s = M_{cs} \) and \( t_0 \leq t_{cr} \leq t_n \).

**Groundwater storage.** In general terms, water held in the zone of saturation is considered to be in this form of storage. Inflow to the groundwater basin occurs both as groundwater movement from adjacent areas and as deep percolation from the overlying unsaturated zone. The deep percolation process has already been discussed. Groundwater movement from the basin appears as base flow in surface streams,
pumping withdrawals, and as subsurface flow to adjacent groundwater reservoirs. Groundwater flow within the zone of saturation is described in the following section.

Runoff and flow routing

The output of the hydrologic system is surface and subsurface outflow, or total runoff. This quantity is the dependent variable in the hydrologic cycle which results when the input precipitation is subjected to the various watershed storages effects discussed earlier. Thus, runoff is obtained by a) chronologically subtracting the various abstractions due to surface storage, subsurface storage, and evapotranspiration, from the precipitation in compatible time intervals (each month in the present model), and b) routing the rainfall excess (runoff supply) through the transient effects of various storages. The routing process is discussed in the following paragraphs.

The movement of water from one point to the other in a hydrologic system is dependent upon the transient effects of the different types of storages, such as those of surface, soil moisture, and groundwater. The storage effects of each of the above three depend upon such characteristics as surface drainage density, shape and slope of the watershed, soil porosity, soil depth and the aquifer constants (hydraulic conductivity and storage coefficient). The problem can be simplified by applying a general routing relationship expressed below.

\[ q = \frac{dS(t)}{dt} = -k S(t) \quad \ldots \quad 3.15 \]
in which \( q \) = discharge rate from the basin

\( S(t) = \) the storage within the basin at anytime \( t \)

\( k = \) a constant depending upon the basin characteristics and is established by model verification procedure.

For this study the above expression was adopted to determine the runoff contribution from groundwater storage. Since the time interval used was one month, both interflow and surface runoff were combined without any delay. Thus, this combined flow appears in the outflow hydrograph of the model as it occurs on the watershed. In other words

\[
Q_{rs} = S_r + N_r \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 3.16
\]

The total outflow from the watershed is given by summing the surface runoff (which includes interflow) and the outflow from groundwater storage (base flow) in the following manner:

\[
Q_{rt} = Q_{rs} + Q_{rb} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 3.17
\]

In this expression \( Q_{rb} \) is given by:

\[
Q_{rb} = k_b G_s(t) \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad 3.18
\]
in which

\[ Q_{rb} \quad \text{= base flow rate from the watershed} \]

\[ k_b \quad \text{= a constant determined by model verification} \]

\[ G_s(t) \quad \text{= quantity of water stored within the groundwater basin during any time interval} \]

**Analog Computer Model**

The analog computer model corresponding to the hydrologic model of the present investigation (Fig. 3.2) is shown by Fig. 3.3. The time scale of the model is one month of real time equal to one second of computer time. The monthly values of precipitation and pan evaporation are the inputs to the model. These are set up on a stepped potentiometric input device which then generates a signal corresponding to the precipitation and evapotranspiration quantities for each month. The logic in equations 3.2, 3.3, 3.5, 3.6, 3.9, 3.13, 3.14 are simulated by comparators in the analog computer model. Long transport delay times, such as the average time required for the groundwater, \( Q_{rb} \), to move off the watershed, are simulated in the model by means of active delay networks. The required delay settings for these networks are established by model verification studies.
Fig. 4.9  Cumulative surface outflow from subbasin 3, 1960 - 1962

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- - - - Measured cumulative outflow

- - - - Computed cumulative outflow

Precipitation
$Y = 14.167 + 0.95X$

$R^2 = 0.861$

$R = 0.93$

Fig. 4.11 Observed versus computed surface runoff for subbasin 3, 1957 - 1965
Fig. 4-12 Hydrographs of the upper Apure River, April 1963 - March 1965.
River between Bruzual and San Fernando is an influent stream during dry periods, thus discharging to groundwater storage. Information in this respect, however, is not at present available.
CHAPTER V
LIMITATIONS AND CONCLUSIONS

Limitations

Conclusions from a study of this nature need to be considered on the basis of limitations imposed by (1) the availability and reliability of data, (2) assumptions made with regard to the physical phenomena of the problem, and (3) the various basin parameters adopted in the model. Before the conclusions are presented, some of the more serious limitations encountered in this study are discussed briefly as follows.

Precipitation and runoff data

In simulation studies of hydrologic systems important limitations are imposed by the precipitation and runoff data. In this particular study both of these forms of data are open to some question. For some of the subbasins gaged annual runoff exceeded the precipitation quantity estimated from gage readings even neglecting the effects of evapotranspiration on the watershed (Table 4.1). The question, of course, occurs as to whether the discrepancy is attributable to the streamflow or the precipitation records (or both). Many of the stream gaging stations within the area are situated at points of unstable channel conditions. On the other hand, within several subbasins the density of the precipitation gage network is insufficient to provide a reliable indication of rainfall distribution. In this study the runoff records
were assumed to be correct and all discrepancies were, therefore, attributed to the precipitation data. As indicated in Chapter III, for several subbasins it was necessary to increase the apparent rainfall quantities by introducing precipitation adjustment factors.

Model parameters

In general, data regarding model parameters, such as soil moisture characteristics and average infiltration rates, are inadequate. Initial estimates of the values of these parameters were made by comparison with similar watersheds. These values were then adjusted during the model verification procedure of the study.

Total basin outflow

Runoff data at Bruzual would considerably aid in verification of the model. In the present study the total model was tested with recorded outflow data at San Fernando, a gaging station downstream of Bruzual.

Conclusions

Taking into account the limitations discussed in the previous section, the conclusions of the study are summarized as follows:

(1) A practical analog simulation model of the hydrologic system within the Upper Apure River Basin of Venezuela has been developed. The close verification of the model is demonstrated by the statistical comparison between the simulated and gaged outflows from the Paguey subbasin.
In addition, good agreement was achieved (on the basis of time distribution) between the simulated runoff records at Bruzual and the gaged flows at San Fernando. Besides establishing a model which can be applied to a wide variety of management problems and solution alternatives, because of the ability of the computer to solve problems at high speeds, simulation usually results in significant savings even when only a single problem is considered. For example, modeling studies at Utah State University have realized significant savings (cost ratios of less than 1:50) when compared with methods which did not use computer simulation in reaching solutions.

(2) The model provides estimates of runoff from ungaged subbasins within the study area.

(3) The numbers of both precipitation and runoff gages need to be increased within the study area.

(4) Data are needed on certain watershed parameters, such as infiltration rates, soil moisture characteristics, and groundwater conditions.

(5) The soil moisture characteristics tend to be uniform for the entire basin, with variations from one subbasin to another being generally not sufficient to affect corresponding outflows.
(6) Variations in evapotranspiration rates have a relatively small effect on outflow values.

(7) Average infiltration rate and groundwater delay are parameters which can significantly influence outflow during wet and dry seasons of the year respectively. In the study, values of these parameters were estimated through the model verification procedure.

(8) The value of additional and more detailed analog simulation investigations of the Paez-Pedraza and other areas of Venezuela is indicated by the study.

Referral to Chapter I indicates that in general the primary objectives of the study were accomplished under the project.
Chapter VI

Summary and Recommendations

Summary

This report presents the findings of a preliminary study on the analog computer simulation of the hydrology of the Paez-Pedraza area of southwestern Venezuela. The basic components of the hydrologic model considered in this study are (1) precipitation input, (2) the various forms of watershed storage which affect and modify the input as it passes through the system, and (3) the runoff or outflow from the basin.

The Paez-Pedraza region was divided into 18 subbasins for spatial integration of the hydrologic phenomena. Integration of the various processes in time was accomplished by choosing a time increment of one month. For subbasins containing an adequate number of precipitation gages, the average value of precipitation was computed by Theissen's weighting procedure. For the remaining subbasins, the average precipitation was estimated with the aid of gaged precipitation data from nearly identical subbasins and the mean annual isohyetal maps of the Paez-Pedraza area.

The mathematical model was tested and verified using available data from the study area and the analog computer at the Utah Water Research Laboratory, Utah State University, Logan, Utah. Average monthly values were assumed for watershed parameters, such as
infiltration, evapotranspiration rates, soil moisture storage, and groundwater delay times. The model was verified by adjusting model parameters until close agreement was achieved between the simulated and the corresponding gaged hydrographs. The parameters subject to manipulation during verification were (a) precipitation adjustment factor, (b) soil moisture storage, (c) average infiltration rate, (d) the groundwater storage delay, and (e) the quantity of surface runoff and its associated detention delay time.

The more important observation from the study include the following:

1. Precipitation and runoff data in the study area are generally inadequate.

2. Groundwater storage delay for most subbasins is about three months.

3. Groundwater inflow rates to a subbasin are directly related to the precipitation rates occurring on adjacent and higher subbasins.

4. Soil moisture and infiltration characteristics do not vary appreciably from one subbasin to the other within the study area.

5. The average infiltration rate and the groundwater storage delay are watershed parameters which play a major role in controlling outflow during the wet and dry seasons of the year respectively.
The adequacy of the model which was developed and tested under the various data limitations encountered is demonstrated by a statistical comparison between the simulated and gaged outflows from Paguey subbasin, and by a comparison of the time and magnitude of the simulated peak discharge rates at Bruzual and the gaged values at San Fernando. This investigation pointed out the need for more comprehensive hydrologic data within the study area, but at the same time demonstrated that, even under conditions of severe data limitations, modeling can be a useful and practical technique for water resource management within the Paez-Pedraza region of Venezuela.

Recommendations

From the list of conclusions and the supporting data presented in this report, the following recommendations are made as part of a continuing study program.

Basic hydrologic data

The current program for improving the basic data network within the region should be given major emphasis. The importance of reliable data conscientiously obtained from stations carefully selected, correctly installed, and properly maintained cannot be overemphasized. In the case of the study discussed herein, the number of stations or sample points (precipitation, evaporation,
and runoff) within the region needs to be increased. For remote stations telemetering might be considered. In addition, it is suggested that the quality of existing runoff data might be carefully examined. Particularly for those subbasins for which further study is proposed, an attempt should be made to establish the consistency of the runoff rating curves. These recommendations do not imply that additional simulation studies be delayed until extensive data networks have been established. On the contrary, considerable insight into the kinds of data needed and the locations of sample points within the system can be obtained from simulation studies. Simulation models are flexible and can be continuously tested and improved as additional data become available.

**Flood studies**

Detailed flood flow simulation studies will provide flood frequency curves. Such frequency curves are useful in the proper design of levies, spillways, and other infrastructures. For flood flow simulation, it will be necessary to consider a short time increment of, for example, one day, in order to simulate the peak discharge rates. This model will be essentially deterministic in nature, and the runoff process will consider the short term effects of interception storage, depression storage, and infiltration. The flood routing procedure will be based on the channel characteristics, such as slope, roughness, and cross sectional area. With stochastic inputs of precipitation, frequency curves for stream flow can be developed from
the deterministic hydrologic model. A study of this nature would have direct application to the Uribante River basin, where a fairly intense hydrologic data network is being installed.

Sediment studies

The flood studies suggested above could be extended to include the sediment parameter. The sediment loads of streams estimated by such a simulation model would be useful in planning sediment control measures.

Water quality studies

Water quality is another dimension which can be added to a sound hydrologic simulation model. A model of this nature facilitates the solution of problems such as those involving the quality of return flows, the reuse capabilities of streams, and the waste assimilation characteristics of streams.

Land and water management studies

The model developed under this study can be applied to study interbasin effects of various land and water use practices on the streamflow. Refinement of the model, particularly in terms of reduced space increments, will enable it to be applied to specific surface and subsurface drainage problems and to those involving the conjunctive use of ground and surface waters. Detailed investigations of this nature would, however, require that groundwater information
be obtained for the area under study. Examples of the kinds of data needed are as follows:

(a) The direction and quantity of groundwater flow.

(b) Maps of the groundwater surface at various times of the year.

These kinds of information would be provided by wells, bore holes, and perhaps seismic explorations within the study area.
SELECTED REFERENCES


APPENDIX

Sources of Data Used

1. Precipitation

All precipitation stations within the area at which records have been or are being taken are shown by the accompanying map. Data were obtained from the following two sources:

(a) A manuscript being prepared for publication by Mr. Rafael Roja's who is employed by the Corporación de Los Andes. This report also contains valuable interpretive information.

(b) The "Anuario Climatológico" published by the Venezuelan Ministry of Public Works (MOP).

In addition to the above data, mean monthly isohyetal lines (period of record 1951-1955) for the area have been prepared by the Servicio de Meteorología, Fuerzas Aéreas, Ministerio de la Defensa, República de Venezuela. Copies of these were obtained.

2. Temperature:

Average values for the years 1951 to 1960 are available from the publication: "Average Climatological Data for Venezuela, 1951/60".

For the subsequent years 1961 to 1966 data were obtained from "Anuario Estadístico Agropecuario". In addition, mean monthly isothermal lines for the area were obtained. These charts were also prepared by the Servicio de Meteorología.
3. **Evaporation**

Data on losses from Class A pans were obtained from "Anuario Estadístico Agropecuario". A good correlation has been established between pan evaporation and plant consumptive use of water (Grassi, 1968). A copy of this report was obtained. Evaporation data were also obtained from records published by the Venezuelan Ministry of Public Works (MOP).

4. **Streamflow**

The rivers within the area for which flow records are available are as follows: Apure at San Fernando, Azuero, Caparo, Chururu, Doradas, Masparro, Pagüey, Santo Domingo, Torbes, Uribante at Puente Colgante, Uribante at Puente Uribante at Puente Uribante. Available records giving mean monthly flows for the period 1962 to 1966 were obtained from the MOP publications "Anuario Hidrométrico".

5. **Topography**

The following sources of information were obtained:

(a) Mosaic air photographs (scale 1:50,000)

(b) Topographic maps at a scale of 1:100,000 (black and white)

(c) Colored topographic maps at a scale of 1:100,000 (6 available)

(d) Miscellaneous maps supplied by CIDIAT.

(e) A composite map of the lower areas supplied by CORPOANDES.

6. **Land Use**

The following sources of information were obtained:

(a) Mosaic air photographs (scale 1:50,000).

(b) Several land use maps supplied by CIDIAT.
(c) Average plant rooting depths were supplied by CIDIAT.

(d) Land use and vegetation map for the area supplied by CORPOANDES.

7. Soil Types

A part of the Pagüey River watershed has been extensively mapped, and this information was obtained. Soil profile data at additional sites were also obtained from CIDIAT.

8. General Geology and Groundwater Conditions

(a) The general geology of the area is indicated by a map obtained from CIDIAT.

(b) During the dry season the groundwater stands at an average depth of two to four meters, depending upon the topography. During the wet season the watertable is at or near the land surface in most locations.