THE USE OF TIME SERIES METHODS IN THE ANALYSIS OF HYDROLOGICAL DATA

by

Mohan Shankar Amatya

B.Eng. (KMIT), M.Eng. (Chula) Thailand

A dissertation submitted in partial
fulfilment of the requirements for the degree of
Master of Resource and Environmental Studies
in the Australian National University

March 1981

DECLARATION

Except where otherwise indicated, this dissertation is my own work

M.S. Amatya

March 1981

ACKNOWLEDGEMENTS

Thanks are due to Dr. A. Jakeman for guidance in the use of CAPTAIN package, to Mr M. Greenaway for helping in other programs, to Mr J. Goodspeed and Mr M. Fleming of LUR/CSIRO for allowing me to use their data on the Lerderderg Catchment area, and to Mr J.P. Brown, the District Forester of Trentham, Victoria for providing information on the fire history of the catchment area.

Helpful guidance of my supervisors Professor P.C. Young in time-series data analysis and Mr D.I. Smith in hydrology are gratefully appreciated. Finally the author is very much obliged to the Director of CRES for providing the ANU scholarship to enable him to study at CRES.

M.S. Amatya

ABSTRACT

The account is based upon recursive time-series analysis and its application to the study of river catchment behaviour in order to predict future events. The Lerderderg Representative Basin, in Victoria, was selected as a range of hydrological data was available for this catchment on magnetic tape from the Land Use Research Division of CSIRO. Additional information on soil morphology and fire history was obtained from other sources.

The rainfall, runoff, evaporation and temperature records was analysed using the CAPTAIN package program and both short-term (hourly data) and long term (daily data) were considered. Since there were no available observations for soil moisture the non-linear soil moisture compensation algorithm of CAPTAIN was used. Transfer functions and steady state gain were calculated and impulse responses analysed.

Short-term response was found to give a better explanation of the behaviour of the Lerderderg river system than that using long-term response. For the long term analysis the model employing temperature effects was found to be more satisfactory than those based upon evaporation. The most successful model used dry bulb temperatures although as might be expected, very similar results were obtained for analysis based upon daily maximum temperature. Problems in using the technique are discussed and suggestions made for future lines of inquiry.

CONTENTS

Page No.

ACKNOWLEDGEMENTS iii
ABSTRACT iv
CONTENTS v
PREFACE vii
LIST OF TABLES x
LIST OF FIGURES xi
LIST OF MAPS xvii

CHAPTER 1 : ENGINEERING HYDROLOGY 1

1.1 Introduction 1
1.2 Hydrological Cycle 1
1.3 Interception 3
1.4 Ground Water 4
1.5 Evaporation 5
1.6 Transpiration 6
1.7 Infiltration 7
1.8 Overland Flow 11
1.9 Measurements in Hydrology 12
1.10 Hydrologic Systems 14

CHAPTER 2 : TIME-SERIES ANALYSIS METHODS IN HYDROLOGY 19

2.1 Unit Hydrograph 19
2.2 Unit Impulse Response 20
2.3 The Time-Series Method 25

CHAPTER 3 : CAPTAIN CONCEPT 34

3.1 Principles 34
3.2 CAPTAIN Use 35

CHAPTER 4 : LERDERDERG RIVER CATCHMENT AREA 39

4.1 Description of the Catchment Area 39
4.2 Soil Morphology 39
4.3 Bushfire History 44
4.4 Effects of Bushfire on the Soil 46

Page No.

CHAPTER 5 : TIME-SERIES MODELLING 48

5.1 Data : Source and Type 48

5.2 Hourly Data Analysis 49

5.3 Daily Data Analysis 53

5.3.1 Analysis of Rainfall and Runoff Data only 54

5.3.2 Analysis of Evaporation, Rainfall and Runoff Data 57

5.3.3 Analysis of Temperature, Rainfall and Runoff Data 59

5.4 Discussion 62

CHAPTER 6 CONCLUSION 64

BIBLIOGRAPHY 67

FIGURES 5.1 - 5.172 72 - 244

PREFACE

Studies of hydrology have played a vital role in the development of human society over the past several thousand years. This study is aimed particularly at evaluating the relevance of system methods and particularly time-series analysis in evaluating catchment behaviour. In particular, it considers the analysis of hydrological data for the Lerderderg River basin catchment and reaches certain conclusions on the hydrologic behaviour of the catchment on the basis of this analysis. It also attempts to evaluate the advantages and disadvantages of the time-series approach to data analysis in this particular application.

Rainfall data were collected from eight stations by the Land Use Research Division of the Commonwealth Scientific and Industrial Research Organization (LUR-CSIRO). Likewise runoff data were collected from a limited number of gauging stations. They were then processed and stored in magnetic tapes for general use. Evaporation data were collected from three stations within the catchment using class A evaporation pans. This limited data base was supplemented by the use of records from stations in neighbouring catchments in order to generalise the overall evaporation figures for the catchment. All these data and daily dry bulb temperature taken at 15.00 hrs and daily maximum temperature were stored on magnetic tapes by LUR-CSIRO.

Data used for this study were retrieved for the period 1970 to 1975 from the tape. The selection of this catchment was based on the relatively small number of missing values in the data set. Missing values were estimated for the rainfall and runoff values from the average value of the previous seven days and for evaporation values from either saturated deficit formula or maximum and minimum temperatures. Six years' daily rainfall, runoff, evaporation, dry bulb temperature and maximum temperature data were used in this study. In addition hourly rainfall and runoff data (Glover, 1979) for short periods were also used.

The basin was assumed to be water-tight, i.e. the catchment behaviour for the purpose of this study was considered to be unaffected by the loss or gain from deep groundwater circulation originating from beyond the catchment boundary. In a strict sense, this is not accurate as some small mineral springs occur within the catchment and these are associated with deeper groundwater circulation, e.g. in the vicinity of the town of Blackwood. In other words the yield of these small springs did not effectively contribute to the overall runoff of the Lerderderg river system. In addition to these points, soil morphology and bush-fire history were studied to consider their possible effects on the catchment behaviour.

A hydrological system can, in general, be either stochastic or deterministic and linear or non-linear. In this study, the deterministic linear system of rainfall-runoff was analysed first and a non-linear analysis was attempted later. A new recursive approach (Young, 1972) was adopted, where estimation of the parameters in a transfer function type model were based on the recursive instrumental variable method suggested by Young and Jakeman (1979).

As infiltration has a considerable effect on the yield of the catchment and depends upon the soil permeability, a particular form of "Antecedent Precipitation Index" (API) was considered to offset the loss due to infiltration.

Data were analysed using the computer package program CAPTAIN (Young *et al.*, 1971) to find the best time-series models with or without consideration of soil moisture, evaporation and temperature effects; to generate their impulse responses (unit hydrographs); and to approximate the standard error of the estimated transfer function parameters. The model structure identification was found to be dependent on the evaluation of the coefficient of determination R_T^2 and the error variance norm EVN (or normalised EVN, NEVN). In order to assess the likely effects of temperature on the rainfall-runoff relationships analysis was initially undertaken for the dry bulb temperature. The method was repeated for the maximum temperature, but as expected, there was little difference in the results.

Daily data were analysed in three ways:

(a) considering the raw rainfall only as sole input;

(b) considering raw rainfall minus evaporation as the input, and

(c) modifying the raw rainfall for temperature effects.

For each of these effects various time periods were considered. It was found that the short-term response from the hourly data analysis explained the behaviour of the catchment much better than the long-term response from the daily data. In the analysis allowing for evaporation effects by simple subtraction the model fitting did not improve significantly as compared to that based on temperature effects.

LIST OF TABLES

Page No.

5.1 Hourly Data Sets 50

5.2 R_T^2 and Log (NEVN) Values for Hourly Data (HOURLY) 51

5.3 R_T^2 and Log (NEVN) Values for Daily Data (RAINDIS) 55

5.4 R_T^2 and Log (NEVN) Values for Daily Data (SUB) 58

5.5 R_T^2 and Log (NEVN) Values for Daily Data (BED) 61

LIST OF FIGURES

		Page No.
1.1	Systems Diagram of the Global Hydrological Cycle	2
1.2	Flow Diagram Showing Interception, Stemflow and Throughflow	4
1.3	Infiltration Loss by ϕ - index	9
1.4	The Production of Overland Flow in Response to Rainfall Intensities in Excess of the Soil Infiltration Capacity	11
1.5	Overland Flow on Slopes	13
1.6	A Systems Representation of a Catchment Water Balance	16
1.7	A Sequential System	17
2.1	Direct Runoff Hydrograph (75 mm), Unit Hydrograph (25 mm), and Effective Rainfall Duration (4 hours)	21
2.2	The Linear Dynamic System	22
2.3	Rainfall-runoff Time-Series Model	25
2.4	Linear Dynamic System with Non-linear Filter	30
3.1	Recursive and Iterative Data Processing	35
3.2	The Major Procedures Available in CAPTAIN	38
5.1	Rainfall 612	72
5.2	Rainfall 661	73
5.3	Rainfall 662	74
5.4	Rainfall 663	75
5.5	Rainfall 664	76
5.6	Runoff 612	77
5.7	Runoff 661, 662, 663 and 664	78
5.8	Raw Data Model 612	79
5.9	Model 612 with Allowance for Soil Moisture Effects (T_s = 5 hours)	80
5.10	Model 612 with Allowance for Soil Moisture Effects (T_s = 10 hours)	81
5.11(a)	Impulse Response for Model Fig. 5.8	82
5.11(b)	Sectional Amplification of Fig. 5.11(a)	83
5.12	Impulse Response for Model Fig. 5.9	84
5.13	Impulse Response for Model Fig. 5.10	85
5.14	Raw Data Model 661	86

Page No.

5.15 Model 661 with Allowance for Soil Moisture Effects (T_s = 8 hours) 87

5.16 Model 661 with Allowance for Soil Moisture Effects (T_s = 10 hours) 88

5.17 Impulse Response for Model Fig. 5.14 89

5.18 Impulse Response for Model Fig. 5.15 90

5.19 Impulse Response for Model Fig. 5.16 91

5.20 Raw Data Model 661 92

5.21 Model 661 with Allowance for Soil Moisture Effects (T_s = 8 hours) 93

5.22 Model 661 with Allowance for Soil Moisture Effects (T_s = 10 hours) 94

5.23 Impulse Response for Model Fig. 5.20 95

5.24 Impulse Response for Model Fig. 5.21 96

5.25 Impulse Response for Model Fig. 5.22 97

5.26 Raw Data Model 662 98

5.27 Model 662 with Allowance for Soil Moisture Effects (T_s = 5 hours) 99

5.28 Model 662 with Allowance for Soil Moisture Effects (T_s = 10 hours) 100

5.29 Impulse Response for Model Fig. 5.26 101

5.30 Impulse Response for Model Fig. 5.27 102

5.31 Impulse Response for Model Fig. 5.28 103

5.32 Raw Data Model 663 104

5.33 Model 663 with Allowance for Soil Moisture Effects (T_s = 10 hours) 105

5.34 Model 663 with Allowance for Soil MOisture Effects (T_s = 15 hours) 106

5.35 Impulse Response for Model Fig. 5.32 107

5.36 Impulse Response for Model Fig. 5.33 108

5.37 Impulse Response for Model Fig. 5.34 109

5.38 Raw Data Model 664 110

5.39 Model 664 with Allowance for Soil Moisture Effects (T_s = 10 hours) 111

5.40 Model 664 with Allowance for Soil Moisture Effects (T_s = 15 hours) 112

5.41 Impulse Response for Model Fig. 5.38 113

5.42 Impulse Response for Model Fig. 5.39 114

5.43 Impulse Response for Model Fig. 5.40 115

Page No.

5.44 Rainfall 1970 116
5.45 Rainfall 1971 117
5.46 Rainfall 1972 118
5.47 Rainfall 1973 119
5.48 Rainfall 1974 120
5.49 Rainfall 1975 121
5.50 Maximum Temperature 1970 122
5.51 Maximum Temperature 1971 123
5.52 Maximum Temperature 1972 124
5.53 Maximum Temperature 1973 125
5.54 Maximum Temperature 1974 126
5.55 Maximum Temperature 1975 127
5.56 Dry Bulb Temperature 1970 128
5.57 Dry Bulb Temperature 1971 129
5.58 Dry Bulb Temperature 1972 130
5.59 Dry Bulb Temperature 1973 131
5.60 Dry Bulb Temperature 1974 132
5.61 Dry Bulb Temperature 1975 133
5.62 Evaporation 1970 134
5.63 Evaporation 1971 135
5.64 Evaporation 1972 136
5.65 Evaporation 1973 137
5.66 Evaporation 1974 138
5.67 Evaporation 1975 139
5.68 Discharge 1970 140
5.69 Discharge 1971 141
5.70 Discharge 1972 142
5.71 Discharge 1973 143
5.72 Discharge 1974 144
5.73 Discharge 1975 145
5.74 Raw Data Model Raindis 70 146
5.75 Raw Data Model Raindis 71 147
5.76 Raw Data Model Raindis 72 148
5.77 Raw Data Model Raindis 73 149
5.78 Raw Data Model Raindis 74 150
5.79 Raw Data Model Raindis 75 151

		Page No.
5.80	Impulse Response for Model Fig. 5.74	152
5.81	Impulse Response for Model Fig. 5.75	153
5.82	Impulse Response for Model Fig. 5.76	154
5.83	Impulse Response for Model Fig. 5.77	155
5.84	Impulse Response for Model Fig. 5.78	156
5.85	Impulse Response for Model Fig. 5.79	157
5.86	Model Raindis 70 with Allowance for Soil Moisture	158
5.87	Model Raindis 71 with Allowance for Soil Moisture	159
5.88	Model Raindis 72 with Allowance for Soil Moisture	160
5.89	Model Raindis 73 with Allowance for Soil Moisture	161
5.90	Model Raindis 74 with Allowance for Soil Moisture	162
5.91	Model Raindis 75 with Allowance for Soil Moisture	163
5.92	Impulse Response for Model Fig. 5.86	164
5.93	Impulse Response for Model Fig. 5.87	165
5.94	Impulse Response for Model Fig. 5.88	166
5.95	Impulse Response for Model Fig. 5.89	167
5.96	Impulse Response for Model Fig. 5.90	168
5.97	Impulse Response for Model Fig. 5.91	169
5.98	1970 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.87)	170
5.99	1972 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.87)	171
5.100	1973 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.87)	172
5.101	1974 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.87)	173
5.102	1975 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.87)	174
5.103	Modified Input SUB 70	175
5.104	Modified Input SUB 71	176
5.105	Modified Input SUB 72	177
5.106	Modified Input SUB 73	178
5.107	Modified Input SUB 74	179
5.108	Modified Input SUB 75	180
5.109	Model for Modified Input and Measured Runoff 1970	181
5.110	Model for Modified Input and Measured Runoff 1971	182
5.111	Model for Modified Input and Measured Runoff 1972	183

Page No.

5.112 Model for Modified Input and Measured Runoff 1973 184

5.113 Model for Modified Input and Measured Runoff 1974 185

5.114 Model for Modified Input and Measured Runoff 1975 186

5.115 Impulse Response for Model Fig. 5.109 187

5.116 Impulse Response for Model Fig. 5.110 188

5.117 Impulse Response for Model Fig. 5.111 189

5.118 Impulse Response for Model Fig. 5.112 190

5.119 Impulse Response for Model Fig. 5.113 191

5.120 Impulse Response for Model Fig. 5.114 192

5.121 Model Fig. 5.109 Allowing T_s of 5 days 193

5.122 Model Fig. 5.110 Allowing T_s of 5 days 194

5.123 Model Fig. 5.111 Allowing T_s of 5 days 195

5.124 Model Fig. 5.112 Allowing T_s of 5 days 196

5.125 Model Fig. 5.113 Allowing T_s of 5 days 197

5.126 Model Fig. 5.114 Allowing T_s of 5 days 198

5.127 Impulse Response for Model Fig. 5.121 199

5.128 Impulse Response for Model Fig. 5.122 200

5.129 Impulse Response for Model Fig. 5.123 201

5.130 Impulse Response for Model Fig. 5.124 202

5.131 Impulse Response for Model Fig. 5.125 203

5.132 Impulse Response for Model Fig. 5.126 204

5.133 1970 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.122) 205

5.134 1972 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.122) 206

5.135 1973 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.122) 207

5.136 1974 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.122) 208

5.137 1975 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.123) 209

5.138 1970 Rainfall Modified by Dry-bulb Temperature 210

5.139 1971 Rainfall Modified by Dry-bulb Temperature 211

5.140 1972 Rainfall Modified by Dry-bulb Temperature 212

5.141 1973 Rainfall Modified by Dry-bulb Temperature 213

5.142 1974 Rainfall Modified by Dry-bulb Temperature 214

5.143 1975 Rainfall Modified by Dry-bulb Temperature 215

Page No.

5.144	1970 Model Allowing for Temperature (dry bulb) Effects	216
5.145	1971 Model Allowing for Temperature (dry bulb) Effects	217
5.146	1972 Model Allowing for Temperature (dry bulb) Effects	218
5.147	1973 Model Allowing for Temperature (dry bulb) Effects	219
5.148	1973 Model Allowing for Temperature (dry bulb) Effects	220
5.149	1974 Model Allowing for Temperature (dry bulb) Effects	221
5.150	Impulse Response for Model Fig. 5.150	222
5.151	Impulse Response for Model Fig. 5.151	223
5.152	Impulse Response for Model Fig. 5.152	224
5.153	Impulse Response for Model Fig. 5.153	225
5.154	Impulse Response for Model Fig. 5.154	226
5.155	Impulse Response for Model Fig. 5.155	227
5.156	Model Fig. 5.150 Allowing for Soil Moisture Effects	228
5.157	Model Fig. 5.151 Allowing for Soil Moisture Effects	229
5.158	Model Fig. 5.152 Allowing for Soil Moisture Effects	230
5.159	Model Fig. 5.153 Allowing for Soil Moisture Effects	231
5.160	Model Fig. 5.154 Allowing for Soil Moisture Effects	232
5.161	Model Fig. 5.155 Allowing for Soil Moisture Effects	233
5.162	Impulse Response for Model Fig. 5.162	234
5.163	Impulse Response for Model Fig. 5.163	235
5.164	Impulse Response for Model Fig. 5.164	236
5.165	Impulse Response for Model Fig. 5.165	237
5.166	Impulse Response for Model Fig. 5.166	238
5.167	Impulse Response for Model Fig. 5.167	239
5.168	1970 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.163)	240
5.169	1972 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.163)	241
5.170	1973 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.163)	242
5.171	1974 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.163)	243
5.172	1975 Model Response with Parameter Values Set to those Estimated for 1971 (Fig. 5.164)	244

LIST OF MAPS

		Page No.
1.	Lerderderg River	40
2.	The Lerderderg River Catchment Basin	41
3.	The Lerderderg River System	42
4.	Fires in the Catchment Area	45

CHAPTER 1

ENGINEERING HYDROLOGY

1.1 Introduction

Hydrology is the branch of science that deals with the occurence, distribution and movement of water on, over and under the surface of the earth (Ward, 1975). It has been defined in numerous ways, one of the most comprehensive being 'the science of the world's waters, the different forms in which they exist' (Batisse, 1964). There are four basic processes in hydrology viz. precipitation, evaporation and transpiration, surface runoff and groundwater flow.

The scope of hydrology is extremely wide. It is closely linked with a number of other environmental sciences such as geomorphology, climatology and ecology (Rodda, Downing and Law, 1976). Engineering hydrology is concerned with various methods of controlling the use of water and, in particular, the amount of rainfall, the length of dry period, the amount of storage, losses due to evapotranspiration in river basin or catchment, the regulations of surface runoff, and the design, plan and construction of storage reservoirs and irrigation canals (Wilson, 1974).

1.2 Hydrological Cycle

The movement of water from the sea to the atmosphere and then by precipitation to the earth, where it collects as runoff and returns to the sea, is known as the hydrological cycle. However, not all the precipitation will reach the ground surface because some will be evaporated while falling and, more importantly, some will be caught or intercepted by the vegetation cover, buildings or other similar structures. Besides that, there is no uniformity in the time a cycle takes. The intensity and frequency of the cycle depend on a variety of geographical and climatological factors. The various parts of the cycle can be complex in detail and a hydrologist can have some control only on the land-phase of the cycle (Wilson, 1974). Figure 1.1 shows the system diagram of the global hydrological cycle.

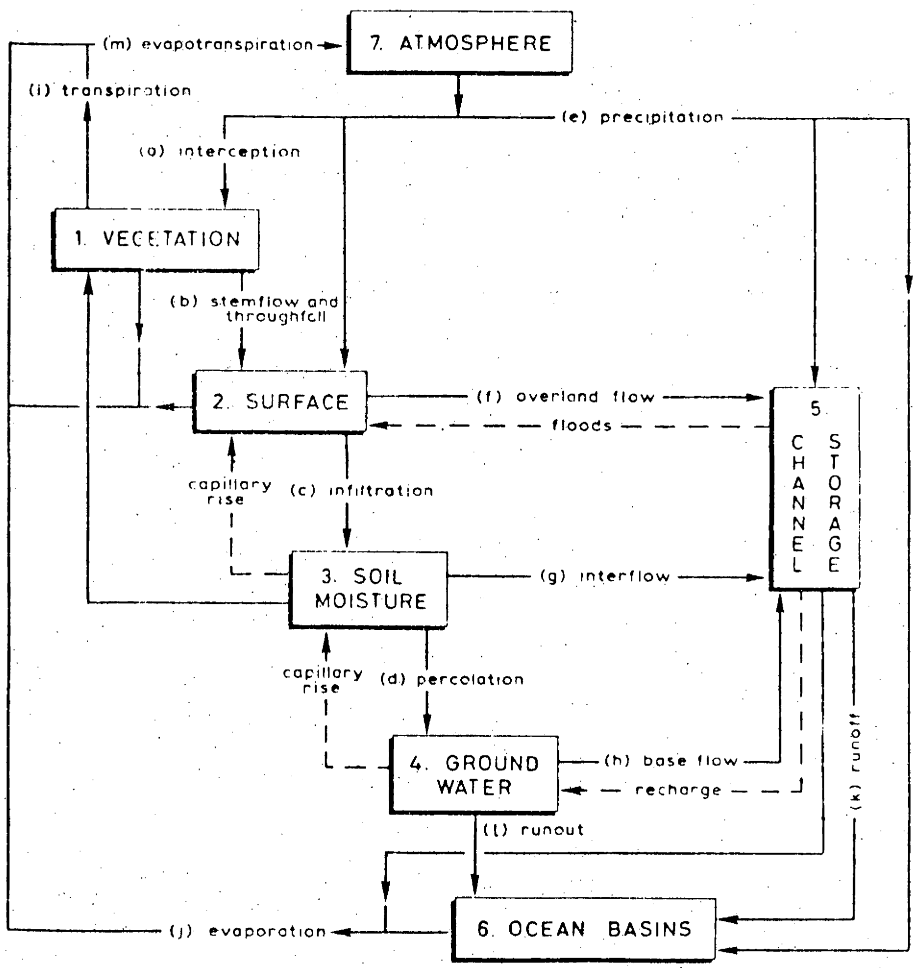


FIGURE 1.1 Systems Diagram of the Global Hydrological Cycle (from Ward, 1975).

The sea-water evaporates due to solar radiation and moves over land areas as water vapour which is precipitated in the form of snow, hail and rain. Part of such precipitation infiltrates into the soil and moves down into the saturated ground zone beneath the water-table. This phreatic zone is usually connected by aquifers to river systems or to the sea. Part of the infiltrated water is transpired from leafy plants of the vegetated surfaces. Further precipitation is intercepted by the branches and foliage of plants. This is known as interception and may take three possible routes. If the water drips off the plant leaves to ground, the process is known as throughfall. If there is another interception to that, it is known as secondary interception. On the other hand, the water may run along the leaves, branches and then stems to reach the ground. This is referred to as stemflow. Part of the water intercepted may return to the atmosphere by evaporation. These processes are shown in Figure 1.2. Part of the surface water returns to the atmosphere by evaporation and the rest form the river systems which again lose a certain amount through evaporation. Another part of the cycle, ground water, moves slowly to join the river systems to return to the sea.

1.3 Interception

Interception loss varies with the duration and intensity of the precipitation. It also varies over time as a result of seasonal variations in the vegetation (Weyman, 1975). Penman (1963) showed that there was a fivefold increase in summer interception under a cover of cereal crops compared to the winter equivalent. There are also spatial variations in interception loss due to various plant species. Lull (1964) has defined gross rainfall as the total amount of rainfall measured in the open or above the vegetation canopy, and net rainfall as the quantity that actually reaches the ground, i.e. the sum of

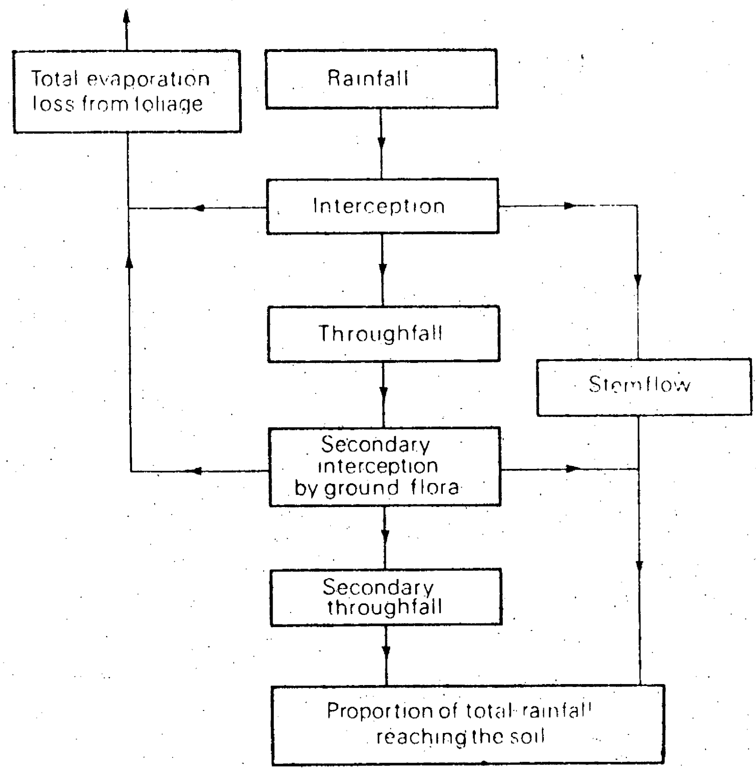


FIGURE 1.2 Flow Diagram Showing Interception Stemflow and Throughflow (from Smith and Stopp, 1978).

throughfall and stemflow. Although the interception has considerable effect upon the reduction of gross precipitation to net precipitation, no rigorous method has been found for the estimation of interception loss.

1.4 Ground Water

Any phenomenon which produces a change in pressure on the ground water causes the ground water level to change. Changes in storage, resulting from differences between recharge and discharge of water, cause levels to vary in time from a few minutes to many years. Variations of runoff stages and evaporation produce localised storage changes. Secular variations in levels extending over periods of several years are produced by alternating series of wet and dry years in which rainfall is above or below the mean. Though recharge is the governing factor of ground water level depending on the rainfall intensity and distribution and the amount of surface runoff, rainfall is not an accurate indicator of groundwater level changes (Todd, 1964). A certain degree of control on ground water levels is possible, for example the regulation of seepage through earth dams and land drainage (Todd, 1959).

The main concern of hydrologists is the detailed quantitative study of water occurence distribution and movement, i.e. precipitation, evapotranspiration, surface runoff, and ground water flow in a specific area, to predict the most likely quantities involved in the extreme cases of flood and drought, and also the likely frequency with which such events will occur, since such a frequency is a very important part of the hydraulic engineering design (Wilson, 1974).

The hydrology of a specific area or a catchment depends on its topography, geology and climate. The important climatic factors like precipitation, humidity, temperature, and winds have strong effects on the process of evapotranspiration. Precipitation and various storage of water and high and low rates of runoff are highly influenced by the topography. Geology is another important factor because it influences the topography and because the groundwater zone is where the catchment's underlying rock lie.

1.5 Evaporation

Evaporation plays an important role in the calculation of the yield of catchments, the capacity of reservoirs, the size of pumping plants, the consumptive use of water by crops, and the yield of underground supplies etc. The rate of evaporation varies with the colour and reflective properties of the surface (the albedo) and differs for various surfaces exposed to or shaded from solar radiation. Solar radiation, wind, relative humidity and temperature are the main factors affecting evaporation. The process of evaporation is most active under the direct radiation of the sun since the process is endothermic. During the process of vaporisation of water the boundary between the earth and air becomes saturated. For the evaporation to continue, the saturated boundary must be replaced by drier air. As the humidity rises, its ability to absorb more water vapour decreases and evaporation slows down. So, unless the boundary layer of the saturated air is replaced by drier one, the evaporation rate will decrease. If the ambient temperature of the air and ground is high, evaporation will take place more rapidly than if they were cool. Since the capacity of air to absorb water vapour increases with the increase in its temperature, the air temperature has a double effect on the process of evaporation. Recent developments in the study of evaporation can be found elsewhere (e.g. Webb, 1975 and Hoy and Stephens, 1979).

1.6 Transpiration

A small portion of the water required for a plant is retained in the plant structure. Transpiration is the process by which water vapour escapes from the living plant, particularly the leaves, and enters the atmosphere (Ward, 1975). In the case of ground covered with vegetation, it is very difficult to differentiate between evaporation and transpiration. Consequently the process is referred to as evapotranspiration. Evapotranspiration depends on many factors, e.g. incidence of precipitation, and on the type of cultivation and the extent of vegetation. Transpiration takes place during the day under the influence of solar radiation, but at night stomata of plants close up and very little moisture leaves the plant surfaces. On the other hand evaporation continues so long as heat input is available and, of course, basically during the day time. Penman (1948) established, for the estimation of evapotranspiration, the first and most complete theoretical relationship which shows that the evapotranspiration is inseparably connected to the amount of radiative energy gained by the surface. This relationship has been widely used in Britain, Australia and the eastern part of the U.S.A. (Veihmeyer, 1964). Further development has been reported elsewhere (e.g. Penman, 1970 and Denmead, 1973).

1.7 Infiltration

In the case of the surface being completely wet, the subsequent rain must either penetrate the surface layers or run off the surface to meet a river system. Runoff or penetration depends upon the permeability of the surface. Vegetated areas are always permeable to some degree. Infiltration, therefore, takes place in all the vegetated areas. Once the infiltrating water passes through the surface layers, it then percolates downwards until it reaches the zone of saturation at the phreatic surface. The infiltration rate varies with the type of soil and is the sum of percolation and water entering storage above the ground-water table.

Horton (1945) established the first relationship for the infiltration rate as:

$$f = f_c + \mu e^{-kt}$$

where

f = infiltration rate at any time t (mm/h)

f_c = infiltration capacity at large value of t(mm/h)

$\mu = f_o - f_c$

f_o = initial infiltration capacity at t = 0 (mm/h)

t = time from beginning of rainfall (min)

k = constant for a particular soil and surface (min^{-1})

(e.g. larger value for smoother surface texture like bare soil, and smaller for vegetated surface)

A number of formulae have been proposed since then but further details can be found elsewhere (e.g. Wilson, 1974; Ward, 1975).

Approximations of infiltration losses can be made by means of infiltration indices (Wilson, 1974). One of them is the ϕ-index which is the average rainfall intensity above which the volume of rainfall equals the volume of runoff. In Figure 1.3 the unshaded area below the line represents the amount of rainfall that is not accounted as a part of runoff but as losses including surface detention, evaporation, and infiltration. This cannot be used in predicting the amount of rainfall being absorbed by the soil, because this is dependent on the state of wetness of the soil at the beginning of the rain. As the infiltration is much the largest loss in many catchments, and the infiltration capacity as well as the amount of run-off depends on the initial soil moisture, forecasting runoff is not simple.

To overcome this difficulty, to a certain degree, an 'antecedent precipitation index' (API) is used in the U.S.A. and an 'estimated soil moisture deficit' in Britain (Wilson, 1974). In the former case, soil moisture is depleted at a rate proportional to the amount in storage in the soil, whereas in the latter, evapotranspiration continuously removes the soil moisture and precipitation replaces it.

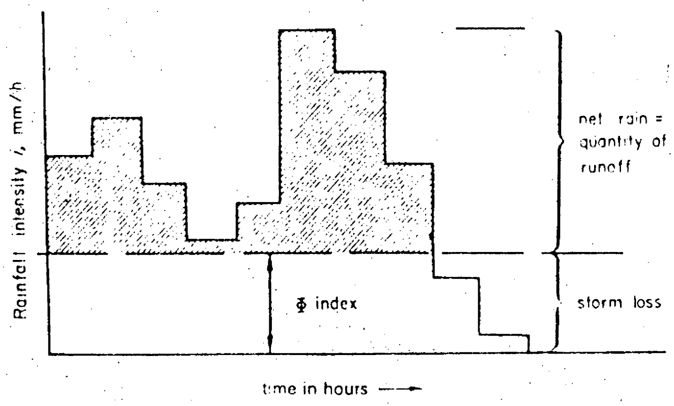


FIGURE 1.3 Infiltration Loss by ϕ-index (from Wilson, 1974)

To predict the catchment behaviour and its response to storms, it is necessary to analyse input and output of the catchment. Such analyses can be carried out with the help of 'black-box' model which will be described, in detail, later. This model establishes a relationship between total storm rainfall and total storm runoff. The validity of the relationship, however, is limited because the runoff does not vary with the rainfall alone but depends on other factors viz. intensity and duration of the rainfall and, more important, antecedent catchment moisture. At early stages of the hydrological development, the base-flow discharge was used as an indication of catchment storage at the start of a storm. One of the earliest methods to forecast direct runoff volumes was the co-axial graphical correlation method of Linsley *et al.* (1949). But, recently the antecedent precipitation index, calculated from the pattern of preceding rainfalls has been used. A number of different equations have been proposed, all of which make an assumption that the impact of rainfall on catchment storage decreases over time. This decrease in effectiveness is in the form of exponential decay. The A.P.I. for a given day is, therefore, calculated from the sum of a series of daily precipitation values, preceding that day, and each decayed according to the time elapsed between precipitation and the day in question (Weyman, 1975). Thus the A.P.I. calculated on the basis of n days preceding rainfall is written as:

$$A.P.I._n = \sum_{t=0}^{n} P_t . k^{-t}$$

where P_t: the precipitation on a day t before the calculation date, and

k : constant.

Runoff can be predicted, by using multiple regression analysis, from the combined effect of rainfall and A.P.I. Weyman (1975) has given a good numerical example. The procedures used in the present study are similar to this but have a sounder grounding in systems and estimation theory.

Using a somewhat more detailed level of analysis, Body (1975) expressed that, under Australian conditions, there could be a significant portion of the early storm rainfall totally lost to runoff. This assumption of loss effect necessitated the introduction of a gross approximation of the water balance for a catchment. The initial loss may be correlated with an indication of catchment moisture status (e.g. A.P.I.), while the ϕ-index can be related to the duration of the excess rainfall. Body (1975) argues that these approximate methods are sufficiently accurate in larger size catchments for two reasons:

1. The considerable storage available damps out short period responses to more intense rainfalls over limited areas, and the catchment contributes runoff only after initial infiltration capacities have been reduced over a significant proportion of the area.

2. The significance of spatial variation in the soil moisture content is reduced by the averaging effect caused by the extent of the area involved, in much the same way as the significance of rainfall variability is reduced when real rainfall estimates are considered.

1.8 Overland Flow

It is generally accepted that the overland flow is the result of rainfall intensities in excess of the infiltration capacity of the soil (Horton, 1945). Figure 1.4 illustrates an infiltration curve superimposed upon the histogram of storm rainfall, where the shaded area indicates the volume of water left on the ground surface. During the course of a storm, the portion of precipitation left over the surface increases, when the infiltration capacity decreases. On flat areas, or those with very low gradients, soil infiltration capacity is exceeded over the entire area of one soil type more or less simultaneously before overland flow is observed. But on slopes, where overland flow is observed, measured infiltration rates are frequently very high. The term 'overland flow' is used for flow physically over the hillslope surface, and 'runoff' is only for streamflows and not associated with any particular hillslope flow component (Carson, 1972). When overland flow occurs on slopes with a high infiltration capacity, surface water is restricted to only part of the slope. The infiltration-excess overland flow may, therefore, be restricted to the special cases of the clay soils or soils suffering from surface compaction (Weyman, 1975).

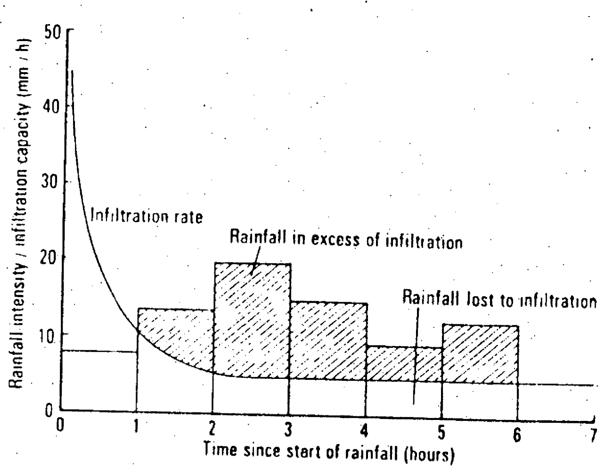


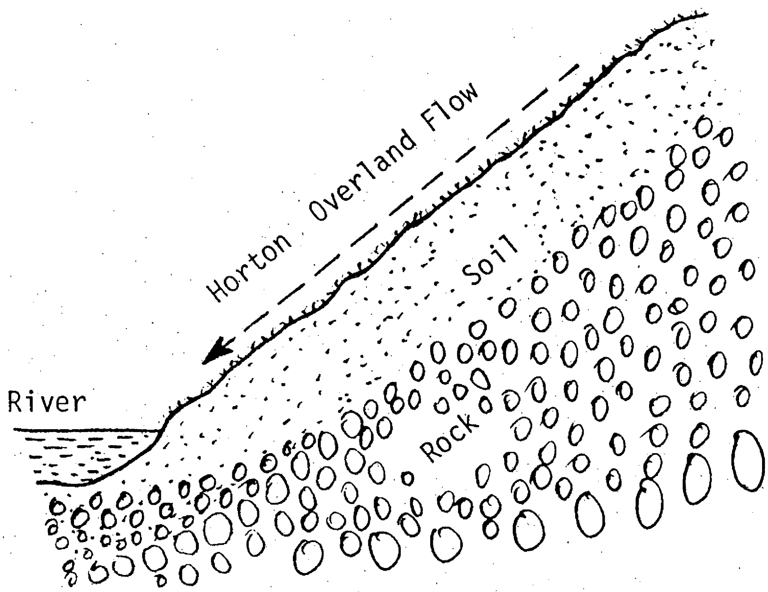
FIGURE 1.4 The Production of Overland Flow in Response to Rainfall Intensities in Excess of the Soil Infiltration Capacity (from Weyman, 1975).

Numerous assumptions have been made on the way precipitation reaches river systems from hillslope areas. Figure 1.5 illustrates the Horton (1945) Overland Flow and Saturated Overland Flow. Movement of runoff over the land surface is overland flow, whereas downslope movement within the soil profile is termed throughflow or interflow and the slower movement through the bedrock is baseflow. The flow seeping through bedrock is termed groundwater flow. These routes basically depend on various factors such as rock permeability, soil texture and depth, and rainfall intensity of the catchment under study. During the process of vertical infiltration, water can enter saturated soil into underlying unsaturated soil. However, if surface saturation is maintained by throughflow from upslope, further precipitation may not be able to enter the soil.

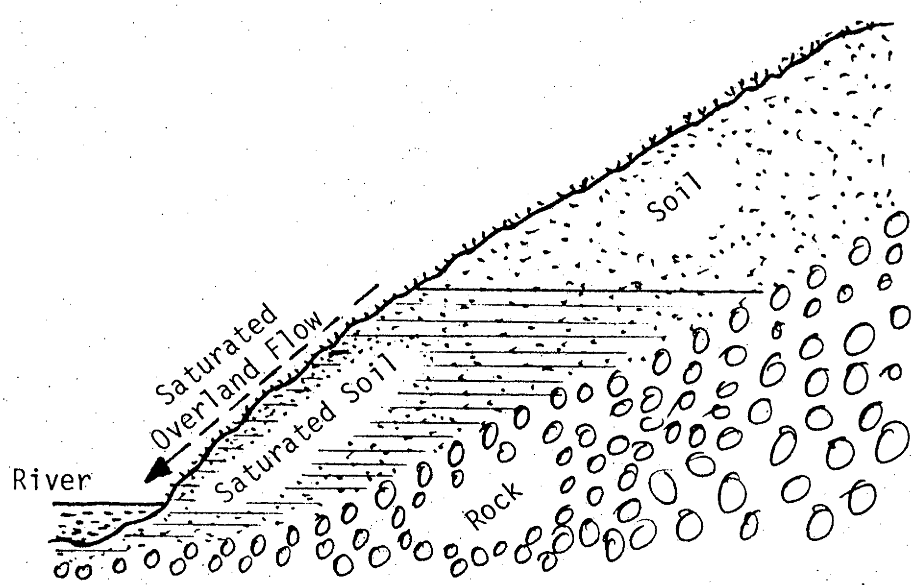
Weyman (1975) argues that the measurement of infiltration capacity under normal conditions does not reveal this characteristic, and the control or saturated overland flow is the pattern of soil moisture existing at the start of a storm or developed during the storm. The water following different routes accumulates in hollows and at the base of hillslopes before it moves laterally to join a river system. Other details of these processes can be found elsewhere (e.g. Ward, 1975).

1.9 Measurements in Hydrology

Runoff is generally measured in cubic meters per second, cumecs. There are various methods used to measure it and they fall into three categories, namely the dye dilution methods, velocity and cross-sectional area method, and methods involving the use of control structures like flumes and weirs. Precipitation is measured by a standard rain gauge



(a) Rainfall intensity more than infiltration capacity.



(b) Rainfall intensity not necessarily more than infiltration capacity.

Fig.1.5 Overland Flow on Slopes.

and in millimeters. Evaporation is directly measured from the free water surface of evaporation pans and in millimetres. But transpiration, being essentially a botanical process, is difficult to measure; direct measurement of evapotranspiration is virtually impossible. The normal practice is to take the measurement of potential evapotranspiration, which is the amount of water loss that would occur if sufficient moisture were always available for the needs of the vegetation that covers the area, and from which an actual evapotranspiration is estimated (Smith and Stopp, 1978).

Infiltration capacity of a soil-cover and soil moisture complex is determined in two ways. One is the analysis of hydrographs of runoff from natural rainfall on plots and watersheds; the other is the use of infiltrometers with artificial application of water to enclosed sample areas. However, both are subject to some error (Musgrave and Holtan, 1964).

1.10 Hydrologic Systems

Every hydraulic project requires a prior knowledge of the catchment behaviour and responses, particularly the exact magnitude and actual time of occurence of all streamflow events and their variations in the catchment. Where full details of this type are not available, various assumptions are necessary in order to derive sensible hypotheses on the hydrological system behaviour which can be tested against the available measurements. This problem has dominated engineering hydrologists' attempts to simplify complex hydrologic systems and to construct appropriate models for the prediction of the catchment responses to various natural and man-made hydraulic phenomena. Early techniques on catchment hydrology are based on the assumption that the historic hydrology of the catchment, as observed over some time, will be repeated either completely or in part. One outcome of this principle is the mass-curve of runoff analysis (Linsley, Kohler and Paulhus, 1958) which is widely used for the determination of storage yield. Further development necessitated the consideration of water balance of catchments. For small areas, Slatyer's (1967) water balance relationship over a time t is:

$$P - O - U - E + \Delta W = 0$$

where P : precipitation

O : runoff

U : deep drainage

E : evapotranspiration and

Δ W : change in soil water storage

since a catchment is of large area, this relationship has been modified (Rodda, Downing and Law, 1976) to the form,

$$P = R + E + \Delta W$$

where P : mean catchment precipitation

R : mean catchment run-off

E : mean catchment actual evapotranspiration

Δ W : mean storage change over the catchment

A systems diagram of a catchment water balance is shown in Figure 1.6, where the classic division of the hydrograph is adopted into storm runoff, interflow and baseflow components. Since no two catchments are identical in either climate or terrain, the quantity of water in each component and residence time of water in storage and runoff vary considerably from one catchment to another. It is the concern and responsibility of the hydrologist to relate the water balance and their adjustments to the local surface and subsurface characteristics on the basis of the available measurements and information.

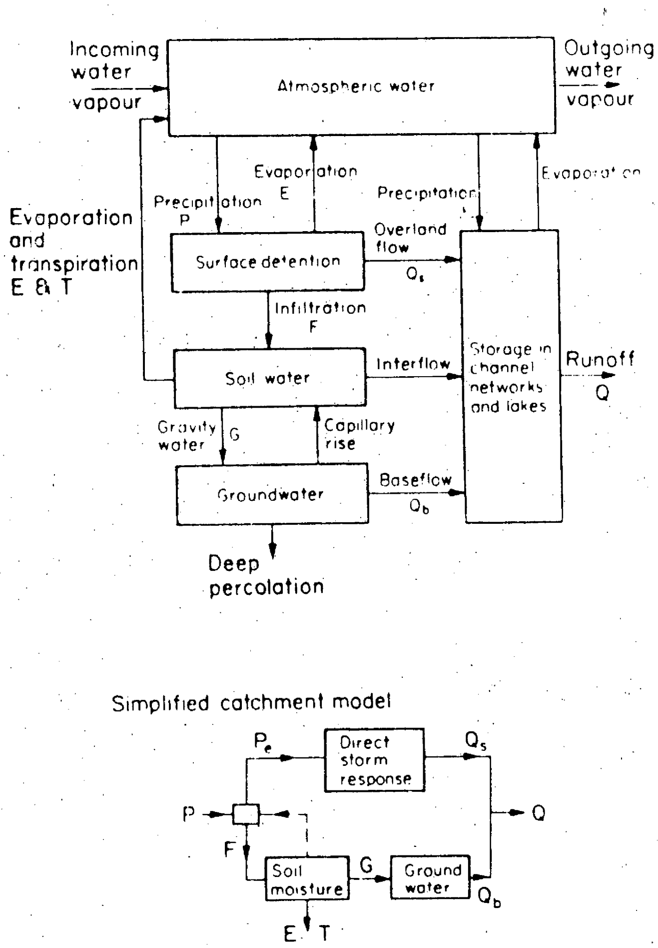


FIGURE 1.6 A Systems Representation of a Catchment Water Balance (from Rodda *et al.*, 1976).

A system has been defined in many ways. One of them is an aggregation or assemblage of objects united by some form of regular interaction or independence (Chow, 1964a). A system is dynamic if there is a temporally important process taking place in it and is stochastic if the process can only be described, at least in part, in probabilistic terms. As the representation of stochastic system is rather complex most of the hydrologic system models used up to the present have been treated in purely deterministic terms. If, in a system, the chance of occurence of the variables involved is ignored and the model is considered only in terms of a definite law of certainty but not any law of probability, the process is known to be deterministic, otherwise stochastic. A detailed analysis of stochastic processes has been given by Papoulis (1965) and Box and Jenkins (1970). And the stochastic system approach has been extensively used by Whitehead, Young and Hornberger (1979) in the Bedford-Ouse River study.

If the system consists of input, output and some working fluid (matter, energy or information) known as throughput passing through the system, it is known as sequential system (Chow, 1964a). Figure 1.7 shows a sequential system representation. A system in a real world is a physical system. So the hydrological cycle is a physical, sequential and dynamic system which operates within a set of constraints or physical laws that control the movement, storage, and disposition of water within the system and which derives its energy from the spatial imbalances between incoming and outgoing radiation (Freeze and Harlan, 1969). A system is said to be linear if none of its terms involves powers or products of the output, and non-linear if it produces an output which does not bear a simple algebraic relation to the components of its inputs (Bennett and Chorley, 1978). In the linear system, the transfer function remains constant for all magnitudes of input, whereas in non-linear one, the transfer function becomes a function of the magnitude of the input.

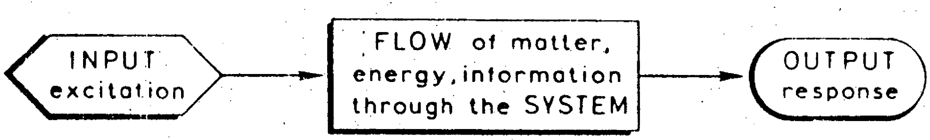


FIGURE 1.7 A Sequential System (from Ward, 1975)

In the present study, deterministic linear system of rainfall-runoff model is first analysed for the Lerderderg River basin catchment and because of the differences of this type of model, a non-linear system approach is attempted later. The study is carried out to analyse the catchment behaviour of the Lerderderg River basin on the basis of both daily data, as well as short period hourly data.
All analysis is based on time-series methodology using the CAPTAIN computer package. The fundamental aspects of this analysis are described in subsequent chapters.

CHAPTER 2

TIME-SERIES ANALYSIS METHODS IN HYDROLOGY

2.1 Unit Hydrograph

A hydrograph is a plot of stage, discharge, velocity or other properties of surface runoff with respect to time (Chow, 1964a). Both the quantity and intensity of the rainfall have a direct effect on the hydrograph. A unit hydrograph approach is normally made to study the distribution of direct runoff volume in time. This technique was first suggested by Sherman (1932). Sherman's approach is that, since a surface runoff hydrograph describes many of the physical characteristics of the catchment area, similar hydrographs will be produced by similar rainfalls occuring with comparable antecedent conditions. So, if the unit hydrograph for a particular catchment and a particular duration of rainfall is known, then the runoff from any other rainfall of any duration or intensity may be predicted, in which case a unit hydrograph functions like an impulse response of a linear system.

A unit hydrograph is the hydrograph of a unit volume of direct runoff from the entire catchment area resulting from a short, uniform rainfall (usually one inch) with an excess of unit duration (Ward, 1975). There are three hypotheses involved with the establishment of the correlation between the effective rainfall (i.e. the rain remaining as runoff after all losses by evaporation, interception and infiltration have been considered) and the surface runoff (i.e. the hydrograph of runoff minus baseflow) (Wilson, 1974):

1. For a particular catchment and for an effective rainfall of uniform intensity, different intensities of rainfall of the same duration yield different quantities of runoff but for the same period of time.

2. For a particular catchment and for an effective rainfall of uniform intensity, different intensities of rainfall of the same duration yield runoff hydrographs whose ordinates, at any given time, are in the same proportion to each other as the rainfall intensities.
3. The principle of superposition applies to hydrographs resulting from contiguous and/or isolated periods of uniform intensity effective rain.

Conventionally a unit hydrograph is generally obtained from a recorded hydrograph of a uniform isolated storm with a fairly large volume of runoff and having separated out the baseflow by dividing the discharge ordinates of the remaining direct runoff hydrograph according to the volume under the hydrograph, i.e. the hydrograph of 1 inch (or 25 mm). Figure 2.1 illustrates one where the direct runoff hydrograph representing a runoff volume of 75 mm has been divided by 3 to yield a unit hydrograph (Ward, 1975). Since the unit storm in this figure is of four hours duration, the derived unit hydrograph is referred to as a 4-hour unit hydrograph.

2.2 Unit Impulse Response

A basic result in Laplace transform theory (Sneddon, 1972 and Bracewell, 1978) concerns the relationship between two time functions $f_1(t)$ and $f_2(t)$. If $f_1(t)$ and $f_2(t)$ are Laplace transformable and have the transforms $F_1(s)$ and $F_2(s)$ respectively, then the product of $F_1(s)$ and $F_2(s)$ is the Laplace transform of $f(t)$ which results from the *convolution* of $f_1(t)$ and $f_2(t)$,

$$f(t) = L^{-1}\,[F_1(s)\;F_2(s)]$$
$$= \int_0^t f_1(\tau)\;f_2(t-\tau)\;d\tau \qquad (2.1)$$

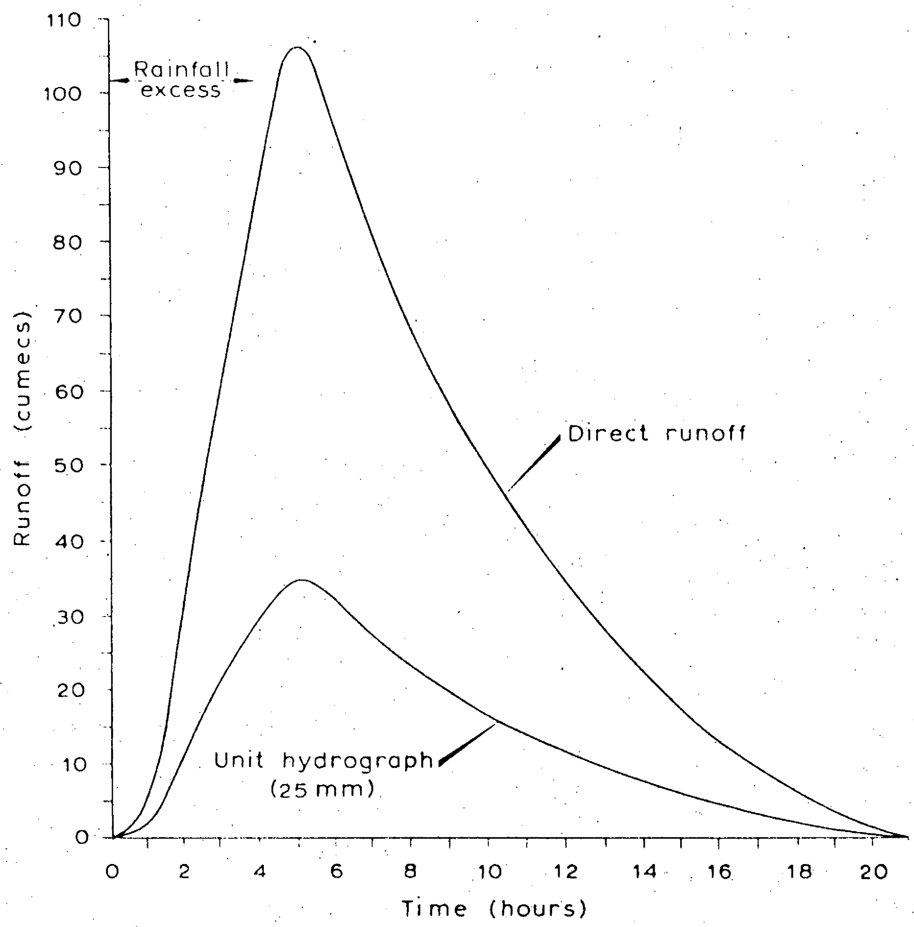


FIGURE 2.1 Direct Runoff Hydrograph (75 mm), Unit Hydrograph (25 mm), and Effective Rainfall Duration (4 hours) - (from Ward, 1975)

$$= \int_0^t f_1(t-\tau)\ f_2(\tau)\ d\tau \qquad (2.2)$$

where τ is a dummy variable for t and L^{-1} denotes inverse Laplace transform.

Now for an ordinary linear dynamic system, if all initial conditions in the system are zero, as in the case of an isolated storm, then the input and output transforms are related by an equation:

$$V_0(s) = H(s)\ V_i(s) \qquad (2.3)$$

where

$H(s)$: transfer function or system function,

$V_i(s)$: input transform, and

$V_0(s)$: output transform

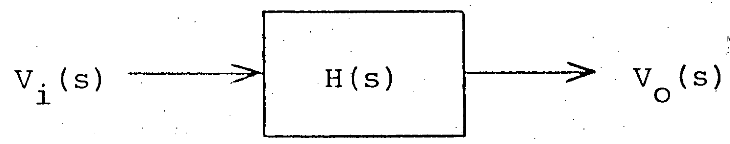


FIGURE 2.2 The Linear Dynamic System

Since $V_o(s)$ in Equation (2.3) is the product of transforms, the convolution integral can be applied as:

$$v_o(t) = L^{-1}\ [H(s)\ V_i(s)] = \int_0^t v_i(\tau)\ h(t-\tau)\ d\tau \qquad (2.4)$$

$$= \int_0^t v_i(t-\tau)\ h(\tau)\ d\tau \qquad (2.5)$$

These Equations (2.4) and (2.5) are similar to Equations (2.1) and (2.2). Now, if $v_i(t) = \delta(t)$, the unit impulse or delta function, then the transform of the unit impulse is $V_i(s) = 1$. Under this condition, $V_0(s) = H(s)$ or $v_0(t) = h(t)$ is the impulse response of the system and the inverse transform of the transfer function H(s) as well. The impulse response is thus another characteristic of the system just in the way the transfer function is. The Equations (2.4) and (2.5) suggest that if h(t), the impulse response, is known, then only the input $V_i(t)$ is to be known in order to determine the output through the convolution operation. That is to say that any input convolved with the unit impulse response yields the output.

Such unit impulse response is known as the weighting function of the corresponding linear system (Davenport and Root, 1958). Although the present output is determined by all past history of the input weighted by the impulse response, the output at any time is mainly determined by recent values of the transient input and output (Panter, 1965, Van Valkenberg, 1974). This is one good method of studying the form of the system response to particular excitation. In other words, a linear system may be described by exciting the system with an impulse function and measuring the output (impulse) response (Kuo, 1962). This method is applicable only to 'linear shift invariant systems' and provides the information on the system needed to calculate an output corresponding to a given input. But it does not necessarily provide any understanding of the internal functioning of the system (Champeney, 1973).

All mathematical models of dynamic systems are characterised by three components (Faurre and Depeyrot, 1977):

(i) time;

(ii) input quantities provide the major mechanism controlling perturbations in the system, and

(iii) output quantities show the results of the system behaviour.

As a result the mathematical model of a dynamic system can be obtained from the *statistical* analysis of time-series data. This is particularly necessary when stochastic disturbances offset the system and distort the observed input-output behaviour. Such time-series models can be expressed in linear differential or difference equations.

There are two approaches to evaluating the dynamic behaviour of stochastic systems of linear differential or difference equation type.

1. Mechanistic Approach: here the transformation of the input into the output is indirectly represented by introducing the notion of the state of the dynamic system (Beck and Young, 1975). The approach is based on the estimation of parameters in a model obtained by the analysis of both the internal mechanisms, i.e. the state equation, that governs the system operation and its external signal topology (Young, 1972). Thus, the input-output relation allows the analyst to determine

the output of the system when overall past history of the input is known. Two examples are intuitive macro-modelling of a socio-economic system, and predicting the behaviour of an automobile from its entire history and all past trips. Therefore, a state of a dynamic system is a set of quantities summarising the past in order to study the future (Faurre and Depeyrot, 1977).

2. Input-output or 'Black-box Approach': this approach utilises the external description of the dynamic system. The overall input-output relationship of the dynamic system is inferred directly from the observed input-output data. According to Eykhoff (1974), this approach is not always very realistic, although experimenters in many cases have derived some physical insight into the system model under consideration by extending the analysis to incorporate *a priori* knowledge. This may provide some information on the system, making the box more or less 'grey' or translucent.

The mechanistic approach can provide valuable information on the system functioning of the model. On the other hand, despite its limitations, the 'black-box' approach is simple in terms of its inherent parametric efficiency (i.e. the model is characterised by very few parameters). No matter how limited the information this approach provides on the internal system functioning, it offers a very useful basis for both assessing input-output behaviour and forecasting future behaviour of the output variable (Box and Jenkins, 1970).

Young (1972) has suggested a new recursive approach to the classical procedures of time-series analysis which allows for the estimation of parameters in linear as well as non-stationary dynamic systems which are subject to both deterministic inputs and stochastic disturbances with rational spectral density. It is a complementary approach to the alternative non-recursive maximum likelihood methods of Box and Jenkins (1970). For example, the recursive approach provides greater flexibility and on-line potential though, in its simplest form (see next chapter), it lacks some of the desirable statistical properties of the en-bloc methods. Before describing this recursive approach to time-series analysis, however, it is necessary to consider the nature of time-series models and their relationship to more conventional hydrological models.

2.3 The Time-Series Model

In a time-series model, the estimation of parameters is usually considered in a discrete time-series or pulse (z) transform transfer function representation of a linear stochastic dynamic system, as shown in Figure 2.3.

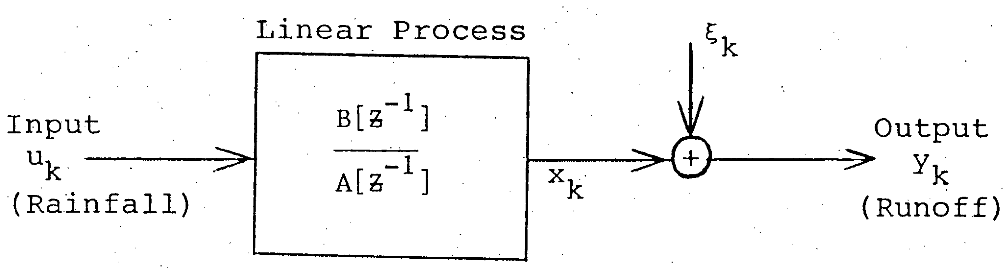


FIGURE 2.3 Rainfall-runoff Time-Series Model

In this model, the output of the system, y_k, is related to two inputs: deterministic and measurable input, u_k, and the disturbances, ξ_k. This noise input is completely uncorrelated with the deterministic input, u_k. In this study the output of the system, y_k is measured runoff flow while u_k is measured rainfall. The purpose of including the disturbance term,

ξ_k, is to consider any uncertainty arising in the overall system because it is extremely difficult to explain the real world in completely deterministic terms.

The observation of hypothetical noise-free runoff, x_k, at the k th instant is related to the past values x_{k-1}, x_{k-2}, ..., x_{k-n} and to the present and past values of the rainfall input u_k by the discrete model (Young, 1972):

$$x_k + a_1 x_{k-1} + \ldots + a_n x_{k-n} = b_o u_k + \ldots + b_n u_{k-n} \qquad (2.6)$$

The output of the whole system, then, becomes:

$$y_k = x_k + \xi_k \qquad (2.7)$$

Rearranging Equation (2.7) as $x_k = y_k - \xi_k$ and substituting this in Equation (2.6), the discrete relationship between the estimated runoff and measured rainfall becomes:

$$y_k + a_1 y_{k-1} + \ldots + a_n y_{k-n} = b_o u_k + \ldots + b_n u_{k-n} + \eta_k \qquad (2.8)$$

where the stochastic part of the system is

$$\eta_k = \xi_k + a_1 \xi_{k-1} + \ldots + a_n \xi_{k-n} \qquad (2.9)$$

which are serially correlated both in time and with y_i, i=k, ..., k-n. Equation (2.8) can now be expressed in vector form as:

$$y_k = z_k^T \underline{a} + \eta_k \qquad (2.10)$$

where

$$z_k^T = [-y_{k-1}, \ldots, -y_{k-n}, u_k, \ldots, u_{k-n}]$$

and

$$\underline{a} = [a_1, \ldots, a_n, b_0, \ldots, b_n]^T$$

From Figure 2.3, we see that the deterministic part of the system is expressed by the difference equation:

$$A[z^{-1}]\ x_k = B[z^{-1}]\ u_k$$

or

$$x_k = \frac{B[z^{-1}]}{A[z^{-1}]}\ u_k = G[z^{-1}]\ u_k \tag{2.11}$$

where the operational notation z^{-1} is the backward shift operator, e.g. $z^{-1}\ x_k = x_{k-1}$, and

$$A[z^{-1}] = 1 + a_1\ z^{-1} + \ldots + a_n\ z^{-n}$$

$$B[z^{-1}] = b_o + b_1\ z^{-1} + \ldots + b_n\ z^{-n}$$

Hence, from Equations (2.7) and (2.11)

$$y_k = \frac{B[z^{-1}]}{A[z^{-1}]}\ u_k + \xi_k \tag{2.12}$$

where $\frac{B[z^{-1}]}{A[z^{-1}]}$ is the transfer function of the system which is normally assumed to be stable, i.e. the roots of the polynomial $A[z^{-1}]$ lie outside the unit circle in the complex plane (Young, 1972).

Alternatively the Equation (2.12) can be written as

$$y_k = G[z^{-1}]\ u_k + \xi_k \tag{2.13}$$

where the polynomial $G[z^{-1}]$ is nominally *infinite* dimensional, as obtained by the division of $B[z^{-1}]$ by $A[z^{-1}]$, and is expressed as

$$G[z^{-1}] = g_0 + g_1\ z^{-1} + \ldots + g_m\ z^{-m} + \ldots + g_\infty\ z^{-\infty} \tag{2.14}$$

Therefore Equation (2.13) becomes

$$y_k = g_o\ u_k + g_1\ u_{k-1} + \ldots + g_\infty\ u_{k-\infty} + \xi_k \tag{2.15}$$

This equation gives an expression for the impulse response or weighting sequence model, in which the output flow of time k is nominally given by the weighted sum of all past values of rainfall and the noise term ξ_k (Whitehead, Young, Hornberger, 1979). For the pure deterministic case, where $u_k = \begin{cases} 1 & k=0 \\ 0 & k \neq 0 \end{cases}$, the response, y_k, to the unit impulse, u_k, is given by $y_k = g_k$, where k=0, 1, ..., ∞

It is now clear that Equation (2.15) is directly equivalent to the unit hydrograph representation. For the purpose of the present study, therefore, the unit impulse u_k is equivalent to a unit storm disturbance and the infinite dimensional unit hydrograph model can be alternatively represented by the *finite* dimensional transfer function model Equation (2.11),

$$x_k = \frac{b_0 + b_1 z^{-1} + \ldots + b_n z^{-n}}{1 + a_1 z^{-1} + \ldots + a_n z^{-n}} u_k$$

or,

$$x_k = -a_1 z^{-1} x_k - a_2 z^{-2} x_k - \ldots - a_n z^{-n} x_k + b_0 u_k + b_1 z^{-1} u_k + \ldots + b_n z^{-n} u_k$$

Eliminating backward shift operators, x_k is given by

$$x_k = -a_1 x_{k-1} - a_2 x_{k-2} - \ldots - a_n x_{k-n} + b_0 u_k + b_1 u_{k-1} + b_2 u_{k-2} + \ldots + b_n u_{k-n} \quad (2.16)$$

Thus, for example, the impulse response of the deterministic system for various observation instants, k's is given by

when k=1 $\quad x_1 = b_0 . 1 = b_o$

k=2 $\quad x_2 = -a_1 x_1 + b_1 . 1 = -a_1 x_1 + b_1$

k=3 $\quad x_3 = -a_1 x_2 - a_2 x_1 + b_2 . 1 = -a_1 x_2 - a_2 x_1 + b_2$

etc.

For other inputs, the calculation is similar provided the history of the input sequence is defined over all k. These calculations are ideally suited to digital computer solution.

As will be seen in later chapters, the model equation (2.12) characterises the rainfall-runoff data, and the impulse response obtained by estimating the $A[z^{-1}]$ and $B[z^{-1}]$ polynomials provides the unit hydrograph resulting from the direct run-off. Since instrumental variable methods of estimation are used in the time-series analysis, a prior base flow separation is not required in such analysis. In the short term response considered predominantly in rainfall-runoff analysis, the base flow can be considered as not correlated with the rainfall input. Consequently it is also not correlated with the "instrumental variables" used in the analyses. As a result, the terms involving base-flow in the estimation equations approaches to zero, i.e.

$$P \lim_{k \to \infty} \frac{1}{k} \Sigma \hat{x}_k \xi_k = 0$$

where $\hat{x}_k$ = the instrumental variable;

ξ_k = that part of the flow which constitutes the base-flow.

In other words, the base-flow is considered as additive noise for the purpose of estimation; so that the resulting model accounts only for the *direct runoff effect* of rainfall. In a real case, if the rainfall input is fed into the estimated model, its output will be "shifted" from the flow data plot by an amount equal to the base-flow (see for example Beer *et al.*, 1981); indeed this can be considered as an objective method of estimating base-flow effects.

So far, we have considered the prediction of output in terms of input of the linear system; for the present study, this means the prediction of runoff in terms of the rainfall measurement. In general, there is considerable disagreement between such predicted runoff and the measured values. This is attributed mainly to two reasons: namely the lack of consideration of (i) evapotranspiration; and (ii) soil moisture effects. These factors adversely affect the linearity of the model system. There is, therefore, a need to introduce a non-linear filter through which the input is passed to compensate for the losses due to evapotranspiration and soil moisture effects before it is fed to the linear dynamic system.

Figure 2.4 illustrates one method for achieving this. Apart from soil moisture content and evapotranspiration processes, the runoff is the function of many other components, e.g. interception, percolation, infiltration, ground water table and flow etc., which may suggest the requirement of a number of non-linear filters cascaded in addition to those in Figure 2.4. But such a detailed consideration would make the system approach extremely complicated and is not justified unless the simple approach proves inadequate (Young, 1978). In other words, the number of non-linear filters required depends on the amount of information in the time-series data as well as the purpose and limit of the intended study.

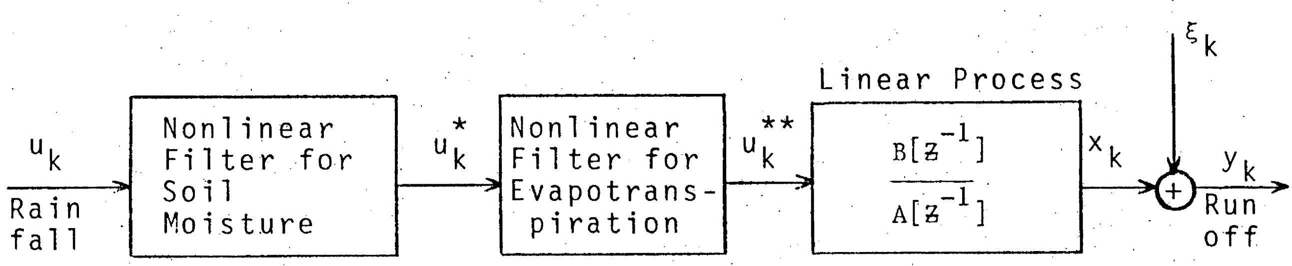


FIGURE 2.4 Linear Dynamic System with Non-linear Filter

Note that in Figure 2.4 the system relation can be written as,

$$x_k = \frac{B[z^{-1}]}{A[z^{-1}]} u_k^{**} \tag{2.17}$$

where u_k^{**} : non-linear function of u_k^*, and

u_k^* : non-linear function of u_k.

The soil moisture concept used in this study is based on the Antecedent Precipitation Index (API) approach, while the evapotranspiration effect is assumed to be highly dependent upon the prevailing temperature. We follow the approach of Whitehead, Young and Hornberger (1979) who suggested the following two relationships on evapotranspiration and soil moisture compensation:

$$r_k^* = K(T_m - T_i)\ r_k \tag{2.18}$$

where K : proportionality constant

r_k : basic rainfall

r_k^* : modified rainfall

T_i : mean monthly temperature and

T_m : overall (annual) maximum temperature

and

$$s_k = s_{k-1} + \frac{1}{T_s}(r_k^* - s_{k-1}) \tag{2.19}$$

where s_k : output of the filter, a measure of soil moisture

T_s : a 'wetting/drying' time constant to be chosen empirically.

The initial value s_o of the variable s_k is set to represent initial soil moisture characteristics and its value of unity is considered to be adequate for the present study.

In Equation (2.18), the modified rainfall measure, r_k* is the basic rainfall r_k modulated by the factor proportional to the difference between the prevailing mean monthly temperature, T_i and the overall maximum temperature, T_m. In Equation (2.19) the measure of soil moisture content is obtained by filtering r_k* through a discrete first order filter which is representative of the lag effects in the soil wetting/drying process. The final effective rainfall, u_k, is, therefore, the modified rainfall, r_k* modulated by s_k, i.e.

$$u_k = \frac{S_k}{(S_k)\max} \; r_k^* \qquad (2.20)$$

Fjeld and Aam (1980) have suggested a more complicated relationship for the soil moisture compensation in the Nordic climatic situation, as:

$$\hat{s}(t) = q_1(t) - m(s).q_1(t) - (1-\alpha(t)).q_2(s(t),t) \qquad (2.21)$$

where $\hat{s}(t)$ = output of the filter

$q_1(t)$ = flow rate to the soil moisture zone

$$m(s) = \begin{cases} \left(\frac{s}{s_{max}}\right)^{\beta} & \text{for } 0<s<s_{max} \\ 1 & \text{for } s \geq s_{max} \end{cases}$$

s = water content in the soil moisture zone

s_{max} = saturation value of s

β = arbitrary constant

$$q_2\,(s(t),\,t) = \begin{cases} q_{2\,pot}(t) & \text{for } s \geq s_{max} \\ \left(\frac{s}{s_{max}}\right).q_{2pot}(t) & \text{for } s<s_{max} \end{cases}$$

$\alpha(t)$ = average fraction of surface covered by snow, and

$q_{2pot}(t)$ = hydrological estimates or measurements, potential value which helps to compute evapotranspiration.

This was felt to be too complex for thp present study.

This study is concerned with Lerderderg River basin catchment for which no soil moisture measurement, as such, has yet been obtained, so that the hypothetical assumption in (2.19) and (2.20) is justified as an initial procedure for accounting for loss due to soil moisture effects. In the case of evapotranspiration the hypothesis is again justified by lack of other information and two temperature measures are considered; one is maximum daily temperature and the other daily dry bulb temperature measured at 3 p.m.

The estimation of parameters in A and B polynomials is based on the recursive instrumental variable method (Young and Jakeman, 1979). A description of this approach appears in the next chapter on the CAPTAIN package. The advantage of the recursive approach is that the possible parameter variation can be allowed over the observation interval and this can be used to assess the adequacy of the estimated model (Young, 1978).

In this study two types of data are used. One is a few sets of hourly data on rainfall and runoff, the other is daily data for six years, from 1970 to 1975. In Equation (2.8), the 'a' and 'b' coefficients are assumed constant parameters which are estimated using the CAPTAIN package and characterise the relationship (2.17) (Young, 1974). For this study, they are estimated for 1971, for which the catchment seemed to behave most consistently in rainfall runoff terms. As these parameters are assumed time invariant, they are used for other years to estimate the output, and, in this manner, the adequacy of the model (and the data) can be assessed.

CHAPTER 3

CAPTAIN CONCEPT

3.1 Principles

The Computer Aided Program for Time-series Analysis and the Identification of Noisy Systems (CAPTAIN) package, was first developed in 1971 (Young *et al.*, 1971). This package is based around several core programs (Young, 1969; Young *et al.*, 1971; Young, 1974) and provides the means of obtaining parametrically efficient mathematical representations of stochastic time-series data such as those discussed in the last chapter. The procedure consists of four steps: model structure identification, parameter estimation, simulation and validation.

The time-series models utilised in the CAPTAIN package are single-input-single-output (SISO) discrete time-series model (2.17). The IVAML analysis used in CAPTAIN can be split into two parts: the IV algorithm is used to estimate the deterministic model parameters; and the AML then provides an ARMA model of the residuals $y_k - \hat{x}_k$, $k = 1, 2, \ldots, N$, where $\hat{x}_k$ is the estimate of the hypothetical 'noise free' output x_k of the deterministic model and N is the sample size (Young and Jakeman, 1979). However, in this study only the IV algorithm is utilised.

The recursive IV algorithm is a technique for updating the parameter estimates on receipt of fresh information or, in some other cases, whilst working through a block of data one item at a time, as shown in Figure 3.1.

The data here are time-series data and the recursion is with respect to time. In Figure 3.1 this recursive process is contrasted with iterative processing which means the sequential processing of a *complete* set of data at each iterative step, where the data base remains

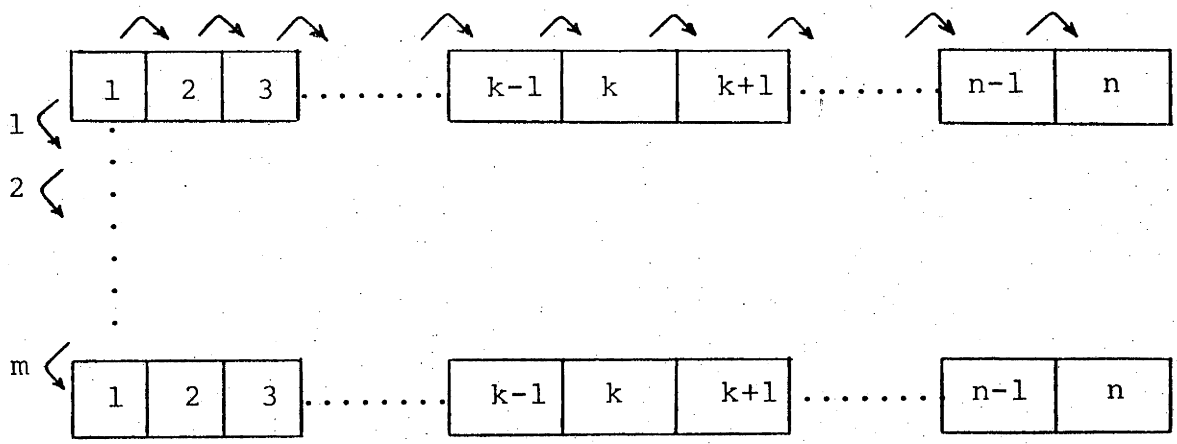


FIGURE 3.1 Recursive and Iterative Data Processing (from Young, 1975)

the same and only some estimated variable, a parametric vector, is modified (Young, 1975).

3.2 CAPTAIN Use

The CAPTAIN operating system provides the user with various options on time-series analysis that includes preliminary model structure identification, e.g. model order and time delay in SISO case (which is extensively used for this study), parameter estimation, model simulation and, finally, validation and statistical forecasting. In addition, the system also provides the user with immediate visual output on storage display screen with hard copy facility and an alternative high quality graphical output on an incremental X-Y plotter; together with the usual typewriter and line-pointer output facilities.

The diagrammatical lay-out of the complete computer aided modelling procedure is shown in Figure 3.2. The dotted path may be followed repeatedly, with visual interaction, before satisfactory results are obtained. During the operation the time-series data and programs are all available on disc file or drum and can be accessed instantly. Although the total connect time during operation is often very high, a complete analysis takes low CPU time. This is mainly due to user interaction, which is the basic usage philosophy of the CAPTAIN program. This connect time reduces with the increasing experience of the user. The visual display provides the user immediate information enabling him to take quick decision and learn and understand the system operation quickly. Further details are found in Young and Jakeman (1979) and also in CRES Users Guide to CAPTAIN.

In a typical run with the CAPTAIN package, the rainfall-flow data are inserted in file and pre-processed, using the non-linear filters, to allow for soil-moisture and evapotranspiration effects. The model time delay and order are then identified using the procedure of Young *et al.*, (1980) and estimates of the model parameters in (2.17) are obtained from the IV algorithm. This process can be repeated a number of times to allow for adjustment of the non-linear filter parameters until a satisfactory model is obtained which has reasonably constant estimated parameters, as evaluated by a time variable parameter version of the IV algorithm called TVAR. This model can then be evaluated in relation to data other than that used in the estimation exercises.

For the present purposes, the CAPTAIN package is used to find the best time-series models with and without consideration of soil moisture and evapotranspiration, and it is also used to generate their impulse responses (unit hydrographs).

As we see in Chapter 5, CAPTAIN also generates the values of the approximate standard error of the estimated a and b coefficients. These standard errors are obtained as the square root of the diagonal elements $\hat{p}^*_{ii}$ of an approximate covariance matrix $\hat{P}^*_k$ generated by the recursive estimation algorithm. Here the covariance matrix $\hat{P}^*_k$ is defined by

$$\hat{P}^*_k = E\{\underline{\tilde{a}}\,\underline{\tilde{a}}^T\} \tag{3.1}$$

where $\underline{\tilde{a}} = \underline{\hat{a}} - \underline{a}$, in which $\underline{a}$ is the vector of unknown parameters (see Equation (2.10)) in the model Equation (2.17) and $\underline{\hat{a}}$ is the IV estimate of $\underline{a}$. Note that $\hat{P}^*$ is only a conservative approximation to the true covariance matrix (Young and Jakeman, 1979); in other words it usually indicates standard errors larger than the true ones.

The model structure identification procedure in CAPTAIN is discussed in detail by Young *et al.*, (1980). It will suffice here to say that it depends upon the evaluation of the following statistics:

1. Coefficient of Determination, R_T^2
2. Error Variance Norm, EVN or its normalised form NEVN.

Young (1968) argued that the multiple correlation analysis (Brownlee, 1965) can be applied to the problem of detecting over-parameterisation. In such analysis the 'coefficient of determination' R_T^2 (Young *et al.*, 1980) is defined as:

$$R_T^2 = 1 - \frac{J_0}{\sum_{k=1}^{N} y_k^2}$$

where

$$J_0 = \sum_{k=1}^{N} \hat{\xi}_k^2 \tag{3.2}$$

$$\hat{\xi}_k = \text{residuals}$$

$$= y_k - \hat{x}_k \tag{3.3}$$

and

$$\hat{x}_k = \text{model output}$$

$$= \frac{\hat{b}_o + \hat{b}_1 z^{-1} + \ldots + \hat{b}_n z^{-n}}{1 + \hat{a}_1 z^{-1} + \ldots + \hat{a}_n z^{-n}}\, u_k \tag{3.4}$$

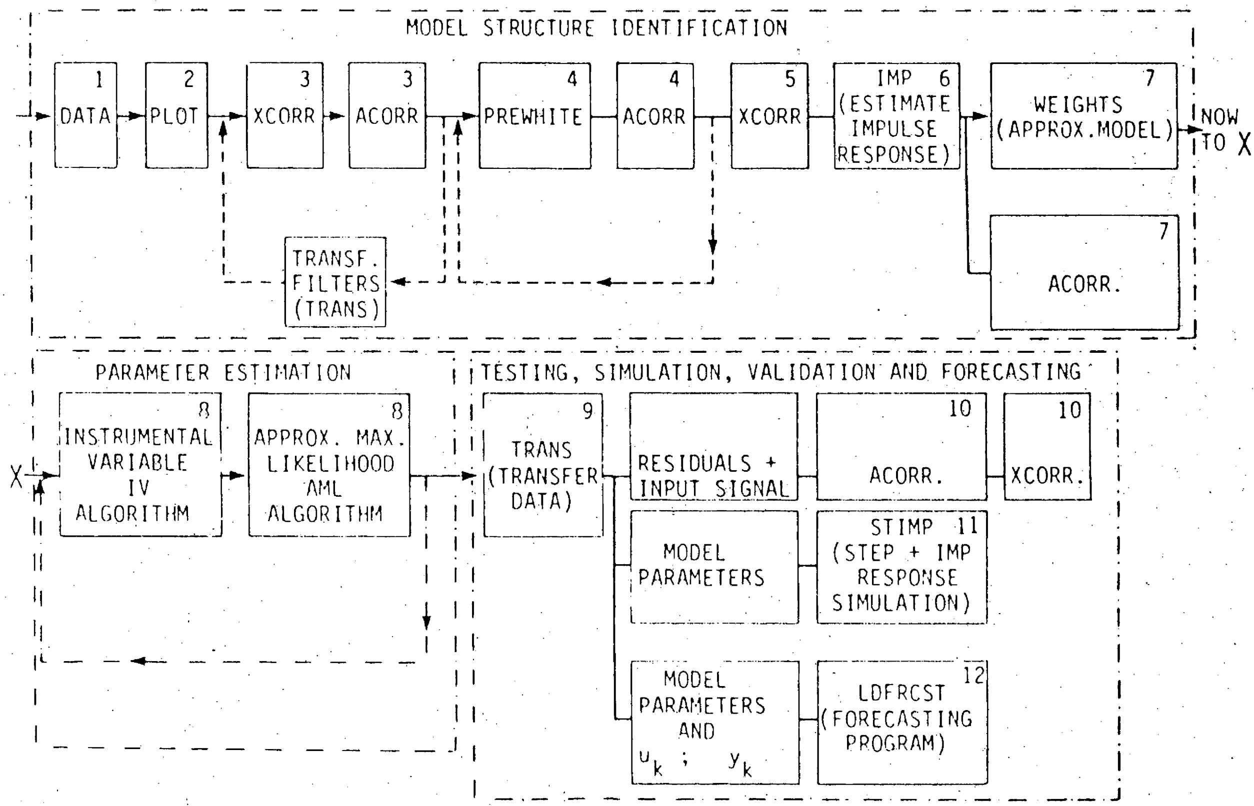


FIGURE 3.2 The Major Procedures Available in CAPTAIN (from Young and Jakeman, 1979).

The value of R_T^2 is obviously in the range of 0 and 1, i.e. $0 < R_T^2 < 1$. The R_T^2 is, therefore, a normalised measure of the degree to which the model explains the data. If the R_T^2 is unity, the model representation of the data is perfect; and if it is zero, the model fails completely.

CHAPTER 4

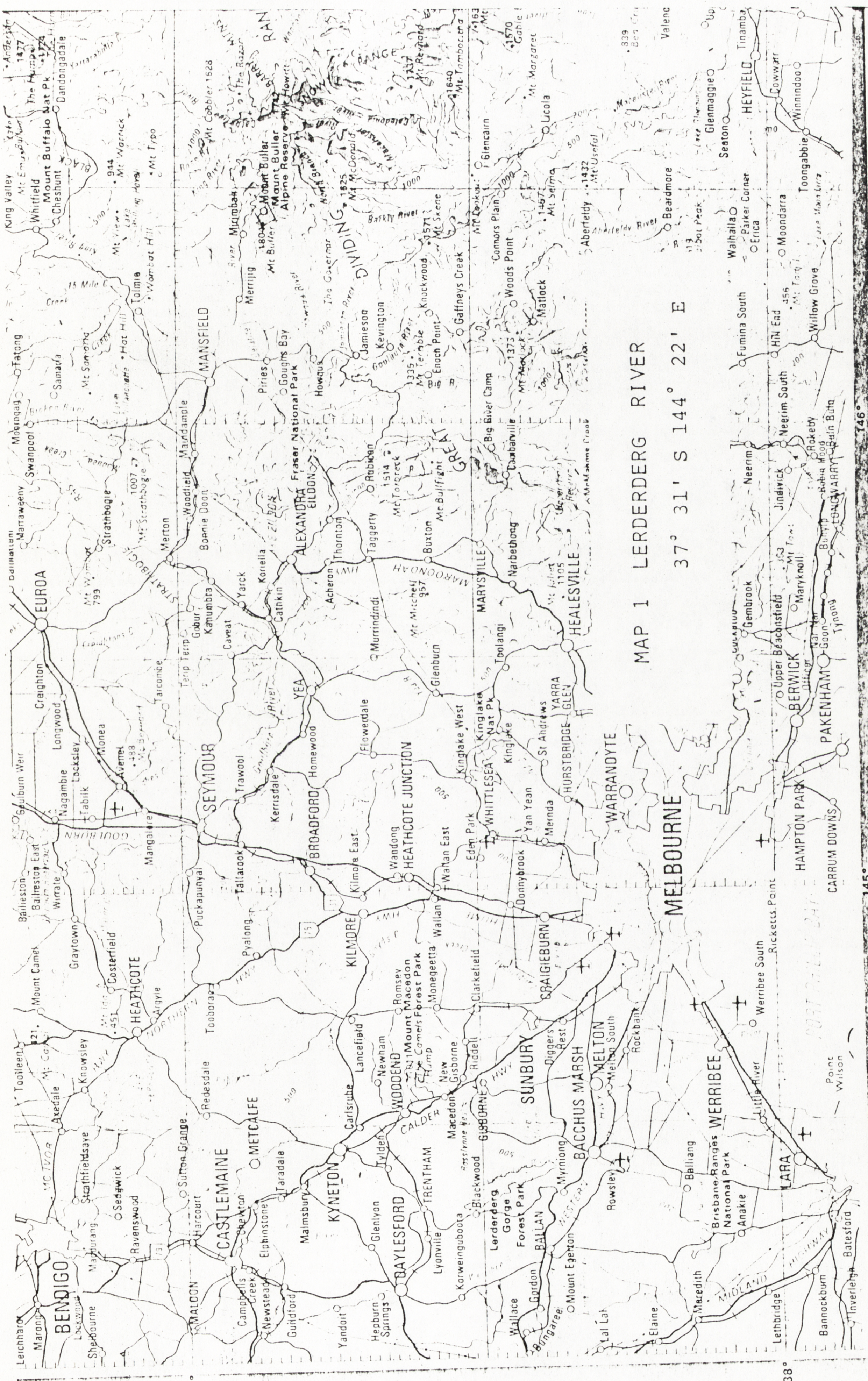
LERDERDERG RIVER CATCHMENT AREA

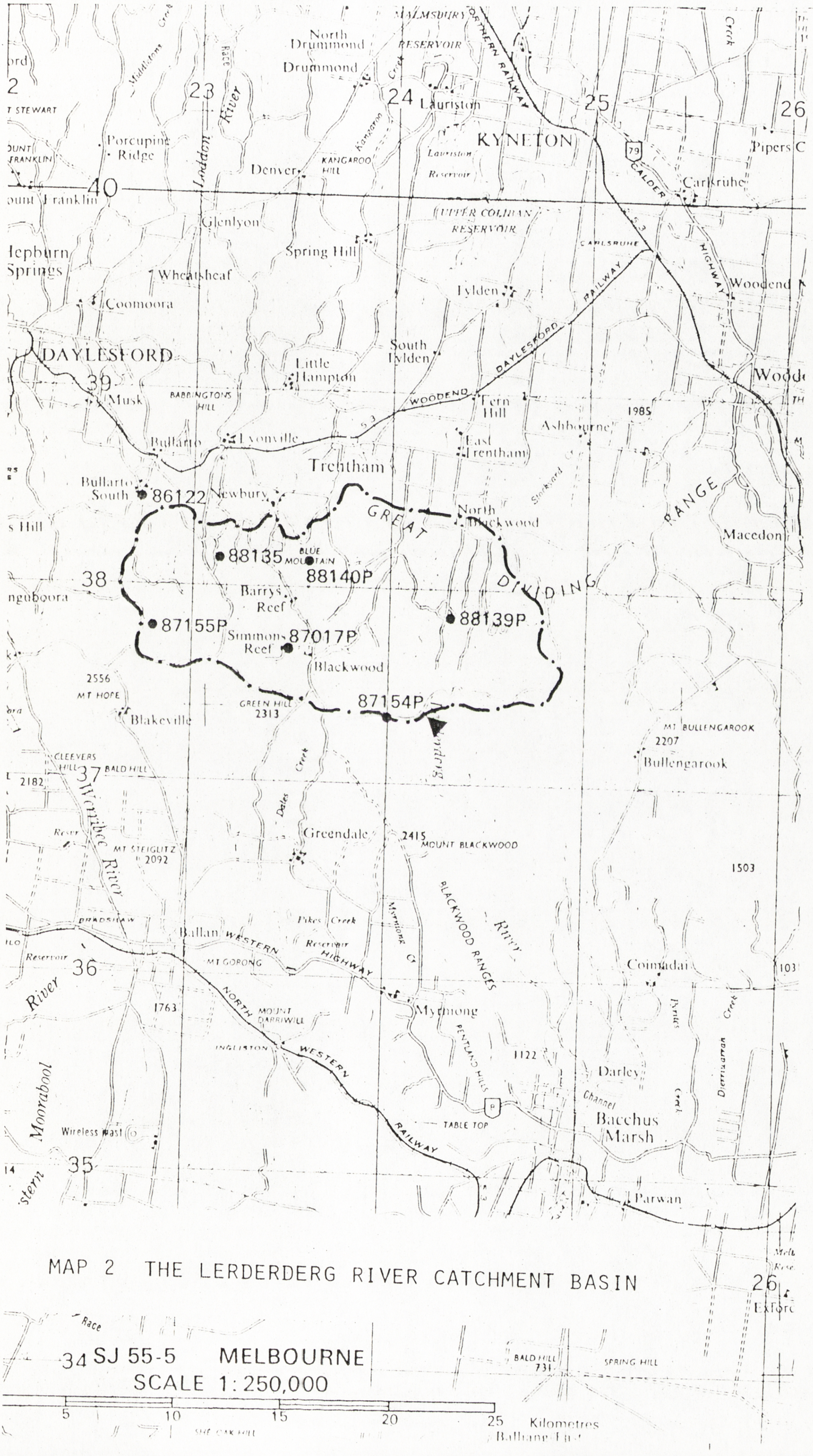
4.1 Description of the Catchment Area

The catchment area is located at distance of 27 km north-west of Bacchus Marsh, Victoria. The catchment has an area of 153 sq km and its altitude varies from 470 to 900 m from the sea level. The catchment has dissected plateaus and mountains whose basic structure consists of consolidated sedimentary rocks, shale and mudstone. The annual rainfall is in the range of 500-900 mm. There is a median annual rainfall of 610 mm and an average annual pan evaporation of 1140 mm. The geology of the area is described as folded Ordovician interbedded slate sandstone and quartzite with Pleistocene volcanics on the northern catchment boundary, and alluviated valley floor. The geomorphology is described as a high relief with a marked north-south lineation of streams due to the fold structure of Ordovician rocks. The river is contained in a gorge in lower reaches and there is a moderate relief on the volcanics with the morphology of extinct volcanoes preserved (Milne, 1975). The vegetation is basically open eucalypt forest (Williams, 1955). The area is used for timber resources with some sheep grazing (Department of Minerals and Energy, 1973). The location is shown in Map 1 (Reader's Digest, 1977), Map 2 (Milne, 1975) and Map 3 which is the Lerderderg River System in detail.

4.2 Soil Morphology

According to Northcote's classification (1962, 1975), soils in the Lerderderg catchment basin are of the Dr 2.21. The A-horizon is of clay and exhibits a blocky structure. In B-horizon, the upper layer of


MAP 1 LERDERG RIVER
37° 31' S 144° 22' E
MELBOURNE
BENDIGO
CASTLEMAINE
KYNETON
DAYLESFORD
HEATHCOTE
KILMORE
SEYMOUR
EUROA
MANSFIELD
ALEXANDRA
YEA
BROADFORD
HEATHCOTE JUNCTION
WHITTLESEA
HEALESVILLE
MARYSVILLE
WARRANDYTE
SUNBURY
MELTON
BACCHUS MARSH
WERRIBEE
LARA
WOODEND
GISBORNE
TRENTHAM
METCALFE
MALDON
BERWICK
PAKENHAM
HAMPTON PARK
CARRUM DOWNS
HEYFIELD
Lerderg Gorge Forest Park
Brisbane Ranges National Park
Fraser National Park
Mount Buller Alpine Reserve
Mount Buffalo Nat Pk
GREAT DIVIDING RANGE
144°
145°
146°
37°
38°



MAP 2 THE LERDERDERG RIVER CATCHMENT BASIN

MAP 3 THE LERDERDERG RIVER SYSTEM

Scale 1:71 280

at least 15 cm is red in colour and mottles do not exceed 10% of the soil mass (Foth, 1978). The subsoil forming the C-horizon is composed of red and red-brown clays with a Pb3 texture (Northcote, 1962) having an acid reaction with the deep subsoil pH values of less than 6.5. Peds are evident throughout the subsoil. The hillslopes have hard acidic red duplex Dy and Dr (Northcote, 1962) with occasional rock outcrops. The permeability of these soils is 'moderate' and decreases with the increase in the amount of exchangeable sodium. Leaching is said to be sufficient to prevent accumulating of lime in the profile (Stephens, 1953). Many of these soils respond very well when treated with gypsum which improves their permeability (Northcote *et al.*, 75). However, the sub-soils are very permeable (Stace, 1968).

The properties can be summarised as surface soil with sandy-loamy texture with a full range of thickness of A horizons ranging from 8-50 cm, the common range being 20-30 cm. B horizons have polyhedral or blocky to prismatic structure with the consistencies of its peds hard when dry, friable to firm when moist and slightly sticky when wet. The most common thickness of sola is 100 cm, although at full range it is 60-200 cm. The soils are generally referred to as red podzolic soils (Black, 1965).

The Lerderderg catchment area, because of its steep terrain, still remains under native hardwood forest with some grass savannah woodland. Limited parts of the catchment area is favoured for horticulture, viticulture and vegetable production and for the grazing of sheep and cattle on both natural and improved pastures (Stephens, 1953).

Two types of information are generally needed in the study of soil-water phenomena: the quantity of water contained in the soil and the energy status of soil water (Hillel, 1971). Differences in parent materials and rainfall are reflected in the principal profile forms developed. Acid soils are found in the moister areas in excess of the rainfall about 600 mm on the more acidic rocks. Unlike soil texture, which is more or less constant, the structure is highly dynamic and may change greatly from time to time in response to changes in natural conditions, biological activities and soil management practices. Further details can be found elsewhere (e.g. Stace, 1968 and Williamson and Turner, 1980).

4.3 Bushfire History

There were numerous unrecorded small scale fires in the catchment area, the first recorded fire dates back to 1921. The events can be grouped into two: big bushfires and small bushfires. Areas affected by fires are given, in shade as far as possible, in the Map 4 with the month of occurrence (Brown, pers. comm., 1981).

The 1921 bushfire originated from Leonards Hill and spread over an area of 200 ha. The fire burnt forest along the source of the Lerderderg River to Mt. Wilson attributing subsequent defects on the timber harvested during the 1930s. The second recorded fire took place at Sardine Creek in 1926 and spread over 120 ha covering Nolans Creek and south and east of the Lerderderg River. The 1939 and 1941 fires, both, originated at Green Hill and spread over an area of 200 ha; the former being a high intensity crown fire destroyed mess-mate forest in the Dales Creek. Another fire started in 1946 at the Greendale Road in Blackwood and spread over 500 ha causing severe crown damage. In 1960s there were two small scale fires, one in 1962 covering 150 ha north, south and west of the Wombat Reservoir and the other in 1967 in the Blue Mount area during drought period. In addition to these wild fires,

MAP 4 Fires in the Catchment Area

the Forests Commission also have a forest fuel reduction burning program occasionally for the protection of the forest in general as well as the township of Blackwood.

But the largest fire was recorded in 1952. It started from east of Blue Mount and lasted over three weeks damaging a huge part of the Lerderderg catchment. It burnt to Toolern Vale, Mt. Blackwood, and Myrniong damaging well over an area of 120 sq km. Another considerably big fire took place in 1965 causing damage over an area of 1,500 ha around the Barrys Reef Settlement.

4.4 Effect of Bushfire on the Soil

Fire affects both the physical and chemical properties of soil indirectly influencing the growth rate of the protective ground flora, and have some bearing on water yield, water-holding properties and the capacity of soil to resist erosion. Normally the temperature of the soil must be raised to 200°c on the surface before the physical properties of the soil are affected. But soil heating has little importance under most Australian conditions when associated with a moving flame front (Luke and McArthur, 1978).

Fires burning only the upper portion of surface litter may have a temporary effect on the capacity of the soil-litter complex to hold water and retard run-off. But fires that remove the complete soil-litter complex, including the decayed and decomposing layer are unacceptable. The intense heat radiated by such fires damage the surface materials and can cause problems of erosion. But if the intense fires produce phosphorous, it promotes rapid plant growth.

The extent of fire damage sustained depends on factors like slope, type of vegetation, soil texture and the intensity and duration of rain after a fire, as well as fire-intensity. Normally, consequences become very serious when intense rain falls on a bare catchment shortly after a destructive fire. In extreme cases sufficient silt may be carried down into dams to significantly diminish their effective life.

Wildfire brings about a considerable change on the hydrological characteristics of river catchments. The magnitude of the change varies from catchment to catchment. In U.S., Anderson *et al.*, (1976) and Tiedmann (1979) have found increases in annual streamflow for the first year after wildfire of from 9 - 1,000%, increased rainfall volumes of from 3 to 8 times and peak flow increases from double to 4 orders of magnitude. In Australia, McArthur (1964) found increases in runoff flow after bushfires in parts of Victoria and Western Australia. Mackay *et al.*, (1980) reported that, for small catchments after wildfire, the runoff from catchments were 3 to 6 times greater than expected.

CHAPTER 5

TIME-SERIES MODELLING

5.1 Data : Source and Type

There are two types of data sets used for this study, one hourly and the other daily. The hourly data are selected samples extracted from Glover's Catalogue on Hydrological Data (1979) and they are listed in Table 5.1.

Daily data were received from the Land Use Research Division of CSIRO, Canberra, on magnetic tape, from which only those for the years 1970 to 1975 were extracted. Such a selection was based on the minimum number of missing values per data set. The few missing values were estimated from the average value of the previous seven days. The rainfall data are recorded as an average value of eight stations: 87017, 87075, 87122, 88059, 88115, 88133, 88135 and 88136. Runoff (discharge) data were recorded at station 231213 and missing values were estimated either from other discharge data or from the climatic data. Evaporation data were measured at 3 stations 87005, 87036, 88019 using Class A evaporation pans. Missing values were estimated from either saturated deficit formula or maximum and minimum temperatures. Two types of temperature measurement are used, one being daily maximum temperature and other dry-bulb temperature recorded at 3.00 p.m. Details of station codes, estimation and interpolation of various missing data, decoding data from the magnetic tapes and other aspects are found in AWRC (1969, 1974, 1976) and Body *et al.*, (1979). A concise map (Milne, 1975) with a few of these stations is shown on Map 2. Both maps, Map 1 and Map 2, give an idea on the location of the catchment area with respect to Melbourne, Dayelsford and Bacchus Marsh. Maps 1 and 2 are given in Chapter 4 on pages 39 and 40.

5.2 Hourly Data Analysis

The Codes used for running CAPTAIN along with their corresponding pluviographic and hydrographic stations, time when the measurement commenced, and the number of data points are tabulated in Table 5.1.

The CAPTAIN package is used to produce plots for input; output model with and without the consideration of soil moisture; evapotranspiration time constant, T_s; and impulse responses. Figures 5.1 - 5.5 show the rainfall for 612, 661, 662, 663 and 664, and Figures 5.6 and 5.7 the corresponding runoff plots. Fig.5.8 shows the model output for 612 raw data for one a and four b coefficients in the transfer function model. Note that, for this study, the *dotted line* in every model output plot represents the plot for observed value and the *full line* represents the model output, while the *full line* below them represents the error $\hat{\xi}_k$. In this figure, R_T^2 has a value of 0.7370, i.e. 73.7% of the variance in the runoff is accounted for by the model. The error variance measure log (NEVN) is -0.777.

Figures 5.9 and 5.10 show the results for models of 612 obtained with effective rainfall inputs adjusted to allow for soil moisture effects (equation 2.19) using T_s values of 5 hours and 10 hours respectively. The values of R_T^2 and log (NEVN) values have now been considerably improved to 0.96 and -2.2 respectively. Various other soil moisture time constants were tried but 5 hours was found to be a minimum and 10 hours a maximum time constant that can be considered for this specific set of data at this specific time of the year. Since 96.1% of the variance in the runoff is accounted for by the model, it would seem that the effective rainfall modification, which is simply the exponential weighting of rainfall into the past used to provide a multiplicative non-linear modification of the input raw rainfall series, is well justified.

TABLE 5.1 Hourly Data Sets

Code	Pluviographic Station	Hydrographic Station	Recorded from	No. of Data Points
612	87153	231213	01.00 Hrs 04.02 1973	167
661	87155	"	06.00 Hrs 13.05 1974	160
662	87153	"	"	"
663	87152	"	"	"
664	87017	"	"	"

Figure 5.11(a) gives the impulse response for the model with unmodified input series for the whole range of data points, whereas Figure 5.11(b) gives the same plot with an amplication of the important section of the response. Here, we see the response has increased to a peak value of 1.20, whilst in Figures 5.12 and 5.13, which show the impulse responses for the non-linear models, the peak value of the impulse response is much higher. In Figure 5.12 where T_s is 5 hours, the response goes up to 1.73 whereas in Figure 5.13 for T_s of 10 hours, it goes over 1.75. It is also evident from the comparison of R_T^2 value and log (NEVN) values for one a and one b, and for the best identified model (see Table 5.2), that the model with T_s of 10 hours is better than for T_s of 5 hours.

The transfer function, $\frac{B[z^{-1}]}{A[z^{-1}]}$ for each model is given by

$$\frac{-0.2407 + 0.1284Z^{-1} + 0.5457Z^{-2} + 0.7586Z^{-3}}{1 - 0.9108Z^{-1}} \quad \text{for Figure 5.11,}$$

TABLE 5.2 R_T^2 and Log (NEVN) values for Hourly Data

File Code	T_s Hrs	For one 'a' and one 'b'		Best Identified Model		
		R_T^2	Log (NEVN)	For a's, b's	R_T^2	Log (NEVN)
612	0	0.2994	-1.954	1,4	0.73701	-0.77695
"	5	0.45339	-2.0430	2,3	0.96166	-2.2251
"	10	0.48929	-2.157	2,3	0.96144	-2.2396
661	0	0.81723	-2.0688	2,1	0.86395	-0.90464
"	8	0.94813	-2.983	1,2	0.97073	-1.7022
"	10	0.94692	-2.9059	1,2	0.96876	-1.6645
662	0	0.80983	-1.9533	2,1	0.88094	-1.412
"	5	0.8957	-2.3164	2,1	0.94436	-2.1653
"	10	0.90946	-2.3939	2,1	0.93846	-2.0379
663	0	0.86681	-2.4765	1,1		
"	10	0.93721	-2.8272	1,1	As Col.3	As Col.4
"	15	0.94221	-2.9161	1,1		
664	0	0.78159	-2.0087	1,1		
"	10	0.92752	-2.8419	1,1		
"	15	0.93024	-2.7870	1,1		

Notes: 1. Number of points available are 167 for file 612 and 160 for the rest.

2. T_s value of zero means the model without consideration of soil moisture.

$$\frac{-0.2028 + 0.3036Z^{-1} + 0.8581Z^{-2}}{1 - 1.5457Z^{-1} + 0.6045Z^{-2}} \qquad \text{for Figure 5.12 and}$$

$$\frac{-0.2468 + 0.3415Z^{-1} + 0.9319Z^{-2}}{1 - 1.5159Z^{-1} + 0.5789Z^{-2}} \qquad \text{for Figure 5.13}$$

The respective steady state gain (SSG), $\frac{B[1]}{A[1]}$, for each model, which is also the area under the impulse response curve, are as follows:

$$SSG_{5.11} = 13.363, \; SSG_{5.12} = 16.308 \text{ and } SSG_{5.13} = 16.295$$

These figures mean that, for example, in the case of the model of Figure 5.11, 1 mm of effective continuous rainfall results in 16.3 cumecs runoff at steady state.

The R_T^2 and log (NEVN) values for models with only one a and one b coefficients, as well as those for the best identified model (usually with more than one a and b coefficient) are given in Table 5.2 along with other information such as the code for specific set of data, number of data points and whether or not soil moisture effects are taken into account. In Figures 5.11 - 5.13, it will be noted that the initial response is small and *negative*. Clearly negative response is not acceptable in physical terms and the reason for this behaviour can be found in the model specification: here a pure time-delay should have been introduced into the model to allow for the pure time lag between rainfall occurrence and its effect on run-off flow; since this was not introduced, the IV estimator in CAPTAIN has indicated small and, in statistical terms, *insignificant* negative responses. Strictly the model should have been re-estimated with the pure timedelay introduced, but this was not considered necessary in the present study since it would make little difference to the overall estimated impulse response characteristics.

For the data set 661, Figures 5.14 - 5.19 give the model outputs and impulse responses. Here we notice that the non-linear model with a T_s of 8 hours has R_T^2 of 0.94813, i.e. 94.813% of the variance in the runoff is accounted for by the model.

Tables 5.1 and 5.2 and Figures 5.20 to 5.43 show the results for the data sets 662 to 664: 662 has best model for T_s of 5 hours with R_T^2 value of 0.944; 663 for T_s of 15 hours with R_T^2 value of 0.942; 664 again for T_s of 15 hours with R_T^2 value of 0.930. From these results we can say that the runoff is more closely correlated with the effective rainfall value for data set 661 than for the others. We also notice that set 612, for 4th February 1973, took more parameters than 661 for 13th May 1974. We can, therefore, say that, for the short term response in the catchment, the number of parameters required for the estimation would appear to be the function of seasonal conditions.

Looking into the log (NEVN) values which are mostly more negative than -2, we can say the average percentage of parameter variance is very low. For example for the date set 663 with T_s value of 15 hours, log (NEVN) = -2.9161, NEVN = $e^{-2.916}$ = 0.05, i.e. the average percentage error variance on the estimates is about 5% of the parameter values.

5.3 Daily Data Analysis

Daily data analysis is carried out in three different ways:

(a) considering the raw rainfall as sole input;

(b) considering the raw rainfall minus evaporation as the input; and

(c) modifying the raw rainfall by the following formula (Whitehead *et al.*, 1979) to get the input:

$$r_k^* = K(T_m - T_i)\, r_k \tag{5.1}$$

where K = proportionality constant (= 1 for this study)

r_k = measured rainfall

T_m = overall (annual) maximum temperature

T_i = mean monthly temperature and

r_k^* = modified rainfall

In all three cases the rainfall so obtained is modified to allow for soil moisture effects, in a manner similar to that used in the hourly data analyses.

Six years' daily data, from 1970 to 1975, of rainfall, maximum temperature, dry bulb temperature measured at 3 p.m., evaporation and discharge are considered. Their respective plots are given in Figures 5.44 to 5.73.

5.3.1 Analysis of Rainfall and Runoff Data Without Evaporation or Temperature Compensation

Figure 5.74 to Figure 5.79 give raw data models for the six years and Figure 5.80 to Figure 5.85 their respective impulse responses. In Table 5.3, it will be observed that the R_T^2 values are very poor: the highest R_T^2 of 0.5282 is obtained for 1975 and second highest R_T^2 of 0.4589 for 1971. Taking soil moisture effects into account, various values of T_s were considered. Those with a T_s value for 5 days are reasonable for all the cases. The R_T^2 and log (NEVN) values improved considerably for 1971 and 1975, whereas for 1972 and 1973 they became worse (see Table 5.3). The poor results for 1972 and 1973 may be due to two reasons:

1. The year 1972 was a very dry year and effects on soil moisture content of the catchment, ground water and soil structure lasted until the following year (see Figures 5.46 and 5.71).

TABLE 5.3 R_T^2 and Log (NEVN) values for Daily Data (RAINDIS)

File Code	T_s Days	For one 'a' and one 'b'		Best Identified Model		
		R_T^2	Log (NEVN)	For a's, b's	R_T^2	Log (NEVN)
70	0	0.26945	-5.3370	1,2	0.42448	-4.6352
"	5	0.23319	-4.9120	1,2	0.42762	-3.8753
71	0	0.44475	-5.5224	1,2	0.45894	-4.5088
"	5	0.71698	-6.1212	1,1	0.71698	-6.1212
72	0	0.29079	-6.3026	1,3	0.37458	-5.9470
"	5	0.016426	-5.7306	1,3	0.16766	-5.1401
73	0	0.25802	-5.6308	1,3	0.42327	-4.6467
"	5	0.093402	-5.0101	1,3	0.26841	-4.0484
74	0	0.24377	-4.9118	1,2	0.29688	-4.1263
"	5	0.40348	-5.1762	1,2	0.45390	-3.7543
75	0	0.47160	-5.8539	1,2	0.52820	-5.2075
"	5	0.69152	-6.3425	1,2	0.73318	-5.6283

2. The dry conditions affected the young vegetation in the area destroyed by the 1957 and 1965 fires (see Map 4).

The peculiar nature of the 1972 year is also clear from the impulse responses: in Figures 5.82 and 5.94 it will be noted that the peak values are much smaller than for any other year indicating the much reduced run-off per unit effective rainfall in this year.

For 1971, 71.7% of the variance in the runoff was accounted for by the model (Figure 5.87), where for 1975, it was 73.3% (Figure 5.91). Their respective log (NEVN) values are -6.12 and -5.63, i.e. the average percentage of parameter variance is less than 0.6%.

Since the 1971 values for R_T^2 and log (NEVN) are best, the parameter values of this model are imposed on the models for other years in order to obtain R_T^2 values for comparative study. These models are represented by Figures 5.98 - 5.102. For example, R_T^2 for Model Figure 5.102 is 0.6289 whereas same for Model Figure 5.91 is 0.73318. In other words, for 1975 the 1971 model provides quite a good explanation of the data, although not as good as for the model estimated from the 1975 data. We notice that the short-term response from the hourly data analysis is explained much better than the long-term response from the daily data analysis of the catchment. Note that in the hourly data case the T_s value is in hours whereas in daily data, the T_s value is in days. The difference in the magnitude of the T_s values for the hourly and daily data is surprising but it has not been possible to account for this difference in the present study. It should, however, receive further attention in any future research on this system.

5.3.2 Analysis of Effective Rainfall and Runoff Data with Allowance for Evaporation Effects

Here, the analysis is based on a very straight-forward method in which the input is modified by simply subtracting evaporation from the rainfall.[†] The rest of the analysis is the same as in 5.3.1. Figures 5.103 - 5.108 give the plots for modified inputs; Figures 5.109 - 5.14 models for modified input and measured runoff; Figures 5.115 - 5.120 the respective impulse responses. Models with allowance for soil moisture effects of 5 days are represented by Figures 5.121 - 5.126 and their respective impulse responses by Figures 5.127 - 5.132. Finally Figures 5.133 - 5.137 represent the model where values of the estimated a and b parameters for the 'best year' model, Figure 5.122, are imposed upon other years.

Comparing R_T^2 and log (NEVN) values from Tables 5.3 and 5.4, we notice that those in Table 5.4 have not improved. From impulse responses too, we see that there is not much difference. In both of the cases for 1971 where allowance is made for soil moisture effects, the R_T^2 has the same value of 0.717, i.e. 71.7% of the variance in the runoff is accounted for by the model. The respective transfer functions are given by

$$\frac{.74148}{1 - .44222z^{-1}}$$

with SSG = 1.33 for SUB71 (Figure 5.122)

and,

$$\frac{.64943}{1 - .42302z^{-1}}$$

with SSG = 1.13 for RAINDIS71 (Figure 5.87)

---

† The rainfall, of course, is set to zero when the evaporation exceeds the rainfall.

TABLE 5.4 R_T^2 and Log (NEVN) values for Daily Data (SUB)

File Code	T_s Days	For one 'a' and one 'b'		Best Identified Model		
		R_T^2	Log (NEVN)	For a's, b's	R_T^2	Log (NEVN)
70	0	0.26765	.52767	1,2	0.42966	-4.5303
"	5	0 *	*	1,2	0.41724	-3.3157
71	0	0.46265	-5.6833	1,2	0.47908	-4.6773
"	5	0.71672	-6.2200	1,1		
72	0	0.31604	-6.4553	1,3	0.41934	-6.2283
"	5	0.059713	-5.9356	1,3	0.22457	-5.0400
73	0	0.26537	-5.6358	1,2	0.40629	-5.3766
"	5	0.075794	-4.9477	1,2	0.21810	-4.5859
74	0	0.26522	-4.9573	1,1		
"	5	0.41281	-5.1632	1,1		
75	0	0.49761	-5.9075	1,1		
	5	0.66555	-6.2042	1,1		

* The model is unstable.

That is, for Model Figure 5.122, 1 mm of continuous effective rainfall results in 1.33 cumecs flow at steady-state whereas for Model Figure 5.87, the flow is 1.13 cumecs flow at steady-state.

Attempts were made to study the model response with parameter values set to those estimated for 1971. For example, for RAINDIS75 (Figure 5.102) R_T^2 is 0.6289 whereas the same model (Figure 5.91), with allowance for soil moisture effects (T_s = 5 days), yields R_T^2 value of 0.733. For SUB75 (Figure 5.137), the R_T^2 value is 0.5764. On the other hand, the same model (Figure 5.126) with allowance for soil moisture effects (T_s = 5 days) yields R_T^2 value of 0.6655. So, in general, it would appear that allowance for evaporation effects by simple subtraction does not significantly improve model fitting.

5.3.3 Analysis of Effective Rainfall and Runoff Data with Allowance for Temperature Effects

In this section of the chapter, data are considered with an allowance for the temperature effects. Both maximum temperature and drybulb temperature at 3 p.m. are used in separate analyses.

Considering the drybulb temperature first, the input rainfall is modified as described in the second chapter by the equation (Whitehead *et al.*, 1979)

$$r_k^* = K(T_m - T_i)\, r_k$$

where the proportionality constant k is considered to be unity. Plots for the modified rainfall are given in Figures 5.138 - 5.143.

The model results allowing for drybulb temperature effects are given by Figures 5.144 - 5.149 and their impulse responses by Figures 5.150 - 5.155. The model results allowing for dry-bulb temperature, as well as soil moisture effects, are shown in Figures 5.156 - 5.161 whereas their impulse responses are given in Figures 5.162 to 5.167. Other model responses with parameter values set to those estimated for 1971 (Figure 5.157) are given in Figures 5.168 - 5.172. All R_T^2 and log (NEVN) values are recorded in Table 5.5.

Note that the R_T^2 and log (NEVN) values are considerably improved compared to those in Tables 5.3 and 5.4. For example the R_T^2 value for 1971 increased from 0.717 to 0.802, i.e. 80.2% of the variance in the runoff is now accounted for by the model. Its transfer function is given by

$$\frac{0.0243}{1 - 0.4048z^{-1}}$$

and SSG = 0.04083 which is the area under the hydrograph. That is, 1 mm of continuous effective rainfall results in a flow of 0.041 cumecs at steady-state condition. Apart from this, we also notice that the log (NEVN) value -6.1212 in Table 5.4 has gone more negative to -7.0036 as shown in Table 5.5 as well as in Figure 5.157, meaning thereby that the model parameters are both defined and the average percentage of parameter variance is less than 0.1%.

Using the daily maximum temperatures, the analysis was repeated exactly the same way as for dry bulb temperatures. The results did not bear any significant difference as compared with those for dry bulb temperatures and, therefore, were not included here.

TABLE 5.5 R_T^2 and Log (NEVN) values for Daily Data (BED)

File Code	T_s Days	For one 'a' and one 'b'		Best Identified Model		
		R_T^2	Log (NEVN)	For a's, b's	R_T^2	Log (NEVN)
70	0	0.20285	-5.4119	1,2	.26207	-4.9941
"	5	0.13433	-5.0823	1,2	.15867	-4.5020
71	0	0.51081	-6.2426	1,1	As Col.3	As Col.4
"	5	0.80256	-7.0036	1,1		
72	0	0.37619	-6.6851	1,4	.45515	-6.6081
"	5	0.30729	-6.5889	1,4	.47222	-6.8384
73	0	0.32098	-6.3326	1,3	.50177	-5.2974
"	5	0.30146	-6.1525	1,4	.52256	-5.4131
74	0	0.27805	-5.6647	1,2	.33855	-4.8638
"	5	0.44989	-6.1204	1,2	.50554	-4.2004
75	0	0.49833	-6.5596	1,2	.55856	-5.9064
"	5	0.71018	-7.2006	1,2	.75255	-6.5220

The R_T^2 and log (NEVN) values in Table 5.5 are far better than those in Tables 5.3 and 5.4. In other words, it would appear that consideration of temperature effects helps to obtain a far better model than those without allowance for temperature effects. This is in contrast to the situation where evaporation information is utilised.

Finally, note that throughout this analysis the SSG values for the hourly data are much higher in magnitude than those for daily. This is because of the difference of scale, i.e. one unit of day scale makes 24 units of hour scale; whereas the vertical axis for runoff remains in the same scale.

5.4 Discussion

We see that the ability to model the short-term response of the catchment is not the same as that for the long-term response. Hourly data analyses give models which are much better (in terms of R_T^2) than those for daily data. This is probably because the various factors affecting the model have not changed considerably in a short period (a few days), whereas they vary considerably with daily data over a whole year. And while allowance for temperature effects improves the situation in the daily data case, there is still room for further improvement.

As regards the impulse responses: in the daily data case, all the plots of impulse responses for 1972 show that they have very low peak value amplitudes compared to those for other years. This confirms that 1972 was a very dry year at the Lerderderg river catchment area. With other impulse response curves, there are different peak values at different conditions and years, showing the dynamic characteristics of the catchment. It would be advantageous to consider this variation in peak values further and so attempt to achieve better model-fitting results, but the author did not have time to carry out such analysis, which clearly deserves further attention.

The fact that long term non-linearities appear to be accounted for by temperature rather than evaporation variations is interesting and reflects results obtained from the analysis of other Australian data. Research into this aspect of the present results is strongly recommended but the author did not have time to pursue such an investigation in the present study.

CHAPTER 6

CONCLUSIONS

Civilization is primarily dependent on water supply for various purposes; for example, drinking, irrigation, industry, power generation and transportation. As a result, studies on hydrology have always been important. And study of catchment behaviour is one of the most important aspects of hydrology. Time-series data analysis, as considered here, is only one method of studying river catchment behaviour in order to predict future events; on the other hand, it is a very easy and systematic method with built-in allowance for stochastic effects in the rainfall-runoff process. The main difficulties with rainfall-runoff models are due to the inter-relationships between many of the variables which make some of the basic assumptions of the methods untenable. The Lerderderg river catchment area has a history of many wild fires frequently causing considerable destruction to its natural vegetation and forest. In cases where the dynamic characteristic variation become large, Kuo (1962) argues that the system modelling under the assumption of known transfer characteristic may fail to provide a satisfactory guidance. However, by using recursive methods it is possible to allow for the modification and adjustment of the system models in accordance with varying parameters and environment in order to attain optimum management of the system.

As there is no data on soil moisture available for the catchment, we have made extensive use of the non-linear soil moisture compensation algorithm in CAPTAIN to allow for these effects. This "soil moisture" compensation is closely related to the Antecedent Precipitation Index (API) used in hydrology and it has, therefore, no greater nor any less degree of hydrological reality than the API. However, it should be noted that "hydrological reality" is a subjective term. For a poorly defined system like the Lerderderg River basin catchment where neither detailed nature of the hydrological processes can be studied nor planned experiments are possible, it is very difficult to point out what the most important hydrological processes are. The time-series method adopted in this study is aimed at identifying the dominant non-linearities and if possible associating these with recognisable physical processes. It has been clearly shown that temperature rather than evaporation explains non-linear behaviour of the system in the *long term*. At this stage it is still difficult to make any speculation on the reasons for this. Similar behaviour has been reported in previous studies such as Body *et al.*, (1979). Whitehead *et al.*,(1979). This, therefore, needs further attention.

In view of the above observations, it is advisable to take great care in drawing physical hydrological conclusions from the time-series analysis. Such an analysis method should be considered as a hypothesis generating device leading to further re-evaluation in physical hydrological terms. On the other hand, the conventional analysis methods which use such term as API or "estimated soil moisture deficit" methods are no less vulnerable. This is because the latter methods are themselves only mathematical devices, the physical significance of which has been often claimed, but they have been rarely validated in any satisfactory sense.

Exposed soils can become almost impermeable by the compacting impact of large rain drops coupled with the tendency to wash very fine particles into the empty spaces, thereby decreasing the infiltration capacity. Whereas dense vegetal cover promotes the infiltration capacity. So, the old vegetation and young vegetation in the fire-affected areas respond to the rainfall differently, as we have seen in the time-series results for 1972.

One of the drawbacks of rainfall-runoff modelling is the unknown quantity of underground outflow and the variation in underground outflow and the variation in underground aquifer storage. So the dividing line between runoff and baseflow is indeterminate and can vary widely. It is, therefore, not possible to analyse every mechanism of the system with limited resources of data. But the great advantage of the time-series analysis approach is that statistical parameter estimates are obtained, together with the degree of uncertainty associated with those estimates. In addition, because of the recursive nature of the estimation algorithm, information on the model stability may be assessed by an inspection of the model parameters over the sample period.

System modelling with hourly data is much better as the short term variation in the dynamic characteristics of the catchment is less than the long term. As a result, we see that R_T^2 values for hourly data analysis are closer to unity than those for daily data analysis. For hourly data analysis, after a storm the soil moisture at any time is greater in the case of model with T_s of 10 hours than for that with 8 hours. As a result, the runoff will also be greater at any time subsequent to the storm. But the occurence of peak flow (as seen from the impulse response) differs from one data set to another and from one condition to another (for example with differing soil moisture and temperature effects) for the same set of data. In many cases, the amplitude of peak flow for one condition is greater than that for other conditions of the same set of data. The author has been unable to consider the implications of these observations on the model structure and the associated non-linearities and they should receive attention in any further research on the use of time-series analysis in rainfall run-off modelling.

BIBLIOGRAPHY

Anderson, H.W., Hoover, M.D. and Reinhard, K.G. (1976) *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply.* USDA Forest Service Gen. Tech. Rep.PSW 18.

AWRC (1969) *The Representative Basin Concept in Australia: A Progress Report.* AWRC Hydrological Series No. 2 Canberra.

AWRC (1974) *Australian Representative Basins Programme - Progress 1973.* AWRC Hydrological Series No. 8 Canberra.

AWRC (1976) *Standards for Interchange of Water Resources Data on Computer Media.* AWRC Hydrological Series No. 10 Canberra.

Batisse, M. (1964) 'The International Hydrological Decade - a World-wide Programme of Scientific Research', *Water and Life,* UNESCO Courier (July-August 1964): 4-9.

Beer, T., Young, P. and Humphries, R.B. (1980) Murrumbidgee River Water Quality Study, Vol. 1. CRES/ANU Report No. AS/R41.

Beck, B. and Young, P. (1975) 'Systematic Identification of a Dynamic Model for Water Quality in a River System'. CRES/ANU Report No. AS/R3.

Bennett, R.J. and Chorley, R.J. (1978) *Environmental Systems.* Methuen & Co.: London.

Black, C.A. (1965) 'Methods of Soil Analysis'. *Amer. Soc. Agron.,* Madison: 82-127.

Body, D.N. (1975) 'Empirical Methods and Approximations in the Determination of Catchment Response' in T.G. Chapman and F.X. Dunin, *Prediction in Catchment Hydrology.* Australian Academy of Science.

Body, D.N., Fleming, P.M., Goodspeed, M.J. and Laut, P. (1979) *Progress Report on AWRC Representative Basins Project.* Division of LUR, CSIRO, Canberra.

Box, G.E.P. and Jenkins, G.M. (1970) *Time Series Analysis: Forecasting and Control.* Holden-day: San Francisco.

Bracewell, R.N. (1978) *The Fourier Transform and its Applications* 2nd Ed. McGraw Hill: New York.

Brown, J.P. (1981) District Forester, Trentham, Victoria. '*Pers. Comm.*'

Brownlee, K.A. (1965) *Statistical Theory and Methodology in Science and Engineering.* John Wiley: New York.

Carson, M.A. and Kirkby, M.J. (1972) *Hillslope Form and Process.* Cambridge University Press: London.

Champeney, D.C. (1973) *Fourier Transforms and their Applications.* Academic Press: London.

Chow, V.T. (1964a) 'Statistical and Probability Analysis of Hydrologic Data Part I Frequency Analysis' in V.T. Chow, *Handbook of Applied Hydrology:* 8.1-8.42. McGraw Hill: New York.

Chow, V.T. (1964b) 'Runoff' in V.T. Chow, *Handbook of Applied Hydrology:* 14.1-14.54. McGraw Hill: New York.

Chow, V.T. (1969) 'Systems Approaches in Hydrology and Water Resources'. *The Progress of Hydrology,* University of Illinois, Urbana, Illinois 1:490-509.

CRES, Guide to CAPTAIN.

Davenport, W.B. and Root, W.L. (1958) *An Introduction to the Theory of Random Signals and Noise.* McGraw Hill: New York.

Denmead, O.T. (1973) 'Relative significance of soil and plant evaporation in estimating evapotranspiration' in *Plant Response to Climatic Factors.* UNESCO: Paris. 505-511.

Department of Mineral and Energy (1973) *Atlas of Australian Resources.* Second Series, Canberra.

Eykhoff, P. (1974) *System Identification.* John Wiley: London.

Faurre, P. and Depeyrot, M. (1977) *Elements of System Theory.* North-Holland Publishing Co.: Amsterdam.

Fjeld, M. and Aam, S. (1980) 'An Implementation of Estimation Techniques to a Hydrological Model for Preciction of Runoff to a Hydroelectric Power Station'. *IEEE Trans. Automatic Control,* AC-25, No. 2 151-163, April 1980.

Foth, H.D. (1978) *Fundamentals of Soil Science* 6th Ed. John Wiley: New York.

Freeze, R.A. and Harlan, R.L. (1969) 'Blueprint for a physically-based, digitally-simulated hydrologic response model'. *J. Hydrology* 9: 237-258.

Glover, A.M. (1979) 'Hydrological Data: A Catalogue of Rainfall and Runoff Data for Eleven Victorian Catchments'. AWRC Report No. 4/79.

Hillel, D. (1971) *Soil and Water: Physical Principles and Processes.* Academic Press: New York.

Horton, R.E. (1945) 'Erosional Development of Streams and their Drainage Basins: Hydrological Approach to Quantitative Morphology'. *Bull. Geol. Soc. America,* 56:275-370.

Hoy, R.D. and Stephens, S.K. (1979) 'Field Study of Lake Evaporation - Analysis of Data from Phase 2 Storages and Summary of Phase 1 and Phase 2'. AWRC Tech. Paper No. 41.

Kohnke, H. (1968) *Soil Physics,* McGraw Hill, New York.

Kuo, B.C. (1962) *Automatic Control Systems.* Prentice-Hall: Englewood Cliffs, N.J.

Kuo, B.C. (1963) *Analysis and Synthesis of Sampled-Data Control Systems.* Prentice-Hall: Englewood Cliffs, N.J.

Linsley, R.K., Kohler, M.A. and Paulhus, J.L.H. (1949) *Applied Hydrology.* McGraw Hill: New York.

Linsley, R.K., Kohler, M.A. and Paulhus, J.L.H. (1958) *Hydrology for Engineers.* McGraw Hill: New York.

Luke, R.H. and McArthur, A.G. (1978) *Bushfires in Australia.* Aust. Govt. Publ. Serv.: Canberra.

Lull, H.W. (1964) 'Ecological and Silvicultural Aspects' in V.T. Chow *Handbook of Applied Hydrology,* 6.1-6.30. McGraw Hill: New York.

Mackay, S.M., Michell, P.A. and Young, P.C. (1980) 'Hydrologic Changes after Wildfire in Small Catchments near Eden N.S.W.'. *Hydrology Symp.* I.E. Aust.: Adelaide.

McArthur, A.G. (1964) 'Streamflow Characteristics of Forested Catchments' *Aust. For.* 28:106-118.

Milne, F.J. (1975) *A Descriptive Catalogue of the Australian Representative Basins.* AWRC: Canberra.

Musgrave, G.W. and Holtan, H.N. (1964) 'Infiltration' in V.T. Chow, *Handbook of Applied Hydrology,* 12.1-12.30. McGraw Hill: New York.

Northcote, K.H. (1962) *Atlas of Australian Soil: Explanatory Data for Sheet 2, Melbourne-Tasmania Area.* CSIRO: Melb. Uni. Press.

Northcote, K.H. (1971) *A Factual Key for the Recognition of Australian Soil.* CSIRO: Glenside, S. Australia.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettenay, E. (1975) *A Description of Australian Soils,* CSIRO.

Panter, P.F. (1965) *Modulation, Noise and Spectral Analysis,* McGraw Hill: New York.

Papoulis, A. (1965) *Probability, Random Variables and Stochastic Processes.* McGraw Hill: New York.

Penman, H.L. (1948) 'Natural Evaporation from Open Water, Bare Soil and Grass' *Proc. Roy. Soc. London,* se.A, 193:120-145.

Penman, H.L. (1963) 'Vegatation and Hydrology'. *Technical Communication* 53:124 Comm. Bur. Soils, Harpenden.

Penman, H.L. (1970) 'The Water Cycle'. *Scientific American* 223:98-108.

Reader's Digest (1977) *Atlas of Australia*, Reader's Digest Services: Sydney.

Rodda, J.C., Downing, R.A. and Law, F.M. (1976) *Systematic Hydrology.* Newnes-Butterworths: London.

Sherman, L.K. (1932) 'Streamflow from rainfall by unit-graph method'. *Eng. News Record* 108:501-505.

Slatyer, R.O. (1967) *Plant-water Relationships.* Academic Press, London.

Smith, D.I. and Stopp, P. (1978) *The River Basin.* Cambridge University Press: London.

Sneddon, I.N. (1972) *The Use of Integral Transforms.* McGraw Hill: New York.

Stace, H.C.T. (1968) *A Handbook of Australian Soils.* Rellim Rech. Publ. Glenside, S.A.

Staley, R.M. and Yue, P.C. (1970) 'On System Parameter Identifiability'. *Information Science* 2:127-138.

Stephens, C.G. (1953) *A Manual of Australian Soil.* CSIRO: Melbourne.

Takahashi, Y., Rabins, M.J., and Auslander, D.M. (1972) *Control and Dynamic Systems.* Addison Wesley: Massachusetts.

Tiedemann, A.R. (1979) 'Effects of Fire on Water'. USDA Forest Serv. Gen. Tech. Report WO-10.

Todd, D.K. (1959) *Ground Water Hydrology*, Toppan Co. Ltd.: Tokyo.

Todd, D.K. (1964) 'Groundwater' in V.T. Chow. *Handbook of Applied Hydrology* 13.1-13.55. McGraw Hill: New York.

Tou, J. (1959) *Digital and Sampled-Data Control Systems.* McGraw Hill: New York.

Van Valkenburg, M.E. (1974) *Network Analysis* 3rd ed. Prentice Hall: Englewood Cliffs, N.J.

Veihmeyer, F.J. (1964) 'Evapotranspiration' in V.T. Chow. *Handbook of Applied Hydrology* 11.1-11.38. McGraw Hill: New York.

Ward, R.C. (1975) *Principles of Hydrology.* McGraw Hill: London.

Webb, E.K. (1975) 'Evaporation from Catchments' in T.G. Chapman and F.X. Dunin. *Prediction in Catchment Hydrology* 203-238. Australian Academy of Science: Canberra.

Weyman, D.R. (1975) *Runoff Processes and Streamflow Modelling.* Oxford University Press: London.

White, R.E. (1979) *Introduction to Principles and Practice of Soil Science.* Blackwell Scientific Publ.: Oxford.

Whitehead, P., Young, P. and Hornberger, G. (1979) 'A Systems Model of Streamflow and Water Quality in the Bedford-Ouse River-1. Stream Flow Modelling' in *Water Research* 13:1155-1169. Pergamon Press: Great Britain.

Williams, R.J. (1955) 'Vegetation Regions' in *Atlas of Australian Resources*. Dept. Nat. Dev.: Canberra.

Williamson, R.J. and Turner, A.K. (1980) 'The Role of Soil Moisture in Catchment Hydrology'. AWRC Tech. Paper No. 53.

Wilson, E.M. (1974) *Engineering Hydrology* 2nd ed. The Macmillan Press: London.

Wong, K.Y. and Polak, E. (1967) 'Identification of Linear Discrete Time Systems Using the Instrumental Variable Method'. *IEEE Trans. Automatic Control*. AC-12, No. 6, 707-718.

Young, P.C. (1966) 'Process Parameter Estimation and Self Adaptive Control' in P.H. Hammond, *The Theory of Self Adaptive Control Systems*. Plenum Press: New York.

Young, P.C. (1968) 'Identification problems associated with the equation-error approach to process parameter estimation'. *Proc. Second Asilomar Conf. on Circuits and Systems* 416-422.

Young, P.C. (1969) 'An Instrumental Variable Methods for Real Time Identification of a Noisy Process'. *Automatica* 6:271-287.

Young, P.C. (1972) 'Lectures on Recursive Approaches to Parameter Estimation and Time Series Analysis' in *Theory and Practice of Systems Modelling and Identification.* Ecole Nationale Superieure de L'Aeronautique et de L'Espace.

Young, P.C. (1974) 'Recursive Approaches to Time-series Analysis'. *Bull. Inst. Math. and Appl.* 10:209-274.

Young, P.C. (1975) 'Optimisation in the Presence of Noise - A Guided Tour'. CRES/ANU Report No. AS/R2.

Young, P.C. (1978) 'A General Theory of Modeling for Badly Defined Systems' in G.C. Vansteenkiste. *Modeling, Identification and Control in Environmental Systems*. North-Holland/American Elsevier.

Young, P. and Jakeman, A. (1979) 'The Development of CAPTAIN' in M.A. Cuenod. *Computer Aided Design of Control Systems*. IFAC Symp. Zurich, 29-31 Aug. 1979, Pergamon Press: Oxford.

Young, P., Jakeman, A. and McMurtrie, R. (1980) 'An Instrumental Variable Method for Model Order Identification'. *Automatica* 16:281-294.

Young, P.C., Shellswell, S.H. and Neethling, C. (1971) 'A Recursive Approach to Time-series Analysis'. Rep. No. CUED/B-Control TR16. Dept. of Engineering, University of Cambridge.

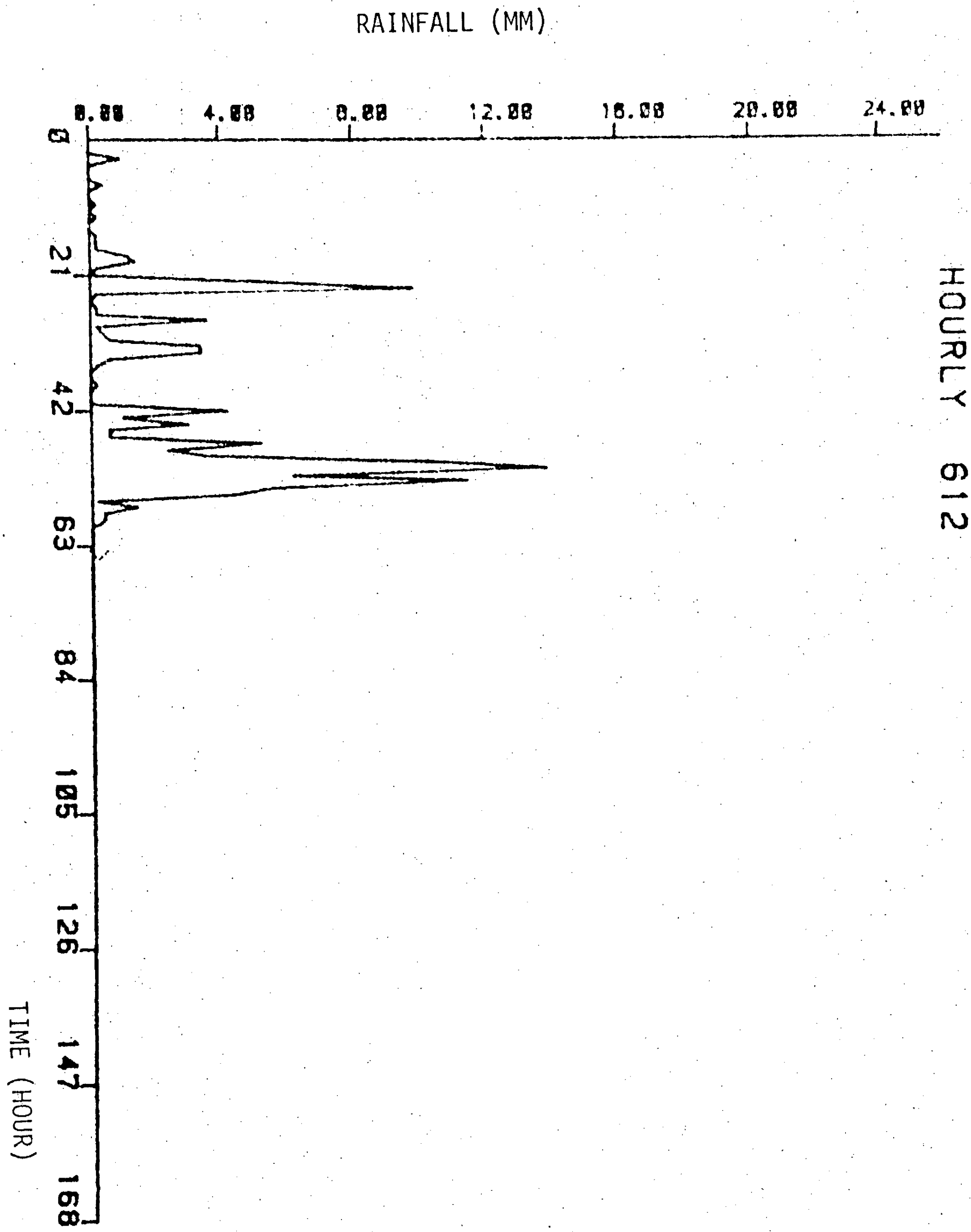


Fig 5.1 Rainfall 612

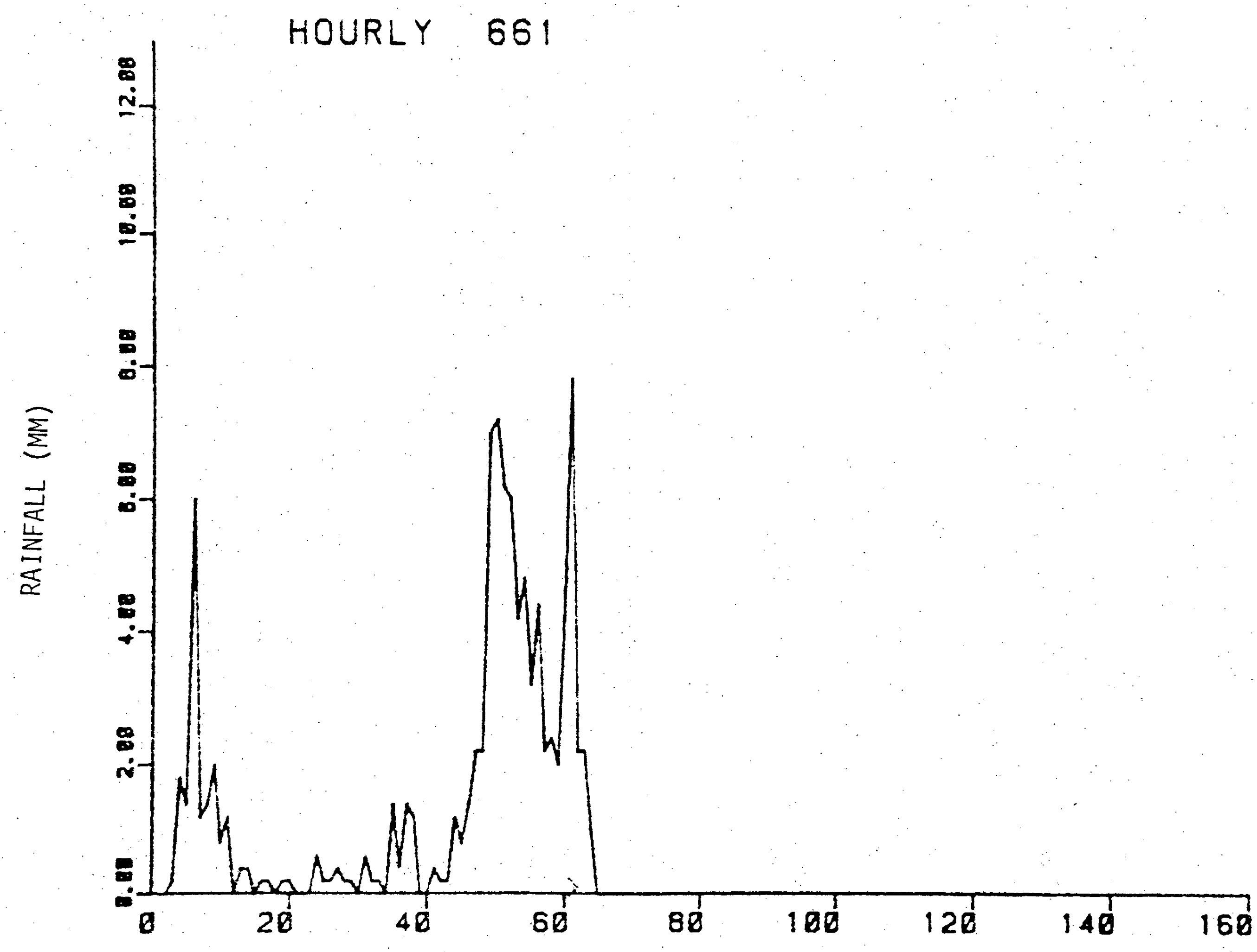


Fig 5.2 Rainfall 661

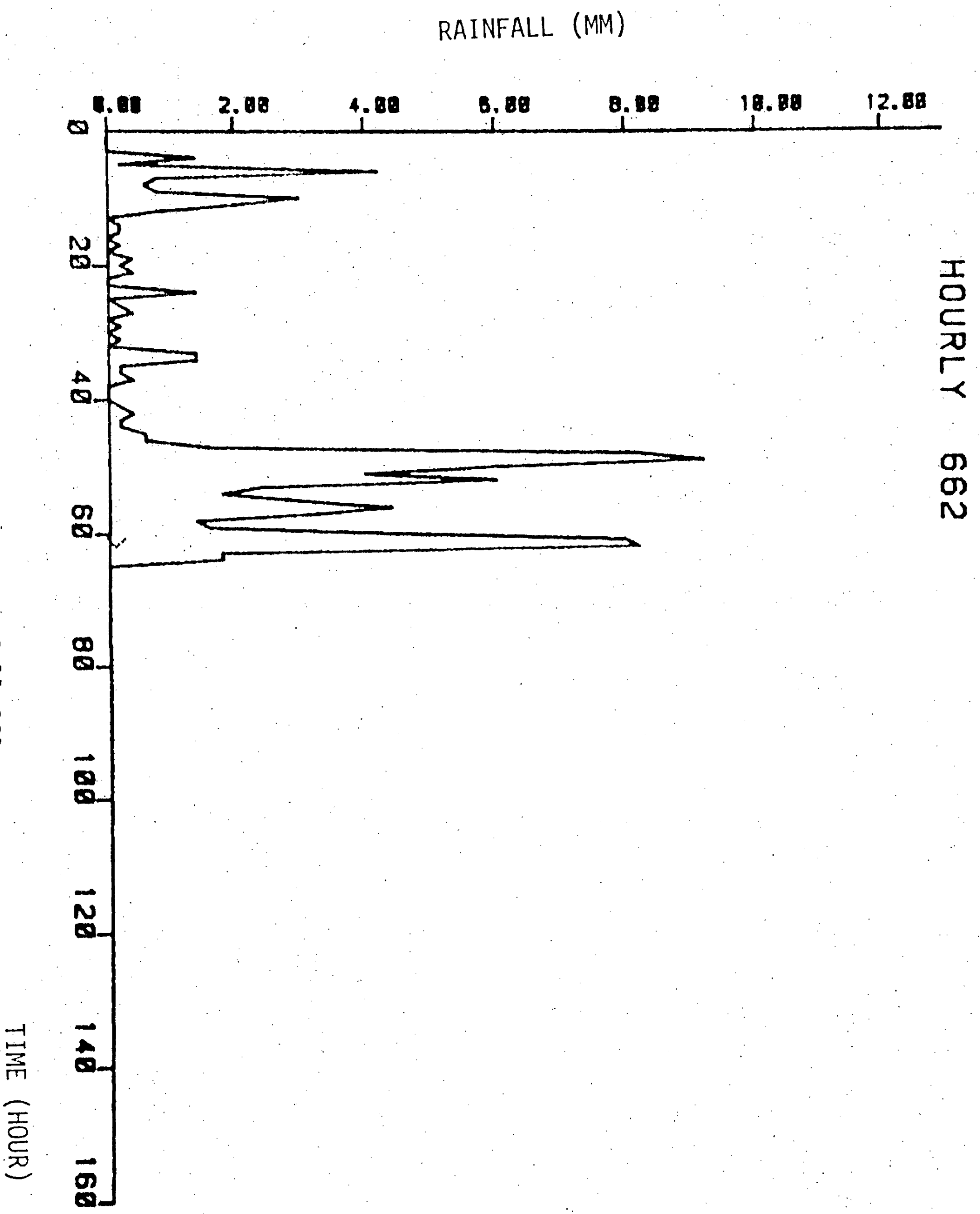


Fig 5.3 Rainfall 662

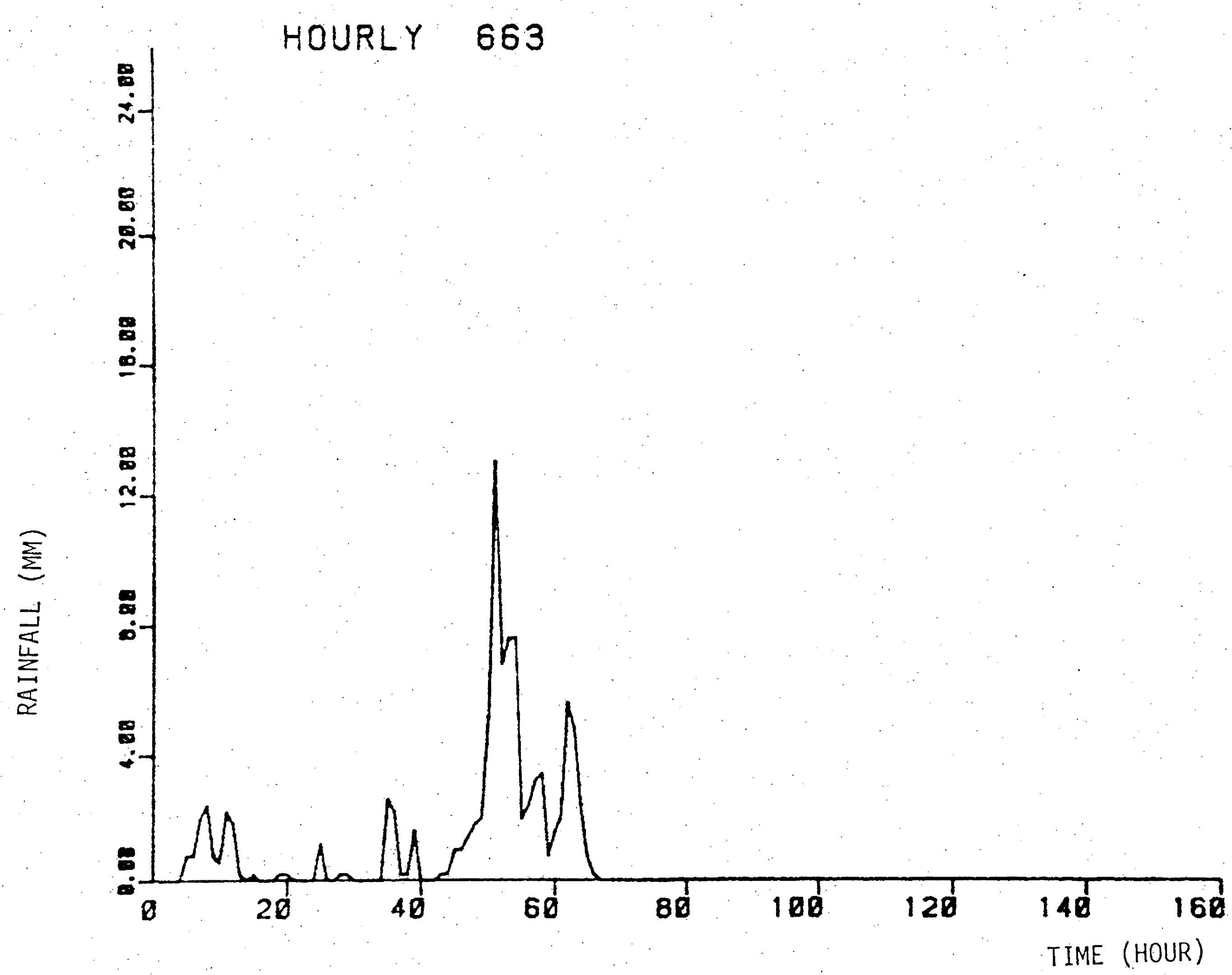


Fig 5.4 Rainfall 663

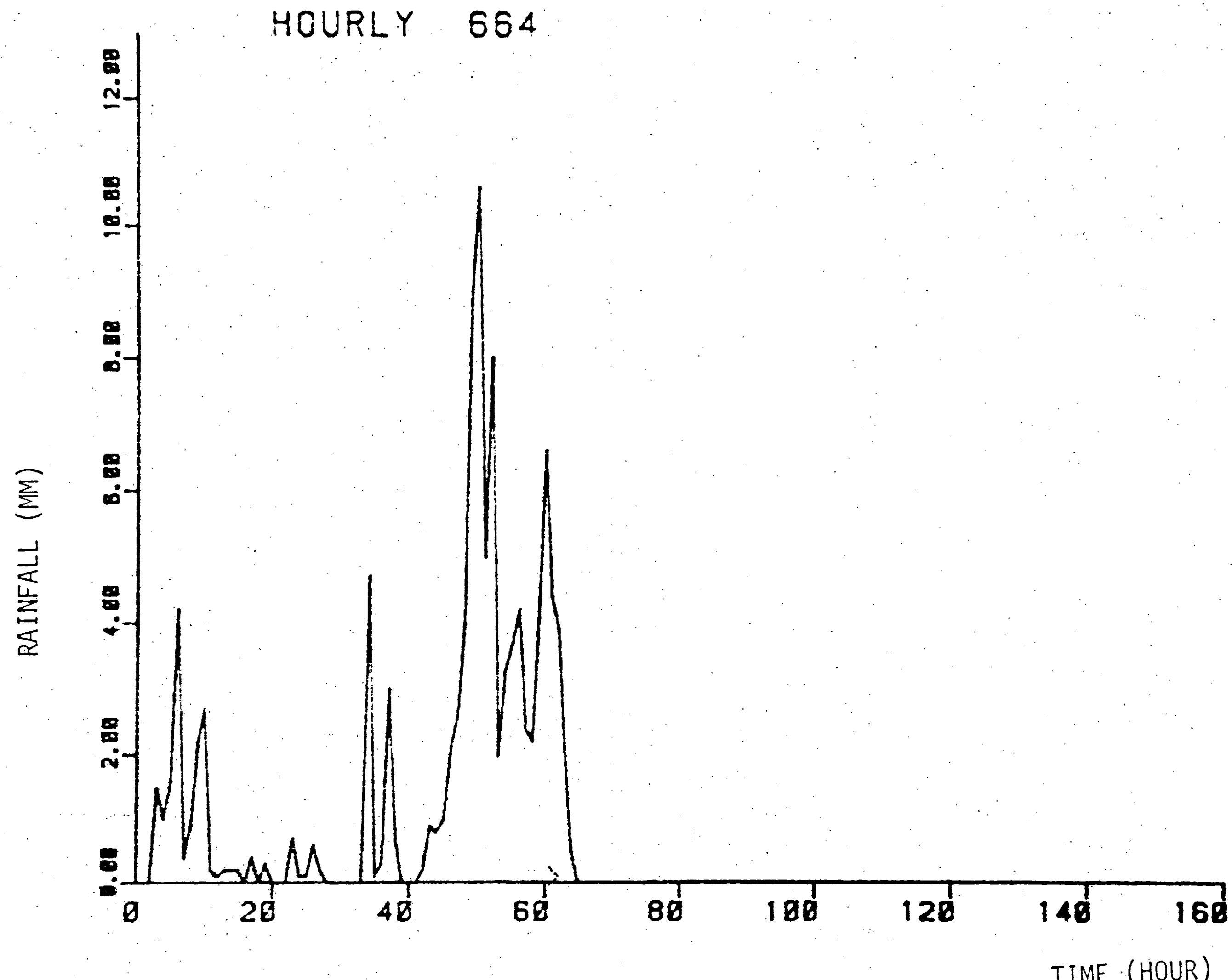


Fig 5.5 Rainfall 664

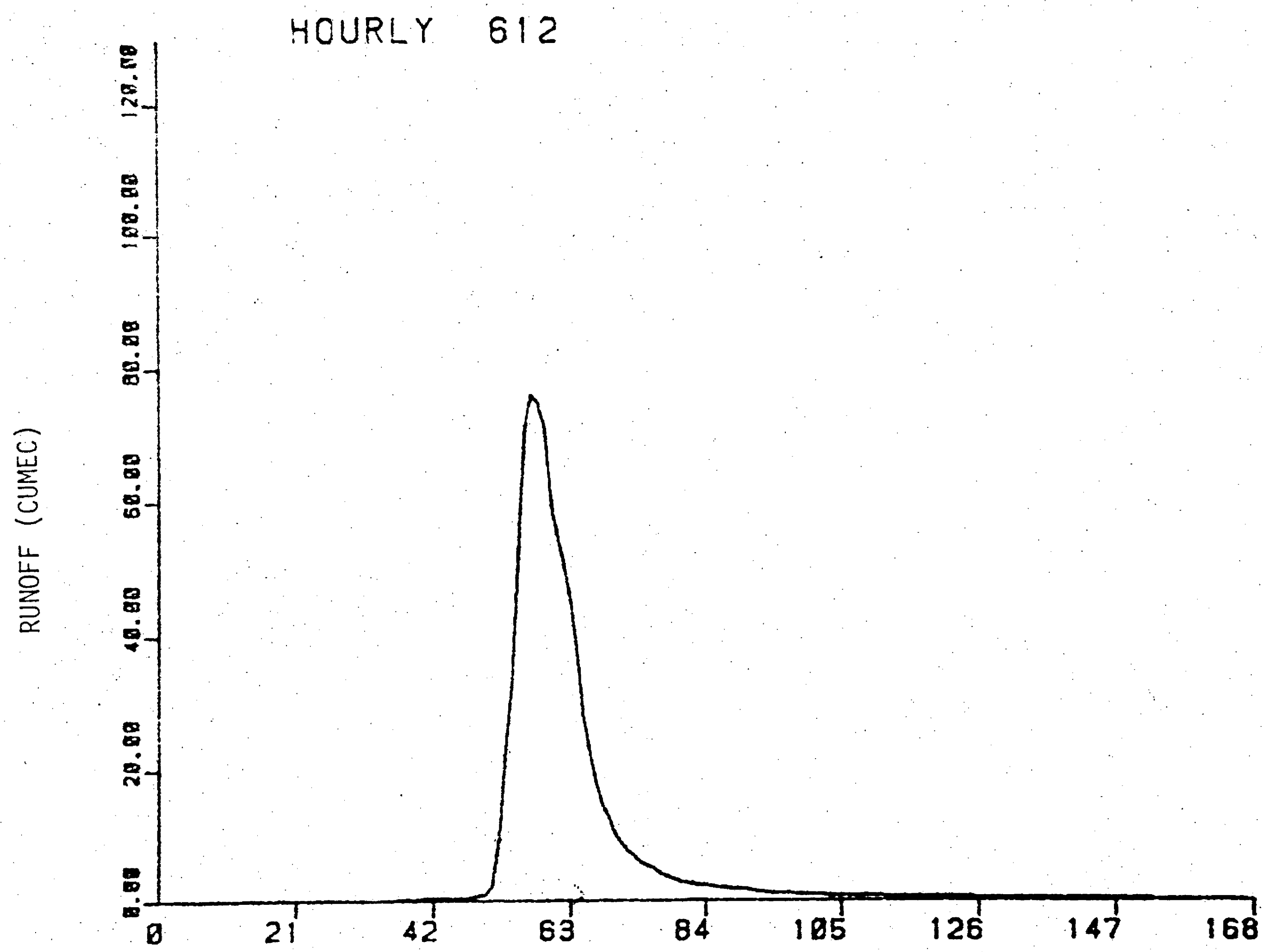


Fig 5.6 Runoff 612

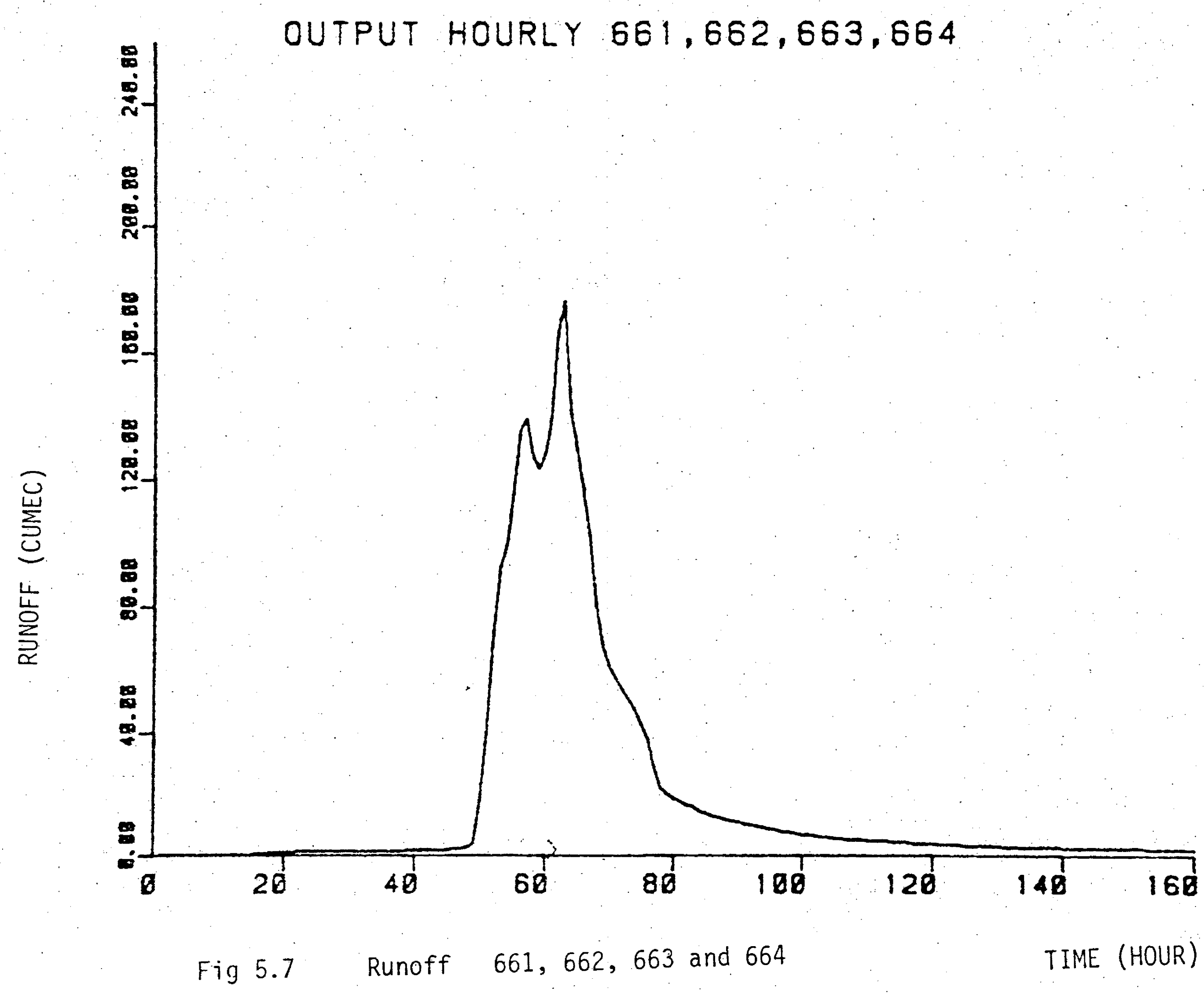


Fig 5.7 Runoff 661, 662, 663 and 664

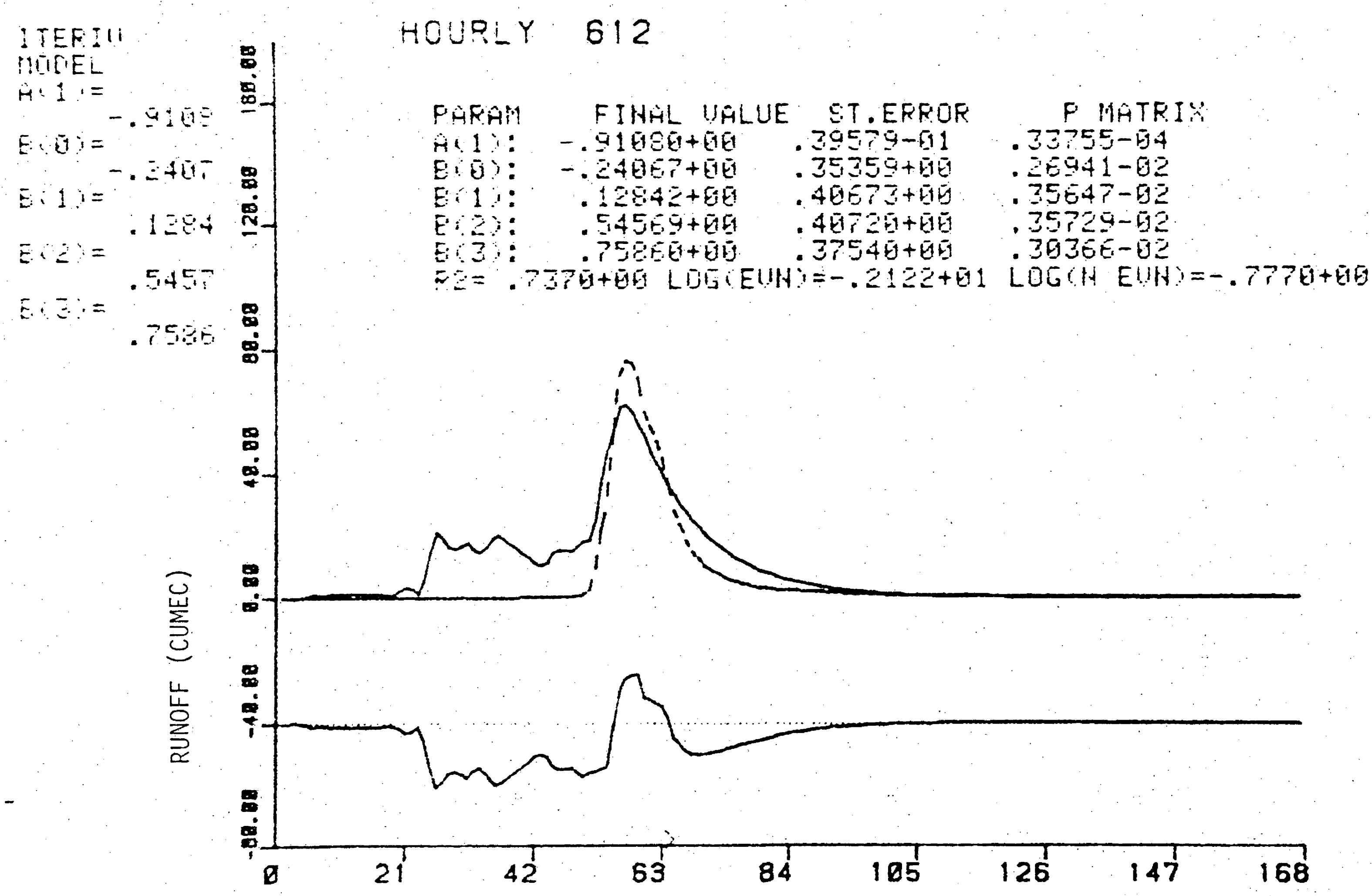


Fig 5.8 Raw Data Model 612

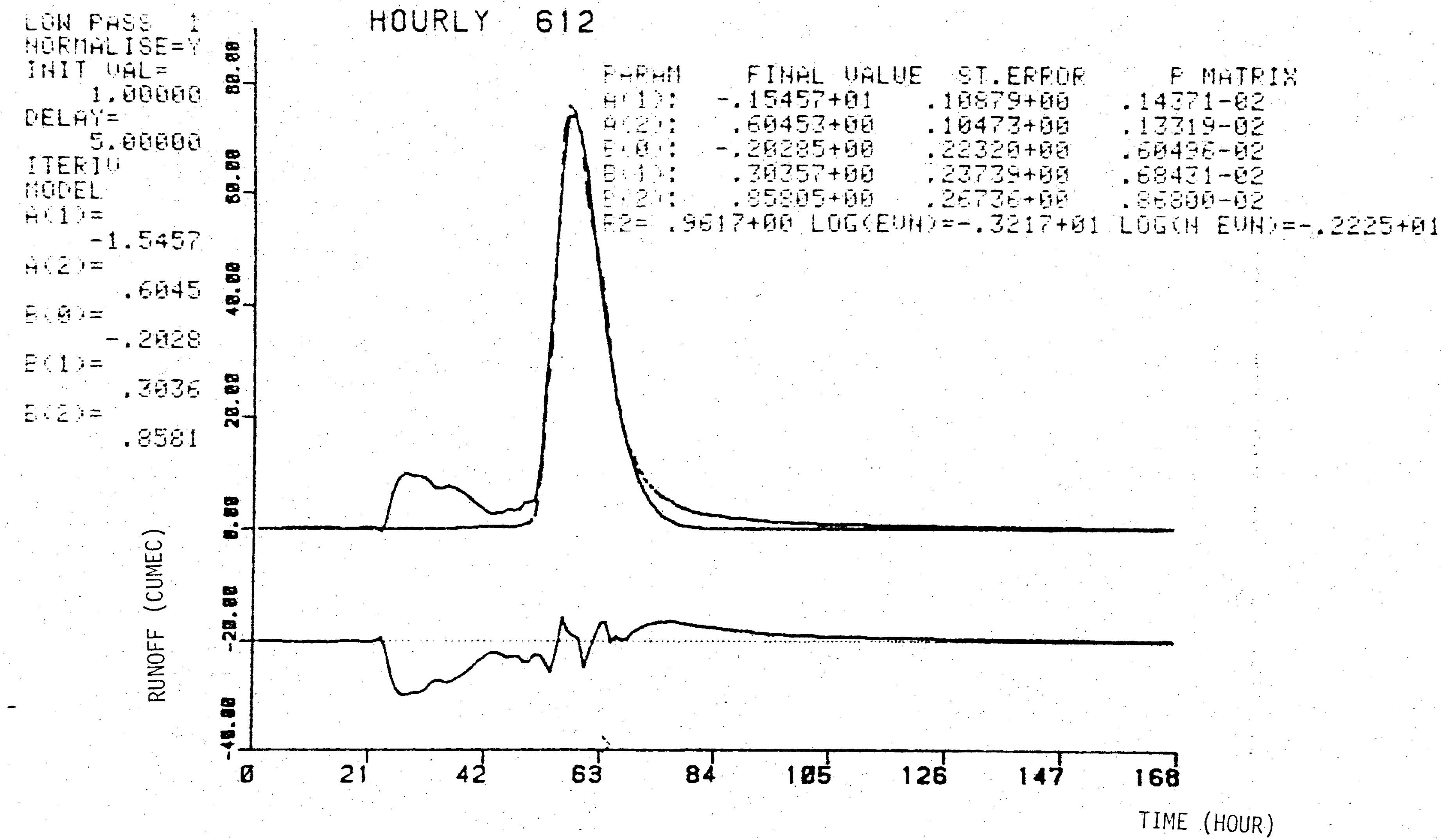


Fig 5.9 Model 612 with allowance for Soil Moisture Effects (T_S=5 hours)

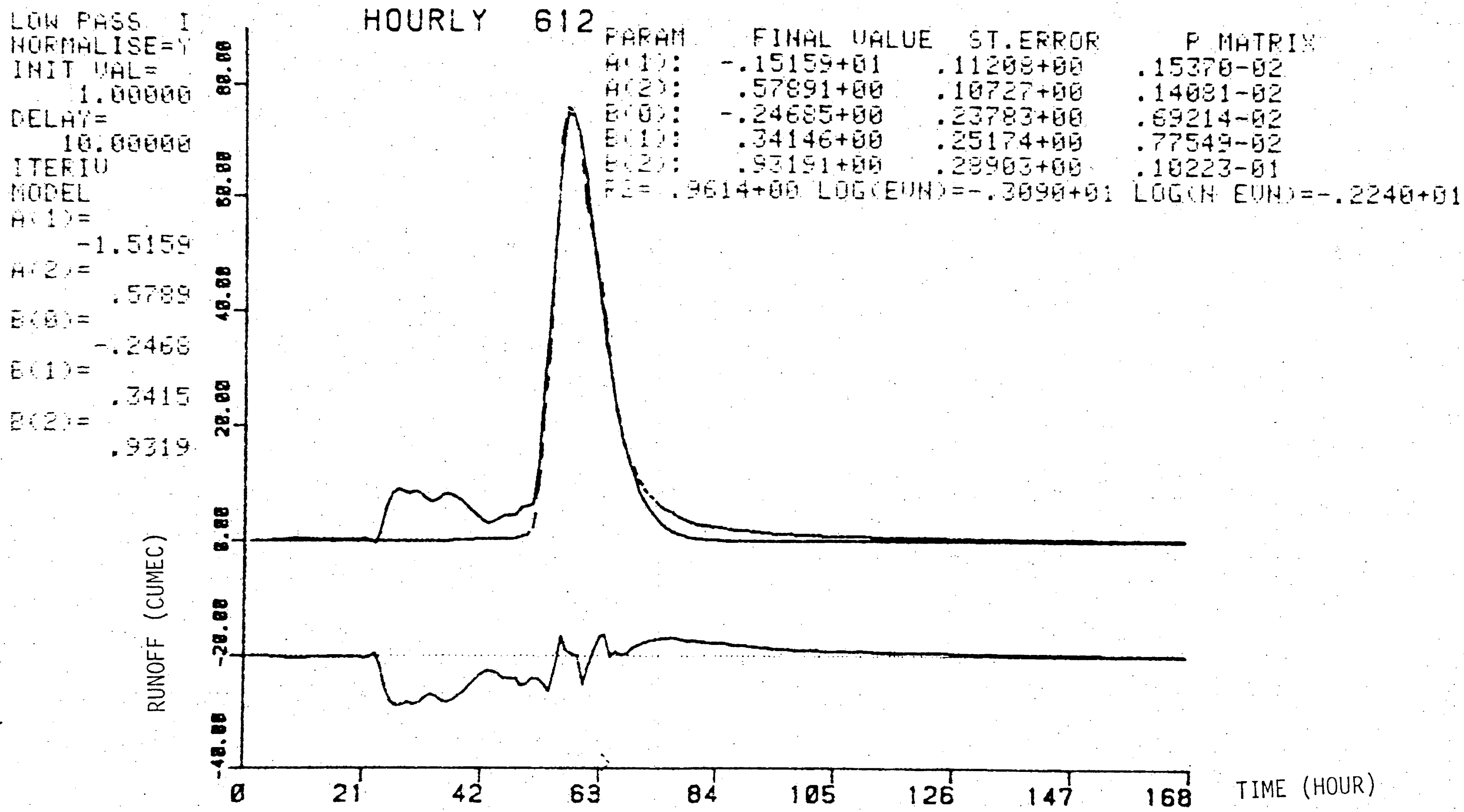


Fig 5.10 Model 612 with allowance for Soil Moisture Effects (T_s=10 hours)

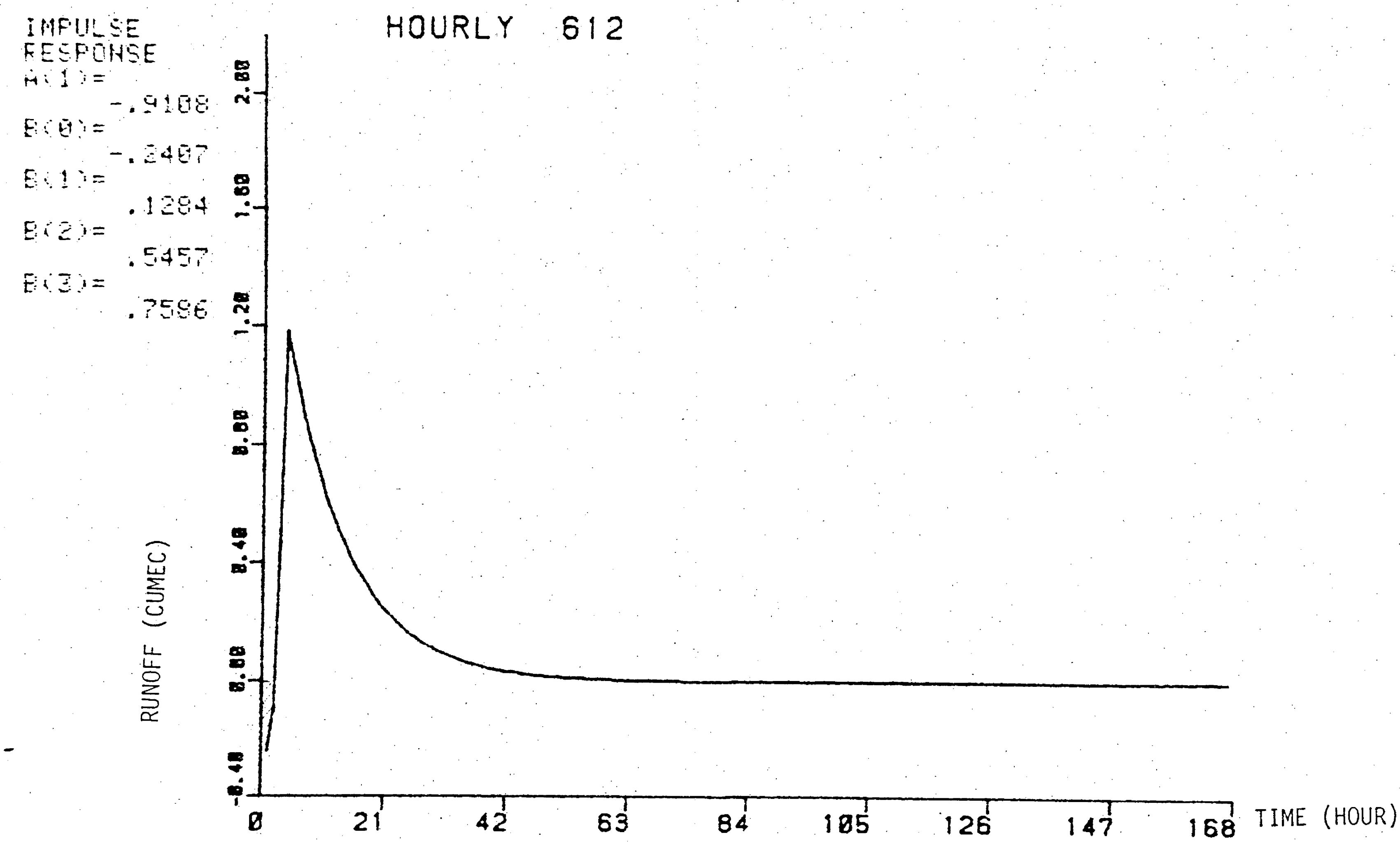


Fig 5.11(a) Impulse Response for Model Fig 5.8

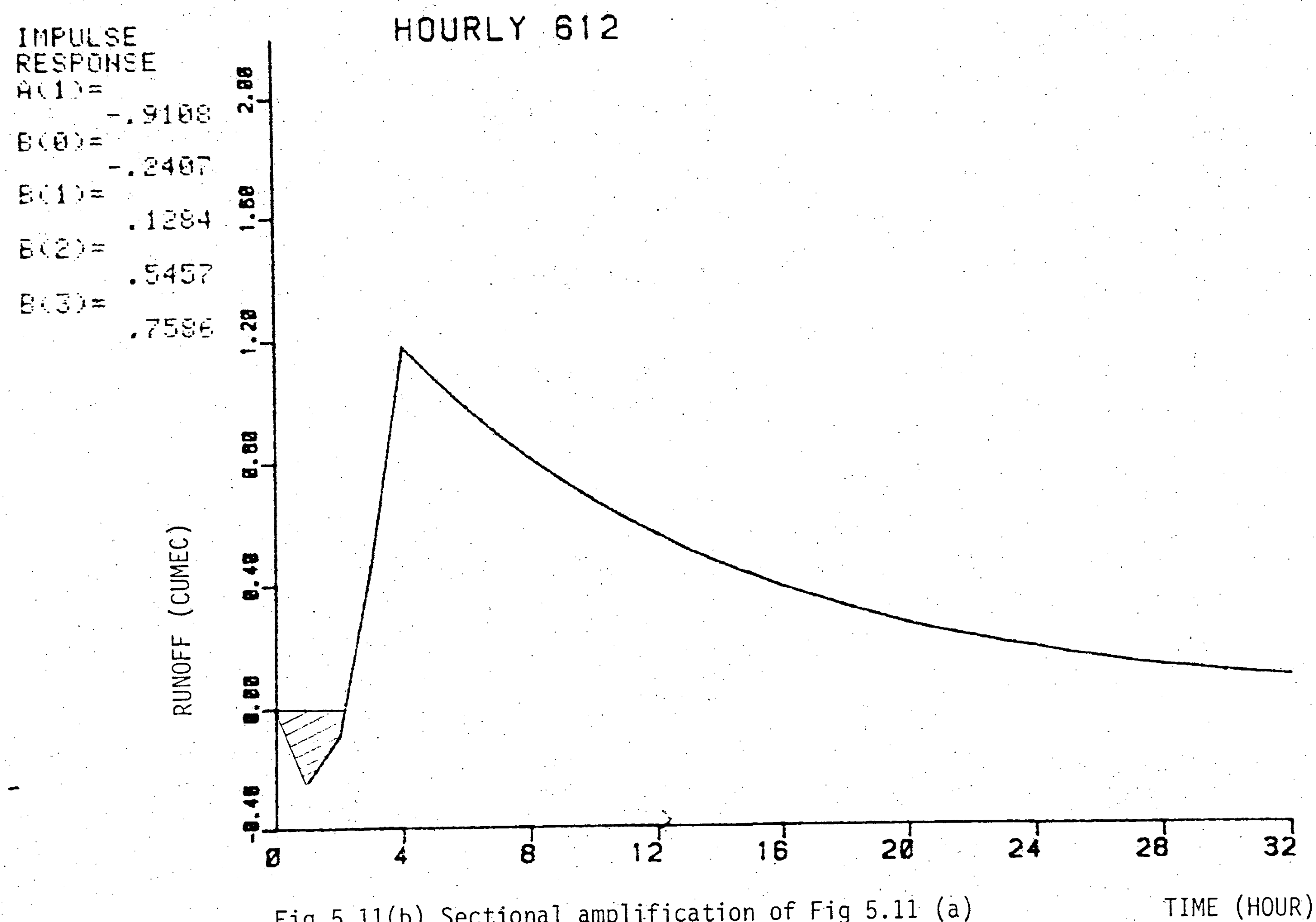


Fig 5.11(b) Sectional amplification of Fig 5.11 (a)

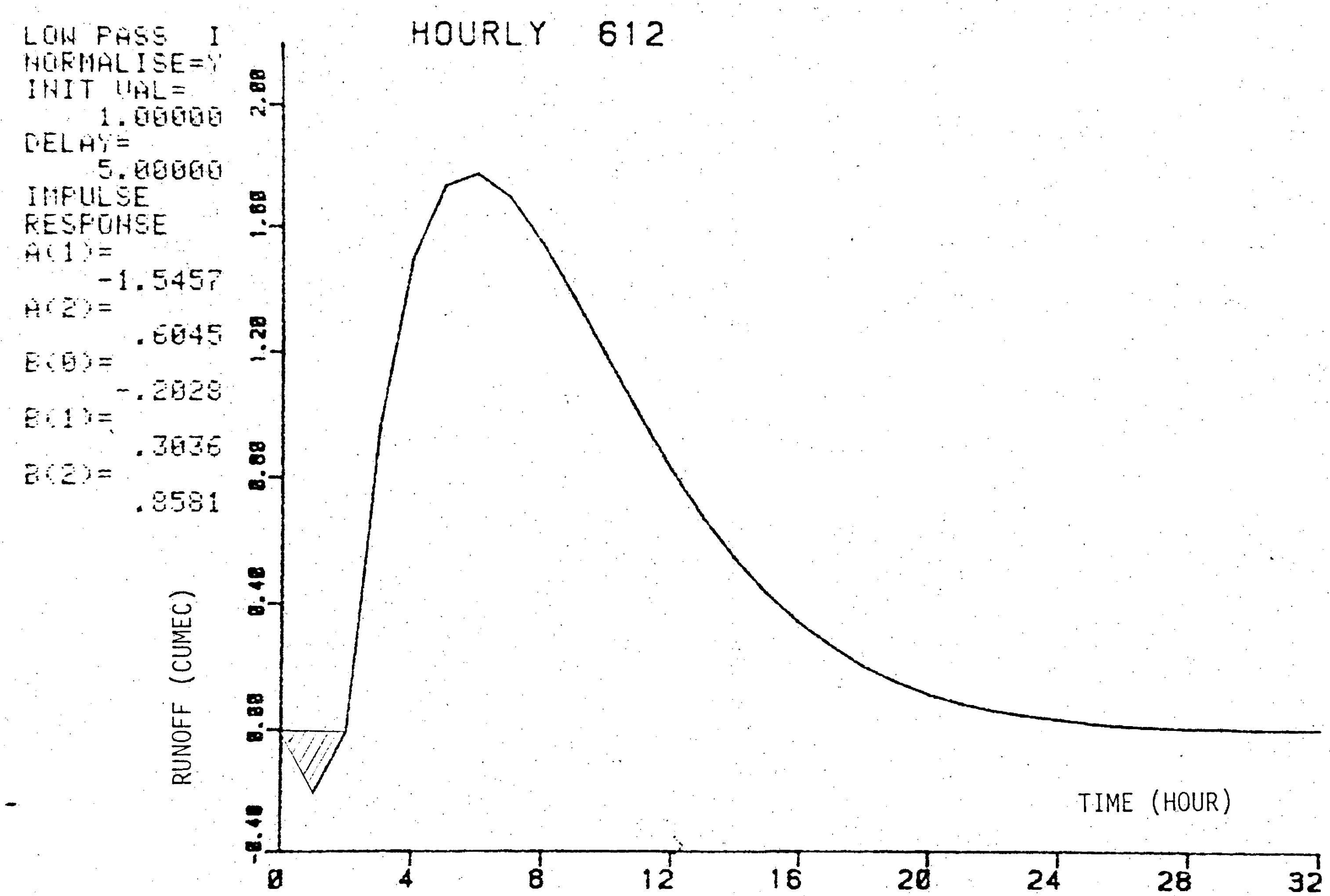


Fig 5.12 Impulse Response fo Model Fig 5.9

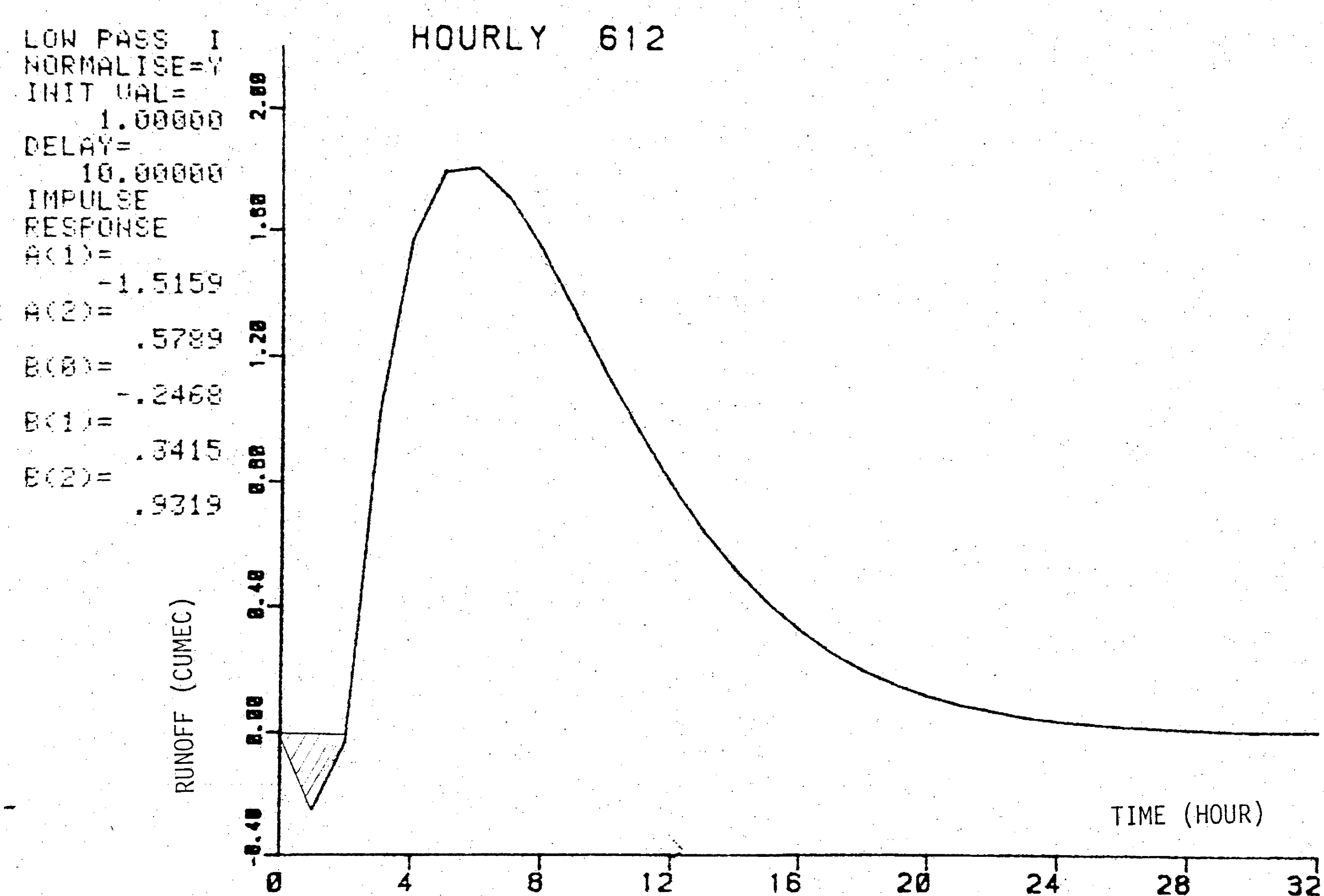


Fig 5.13 Impulse Response for Model Fig 5.10

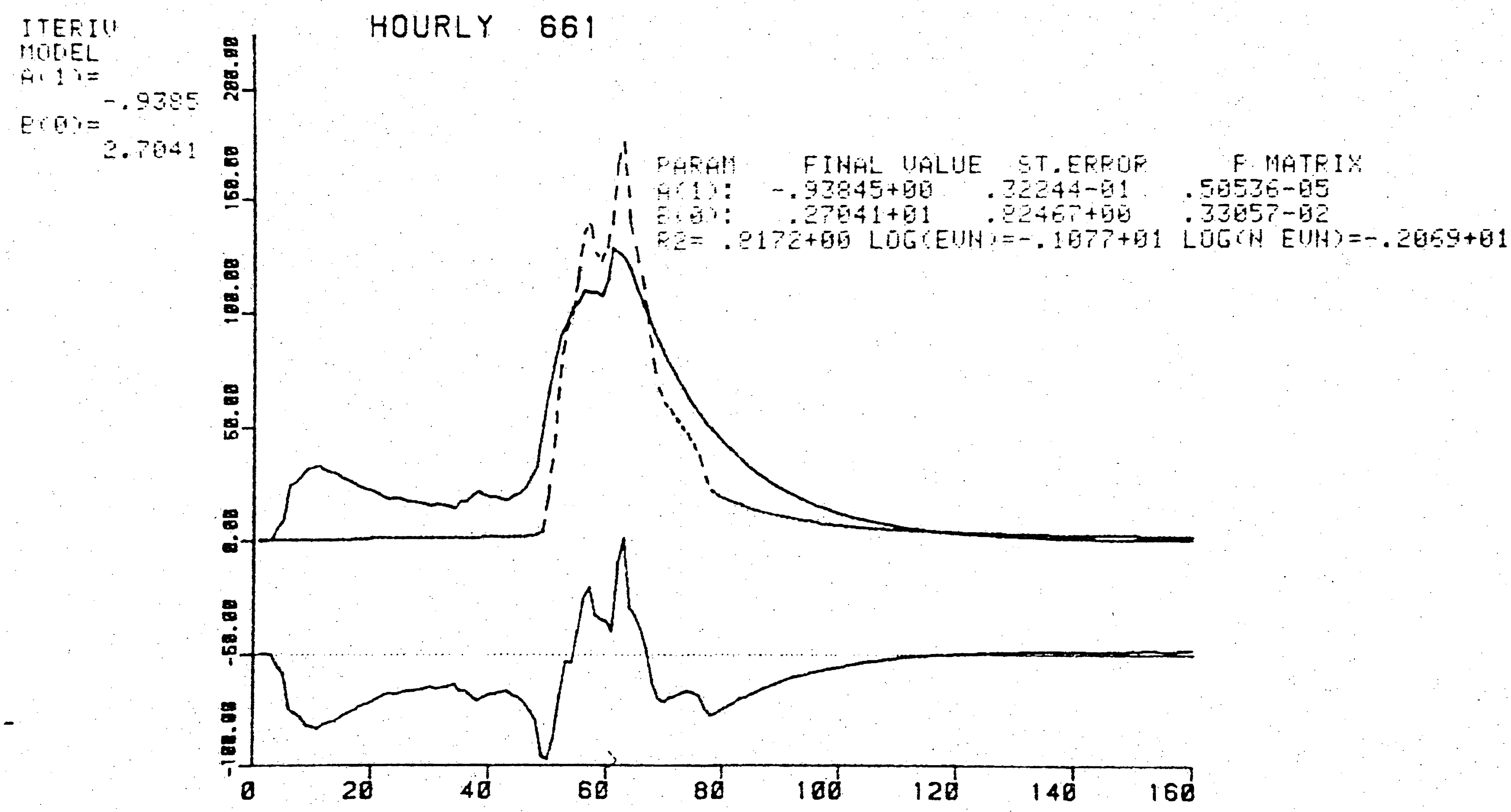


Fig 5.14 Raw Data Model 661

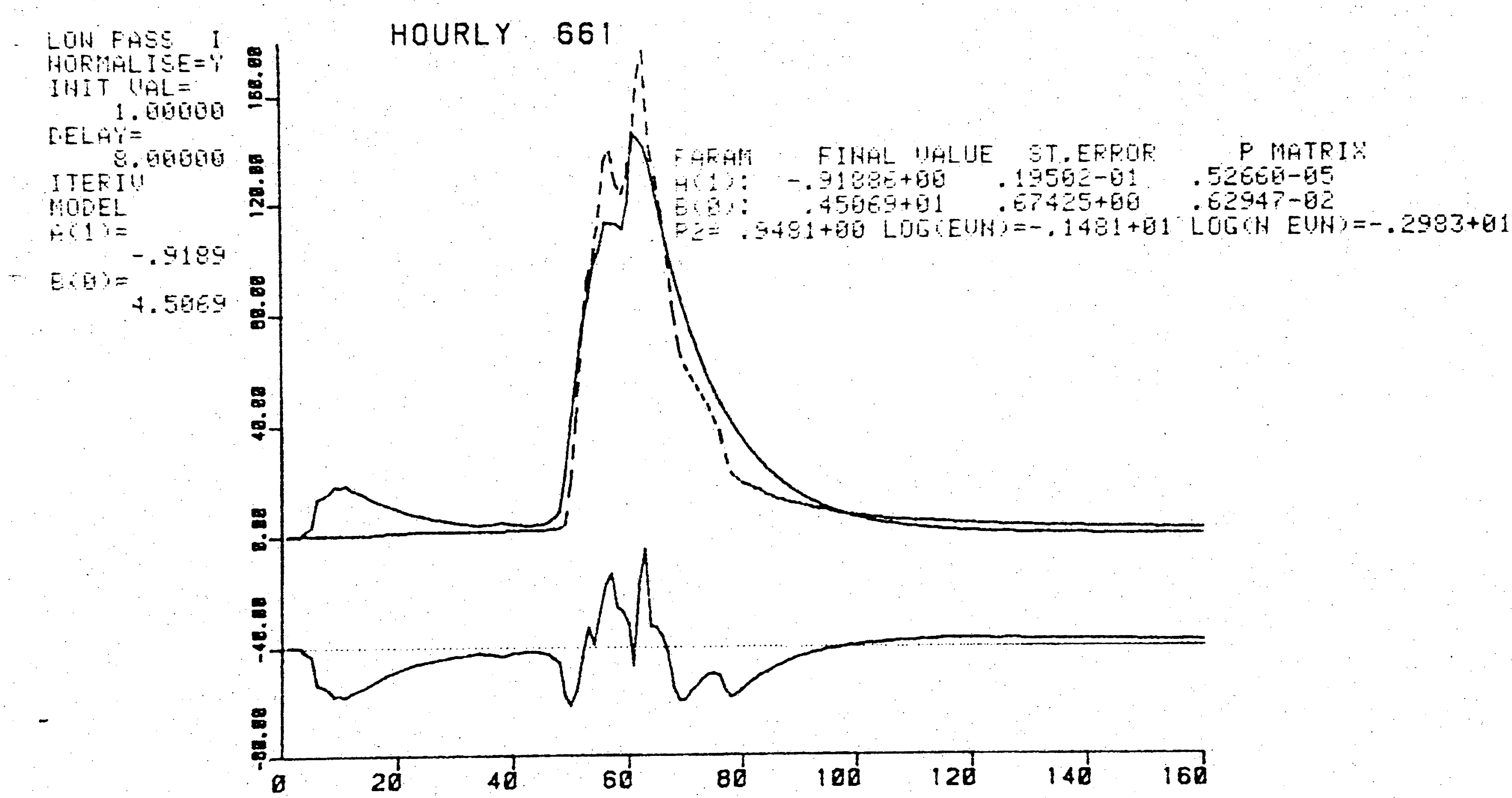


Fig 5.15 Model 661 with allowance for Soil Moisture Effects (T_S=8 hours)

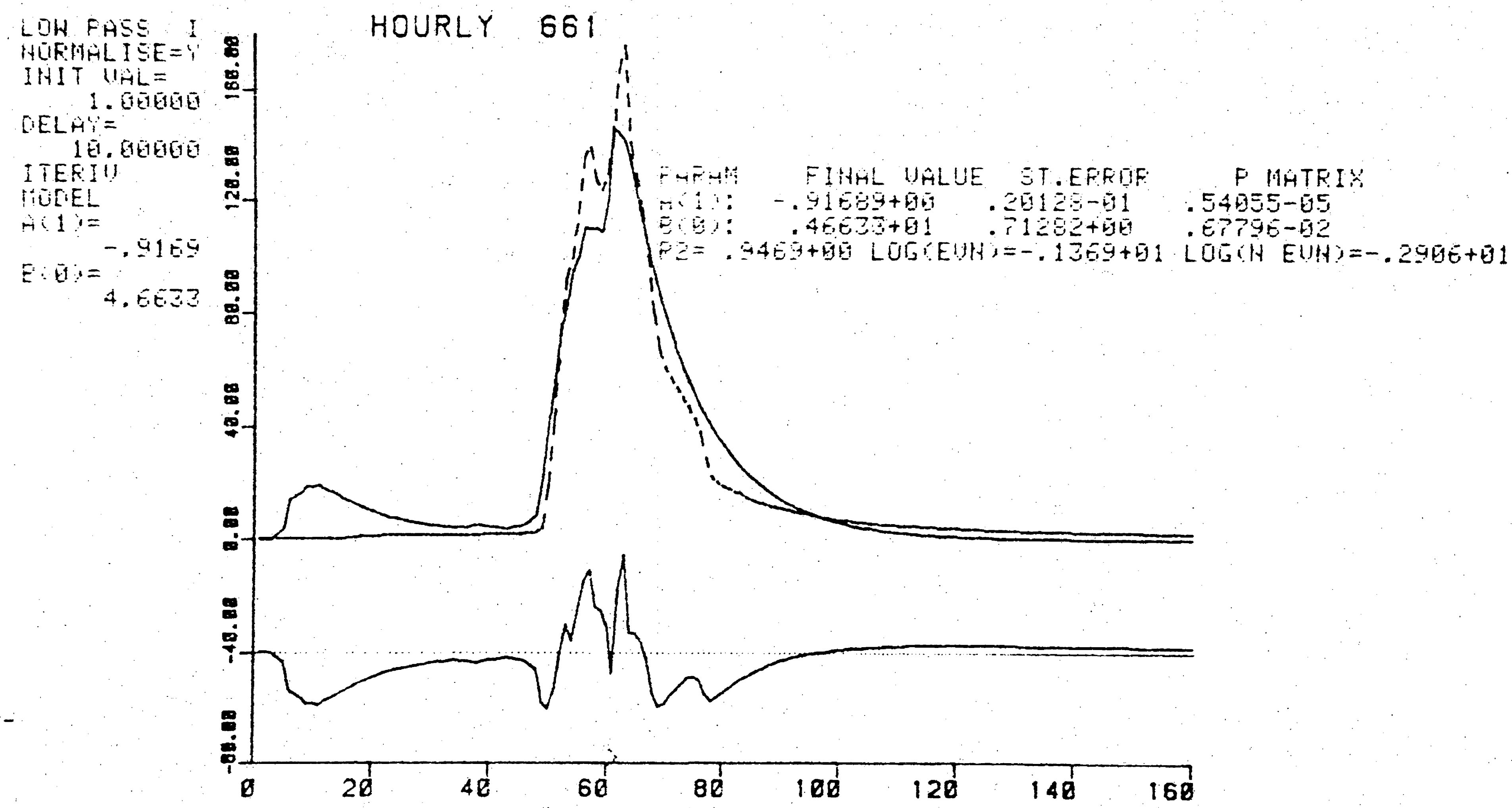


Fig 5.16 Model 661 with allowance for Soil Moisture Effects (T_s=10 hours)

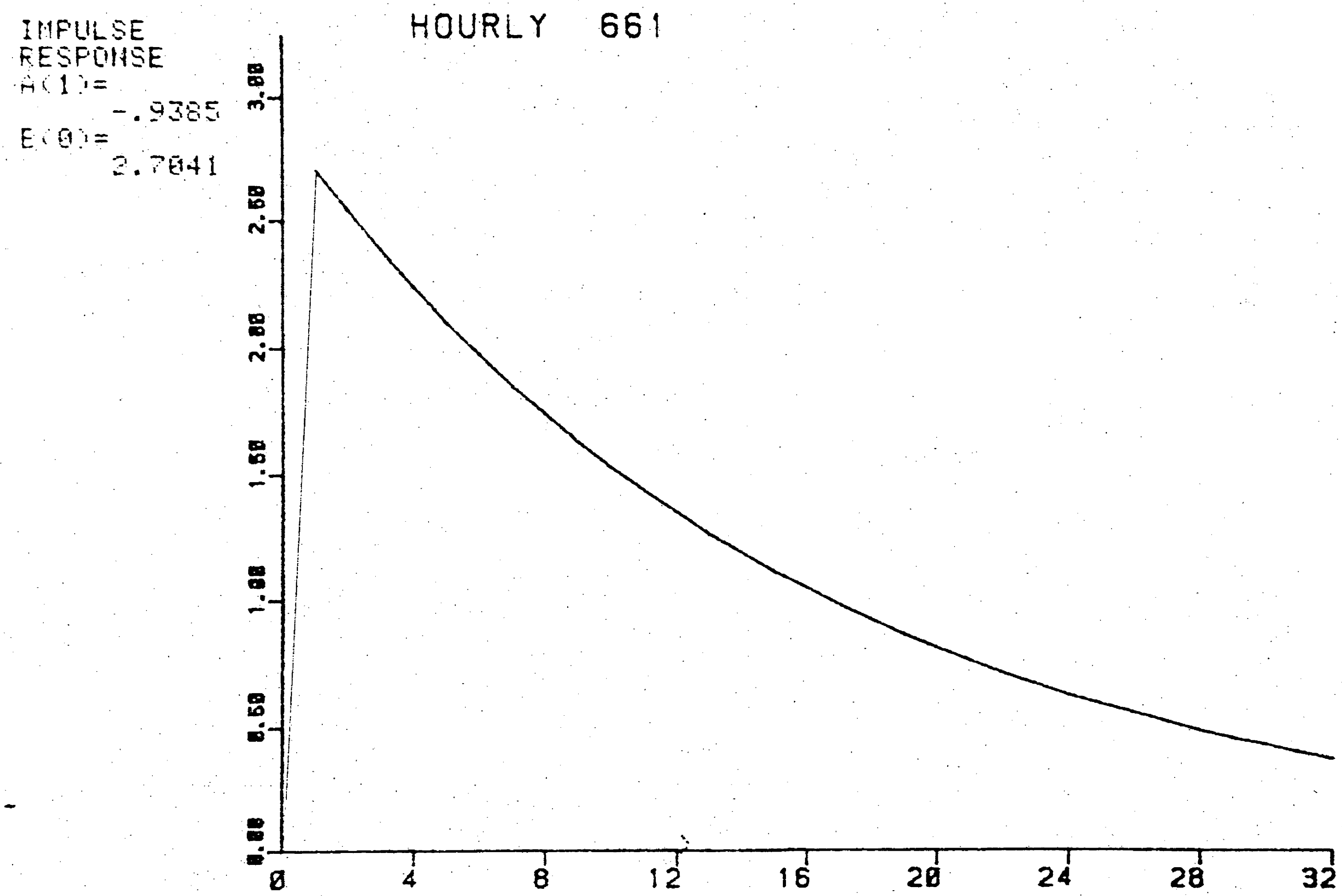


Fig 5.17 Impulse Response for Model Fig 5.14

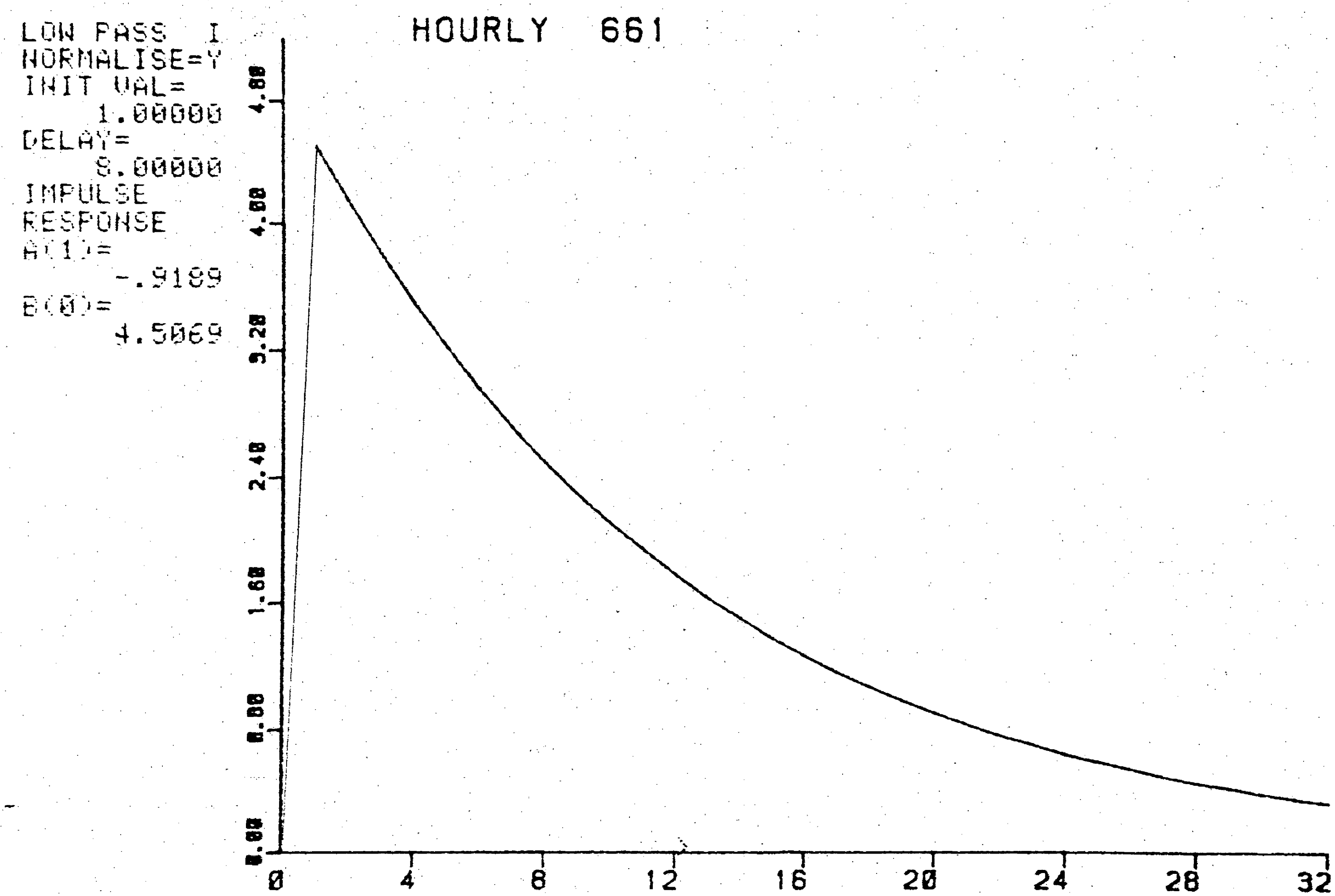


Fig 5.18 Impulse Response for Model Fig 5.15

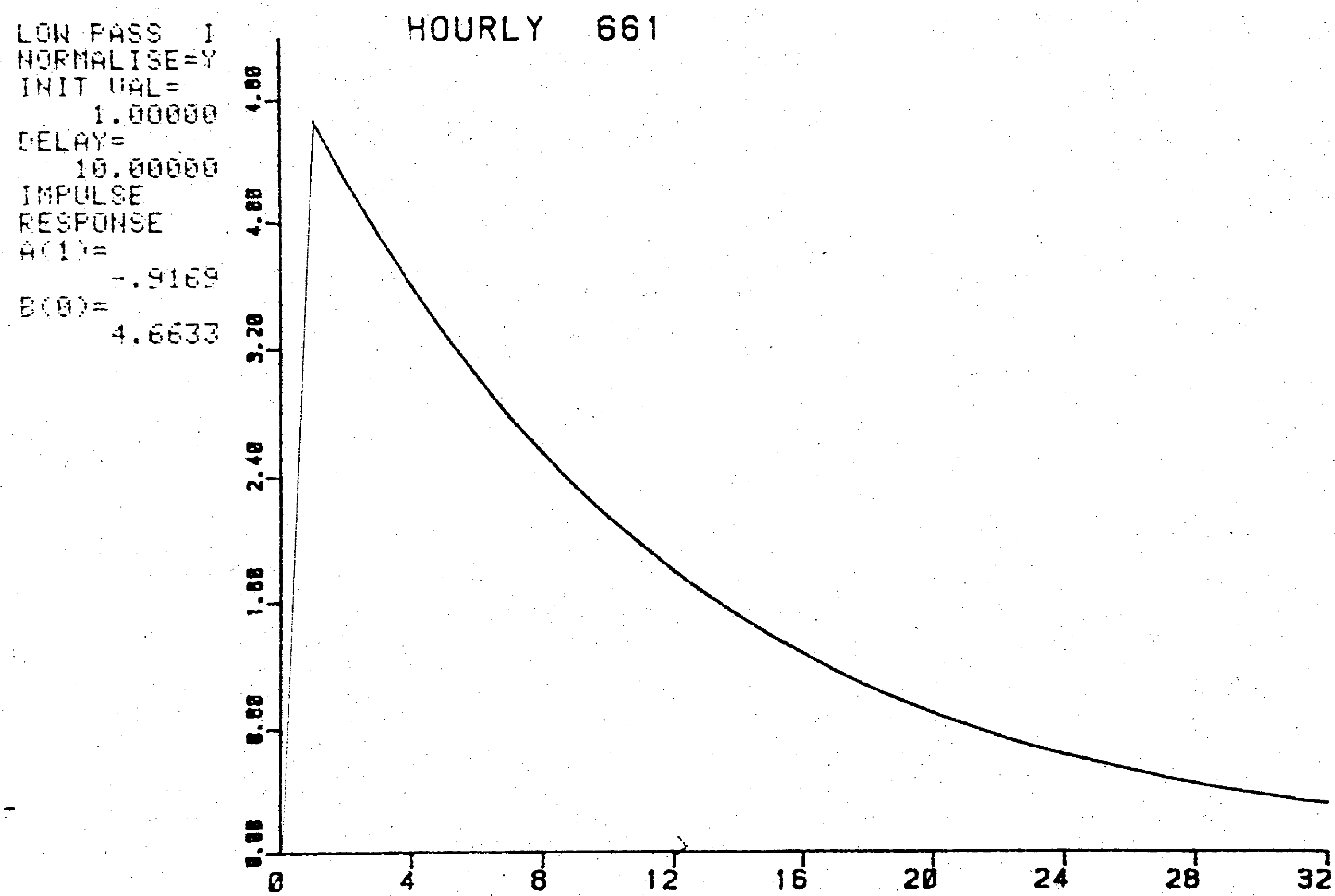


Fig 5.19 Impulse Respones for Model Fig 5.16

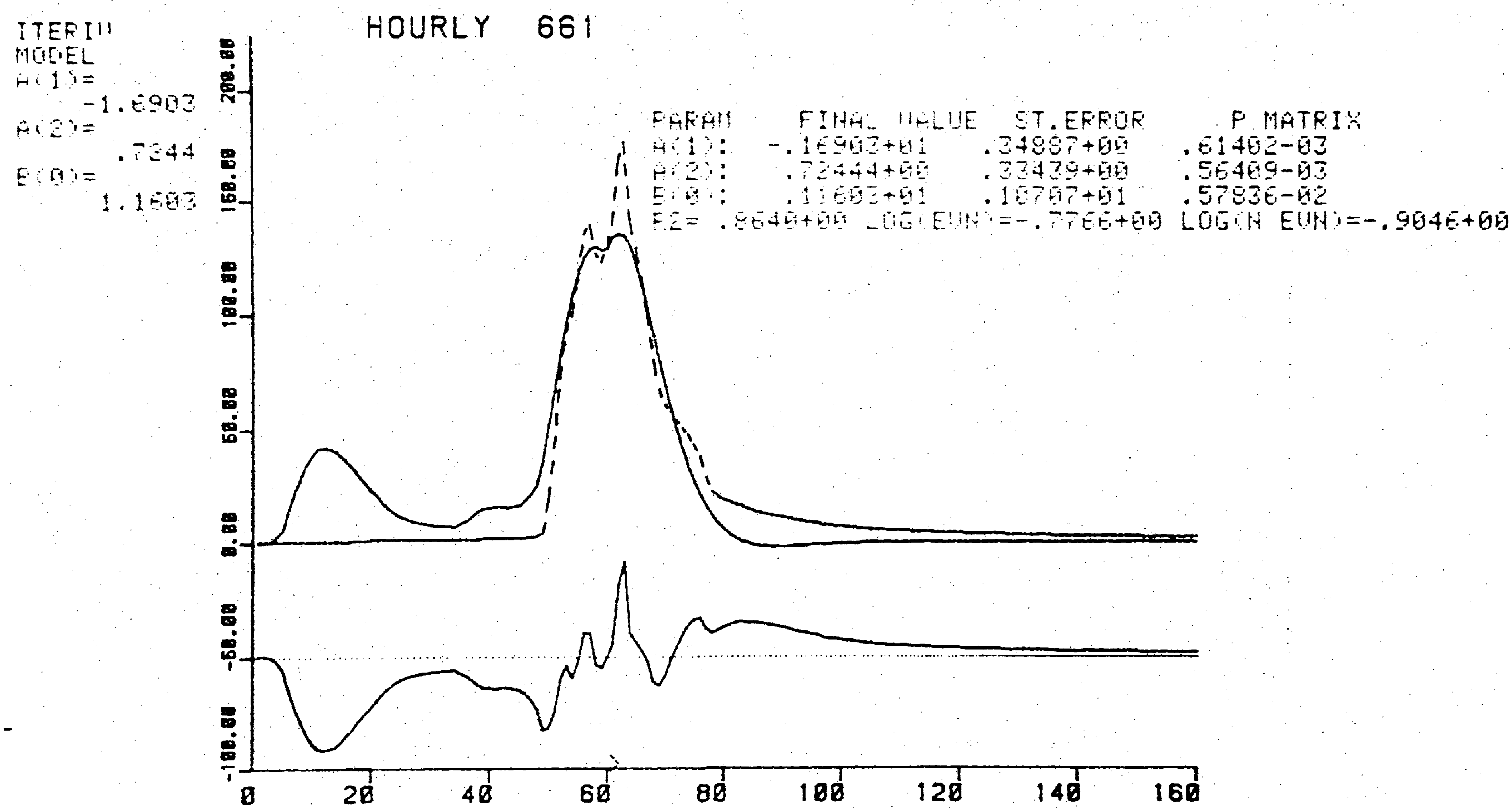


Fig 5.20 Raw Data Model 661

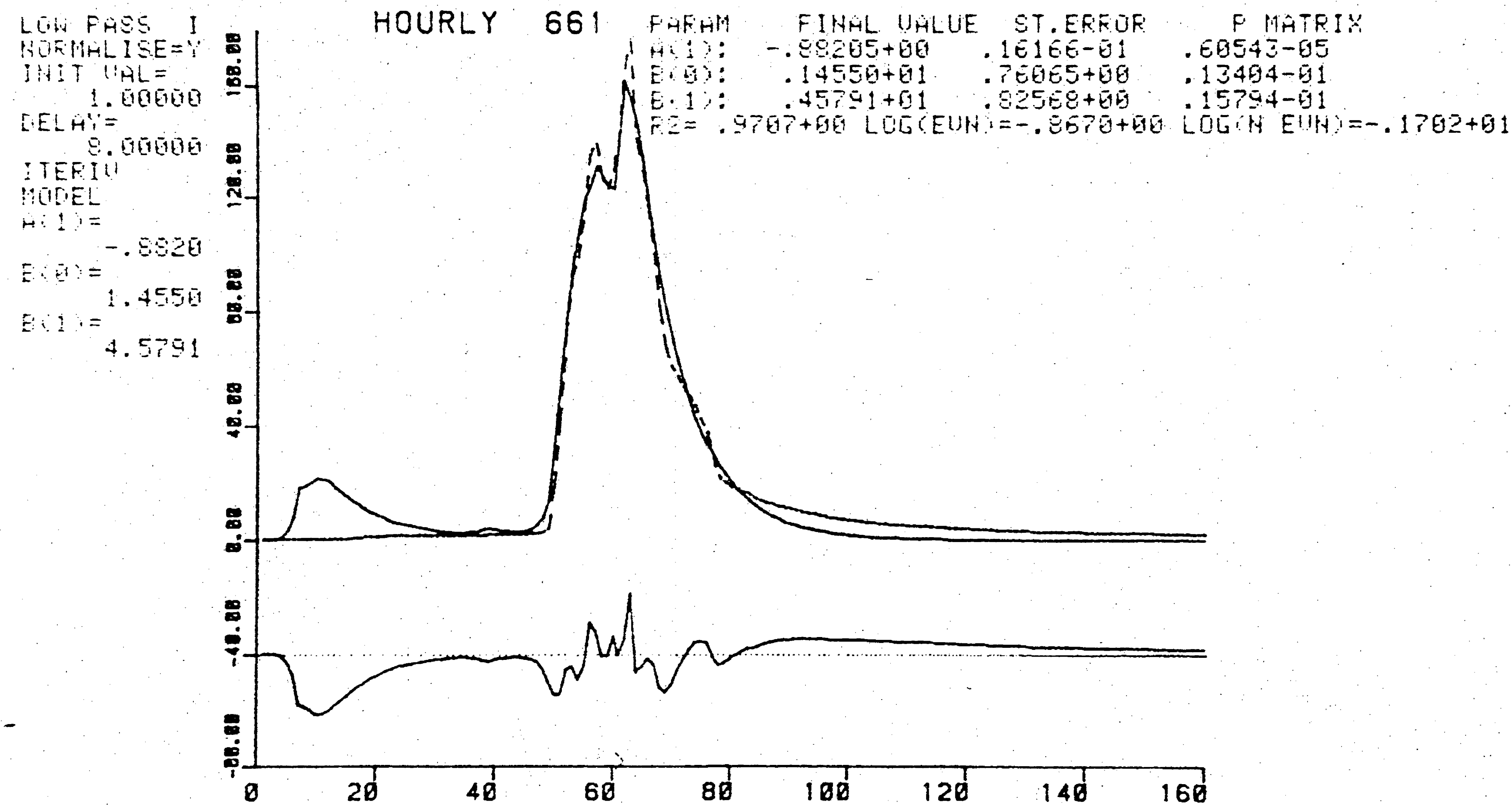


Fig 5.21 Model 661 with allowance for Soil Moisture Effects (T_s=8 hours)

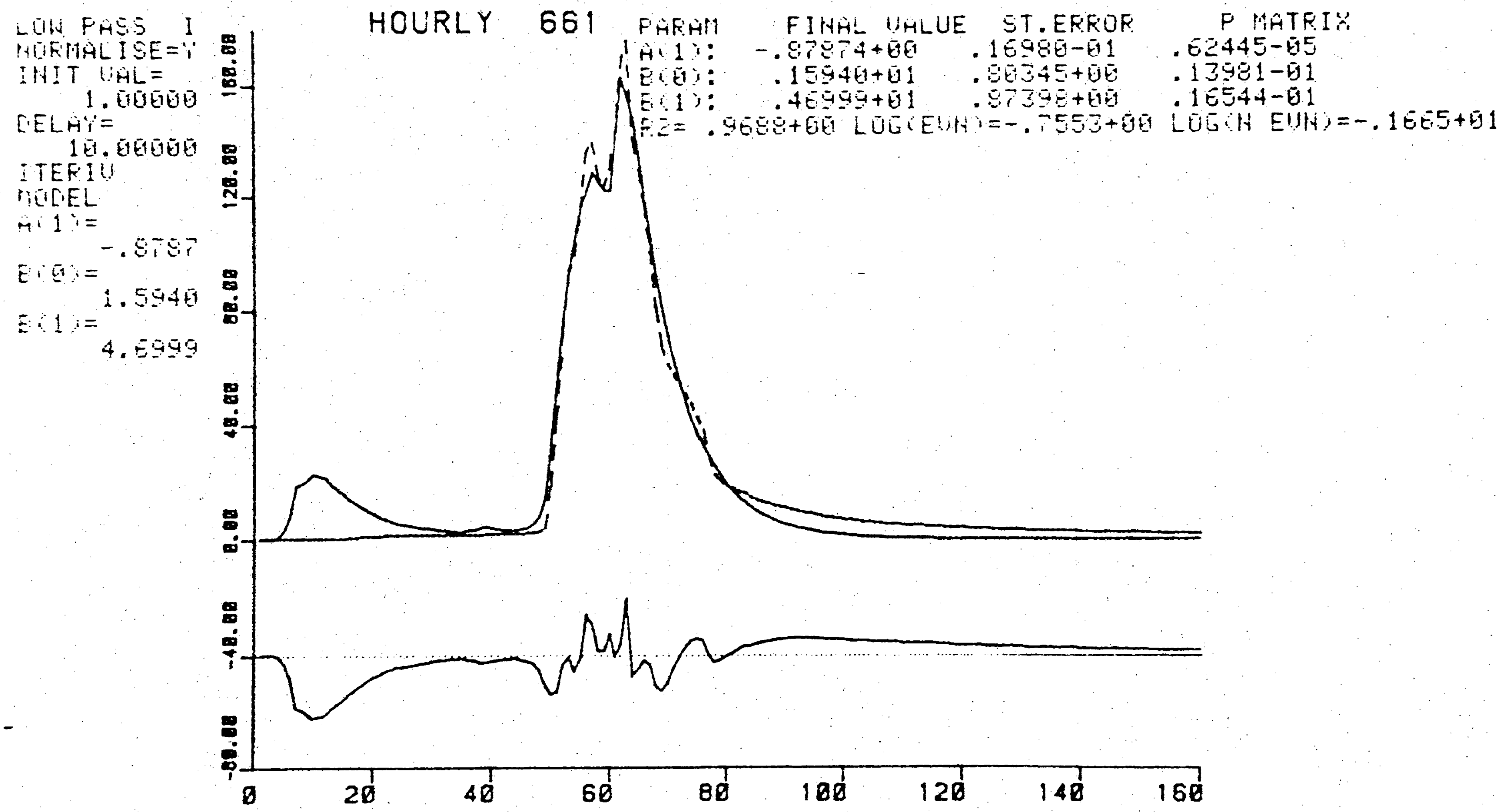


Fig 5.22 Model 661 with allowance for Soil Moisture Effects (T_s=10 jours)

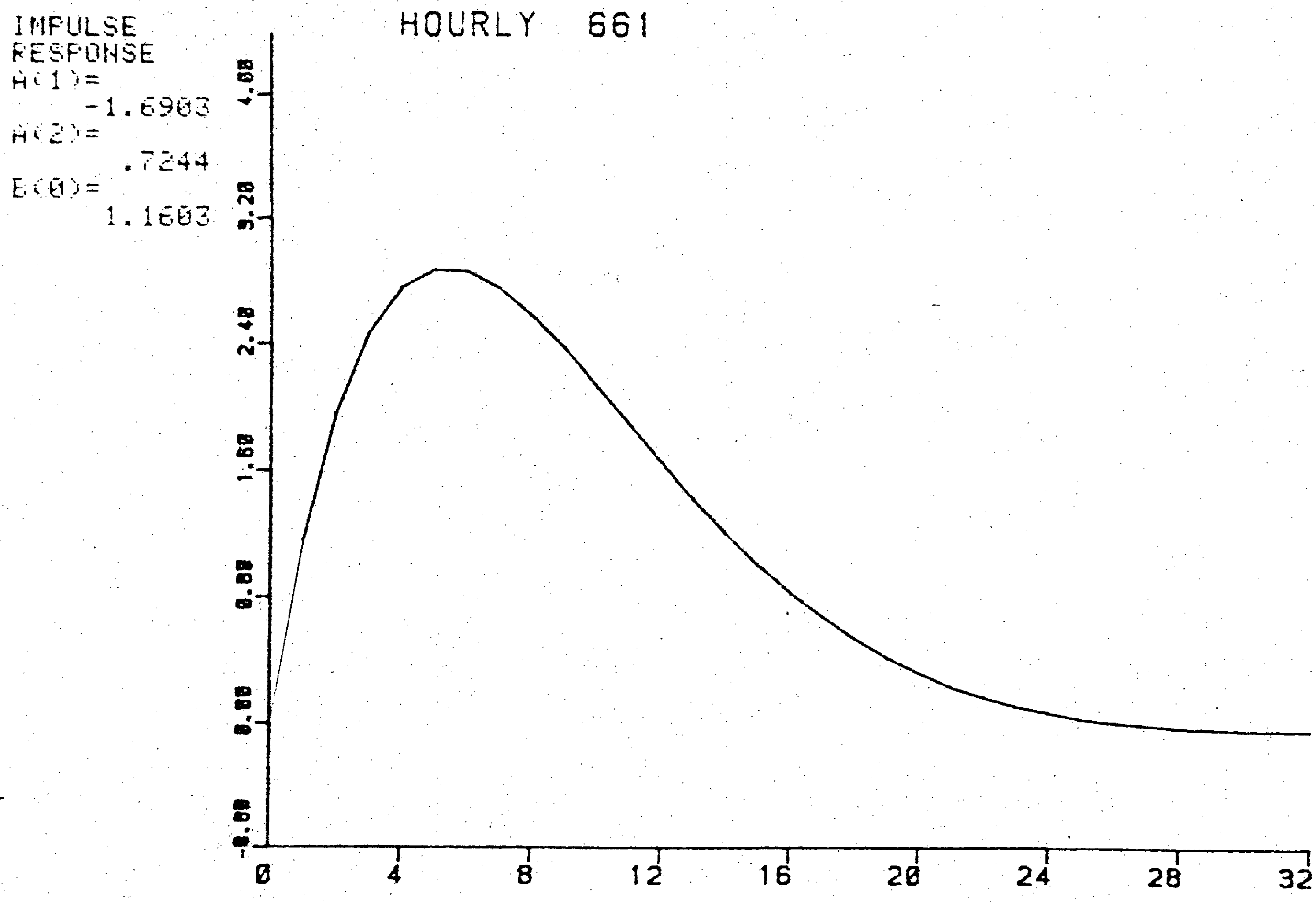


Fig 5.23 Impulse Response for Model Fig 5.20

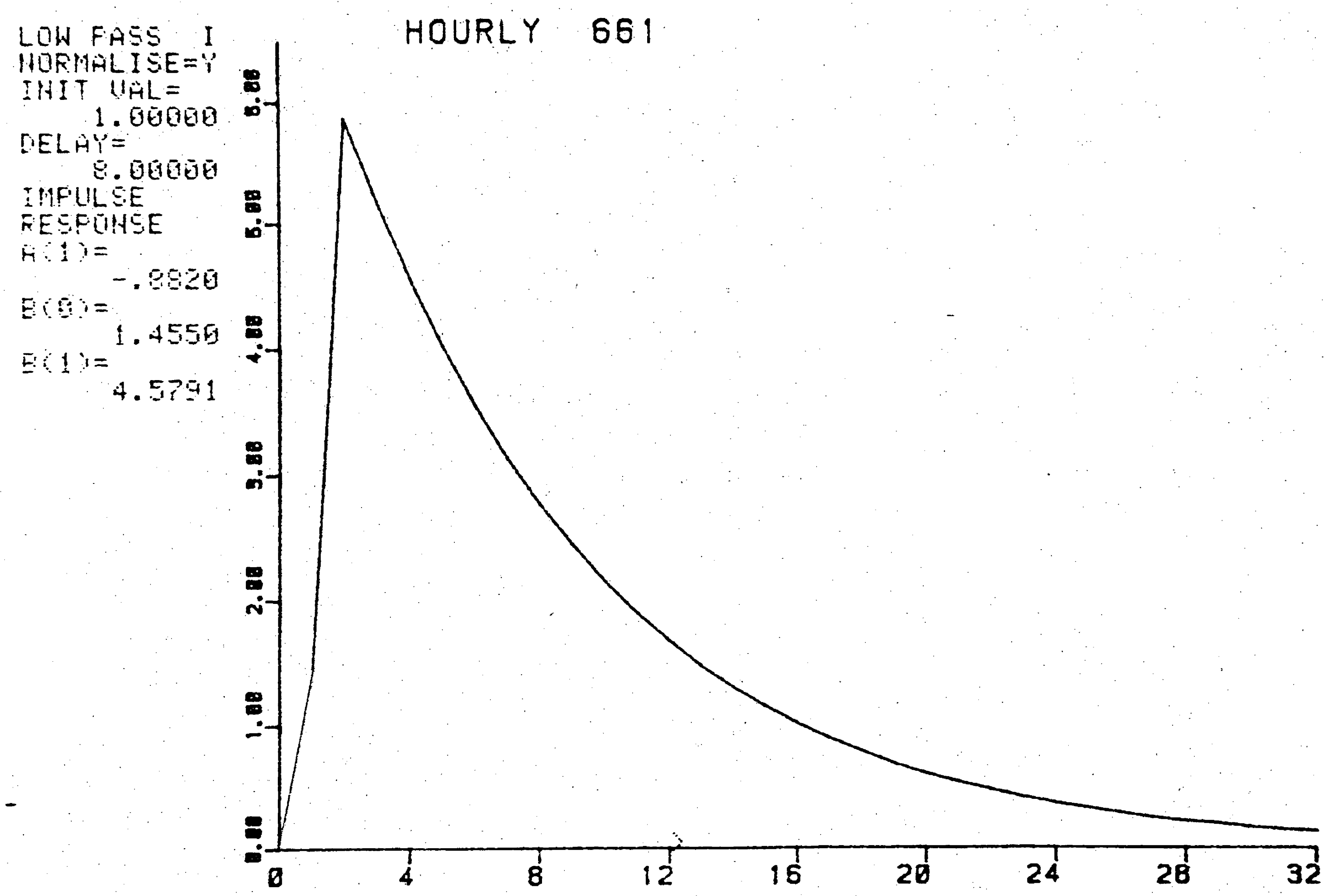


Fig 5.24 Impulse Response for Model Fig 5.21

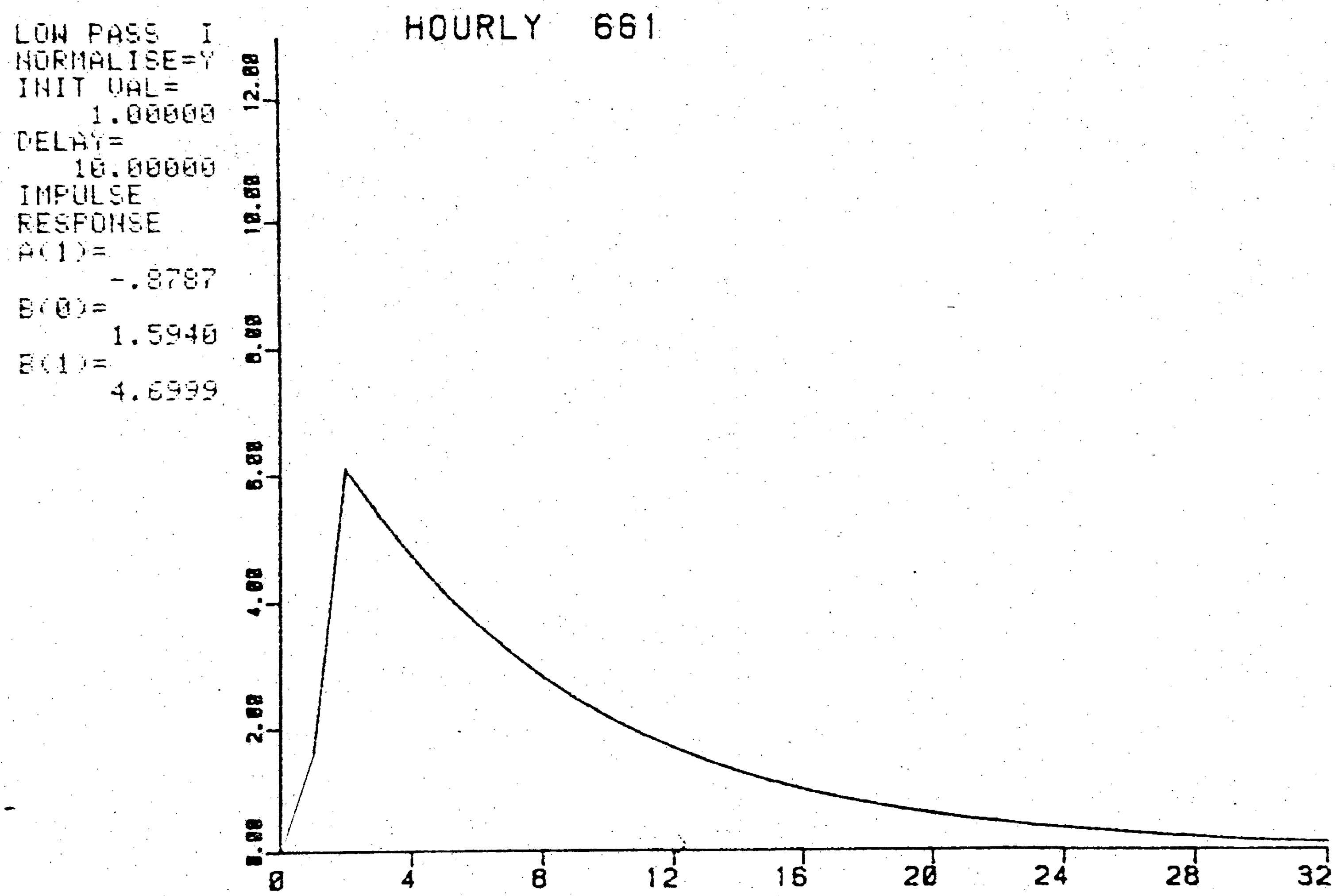


Fig 5.25 Impulse Response for Model Fig 5.22

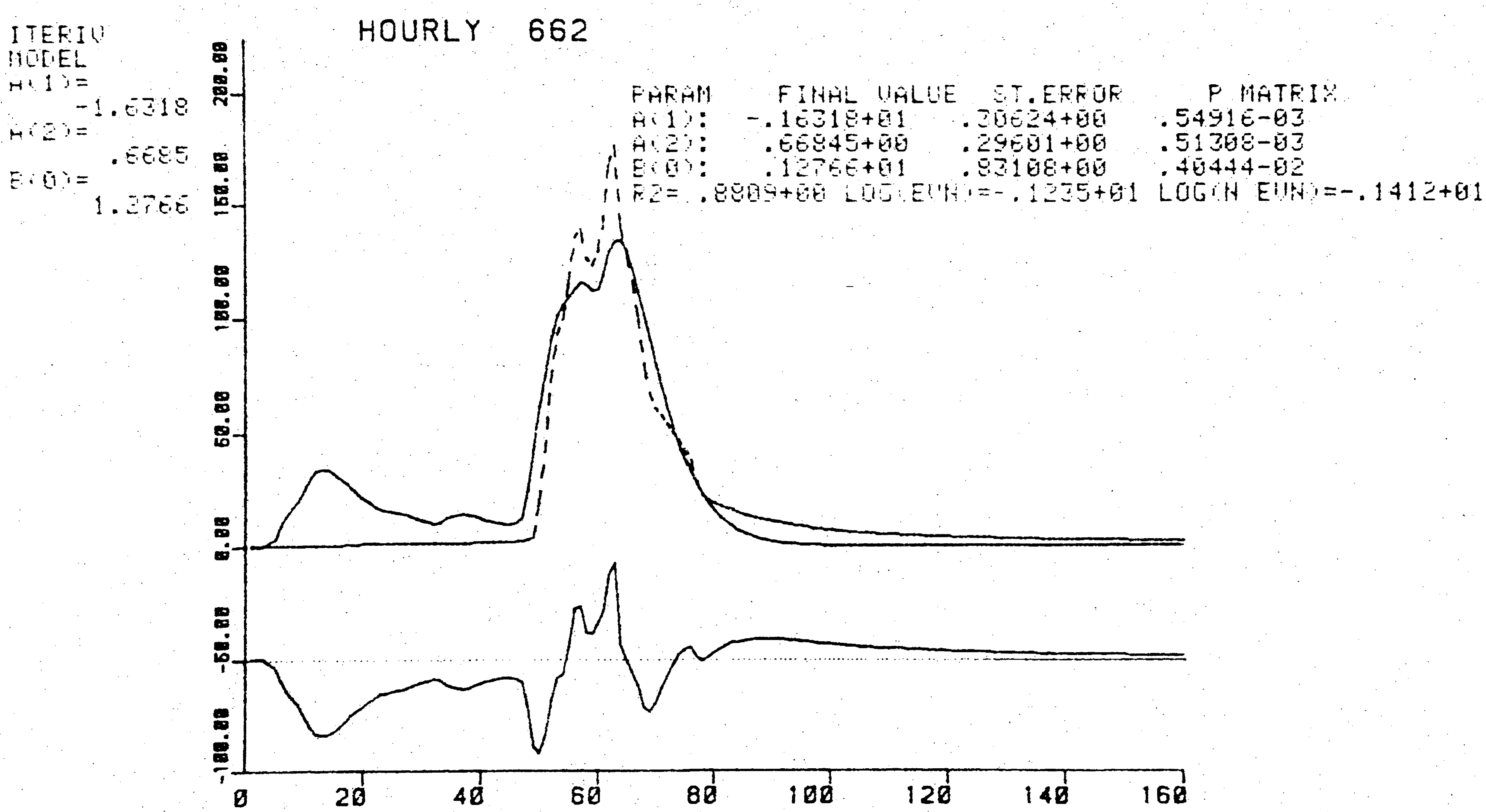


Fig 5.26 Raw Data Model 662

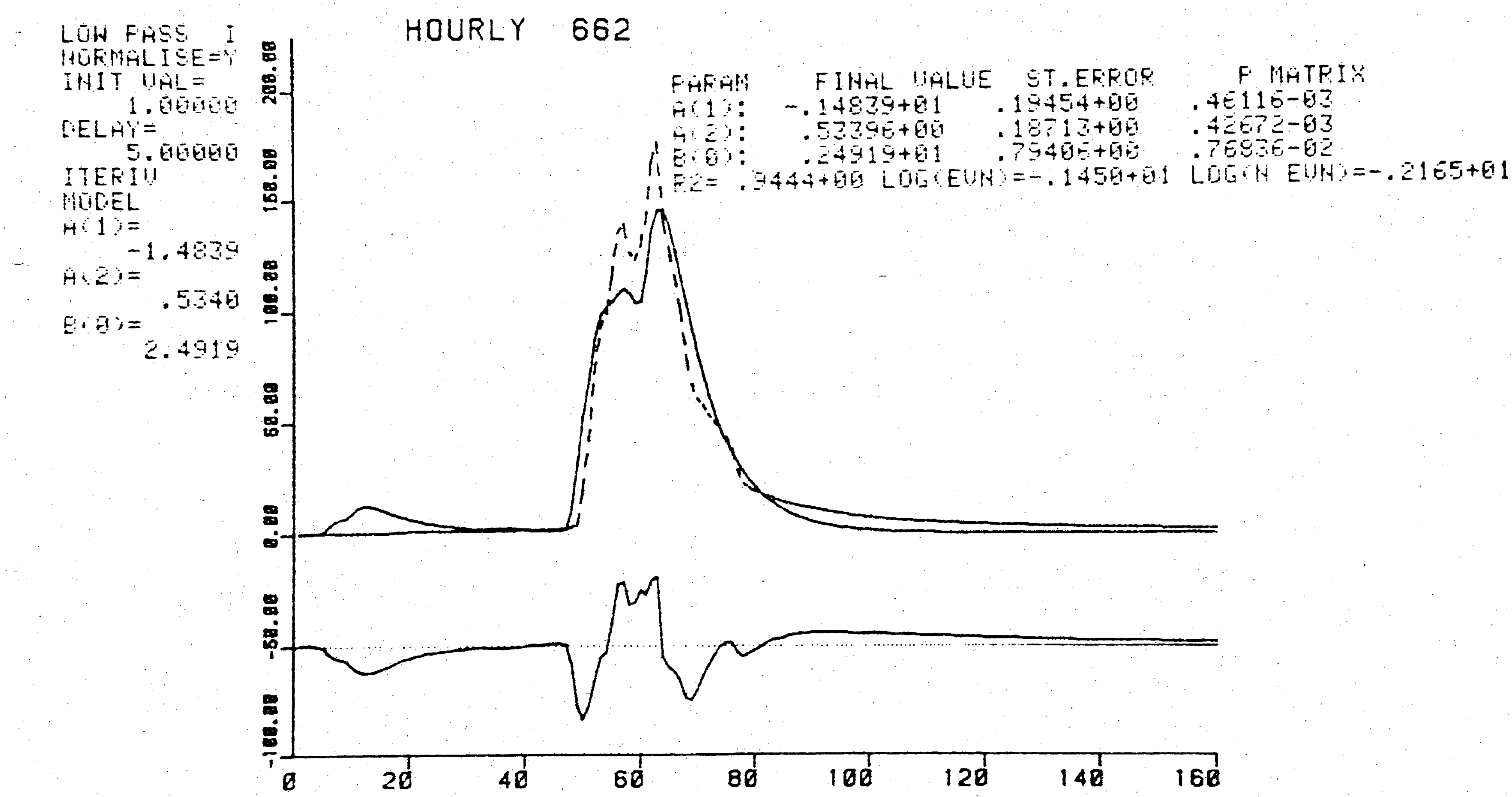


Fig 5.27 Model 662 with allowance for Soil Moisture Effects (T_s=5 hours)

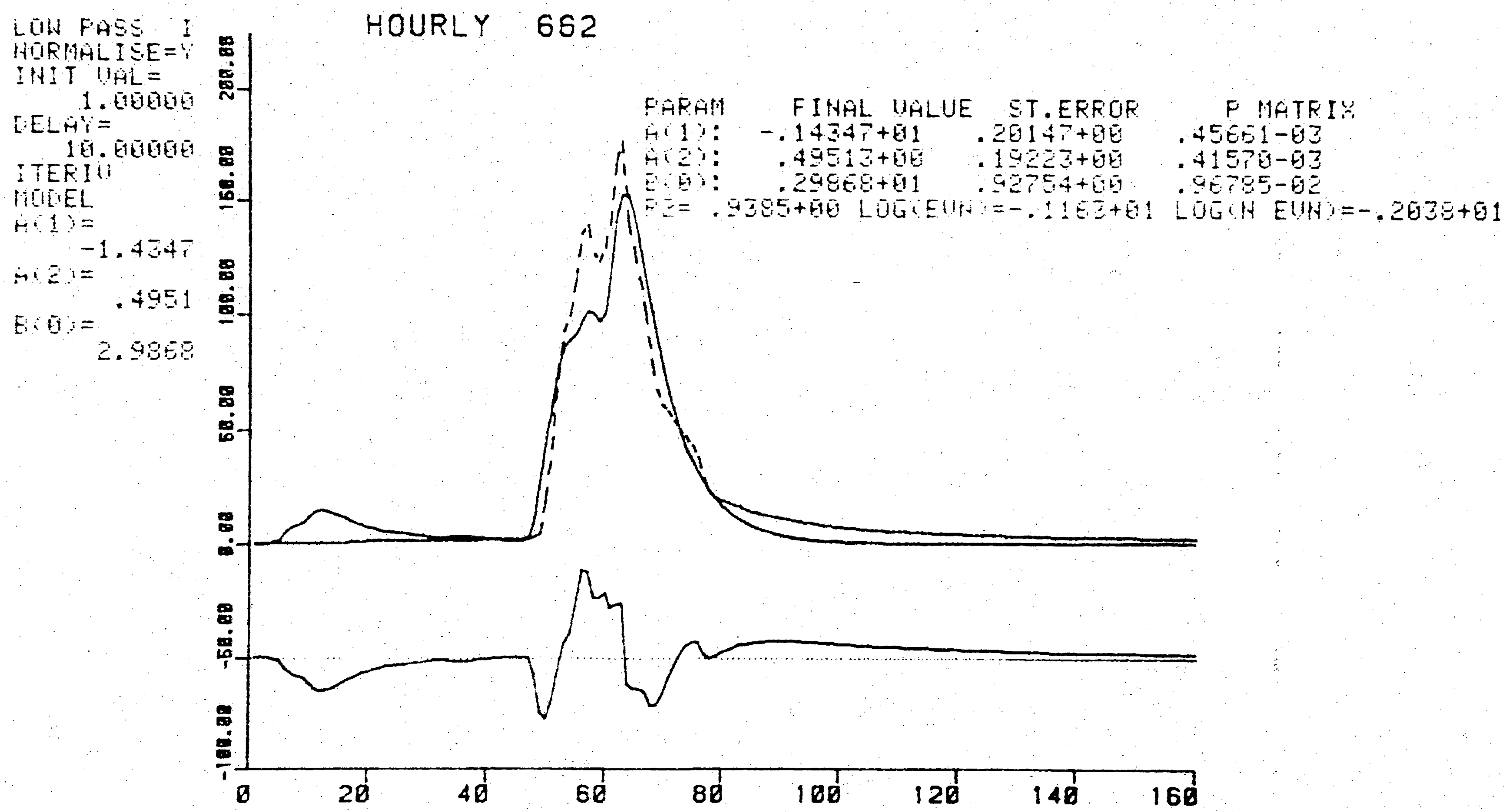


Fig 5.28 Model 662 with allowance for Soil Moisture Effects (T_s=10 hours)

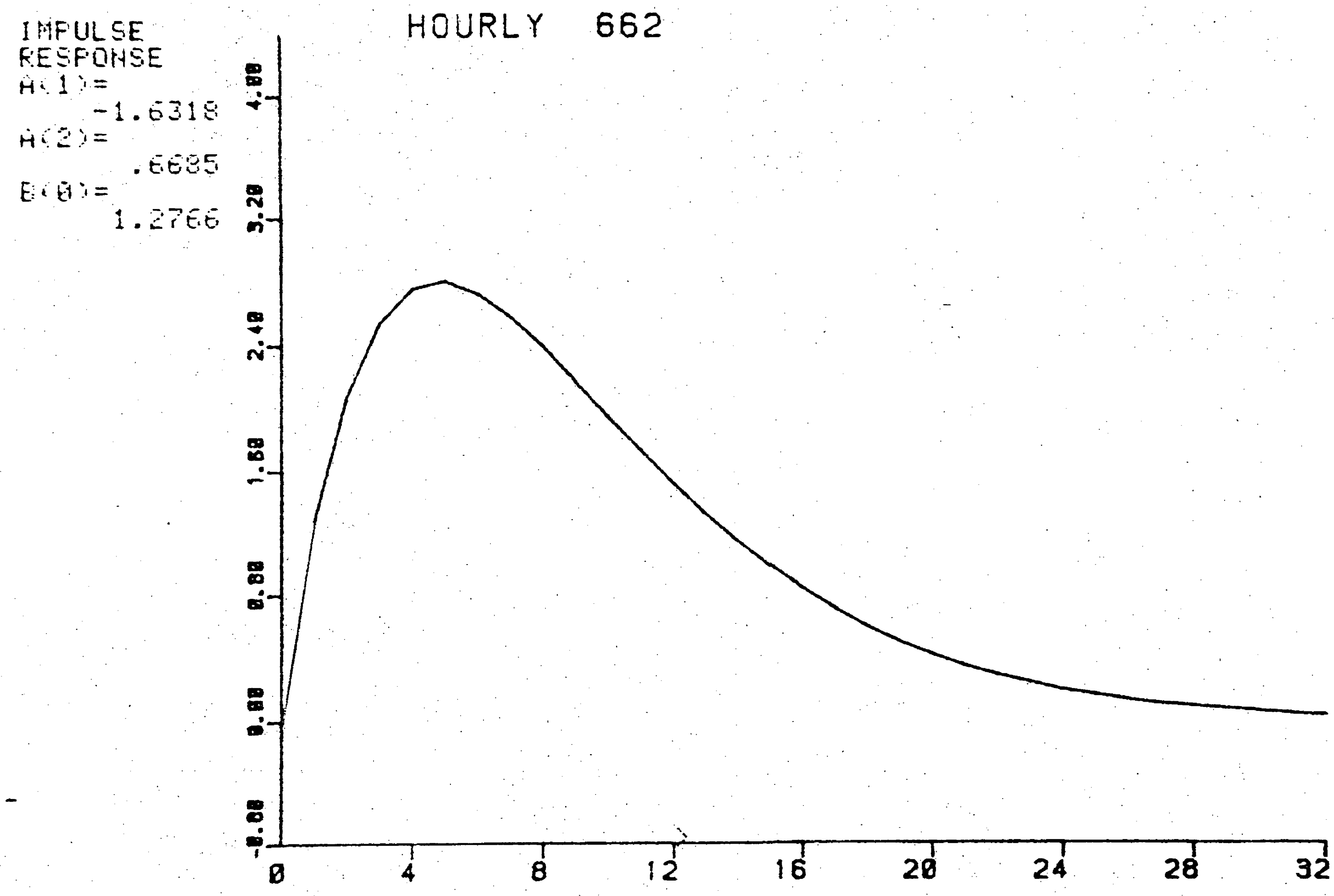


Fig 5.29 Impulse Response for Model Fig 5.26

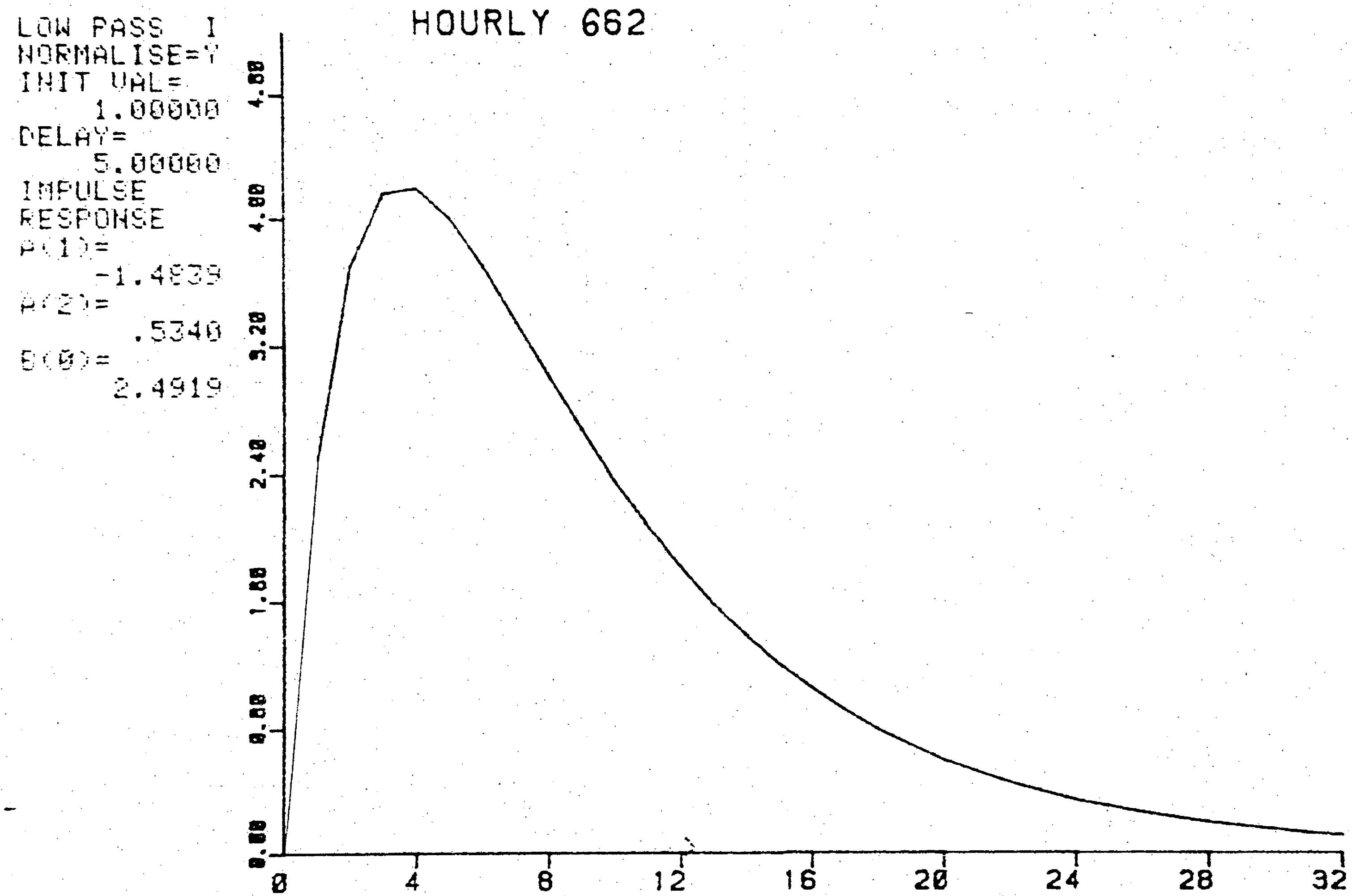


Fig 5.30   Impulse Response for Model Fig 5.27

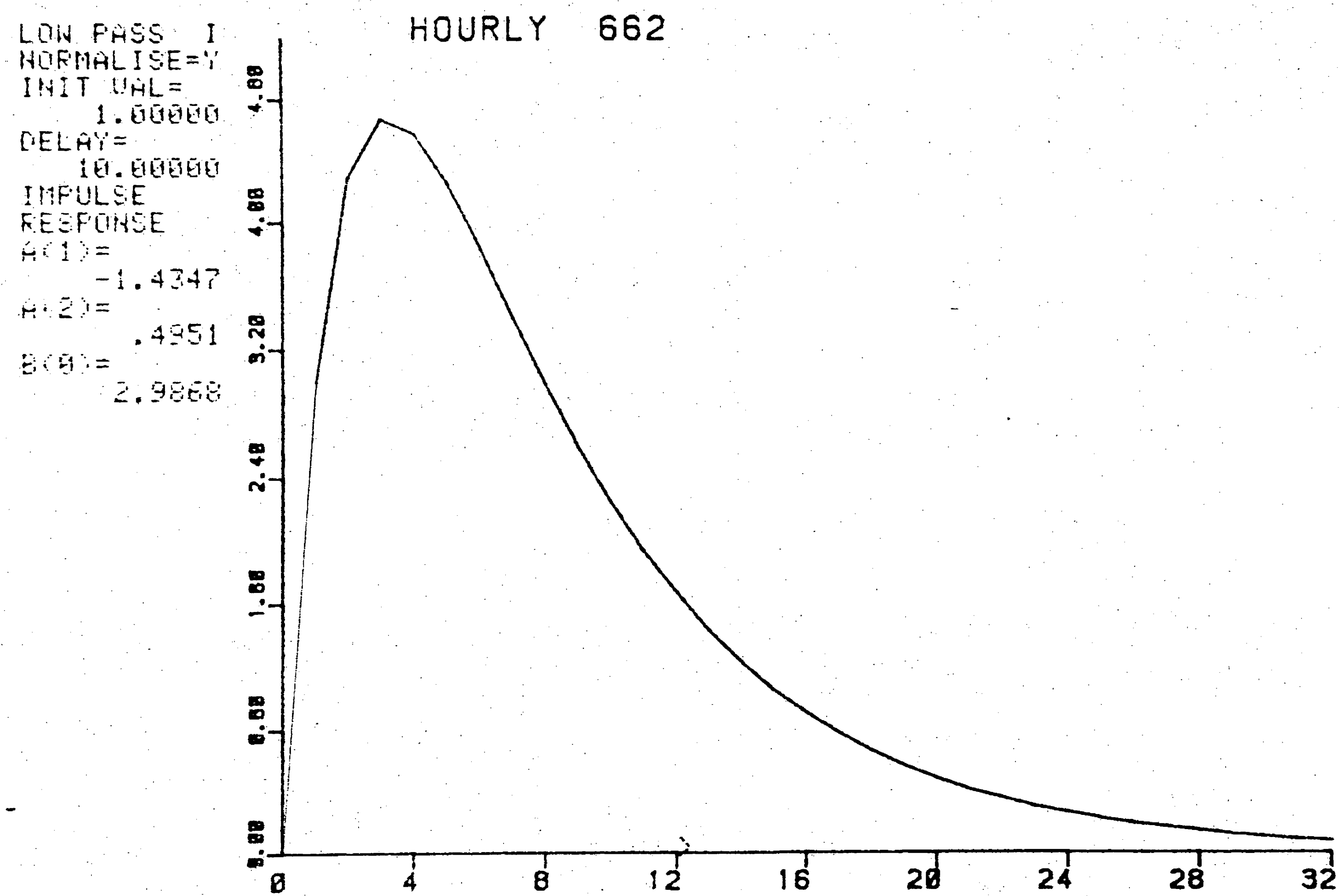


Fig 5.31 Impulse Response for Model Fig 5.28

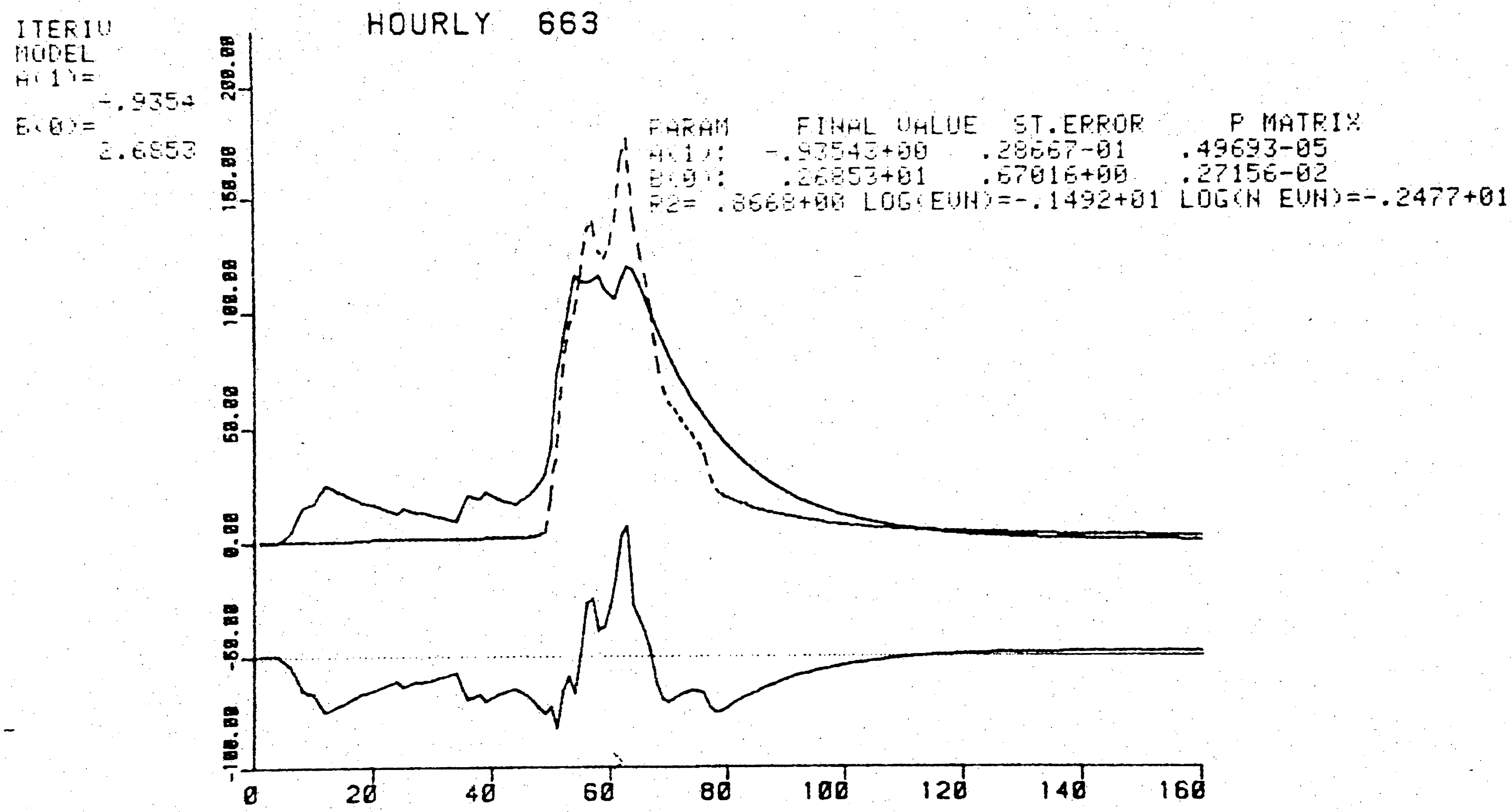


Fig 5.32 Raw Data Model 663

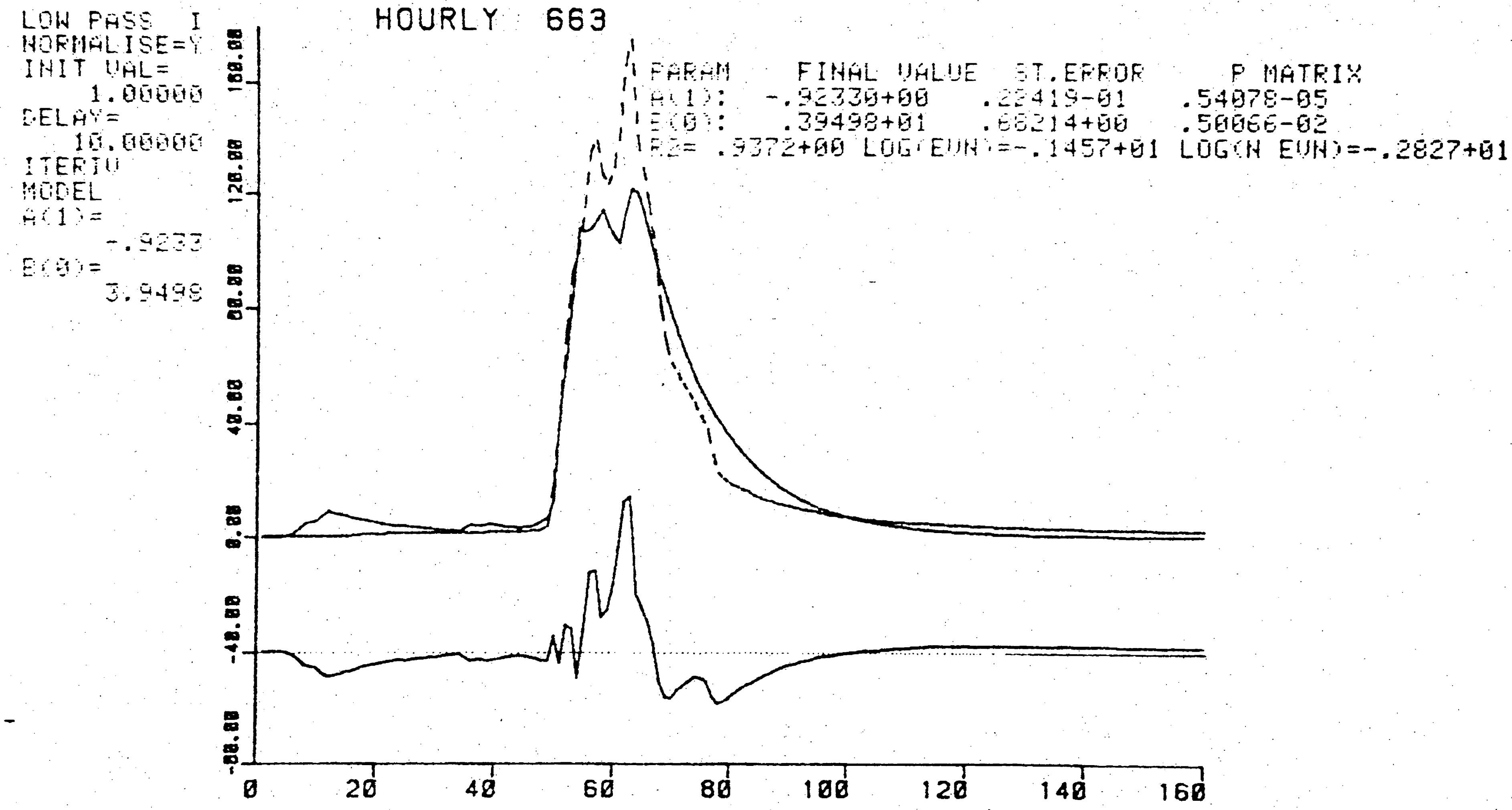


Fig 5.33 Model 663 with allowance for Soil Moisture Effects (T_S=10 hours)

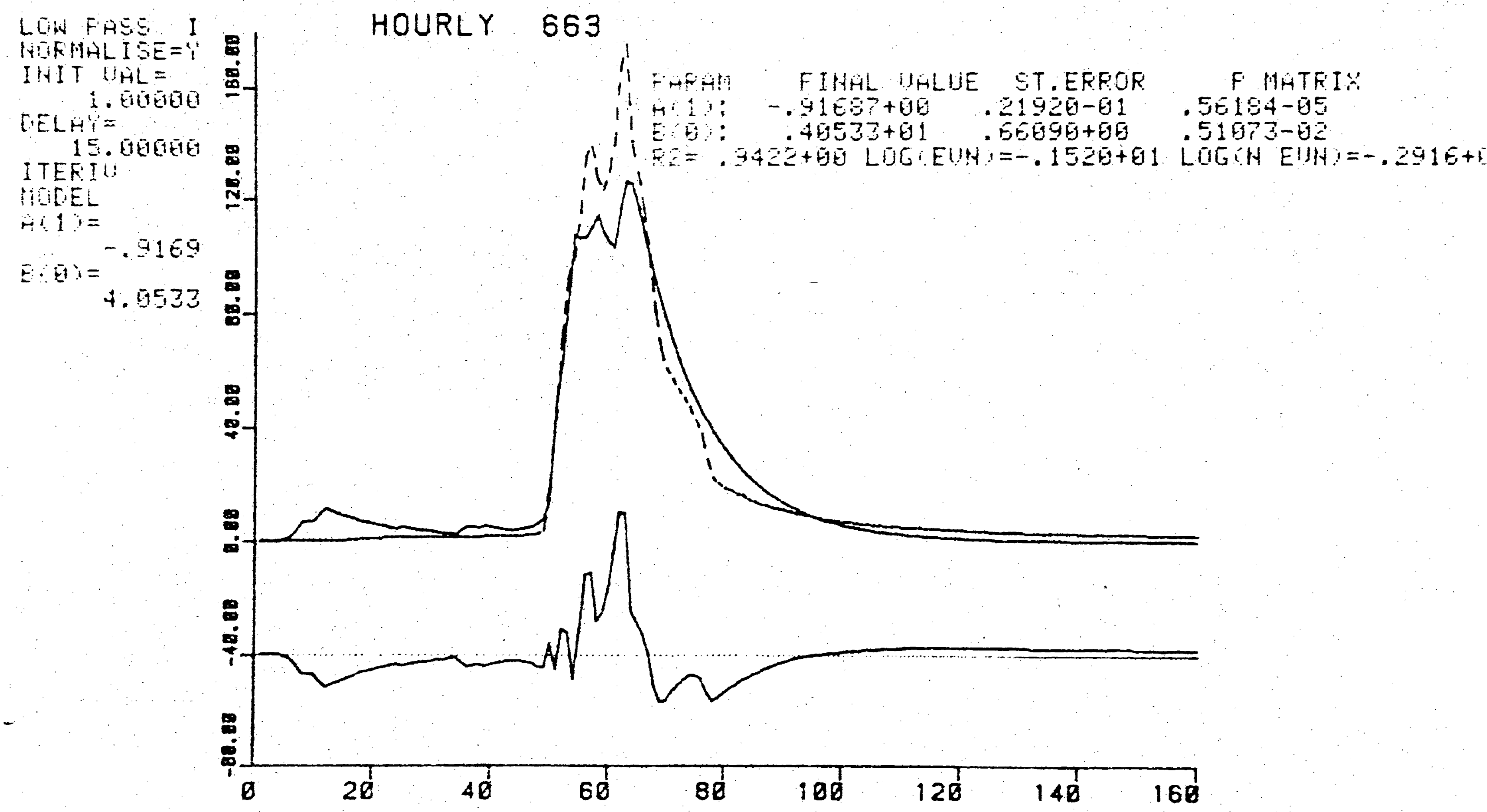


Fig 5.34 Model 663 with allowance for Soil Moisture Effects (T_S=15 hours)

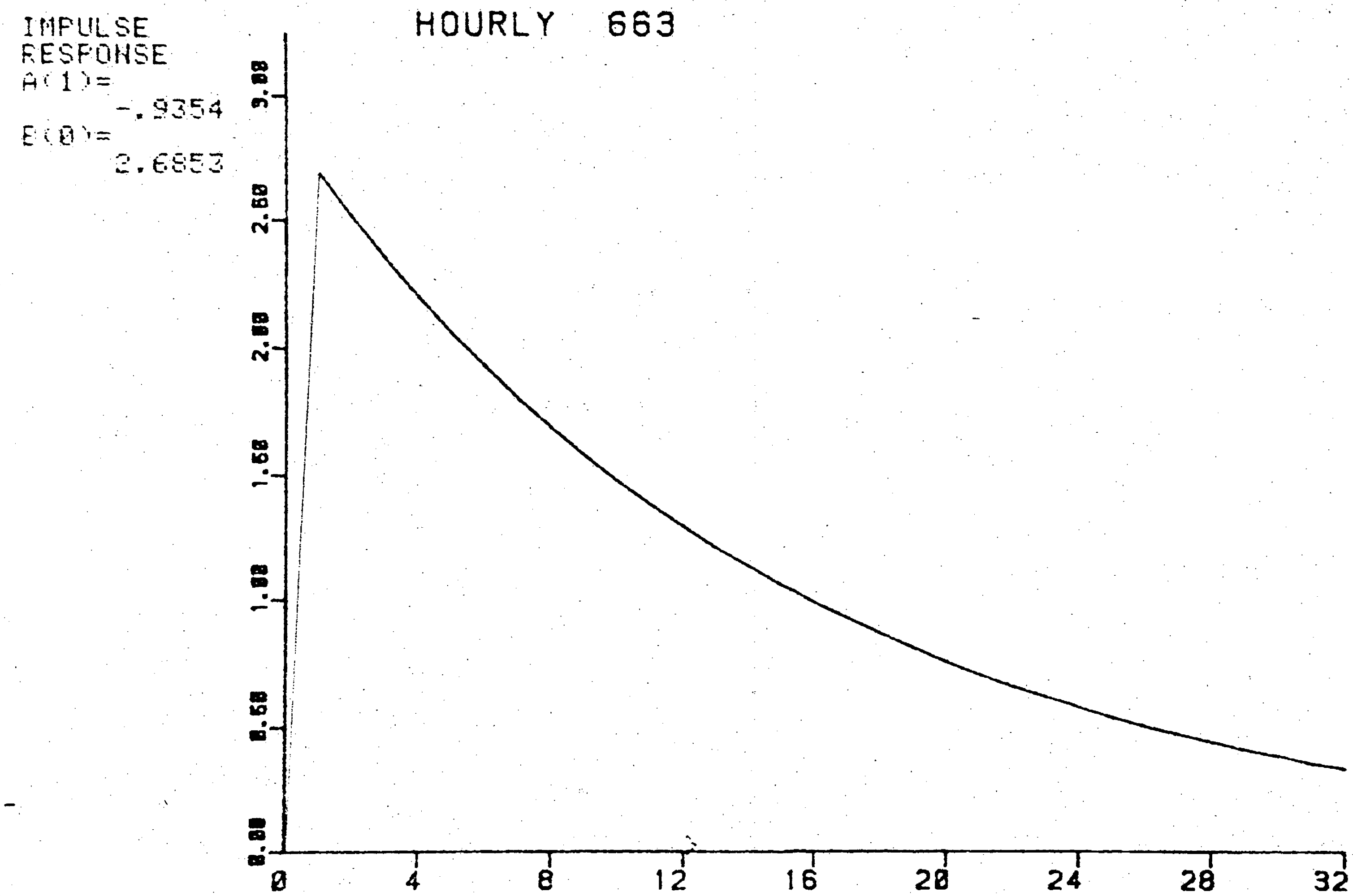


Fig 5.35 Impulse Response for Model Fig 5.32

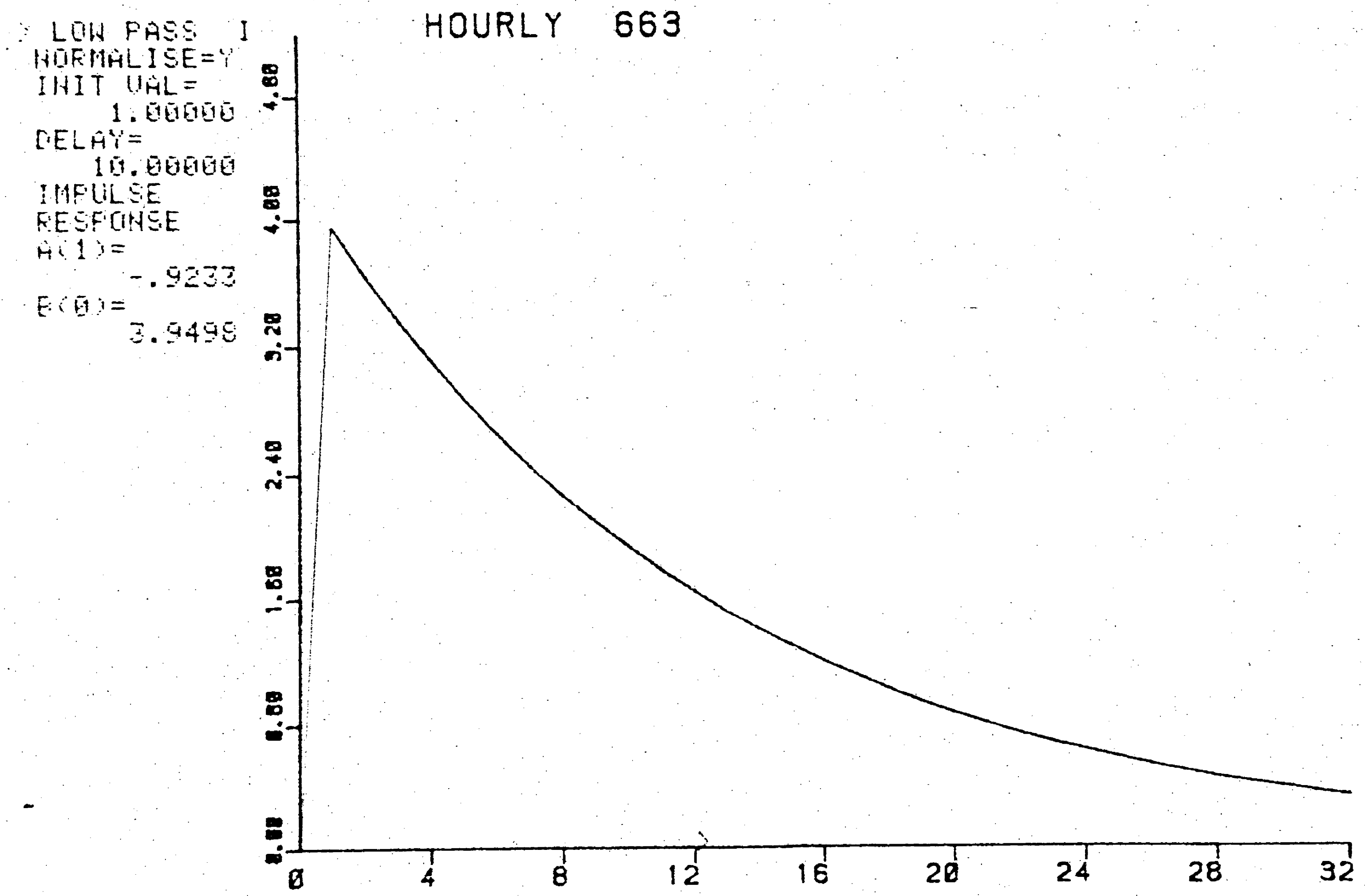


Fig 5.36 Impulse Response for Model Fig 5.33

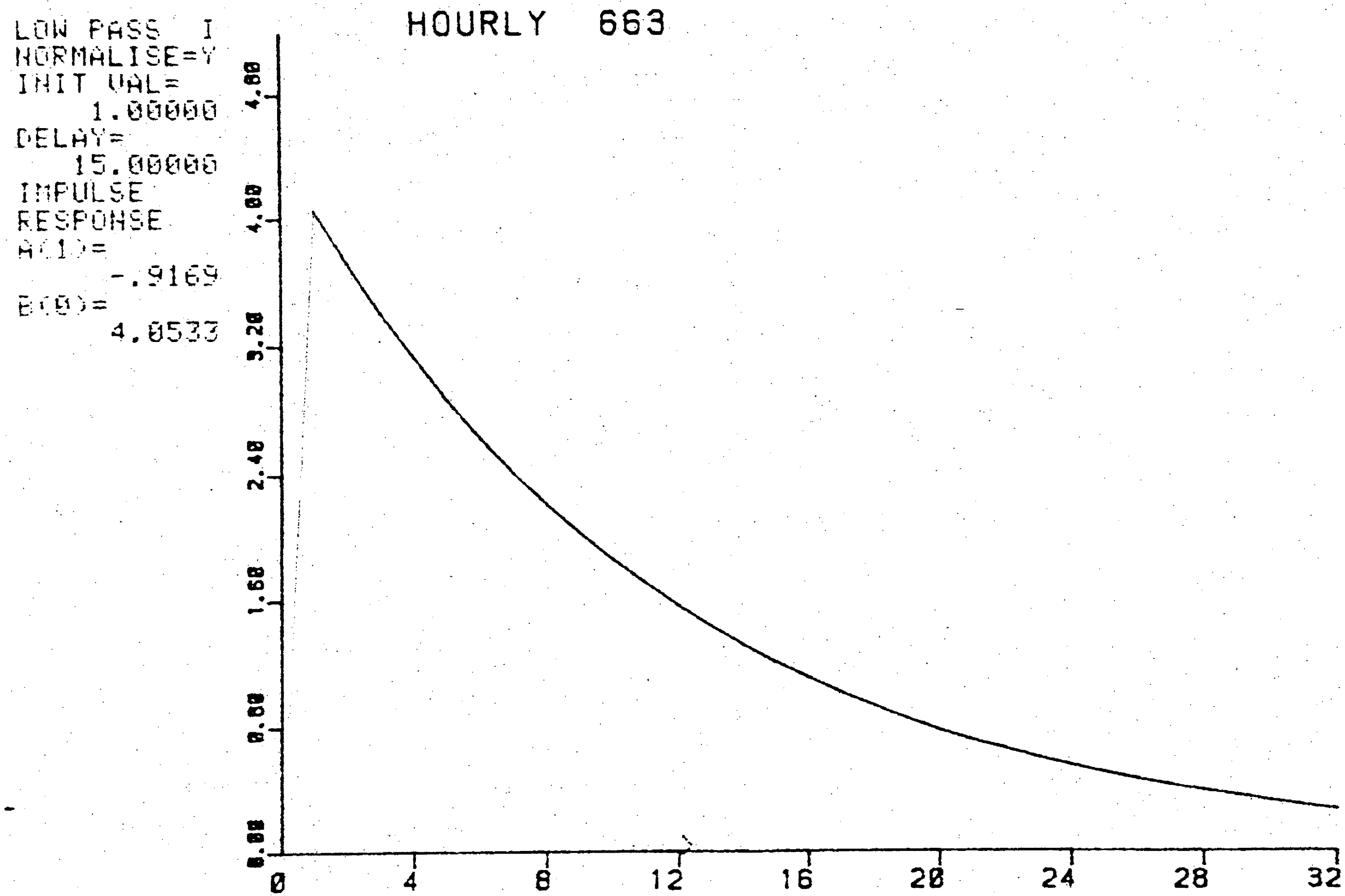


Fig 5.37 Impulse Response for Model Fig 5.34

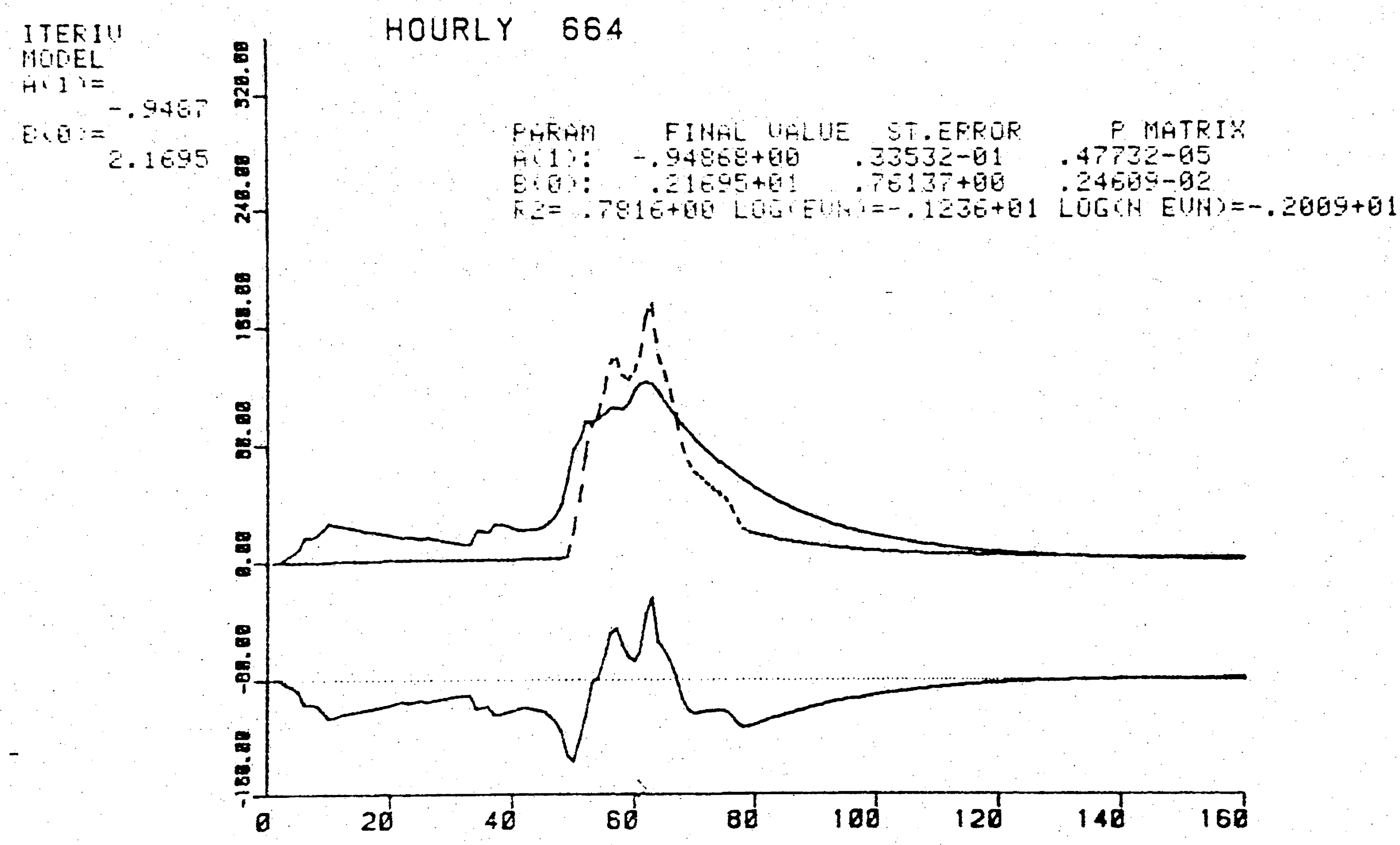


Fig 5.38 Raw Data Model 664

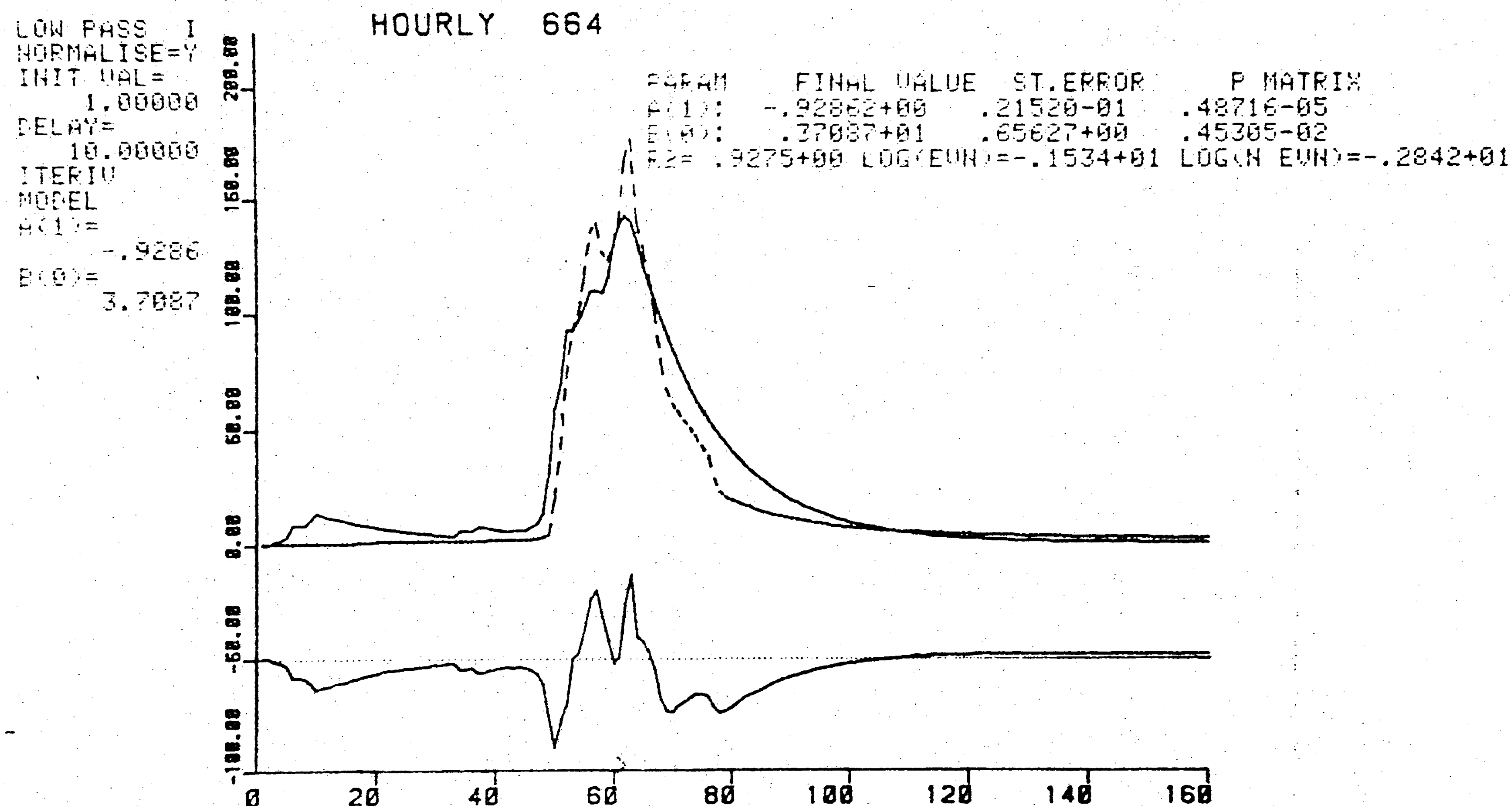


Fig 5.39 Model 664 with allowance for Soil Moisture Effects (T_S=10 hours)

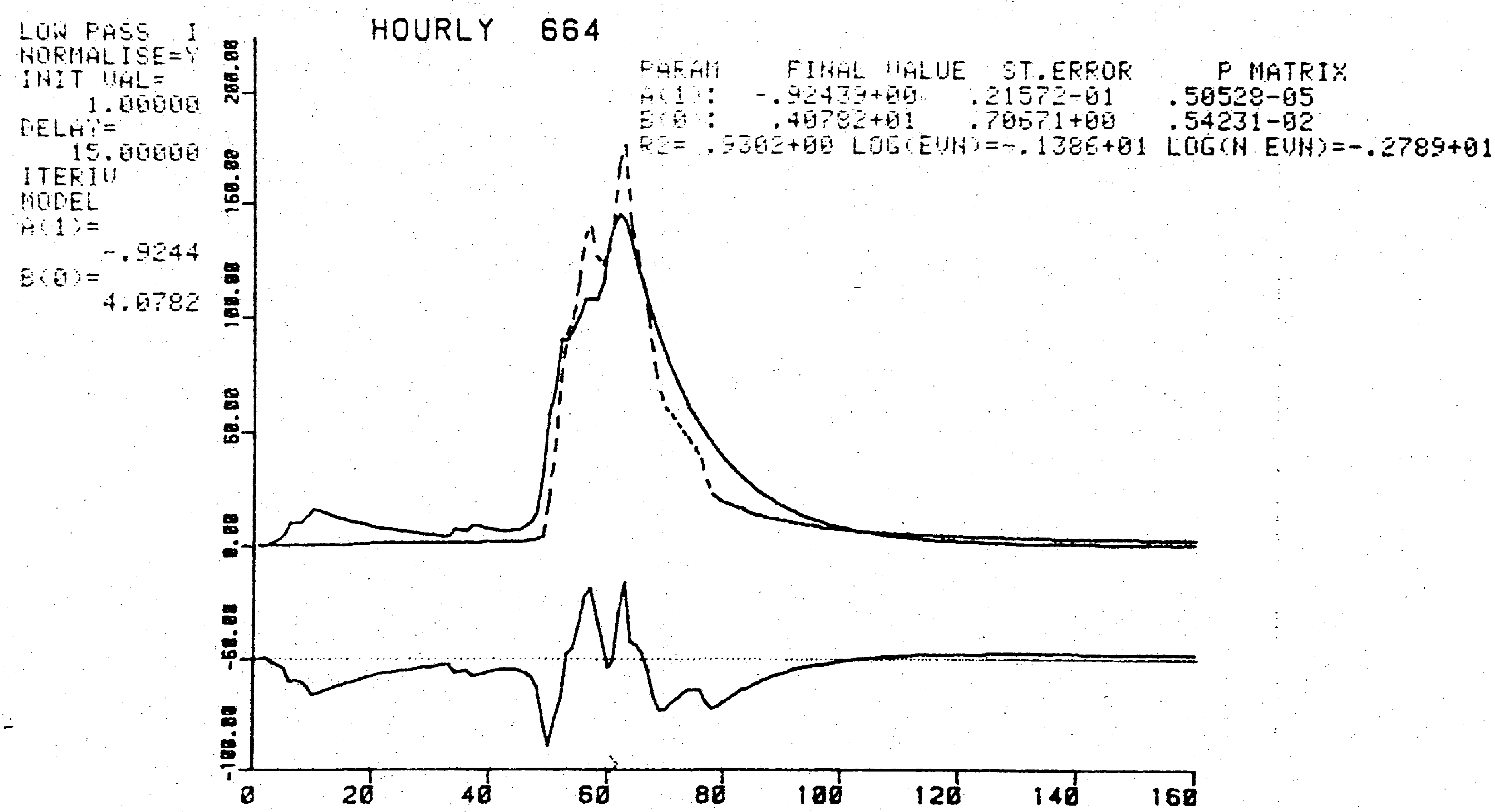


Fig 5.40 Model 664 with allowance for Soil Moisture Effects (T_S=15 hours)

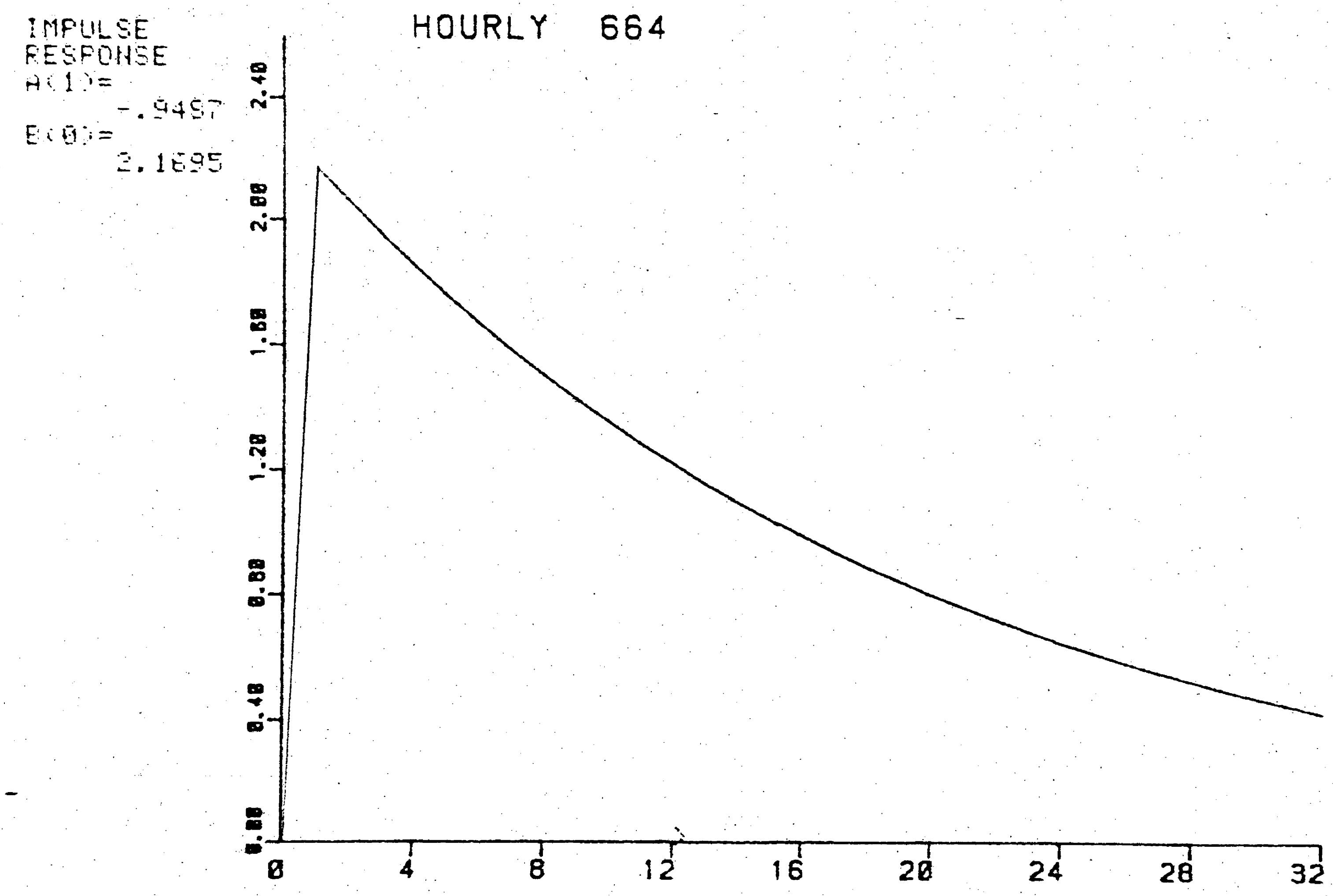


Fig 5.41 Impulse Response for Model Fig 5.38

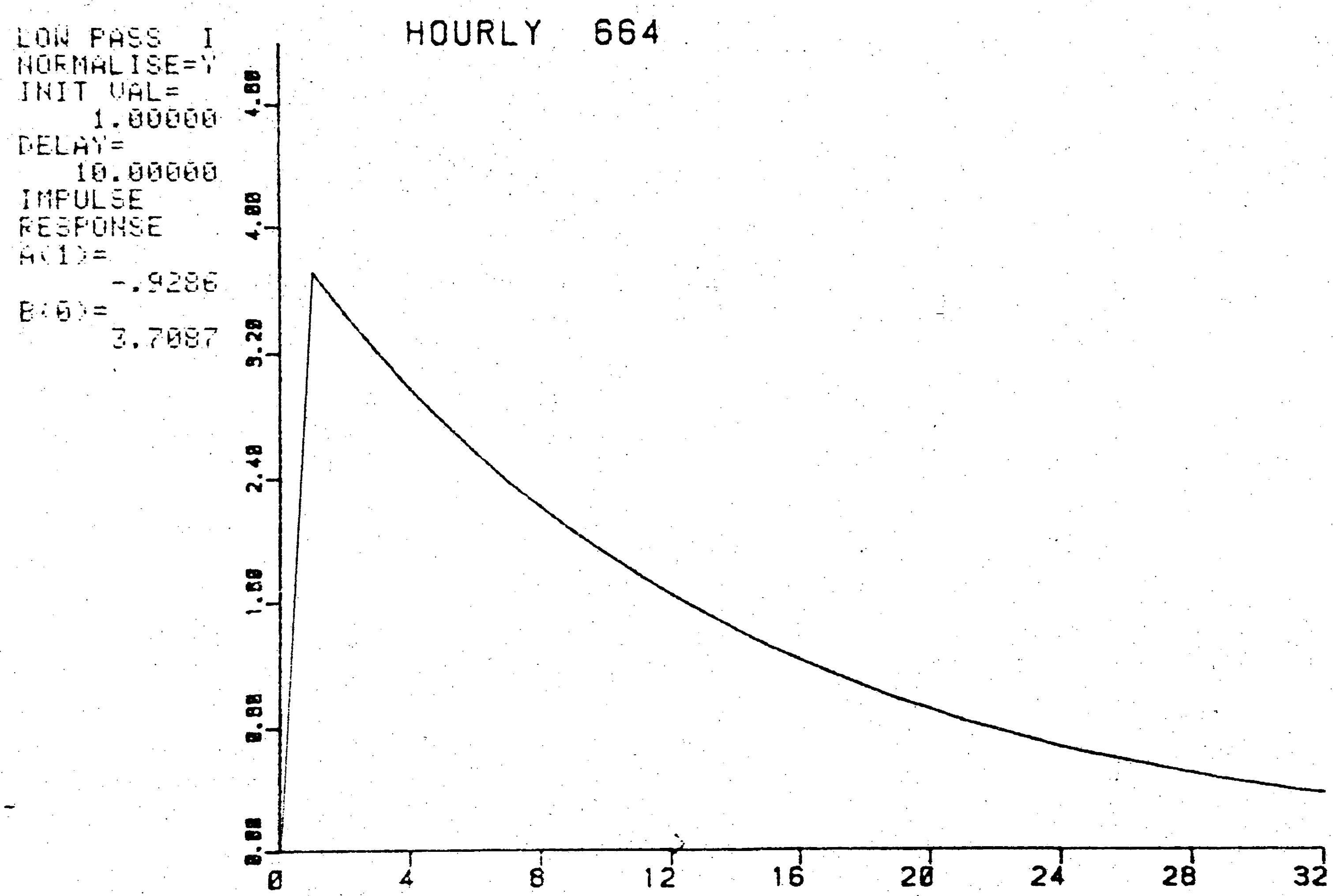


Fig 5.42 Impulse Response for Model Fig 5.39

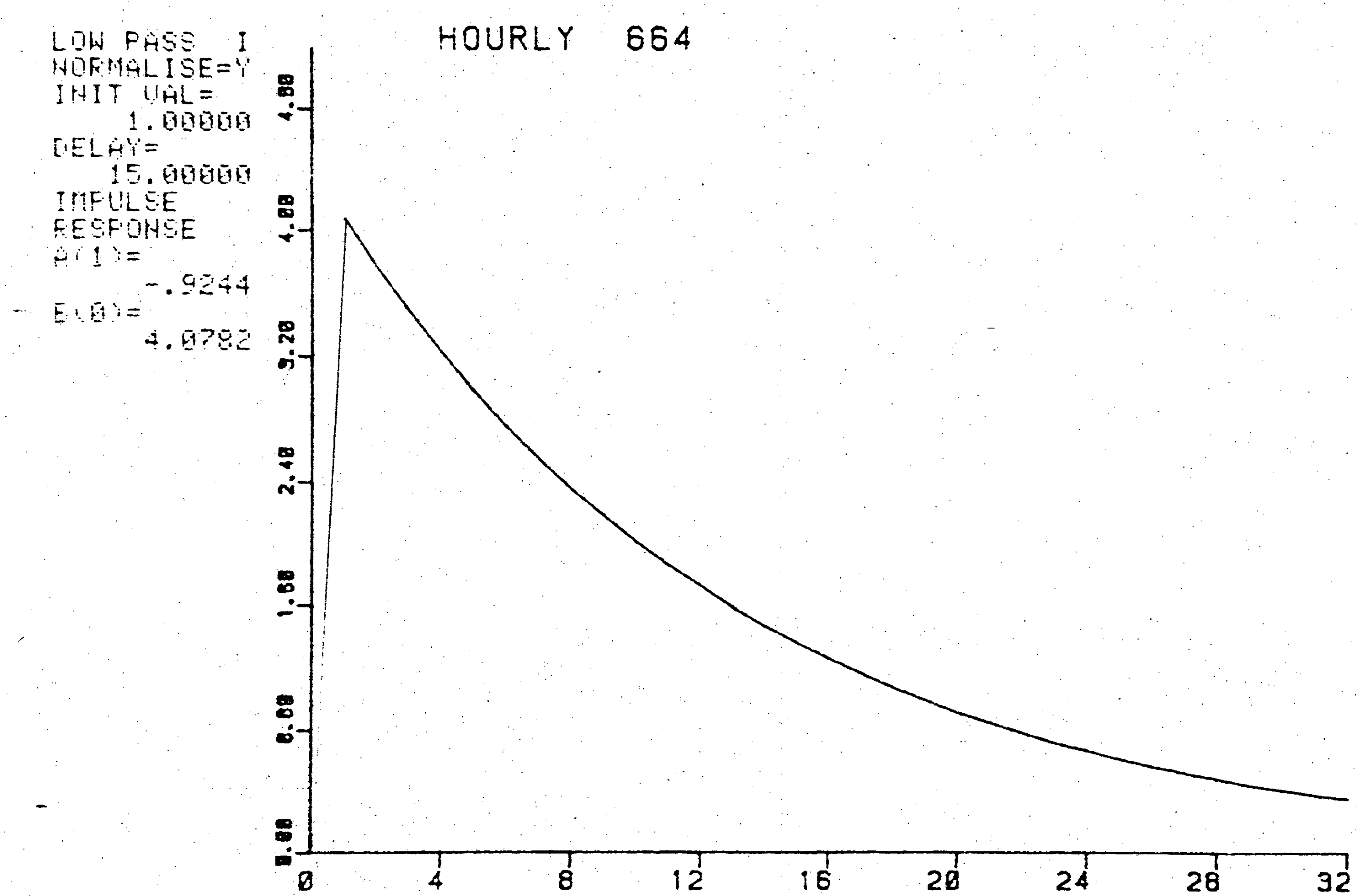


Fig 5.43 Impulse Response for Model Fig 5.40

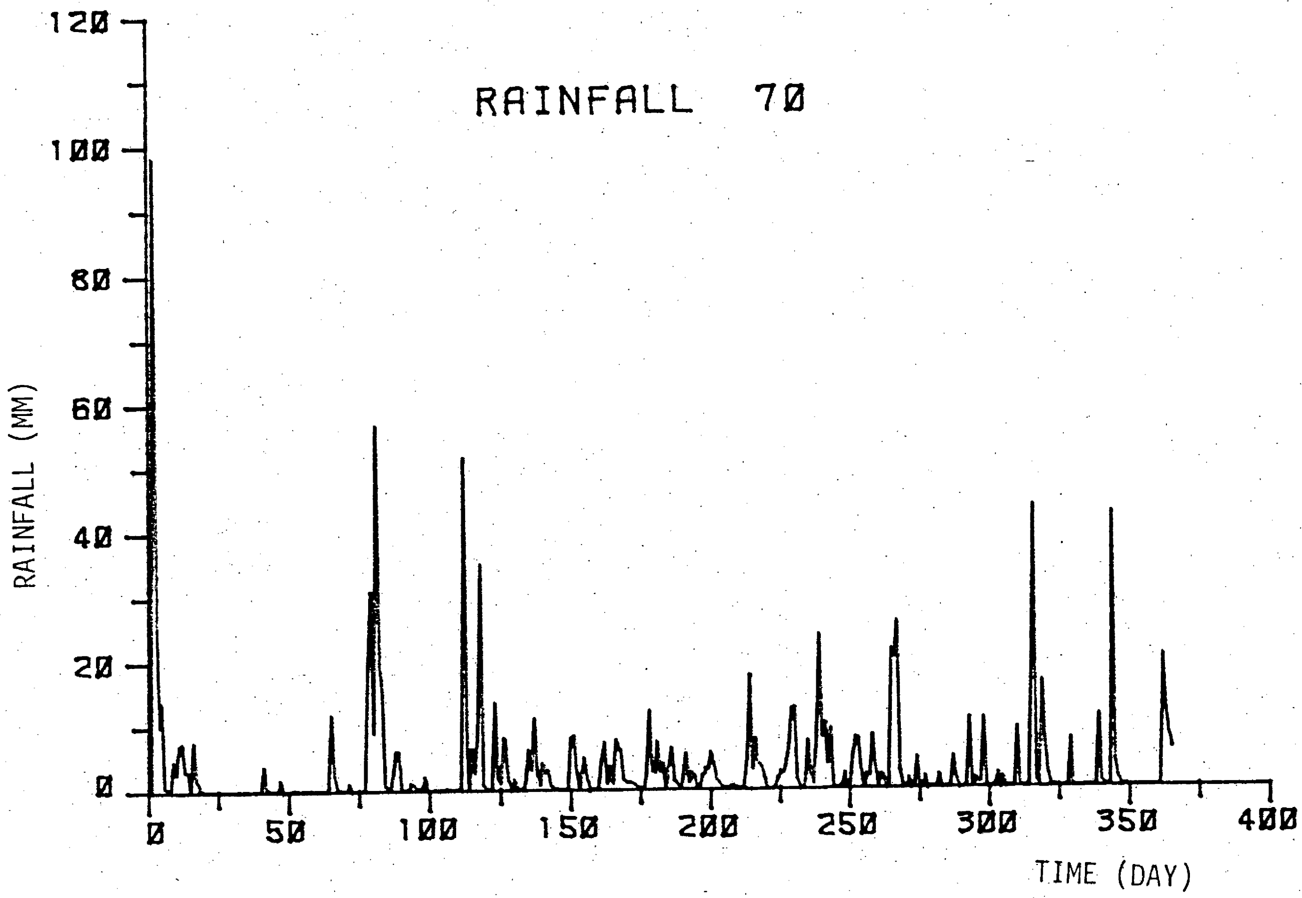


Fig 5.44 Rainfall 1970

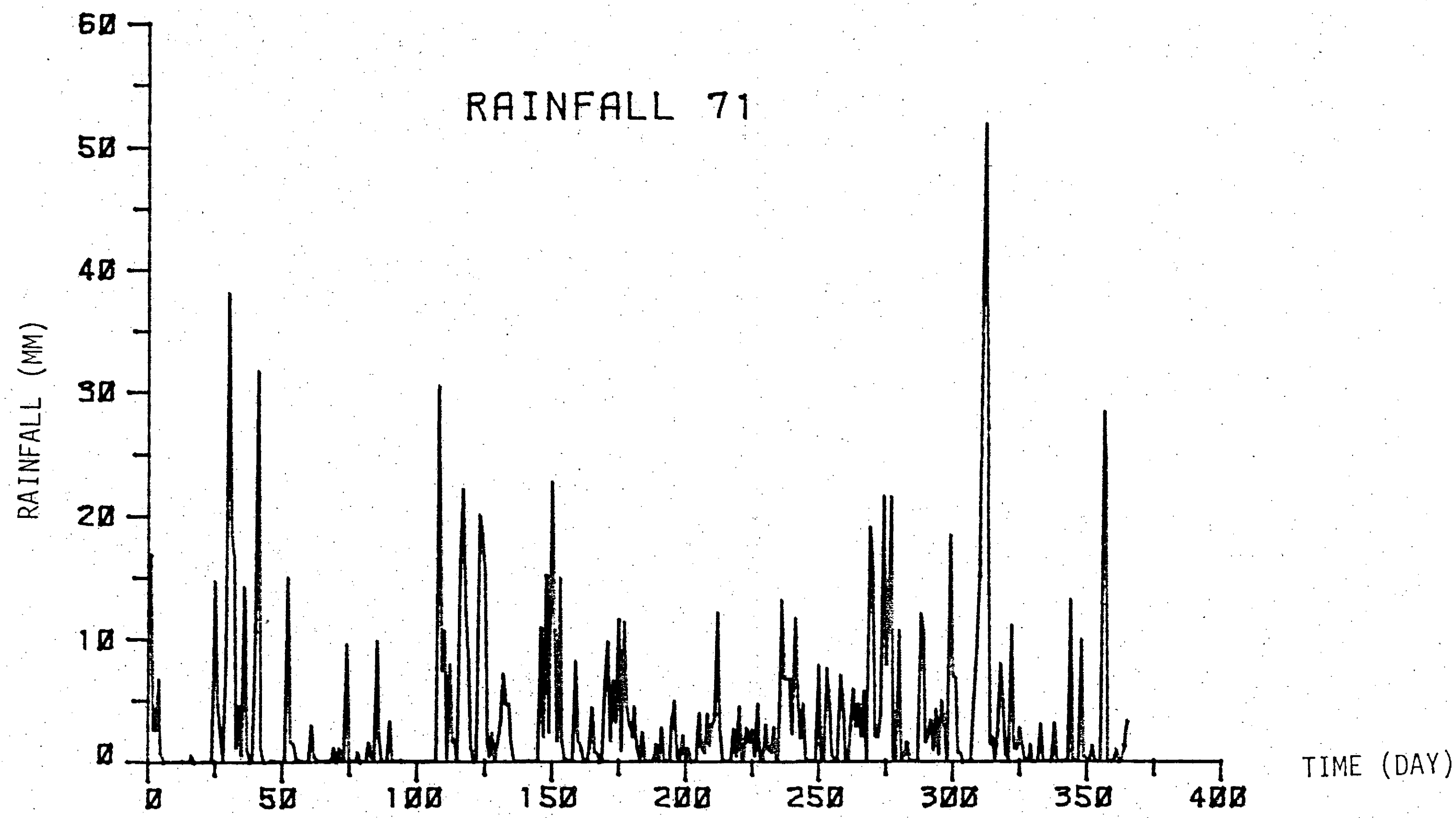


Fig 5.45 Rainfall 1971

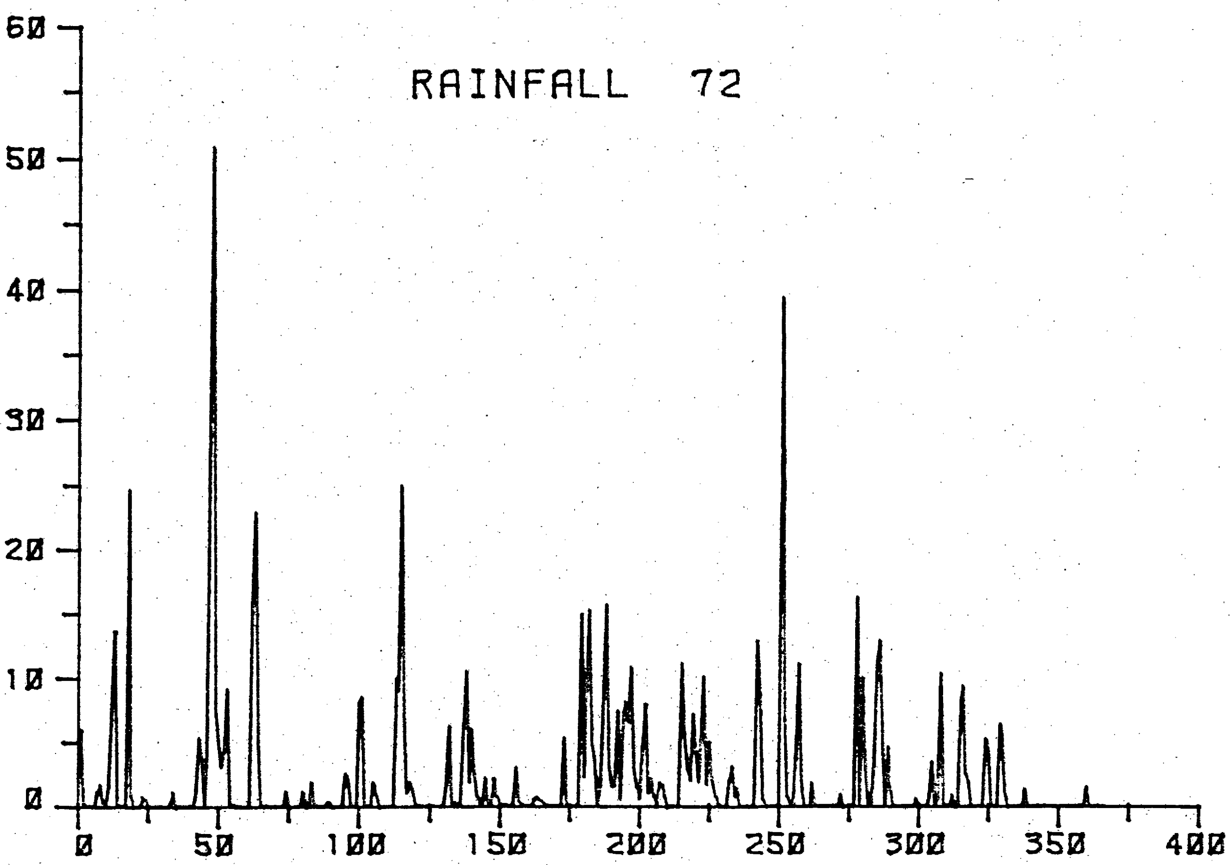


Fig 5.46   Rainfall 1972

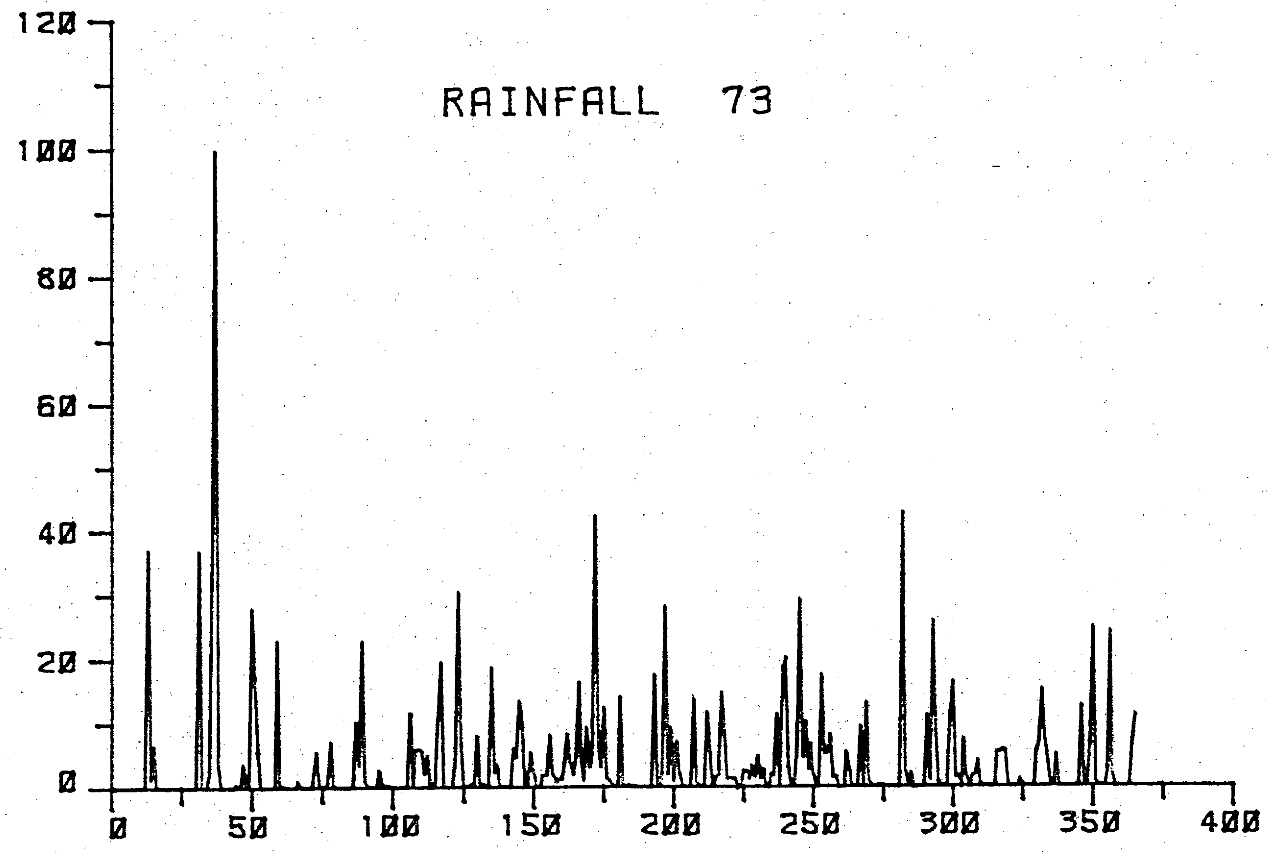


Fig 5.47 Rainfall 1973

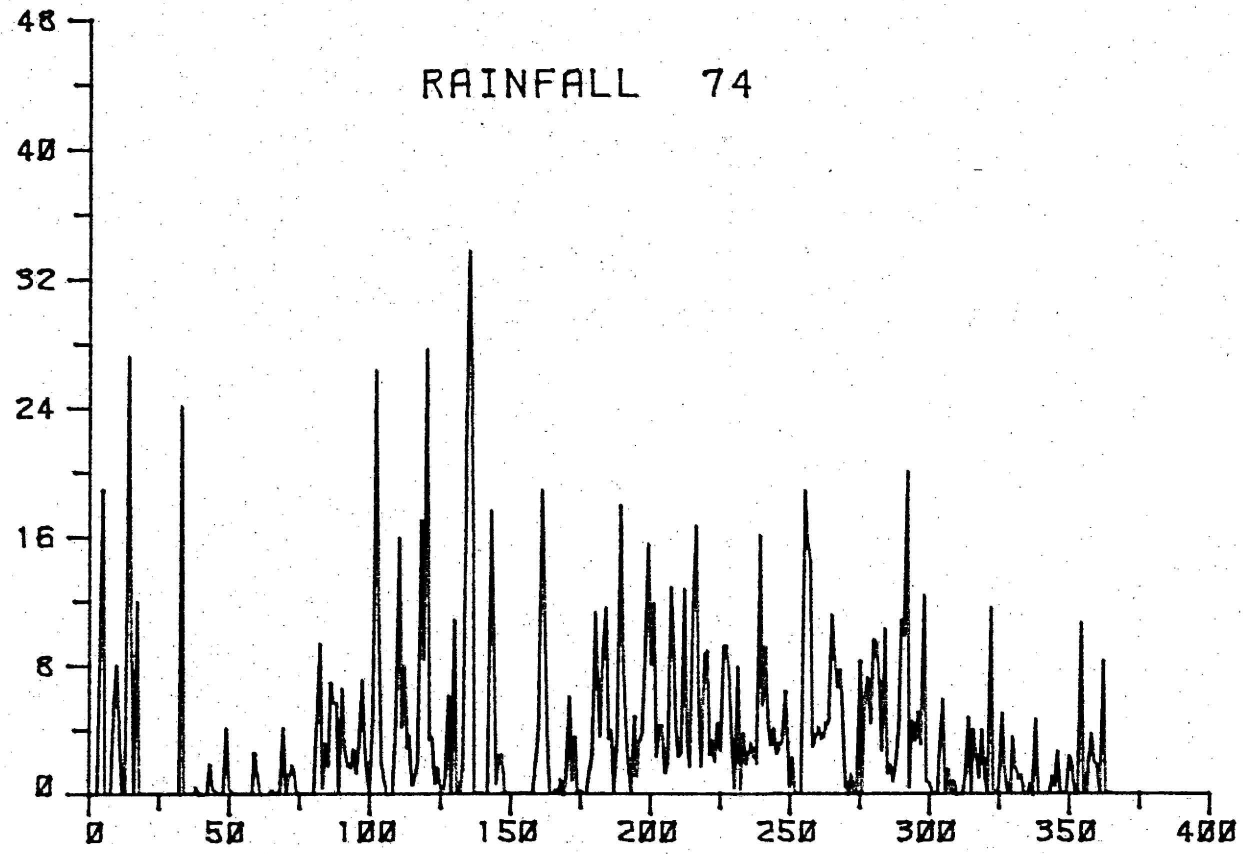


Fig 5.48 Rainfall 1974

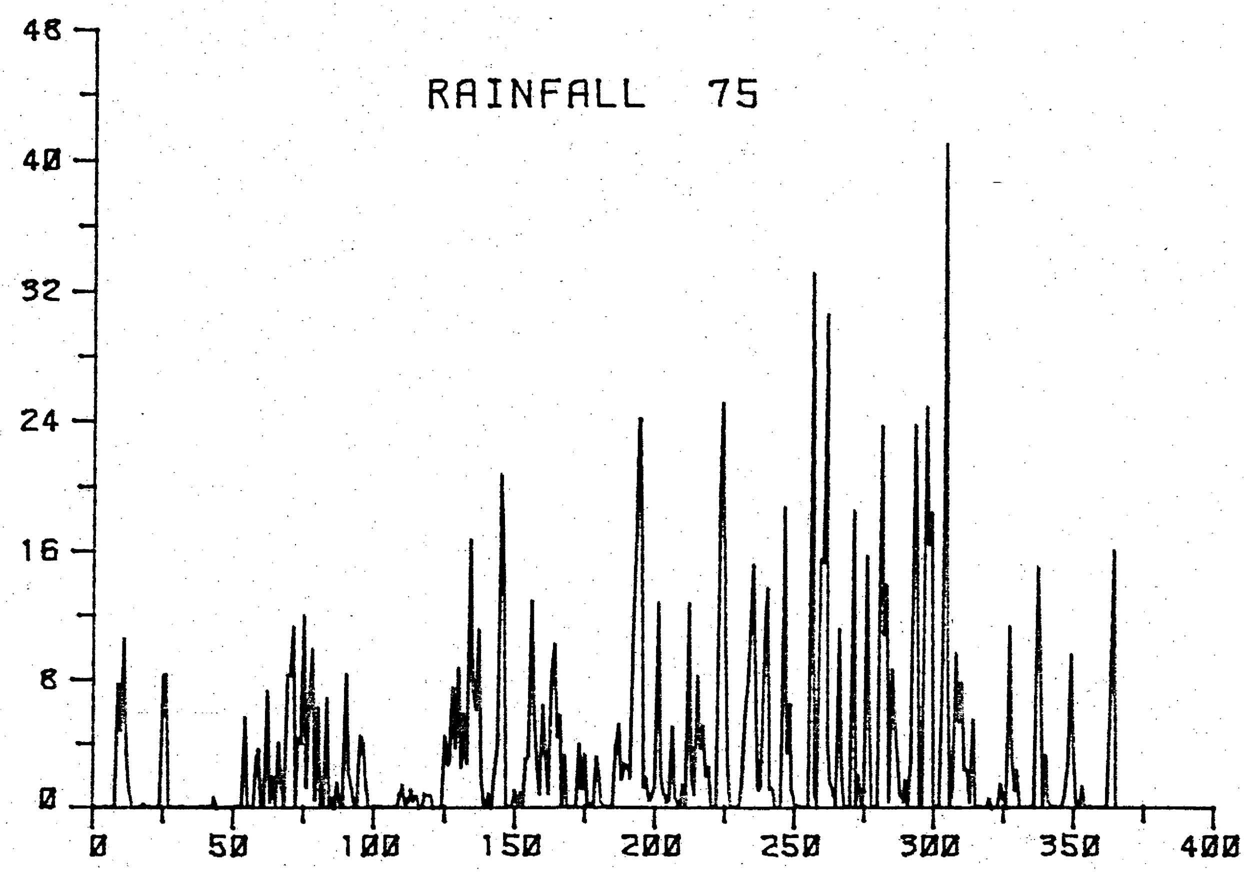


Fig 5.49 Rainfall 1975

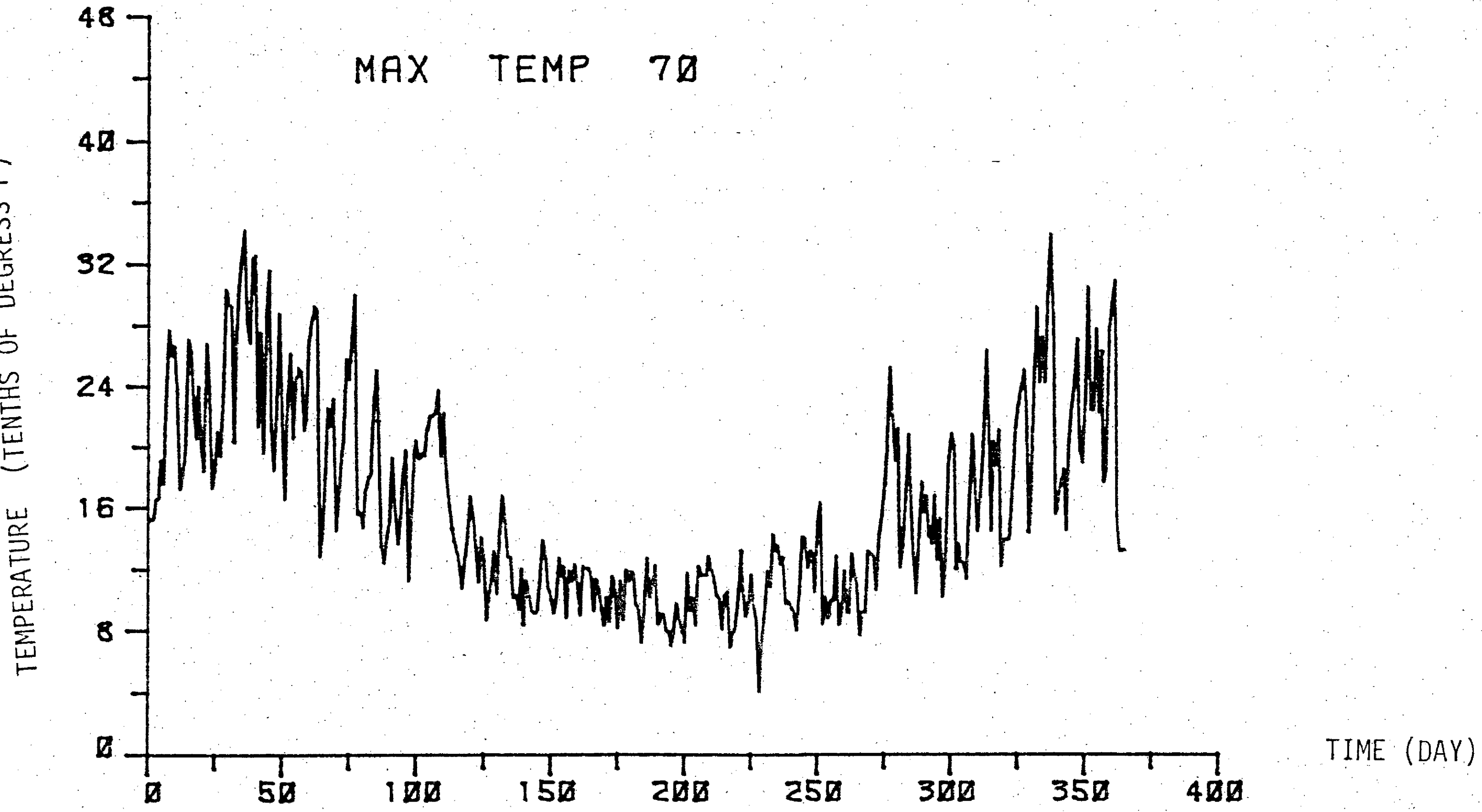


Fig 5.50 Maximum Temperature 1970

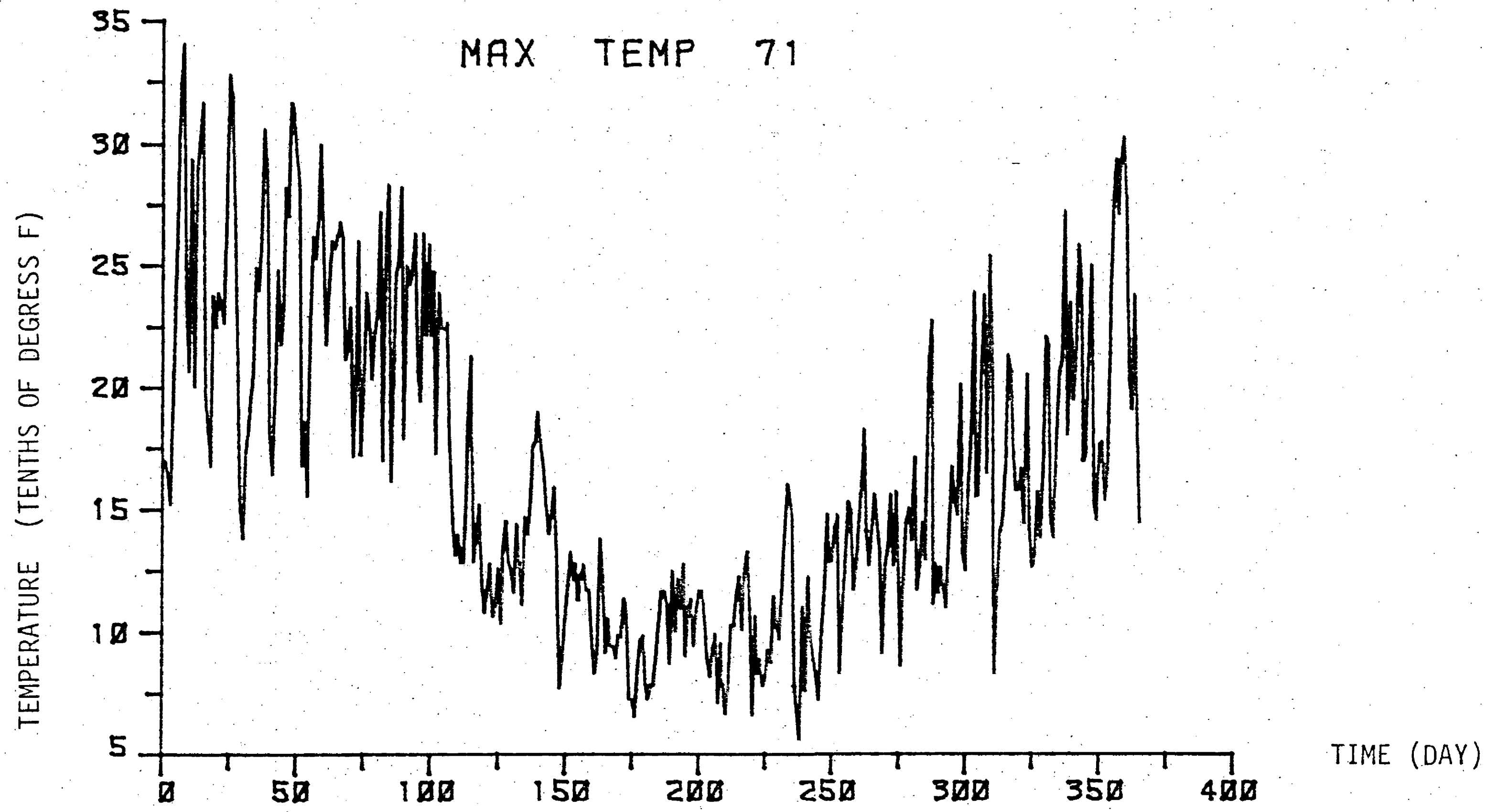


Fig 5.51 Maximum Temperature 1971

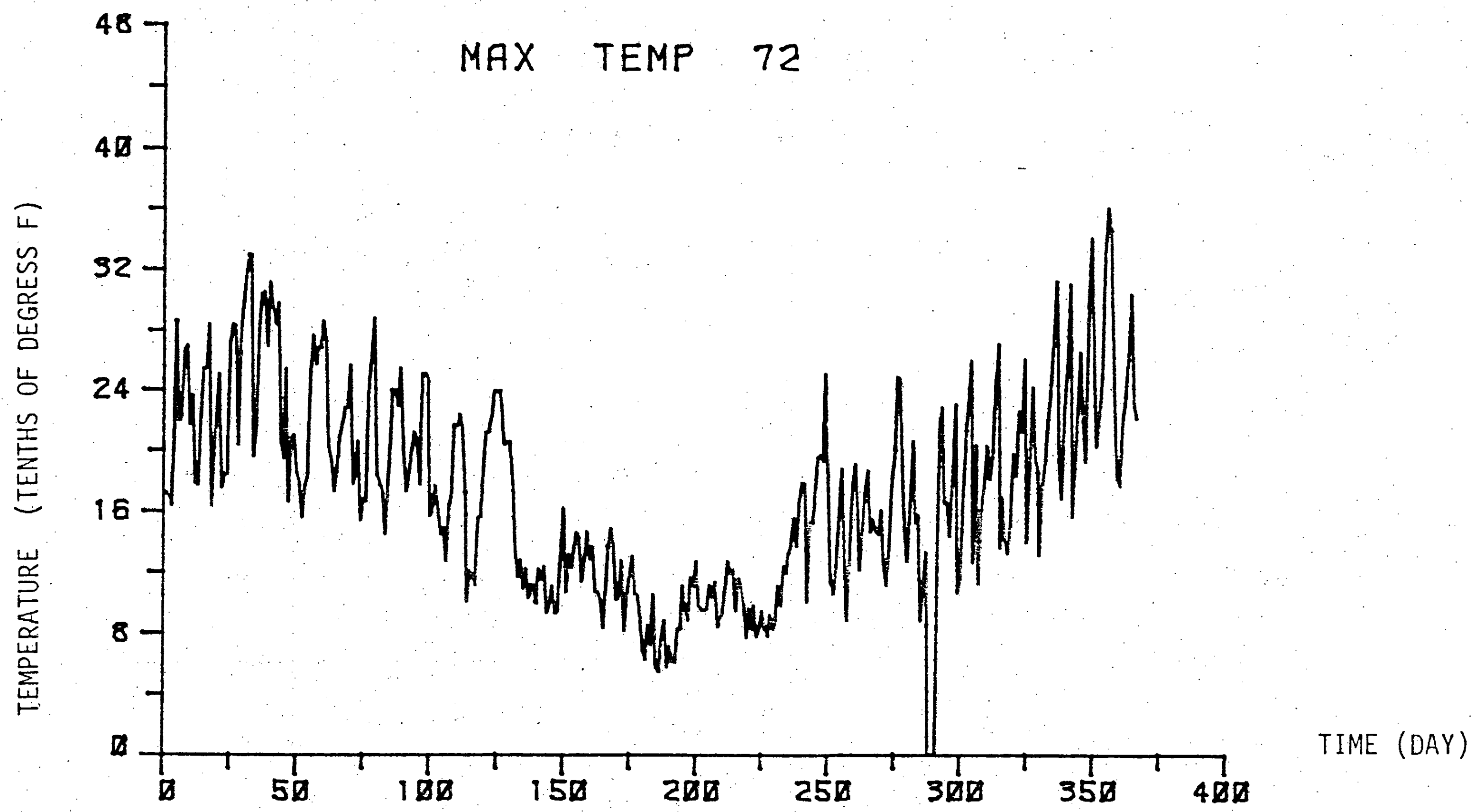


Fig 5.52 Maximum Temperature 1972

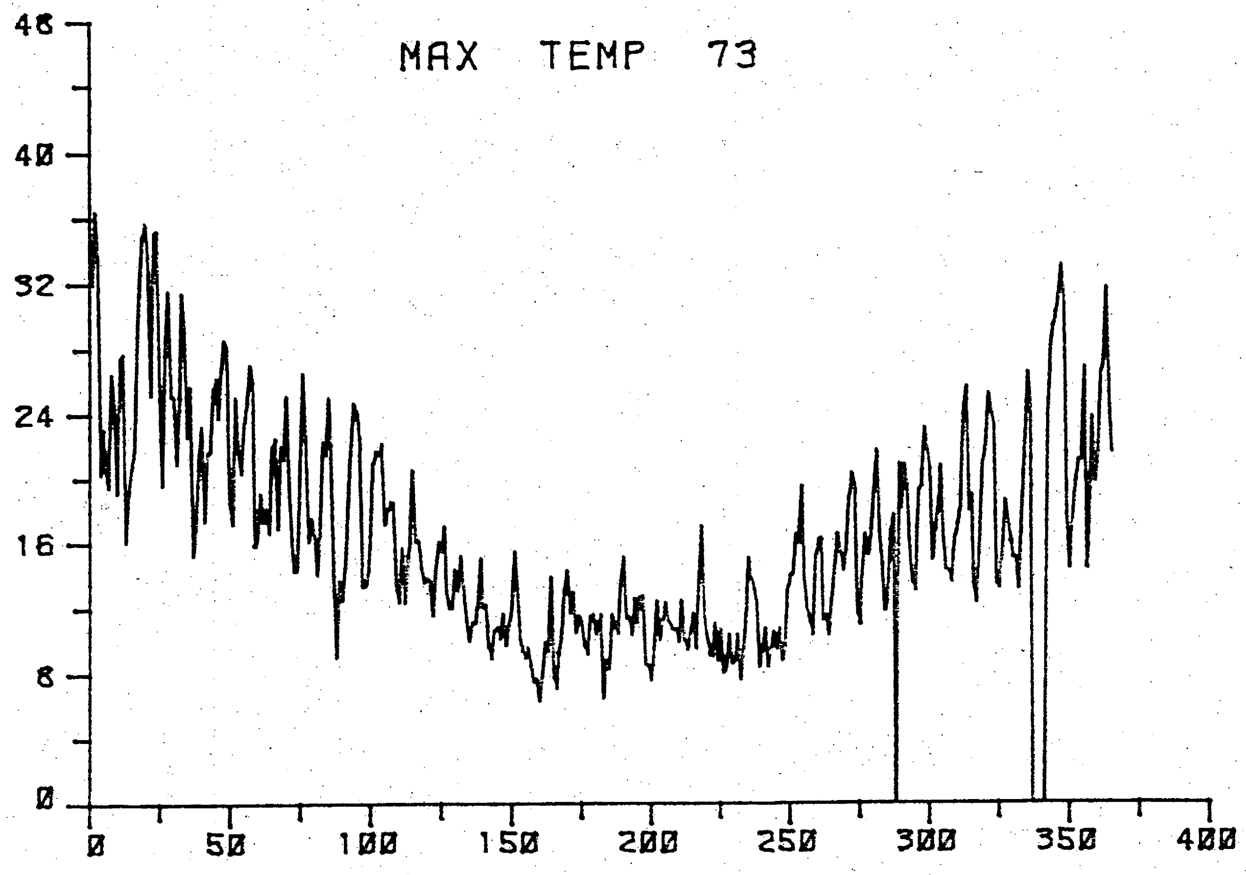


Fig.5.53 Maximum Temperature 1973

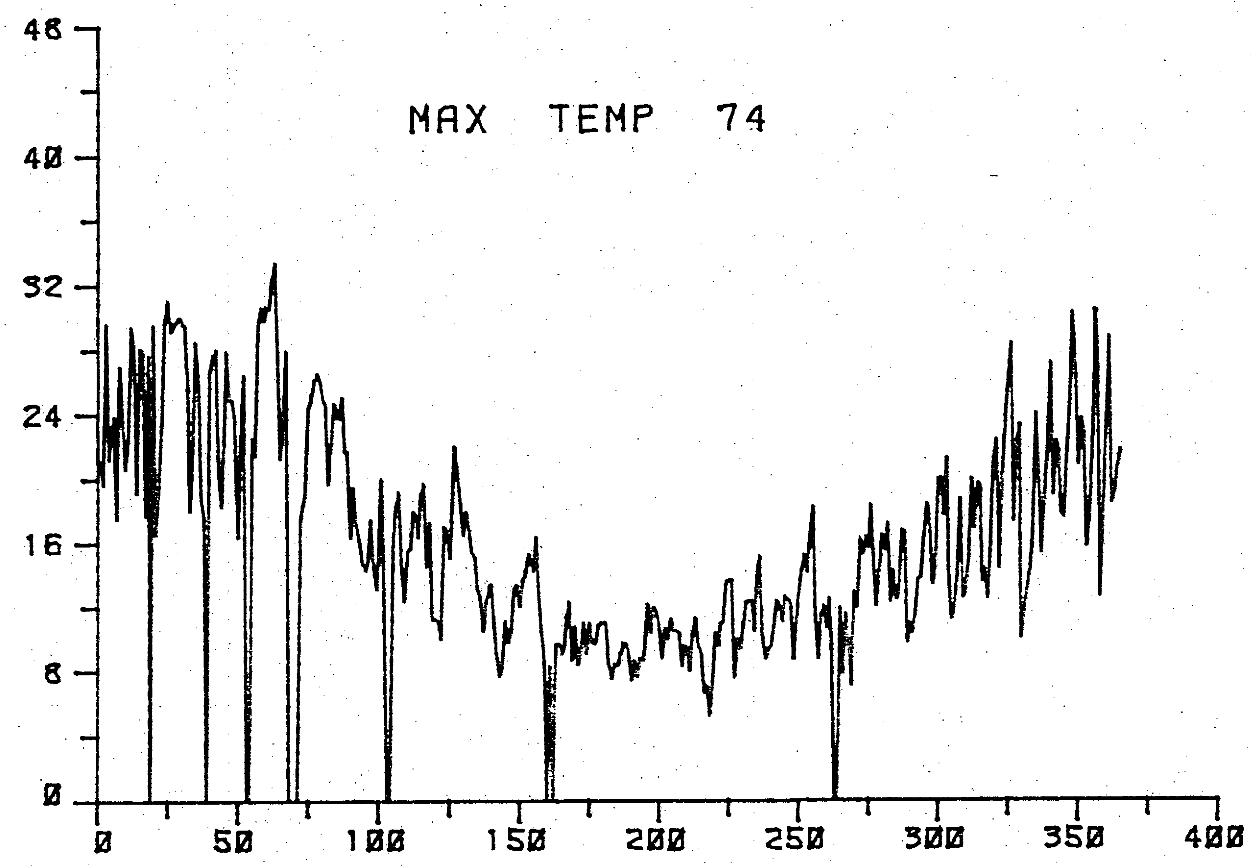


Fig 5.54 Maximum Temperature 1974

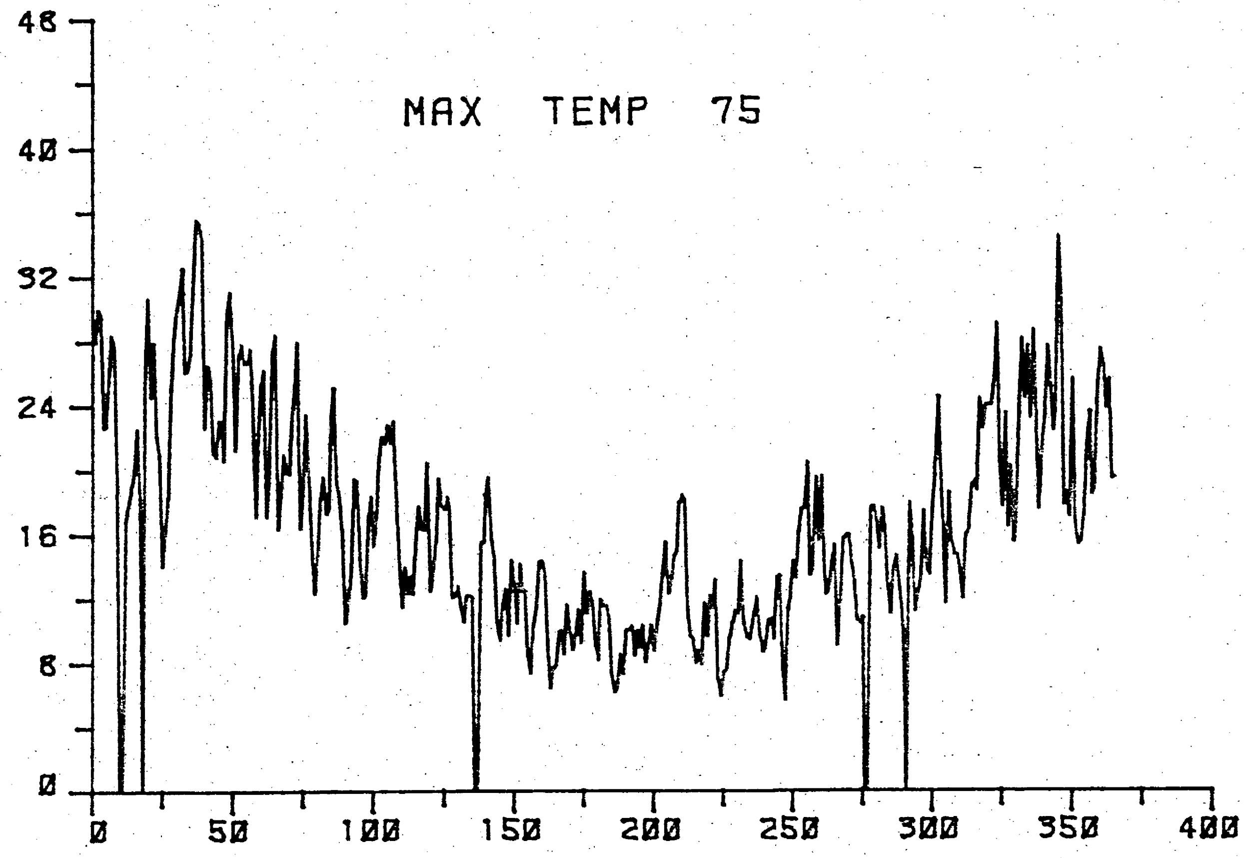


Fig 5.55 Maximum Temperature 1975

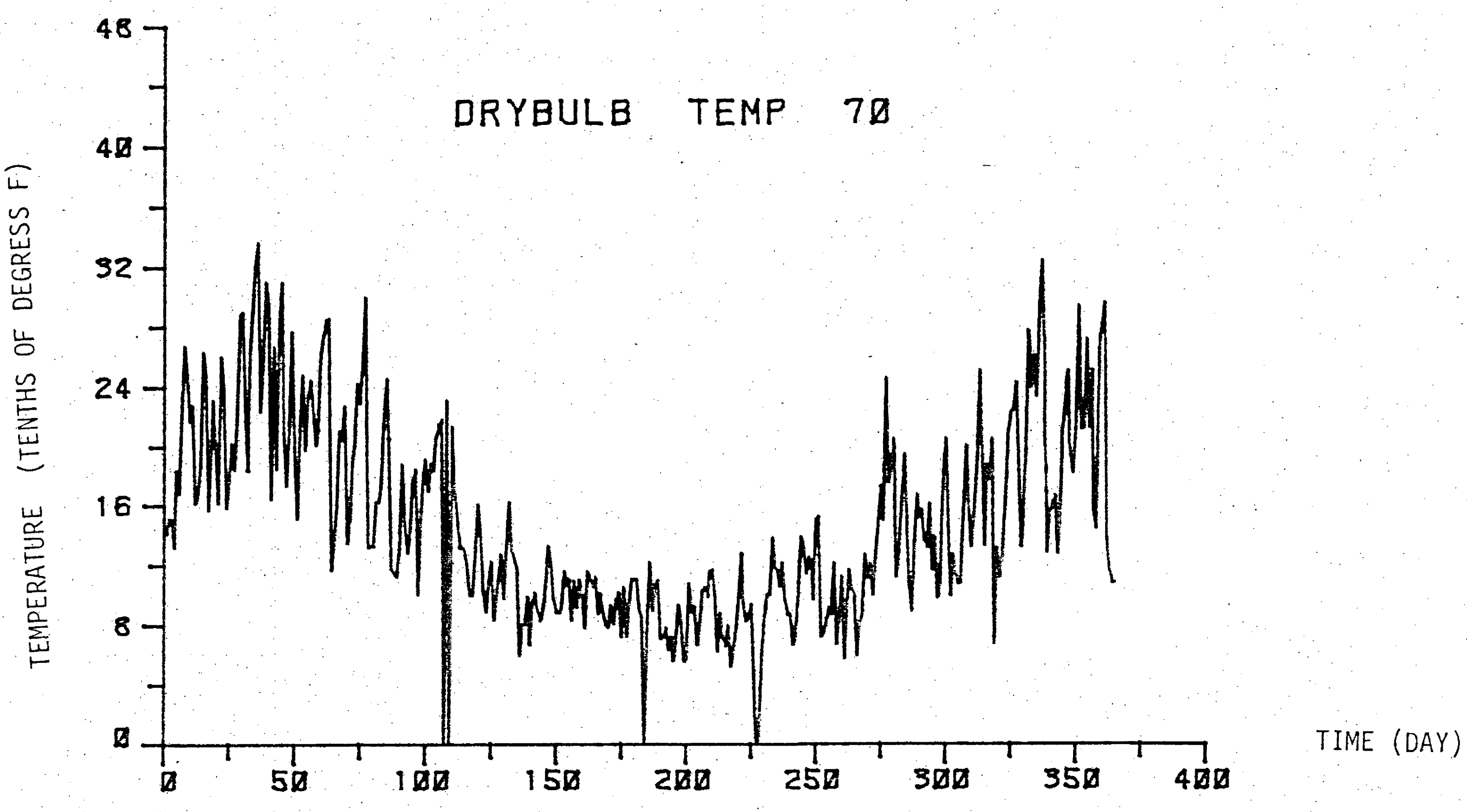


Fig 5.56 Dry Bulb Temperature 1970

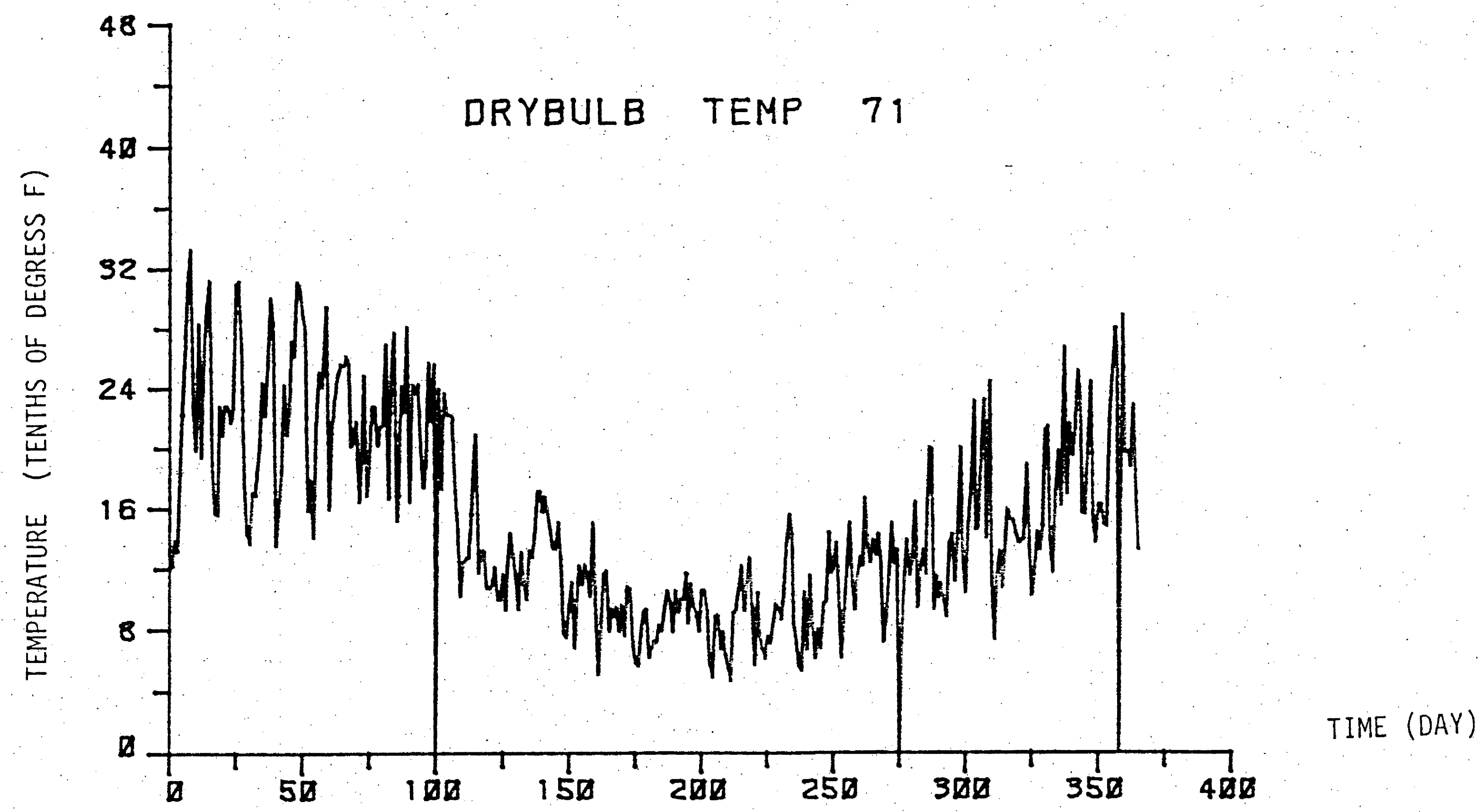


Fig 5.57 Dry Bulb Temperature 1971

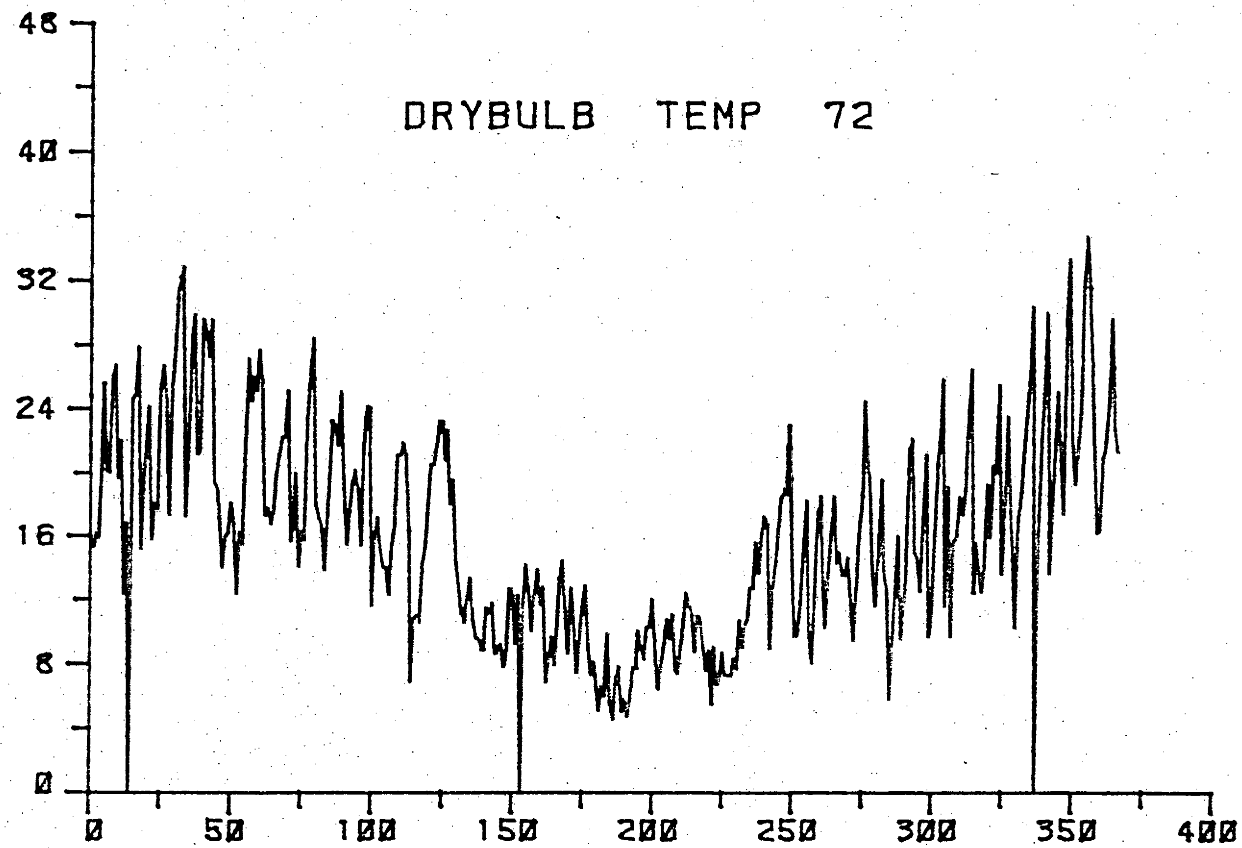


Fig 5.58 Dry Bulb Temperature 1972

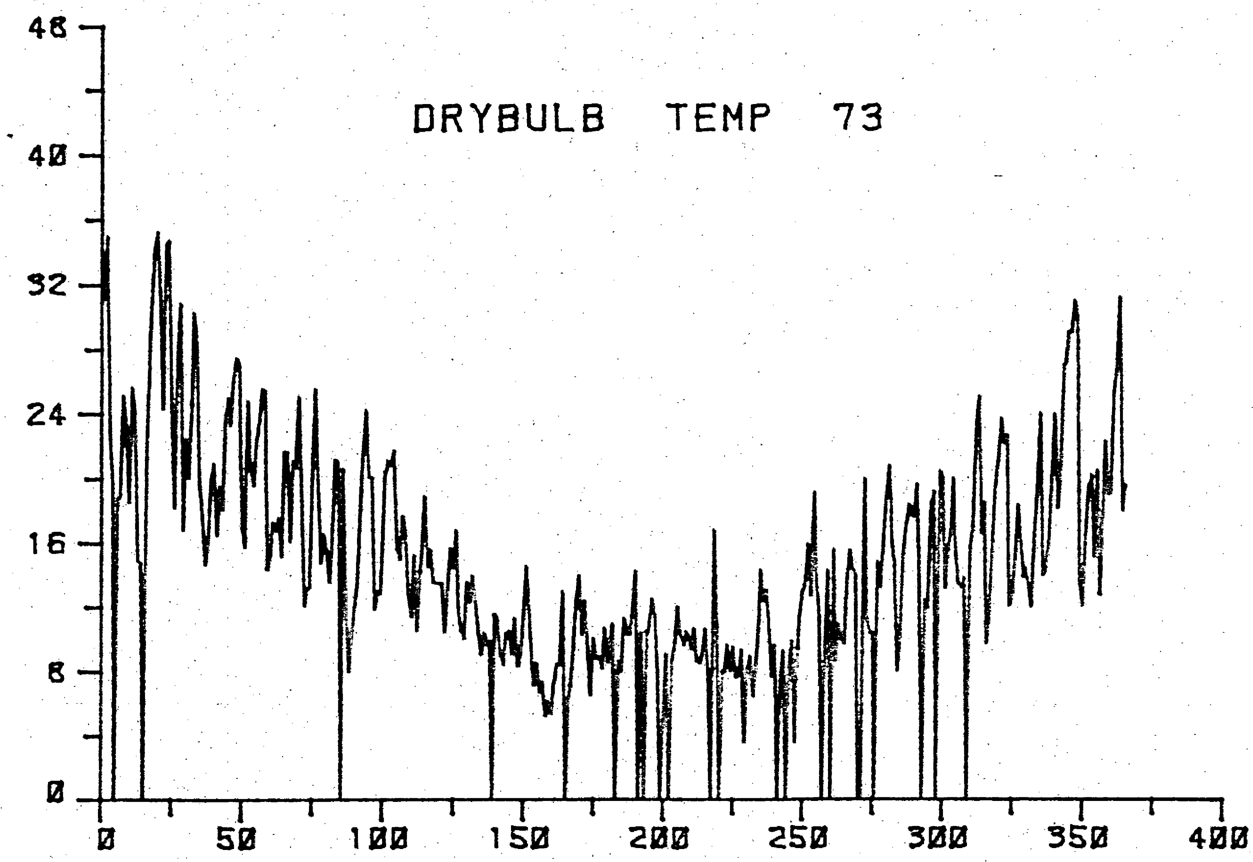


Fig 5.59 Dry Bulb Temperature 1973

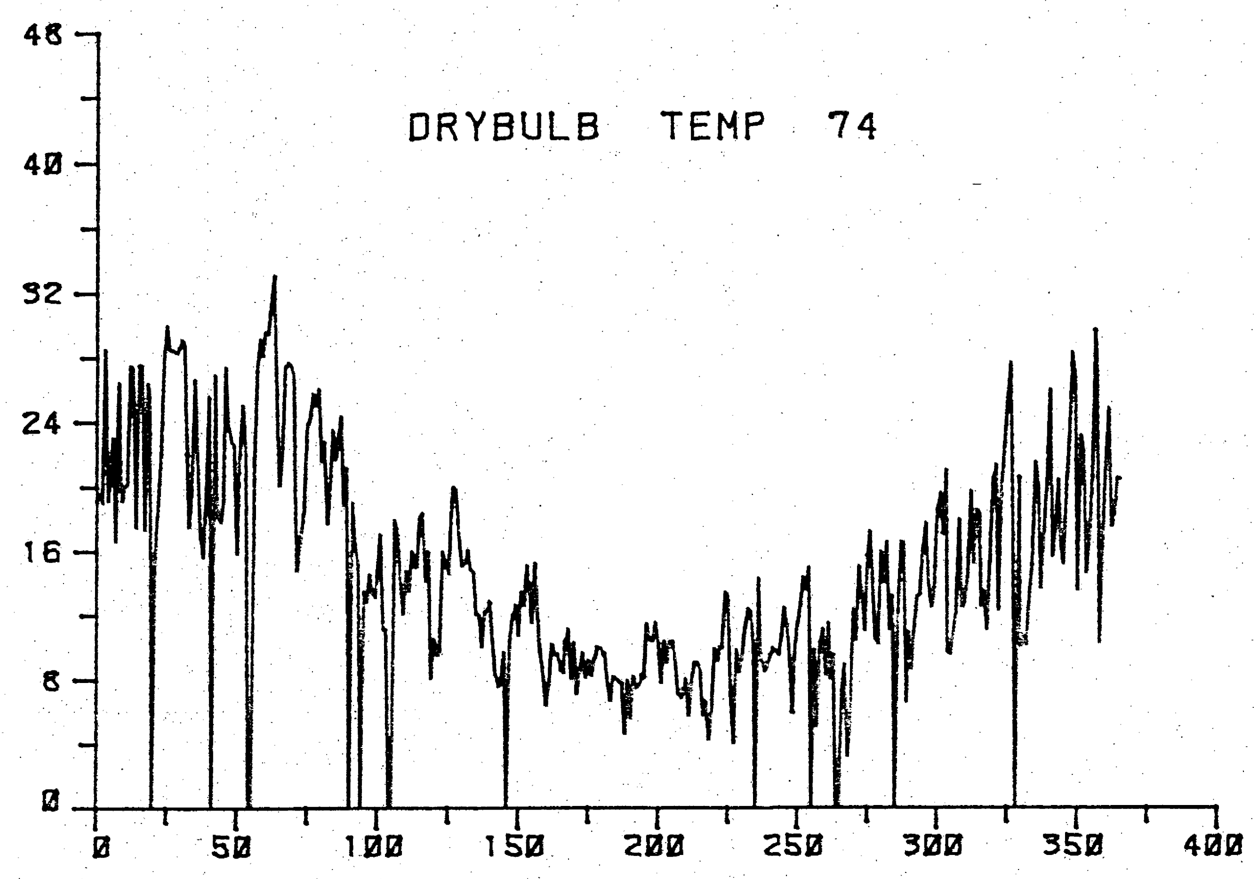


Fig 5.60 Dry Bulb Temperature 1974

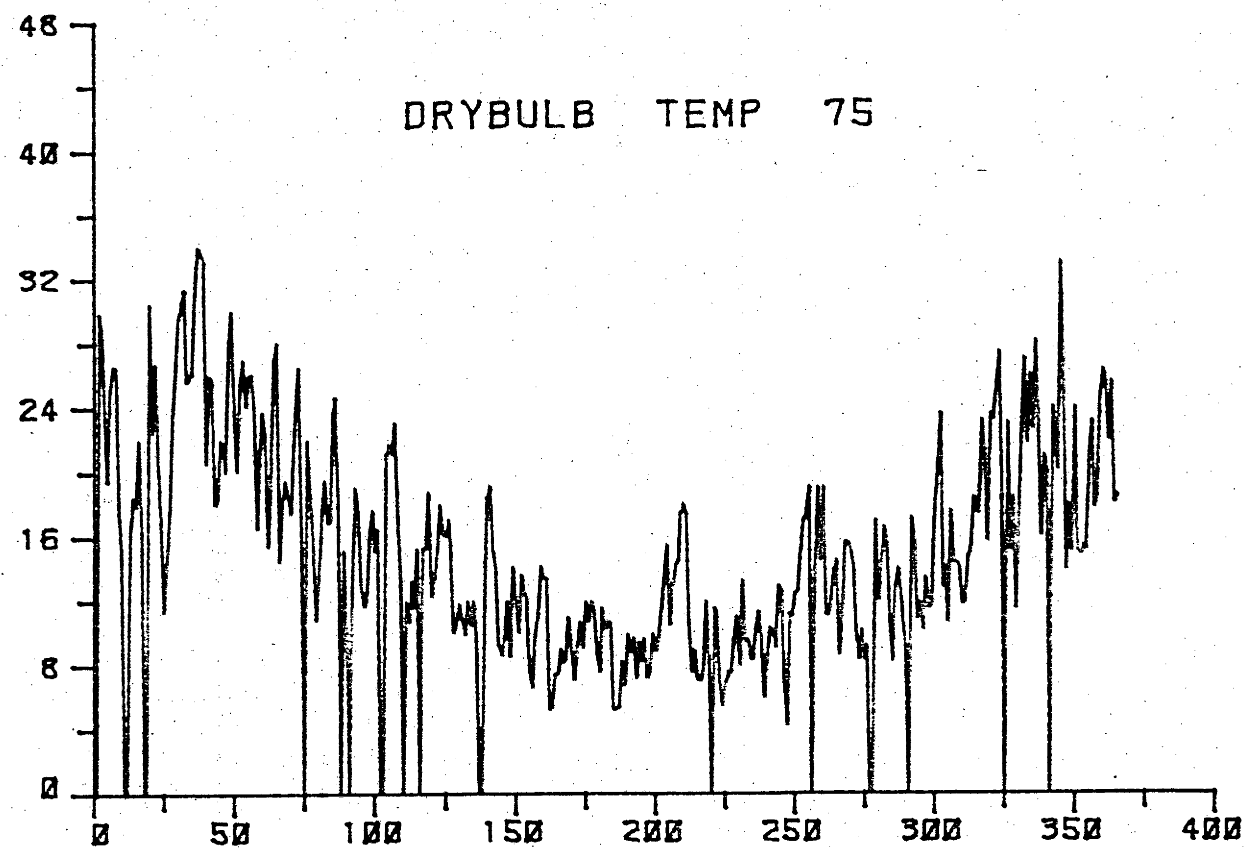


Fig 5.61 Dry Bulb Temperature 1975

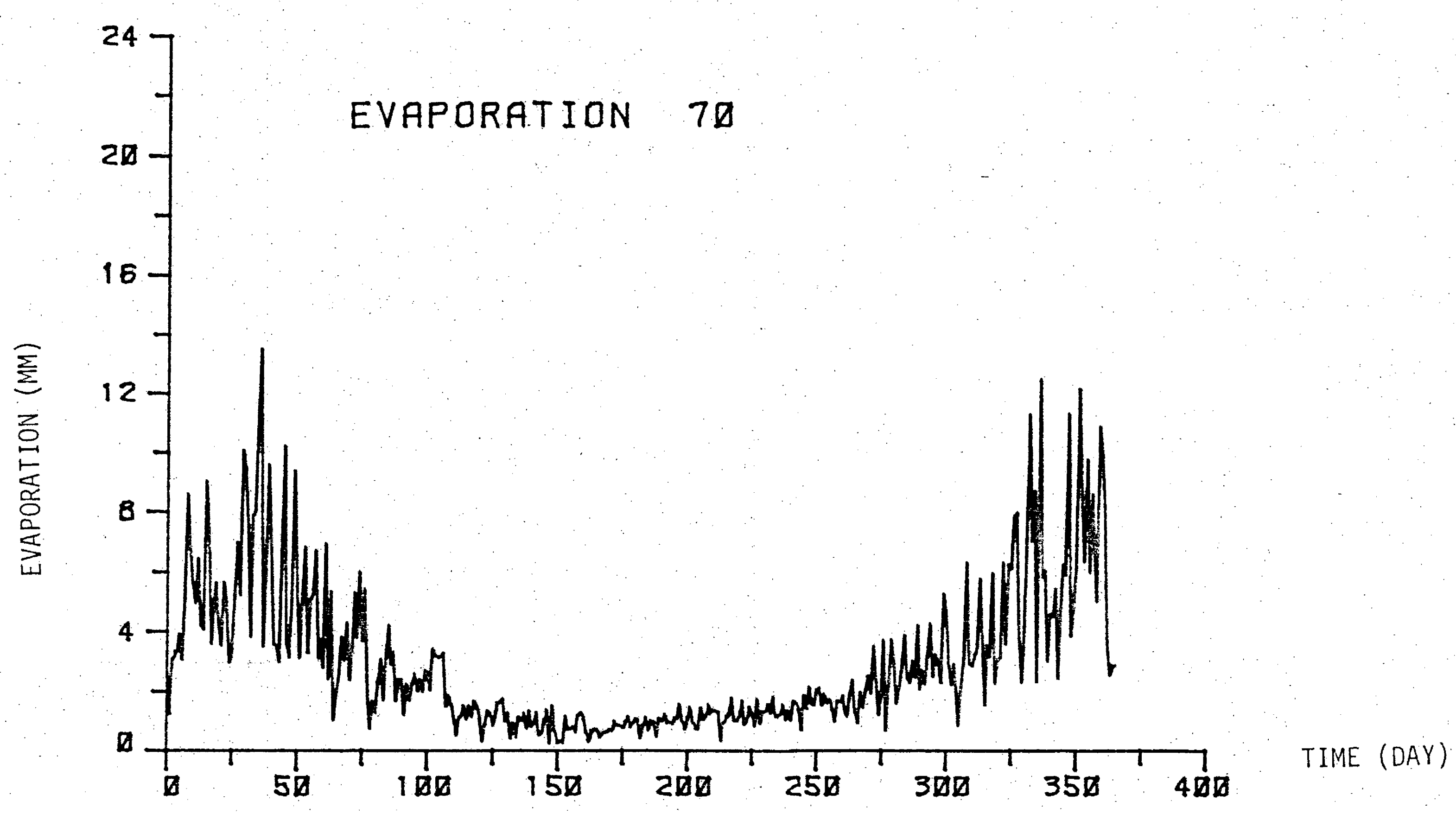


Fig 5.62 Evaporation 1970

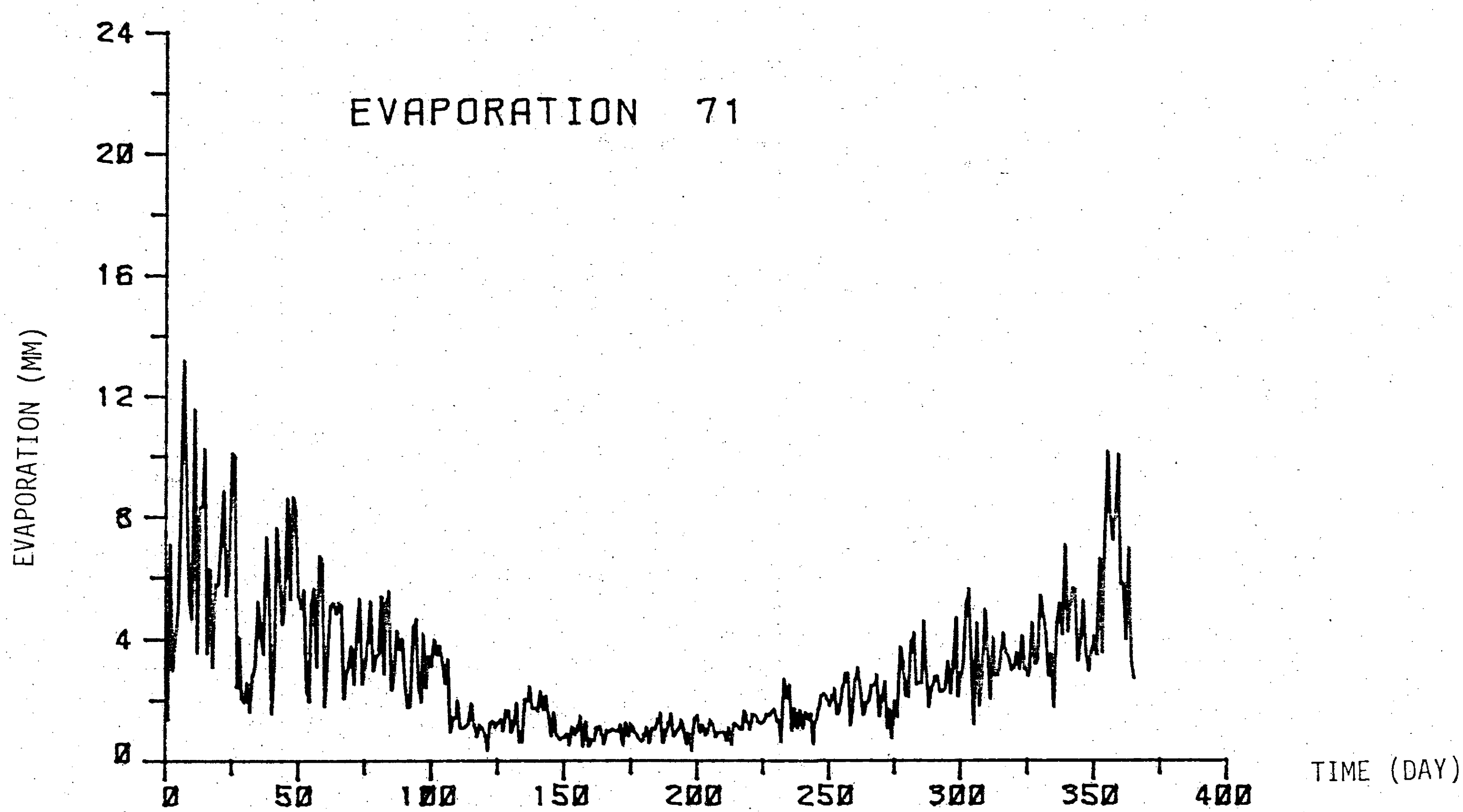


Fig 5.63 Evaporation 1971

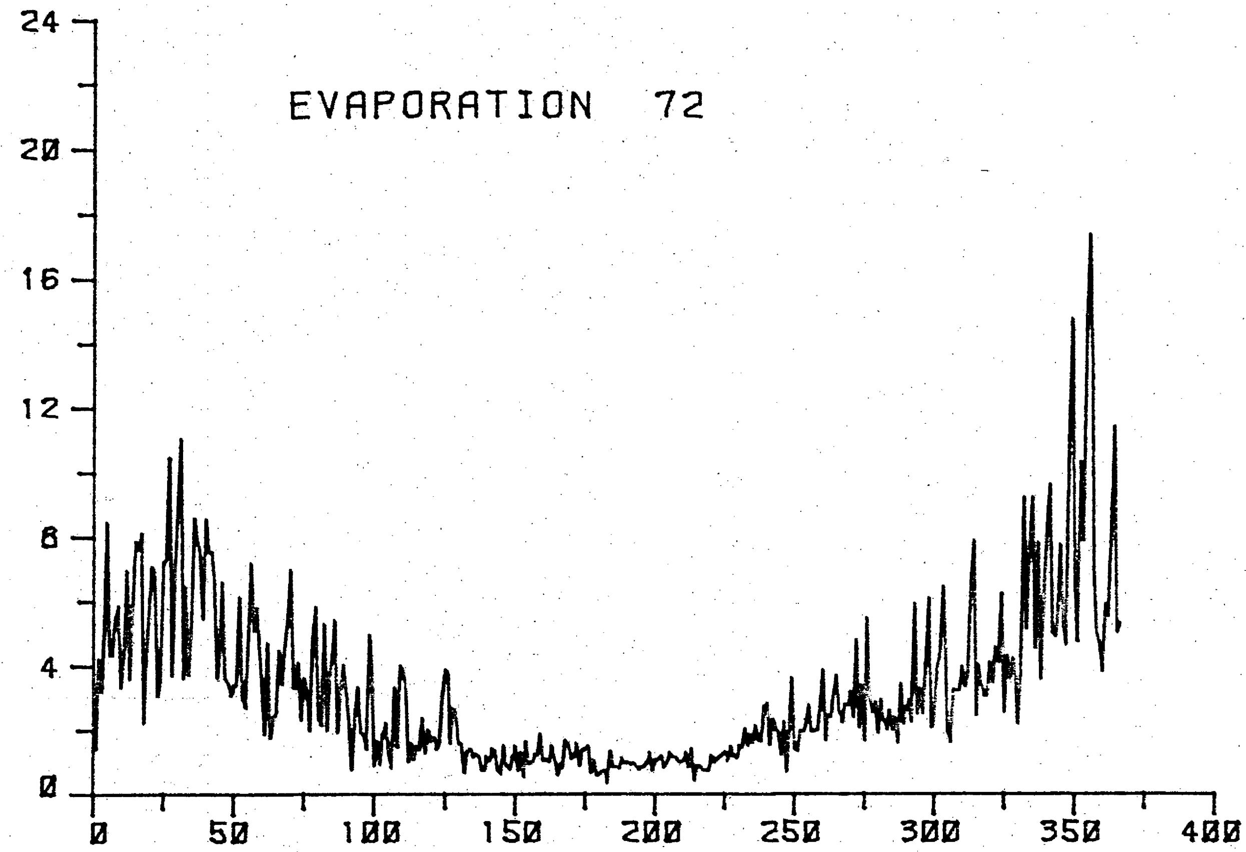


Fig 5.64 Evaporation 1972

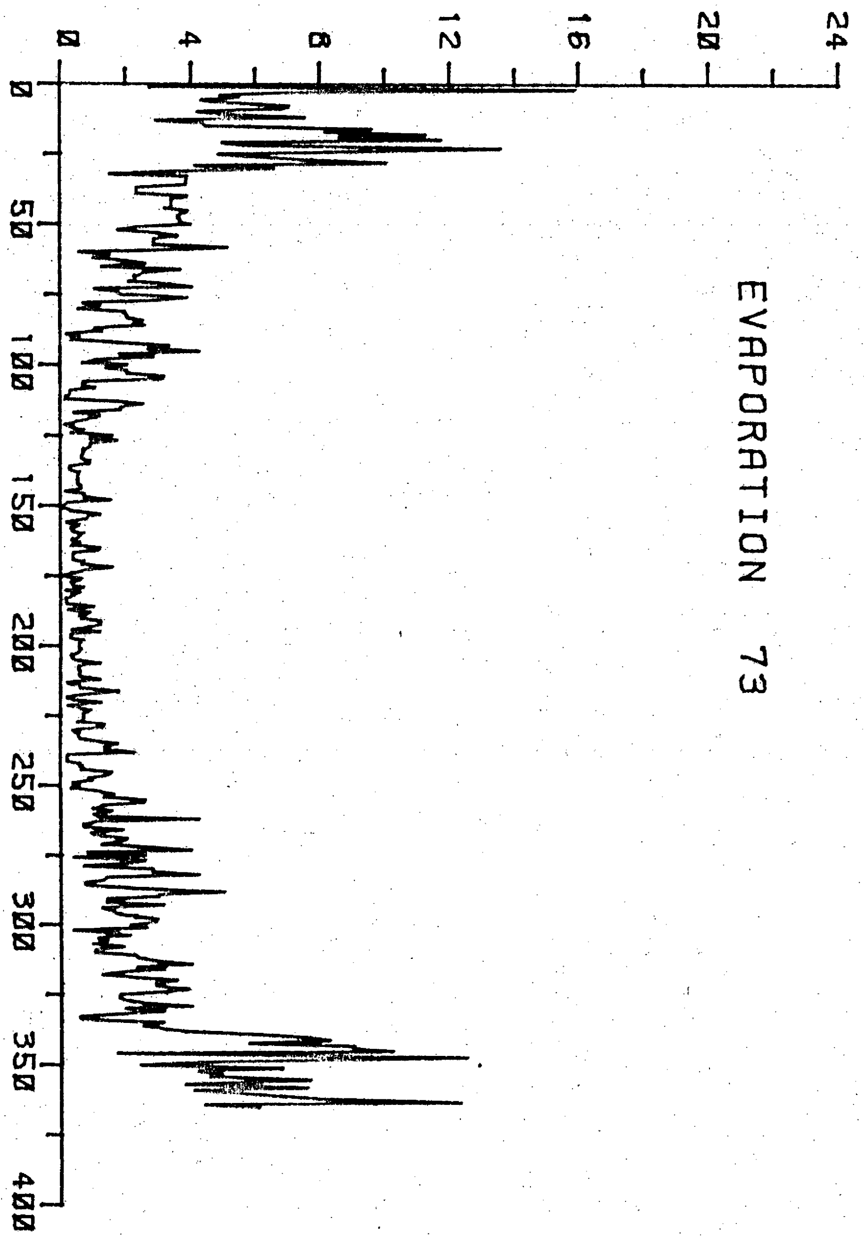


Fig 5.65 Evaporation 1973

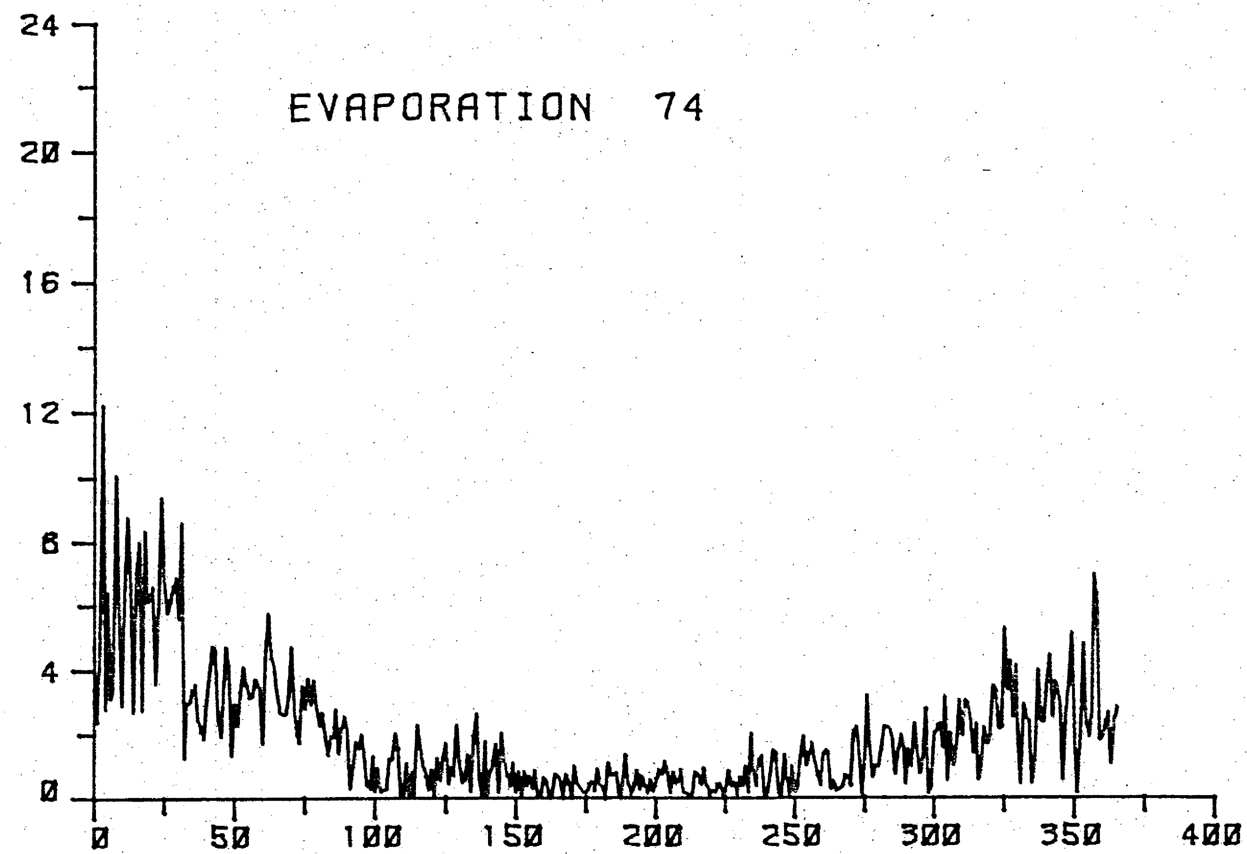


Fig 5.66 Evaporation 1974

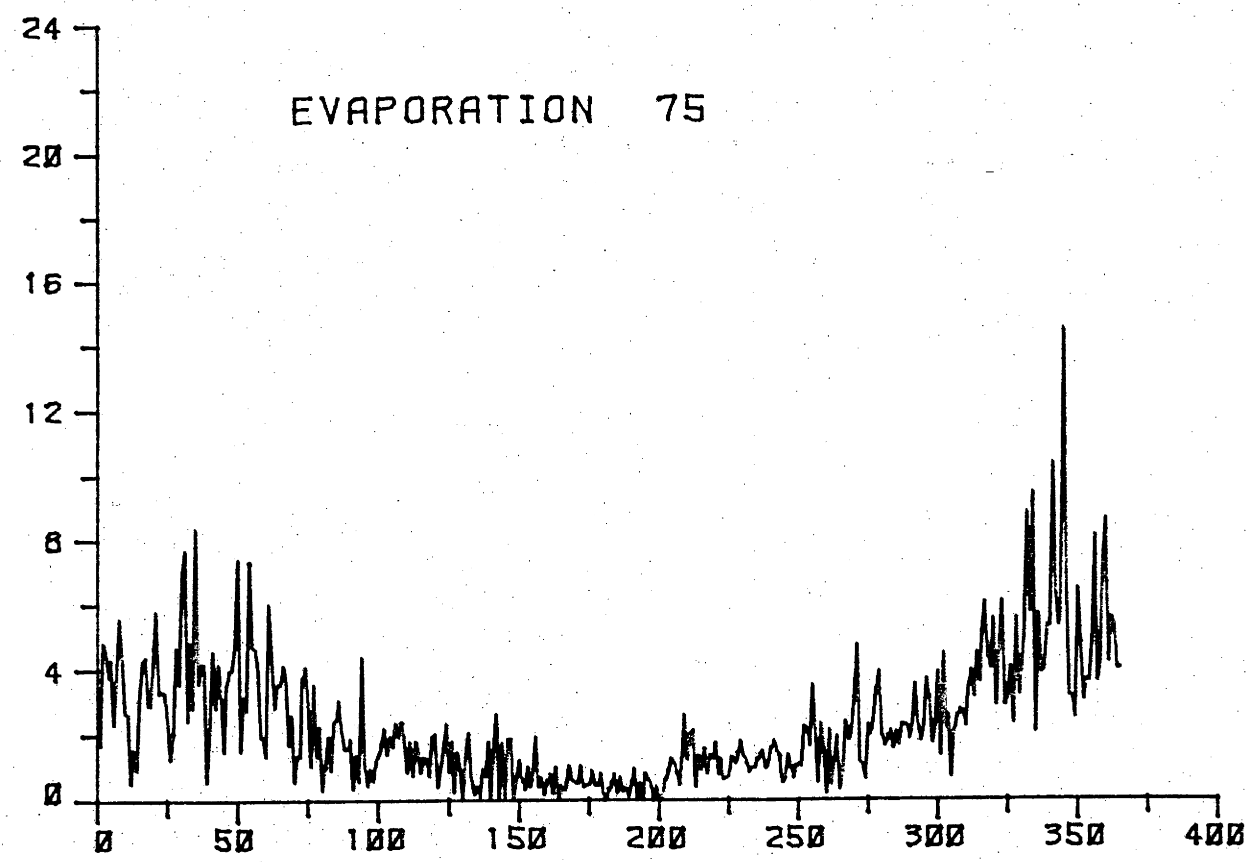


Fig 5.67 Evaporation 1975

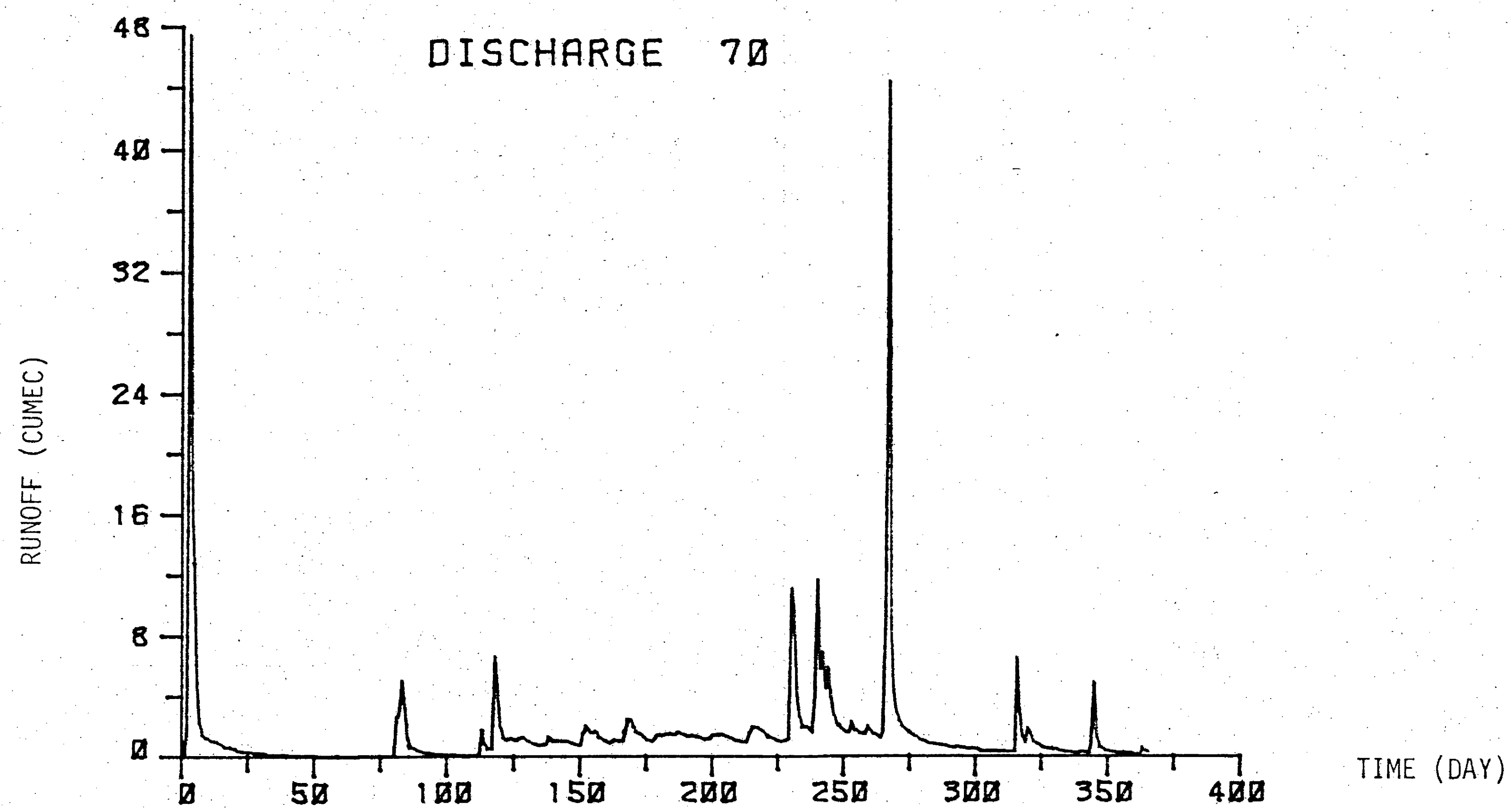


Fig 5.68 Discharge 1970

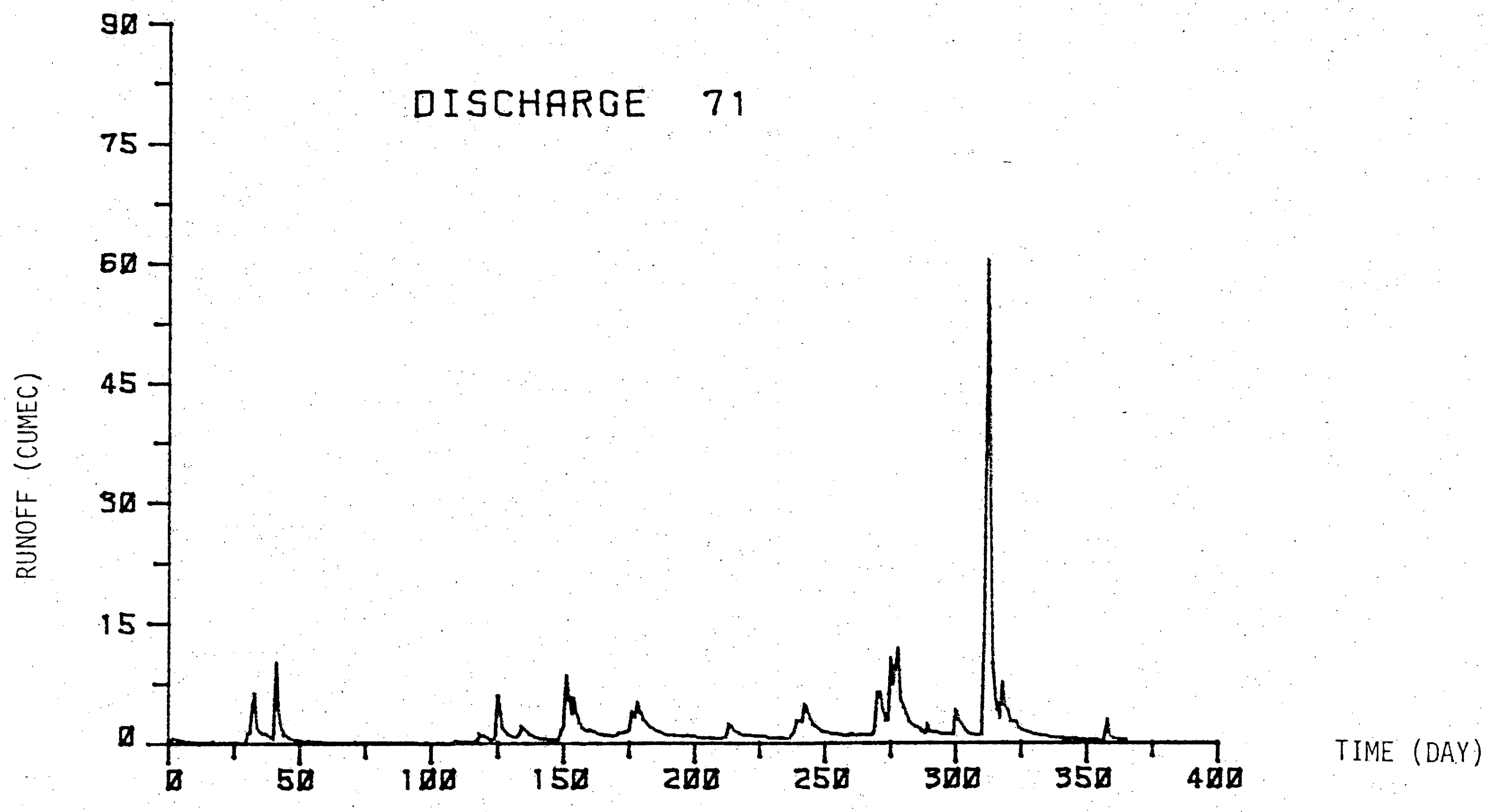


Fig 5.69 Discharge 1971

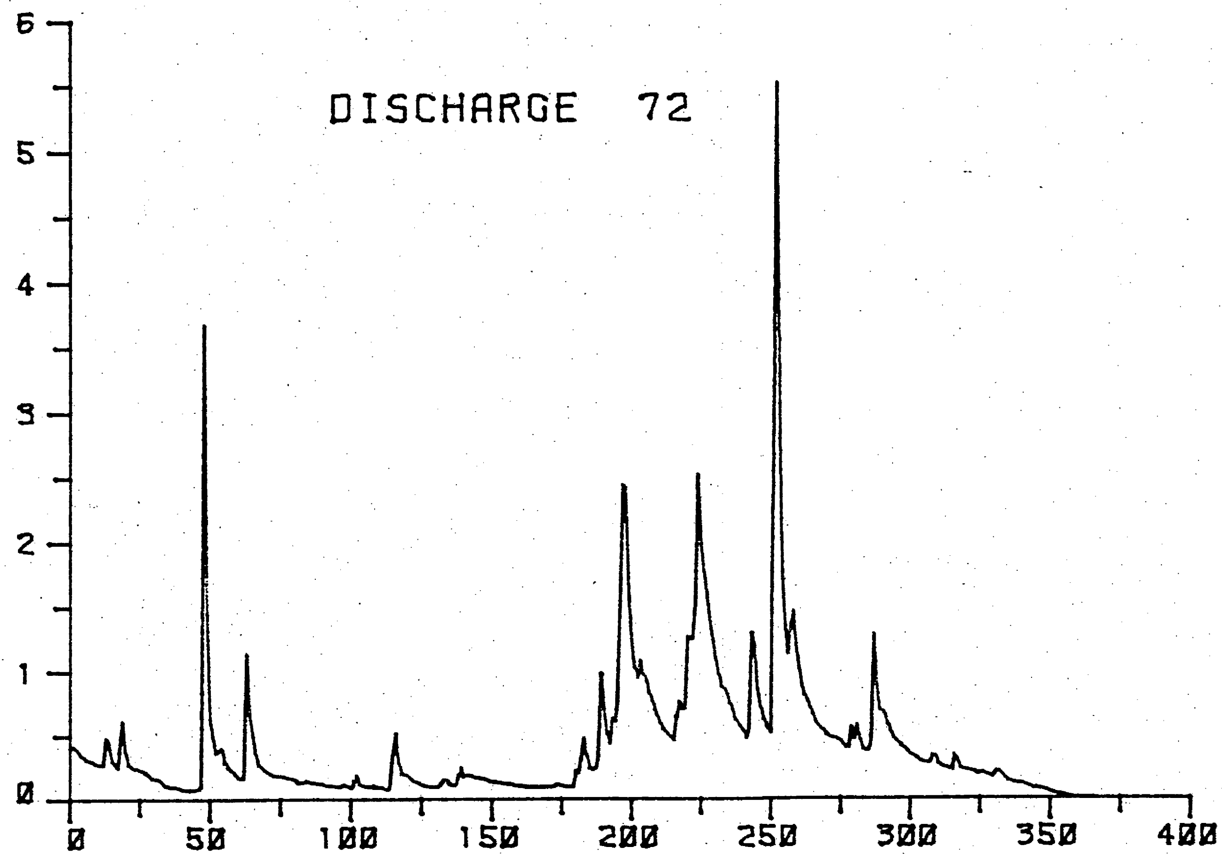


Fig 5.70 Discharge 1972

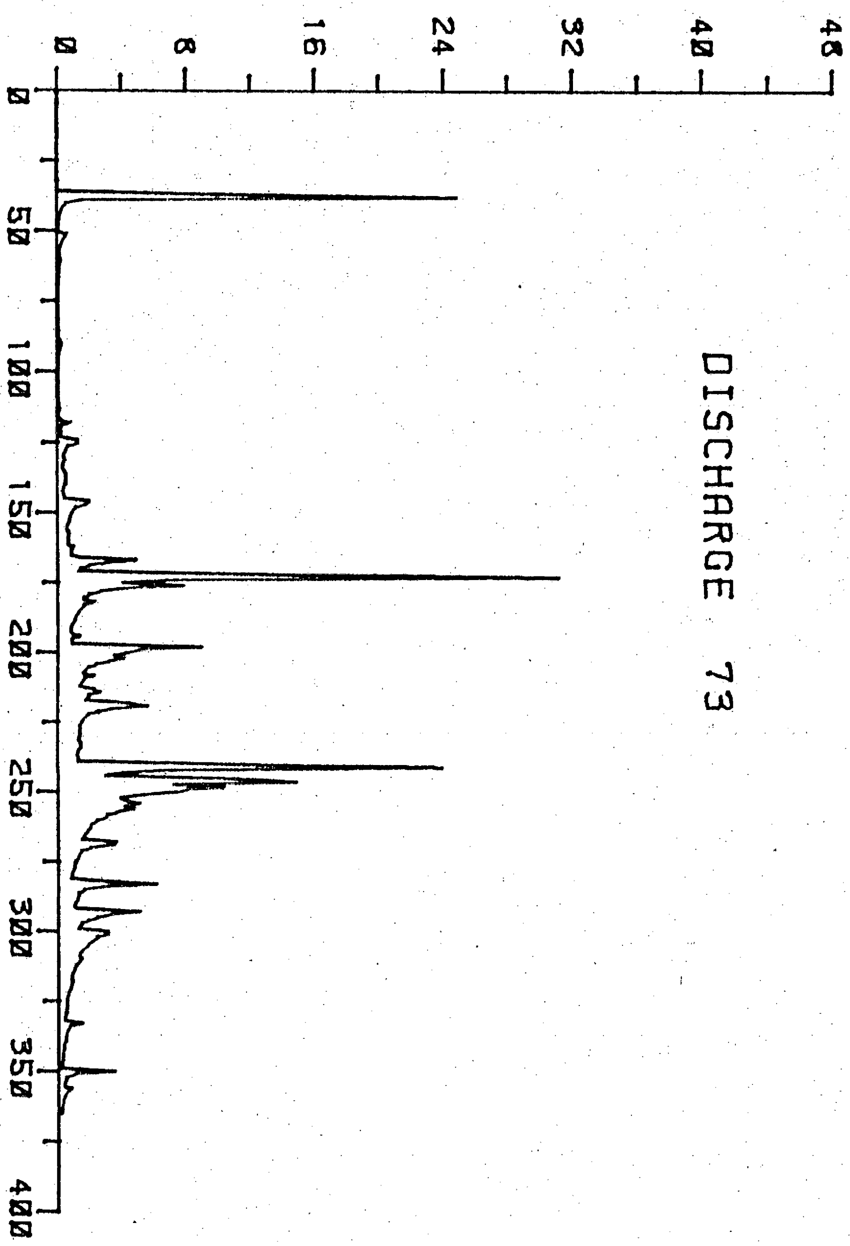


Fig 5.71 Discharge 1973

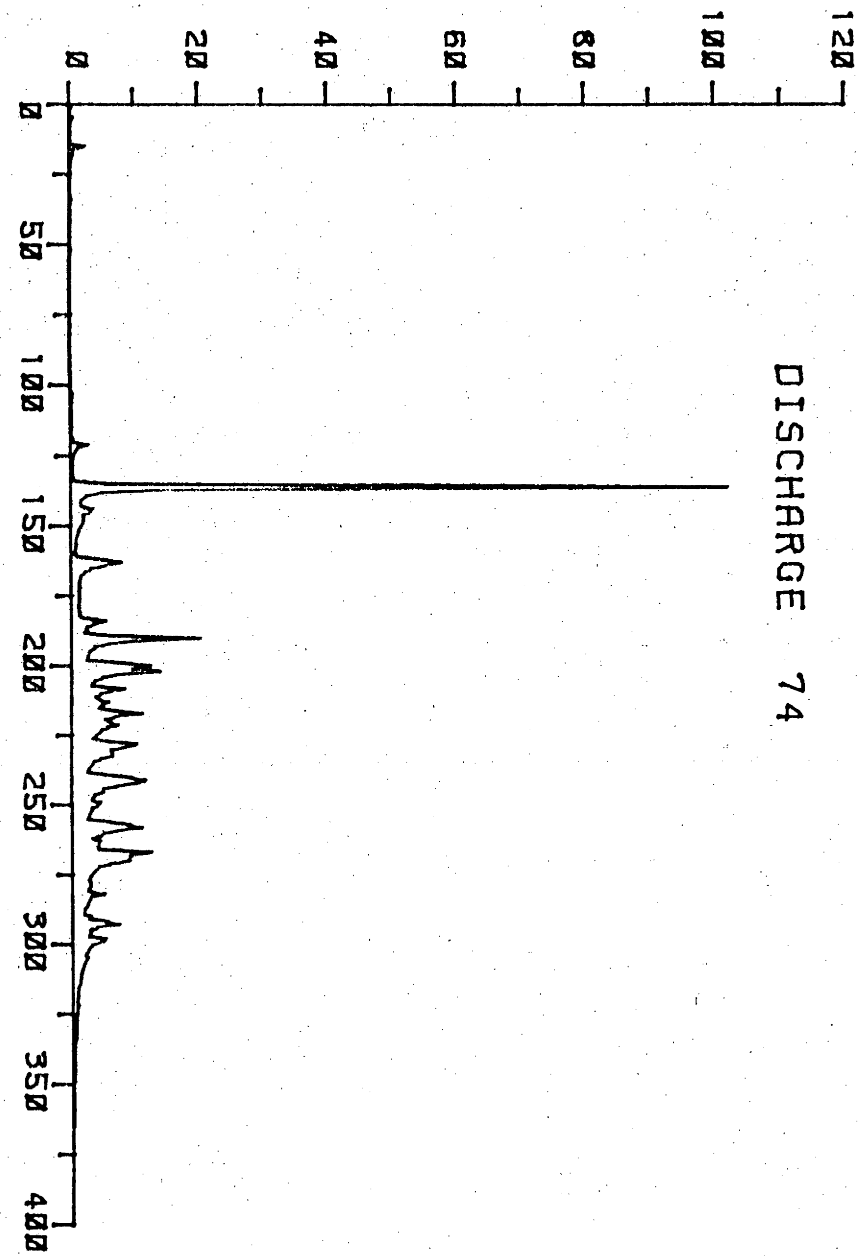


Fig 5.72 Discharge 1974

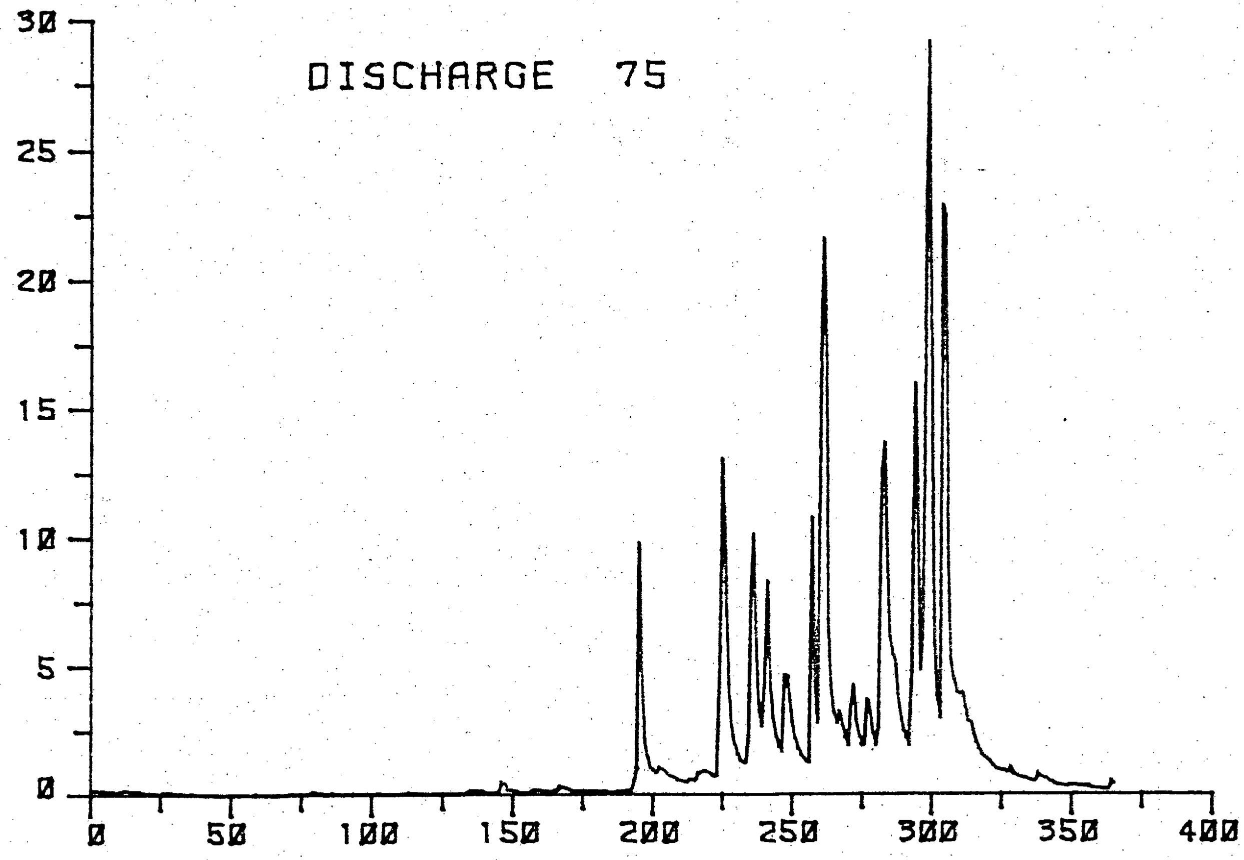


Fig 5.73 Discharge 1975

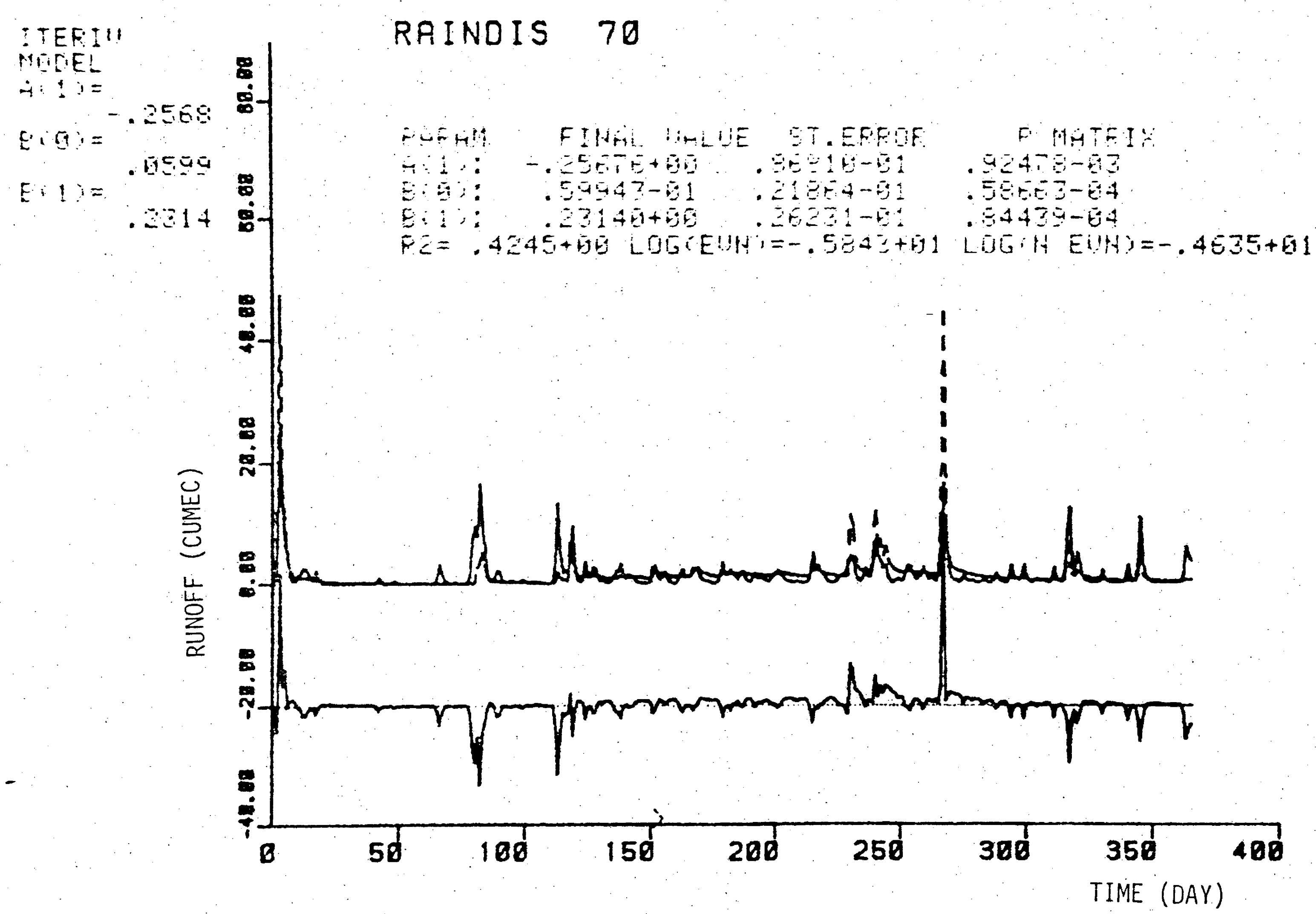


Fig 5.74 Raw Data Model Raindis 70

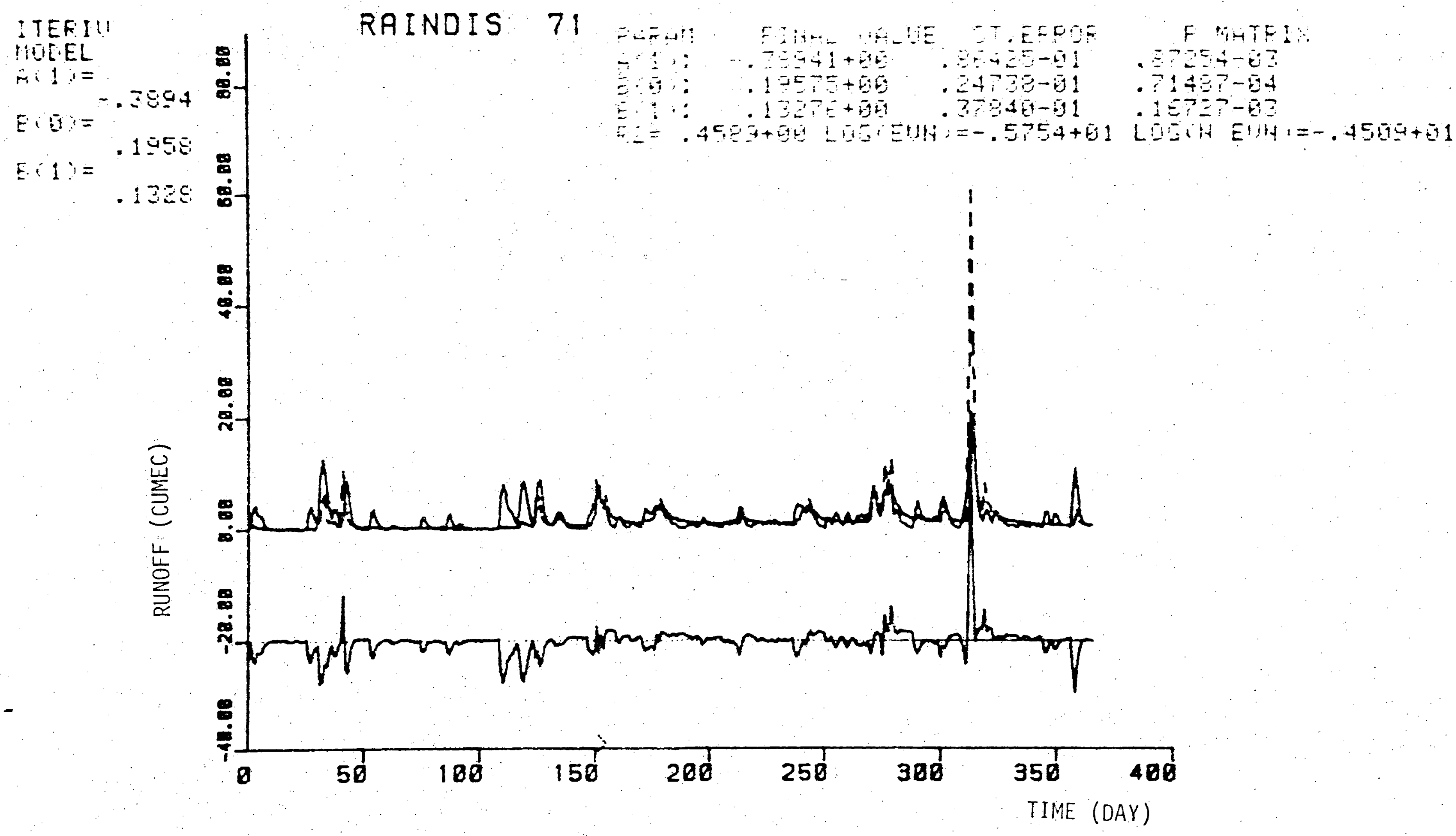


Fig 5.75 Raw Data Model Raindis 71

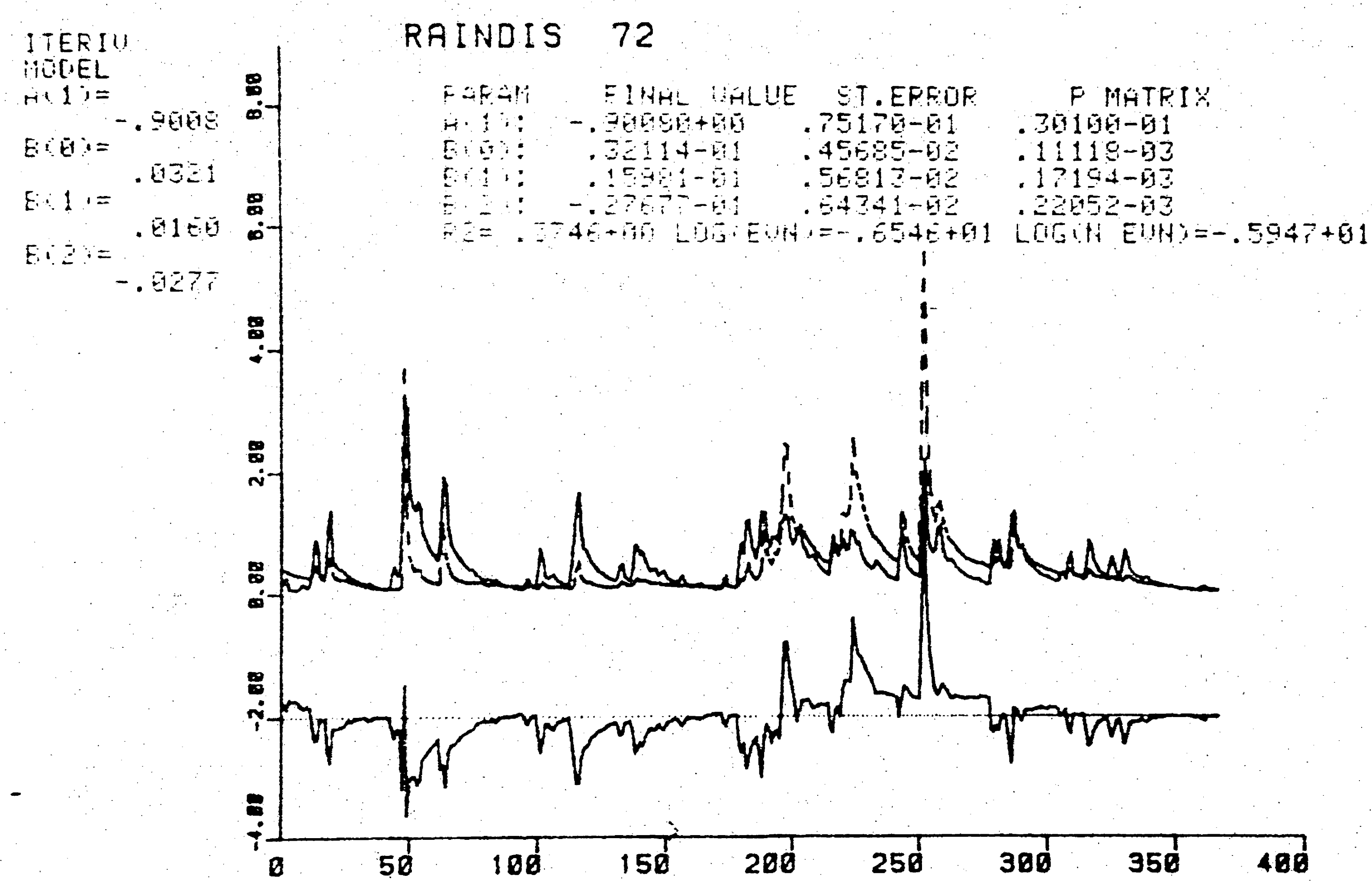


Fig 5.76 Raw Data Model Raindis 72

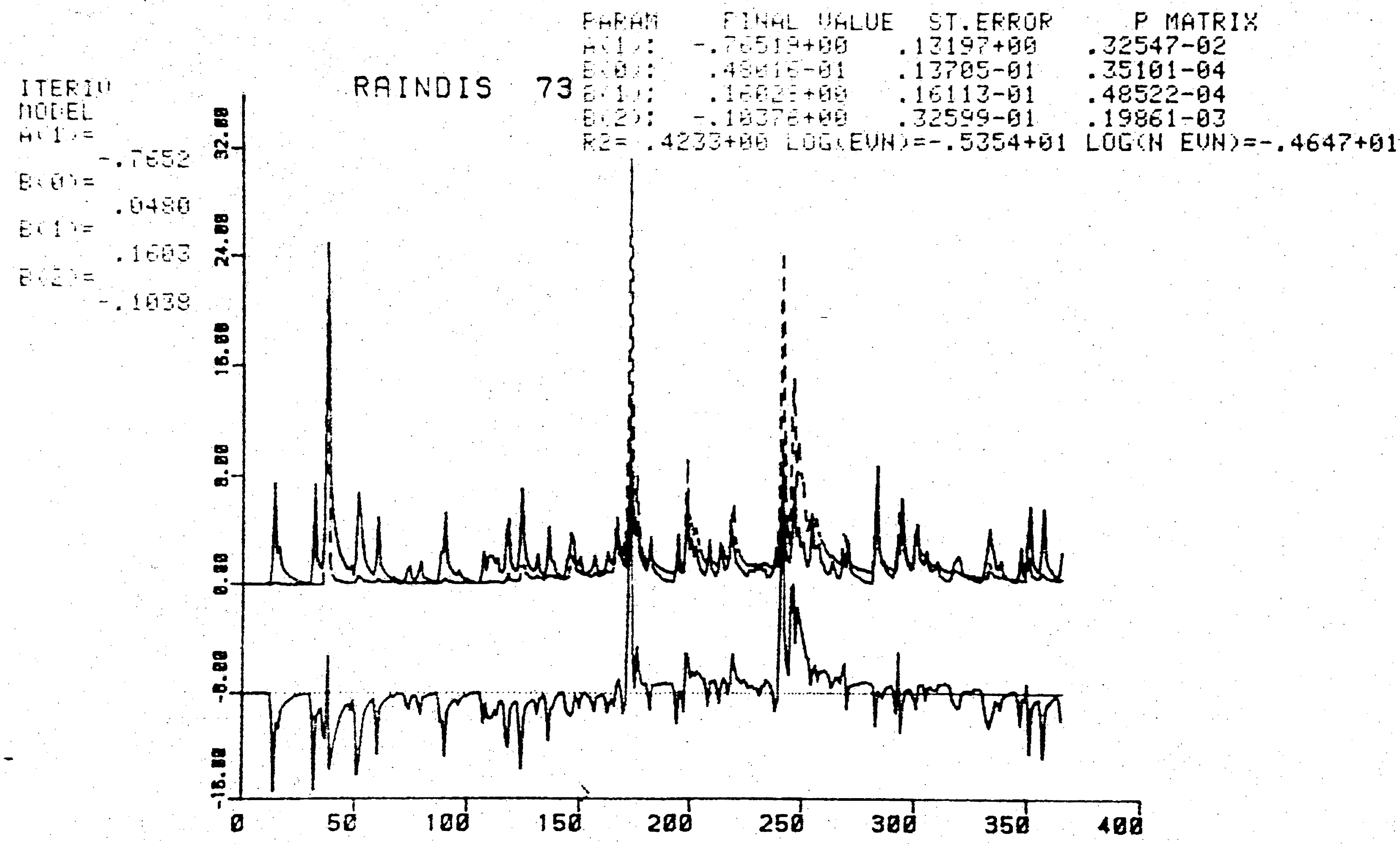


Fig 5.77 Raw Data Model Raindis 73

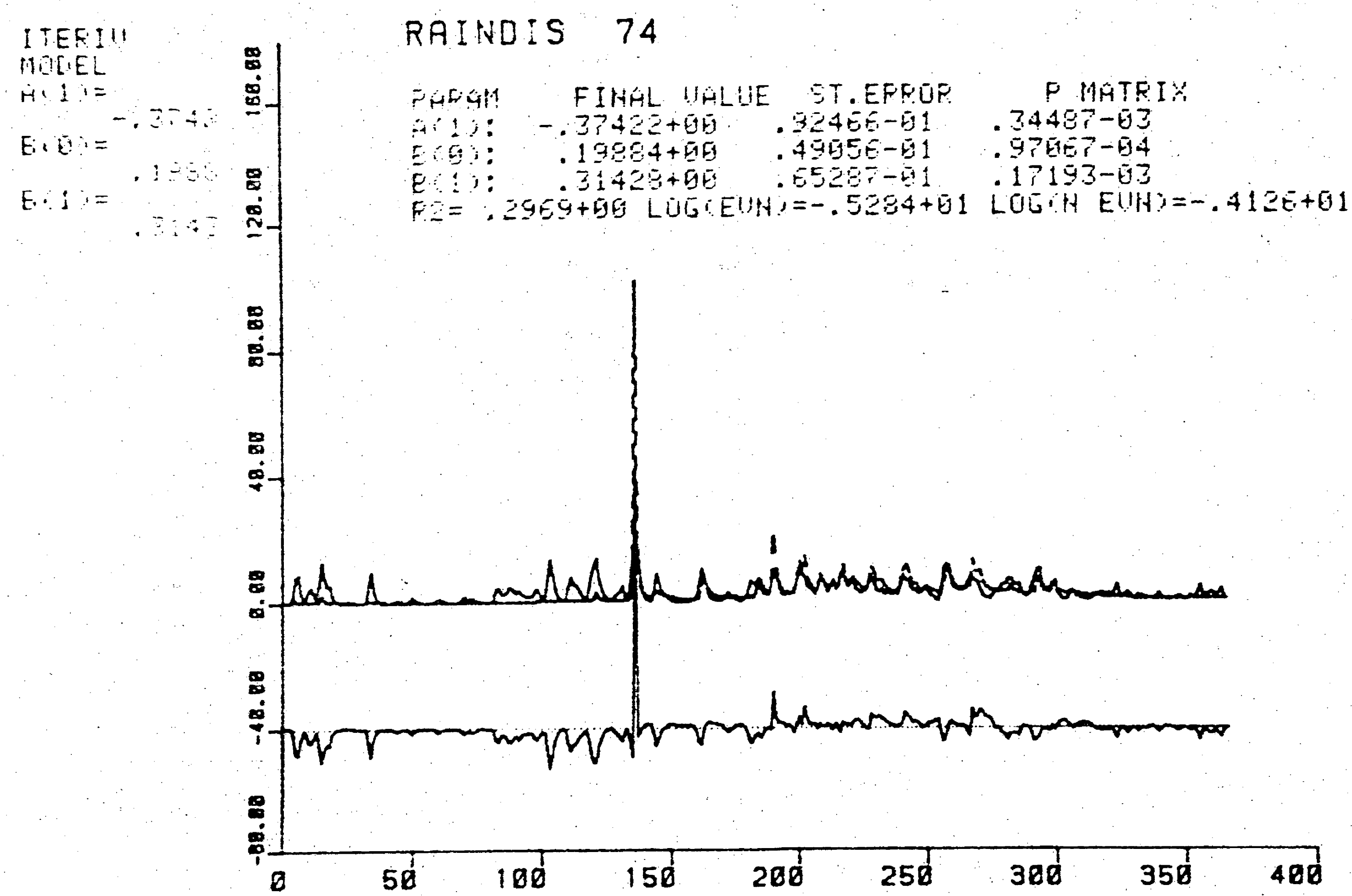


Fig 5.78 Raw Data Model Raindis 74

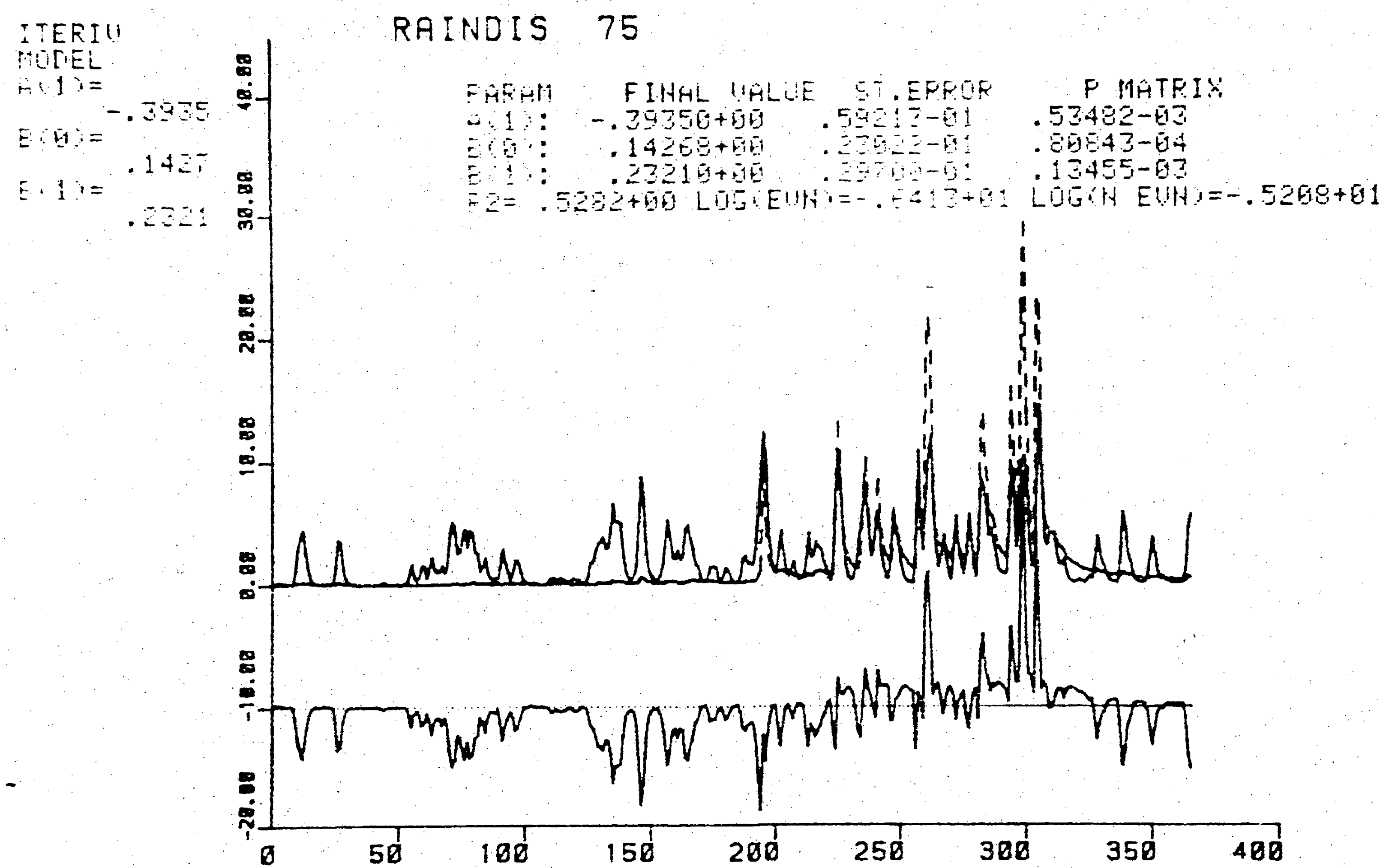


Fig 5.79 Raw Data Model Raindis 75

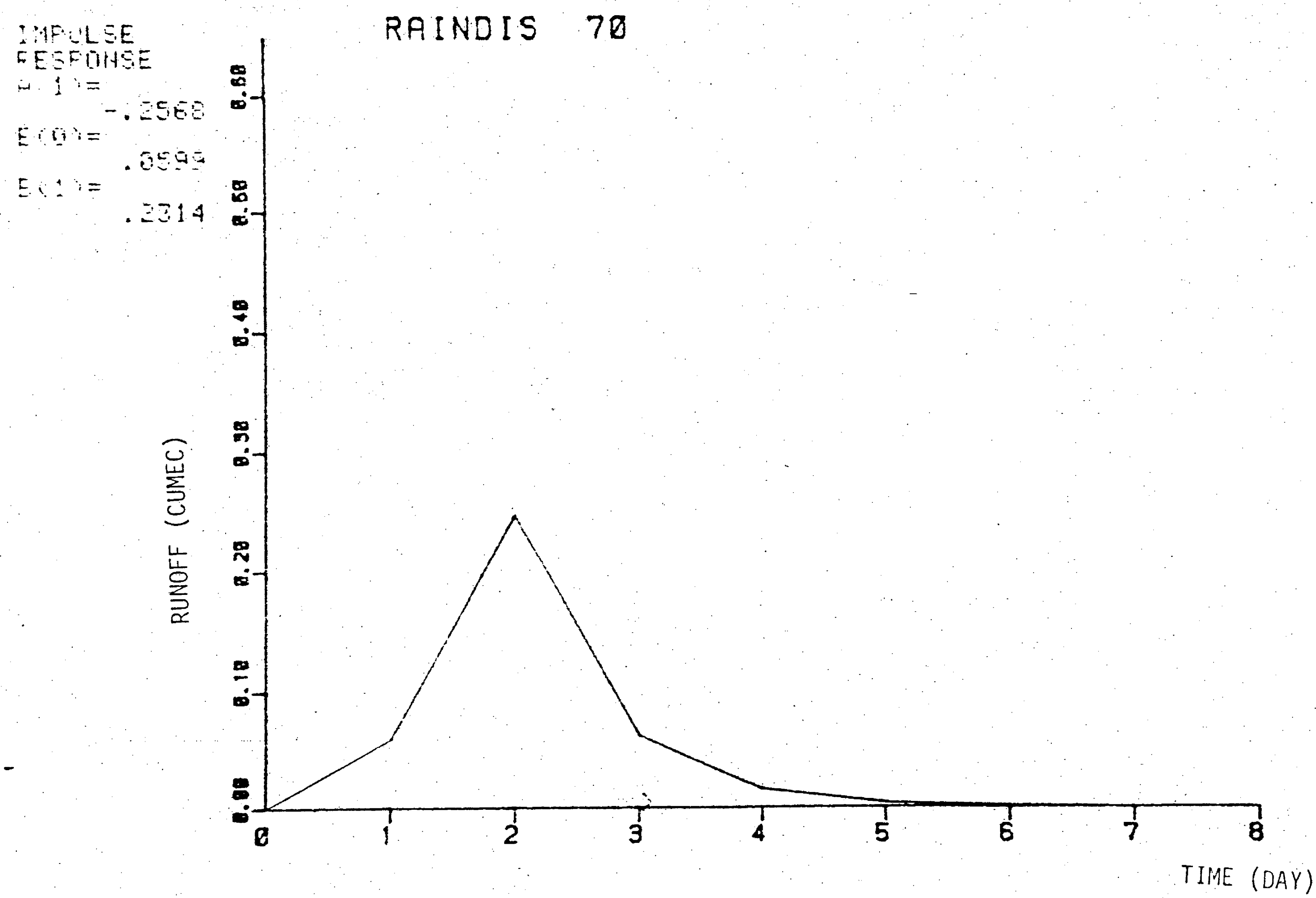


Fig 5.80 Impulse Response for Model Fig 5.74

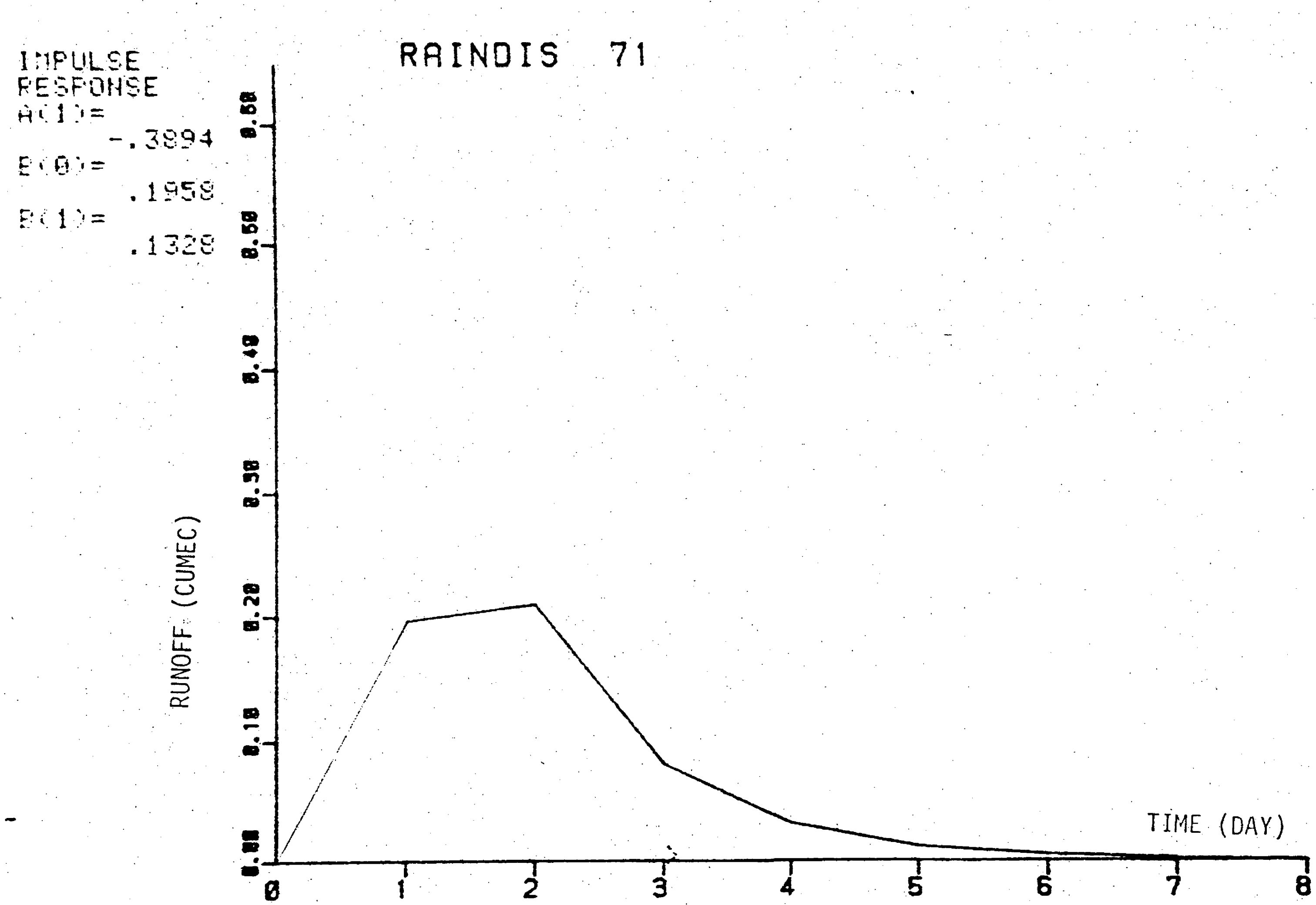


Fig 5.81 Impulse Response for Model Fig 5.75

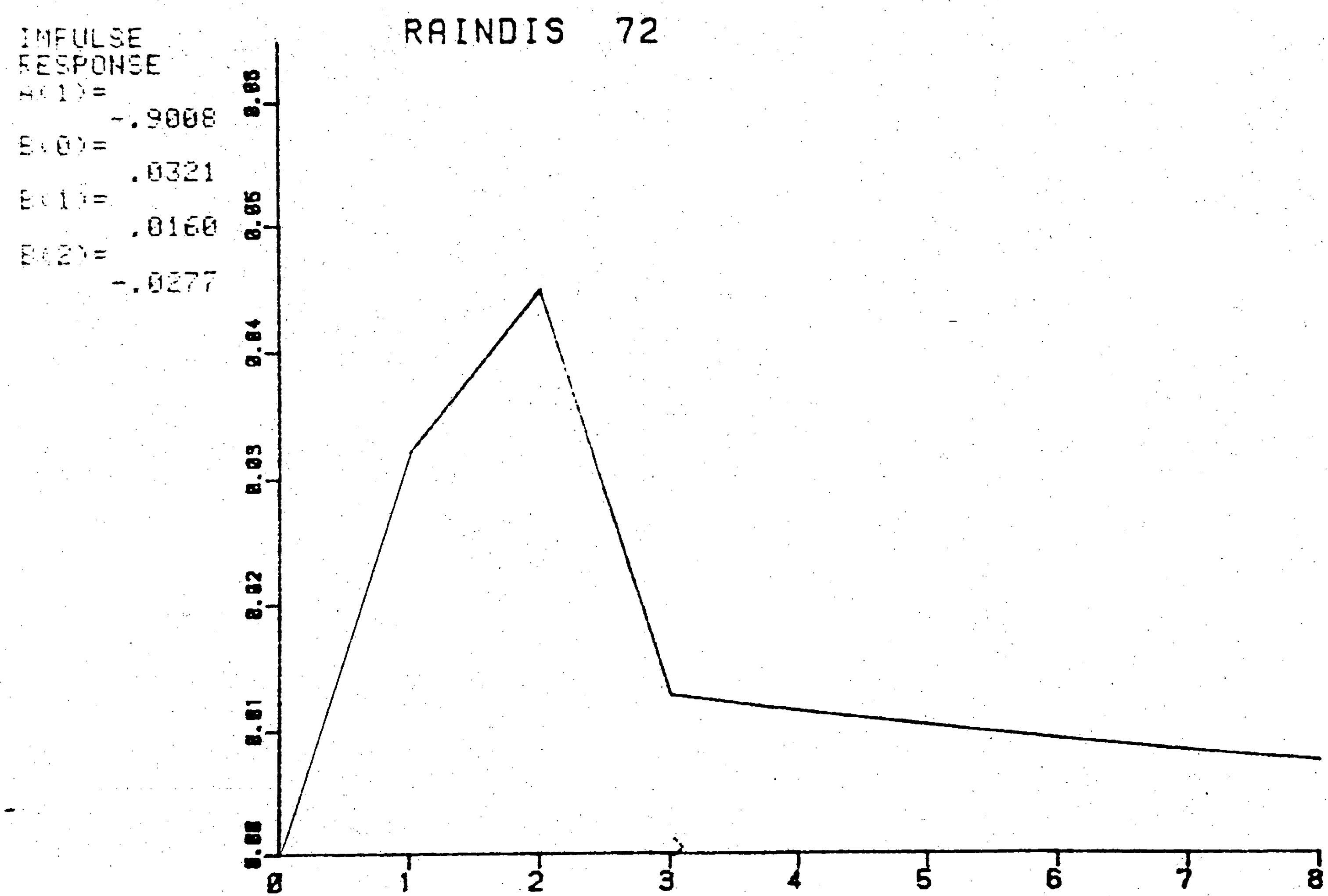


Fig 5.82 Impulse Response for Model Fig 5.76

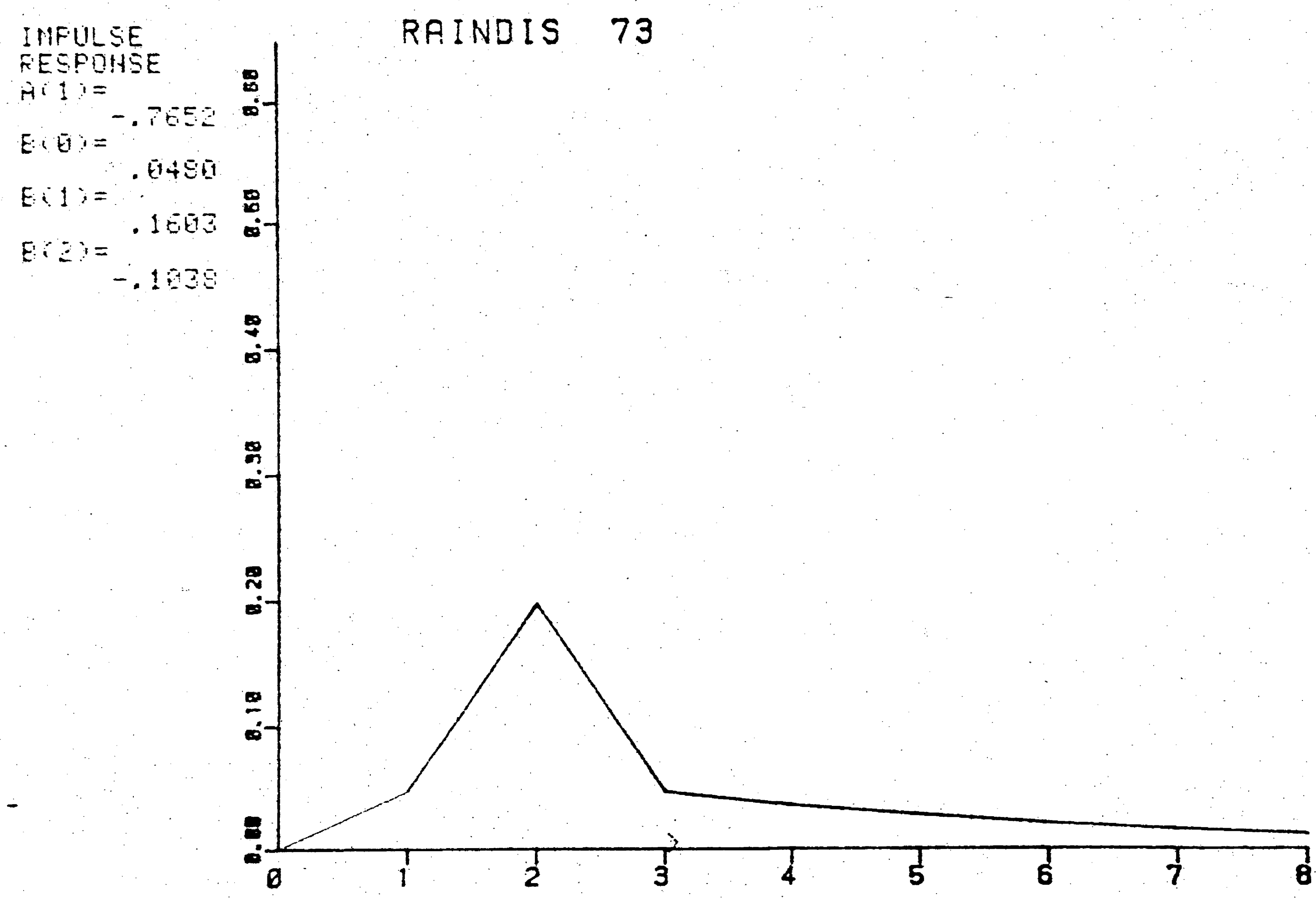


Fig 5.83 Impulse Response for Model Fig 5.77

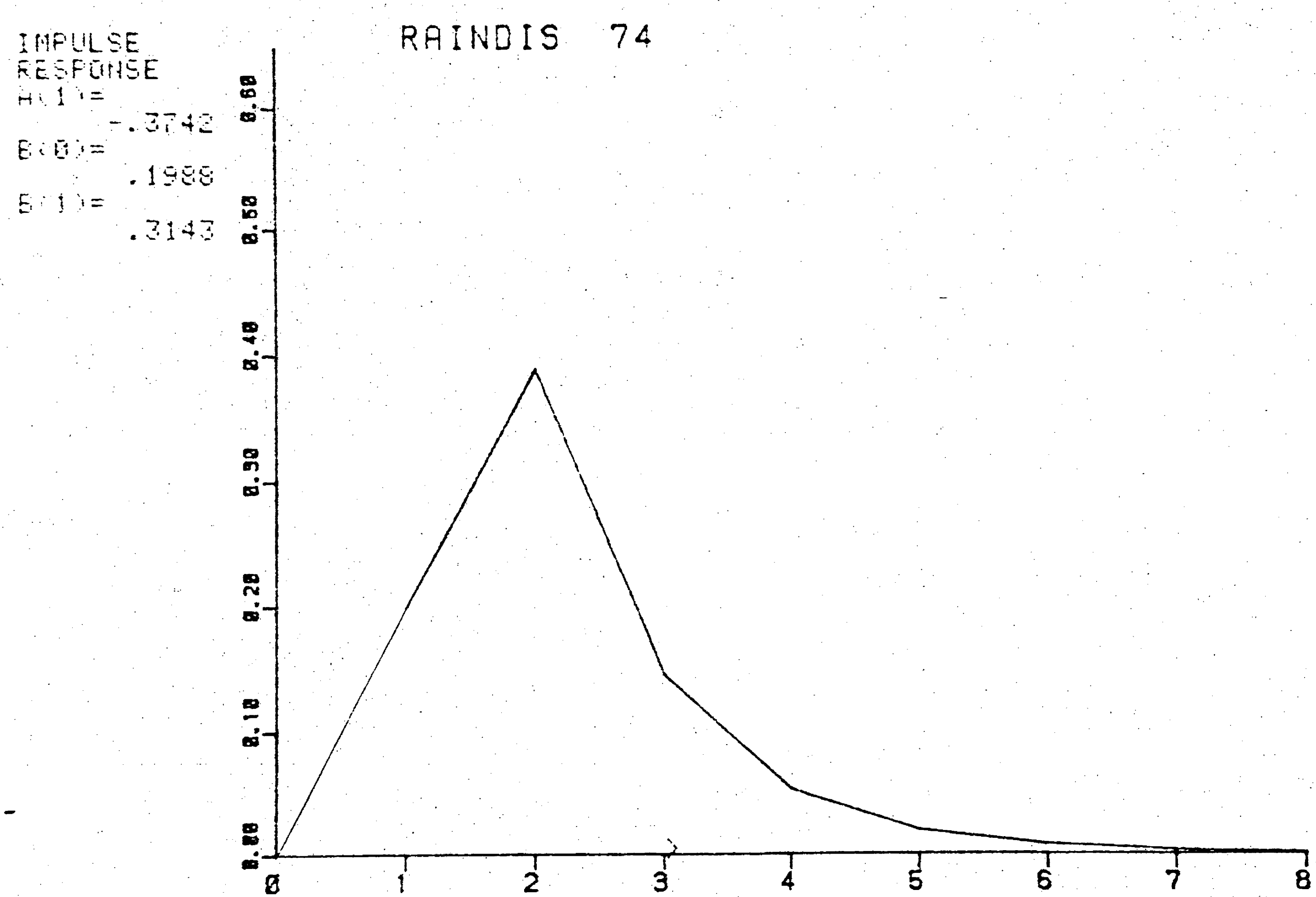


Fig 5.84 Impulse Response for Model Fig 5.78

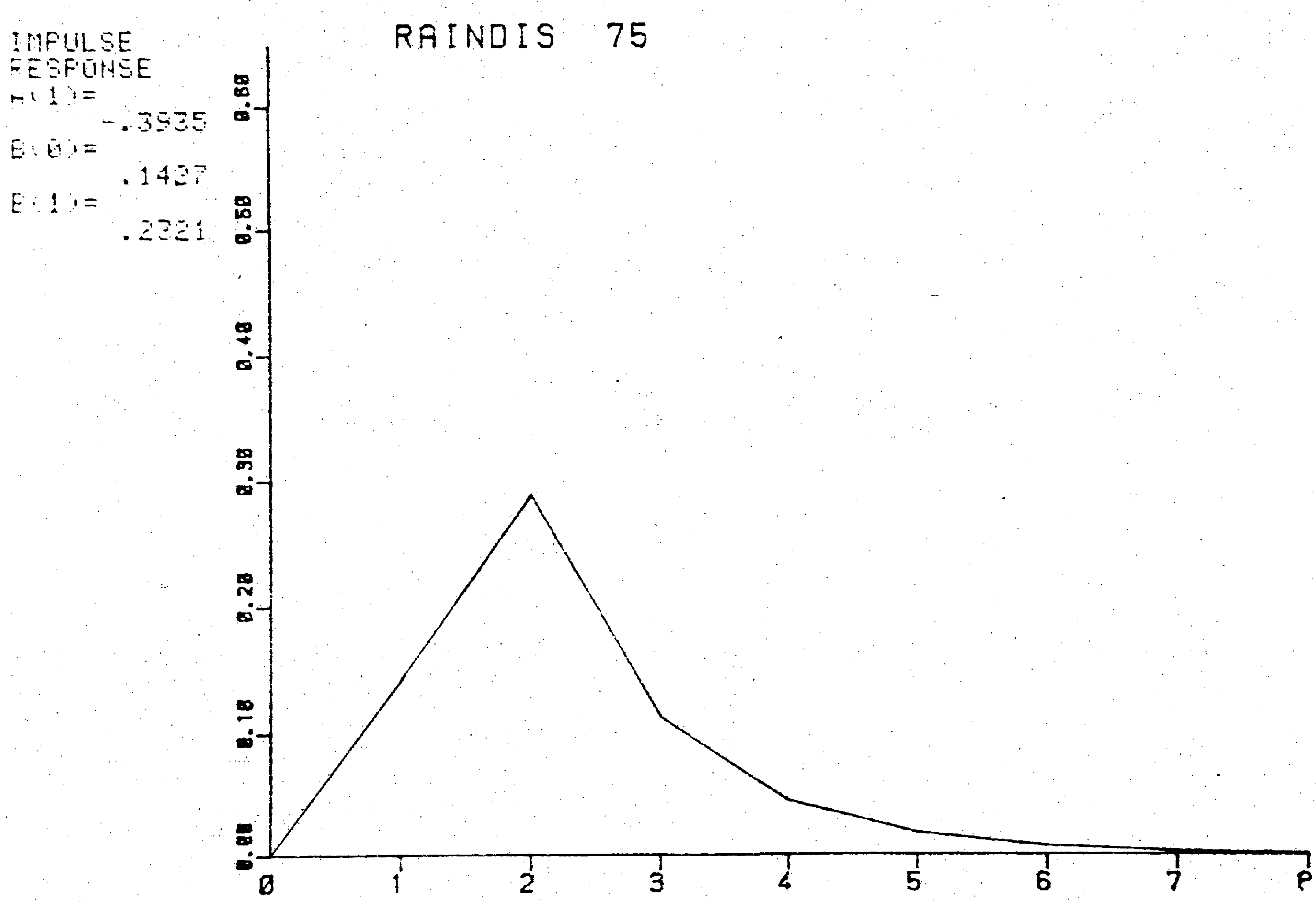


Fig 5.85 Impulse Response for Model Fig 5.79

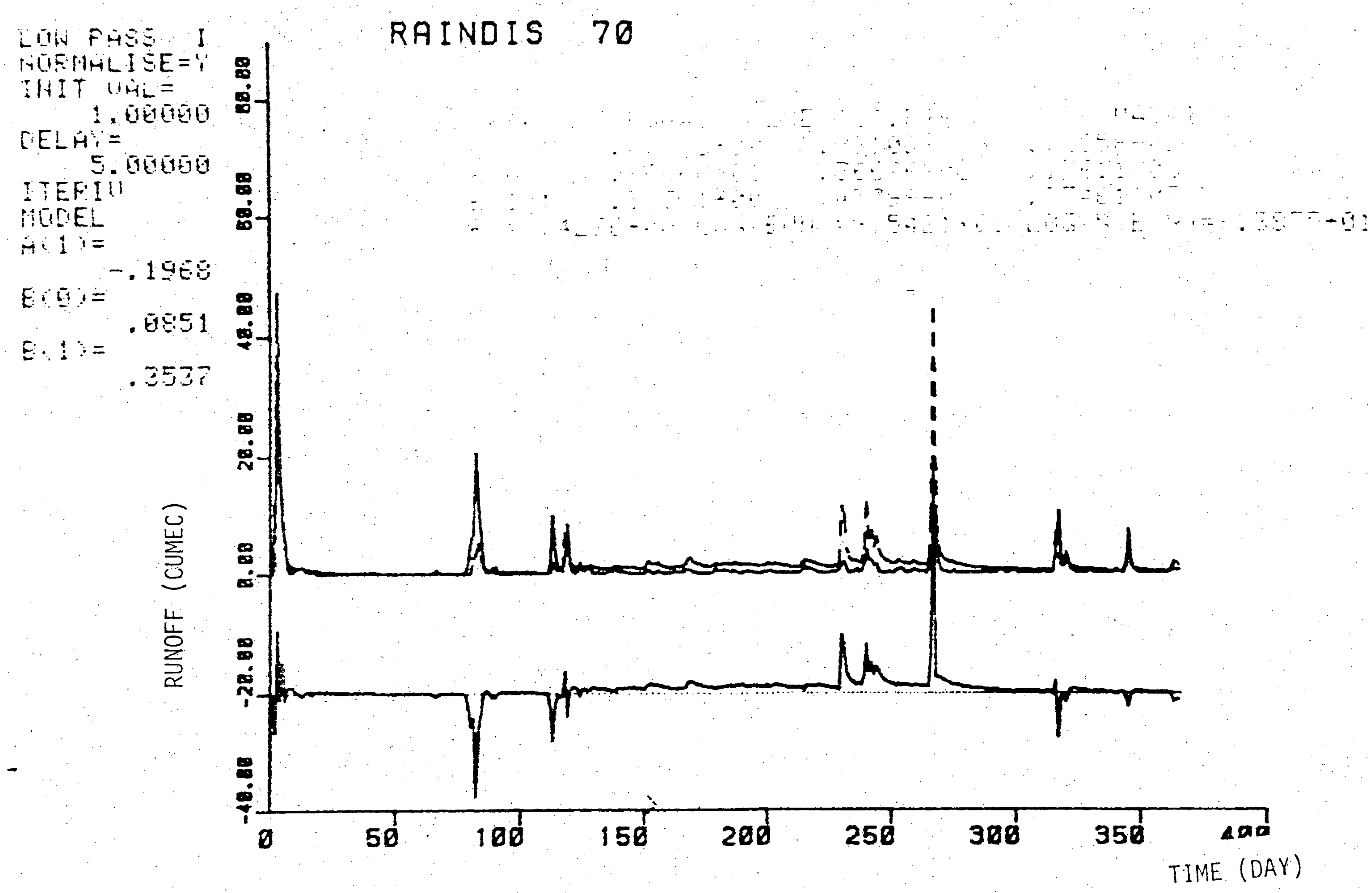


Fig 5.86 Model Raindis 70 with allowance for Soil Moisture

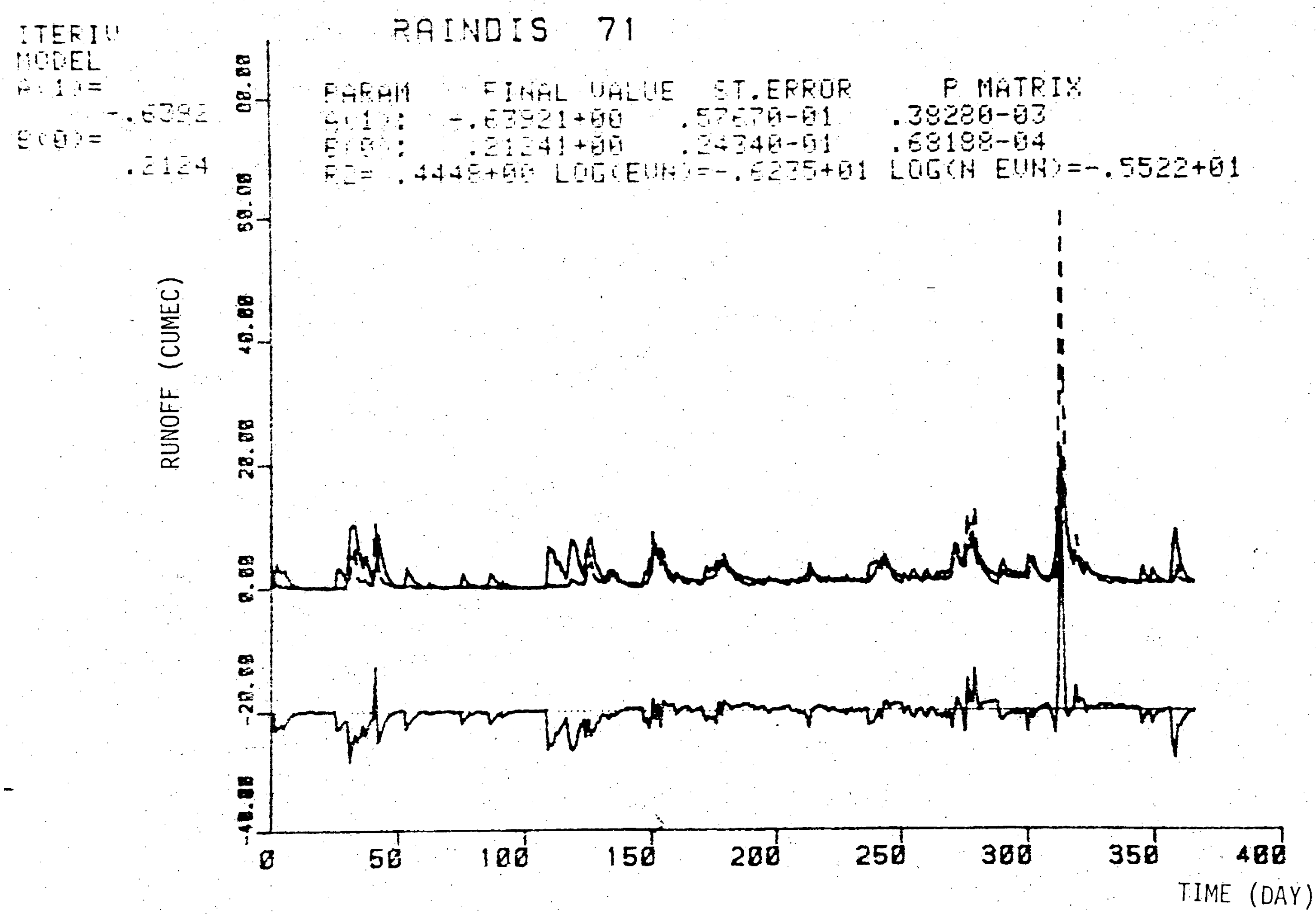


Fig 5.87 Model Raindis 71 with allowance for Soil Moisture

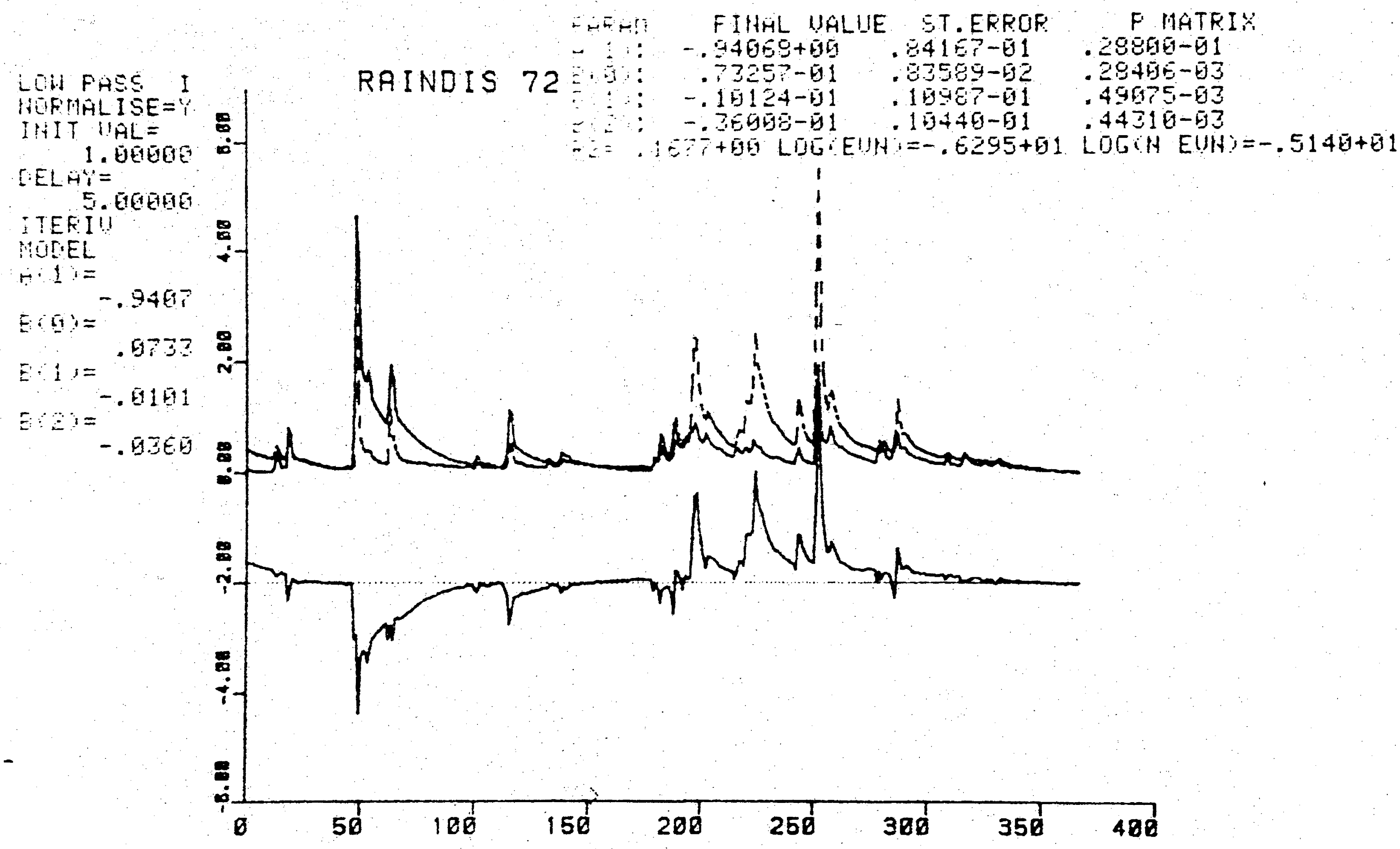


Fig 5.88 Model Raindis 72 with allowance for Soil Moisture

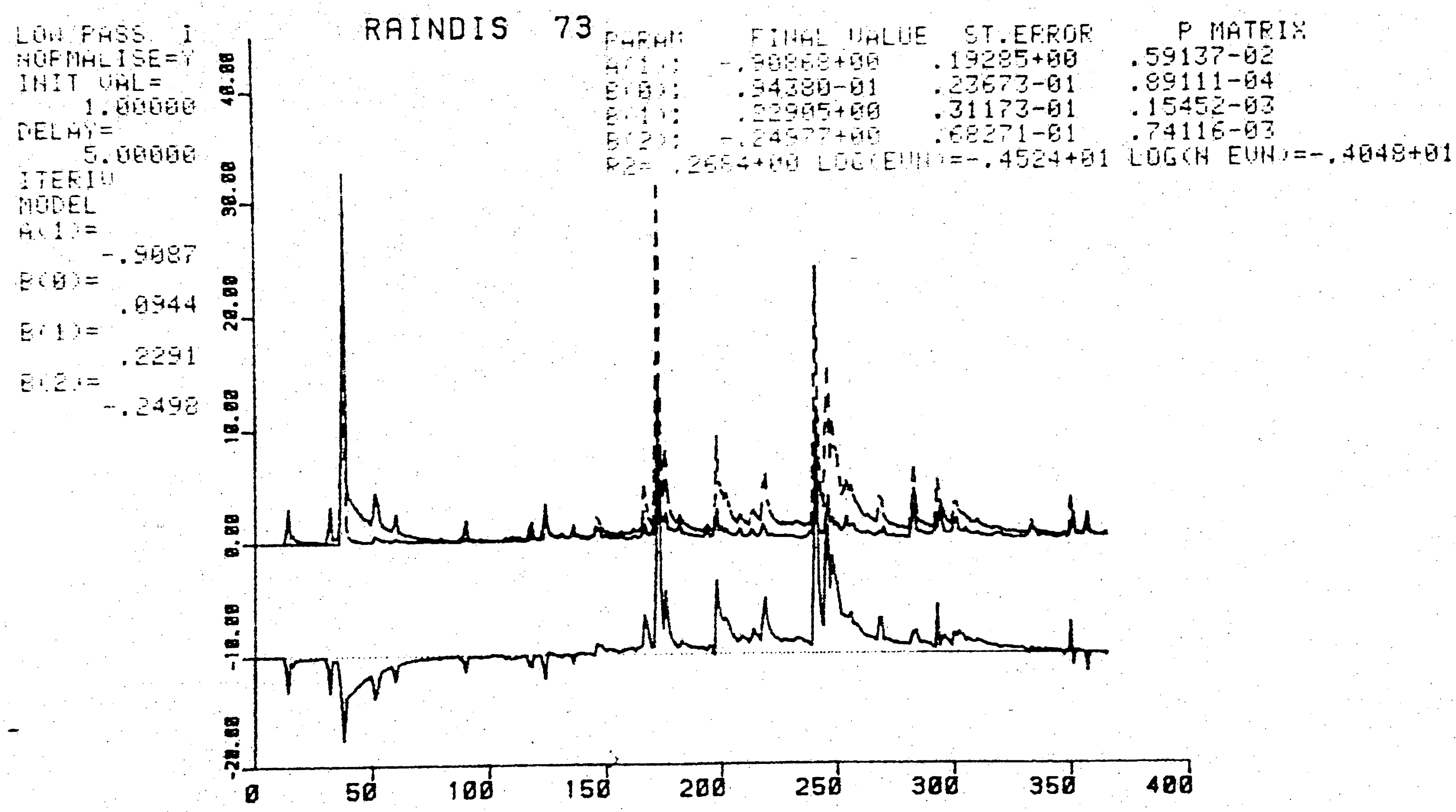


Fig 5.89 Model Raindis 73 with allowance for Soil Moisture

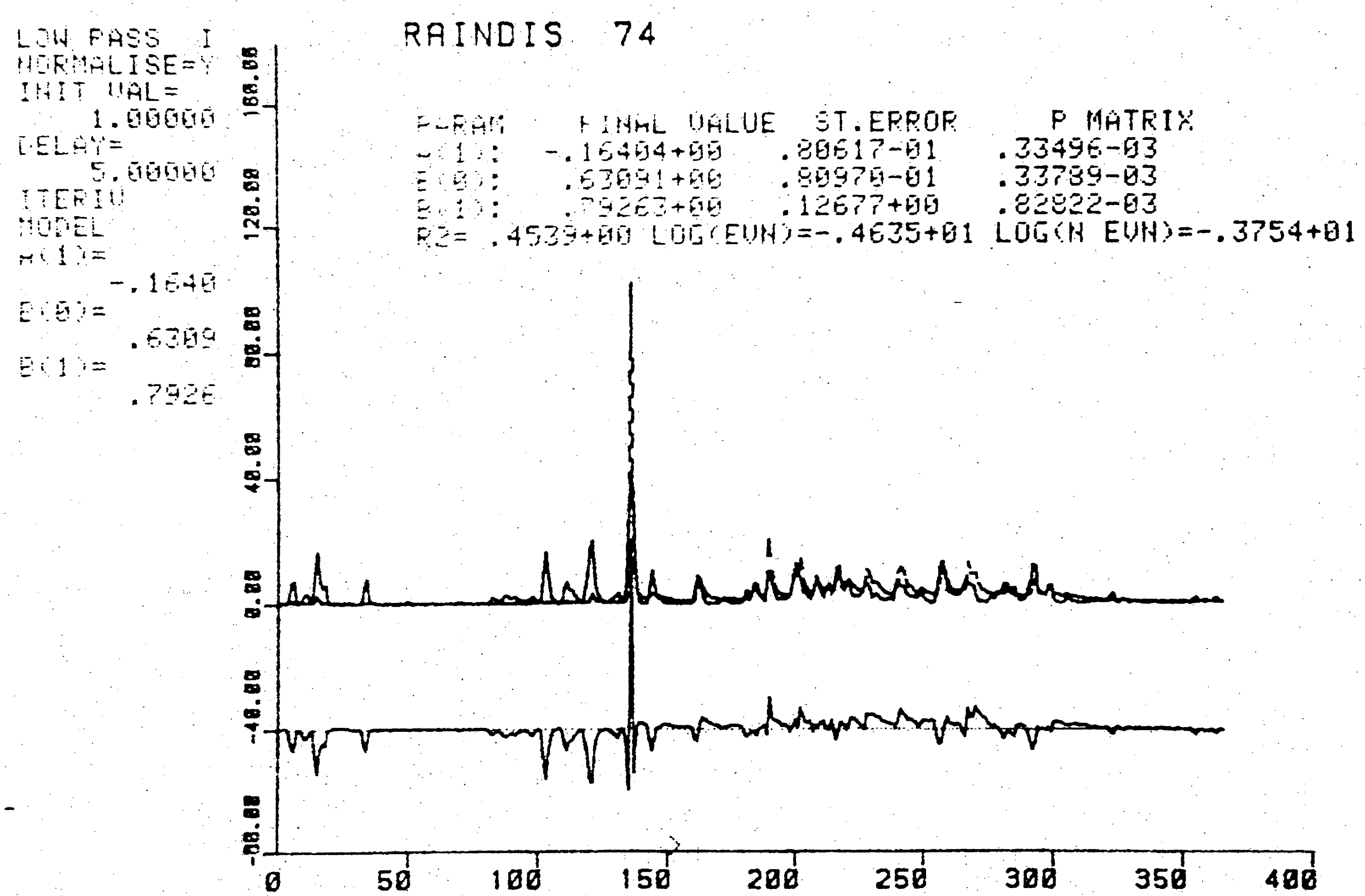


Fig 5.90 Model Raindis 74 with allowance for Soil Moisture

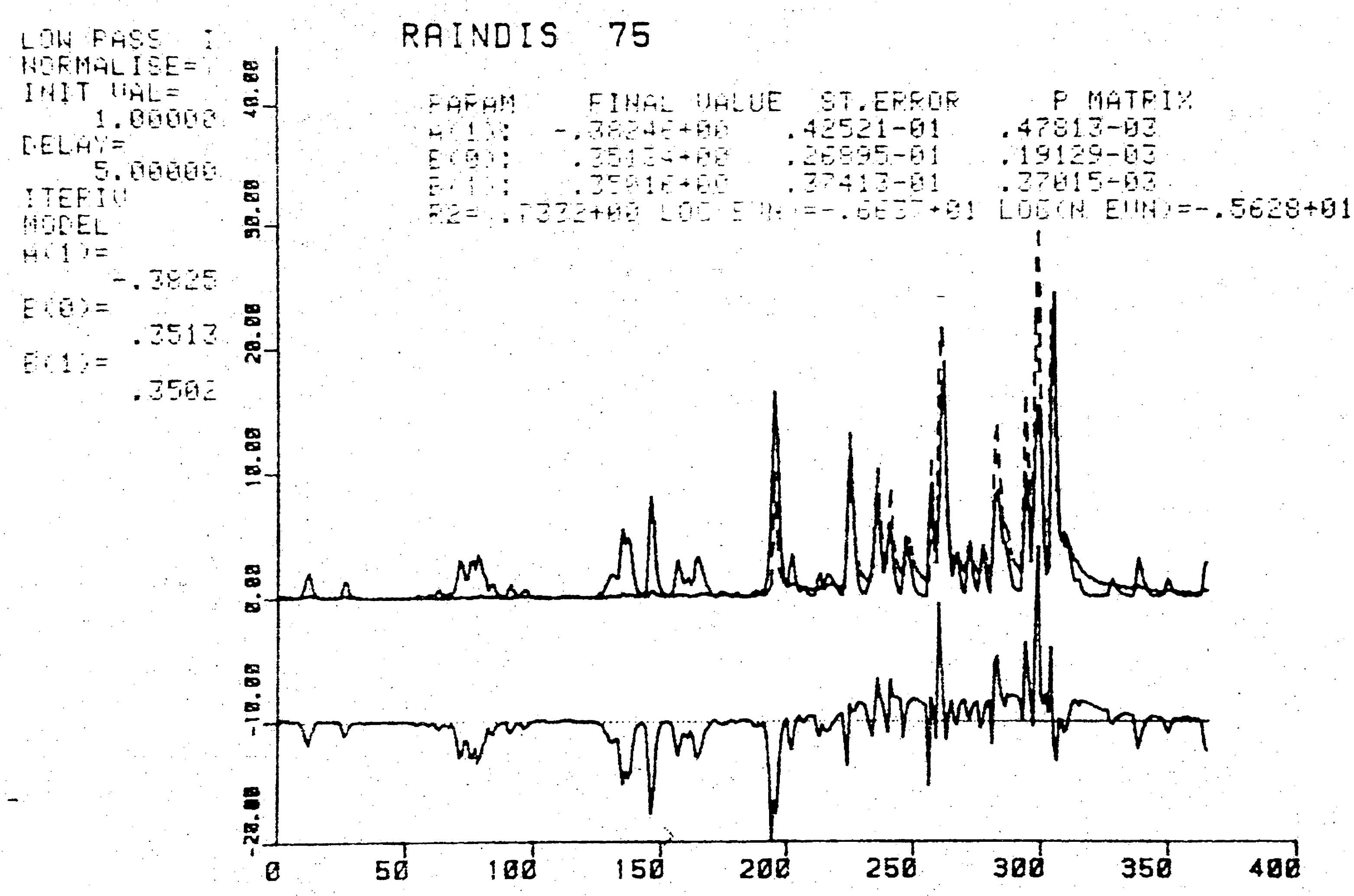


Fig 5.91 Model Raindis 75 with allowance for Soil Moisture

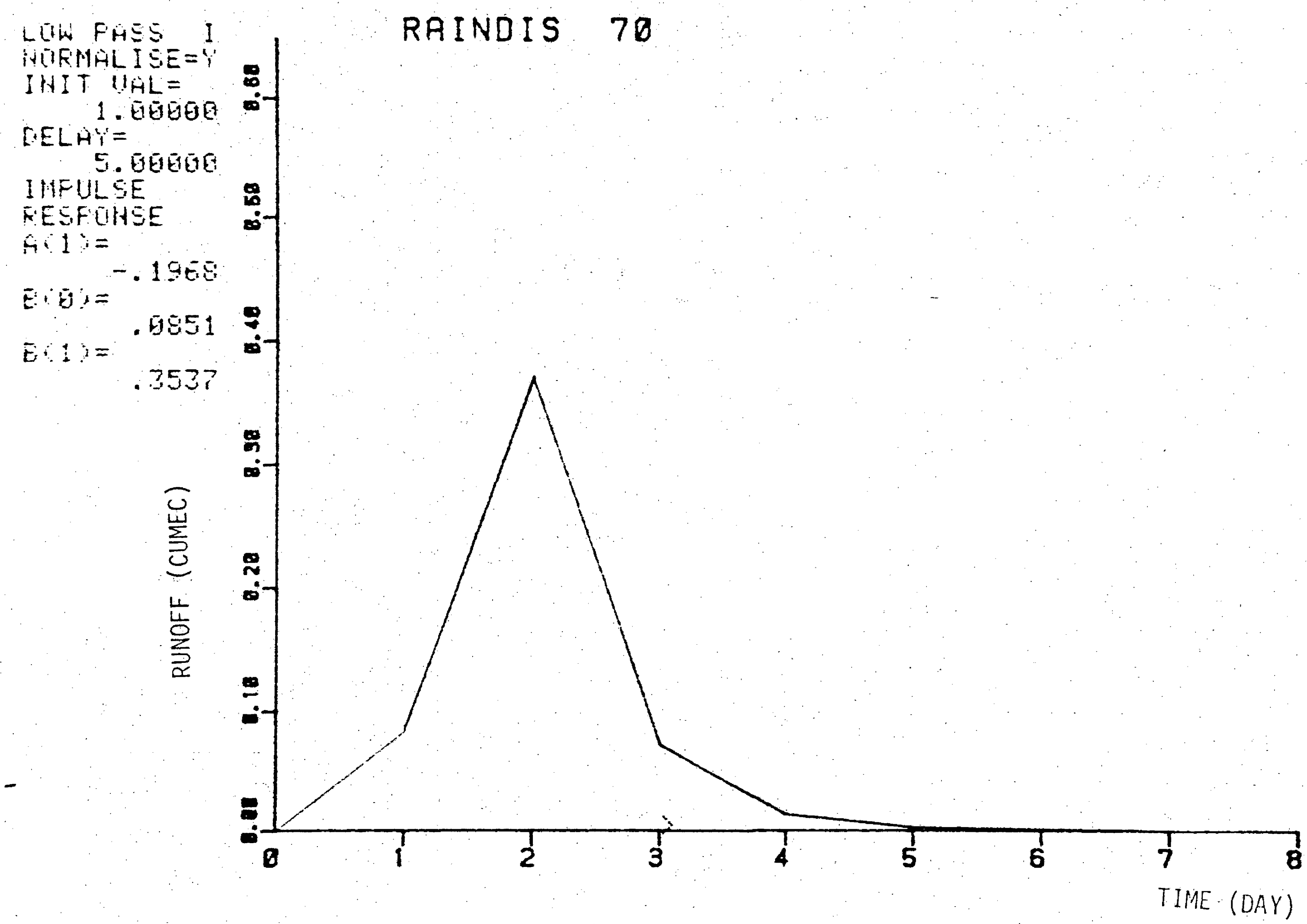


Fig 5.92 Impulse Response for Model Fig 5.86

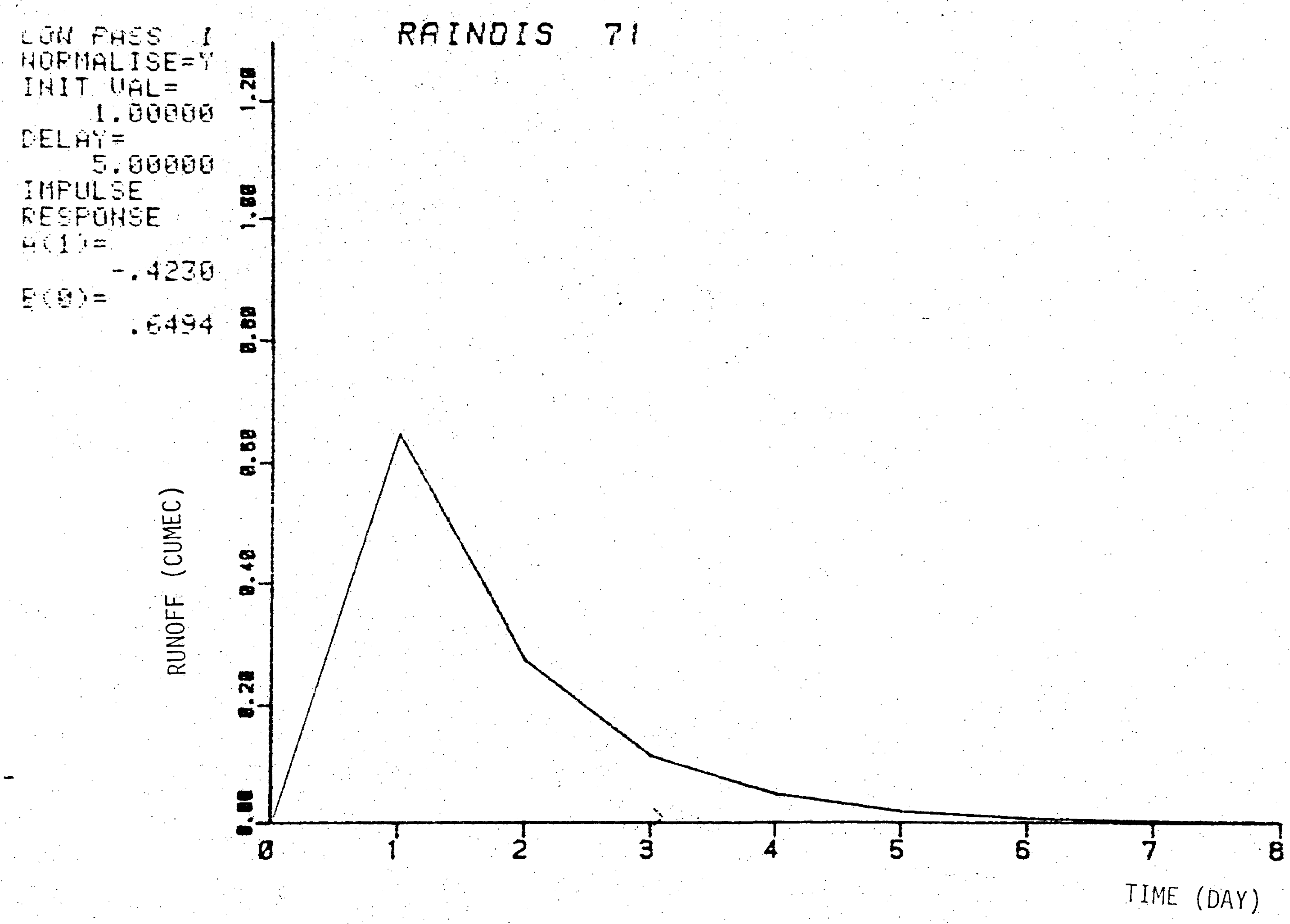


Fig 5.93 Impulse Response for Model Fig 5.87

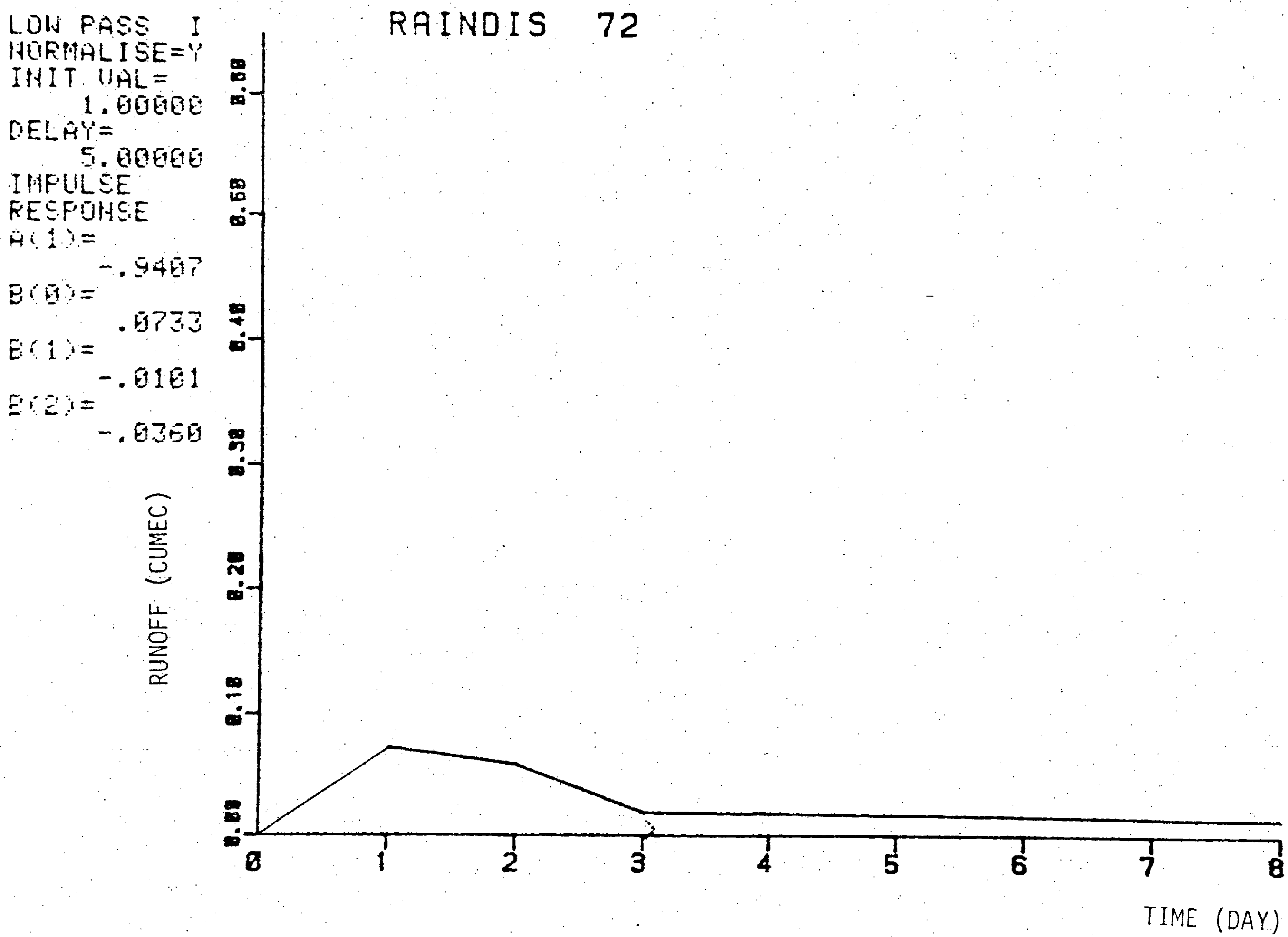


Fig 5.94 Impulse Response for Model Fig 5.88

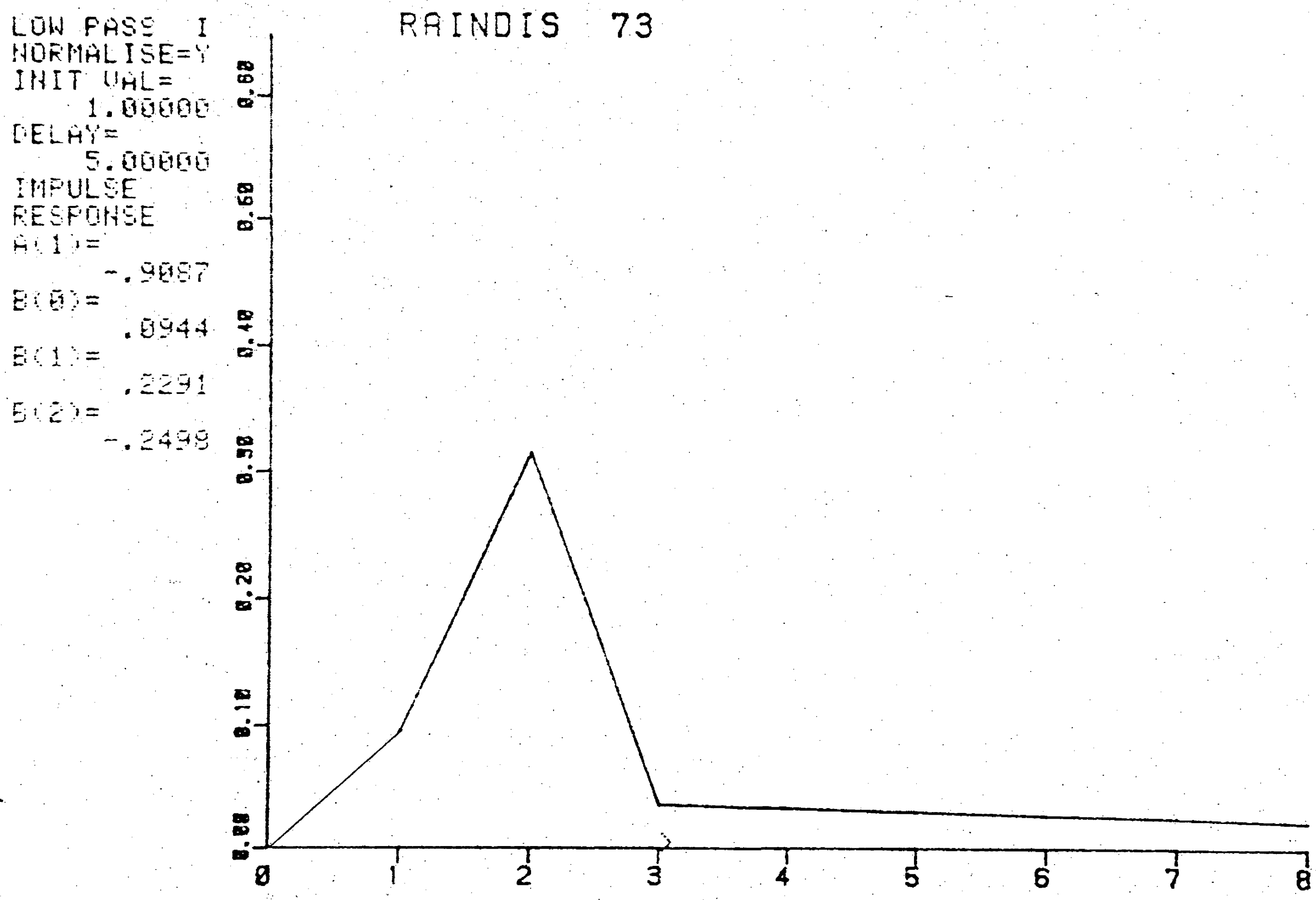


Fig 5.95 Impulse Response for Model Fig 5.89

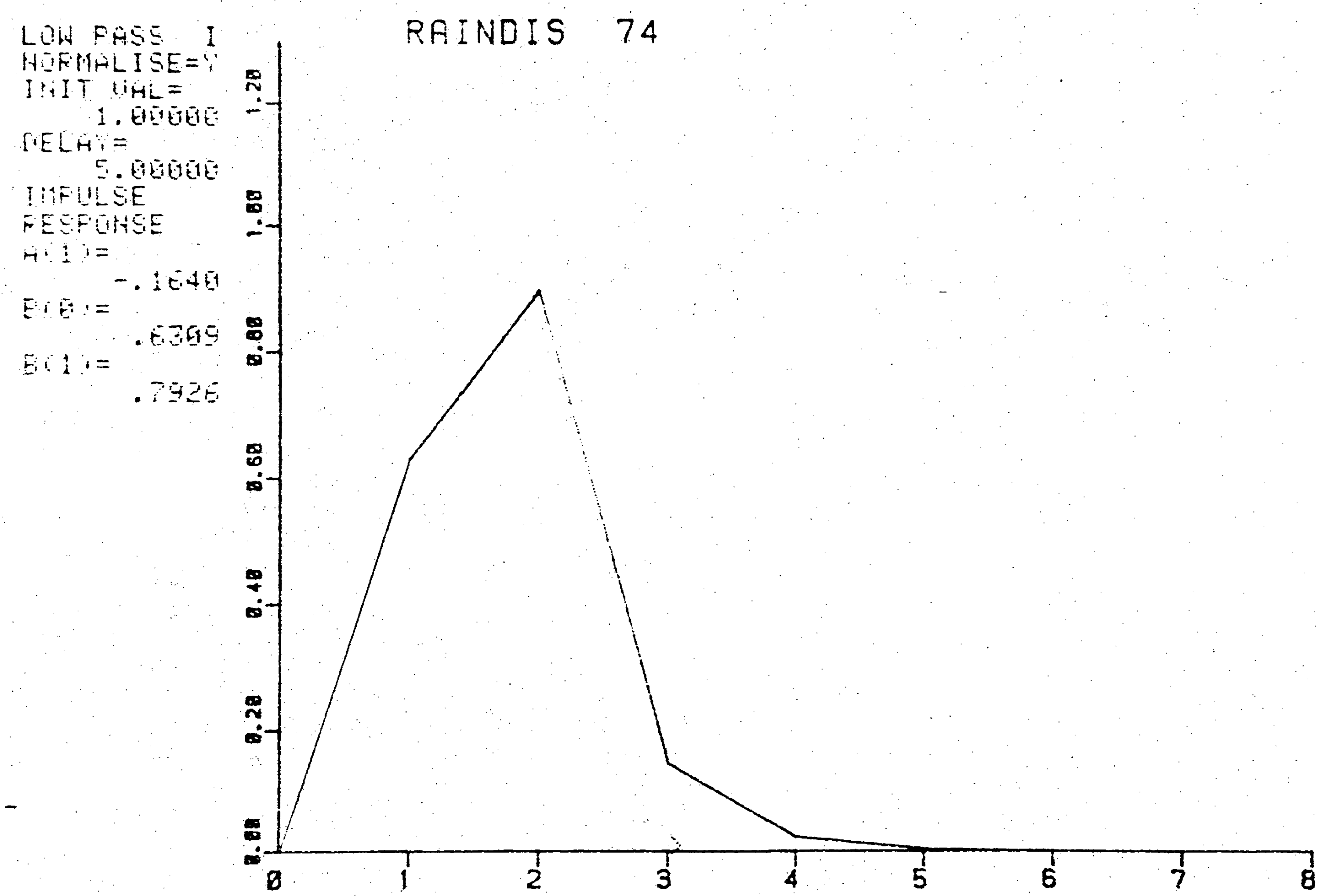


Fig 5.96 Impulse Response for Model Fig 5.90

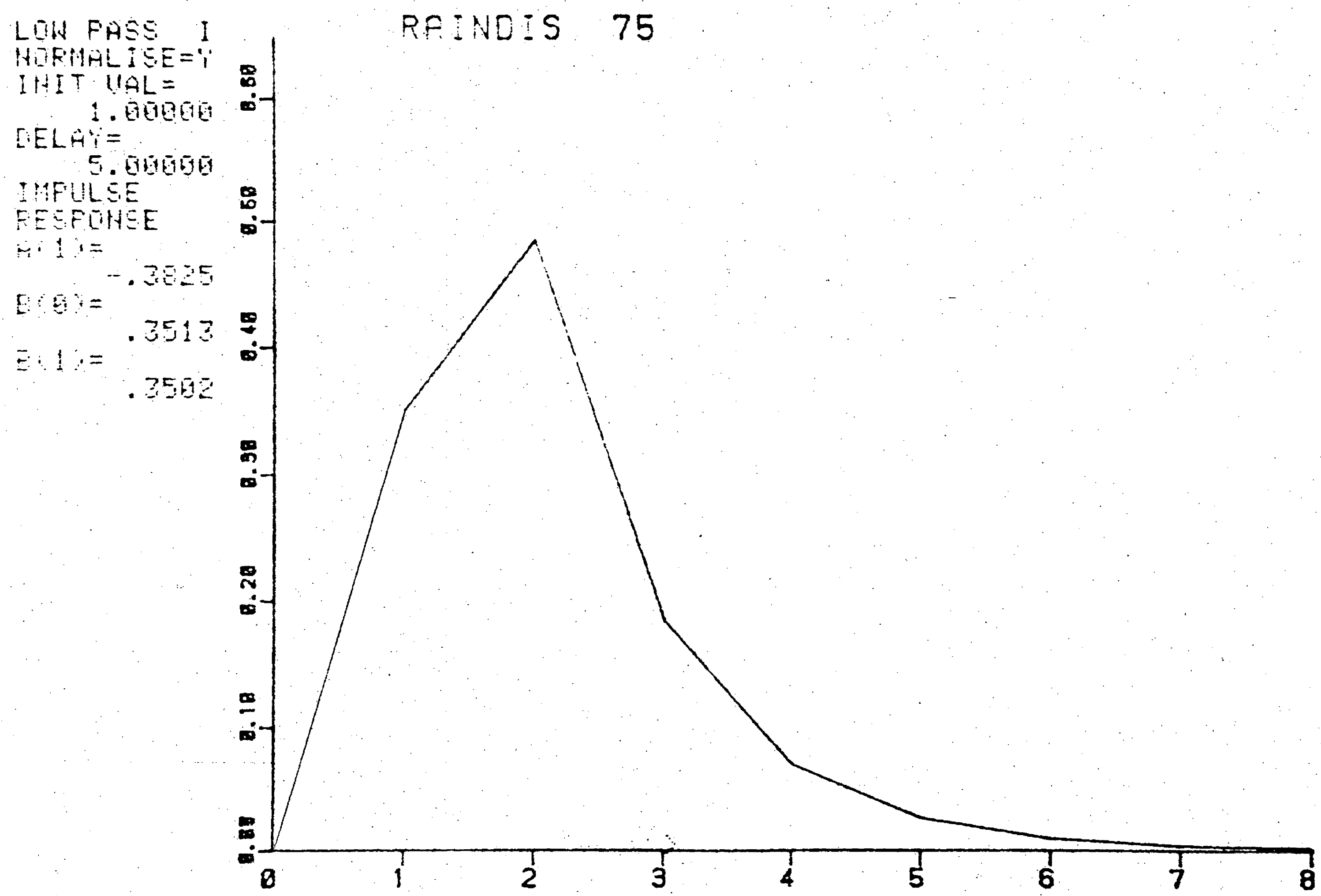


Fig 5.97 Impulse Response for Model Fig 5.91

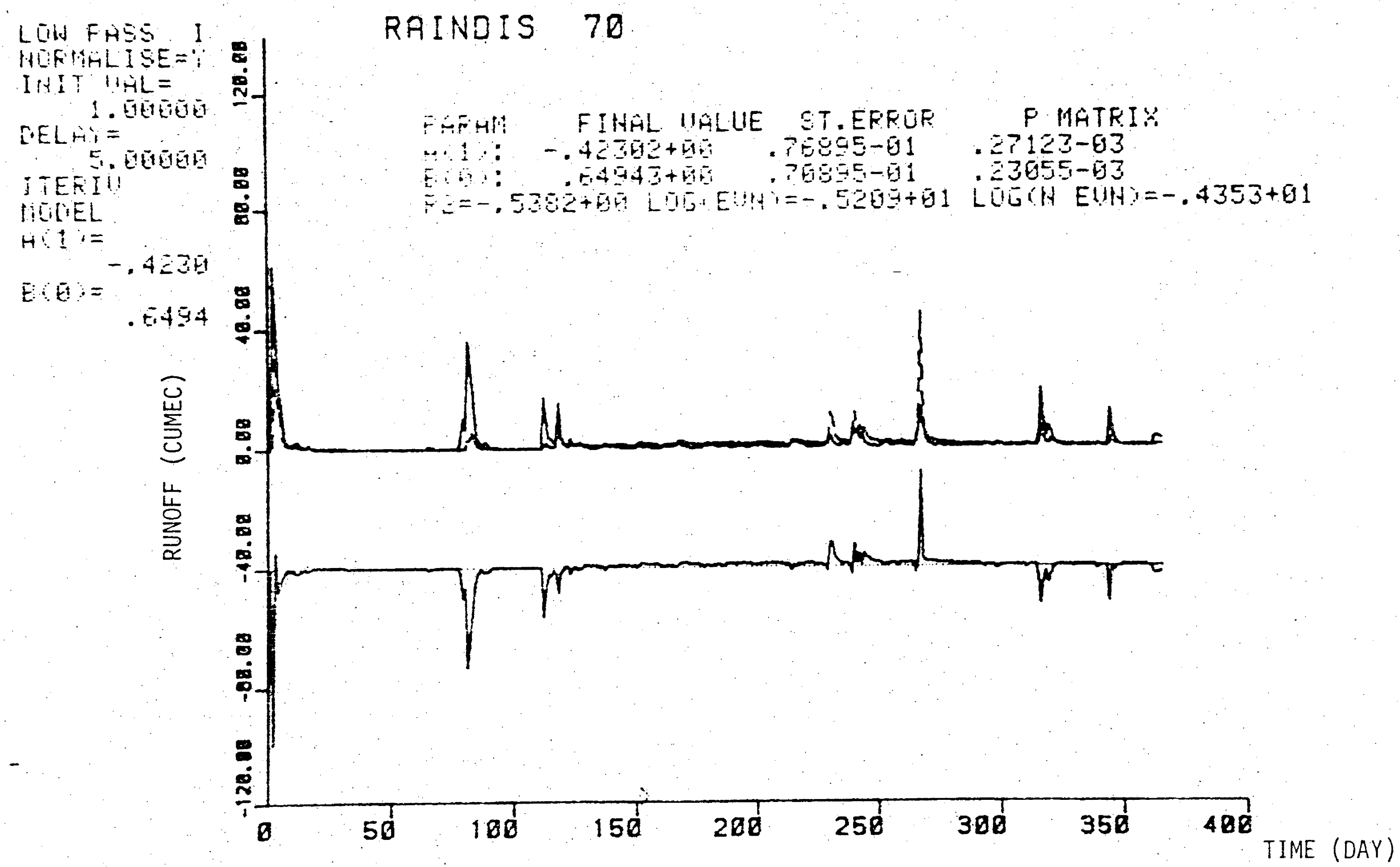


Fig 5.98 1970 Model response with parameter values set to those estimated for 1971 (fig 5.87)

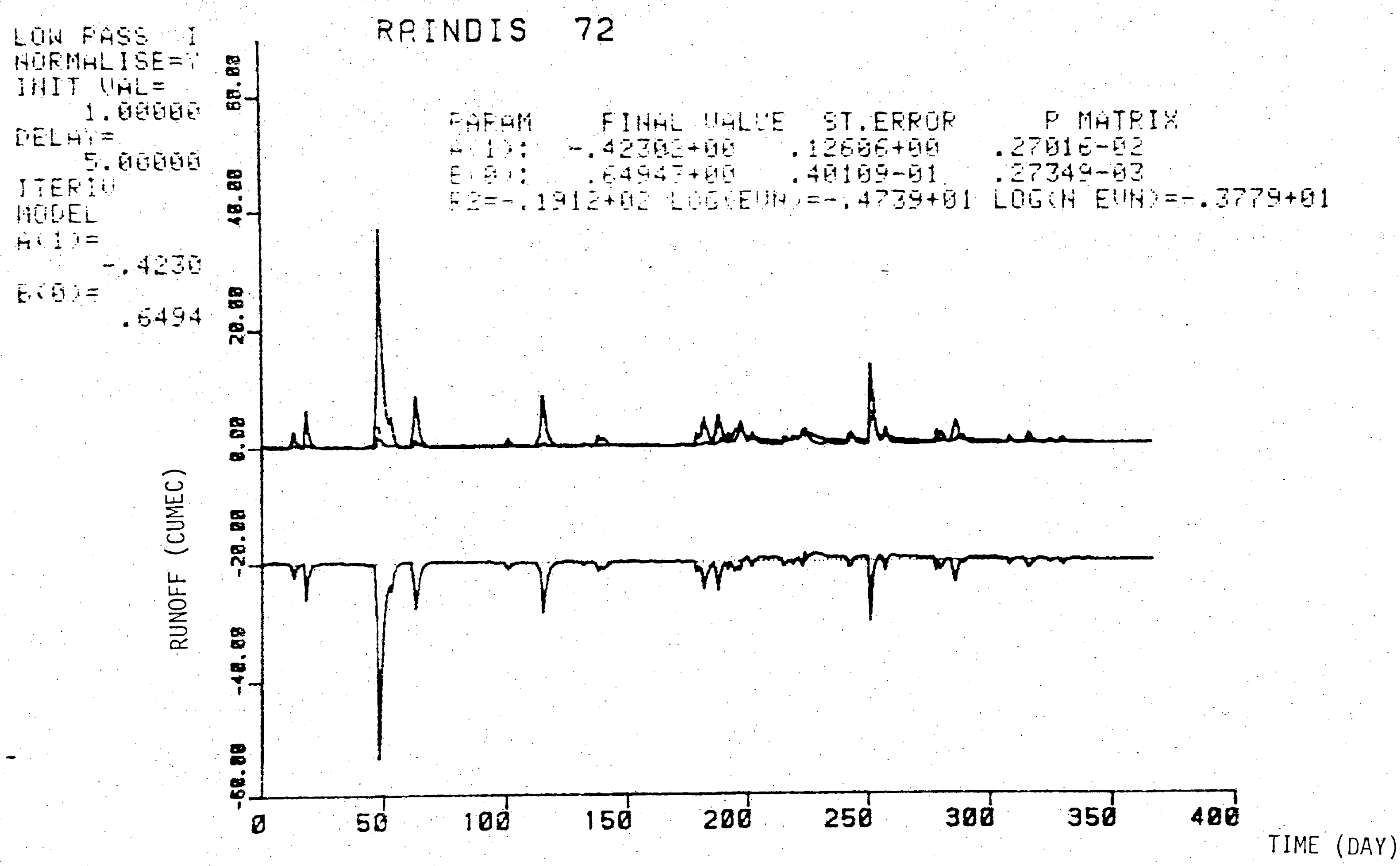


Fig 5.99 1972 Model response with parameter values set to those estimated for 1971 (fig 5.87)

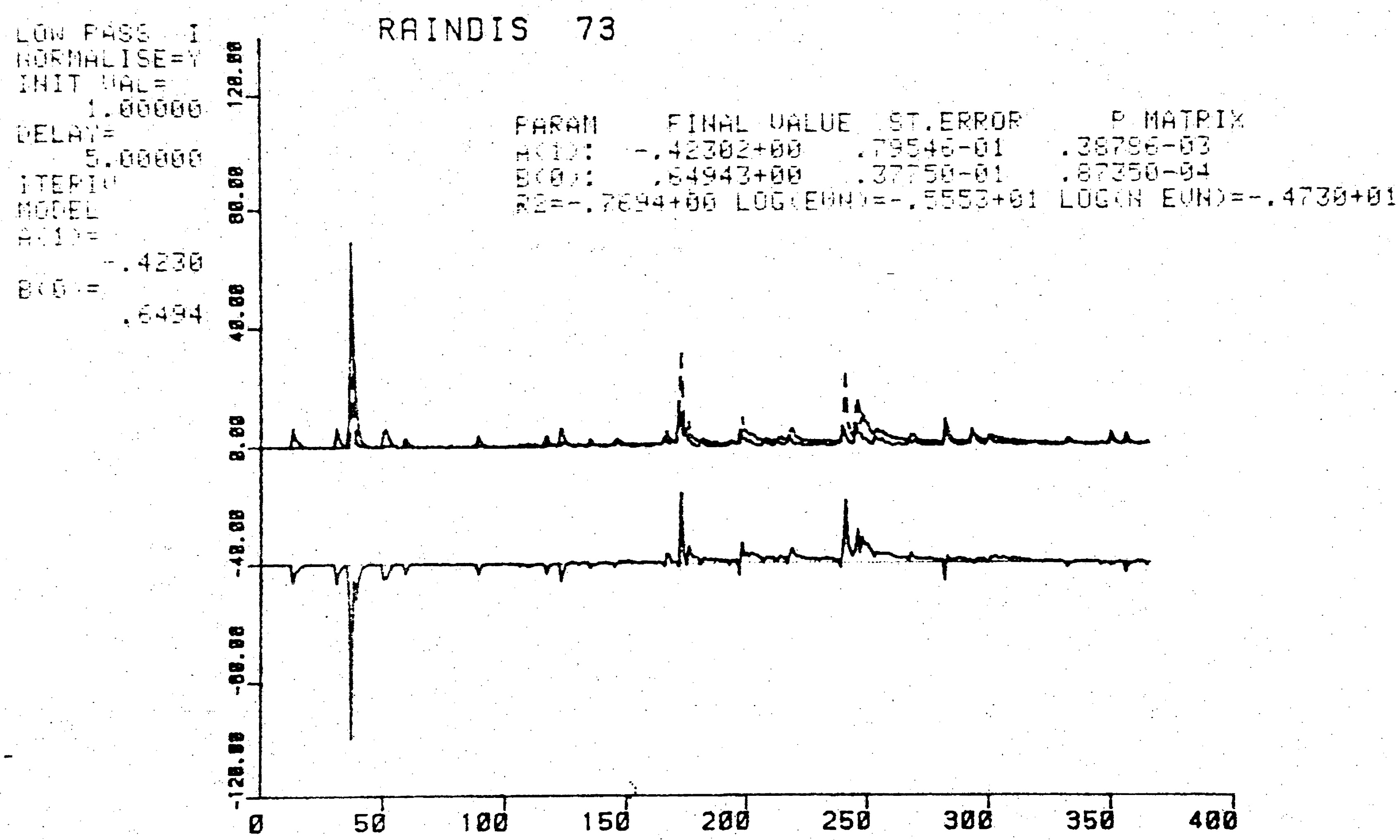


Fig 5.100 1973 Model response with parameter values set to those estimated for 1971 (fig 5.87)

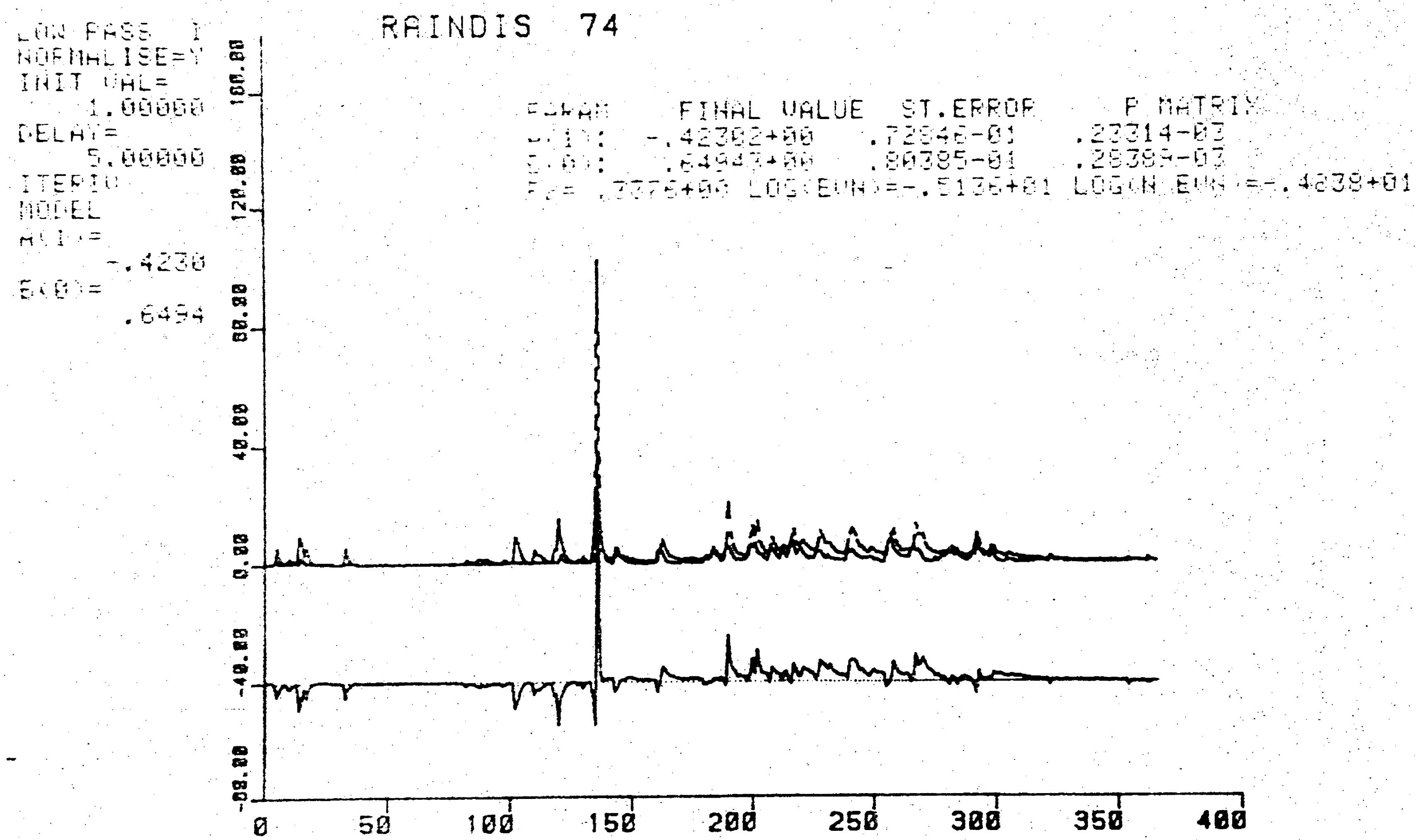


Fig 5.101 1974 Model response with parameter values set to those estimated for 1971 (fig 5.87)

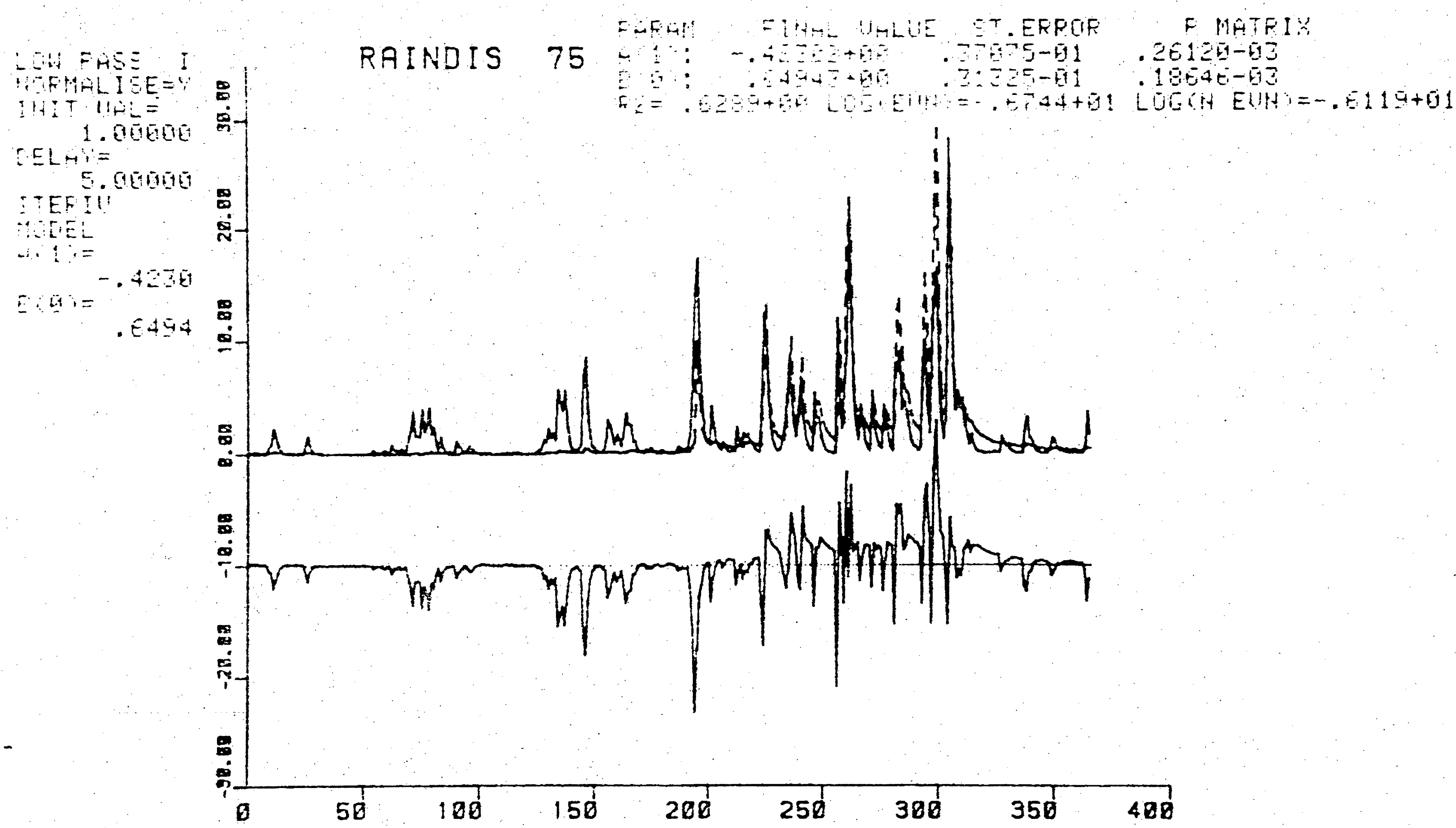


Fig 5.102 1975 Model response with paramenter values set to those estimated for 1971 (fig 5.87)

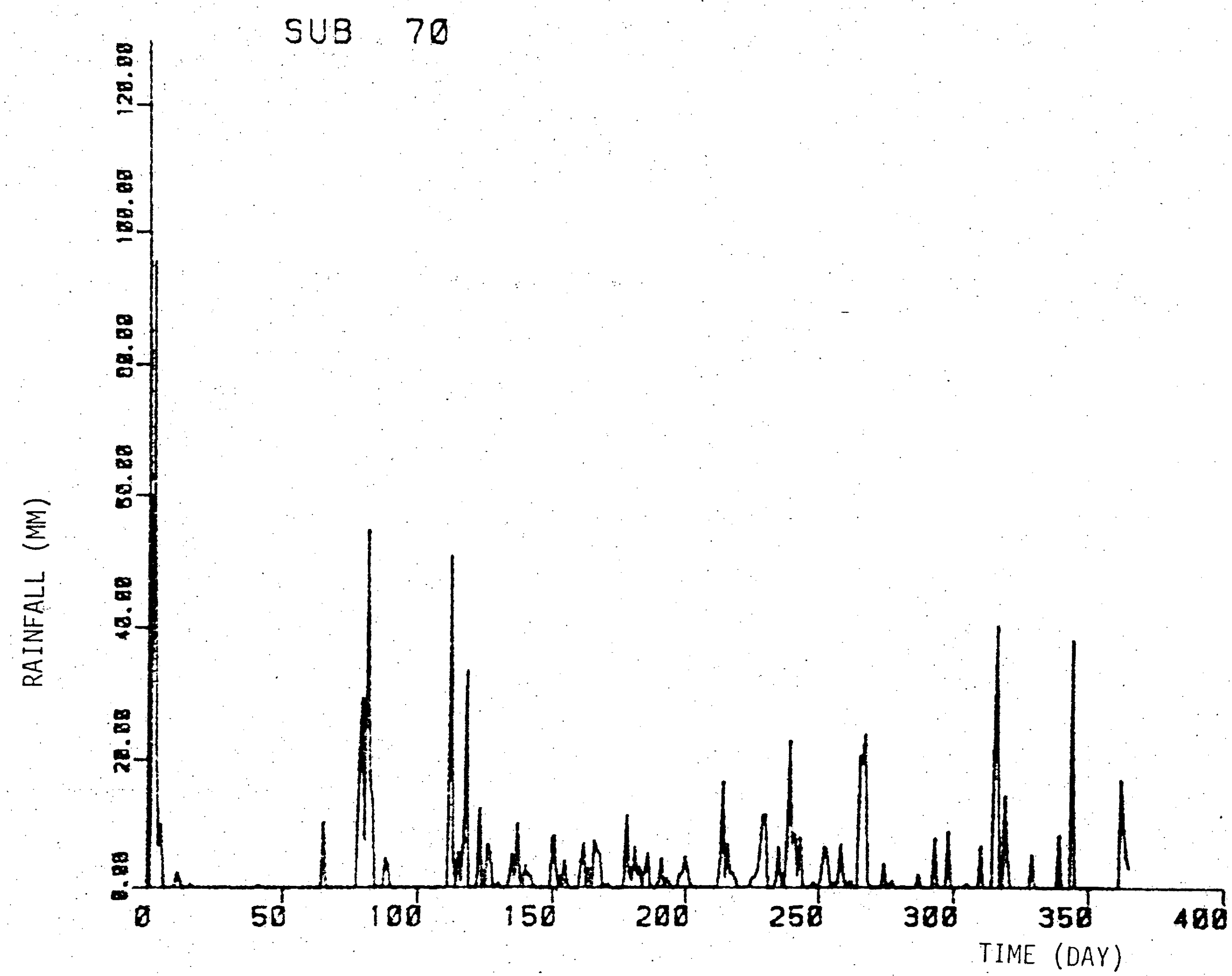


Fig 5.103 Modified Input SUB 70

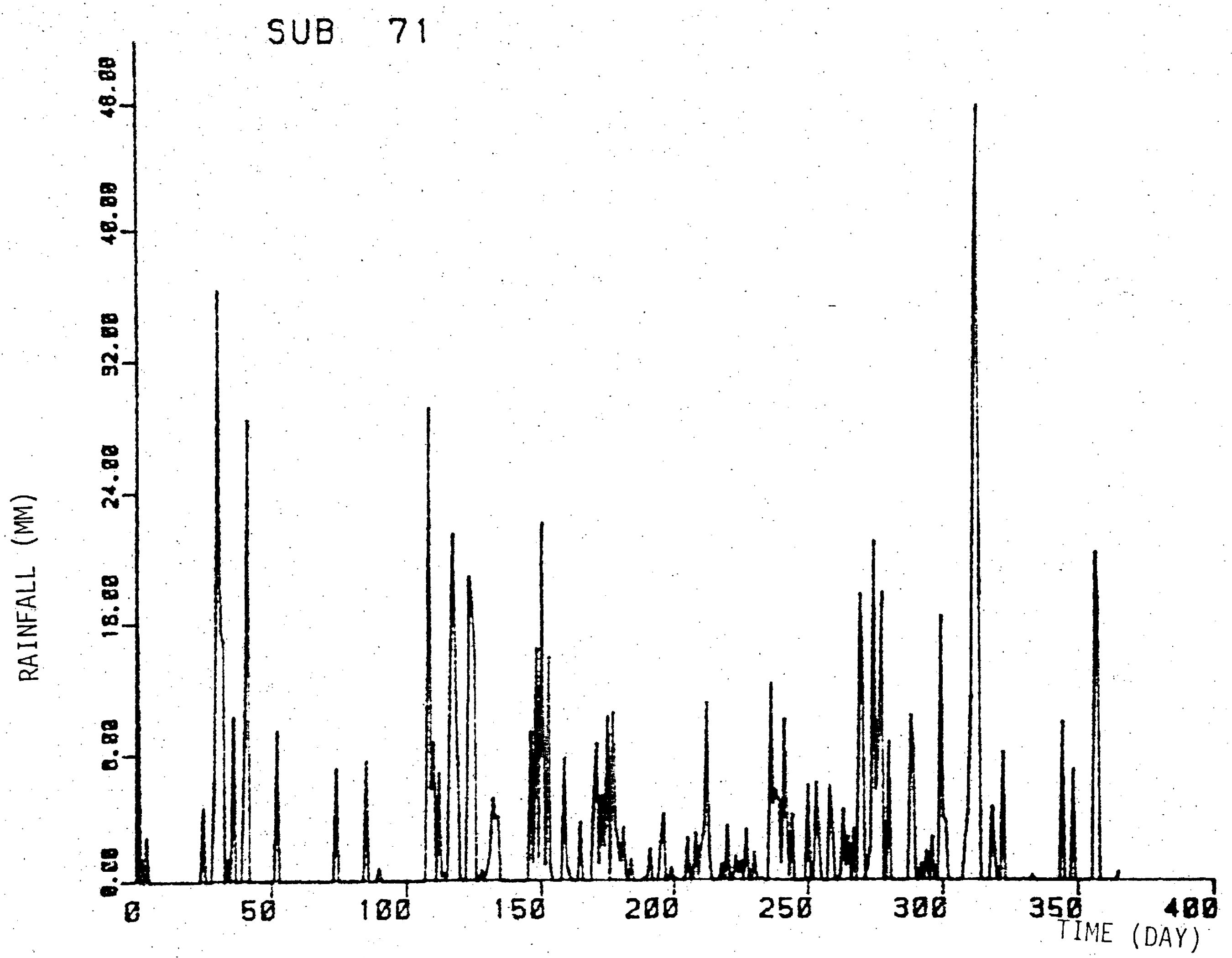


Fig 5.104 Modified Input SUB 71

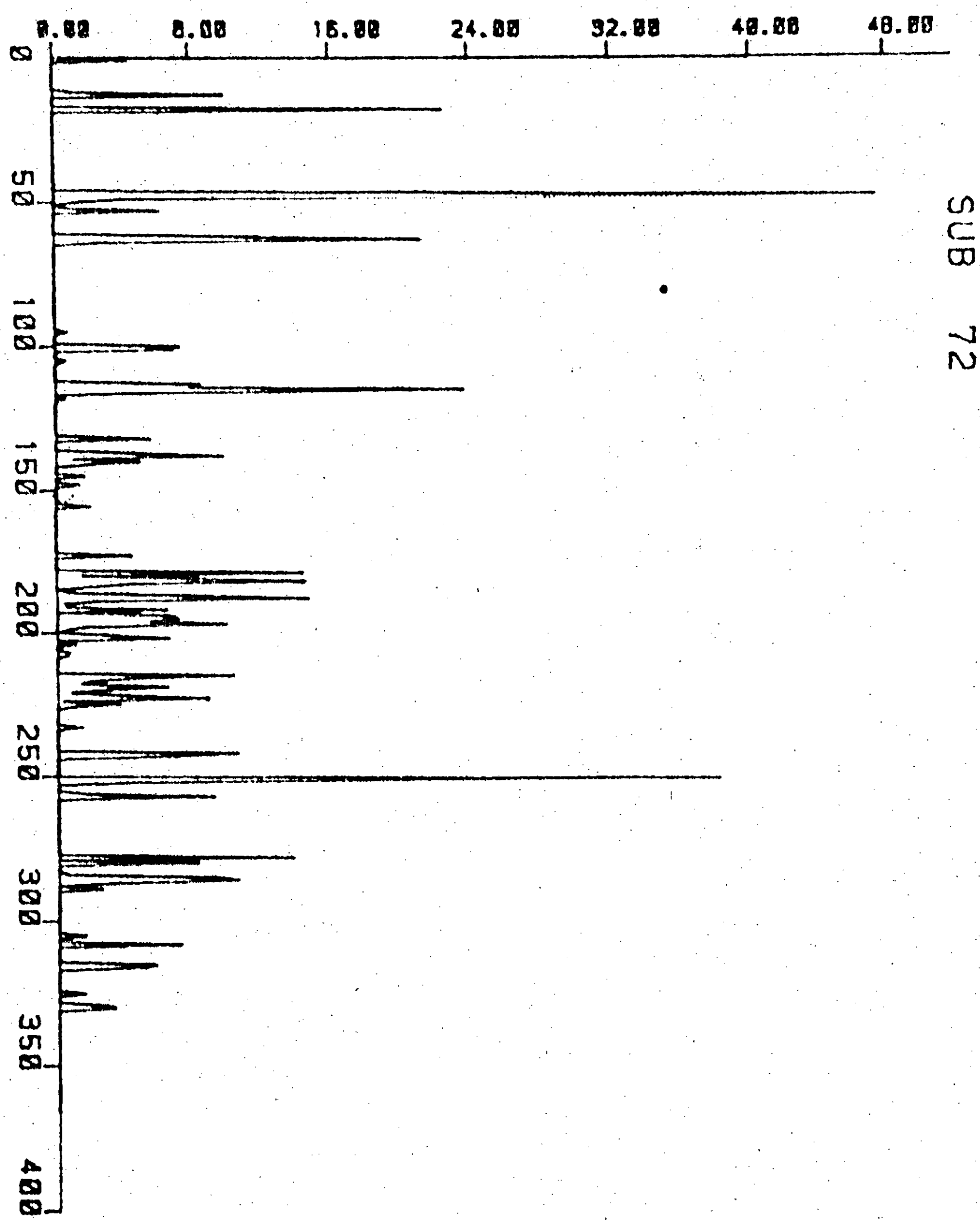


Fig 5.105 Modified Input SUB 72

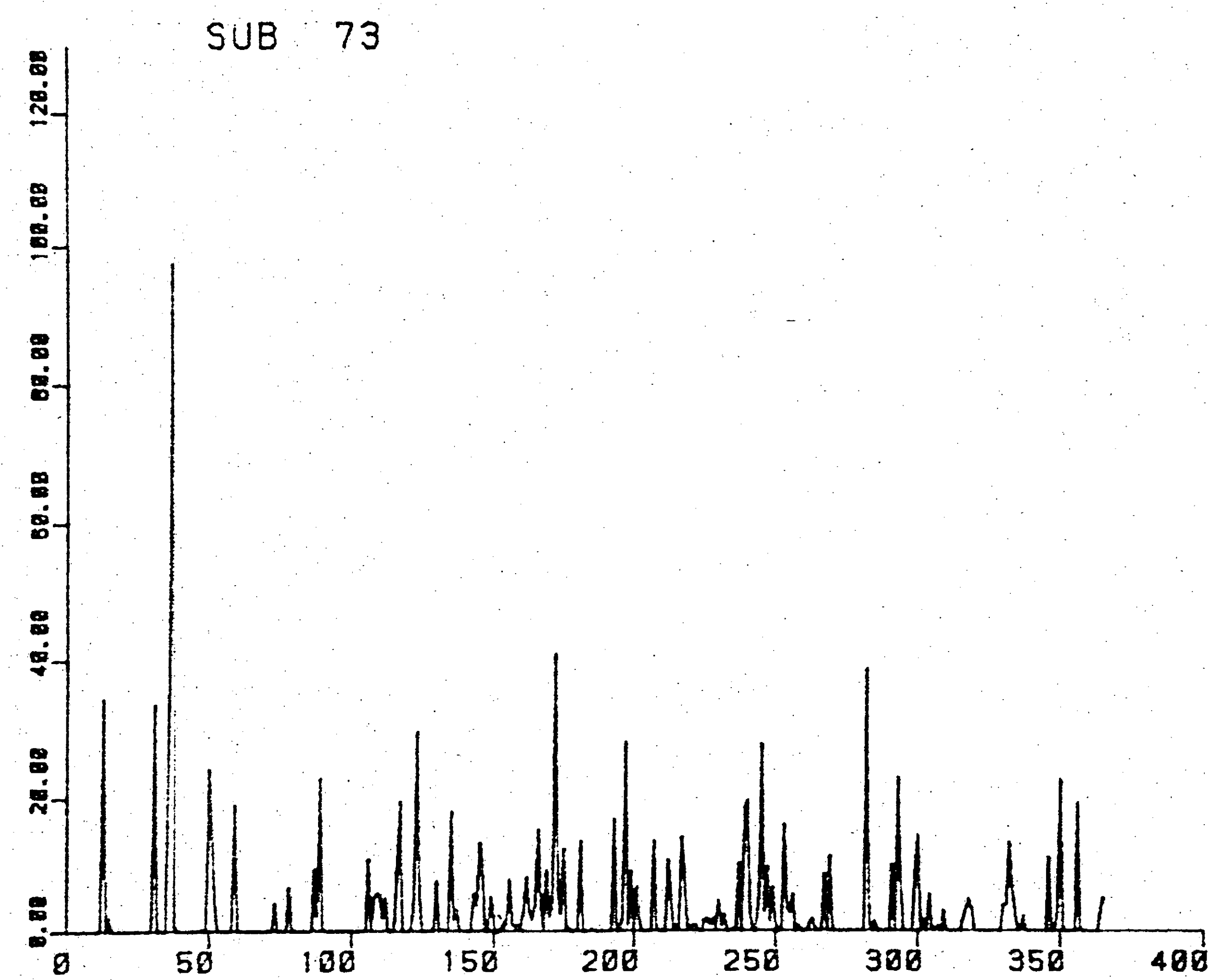


Fig 5.106 Modified Input SUB 73

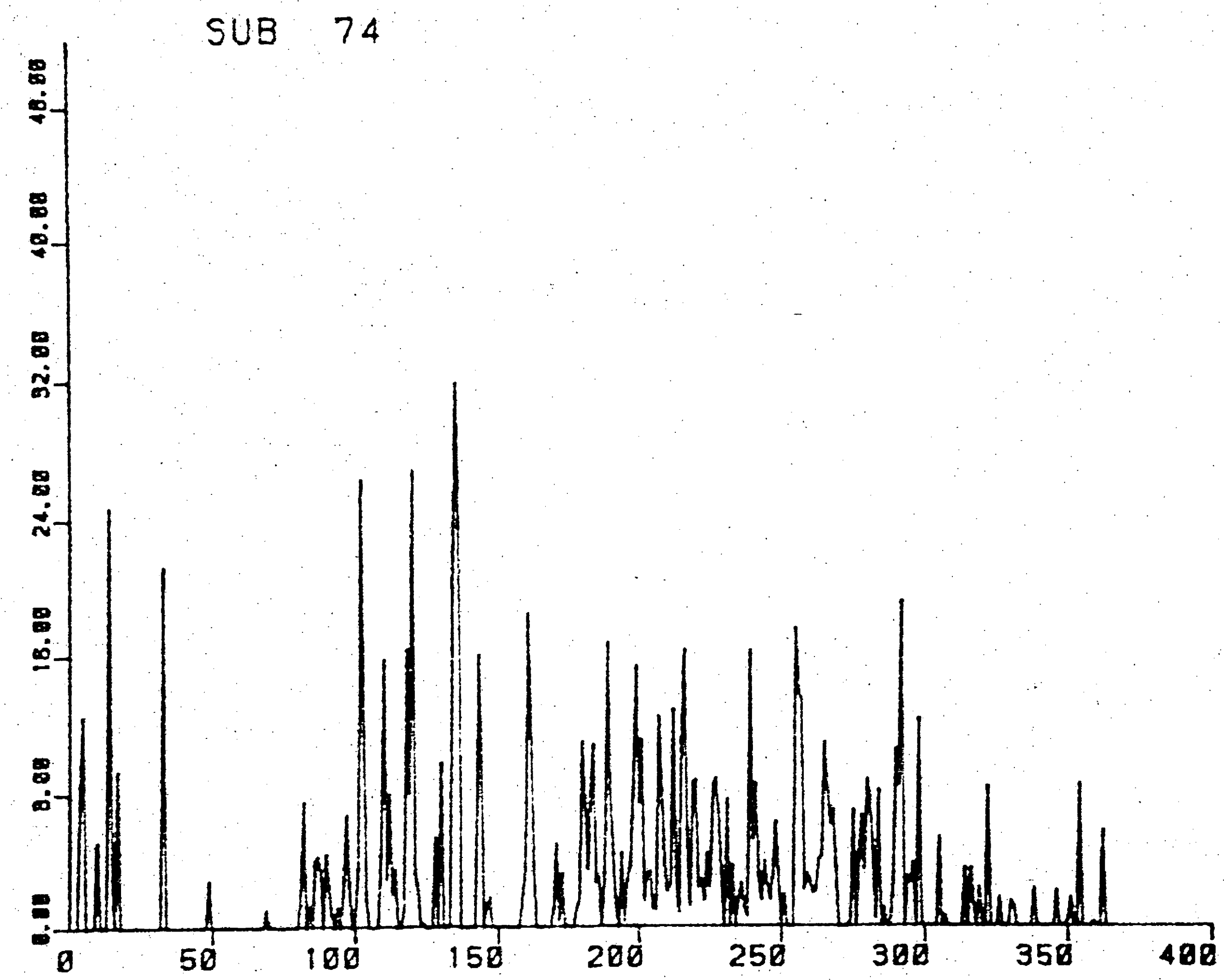


Fig 5.107 Modified Input SUB 74

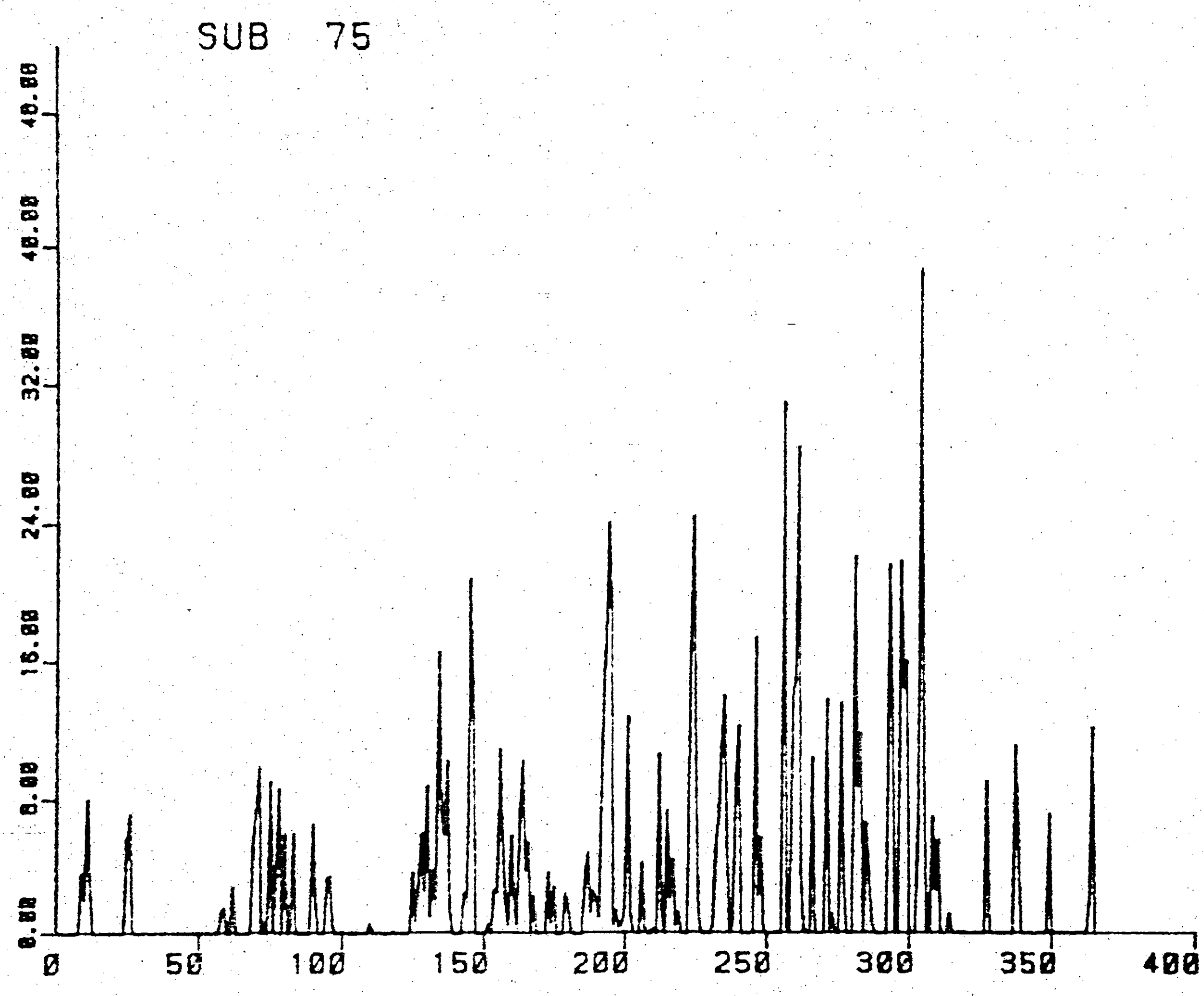


Fig 5.108 Modified Input SUB 75

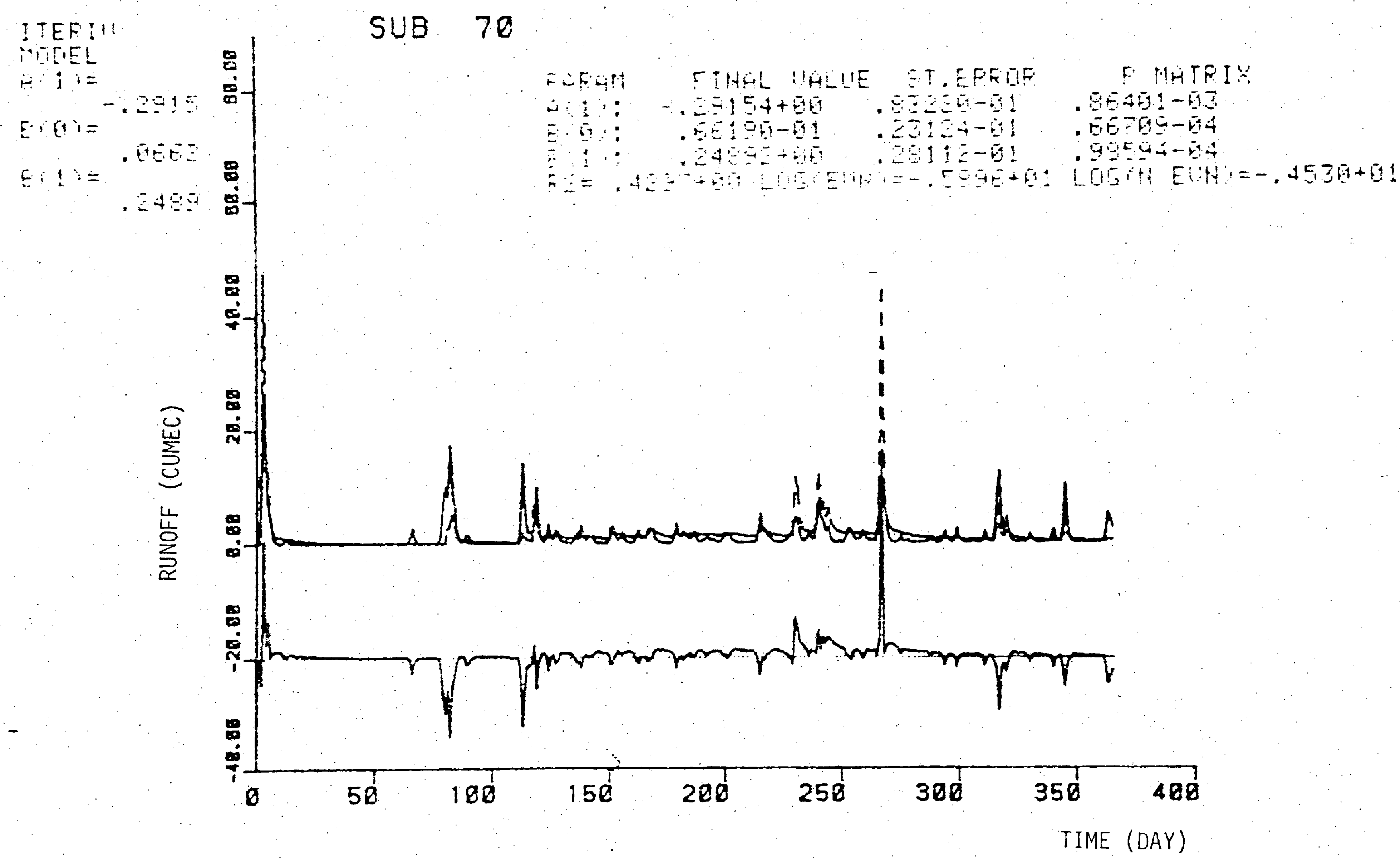


Fig 5.109 Model for Modified Input and Measured Runoff 1970

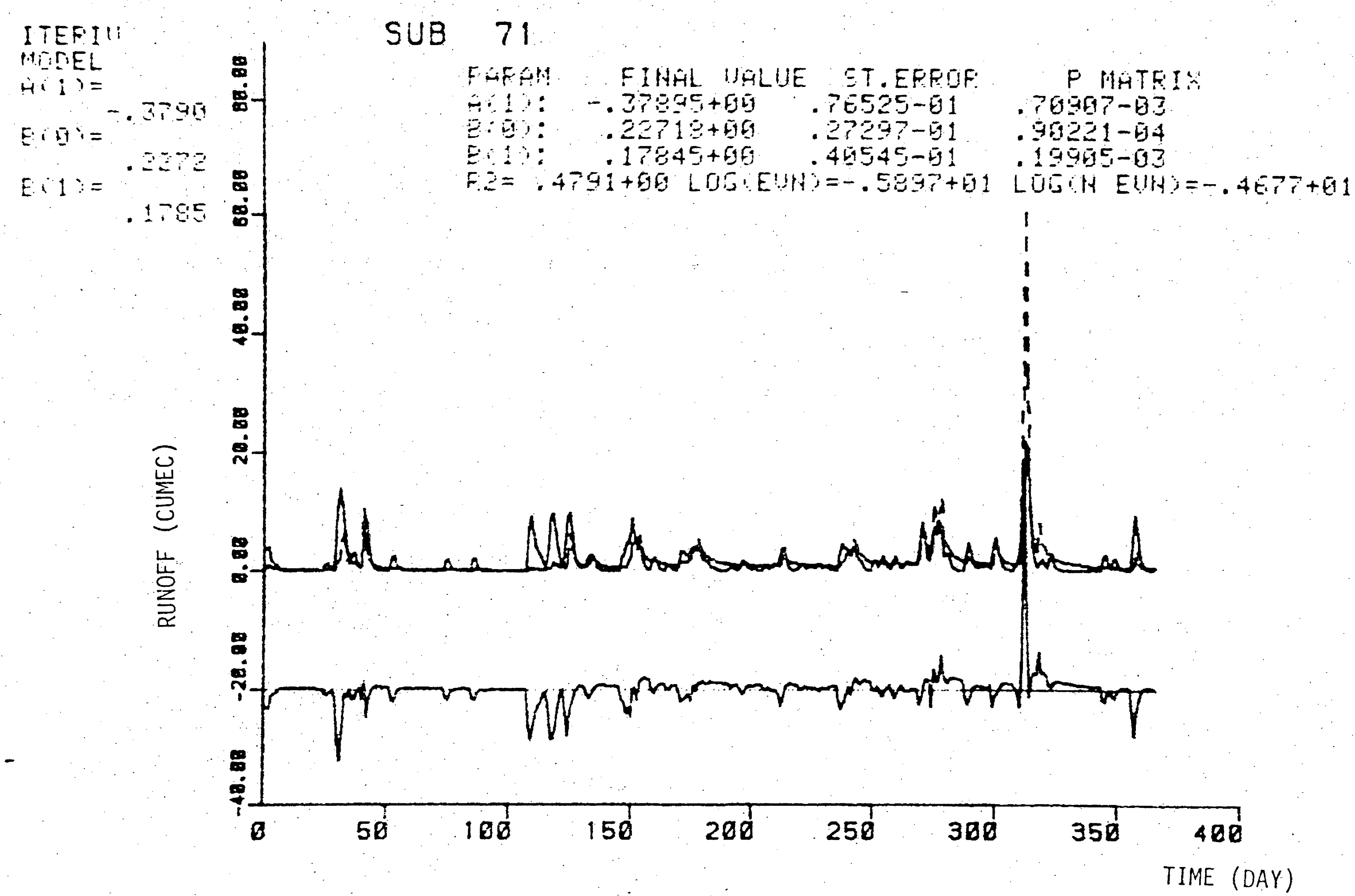


Fig 5.110 Model for Modified Input and Measured Runoff 1971

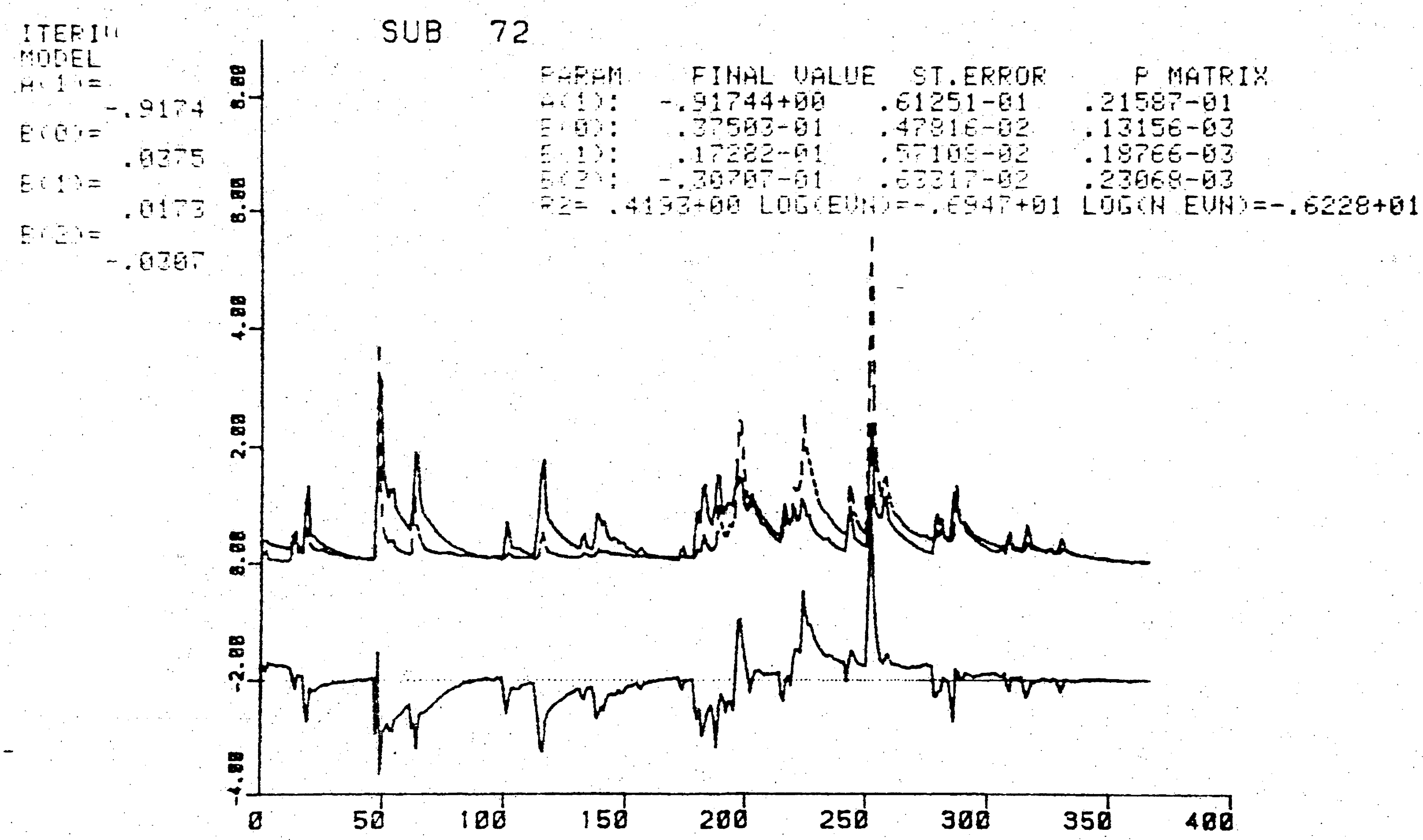


Fig 5.111 Model for Modified Input and Measured Runoff 1972

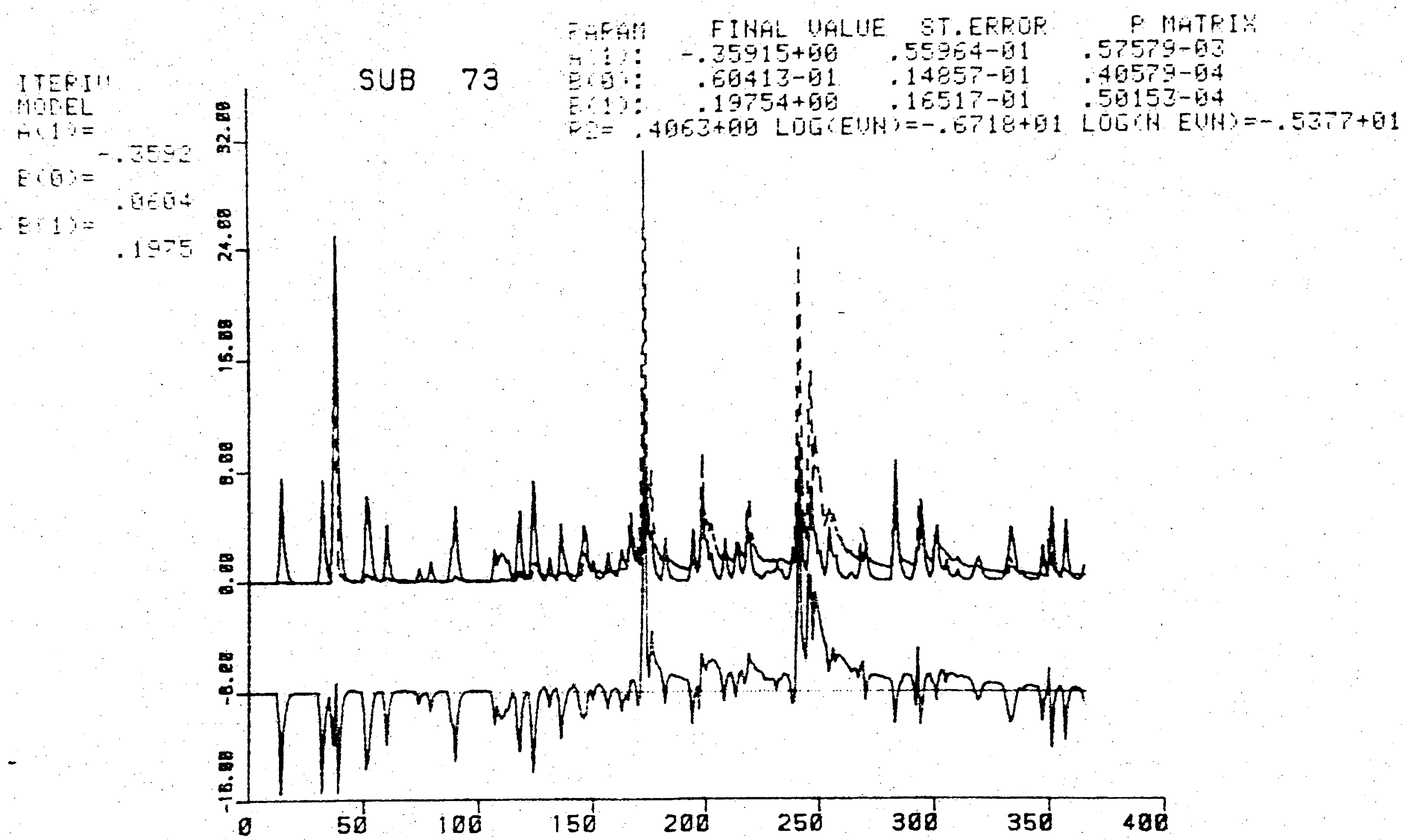


Fig 5.112 Model for Modified Input and Measured Runoff 1973

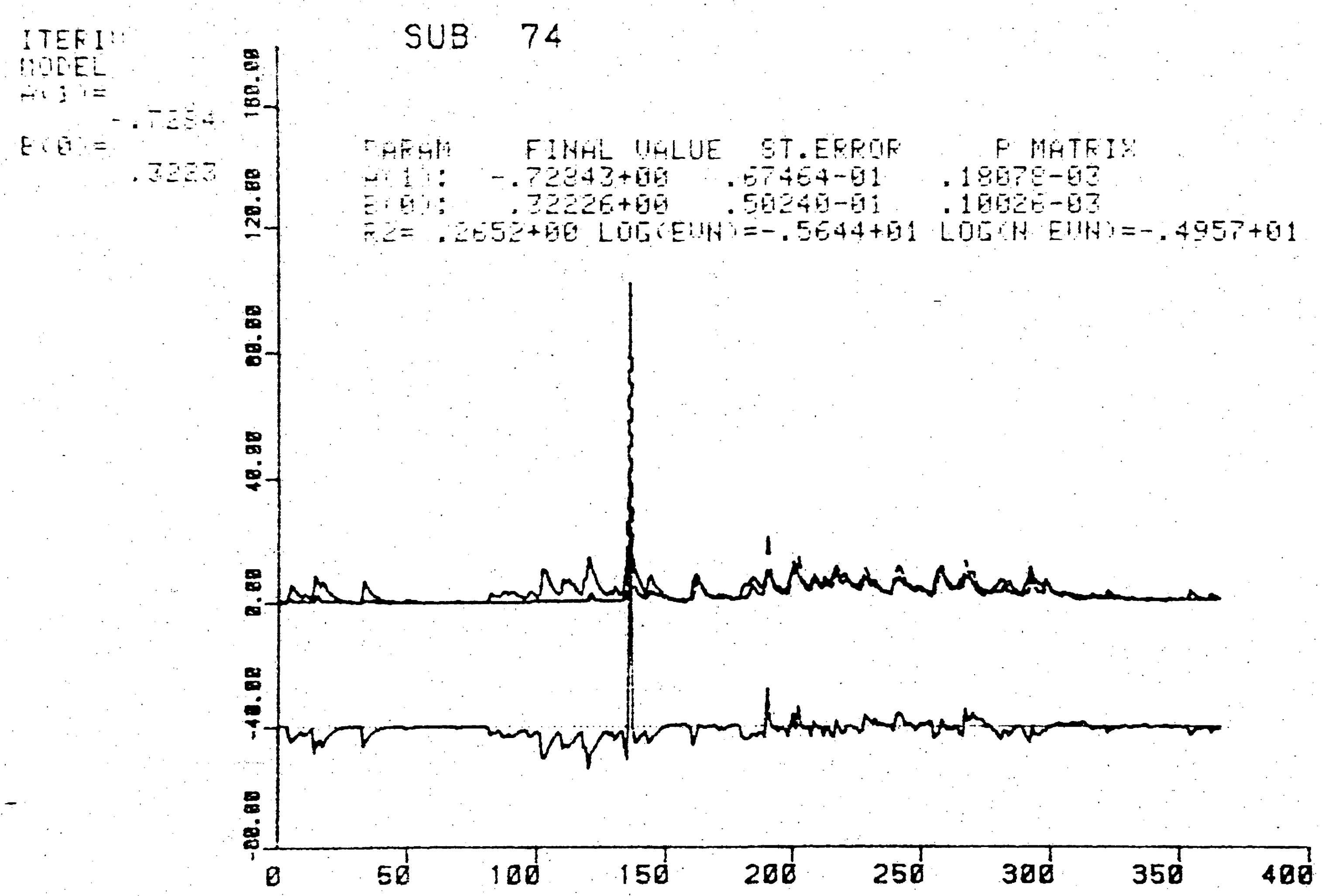


Fig 5.113 Model for Modified Input and Measure Runoff 1974

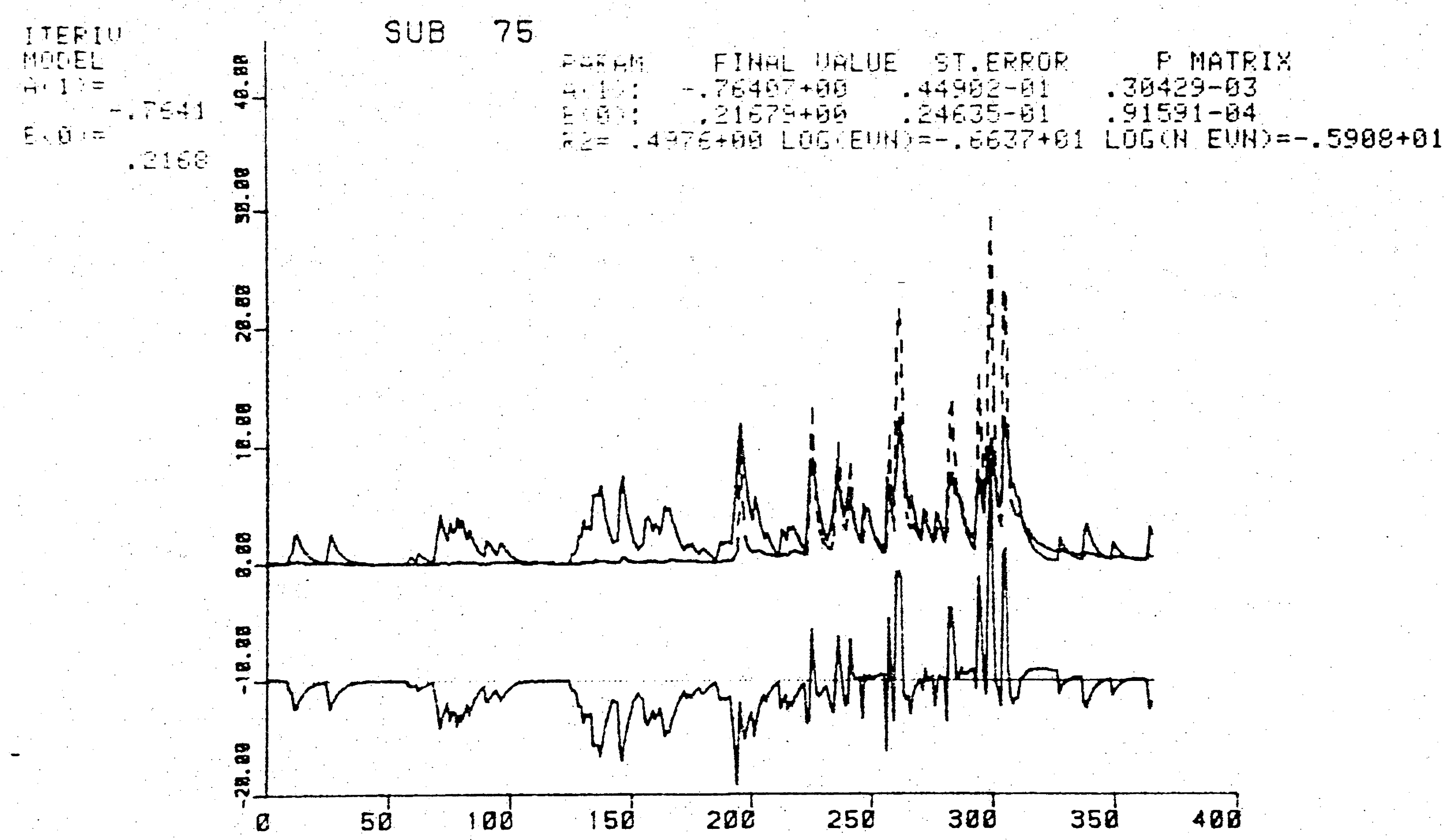


Fig 5.114 Model for Modified Input and Measure Runoff 1975

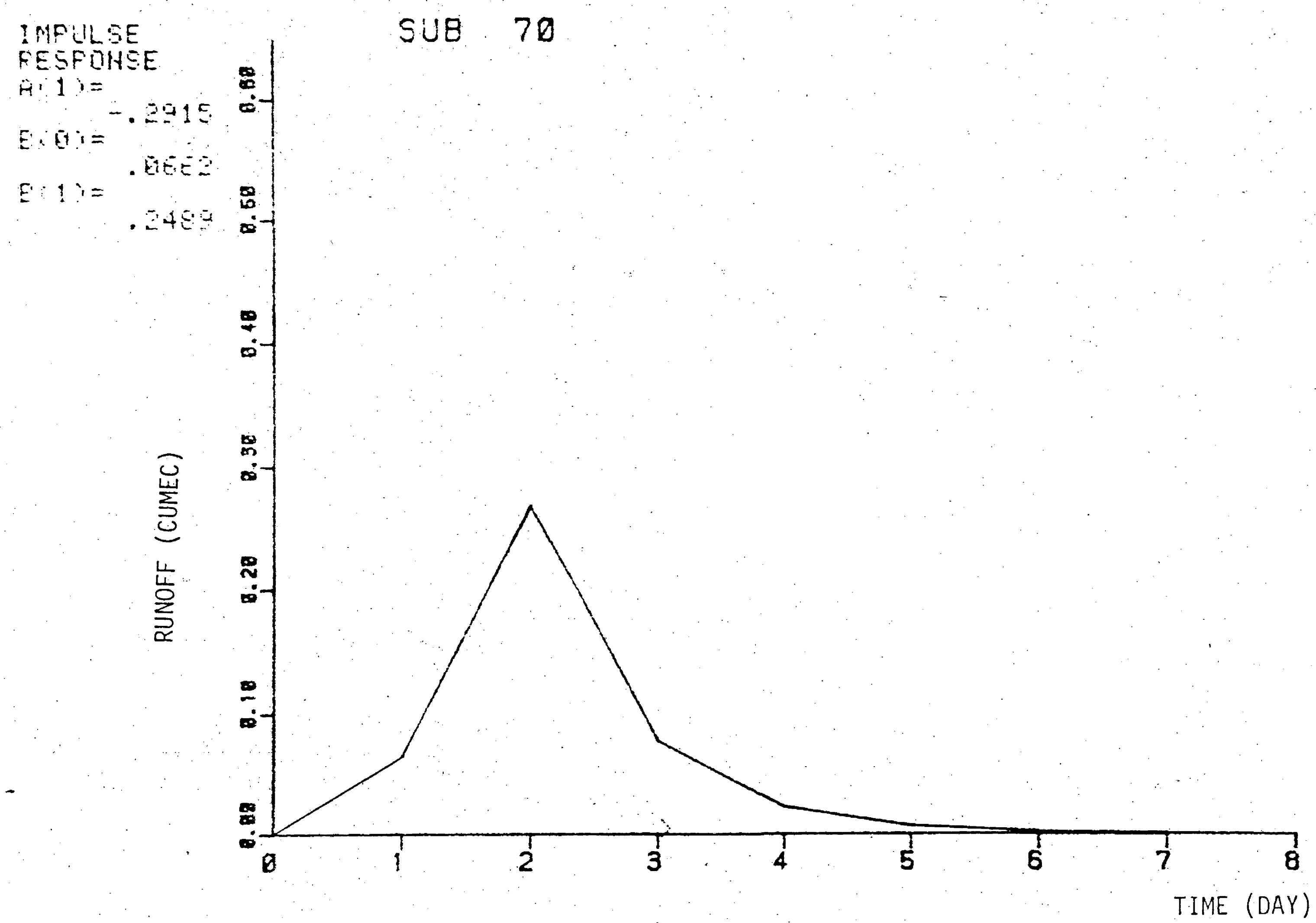


Fig 5.115 Impulse Response for Model Fig 5.109

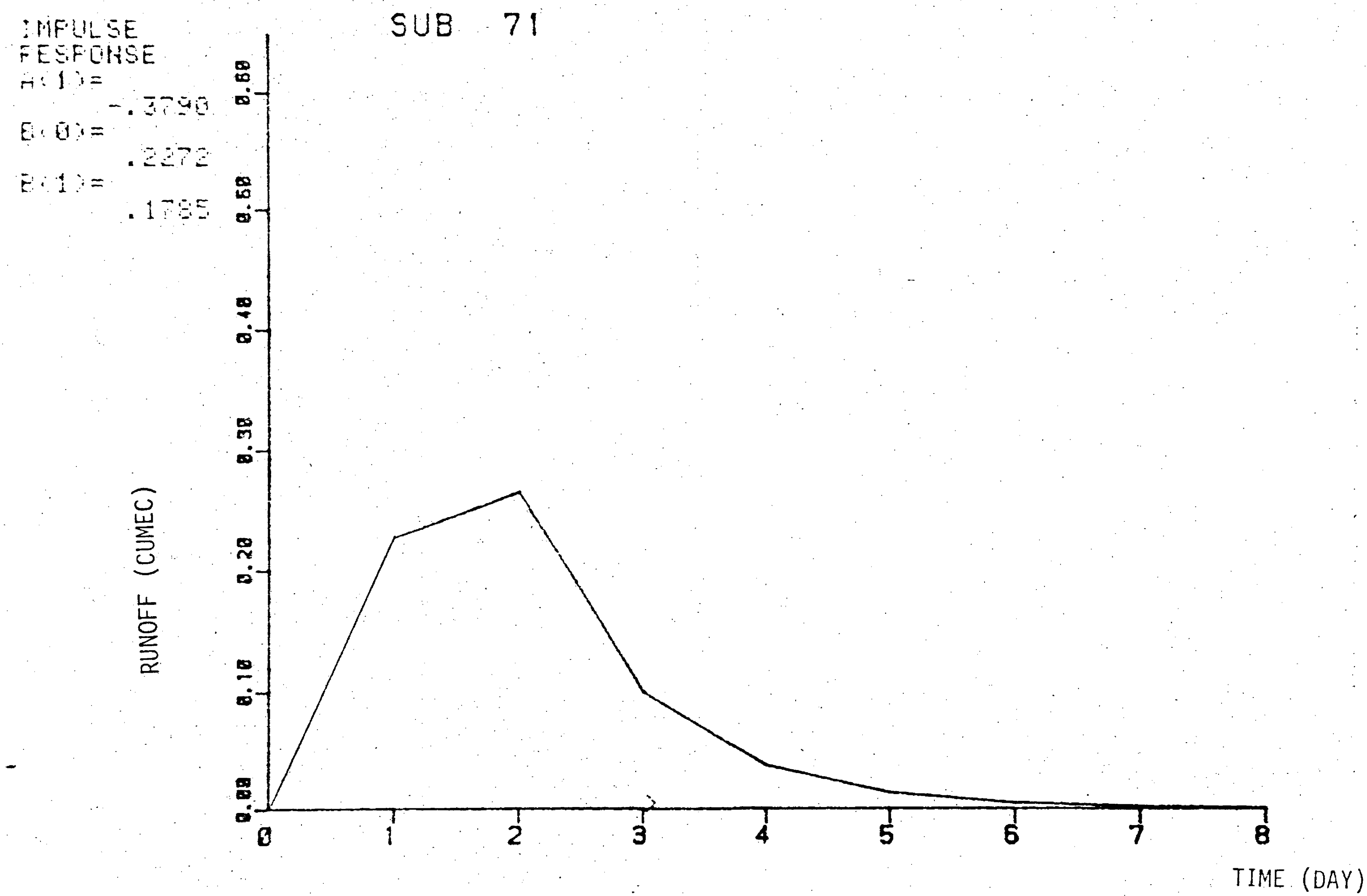


Fig 5.116 Impulse Response for Model Fig 5.110

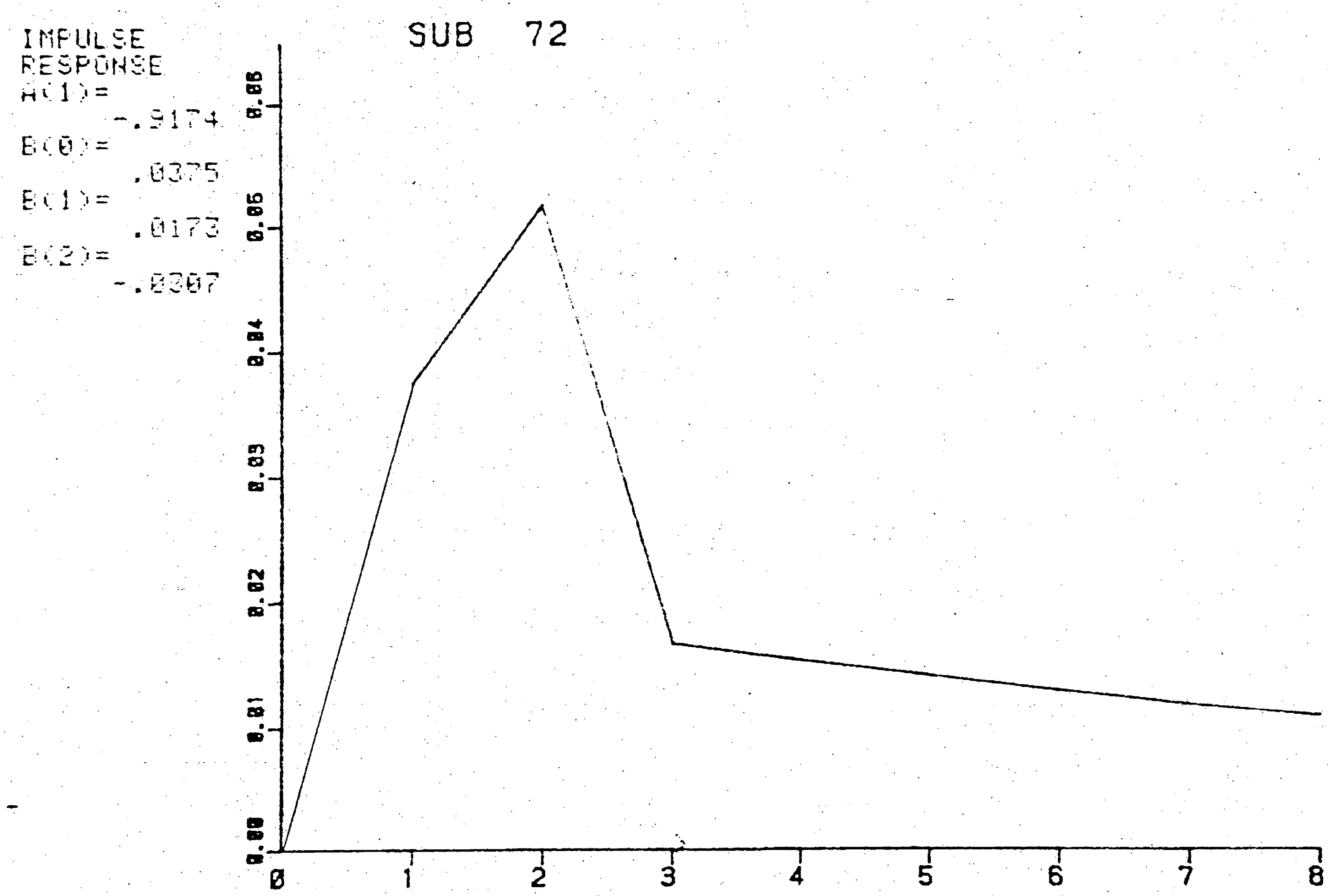


Fig 5.117 Impulse Response for Model Fig 5.111

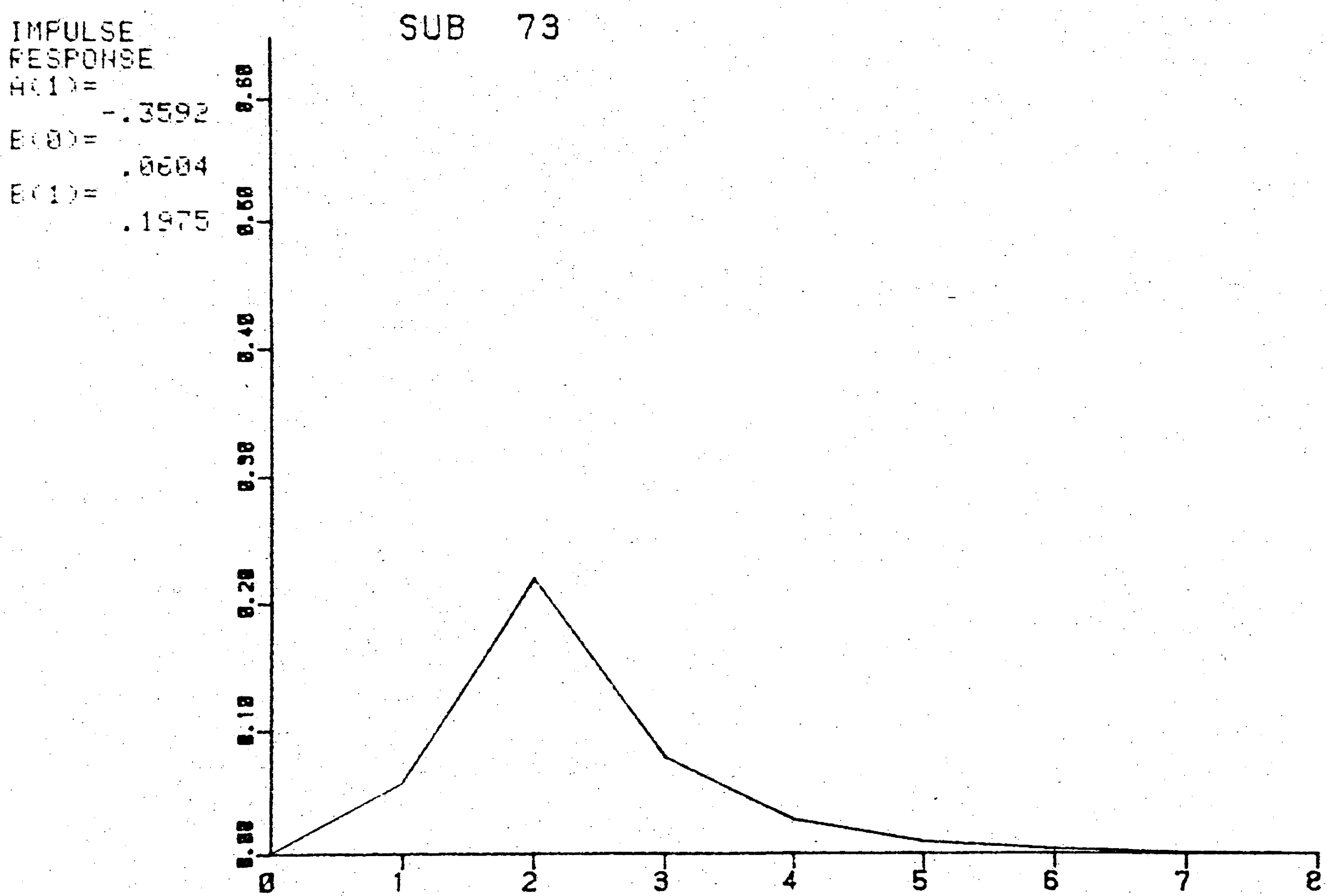


Fig 5.118 Impulse Response for Model Fig 5.112

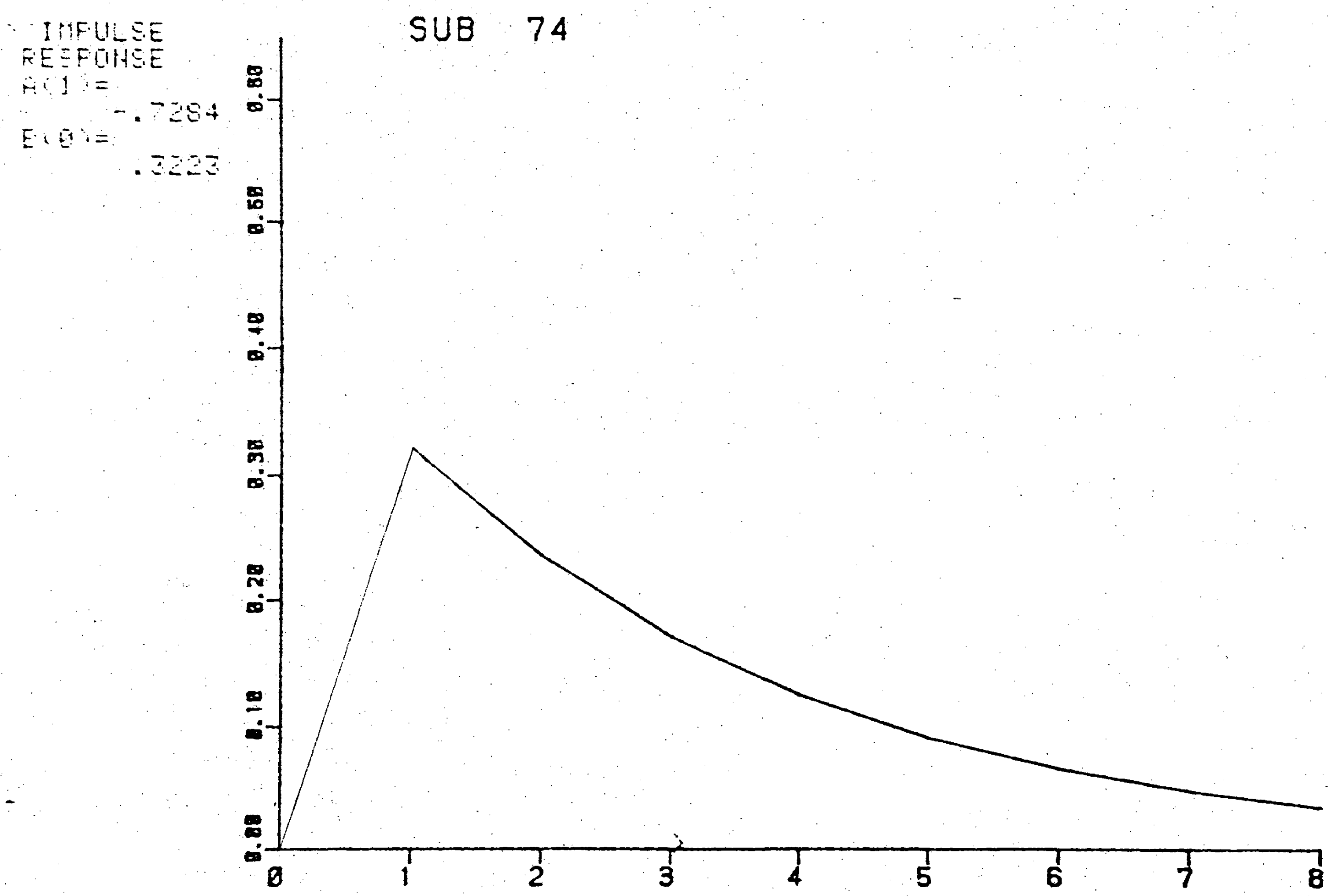


Fig 5.119 Impulse Response for Model Fig 5.113

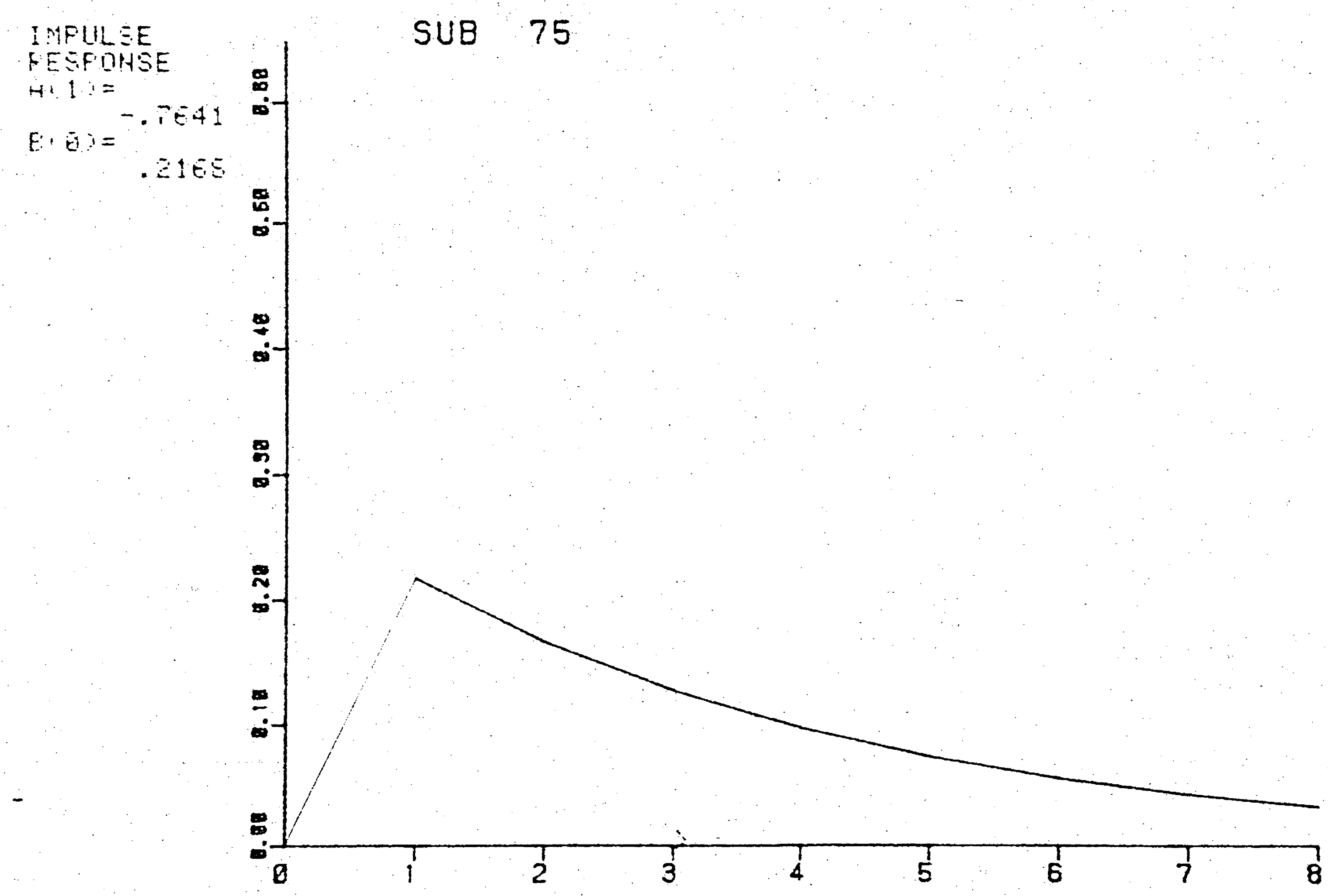


Fig 5.120 Impulse Response for Model Fig 5.114

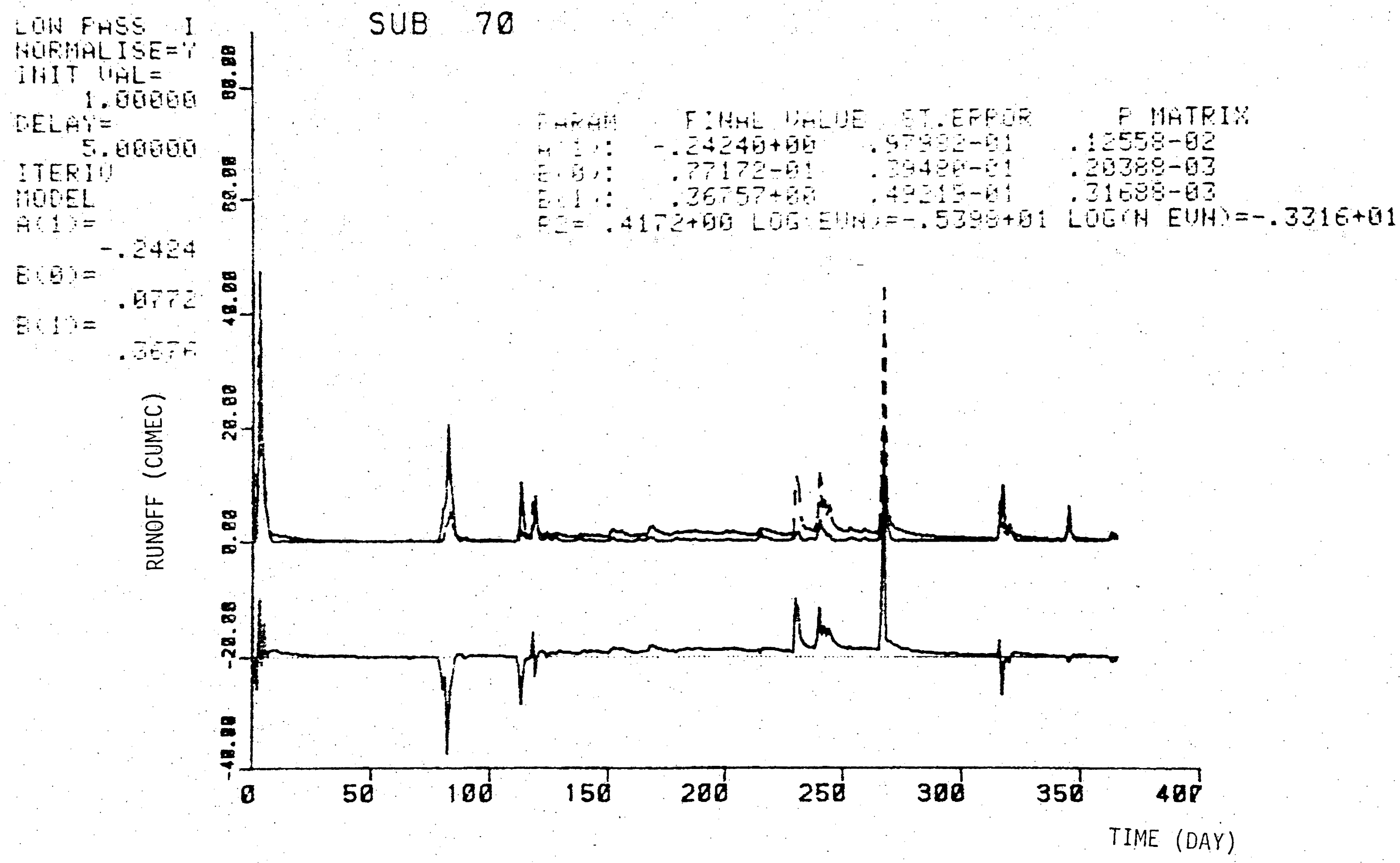


Fig 5.121 Model Fig 5.109 allowing T_s of 5 day

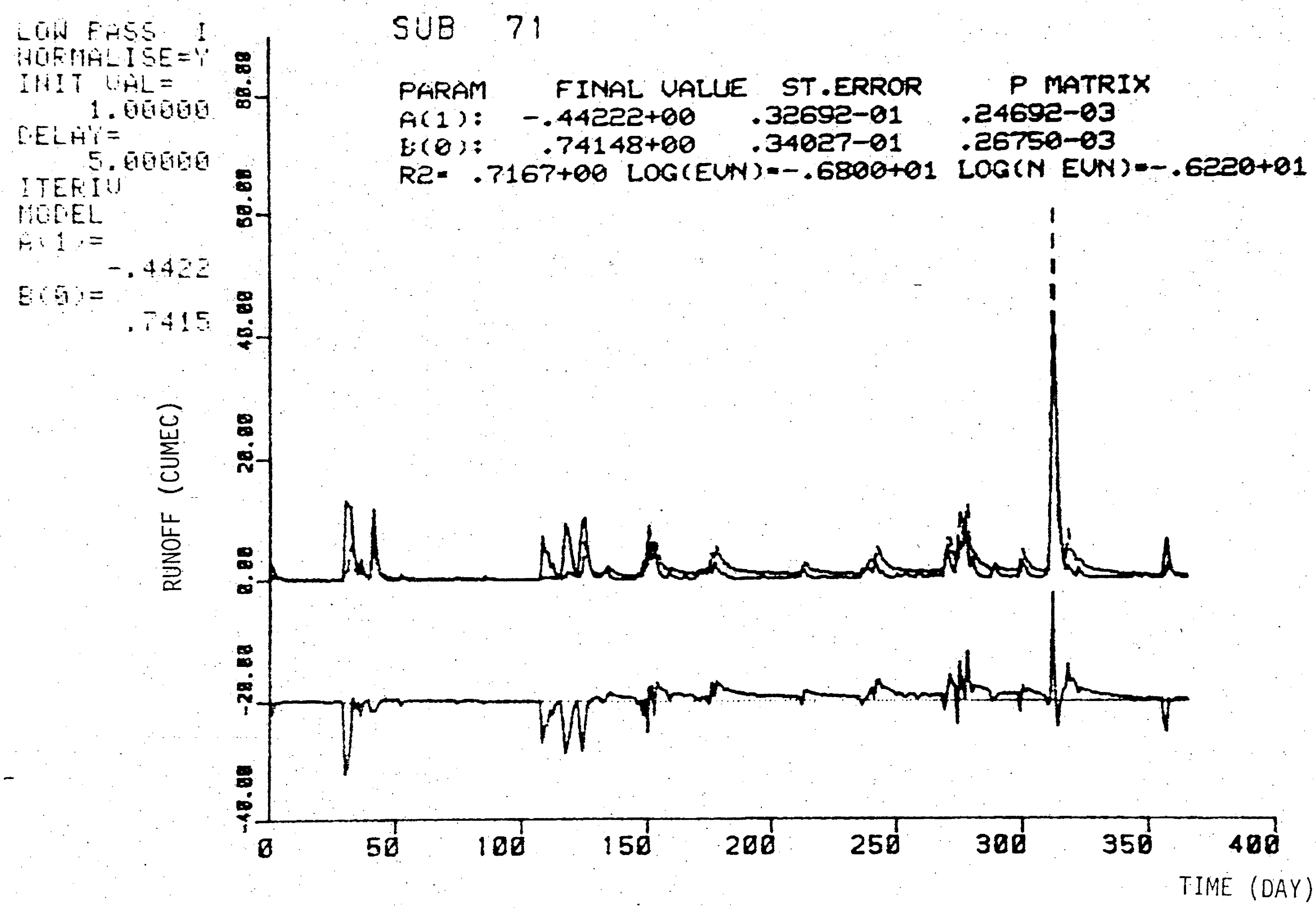


Fig 5.122 Model Fig 5.110 allowing T_S of 5 day

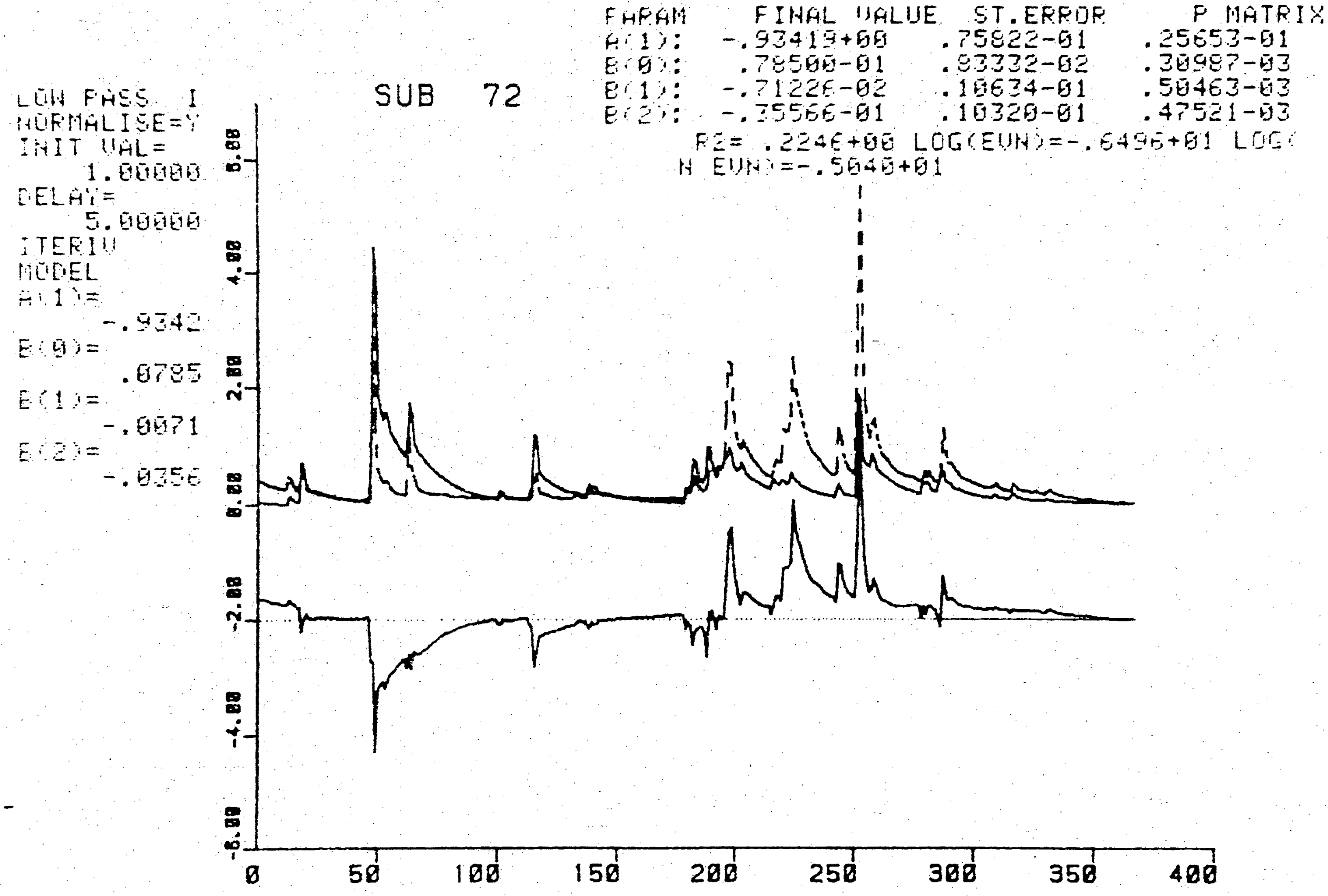


Fig 5.123 Model Fig 5.111 allowing T_s of 5 days

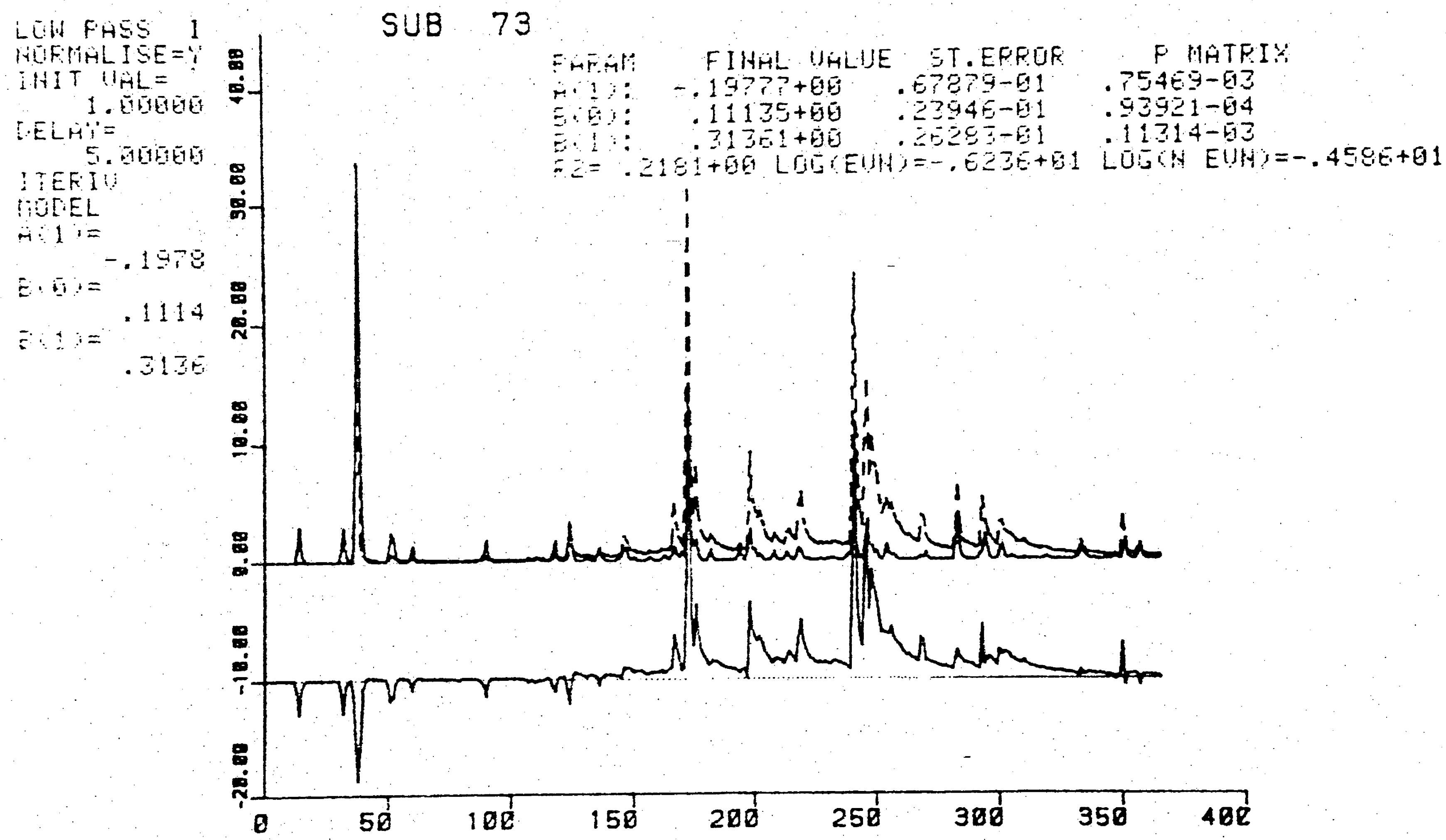


Fig 5.124 Model Fig 5.112 allowing T_s of 5 days

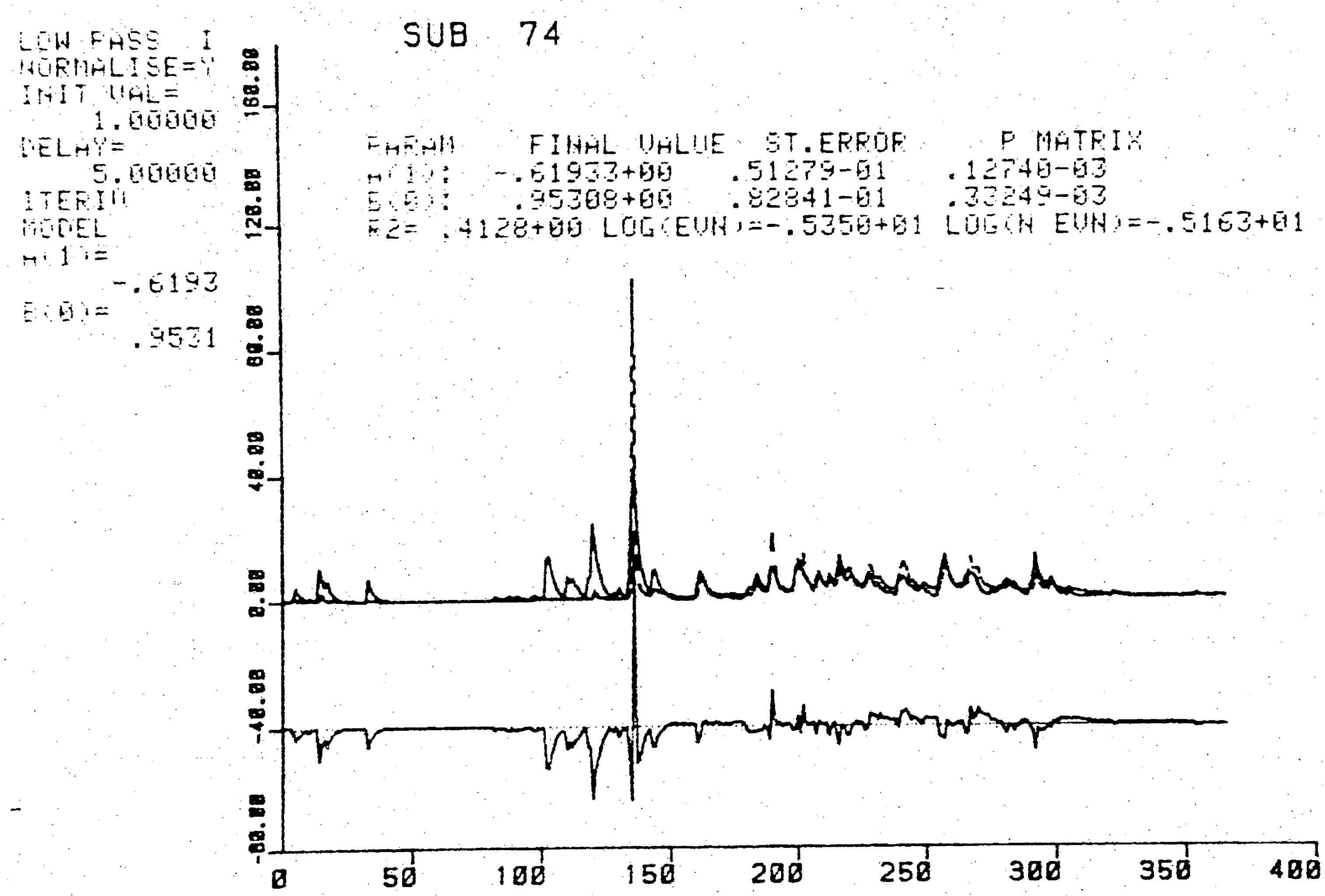


Fig 5.125 Model Fig 5.113 allowing T_s of 5 days

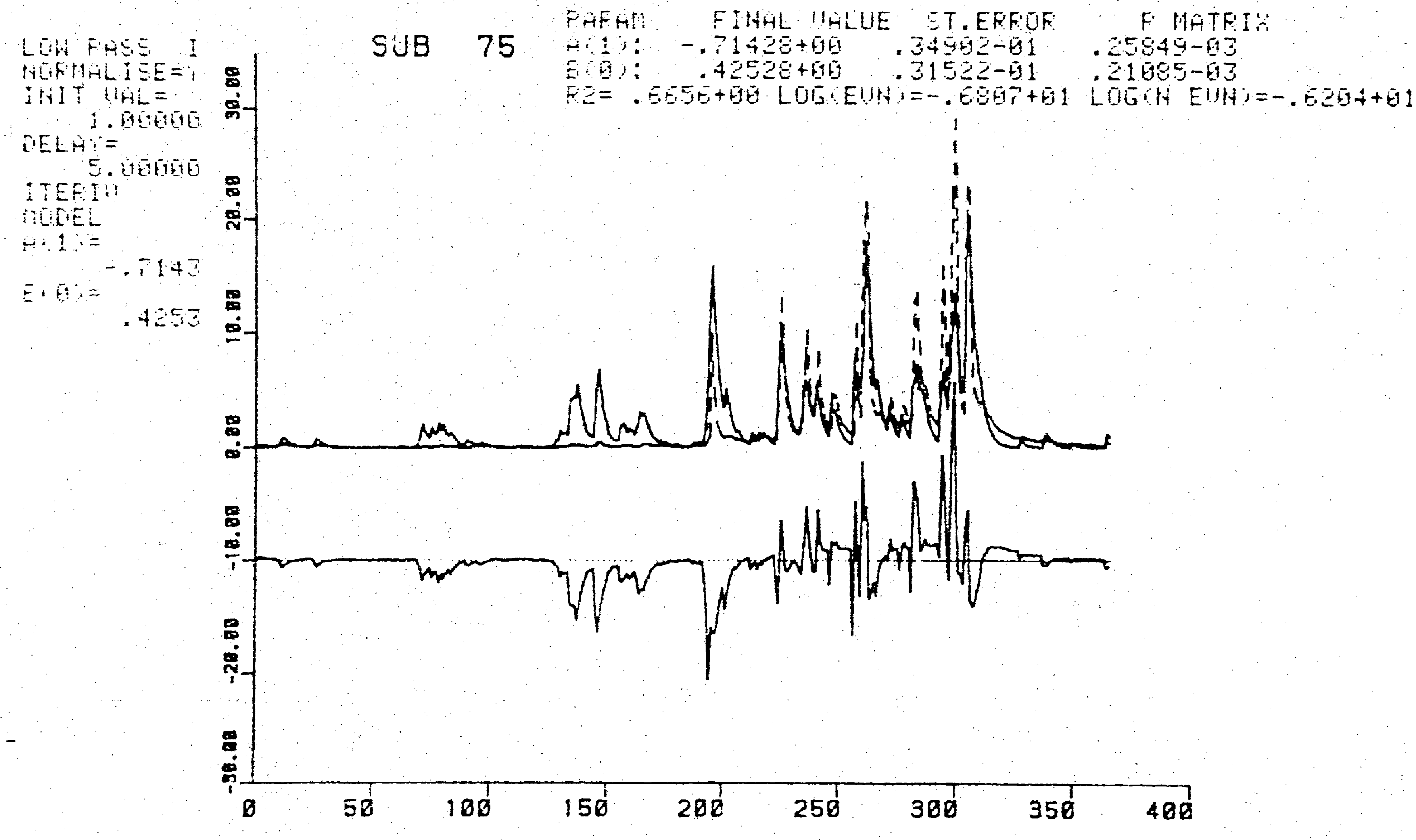


Fig 5.126 Model Fig 5.114 allowing T_s of 5 days

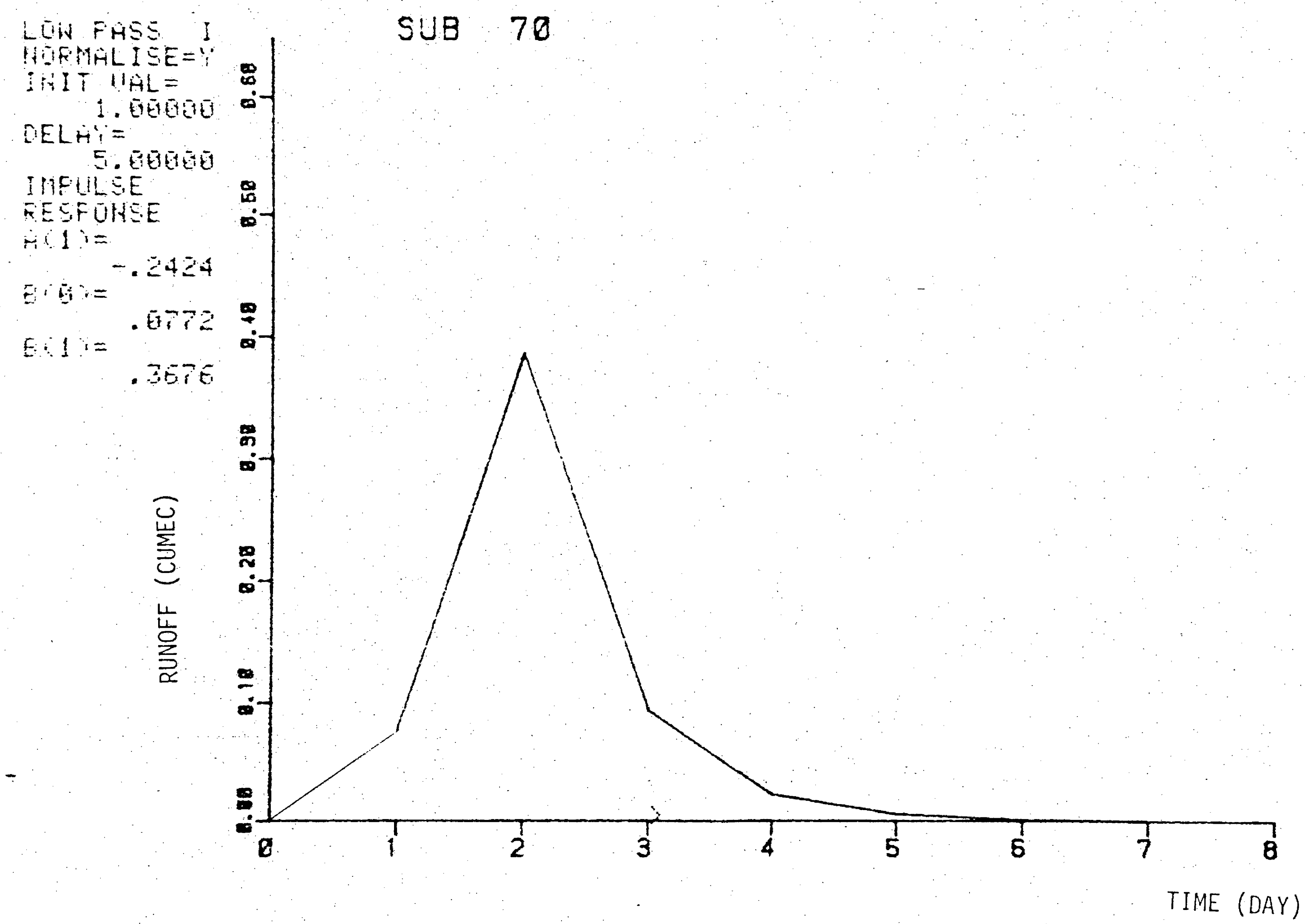


Fig 5.127 Impulse Response for Model Fig 5.121

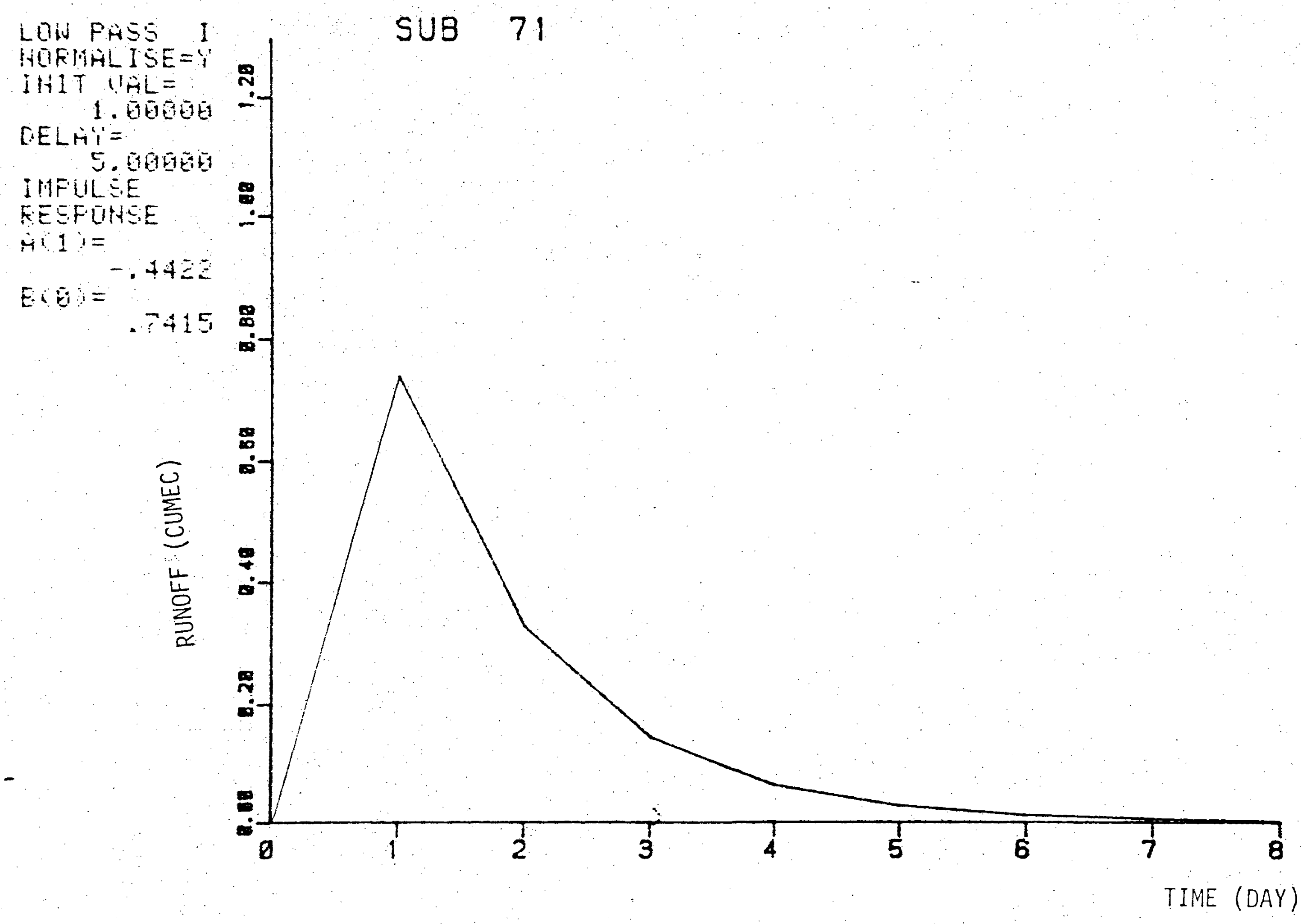


Fig 5.128 Impulse Response for Model Fig 5.122

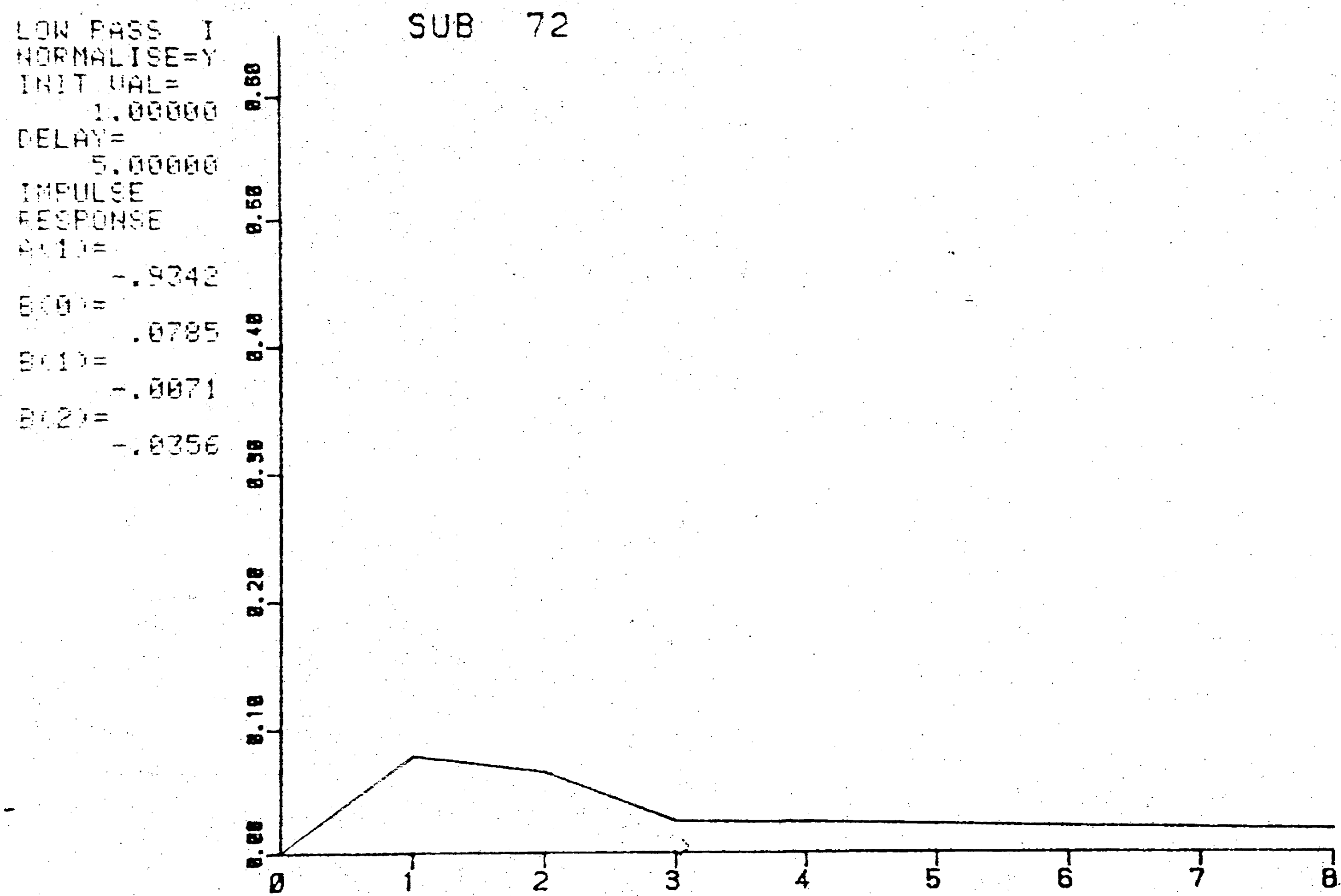


Fig 5.129 Impulse Response for Model Fig 5.123

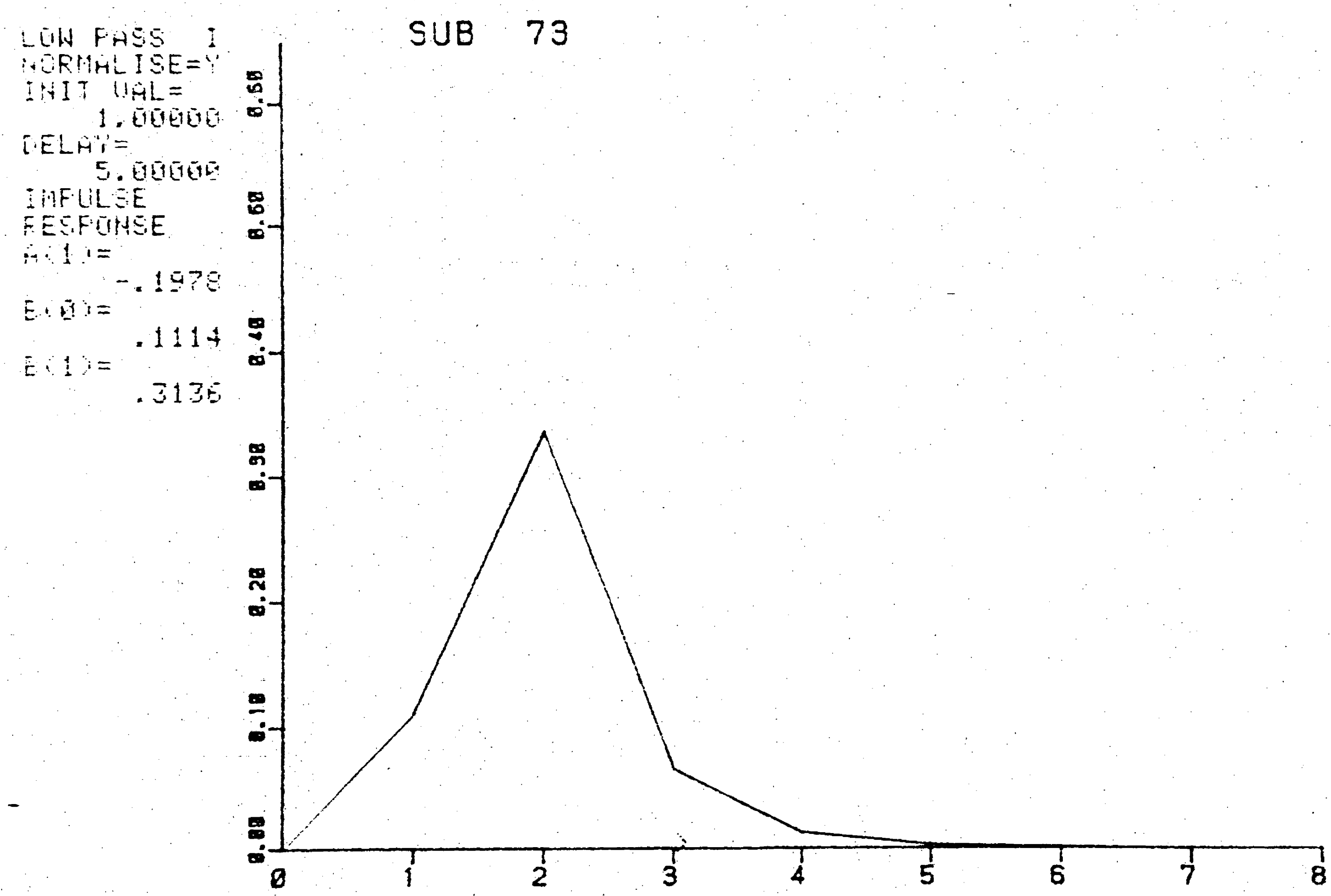


Fig 5.130 Impulse Response for Model Fig 5.124

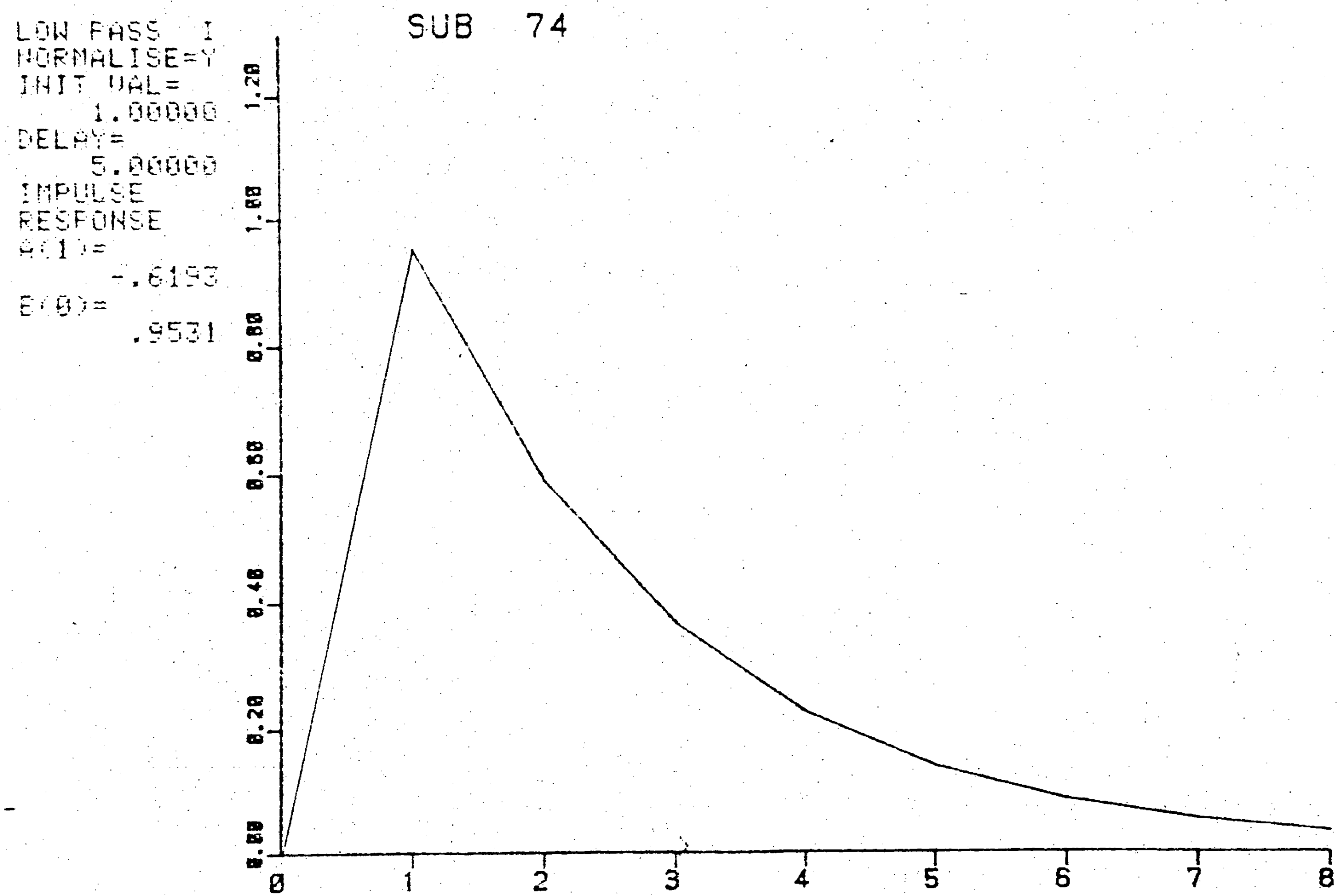


Fig 5.131 Impulse Response for Model Fig 5.125

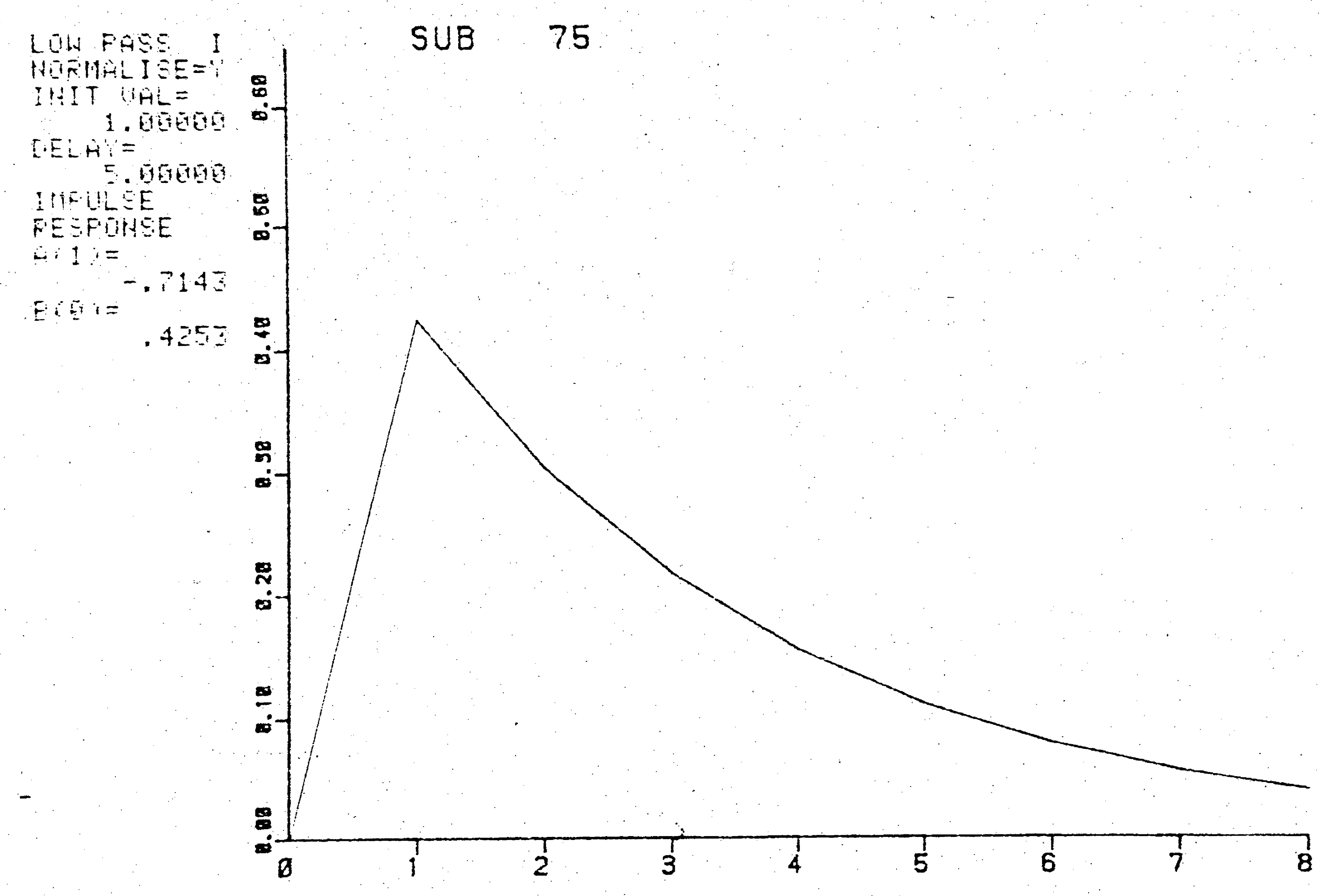


Fig 5. 132 Impulse Response for Model Fig 5.126

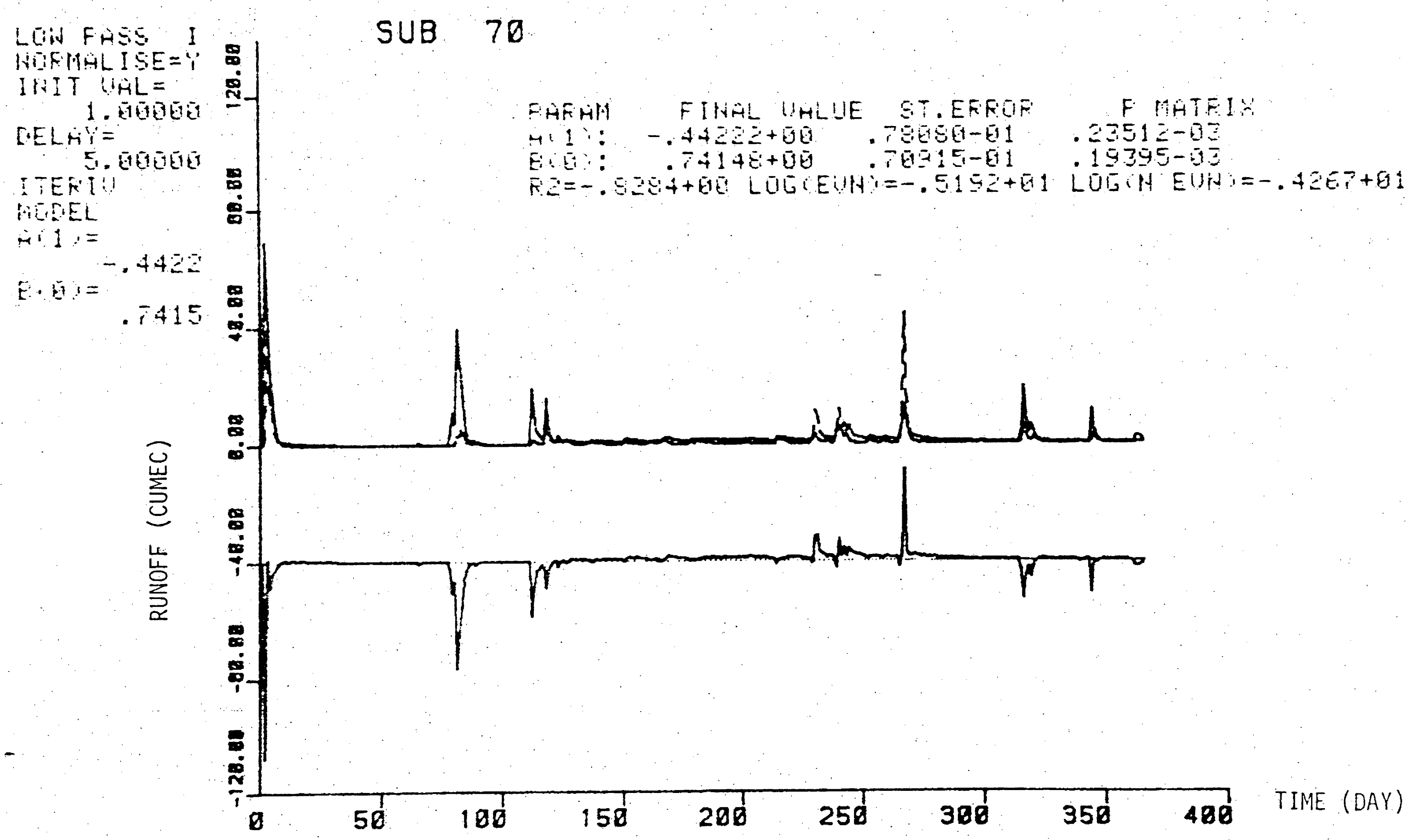


Fig 5.133 1970 Model response with parameter values set to those estimated for 1971 (Fig 5.122)

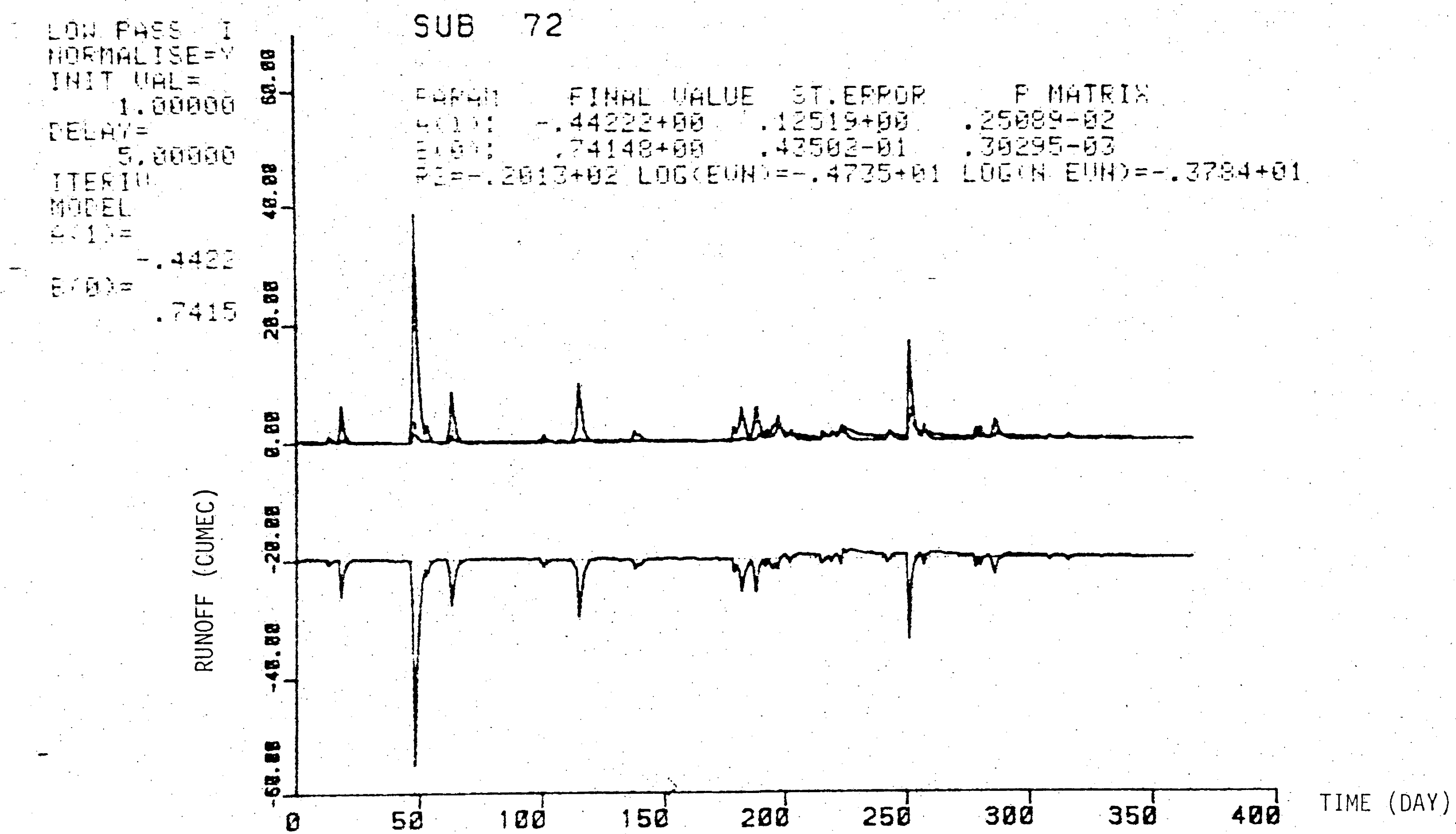


Fig 5.134 1972 Model response with parameter values set to those estimated for 1971 (Fig 5.122)

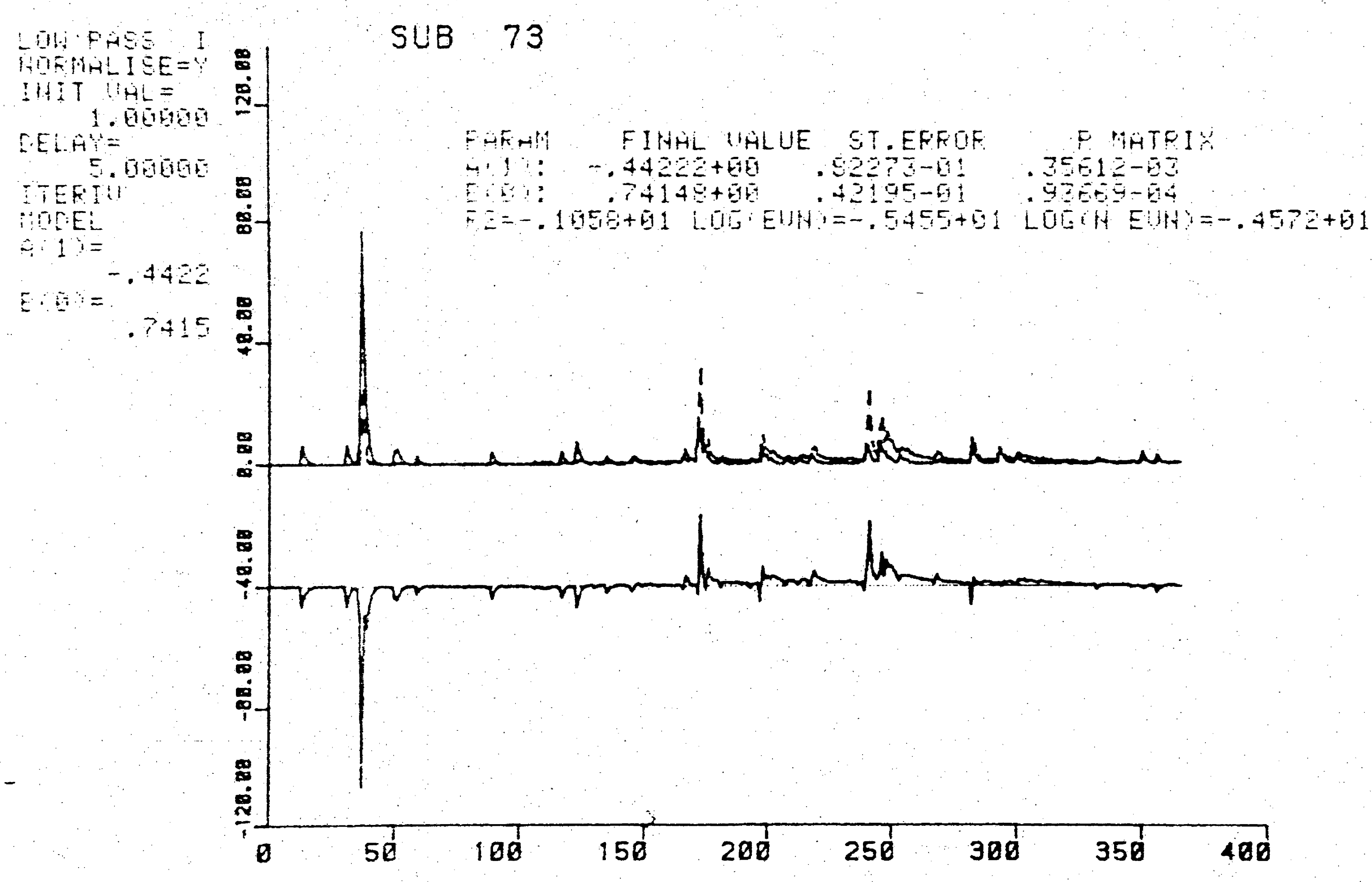


Fig 5.135 1973 Model response with parameter values set to those estimated for 1971 (Fig 5.122)

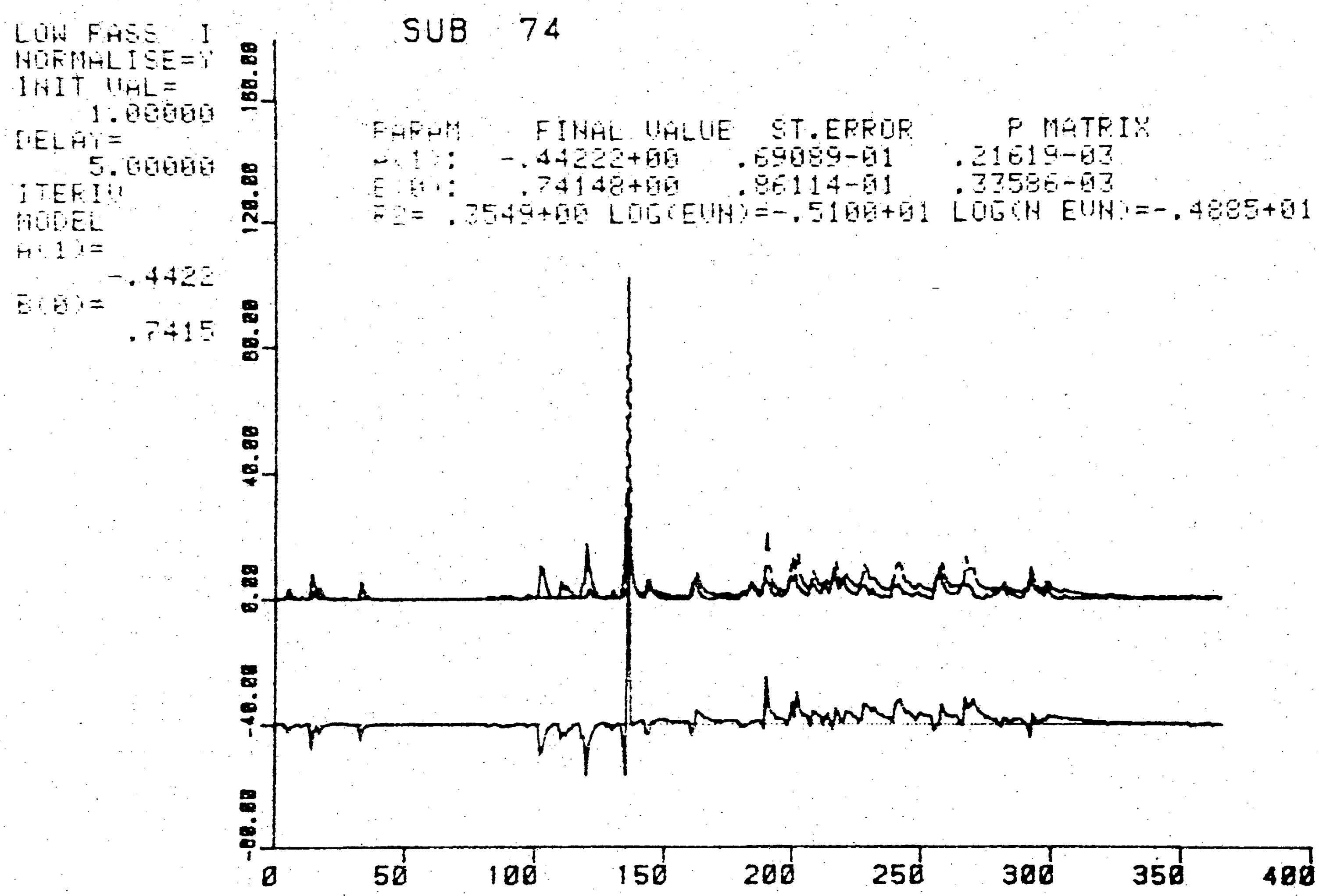


Fig 5.136 1974 Model response with parameter values set to those estimated for 1971 (Fig 5.122)

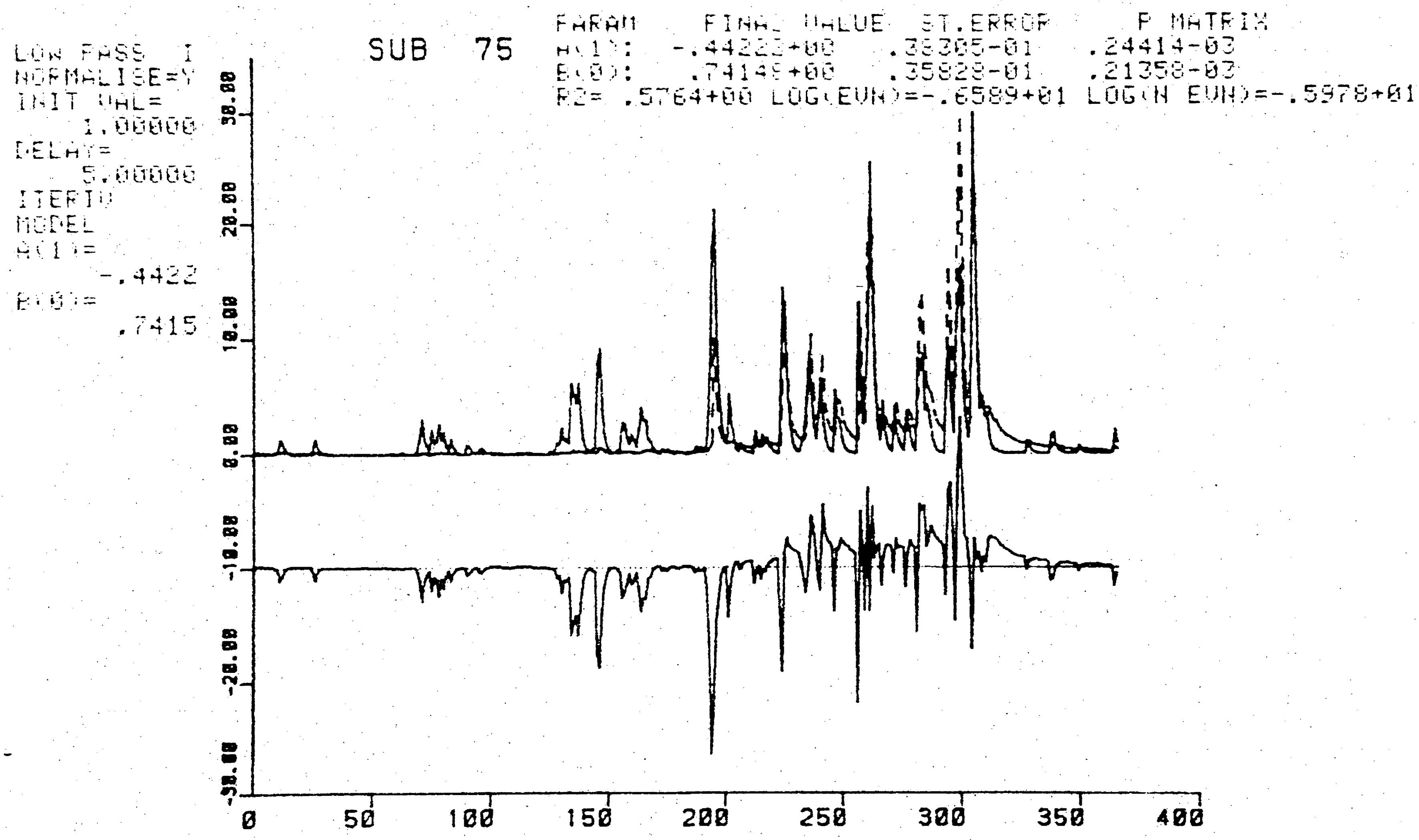


Fig 5.137 1975 Model response with parameter values set to those estimated for 1971 (Fig 5.122)

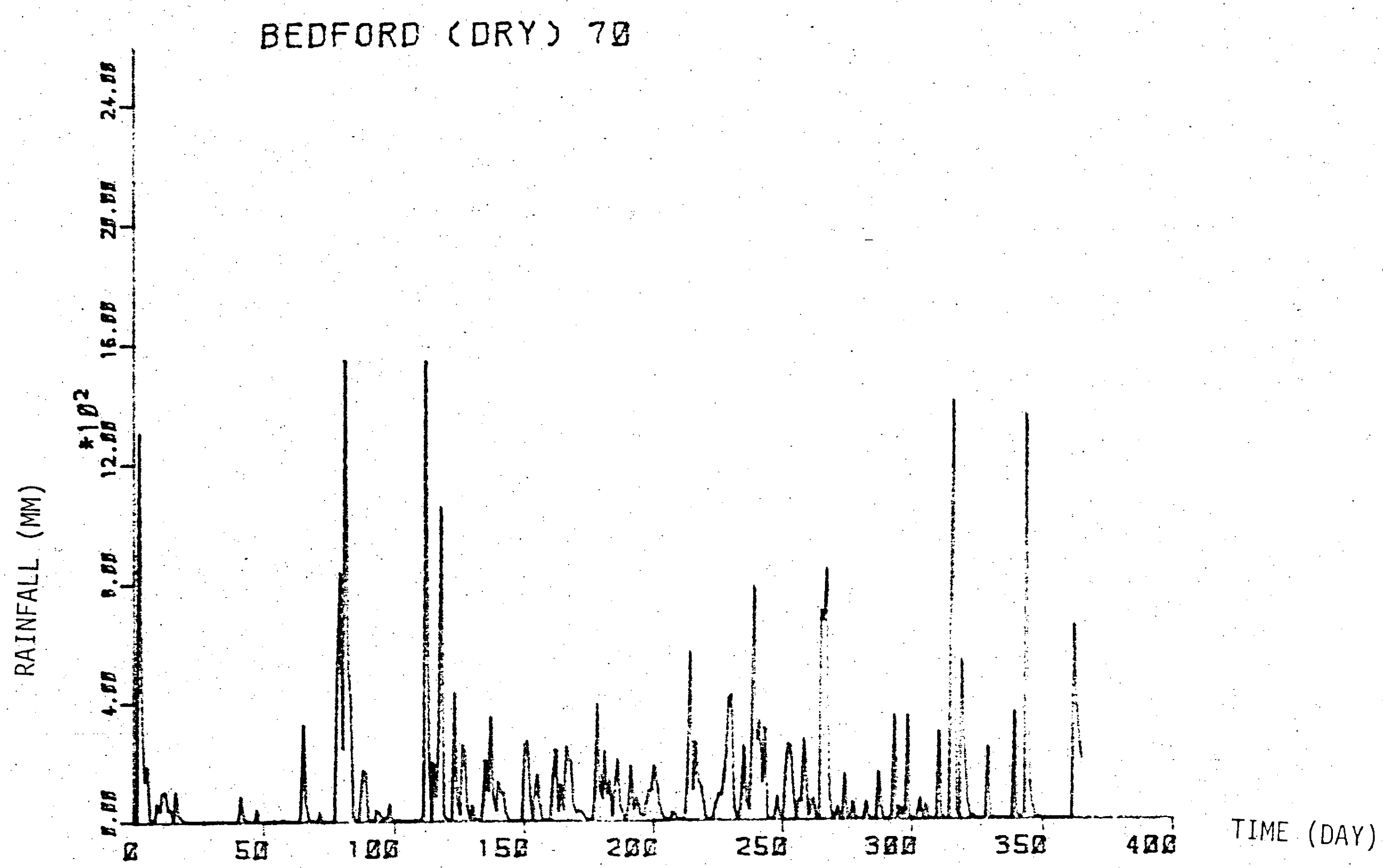


Fig 5.138 1970 Rainfall modified by dry-bulb temperature

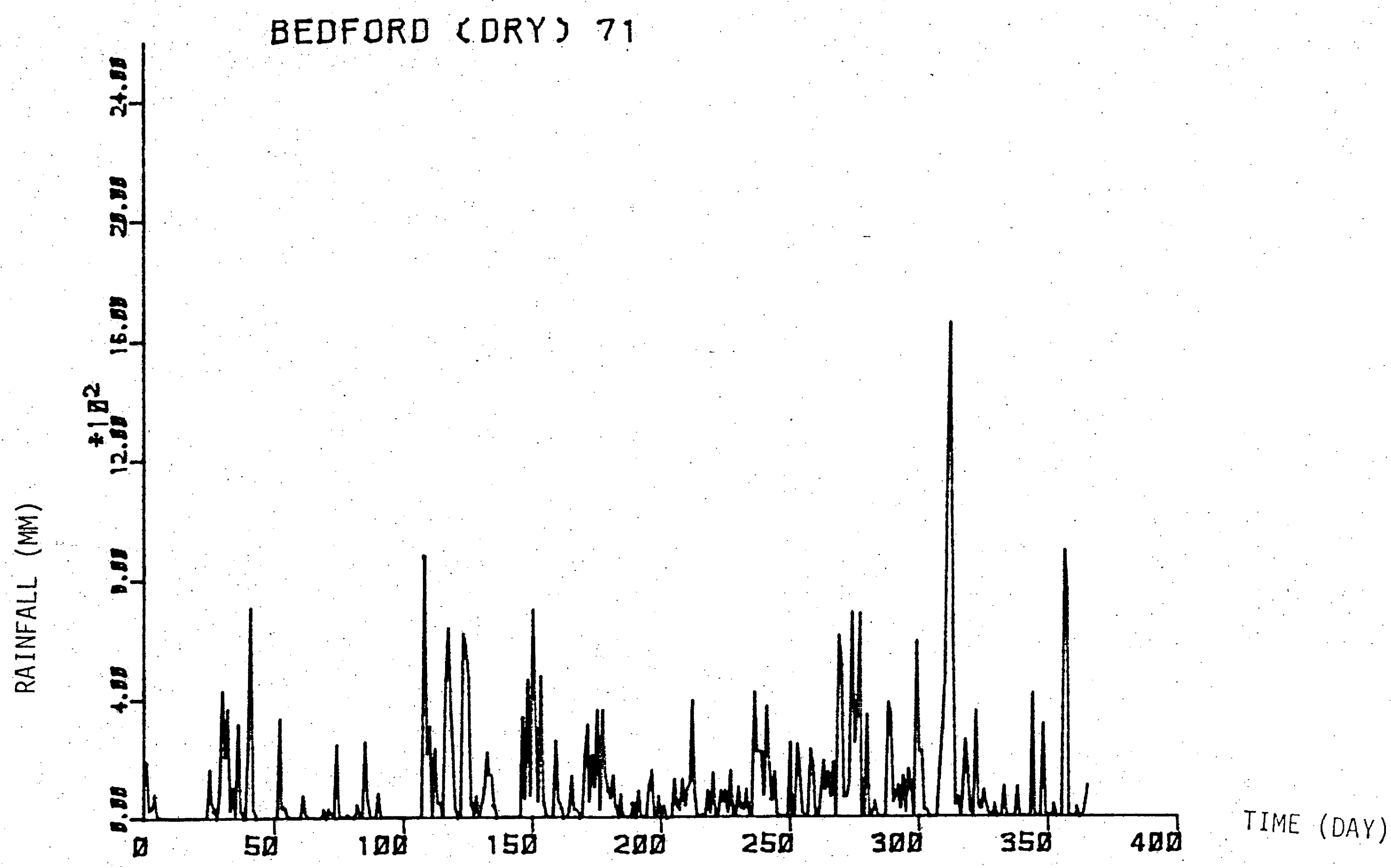


Fig 5.139 1971 Rainfall modified by dry-bulb temperature

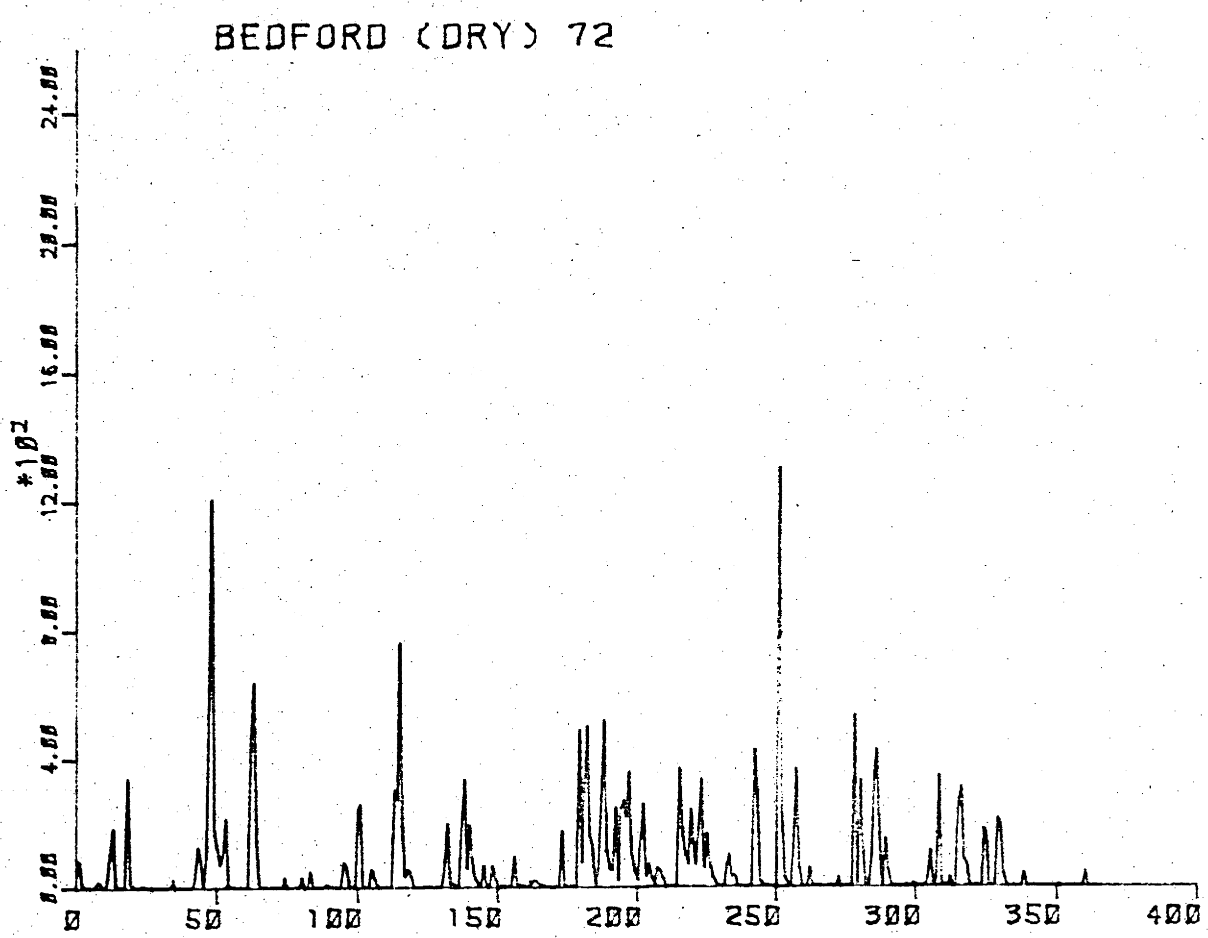


Fig 5.140 1972 Rainfall modified by dry-bulb temperature

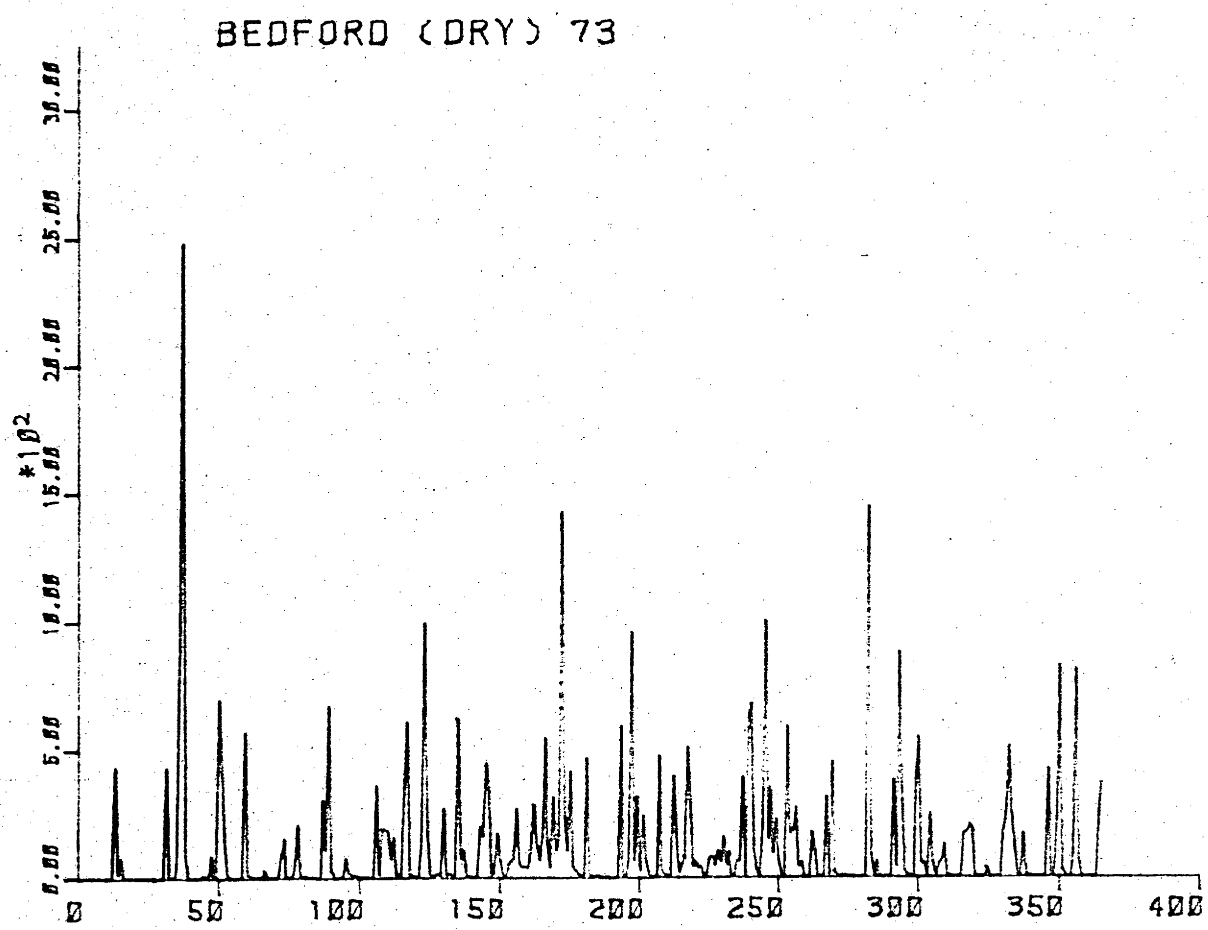


Fig 5.141 1973 Rainfall modified by dry-bulb temperature

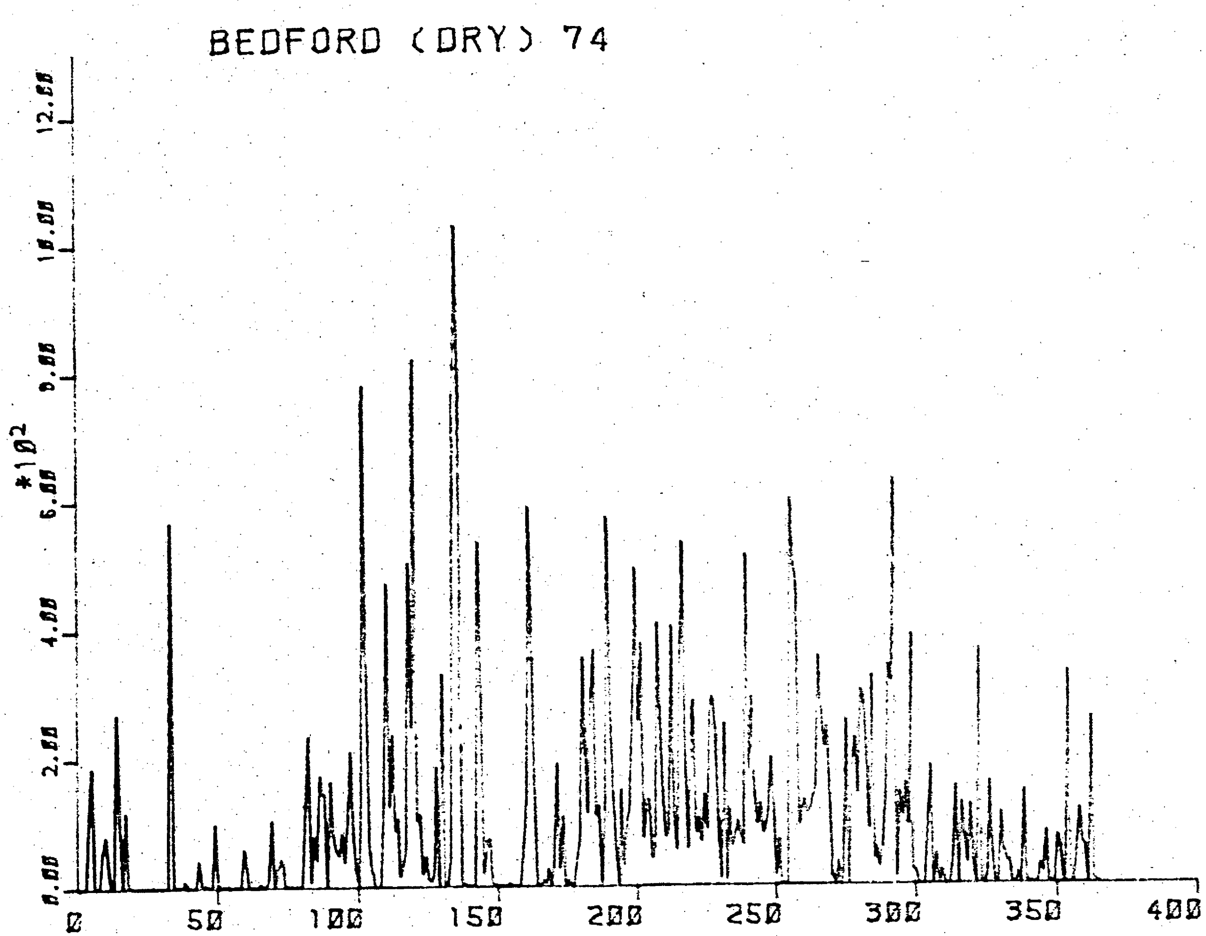


Fig 5.142 1974 Rainfall modified by dry-bulb temperature

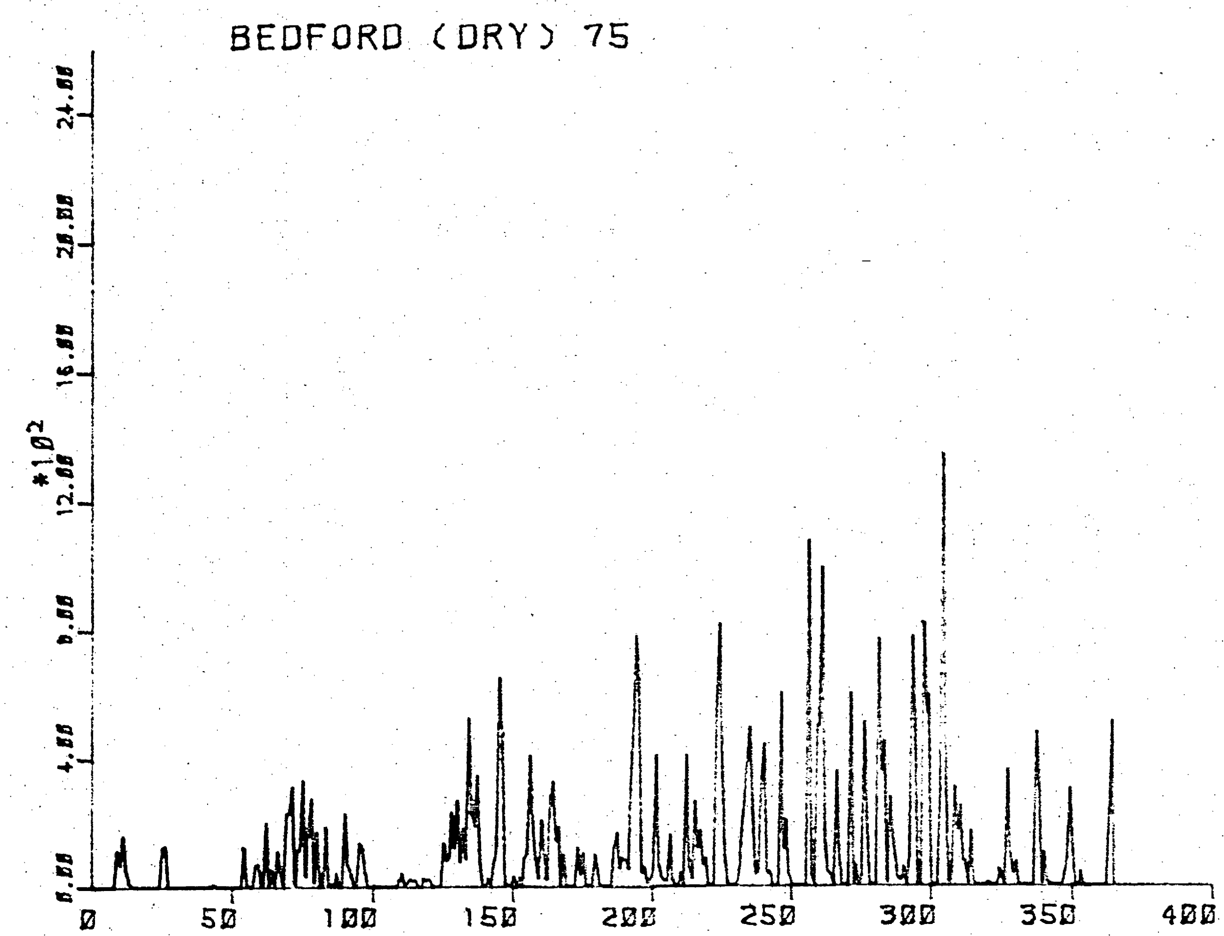


Fig 5.143 1975 Rainfall modified by dry-bulb temperature

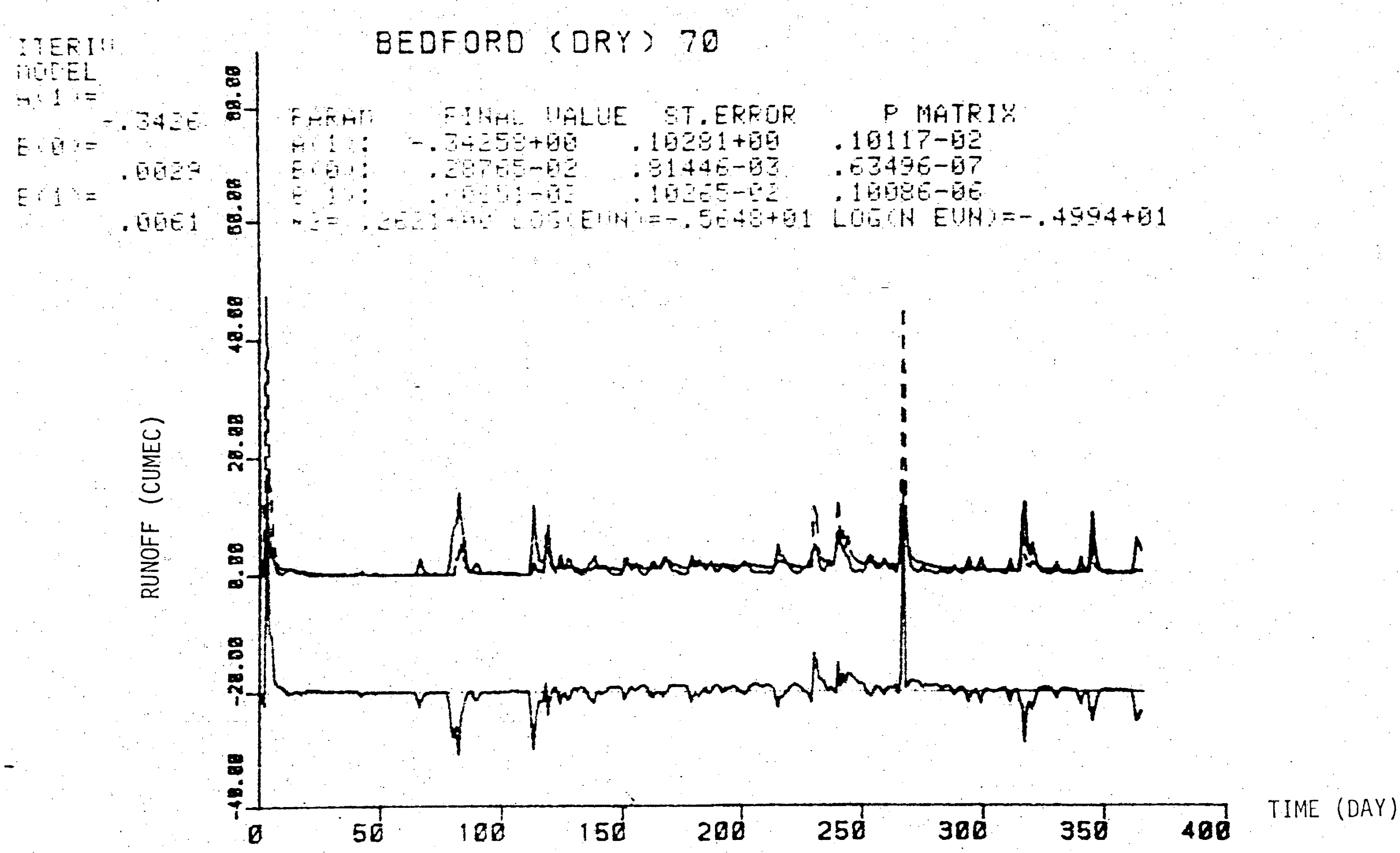


Fig 5.144 1970 Model allowing for temperature (dry bulb) effects

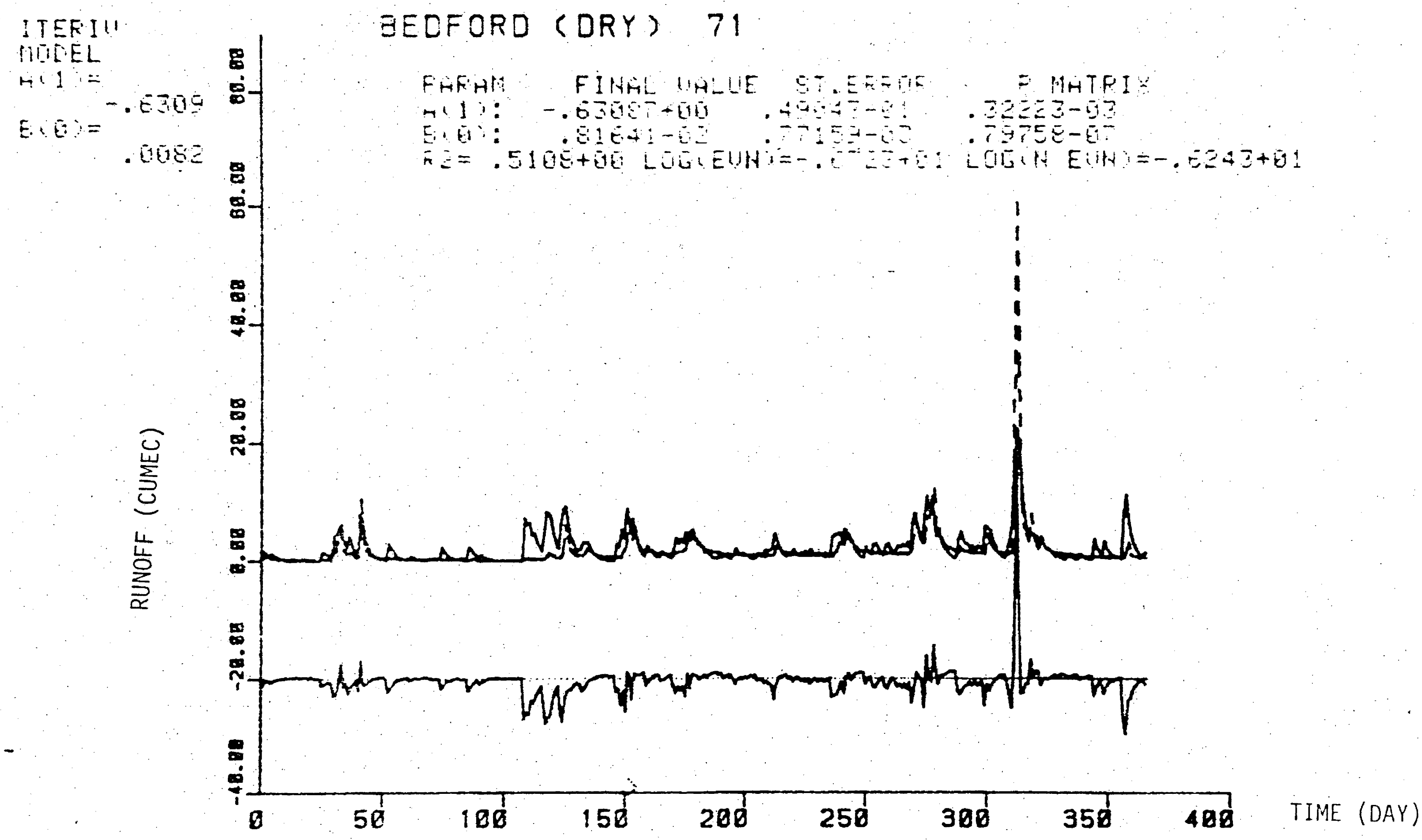


Fig 5.145 1971 Model allowing for temperature (dry bulb) effects

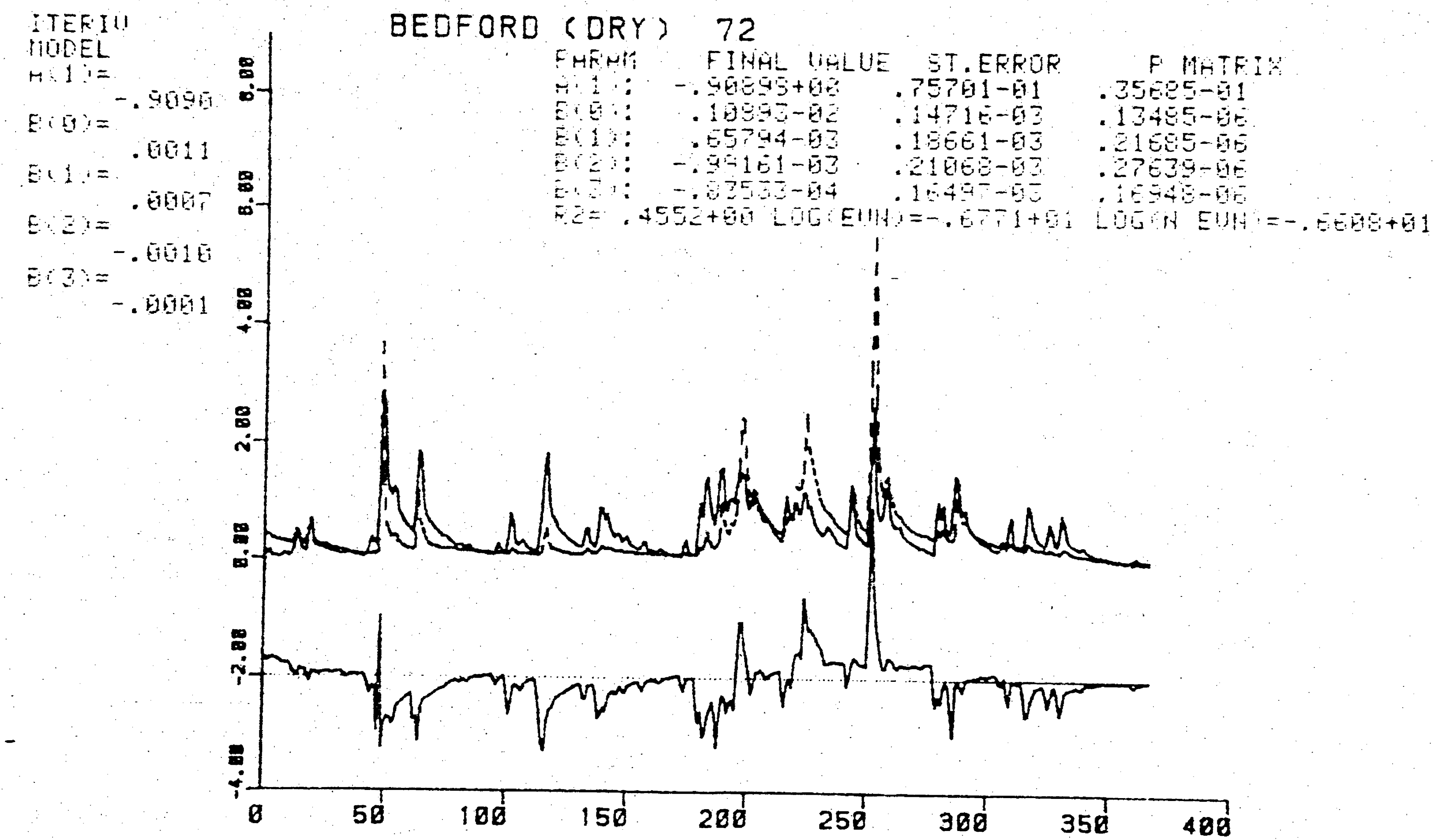


Fig 5.146 1972 Model allowing for temperature (dry bulb) effects

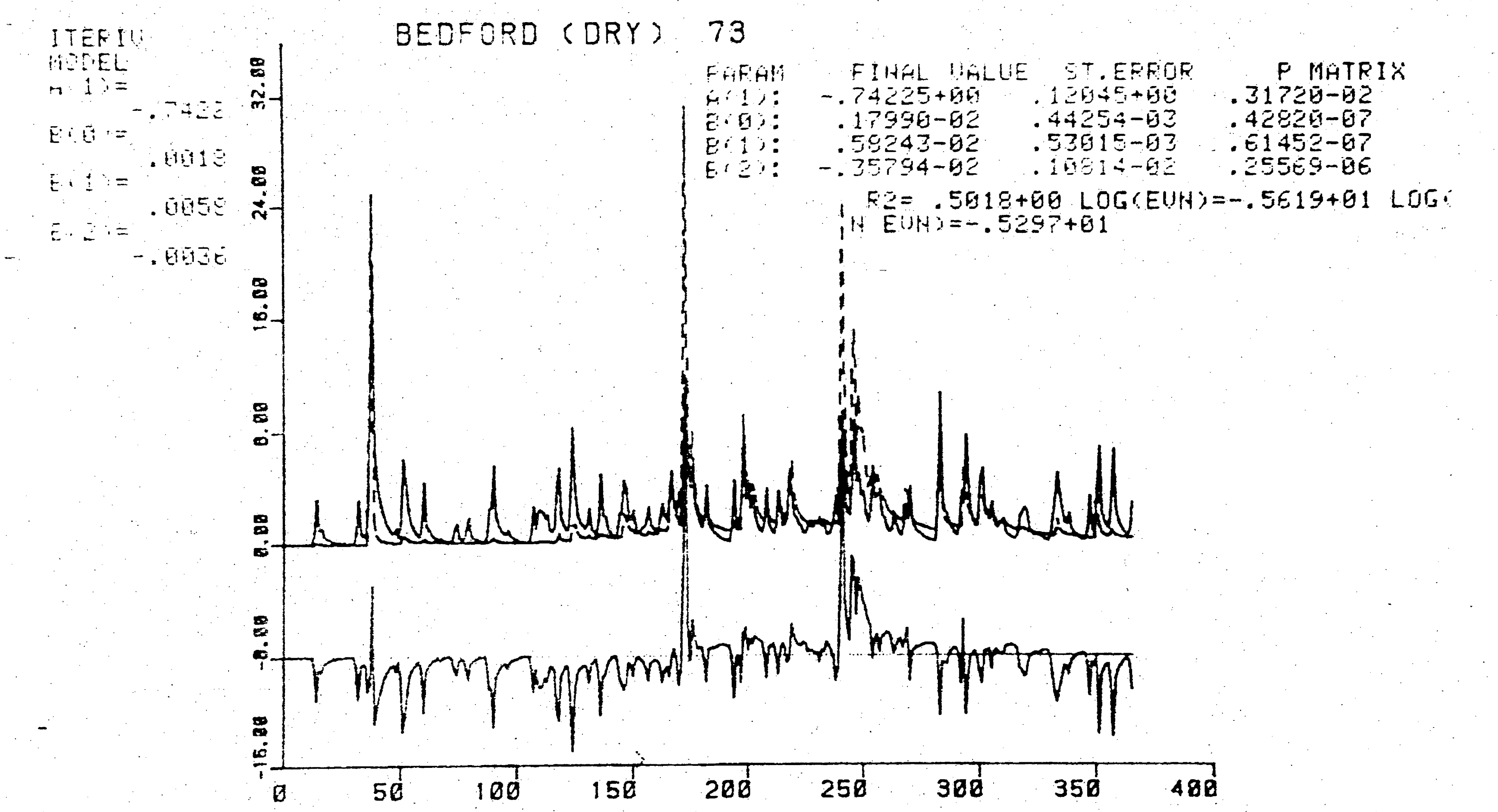


Fig 5.147 1973 Model allowing for temperature (dry bulb) effects

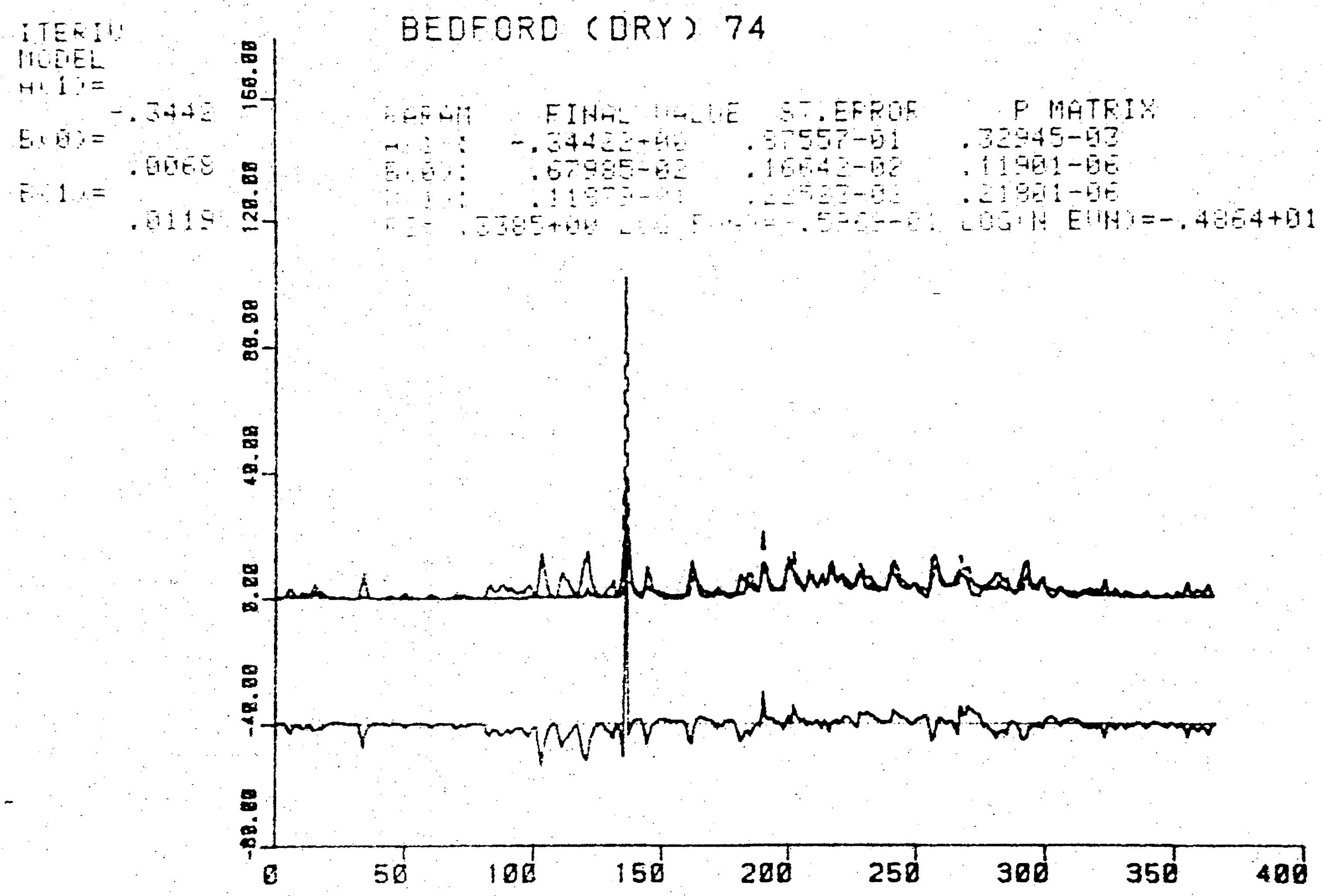


Fig 5.148 1974 Model allowing for temperature (dry bulb) effects

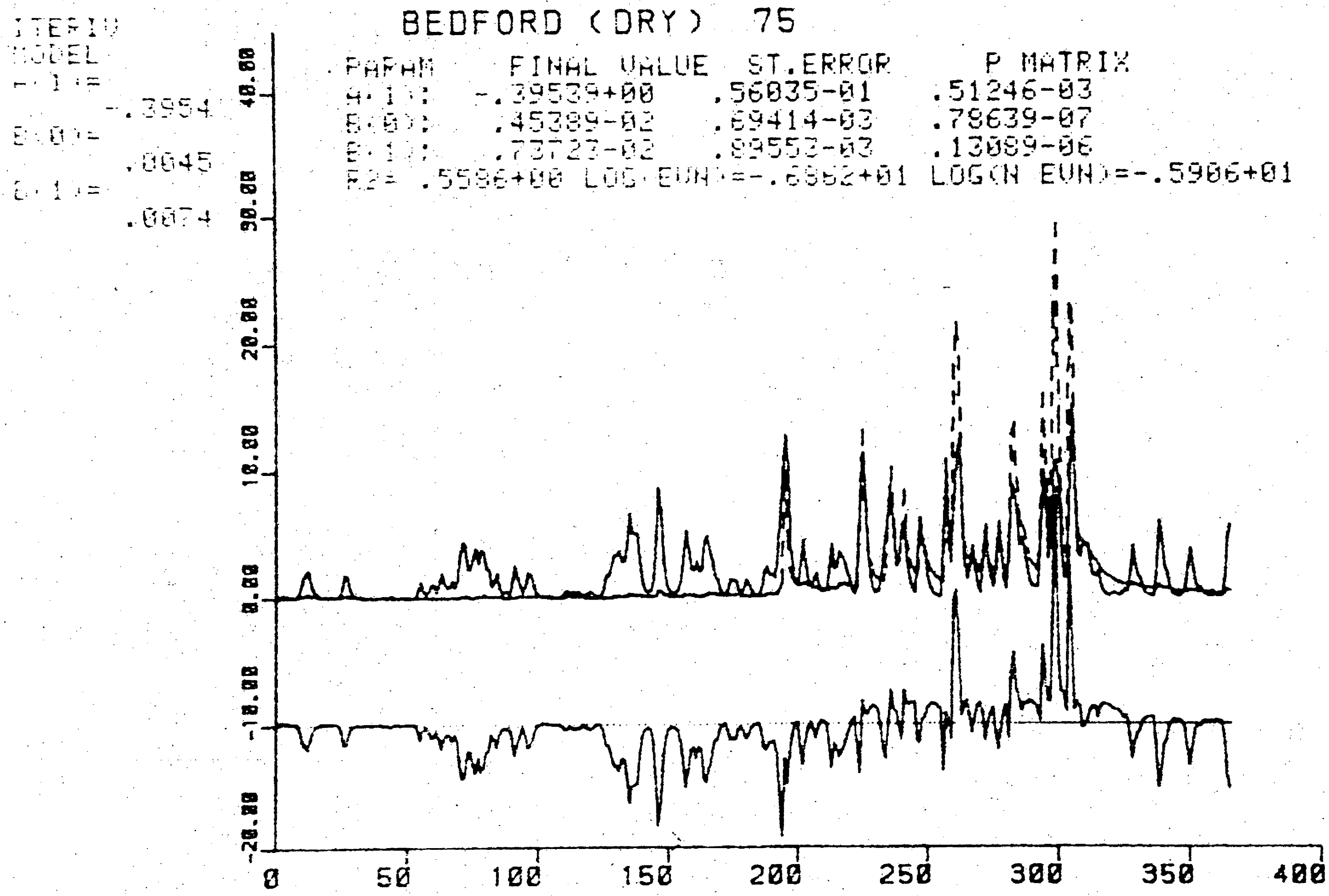


Fig 5.149 1975 Model allowing for temperature (dry bulb) effects

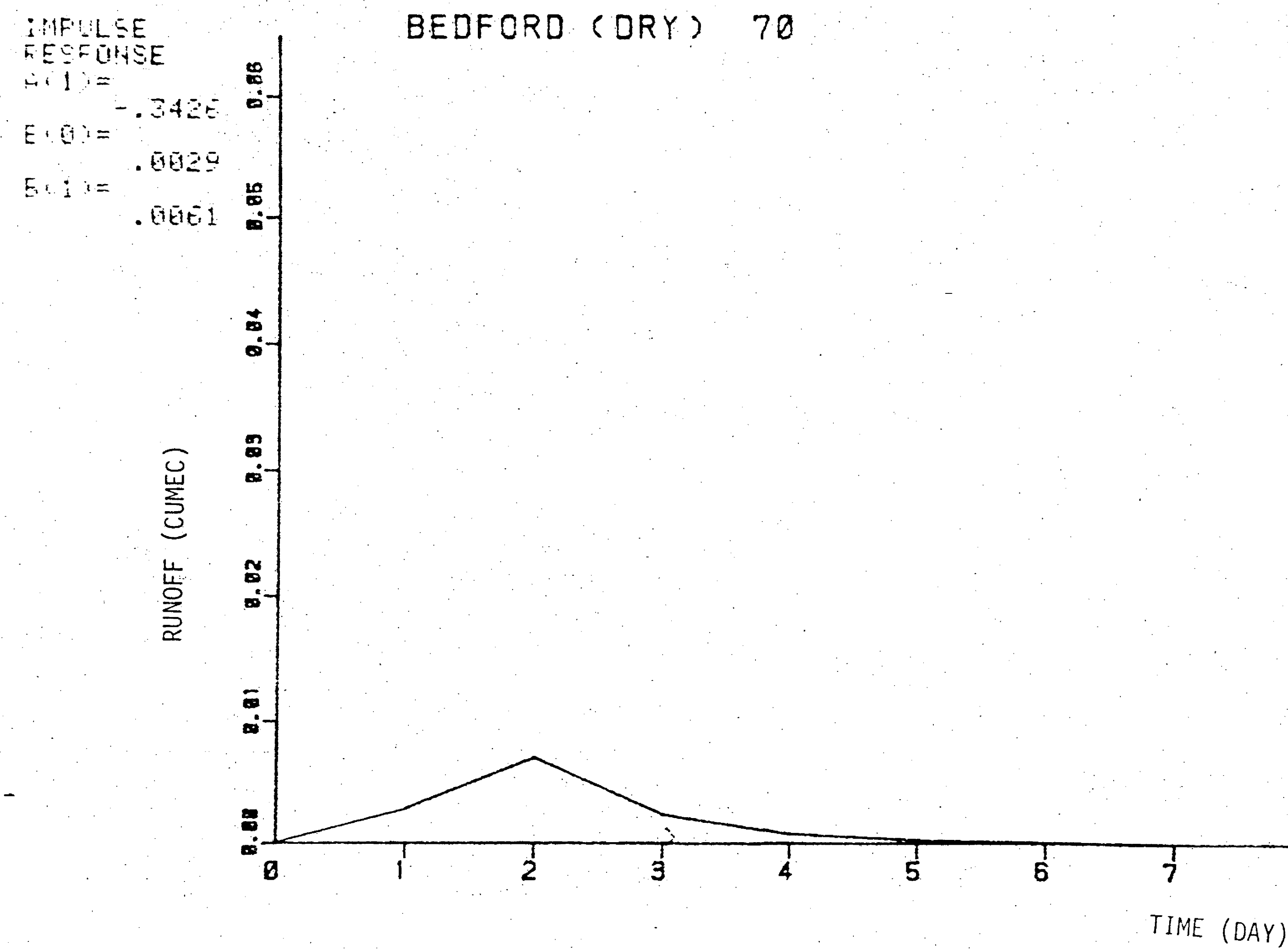


Fig 5.150 Impulse Response for Model Fig 5.150

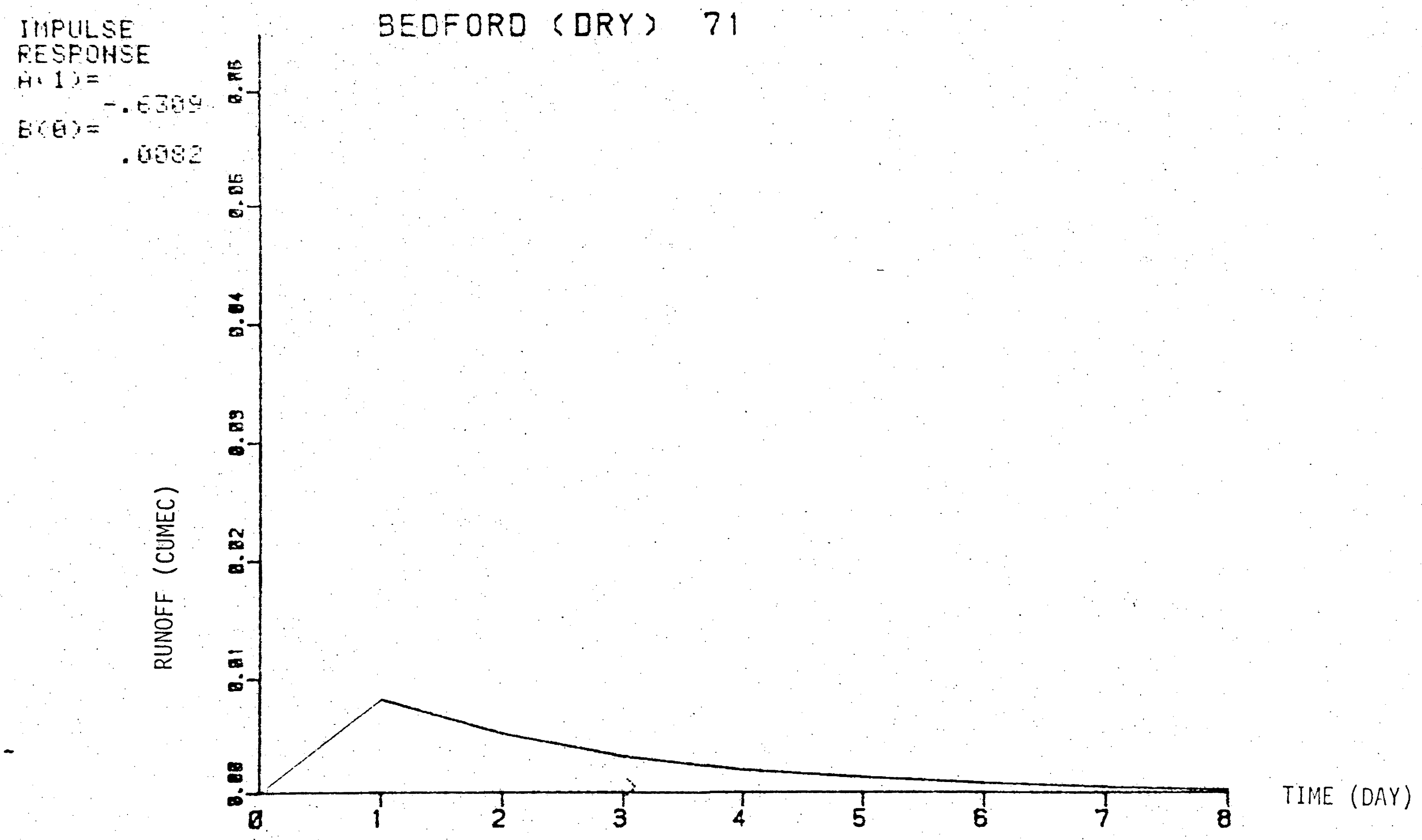


Fig 5. 151 Impulse Response for Model Fig 5.151

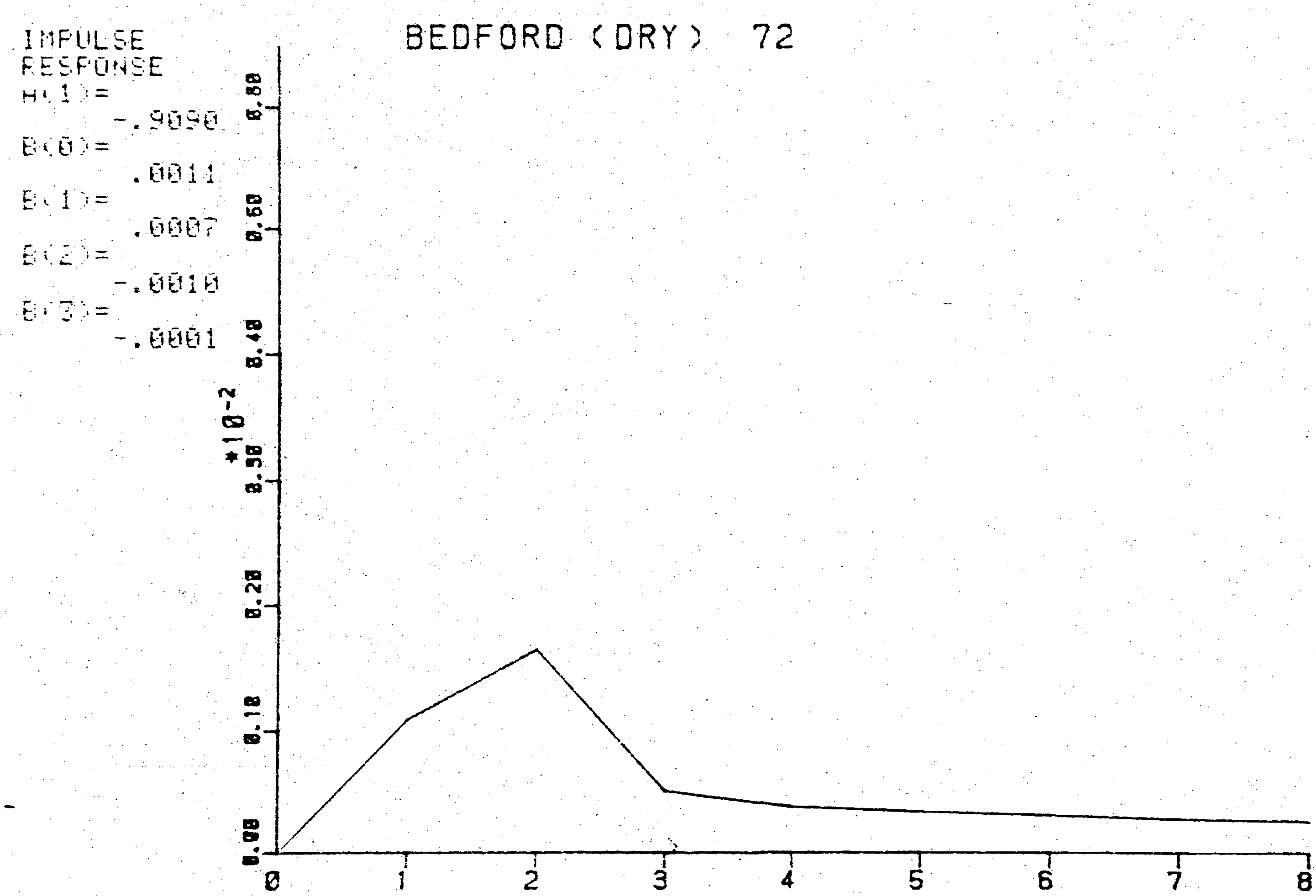


Fig 5.152 Impulse Response for Model Fig 5.152

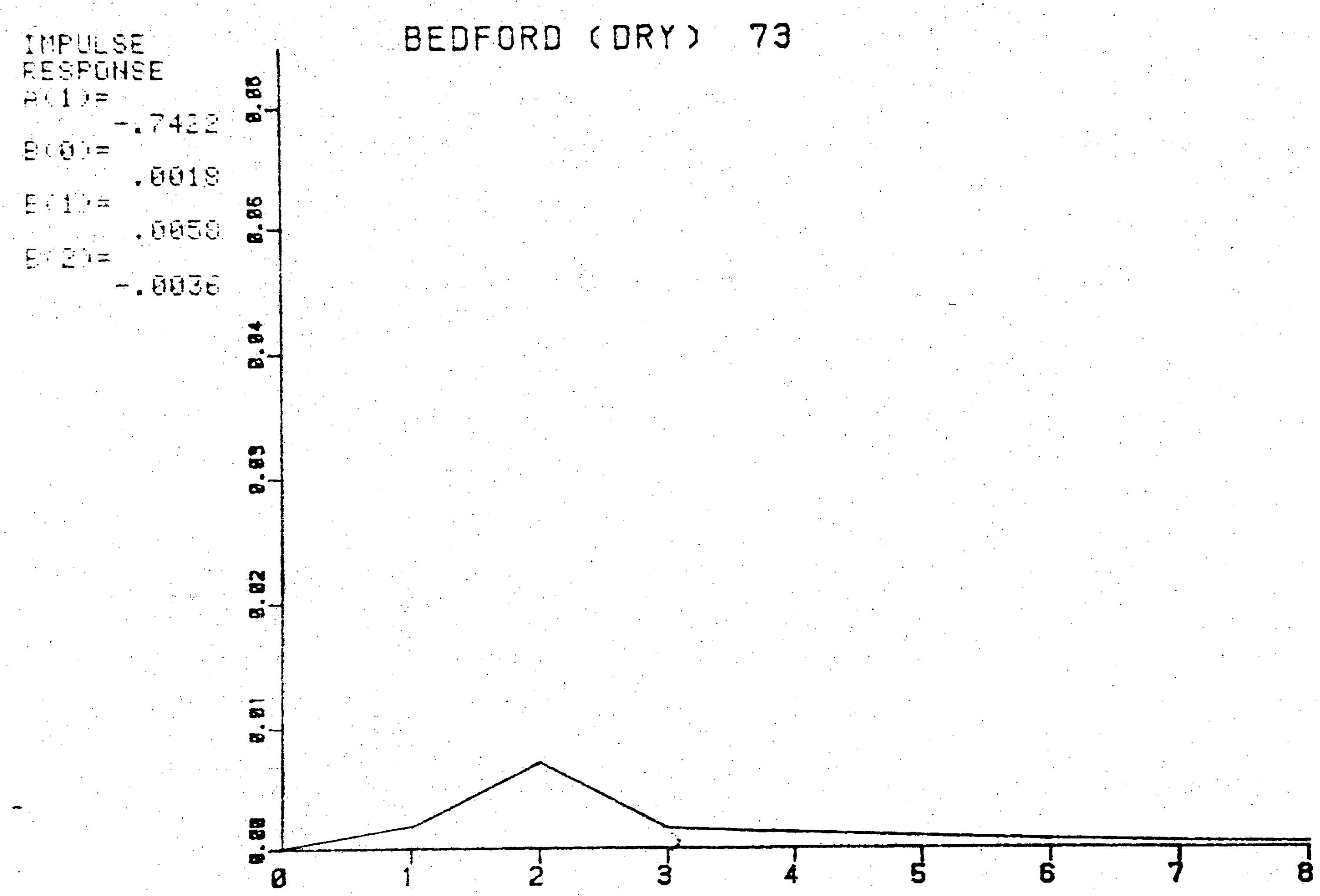


Fig 5.153 Impulse Response for Model Fig 5.153

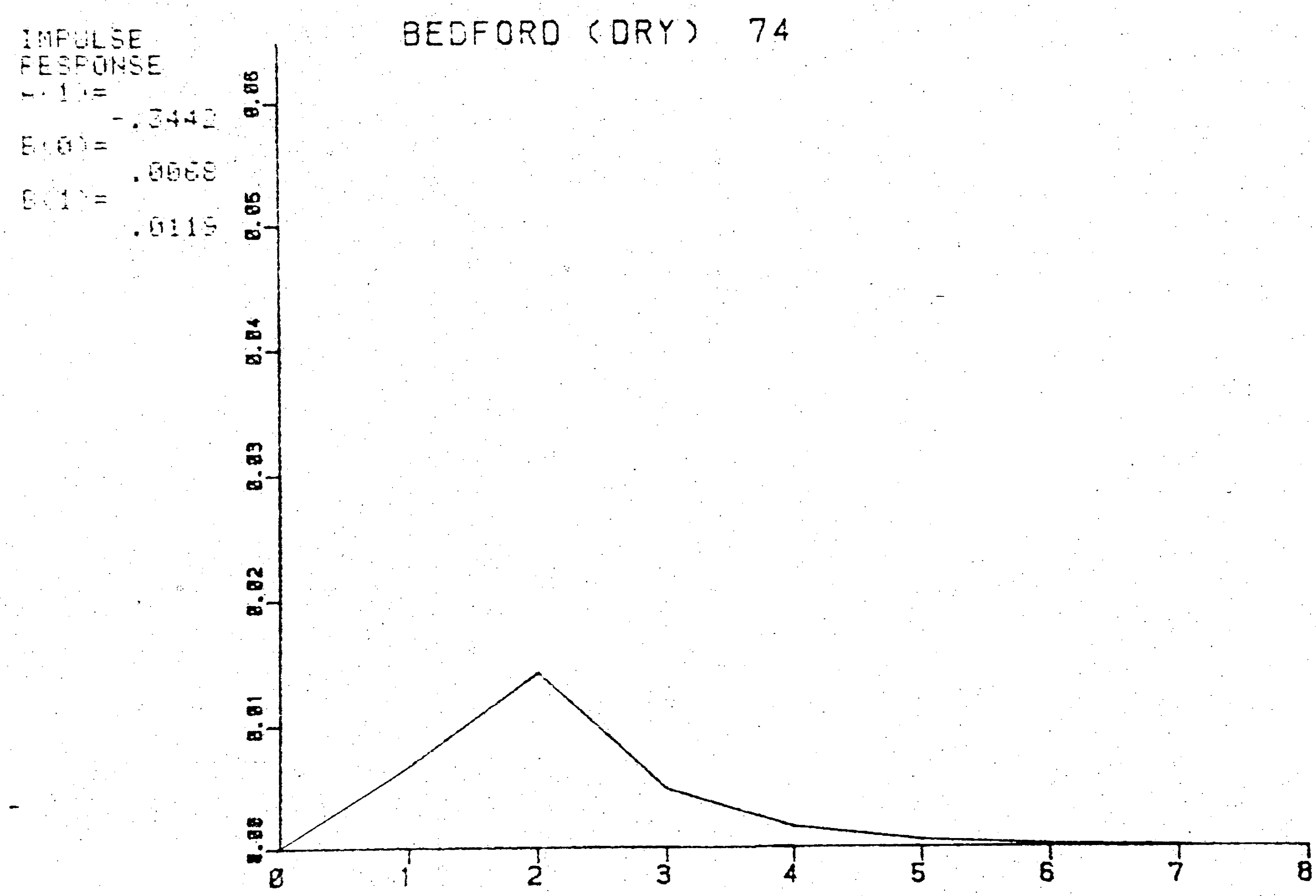


Fig 5.154 Impulse Response for Model Fig 5.154

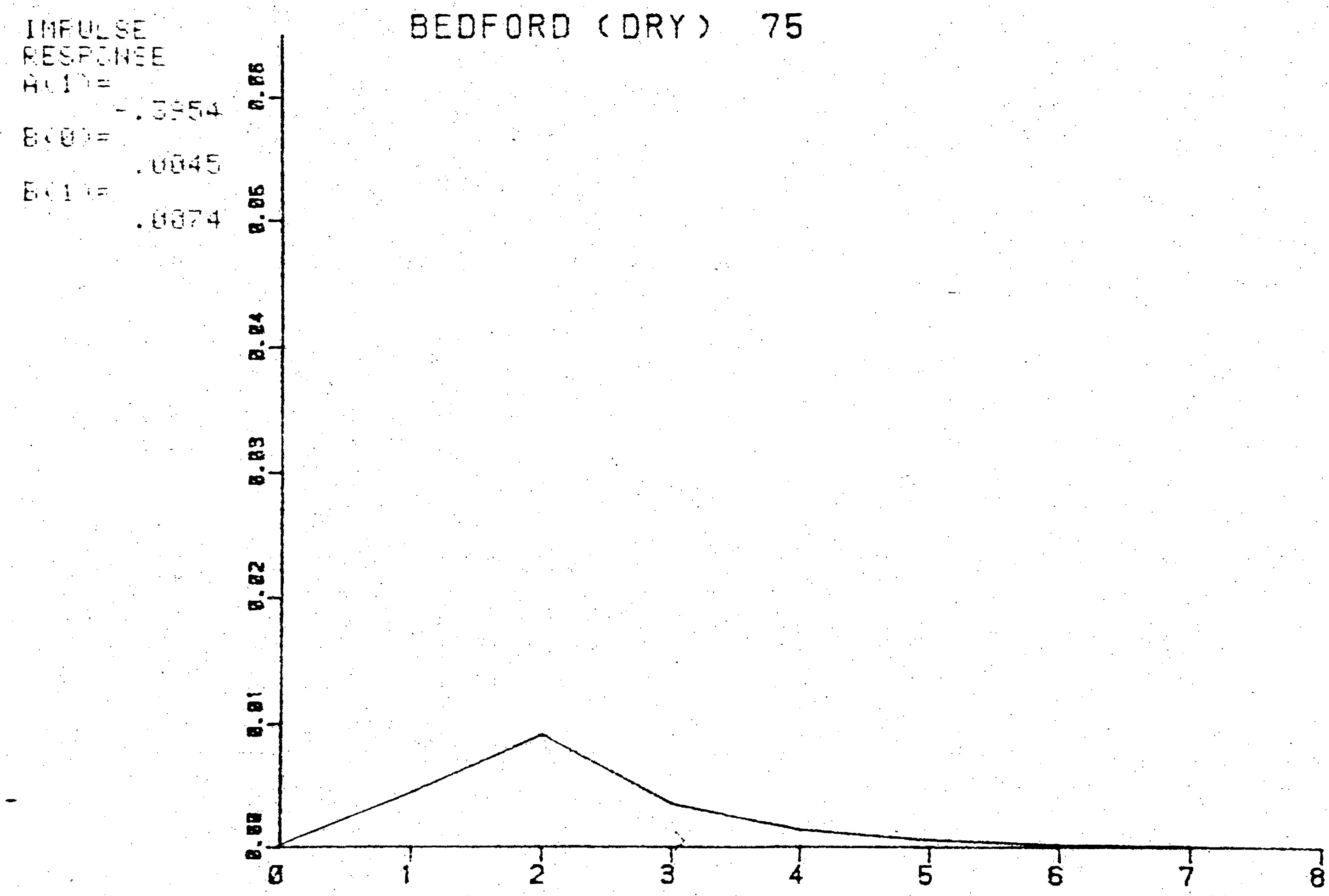


Fig 5. 155 Impulse Response for Model Fig 5.155

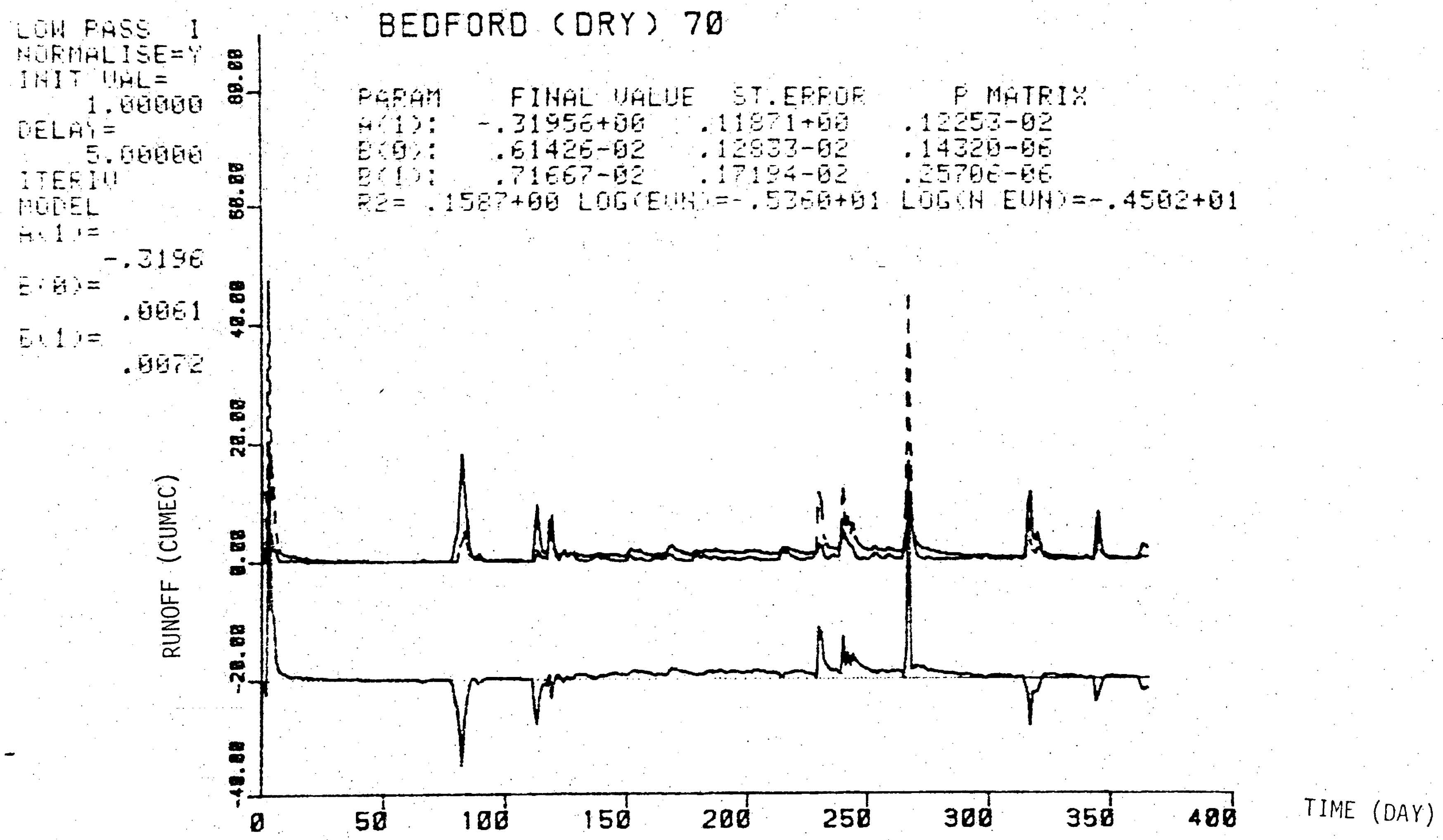


Fig 5.156 Model Fig 5.150 allowing for soil moisture effects

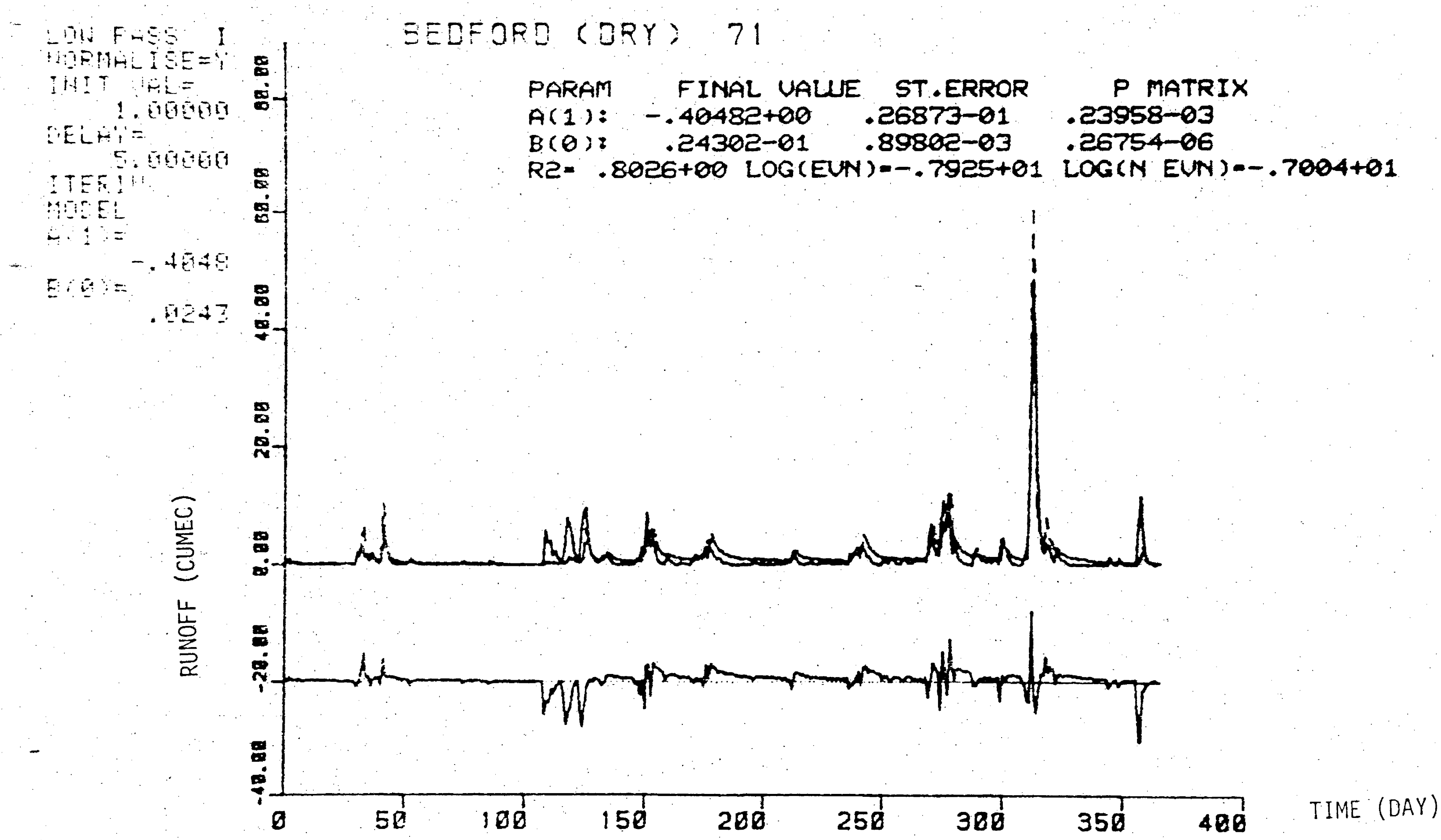


Fig 5.157 Model Fig 5.151 allowing for soil moisture effects

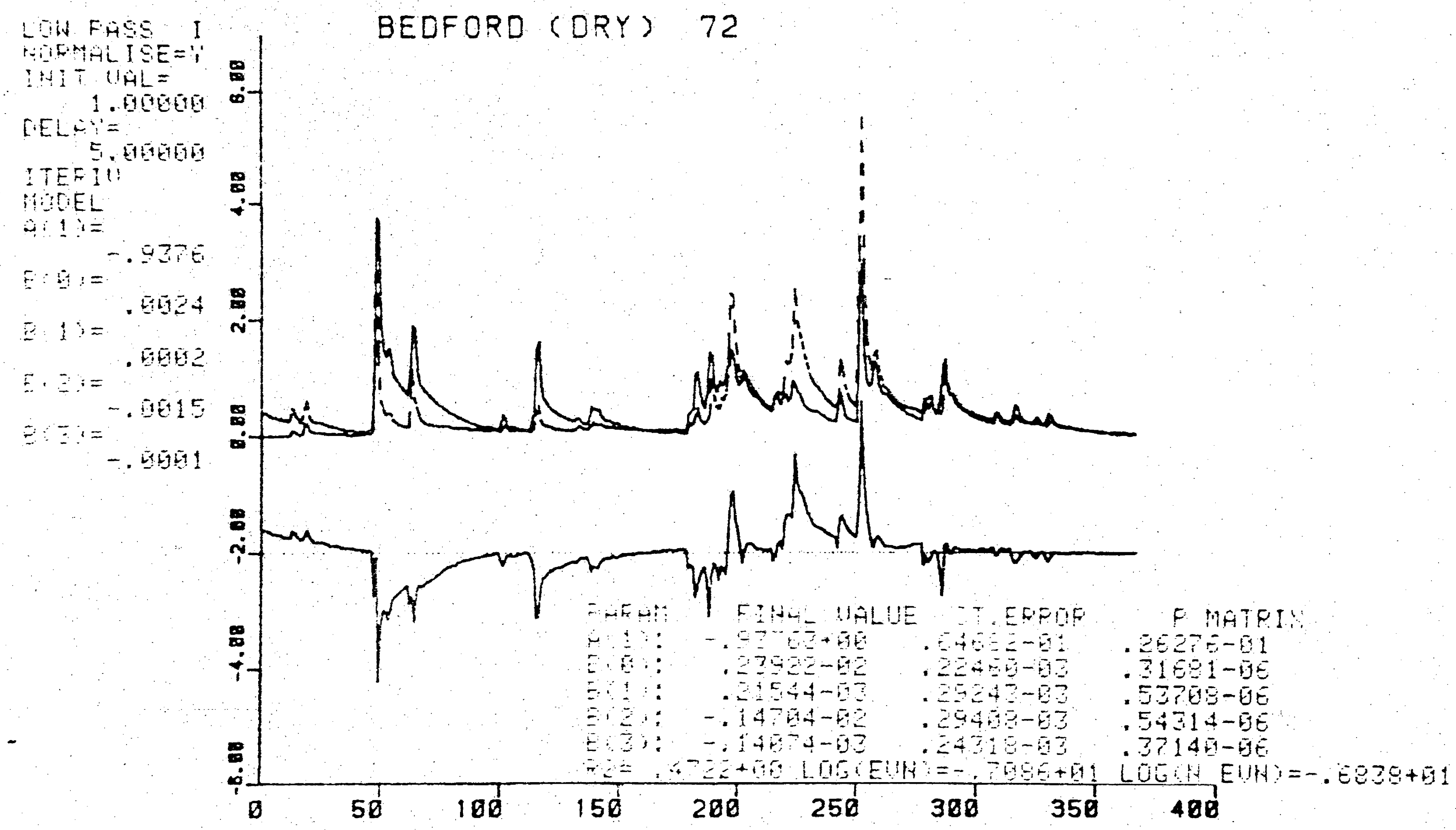


Fig 5. 158 Model Fig 5.152 allowing for soil moisture effects

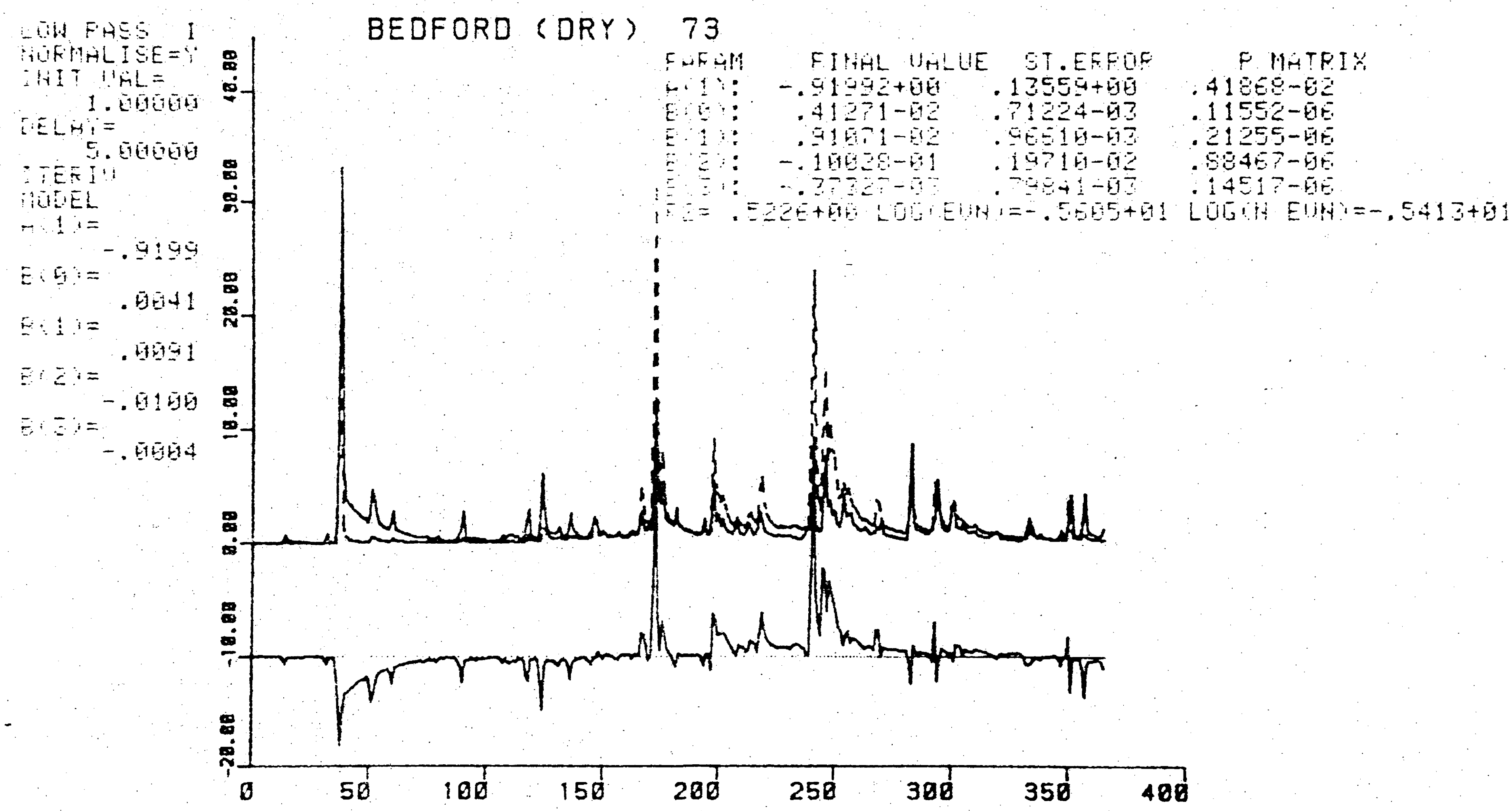


Fig 5.159 Model Fig 5.153 allowing for soil moisture effects

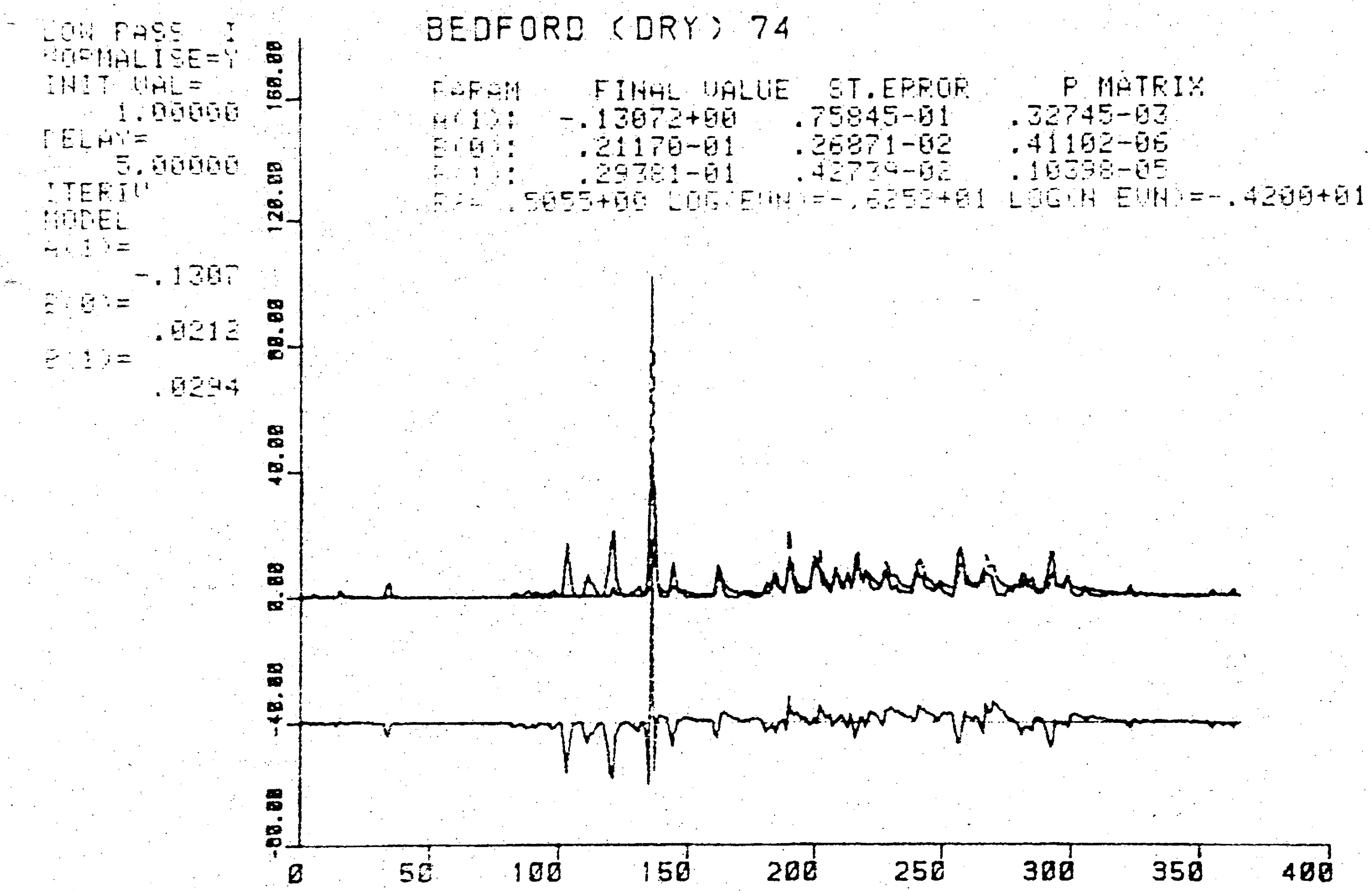


Fig 5.160 Model Fig 5.154 allowing for soil moisture effects

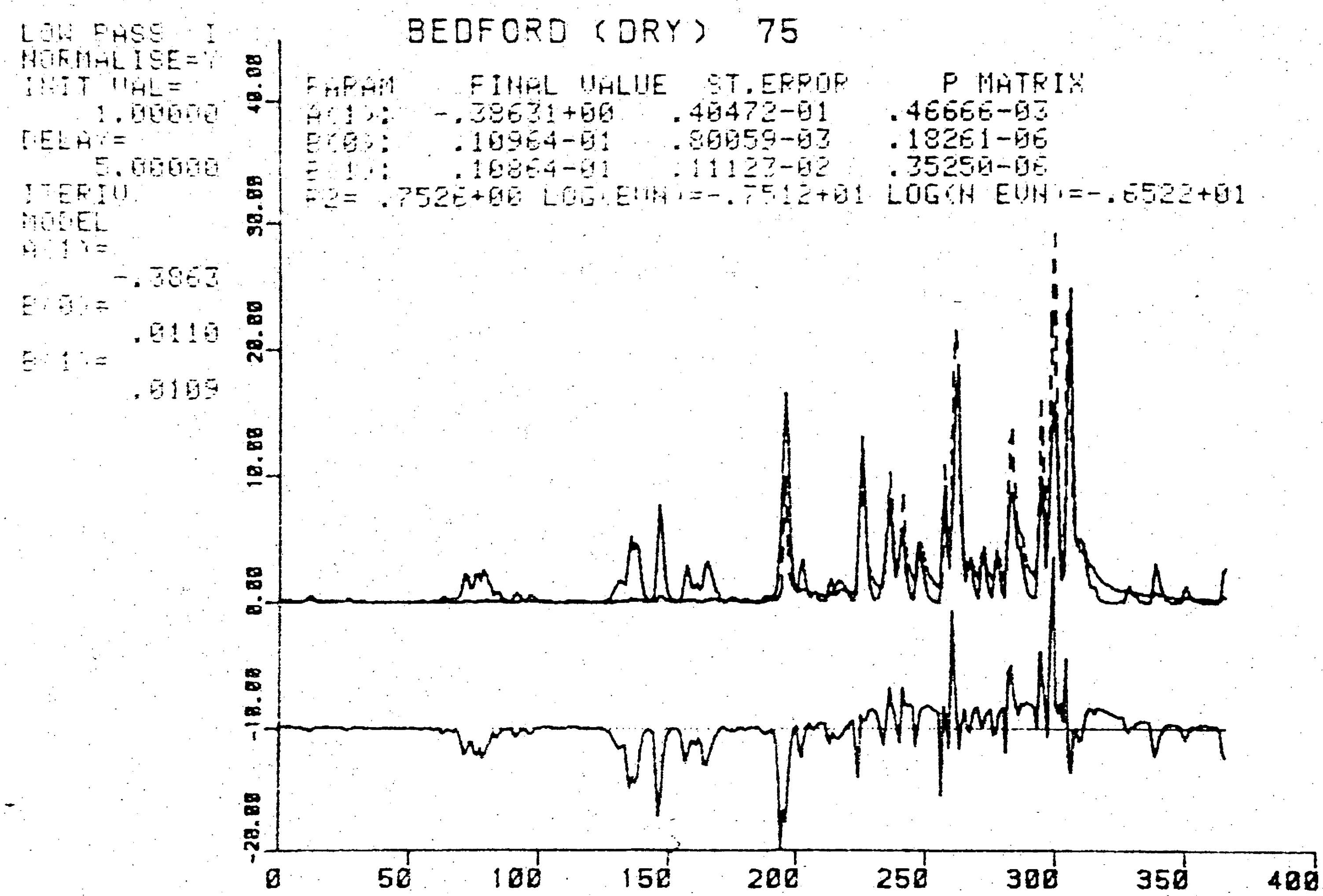


Fig 5.161 Model Fig 5.155 allowing for soil moisture effects

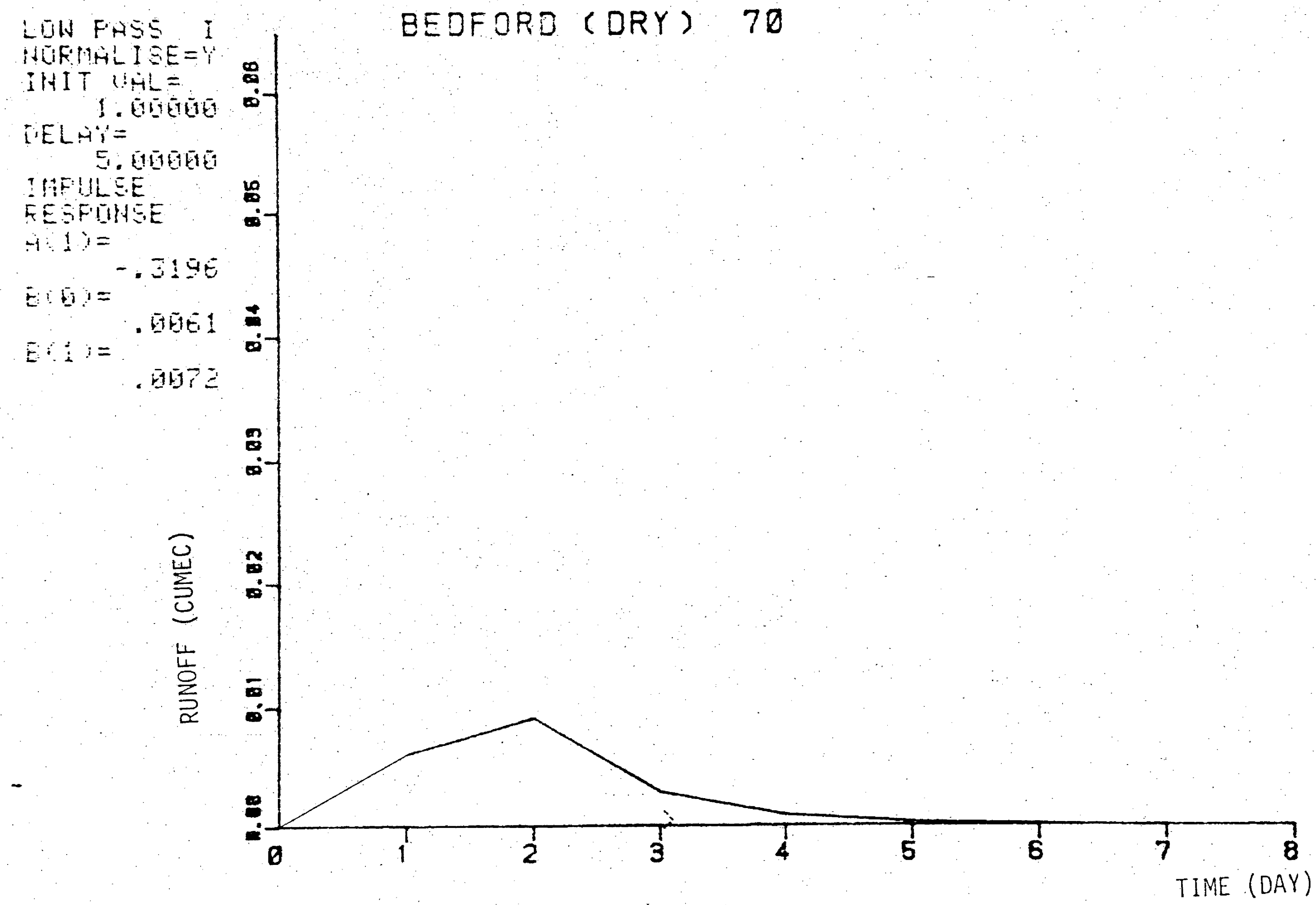


Fig 5.162 Impluse Response for Model Fig 5.162

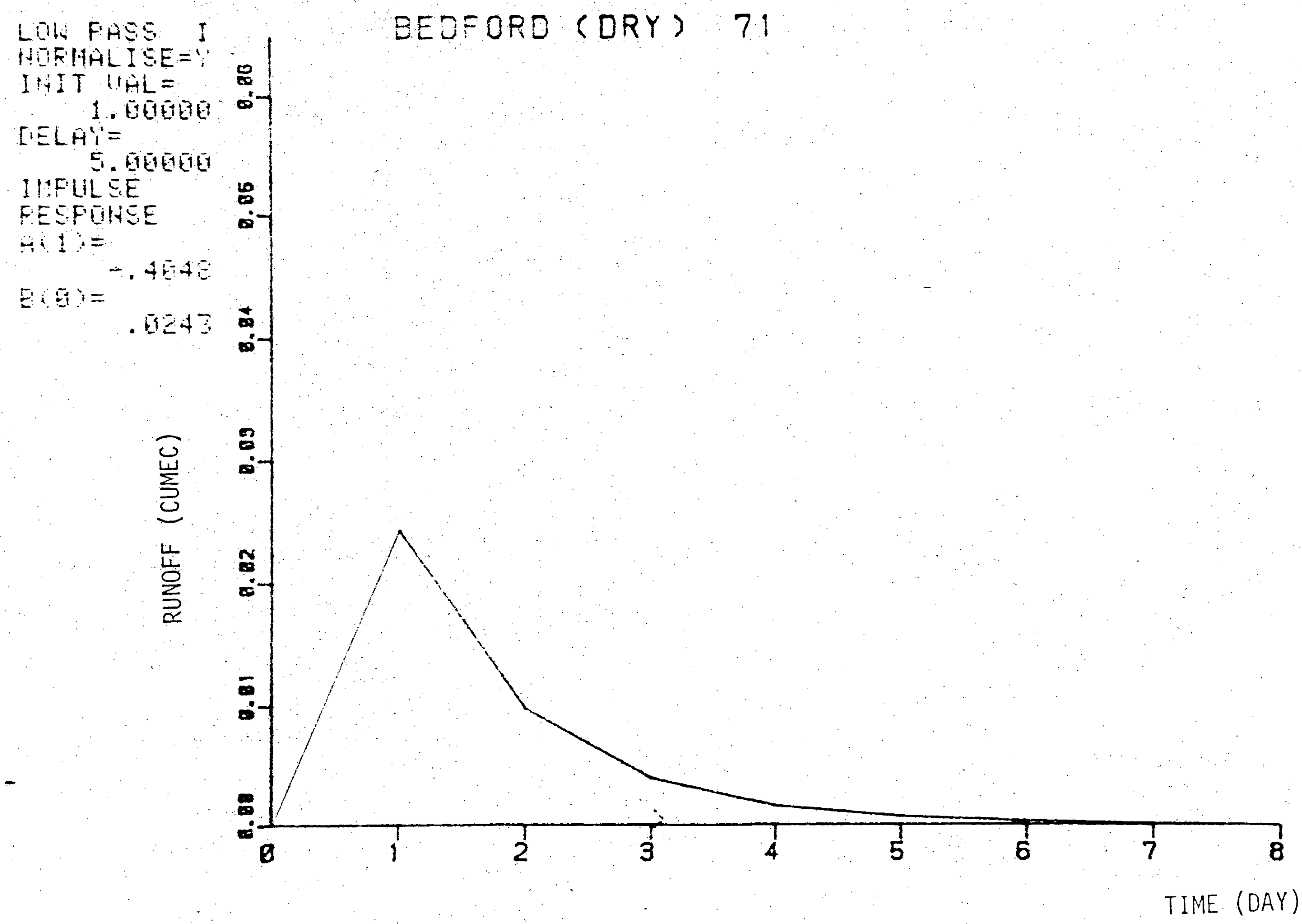


Fig 5.163 Impulse Response for Model Fig 5.163

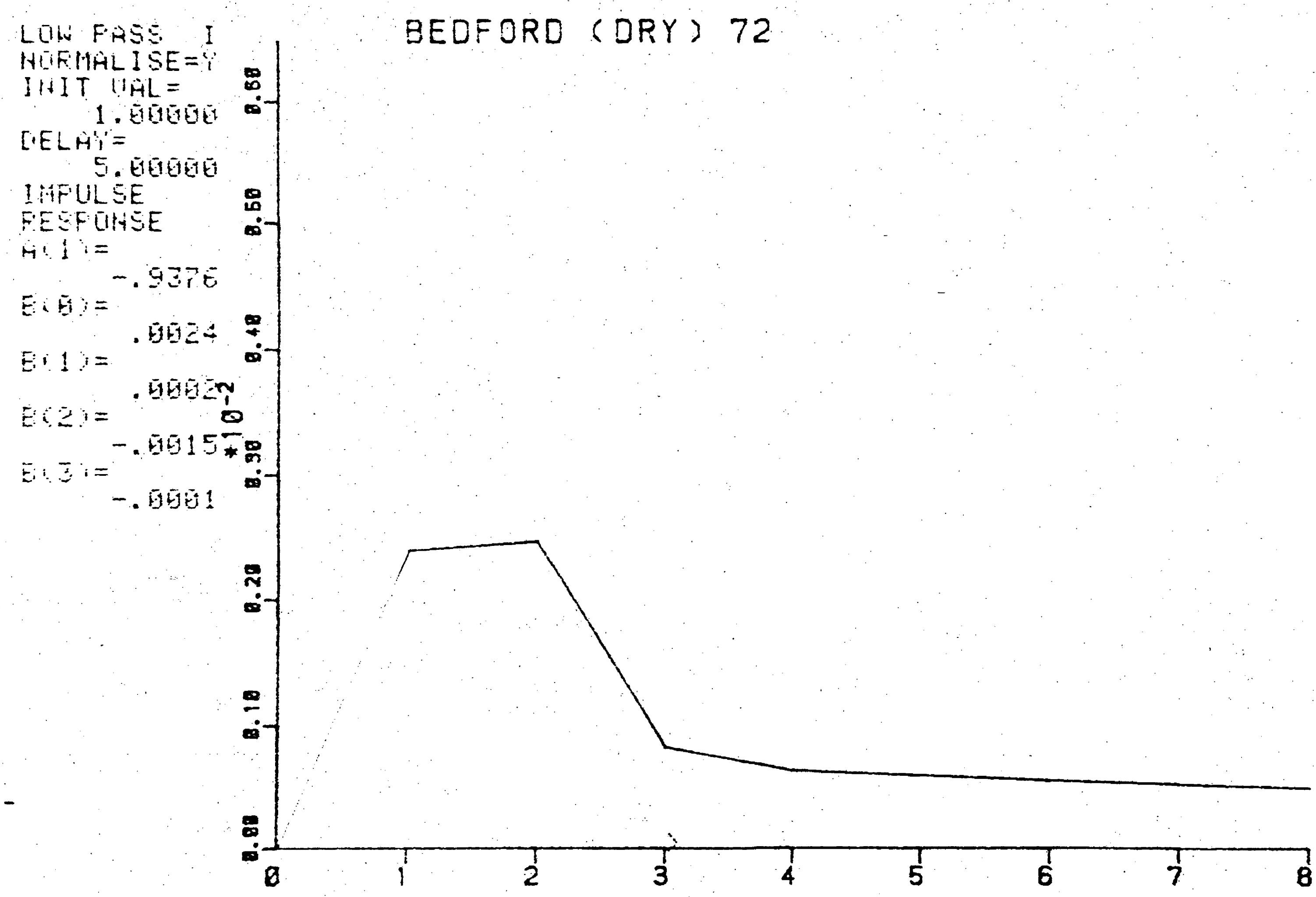


Fig 5.164 Impulse Response for Model Fig 5.164

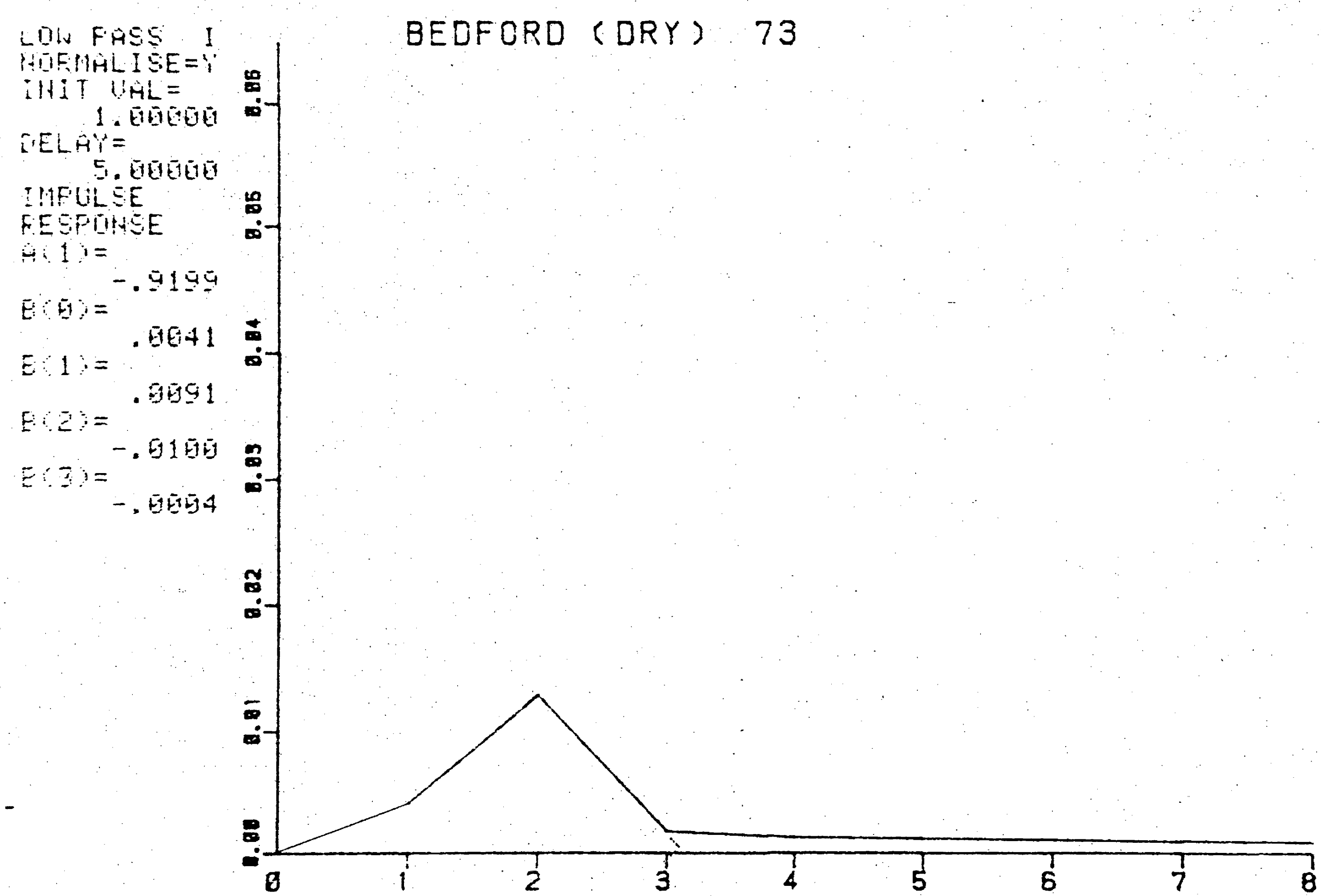


Fig 5.165 Impulse Response for Model Fig 5.165

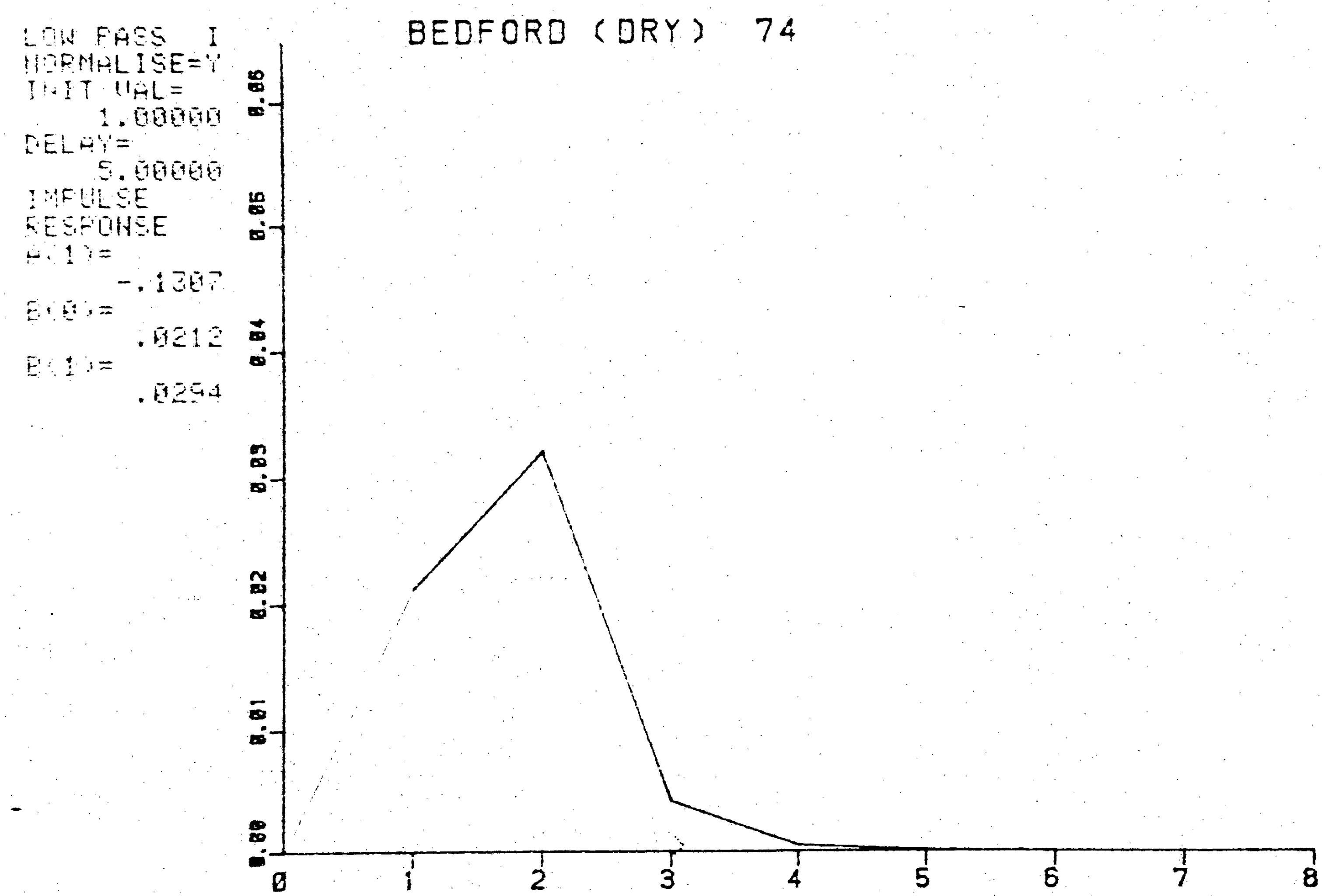


Fig 5.166 Impulse Response for Model Fig 5.166

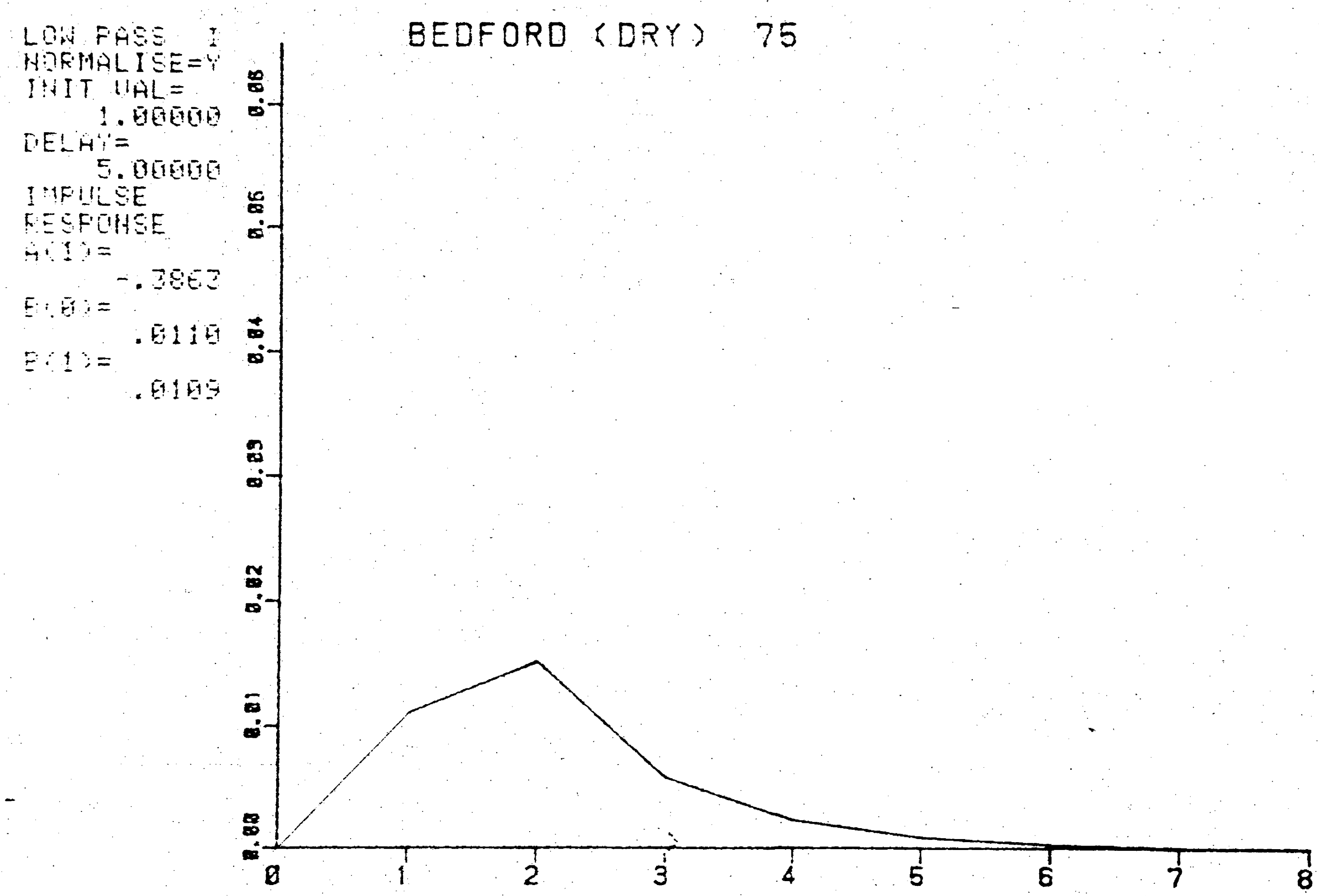


Fig 5.167 Impulse Response for Model Fig 5.167

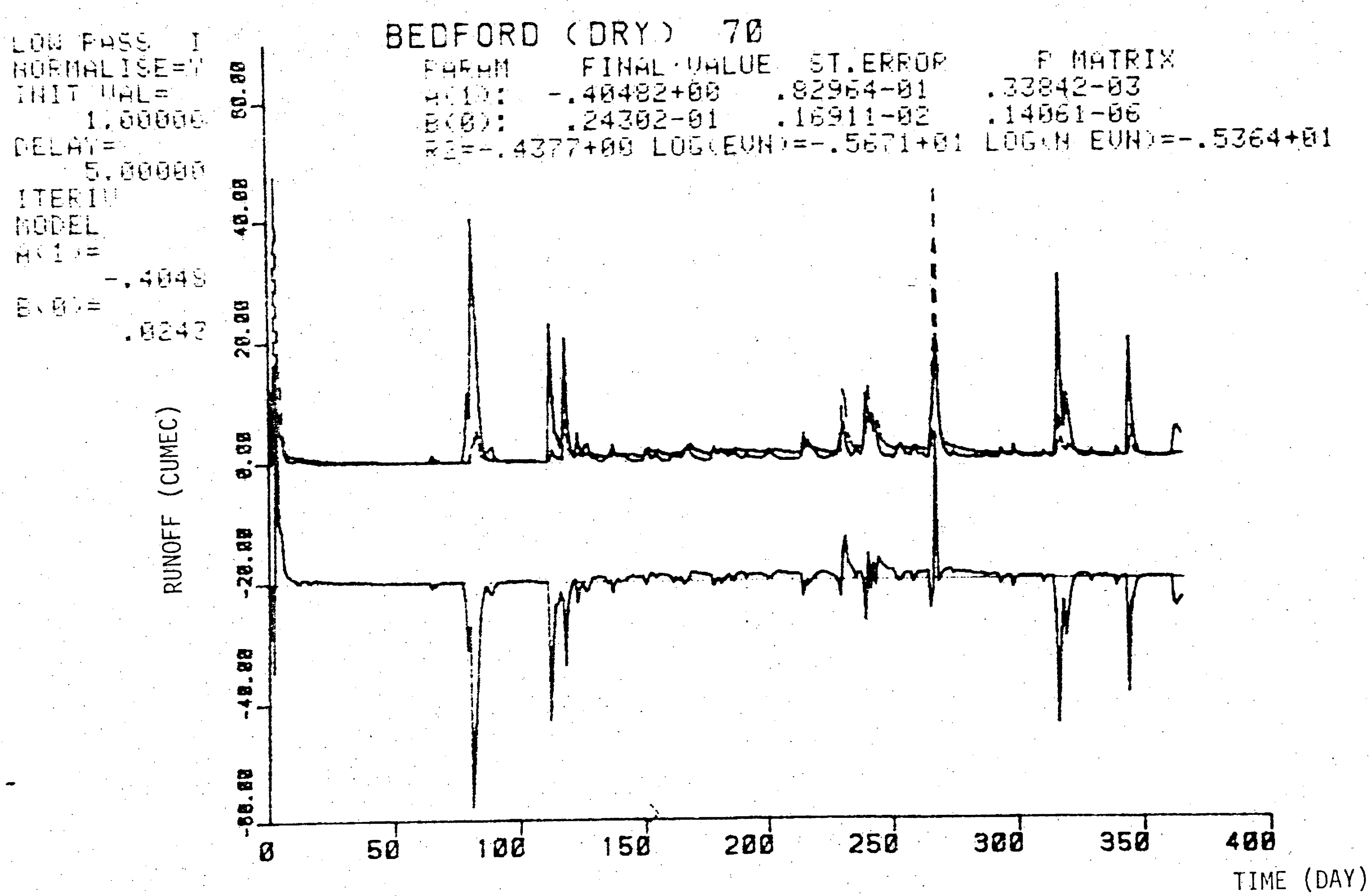


Fig 5.168 1970 Model response with parameter values set to those estimated for 1971 (Fig 5.163)

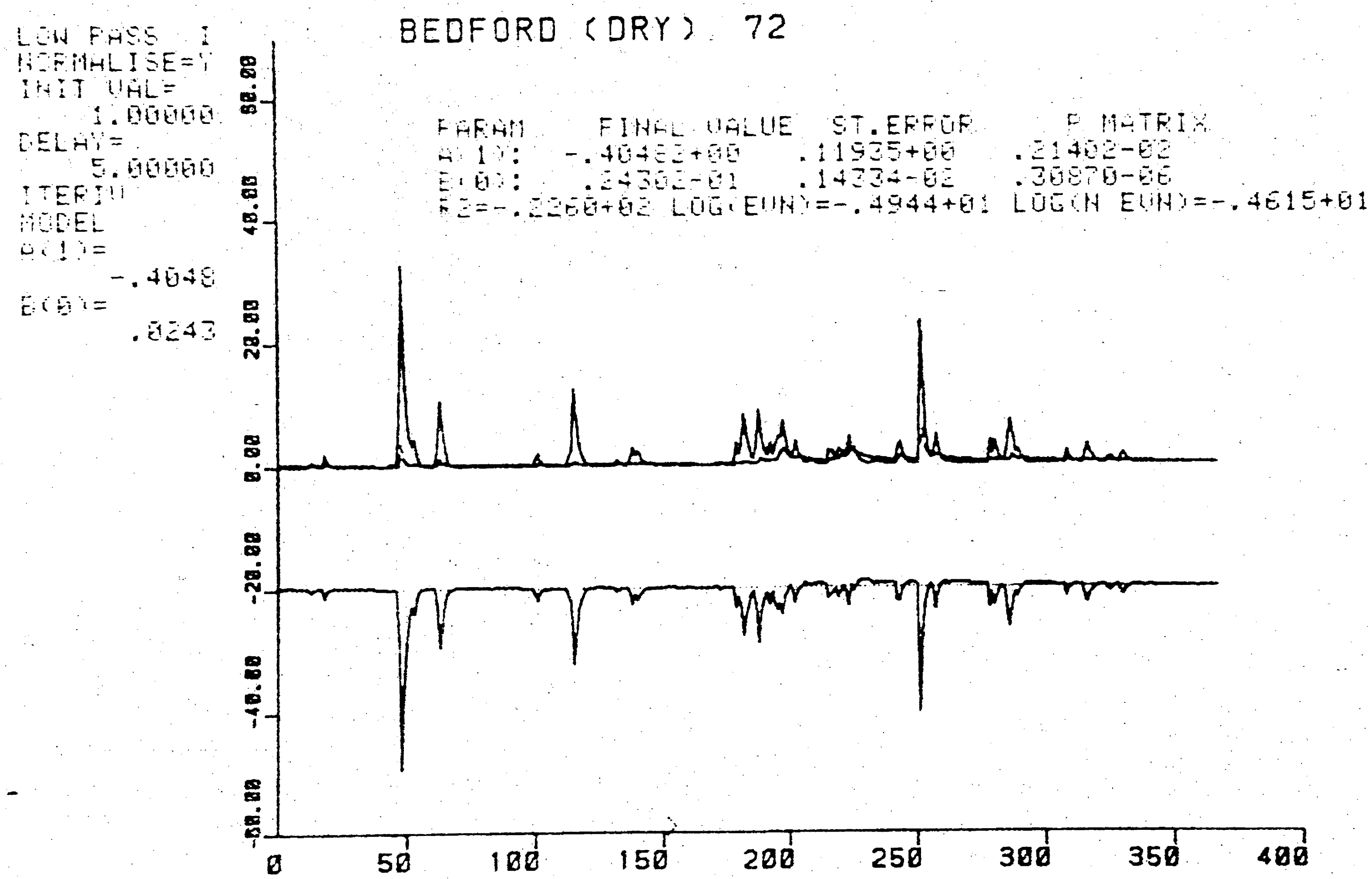


Fig 5.169 1972 Model response with parameter values set to those estimated for 1971 (Fig 5.163)

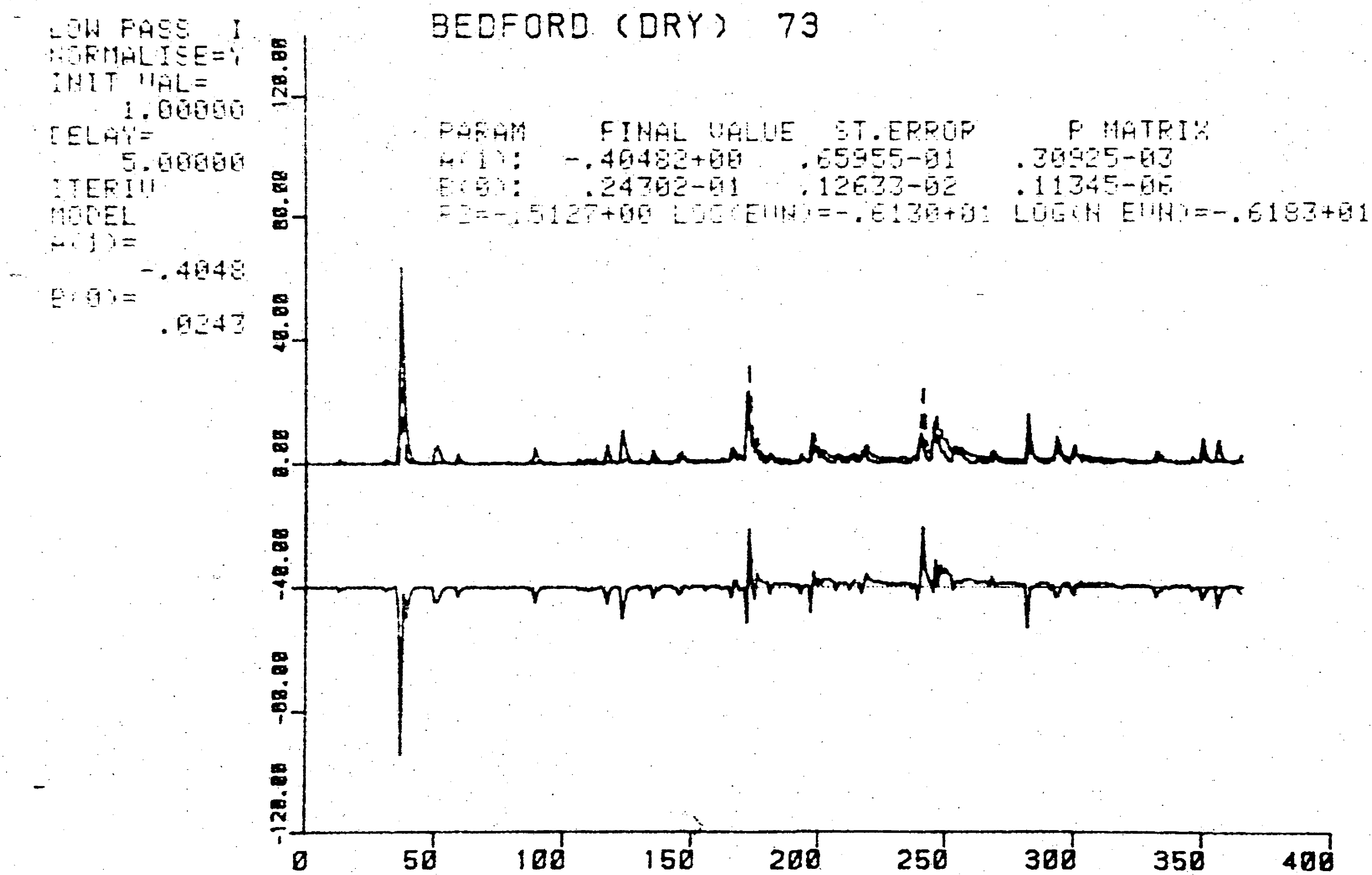


Fig 5.170 1973 Model response with parameter values set to those estimated for 1971 (Fig 5.163)

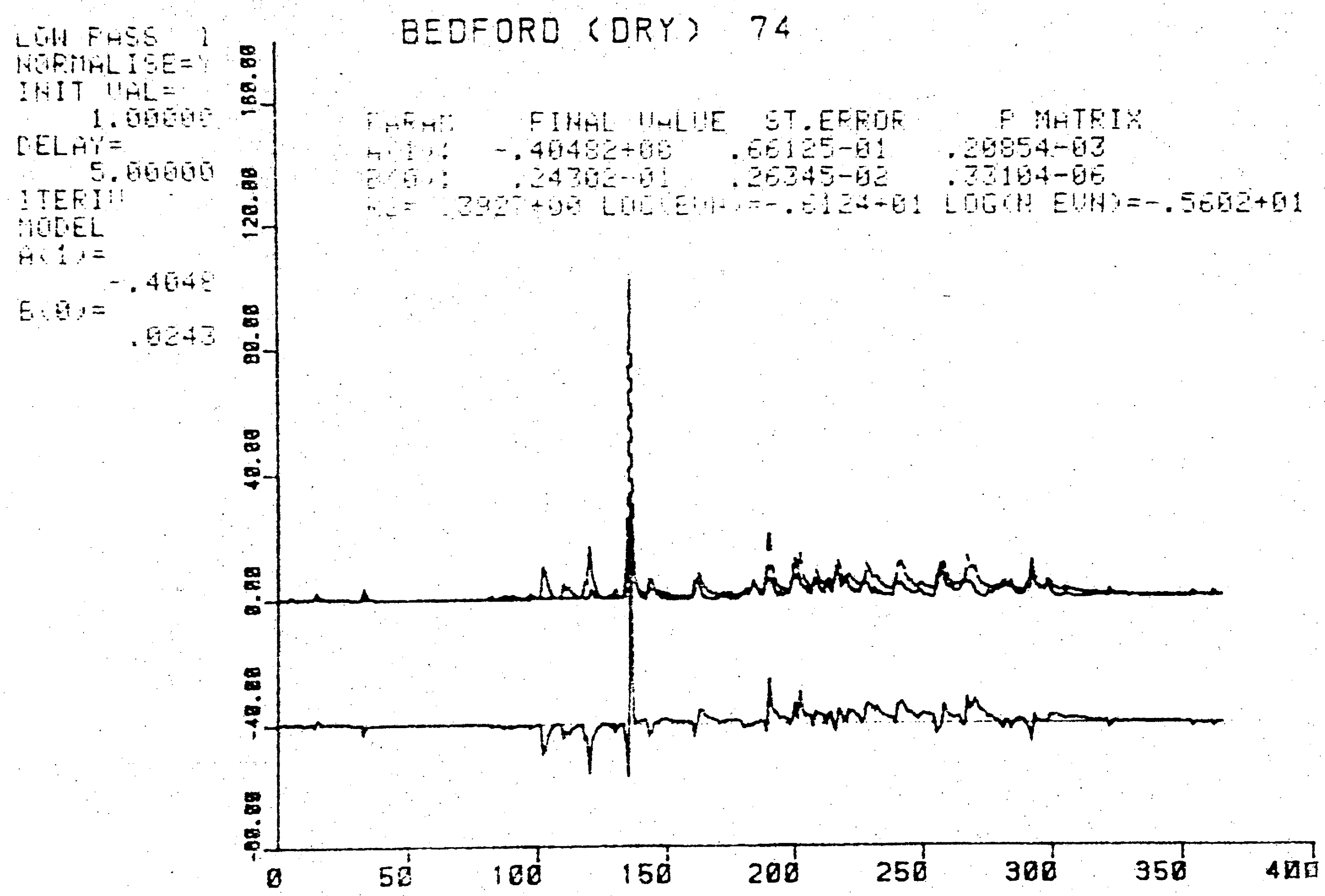


Fig 5.171 1974 Model response with parameter values set to those estimated for 1971 (Fig 5.163)

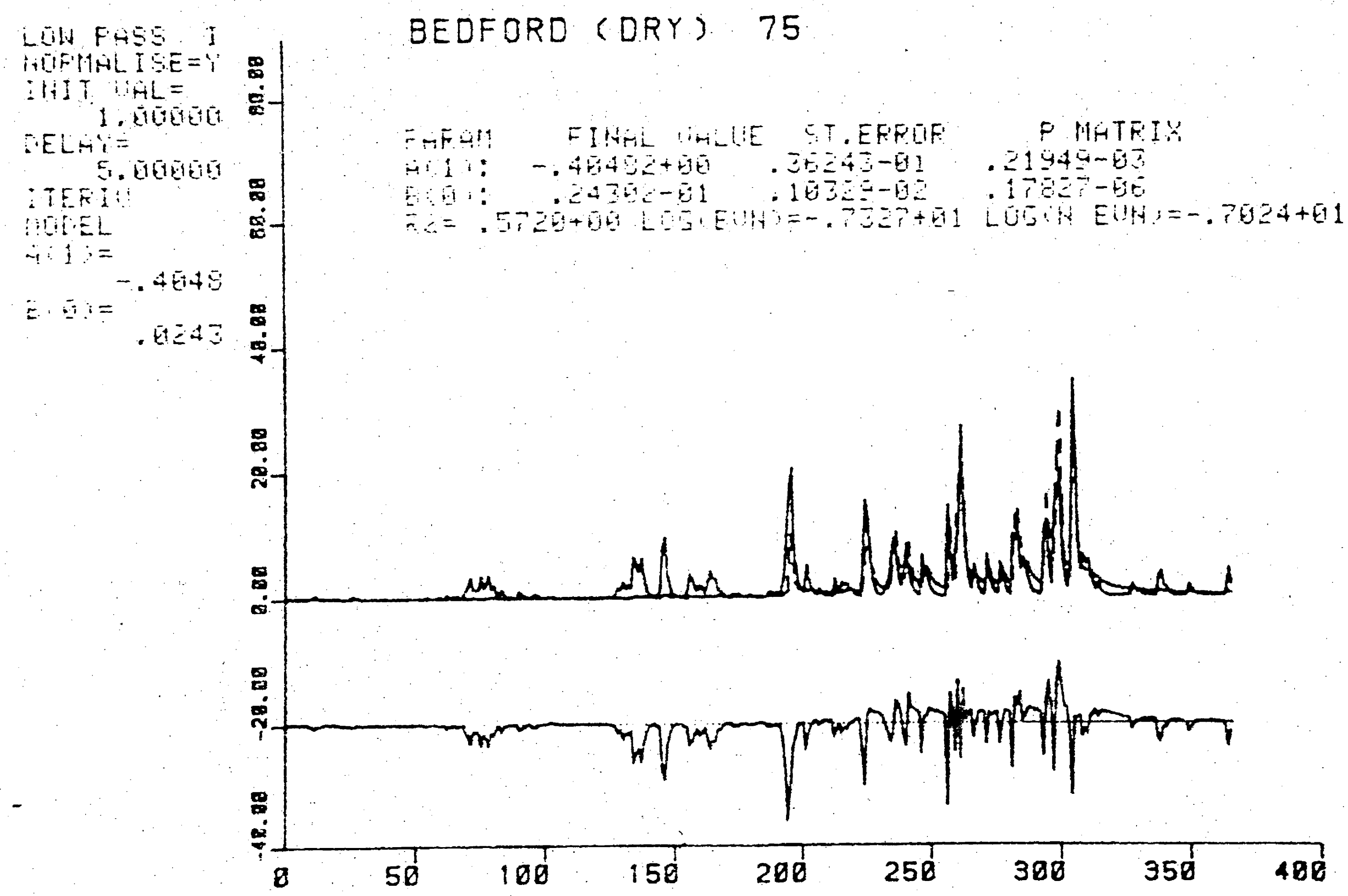


Fig 5.172 1975 Model response with parameter values set to those estimated for 1971 (Fig 5.163)