However, only the Suviana dam has a large storage capacity, the dams at Molino del Pallone and Pavana being merely basins connected to the Suviana dam.

The Suviana dam is used principally to generate electrical power. The Suviana and Brasimone reservoirs are connected by a repumping station which, as is known, pumps water at night into the reservoir at a higher elevation (from Suviana to Brasimone) when electrical power consumption is low, and restores peak power during the day by means of the turbine-powered plant (from Brasimone to Suviana).

The system of reservoirs has a total capacity of approximately 40 $x10^6$ m^3 (only Suviana has a useful capacity of approximately 34 $x10^6$ m^3), while the area of the connected basins is approximately 223 Km^2.

The Reno rises at the confluence of two branches (the Reno di Prunetta and the Reno di Campolungo) and its initial reach is a watercourse in a state of perfect balance thanks both to the absolute stability of the soil and the gentle slopes traversed. The river drops from a height of 958 metres (Prunetta) to 650 metres (Pontepetri, where the left bank tributary Maresca empties into the Reno), over a distance of 8.3 Km with an average gradient of 3.7% which reaches 1.7% in the lowest portion of the reach in question (from Piastre to Pontepetri)

At Pontepetri the valley is deeply confined in the last section about 3 Km from Ponte della Venturina. In this section, which is 15 Km in length and drops from a height of 650 m to 387 m with an average gradient of 1.8%, the Reno receives two left-bank tributaries, the Orsigna and Randaragna, and, on the right bank, the Limentra di Sambuca, which discharges the water arriving from its basin of approximately 45 Km^2, the whole of which is situated in the highest reservoir of the Apennines known as "Collina". In this area the Reno valley extends mainly along the left branch, from which descend the tributaries Orsigna and Randaragna that rise in the aquifers of the massif of Corno alle Scale which, with the peaks La Nuda and M. Gennaio situated approximately 2,000 metres above sea level, form one of the highest points in the Tuscan-Emilian Apennines. Like the former reach, this one is also characterised by the stability of the slopes and the watercourse.

Evident on the left-bank from Ponte della Venturina, apart from the occasional platform of sandstone rock, is the gradual transition from marly clay to an almost plastic clay starting at the Marano (the Rio Maggiore, Silla and Marano empty into this section); from here to Lissano the soil traversed is sandy marl; from Lissano to Vergato (to the confluence of the Vergatello) the plastic clay becomes predominant again.

On the right side, after Ponte della Venturina, a marly clay formation gives way to sand after Porretta, and from there to Riola (to the confluence of the Limentra di Treppio) to plastic clay in a highly unstable condition.

The Camperolo feeds into the Reno a short distance from Vergato. In this section the river drops from a height of 387 metres to 170 metres, while the average gradient falls to 0.8%.

Before Vergato the valley abounds in clay and enters the myocene formation within which the river bed is confined before changing, prior to Pian di Venola, to an area of deposits in which the channel cuts through soil of recent alluvial formation.

Between Ca' Lelli (Vergato) and Pian di Venola (at the left-bank confluence of the Venola) the river extends for 7 Km, with a height difference of 42 metres (dropping from 170 metres to 128 metres) and an average gradient of 0.6%; between Pian di Venola and the confluence of the Setta (on the right bank), the length of the river is 10 Km, the height difference is 28 metres (from 128 metres to 100 metres) and the average gradient is 0.3%.

The river then crosses soil consisting of recent alluvial deposits.

The transition from hill to plain is marked by the Casalecchio weir. The section of the Reno at the foot of the hills is of great hydraulic importance since it acts as the link between the upland basins and the embanked channel downstream.

These features are made even more marked by the location of this section of the river which lies in an urban area (the city of Bologna).

7.1.3. The basin downstream of the Casalecchio section

The river Reno then winds across the plain in the districts of Bologna, Ferrara and Ravenna, covering a total length of approximately 124 km, into which flow the Samoggia, Canale Navile, Savena Abbandonato, Idice, Sillaro, Santerno and Senio.

The morphological characteristics of the main channel are extremely variable inasmuch as they have been affected by the various hydraulic works which, over the years, have determined the current course of the Reno.

It is in fact known that the natural basin of the Reno originally terminated at the confluence with the Samoggia, becoming a right-hand tributary of the river Po further downstream.

Further to the large-scale hydraulic works designed to rehabilitate and reclaim the lowlands around Ferrara, the Reno was diverted through the Benedettino Channel and the final reach of the Primaro Po before acquiring, through a series of routing works, its current course, which may be summarized as follows:

- first reach (approximately 19 km) as far as Ponte Bagno, presenting a tortuous course, broad berms alternating with embanked narrows whose purpose is to regulate flood flow;

- second reach (approximately 18 km) as far as Cento, presenting a relatively regular course;

- third reach (approximately 47 km) as far as Bastia, presenting a markedly canalized channel which is in places totally insufficient to discharge peak flood flows with any degree of hydraulic safety;

- fourth reach (approximately 40 km) as far as the sea, where the characteristics of the channel are generally satisfactory.

The particularly delicate state of the third reach is clear from the foregoing summary. It was here that in the 1950s the river burst its left bank at Gallo di Poggio Renatico, and a free spillway is still in place at this point to ensure the natural channelling of overflow into the adjacent "Cembalina" reclamation channel. It should be pointed out that the Cavo Napoleonico outlet, installed as a flood channel for the Reno, is also located in this reach.

7.1.4 Current state of the lower Reno river. The hydraulic/hydrologic problems

As far as the current state of the basin is concerned, the hydrographic network presents the features typical of Appennine watercourses, characterized in general by unstable and readily erodable highland soils, densely inhabited areas in the foothills where the watercourses have to be stabilized in terms both of horizontal development and height, and long embanked reaches in the plains subject to frequently rapid and violent floods.

In respect of the highland reaches, the question of hydraulic protection is combined with the need for stabilization of the region with particular attention to the landslip-prone areas underlying villages and community infrastructures.

In these cases operations such as afforestation, hydraulic forestry organization and slope consolidation works are planned and are being implemented in order to reduce deal with the possibility of landslips and collapses and their consequences which are very common in hillside regions.

Moving downstream, the Reno protection system in the plain is extremely complex and delicate as far as its management is concerned in the event of flooding, not just because of the large number of tributaries (some of them large) which flow into the main channel in the plain, but also because of the existence of a non-automatic peak flow subsidence and control system in the form of the Napoleonic Channel and flood channels adjacent to the watercourse.

Analyzing the maximum discharge rates which should flow safely in the lowland reach of the Reno, the following list of maxima in flows is obteined:

- 2000 m^3/s at Casalecchio;
- 1500 m^3/s at Passo Bagnetto (including discharge from the Samoggia, estimated at 300 m^3/s);
- 1350 m^3/s at Cento;

- 1200 m^3/s at Panfilia (this discharge could be reduced to 700 m^3/s considering the Napoleonic Channel to be perfectly efficient with a peak flood flow reduction rate of 500 m^3/s);
- 670 m^3/s at Gallo;
- 660 m^3/s at Passo Segni;
- 650 m^3/s at Gandazzolo;
- 1250 m^3/s at Bastia (including inflow from the Idice and Sillaro, equivalent to 650 m^3/s).

It will be noted that in the reach extending from Gallo to Bastia there are complex water control problems which are exacerbated by the need to discharge the drainage water from the surrounding land reclamation works.

In view of these considerations, and given the particular importance attached to protection against the risk of flooding of the surrounding plains, the principal hydraulic operations have been aimed at reducing this hydraulic risk by a thorough evaluation of the design flood discharge rates and the redesign of the sections by means of internal widening works, bank raising and reinforcements in the stop bank areas.

Lastly, as far as the management of flood events is concerned, the structures, such as the Napoleonic Channel, which are designed to reduce the risk of flooding, must be made operational, while operational management rules must be defined for the discharge of the reclamation drainage water, without this being added to the peak flow rates. In the Reno basin and in the heavily populated plain, reclamation works were installed a long time ago and are managed by consortia operating in the basin (Consorzio Bonifica Renana, Consorzio Reno-Palata, Consorzio Romagna-Centrale, Consorzio Romagna-Occidentale); these consortia are primarily engaged in the maintenance of the hydraulic reclamation structures, and they are today increasingly concerned with water management and distribution for agriculture. The operations planned for the reclamation areas basically entail adapting the drainage network to the altered hydrological behaviour (largely due to the increase in the urbanized area and the resulting variation in the hydraulic coefficient), upgrading the pumping stations, and normal network maintenance.

At the present time a real time flood monitoring and forecasting system is in operation; this system, based on the measurements made at Casalecchio, provides flood forecasts with a 12 hour advance warning in the Cento, Gallo, Gandazzolo and Bastia sections. Capitalizing on this availability, a feasibility study on the possiblity of developing a comprehensive decision support system, designed to minimize the risk of flooding on the basis of forecasts provided by various sources (such as meteorological radar, rainfall forecasting models, flood forecast models), was carried out within the frame of AFORISM. The study gave not only the opportunity of analizing the status and the quality of available data, but also to analyse the actual needs of an operational flood forecasting and flood control service.

Water Resources of the Reno Basin

From the point of view of the use of water resources, the basin is basically in a state of equilibrium, at least for civil, municipal and and industrial uses. In the Bologna area one of the top priorities is to limit the use of groundwater, mainly from the Reno basin, so as to reduce subsidence, and to step up surface draw-off from the Setta river. A separate problem is posed by the highland areas which, with the growth of tourism and the fragmentation of network intake points, have witnessed an increasing imbalance between supply and demand, with attendant shortcomings in water supply service. Some connection between the highland networks and linkage between the highland and the plain systems is accordingly required in order to achieve efficient operation in both of these areas.

In the Ravenna region, where the use of groundwater has been entirely abandoned in order to halt subsidence and the infiltration of brackish water in the aquifers, the problem to be faced entails ensuring water supply from the surface resources during the dry months.

Water Quality in the Reno Basin

Other problems in the Reno basin that could affect the availability of drinking water are connected with the quality of the water from the river and the aquifers. The organic matter present in the water of the Reno derives mainly from sewage (65%), compared with 34% from industry and small manufacturing concerns. With regard to the eutrophication component, the largest proportion is attributable to agriculture (51%), followed by the sewage network of civilian structures and industry/small manufacture (27%) and animal husbandry (20%). Consequently, the projects planned in this area aim to contain the polluting and eutrophicating substances which actually feed into the drainage network from widespread point sources. Under the planned action, the course of the river Reno has been divided into three reaches, to which different quality standards have been assigned:

1) from the springs at Sasso Marconi: water for salmonids and purification;

2) from Sasso Marconi to Sala Bolognese: water for cyprinids and social-recreational use;

3) from Sala Bolognese to the sea: water for cyprinids and irrigation.

River Environmental

Lastly, since the river environment in its broadest sense is considerably threatened by numerous factors of aggression that have distorted its structure (morphological and ecosystem simplification) and reduced its territorial size in favour of other activities (agriculture, settlements, infrastructures), various projects have been designed to rehabilitate the degraded state of the river and to preserve the river's amenities and ecosystems.

Mindful of this complex background, an efficient flood management system is to be designed for the Reno River. This chapter proceeds to show that such a system is not only feasible but is merely a step away from implementation.

7.2 DESCRIPTION OF AVAILABLE DATA

7.2.1 Definition of the hydro-meteorological data required for the mathematical models

As has been said, the flow conditions in the river Reno basin have to be described by means of mathematical models which require the collection of a series of basic hydro-meteorological data. The basic purpose of the mathematical models is to calculate:

a) surface flow regimes in the complete hydrological year (rainfall-runoff model);

b) extreme rainfall and discharge values to be used in the surface runoff analysis and for the resulting assessment of the areas subject to the risk of flooding.

On the basis of experimental observations and partial analytical models, these models aim at simulating the individual hydrological processes that occur in the basins and to connect them together by means of mathematical relations so as to obtain a detailed quantitative relation of the complex phenomenon of hydrological transformation.

The hydro-meteorological input data required for this type of models include rainfall, temperature and discharge values, at hourly intervals, recorded at the measuring stations in the basin. Figure 7.1 shows the network of stations for the measuring of hydro-meteorological data currently in place in the river Reno basin.

The network comprises stations for the measurement of:

- rainfall;
- temperature;
- water levels in the river.

At the present time the level stations and several rainfall stations are telemetric (i.e. connected in real time to a data collection centre), while the remaining stations are of the traditional mechanical kind with the recording of data on paper.

Table 7.1 shows a list of the stations and their characteristics (geographical position, type of station, elevation of station in metres a.s.l., etc.).

The traditional stations form part of the network operated by the Hydrographic Service, while the telemetric level and rainfall networks are divided between the Hydrographic Service and "Consorzio della Bonifica Renana" (the Reno Consortium).

7.2.2. Collection and analysis of meteorological data required for the rainfall-runoff model

As it was pointed out, most of the rainfall and temperature stations located in the Reno basin are of the traditional kind with the mechanical recording of data on paper. This required the digitization of the weekly data charts such as the ones shown in Figures 7.5 and 7.6 for two rainfall and temperature stations in the Reno basin.

Next, a computer code was used to translate the coordinates of the sample data into a file of the following type:

YEAR	MONTH	DAY	HOUR	MIN	DATA
XX	XX	XX	XX	XX	XXXX

The data collected in this manner revealed several periods of non-operation of the station. Therefore, the data were reconstructed on the basis of a space-time correlation with the other stations of the same kind, using a method based on Kalman filters as described in Section 4.3.2. In order to verify and validate the results of this reconstruction, the data .of several stations were completely reconstructed and compared with the data actually recorded (see figures 7.7 and 7.8). This type of operation was performed for the period extending from 1st February 1990 to 31st December 1992, i.e. the period deemed strictly necessary for the calibration and verification of the rainfall-runoff model.

Code	Gauging Station	LATIT.[1]	LONG.[2]	Elevation m as.l.	Station type[3]		
0001	Piastre	44°00'	1°37' W	741	R		
0002	Maresca	44°04'	1°36' W	1043	R	T	
0003	Pracchia	44°03'	1°32' W	627	R	T	
0004	Orsigna	44°05'	1°34' W	806	R		
0005	Monte Pidocchina	44°04'	1°31' W	1100	R		
0006	Diga di Pavana	44°07'	1°27' W	480	R		
0007	Porretta Terme	44°09'	1°28' W	349	R	T	
0008	Monteacuto delle Alpi	44°08'	1°34' W	915	R		
0009	Lizzano in Belvedere	44°09'	1°33' W	640	R		
0010	Bombiana	44°13'	1°29' W	804	R		
0011	Acquerino	44°00'	1°26' W	890	R	T	
0012	Treppio	44°05'	1°25' W	710	R		
0013	Diga di Suviana	44°08'	1°25' W	500	R	T	
0014	Riola di Vergato	44°13'	1°23' W	240	R		
0015	Vergato (RENO)	44°17'	1°20' W	195	R		L
0016	Cottede	44°07'	1°16' W	850	R	T	
0017	Diga del Brasimone	44°07'	1°20' W	830	R		
0018	Monteacuto Vallese	44°14'	1°15' W	747	R		
0019	Monzuno	44°16'	1°11' W	620	R	T	
0020	Sasso Marconi	44°23'	1°13' W	130	R		
0021	Monteombraro	44°23'	1°27' W	727	R	T	

Table 7.1 List of hydro-meteorological gauging stations in the Reno river catchment. (continued)

1 1' in latitude is equivalent to 1850 m.

2 Longitude is relevant to Rome Meridian (Monte Mario). The longitude of Monte Mario relevant to Greenwich is 12°27'08"
1' in longitude is equival'ent to 1330 m.

3 Station type:
R: rain gauge;
T: temperature gauge;
L: level gauge.

Code	Gauging station	LATIT.	LONG.	Elevation m a.s.l.	Station type		
0022	Montepastore	44°22'	1°20' W	596	R		
0023	Monte San Pietro	44°26'	1°19' W	317	R		
0024	Bologna San Luca	44°29'	1°09' W	286	R		
0025	Bologna oss. sez. idrogr.	44°30'	1°06' W	51	R	T	
0026	S. Benedetto del Querceto	44°15'	1°04' W	340	R		
0027	Monghidoro	44°13'	1°08' W	841	R		
0028	Pianoro (SAVENA)	44°22'	1°06' W	187	R		L
0029	Prugnolo	44°24'	0°58' W	276	R		
0030	San Clemente	44°19'	0°58' W	177	R		
0031	Montecatone	44°21'	0°49' W	286	R		
0032	Traversa	44°06'	1°10' W	871	R		
0033	Firenzuola	44°07'	1°04' W	422	R	T	
0034	Barco	44°04'	1°03' W	741	R		
0035	Pietramala	44°09'	1°04' W	845	R		
0036	Fontanelice	44°15'	0°53' W	165	R		
0037	Bibbiana	44°08'	0°56' W	658	R		
0038	Casola Valsenio	44°12'	0°49' W	195	R		
0039	Riolo Terme	44°17'	0°44' W	73	R		
0040	Ferrara	44°50'	0°50' W	15		T	
0041	Idrovora di Guagnino	44°41'	0°14' W	1		T	
0042	Anzola dell'Emilia	44°33'	1°15' W	40		T	
0043	Imola	44°21'	0°44' W	47		T	
0044	Alfonsine (SENIO)	44°30'	0°25' W	7		T	L
0045	Casalecchio (RENO)						L
0046	Cento (RENO)						L
0047	Dosso (RENO)						L
0048	Panfilia (RENO)						L
0049	Gallo (RENO)						L

Table 7.1 List of hydro-meteorological gauging stations in the Reno river catchment. (continued)

Code	Gauging station	LATIT.	LONG.	Elevation m a.s.l.	Station type		
0050	Bastia (RENO)						L
0051	Volta Scirocco m. (RENO)						L
0052	Volta Scirocco v. (RENO)						L
0053	Calcara (SAMOGGIA)						L
0054	Forcelli (SAMOGGIA)						L
0055	Sasso Marconi (SETTA)						L
0056	Ponte Caselle (SAVENA)						L
0057	Pizzocalvo (IDICE)						L
0058	S. Antonio (IDICE)						L
0059	Castel S. Pietro (SILLARO)						L
0060	Portonovo (SILLARO)						L
0061	Codrignano (SANTERNO)						L
0062	S. Bernardino (SANTERNO)						L
0063	Castelbolognese (SENIO)						L
0064	Botte Sillaro	44°25'	0°42' W		R		
0065	Budrio Olmo	44°33'	0°53' W		R		
0066	Correcchio	44°22'	0°46' W		R		
0067	Loiano	44°15'	1°06' W		R		
0068	Madonna	44°44'	1°01' W		R		
0069	Massarolo	44°32'	0°58' W		R		
0070	Molinetto	44°26'	0°45' W		R		
0071	Monte Ceresa	44°20'	1°03' W		R		
0072	Travallino	44°40'	0°52' W		R		

Table 7.1 List of hydro-meteorological gauging stations in the Reno river catchment.

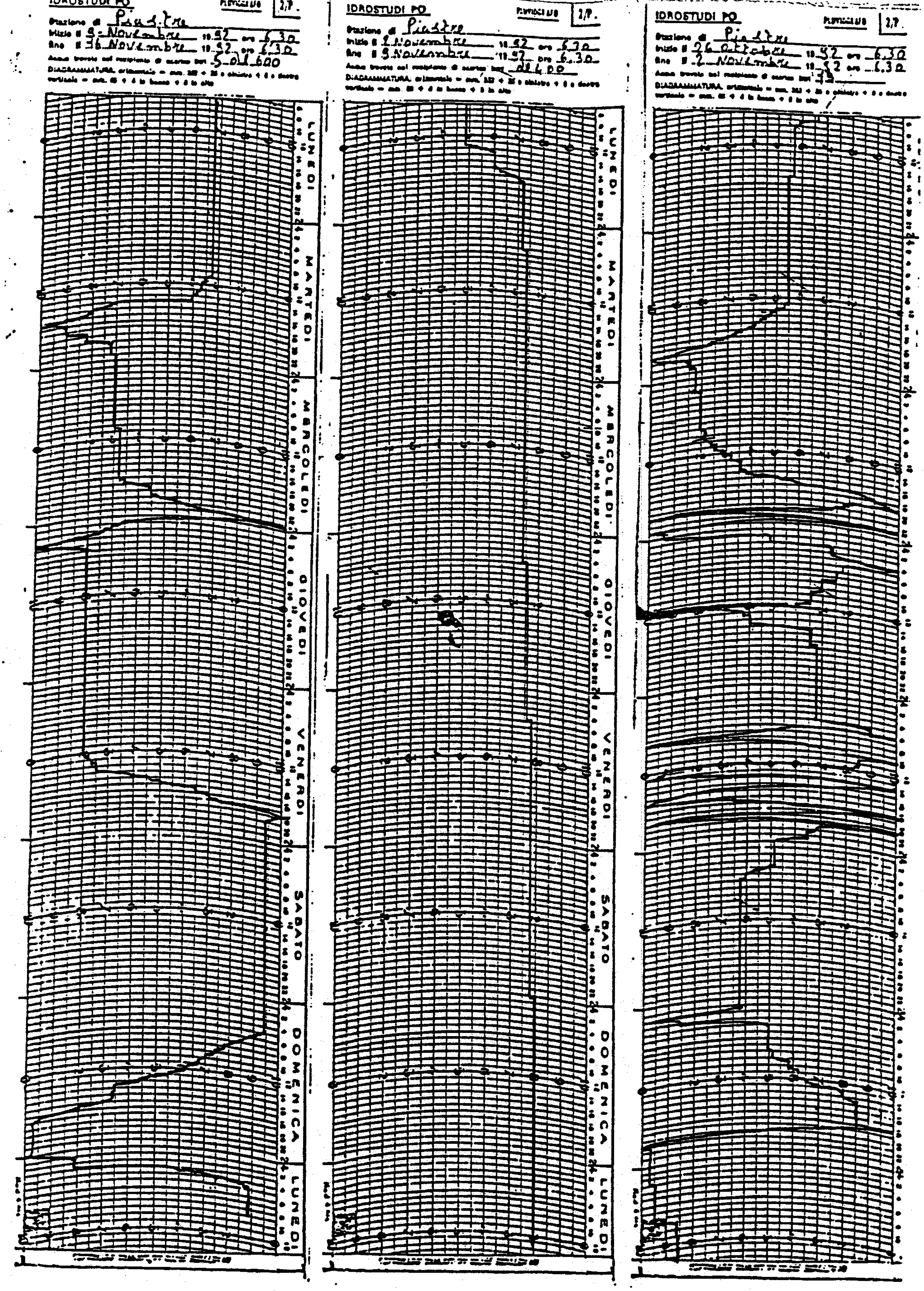


Figure 7.5 - Three charts recording three weeks from the tipping bucket rain-gauge at Piastre

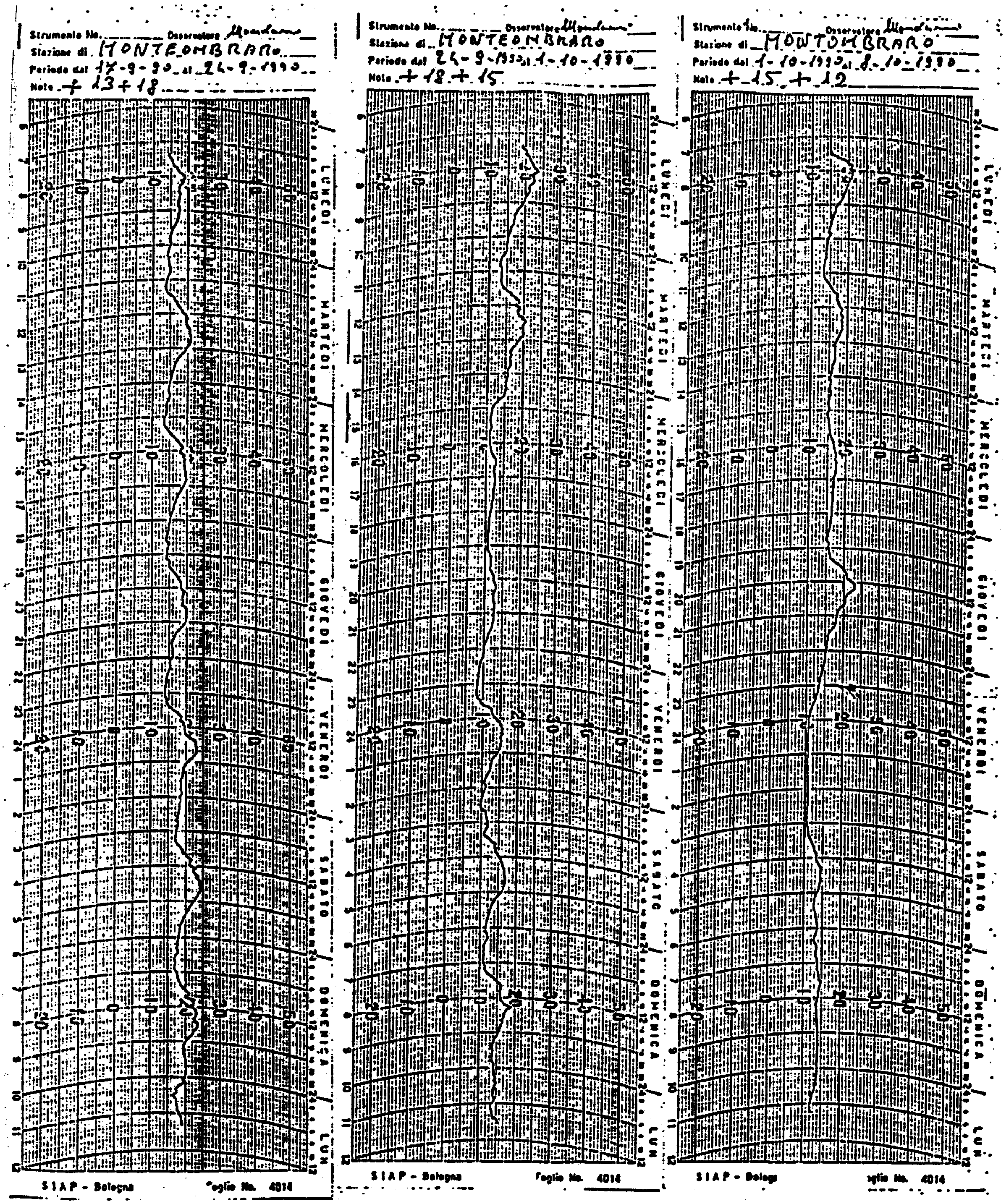


Figure 7.6 - Three weeks of temperature continuously recorded at the Monteombraro station

Figure 7.7 - One year (1990) of hourly rainfall at the Botte Sillaro station. Upper: recorded data; lower: reconstructed data.

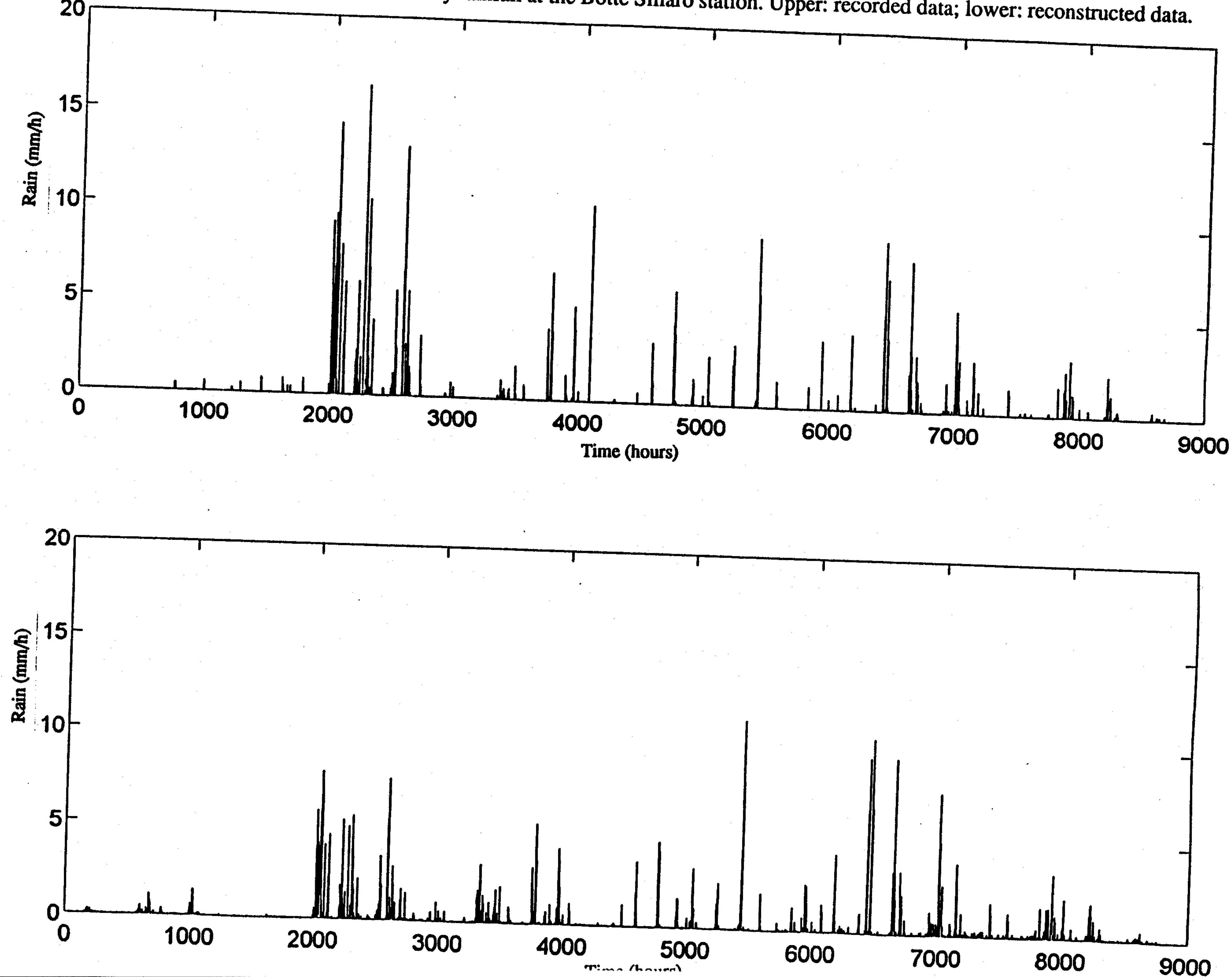
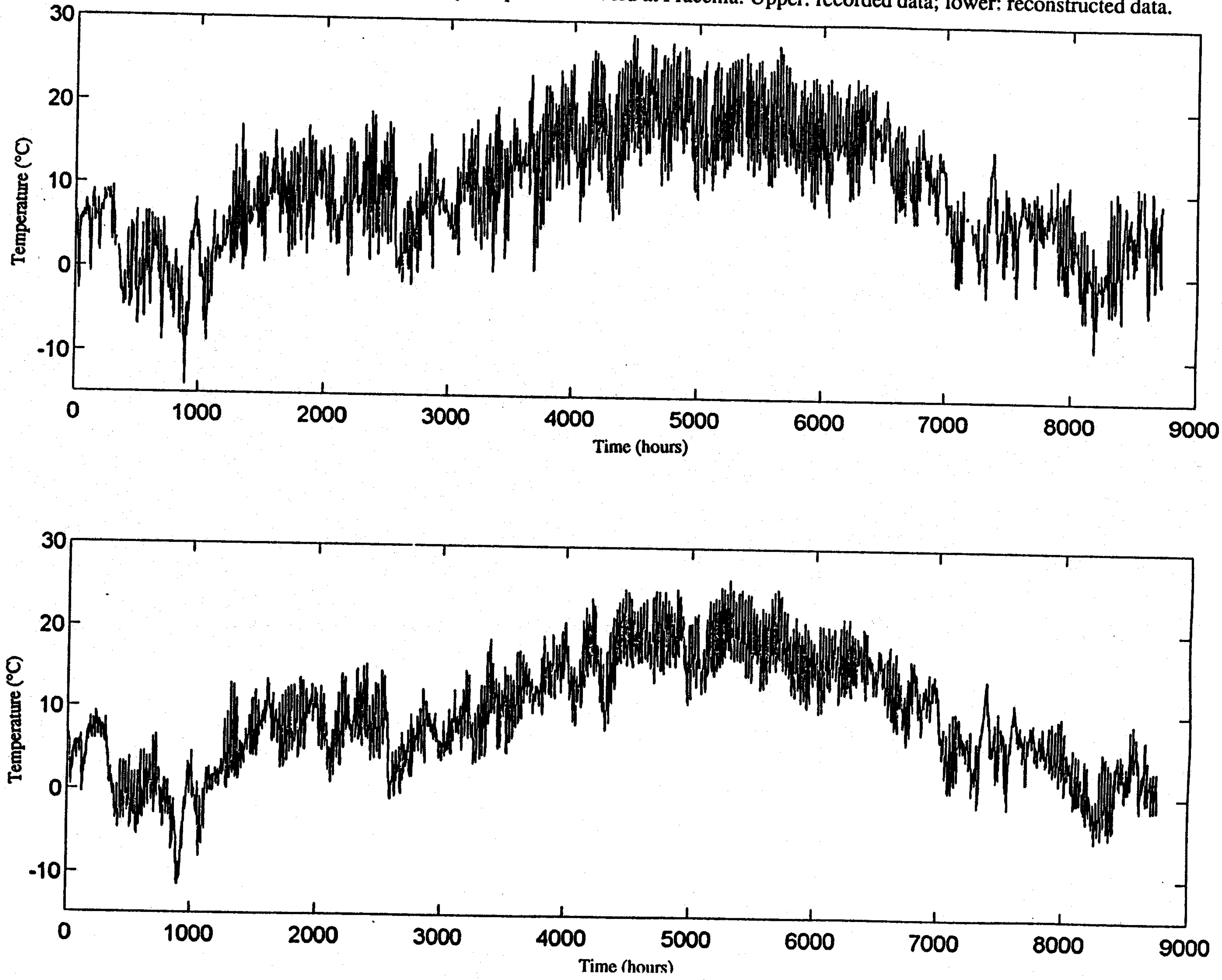


Figure 7.8 - One year (1991) hourly temperature record at Pracchia. Upper: recorded data; lower: reconstructed data.



7.2.3 Data required by the rainfall-runoff models

7.2.3.1 The rating curves for several level measuring sections

The calibration of the rainfall-runoff model for flood forecasting in the upland basins, as well as the flood routing models in the downstream section of the basin, requires the calibration of the rating curves relevant to several level gauging stations. The water level gauging network in the Reno basin is shown in Figure 7.9. Tables from 7.2 to 7.9 list the stations for each watercourse.

Code	Station
0015	Vergato
0045	Casalecchio
0046	Cento
0047	Dosso
0048	Panfilia
0049	Gallo
0050	Bastia
0051	Volta a Scirocco a monte
0052	Volta a Scirocco a valle

Table 7.2 - Level gauging stations in the Reno River.

Code	Station
0053	Calcara
0054	Forcelli

Table 7.3 - Level gauging stations in the Samoggia torrent.

Code	Station
0055	Sasso Marconi

Table 7.4 - Level gauging stations in the Setta torrent.

Code	Station
0056	Ponte Caselle
0028	Pianoro

Table 7.5 - Level gauging stations in the Savena torrent.

Code	Station
0057	Pizzocalvo
0058	S.Antonio

Table 7.6 - Level gauging stations in the Idice torrent.

Code	Station
0059	Castel S.Pietro
0060	Portonovo

Table 7.7 - Level gauging stations in the Sillaro torrent.

Code	Station
0061	Codrignano
0062	S.Bernardino

Table 7.8 - Level gauging stations in the Santerno torrent.

Code	Station
0063	Castelbolognese
0044	Alfonsine

Table 7.9 - Level gauging stations in the Senio torrent.

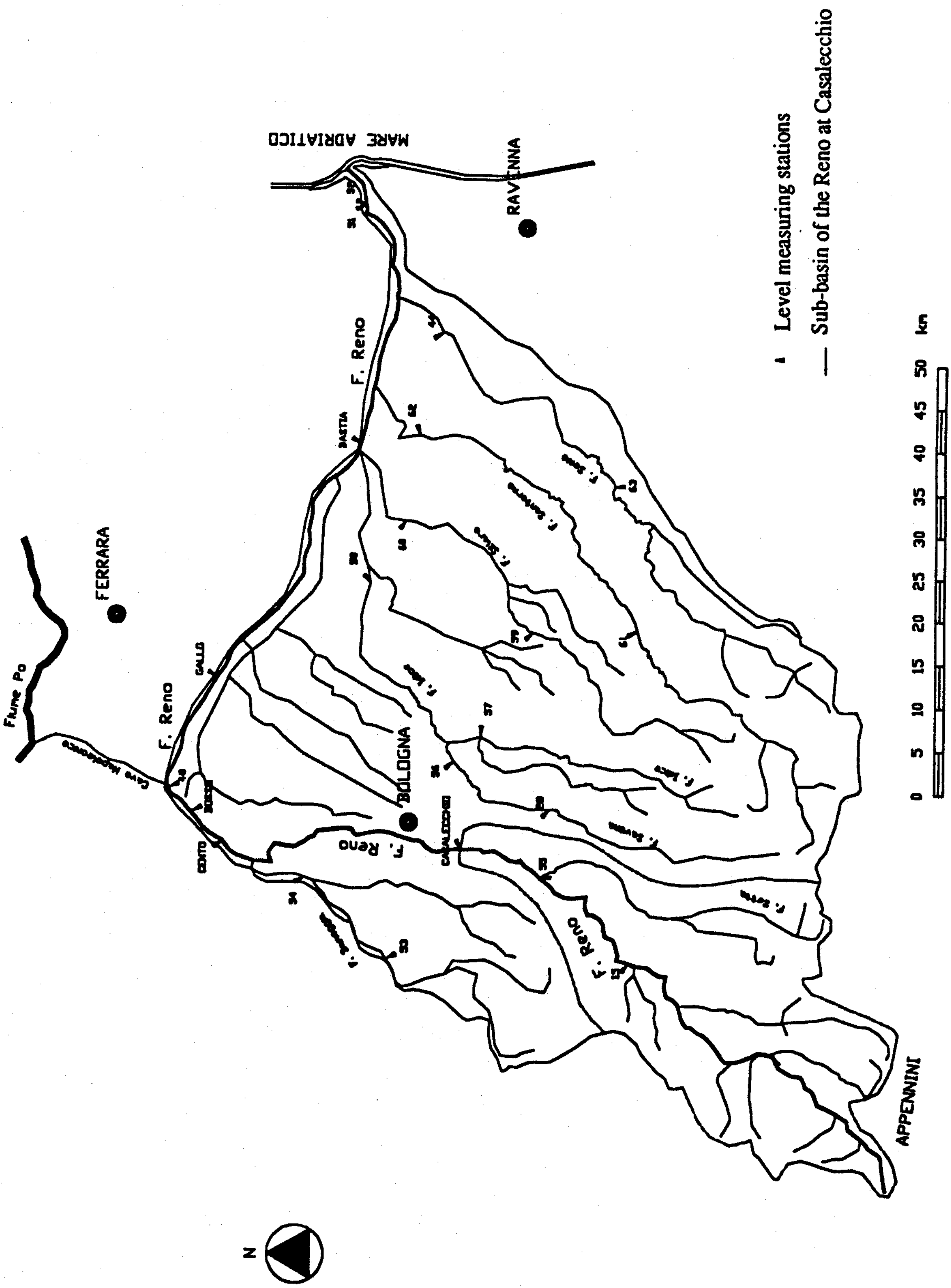


Figure 7.9 - Level gauges in the Reno river basin

On the basis of the considerations which will be discussed in detail in the following chapters, it was necessary to calculate the rating curves of the measuring stations:

Water Course	Gauging Station
Reno	Casalecchio
Reno	Bastia
Samoggia	Calcara
Savena	Ponte Caselle
Idice	Pizzo Calvo
Sillaro	Castel S.Pietro
Santerno	Codrignano
Senio	Castel Bolognese

The remote hydrometric stations (see figure 7.10) show the water surface elevation "d" at hourly intervals .

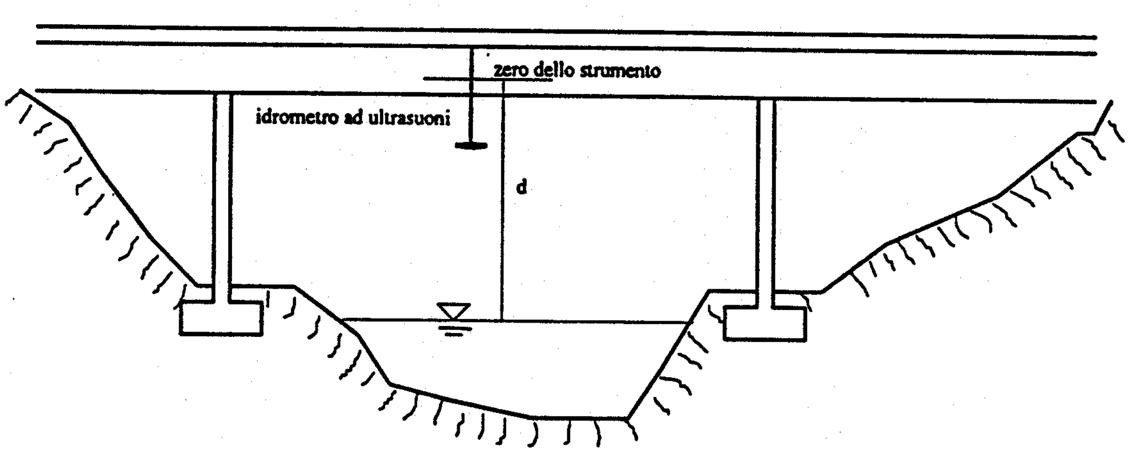


Figure 7.10 - Example of positioning of an ultra-sound based level gauge

The data is then stored in a file of the following type:

YEAR	MONTH	DAY	HOUR	MIN.	DATA
XX	XX	XX	XX	XX	XXXX

It will immediately be seen that the translation of a data item of this type into an element sufficient to determine the discharge entails the determination of the absolute elevation (in metres above sea level) of the gauge zero. In fact, only in this way is it possible to obtain an elevation comparable with that of the other stations and to calculate the rating curve. Table 7.10, which summarises the data under study for several Reno basin stations, was obtained on the basis of the data supplied by the remote hydrometer operators (Hydrographic Service and "Bonifica Renana").

Code	Gauging Station	Elevation of the Instrument Zero (m a.s.l.)
0045	Casalecchio	60.300
0046	Cento	16.490
0047	Dosso	11.250
0049	Gallo	5.010
0050	Bastia	0.000
0053	Calcara	43.950
0056	Ponte Caselle	34.500
0057	Pizzo Calvo	48.100
0059	Castel S.Pietro	70.500
0061	Codrignano	66.460
0063	Castel Bolognese	32.630

Table 7.10 Absolute elevation (m a.s.l.) of the instrument zeroes for a number of telemetering level gauges installed in the Reno river basin.

As is known, the rating curves translate the levels measured on the river into discharges, e.g. the elevation of the water surface, measured in metres above sea level, into discharge, measured in cubic metres per second.

In the case of the Reno river many of the stations of the telemetering network are located at pre-existing traditional level gauges, for which the Hydrographic Service had calibrated the rating curves. Other stations are situated in new locations and, moreover, they are generally sited so as to protect specific structures (for example, bridges, dikes by heavily urbanised areas, etc.).

It should be pointed out that the rating curves calibrated by the Hydrographic Service go back in the best cases to 1974, and in any case the location of the remote hydrometer is very different from that of the pre-existing traditional hydrometer. Therefore, the characteristic elements (basin involved, pre-existence of a hydrographic station, presence of a jump sill, etc.) were collected for the focus stations in order to obtain a complete overview of each station and therefore decide whether to proceed, albeit rapidly, with topographic surveys of the sections.

At this stage of the study, in view of the preliminary nature of the feasibility study, the possibility of conducting extensive stream gauging operations in loco (measurements with current meters, etc.) was rejected. As has been said, since discharge measuring campaigns were not conducted, the determination of the rating curves, where these were missing or unreliable, was performed by means of geometrical measurements of the gauging section and appropriate applications of the flow equations or, in the case of an instrument placed on elements comparable to broad-crested weirs, the weir equation.

The reliability of the rating curves determined in this manner was verified by performing runoff balances and by checking the correspondence with any previously calibrated curves or, in the absence of earlier rating curves, checking that the runoff coefficient obtained in the verification period matched the values of hydrologically similar basins.

By using all these elements it was possible to determine the rating curves for the focus stations by means of fitting. The rating curves are expressed by means of curves divided into three branches, using the general formula:

$$Q-Q_i = A_i\,(H-H_i)^{B_i} \quad \text{with } Z_i < H < Z_{i+1}$$

where:

Q discharge at level H (in m^3/s);
H absolute level of water surface (in m a.s.l.);
H_i parameter obtained by fitting (in m a.s.l.);
Z_i lower elevation of curve validity limit;
Z_{i+1} upper elevation of curve validity limit;
Q_i discharge at level H_i (in m^3/s);
A_i, B_i fitting parameters.

Tables 7.11 - 7.13 set out the data indicated above for the focus stations.

Code	Gauging Station	Z0	H0	A0	B0	Q0
0045	Casalecchio	58.350	58.350	4.243	0.500	0.000
0050	Bastia	0.801	0.801	2.272	1.522	0.000
0053	Calcara	45.000	45.000	48.715	1.399	0.000
0056	Ponte Caselle	43.200	43.200	57.319	2.505	0.000
0057	Pizzo Calvo	47.400	47.400	1.429	1.000	0.000
0059	Castel S.Pietro	71.210	71.210	159.926	2.167	0.000
0061	Codrignano	66.500	66.500	181.643	1.541	0.000
0063	Castel Bolognese	31.660	31.660	0.636	1.000	0.000

Table 7.11 - Coefficients relevant to the first segment of the rating curves for a number of level gauging stations in the Reno river.

Code	Gauging Station	Z0	H0	A0	B0	Q0
0045	Casalecchio	60.350	60.350	227.560	1.907	6.000
0050	Bastia	2.201	2.201	11.979	1.421	3.792
0056	Ponte Caselle	43.300	43.300	17.813	1.627	0.179
0057	Pizzo Calvo	48.100	48.100	172.265	1.500	1.000
0059	Castel S.Pietro	71.750	71.750	268.216	1.206	42.097
0061	Codrignano	67.090	67.090	383.425	1.193	80.631
0063	Castel Bolognese	34.710	34.710	6.498	1.263	1.940

Table 7.12 - Coefficients relevant to the second segment of the rating curves for a number of level gauging stations in the Reno river.

Code	Gauging Station	Z0	H0	A0	B0	Q0
0045	Casalecchio	63.010	63.010	1362.474	0.967	1476.094
0050	Bastia	9.001	9.001	127.713	1.246	186.356
0056	Ponte Caselle	45.847	45.847	75.038	1.060	81.741
0059	Castel S.Pietro	72.026	72.026	710.380	1.304	98.763
0061	Codrignano	67.608	67.608	1050.918	1.351	255.343
0063	Castel Bolognese	36.910	36.910	29.041	1.728	19.540

Table 7.13 - Coefficients relevant to the third segment of the rating curves for a number of level gauging stations in the Reno river.

7.2.3.2 Basic maps and digital terrain model of the reno basin

In order to characterise the geomorphology of the Reno river (closed at the Casalecchio section), appropriate maps are required. The method used in this study was to obtain, in addition to the traditional maps (I.G.M. map, Regional Technical Map), a numerical map better suited to the processing of morphological basin indexes. A numerical map is quite simply a map furnished not on paper but on computer media. The elevation information is accordingly related to a fixed-interval grid which covers the area. It should be borne in mind that most of the upland basin of the river Reno falls under the Emilia Romagna Regional Authority, while the more southern part lies in the Tuscany Region. Although both of these Authorities have numerical maps of their regions, they have adopted a different grid interval (400 metres for Emilia Romagna, 200 metres for Tuscany). The file was constructed by combining the two numerical maps with different grid sizes and adopting the 400 m grid size. The result is a data file of the following type:

UTM coordinates (in metres)

East	*North*	*Elevation (in m a.s.l.)*
683800	*4930400*	*200.1*

The numerical map obtained can readily be used for calculations aimed at determining particular indices characterising the geomorphology of the basin. Figure 7.2 shows the final map obtained by GIS processing of the original data file formed by combining the two numerical maps.

7.2.4 Data required for the flood routing model

Th.e Parabolic and Backwater (PAB) flood routing model used, requires a suitable topographic description of the watercourse.

As we shall see below, this model will refer to the section of the Reno between the Chiusa at Casalecchio and the Bastia bridge, covering a total length of approximately 92 Km. The topographic description of the watercourse adopted is based on the Carra survey of 1971, as given in the Bologna Hydrographic Service study "Comparison of levels of the main hydrographic network in the river Reno basin" (1977). Specifically, there are 194 sections in the reach with which we are concerned, the elevation in metres above sea level being given for each point on the watercourse.

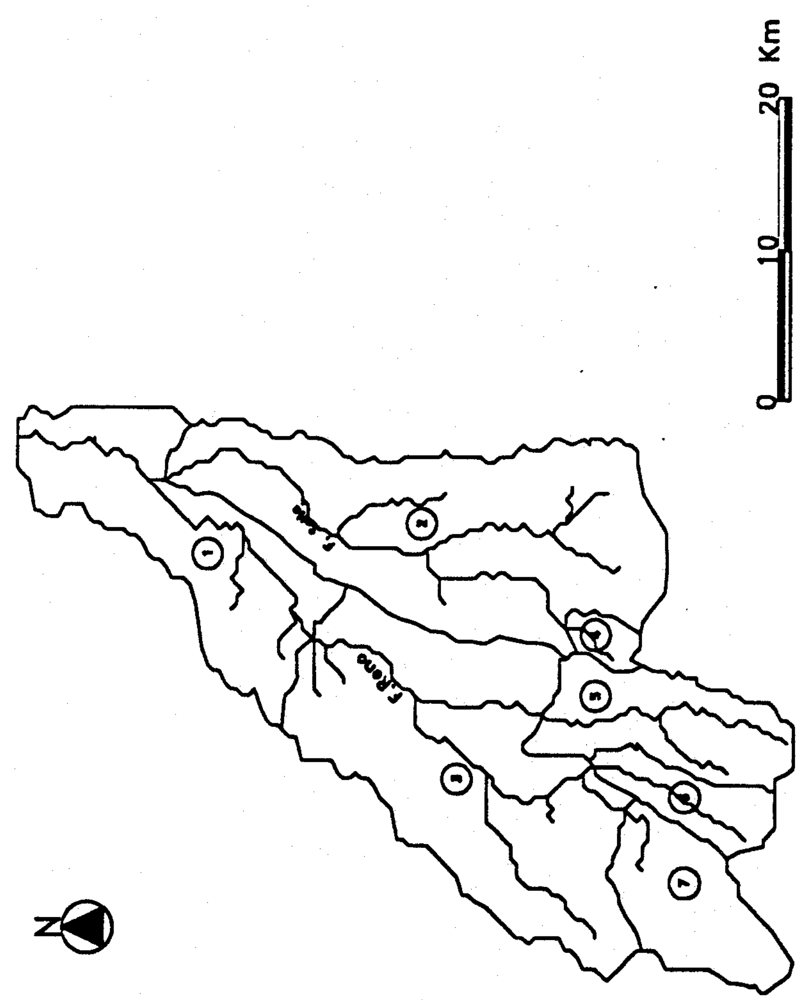
It should be said immediately that, as the flood routing model will make clear, as a result of subsidence the river has changed in a variety of respects in the twenty years following the survey, especially with regard to the channel and berm vegetation and the river bed elevations, as borne out by a number of partial surveys conducted in recent years; the hydraulic head in various reaches of the river has also changed considerably.

Since the geometrical description of the watercourse has a major effect on the results of the flood routing model, it should be stated at once that, of all the basic data involved in the study of the Reno basin, this is the part which would definitely need to be supplemented in a later study by means of a new, systematic survey of the watercourse.

7.3 THE REAL TIME RAINFALL-RUNOFF MODEL

The whole of the Reno basin at Casalecchio has been divided into 7 sub-basins (Figure 7.11), chosen according both to the location of the hydrometric stations (as with the final Casalecchio section and the Vergato section) and to particular hydraulic structures the operation of which could affect the river's flow.

Figure 7.12 shows a scheme of the sub-basins and their connections as used by the computer programmes. Table 7.14 shows the correspondence between the level stations (where present), the name of the sub-basin and the corresponding watercourse.



① Sub-basins

N.	Sub-basin	Area [Km2]
1	Reno a Casalecchio	155.26
2	Reno a Sasso Marconi	300.24
3	Reno a Vergato	313.76
4	Reno a Brasimone	14.50
5	Reno a Suviana	77.00
6	Reno a Pavana	39.50
7	Reno a Molino del Pallone	93.50

Figure 7.11 - Reno river basin above the Casalecchio weir divided into sub-basins.

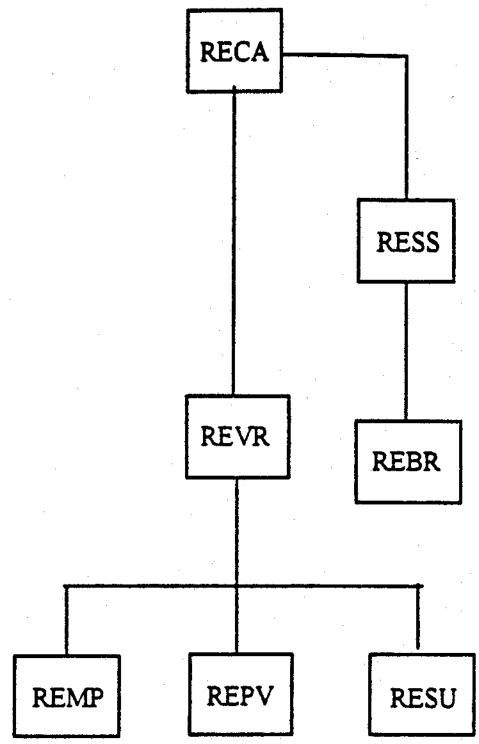


Figure 7.12 - Sub-basins and their connections

Gauging Station	Water Course	Code	Sub-basin
Molino del Pallone	Reno	0045	REMP
Pavana	Limentra di Sambuca	-	REPV
Suviana	Limetra di Treppio	-	RESU
Vergato	Reno	0015	REVR
Brasimone	Brasimone	-	REBR
Sasso Marconi	Setta	-	RESS
Casalecchio	Reno	-	RECA

Table 7.14 - Names and codes for several gauging stations

In order to calibrate the models, the period of available data (February 1990 - December 1992) was divided into two parts: a first period from February '90 to December '90, and a second period from January '91 to December '92.

The first of these periods (calibration period) was used to determine the model parameters, while the second (validation period) was used to test the validity of the model.

The calibration of the rainfall-runoff model can be divided into two phases:

- calibration of the soil water balance model parameters;
- calibration of the parabolic transfer parameters.

In order to calibrate these quantities, a number of characteristic values of each sub-basin must be known, including area, elevation, the relevant rain and temperature gauges plus their weights, and the parameters needed to calculate evapotranspiration. The following paragraphs provide a more detailed description of the various calibration components.

7.3.1 Parameters of the soil water balance model

7.3.1.1. Snow module

The snow melt module coefficients are mostly fixed and correspond to the following values:

- conversion factor of latent heat to radiation	606 Kcal/Kg
- efficiency factor to account for albedo	0.6
- latent heat of fusion for water	79.6 Kcal/Kg
- latent heat of evaporation	359 Kcal/Kg
- specific heat of water	1.0 Kcal/Kg °K
- specific heat of ice	0.5 Kcal/Kg °K

The characteristic values of each sub-basin are the snow formation threshold and the average elevation which are shown in Table 7.15.

Sub-basin	Elevation of the closing section (m a.s.l.)	Mean altitude of the sub-basin from the closing section (m)	Surface area (Km^2)	Solid-liquid separation threshold (in °C)
RECA	60.0	273.5	155.26	-2
RESS	130.0	459.7	300.24	-2
REVR	225.0	410.0	371.00	-2
REBR	846.0	132.9	14.50	-2
RESU	470.0	336.6	77.00	-2
REPV	471.0	404.5	39.50	-2
REMP	530.0	431.7	93.50	-2

Table 7.15 - Sub-basins elevation, surface and snowmelt parameters

7.3.1.2 Evapotranspiration module

In order to calculate the evapotranspiration, the mean monthly long-term temperatures of the temperature stations used in the system must be known.

In our case this information is available for all the stations. Table 7.16 shows the values obtained.

Code	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0002	1.5	1.9	4.0	7.2	11.2	14.9	17.7	17.8	14.8	10.6	5.9	2.5
0003	1.9	3.1	4.9	7.8	11.8	15.2	17.5	17.5	14.4	10.2	5.7	2.4
0007	2.0	3.7	7.0	10.8	14.8	18.6	21.2	21.0	21.0	17.8	12.6	7.8
0011	0.9	1.6	3.7	6.9	11.1	14.7	17.4	17.3	14.2	9.8	5.3	2.2
0013	2.9	4.4	7.0	10.7	14.8	18.3	21.1	21.0	17.9	13.0	8.1	4.3
0016	1.4	2.4	4.9	8.5	12.3	15.7	18.8	18.8	15.7	10.9	6.2	2.4
0019	1.9	3.5	6.3	10.2	14.3	18.5	21.2	21.0	17.4	12.2	7.3	3.4
0021	1.5	2.8	5.5	9.4	13.3	17.4	20.0	19.7	16.3	11.1	6.5	2.5
0042	0.9	3.5	7.7	11.9	16.2	20.4	22.9	22.7	19.2	13.5	7.4	2.5
0025	2.6	5.3	9.6	13.9	18.2	22.5	25.1	24.5	21.0	15.2	8.8	4.1

Table 7.16 - Mean montly temperature at different stations

Using the weights obtained from the Thiessen polygons for the temperatures, the mean converted temperatures over the sub-basins were calculated.

In this calculation account was taken of the temperature variation due to elevation by means of a temperature gradient value of around 0.50 °C/100 metres. Tables 7.15 and 7.17 give the heights of the sub-basins and temperature gauges.

Code	Elevation (m.a.s.l.)
0002	1043
0003	627
0007	349
0011	890
0013	500
0016	850
0019	620
0021	727
0042	40
0025	51

Table 7.17 - Elevation of temperature gauges

Table 7.18 shows the final temperature values.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
RECA	3.09	4.57	8.01	12.02	16.14	20.39	23.11	22.65	19.16	13.78	8.46	4.47
RESS	2.35	3.45	6.30	9.99	14.09	17.99	20.84	20.54	17.30	12.40	7.40	3.60
REVR	1.27	2.56	5.83	9.73	13.92	17.97	20.85	20.55	17.13	11.95	6.78	2.52
REBR	0.00	1.10	3.80	7.30	11.40	15.00	17.90	17.70	14.70	10.10	5.00	1.10
RESU	1.10	1.86	4.37	7.68	11.78	15.43	18.23	18.03	15.08	10.62	5.81	2.20
REPV	1.28	1.89	4.10	7.35	11.57	15.07	17.93	17.85	14.87	10.44	5.87	2.38
REMP	0.89	1.39	3.39	6.59	10.89	14.29	17.19	17.19	14.19	9.79	5.39	1.99

Table 7.18 - Mean monthly temperature value in the different sub-basins

Next, the monthly evapotranspiration values were calculated according to the methodology used in the ARNO model described in Chapter 3.

Table 7.19 shows the results .

Sub-basin	a	b
RECA	-13.2405	1.0324
RESS	-5.7962	0.9338
REVR	-3.9670	0.9128
REBR	1.2820	0.8514
RESU	0.0897	0.8640
REPV	0.3614	0.8619
REMP	1.5566	0.8521

Table 7.19 Regression coefficients for the computation of evapo-transpiration

7.3.1.3 Runoff formation module

In order to calculate the inflow and the mean temperatures in the sub-basins, the Thiessen polygon method was used (Figures 7.13 and 7.14). The weights and codes of the rain and temperature gauges are shown in Tables 7.20 and 7.21.

Table 7.22 lists the final values of the parameters obtained from the calibration of the soil water balance model.

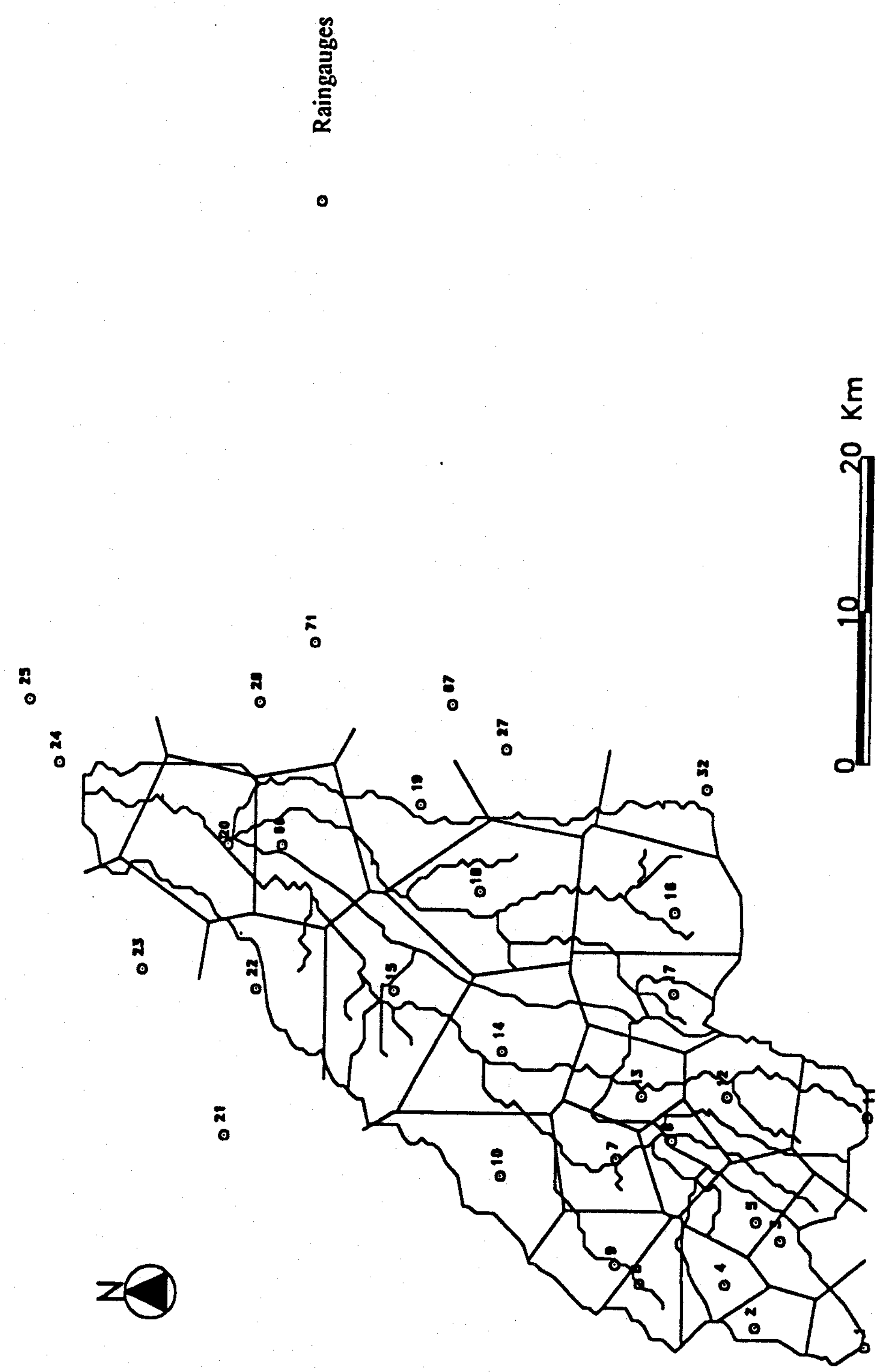


Figure 7.13 - Thiessen polygons derived for the raingauge network in the Reno basin above Casalecchio weir

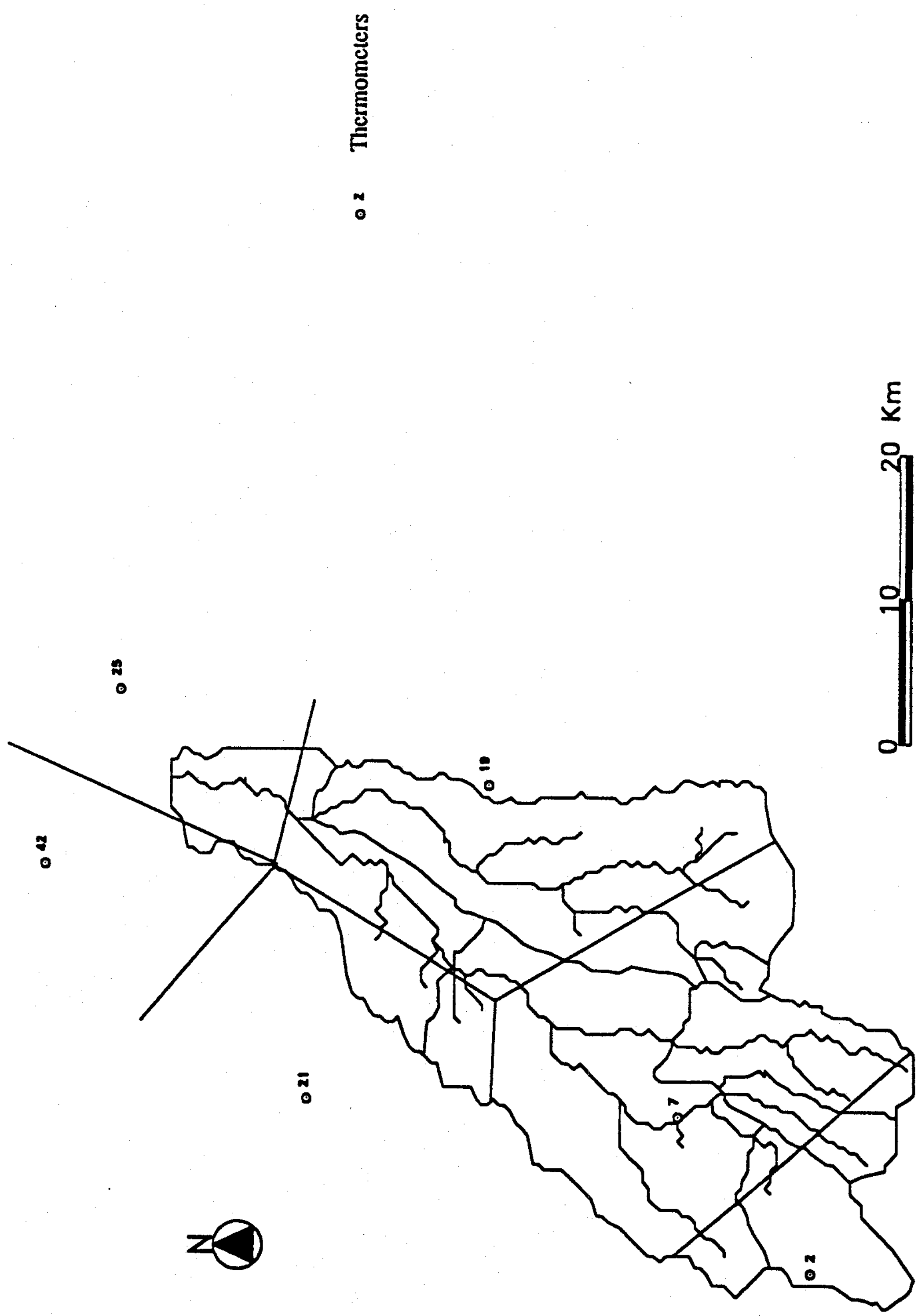


Figure 7.14 - Thiessen polygons developed for the temperature gauging stations of the Reno basin above Casalecchio weir.

Code	RECA	RESS	REVR	REBR	RESU	REPV	REMP
0001	0.00	0.00	0.00	0.00	0.00	0.00	0.05
0002	0.00	0.00	0.00	0.00	0.00	0.00	0.21
0003	0.00	0.00	0.00	0.00	0.00	0.18	0.19
0004	0.00	0.00	0.02	0.00	0.00	0.00	0.27
0005	0.00	0.00	0.01	0.00	0.00	0.32	0.25
0006	0.00	0.00	0.04	0.00	0.02	0.22	0.03
0007	0.00	0.00	0.12	0.00	0.00	0.00	0.00
0008	0.00	0.00	0.08	0.00	0.00	0.00	0.00
0009	0.00	0.00	0.11	0.00	0.00	0.00	0.00
0010	0.00	0.00	0.18	0.00	0.00	0.00	0.00
0011	0.00	0.00	0.00	0.00	0.25	0.13	0.00
0012	0.00	0.00	0.00	0.00	0.44	0.15	0.00
0013	0.00	0.00	0.05	0.00	0.22	0.00	0.00
0014	0.00	0.05	0.23	0.00	0.00	0.00	0.00
0015	0.21	0.04	0.15	0.00	0.00	0.00	0.00
0016	0.00	0.22	0.00	0.00	0.00	0.00	0.00
0017	0.00	0.07	0.01	1.00	0.07	0.00	0.00
0018	0.00	0.30	0.00	0.00	0.00	0.00	0.00
0019	0.00	0.11	0.00	0.00	0.00	0.00	0.00
0020	0.35	0.01	0.00	0.00	0.00	0.00	0.00
0022	0.19	0.00	0.00	0.00	0.00	0.00	0.00
0023	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0024	0.12	0.00	0.00	0.00	0.00	0.00	0.00
0028	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0066	0.12	0.13	0.00	0.00	0.00	0.00	0.00
0032	0.00	0.06	0.00	0.00	0.00	0.00	0.00
0027	0.00	0.01	0.00	0.00	0.00	0.00	0.00

Table 7.20 - Rainfall weights for computing areal average in the different sub-basins

code	RECA	RESS	REVR	REBR	RESU	REPV	REMP
2	0.00	0.00	0.07	0.00	0.00	0.00	0.40
3	0.00	0.00	0.01	0.00	0.00	0.59	0.57
7	0.00	0.16	0.55	0.00	0.01	0.02	0.03
11	0.00	0.00	0.00	0.00	0.42	0.14	0.00
13	0.00	0.04	0.21	0.45	0.53	0.25	0.00
16	0.00	0.45	0.00	0.55	0.00	0.00	0.00
19	0.45	0.51	0.06	0.00	0.00	0.00	0.00
21	0.23	0.00	0.10	0.00	0.00	0.00	0.00
25	0.29	0.00	0.00	0.00	0.00	0.00	0.00
42	0.03	0.00	0.00	0.00	0.00	0.00	0.00

Table 7.21 - Temperature weights for computing areal averages in the different sub-basins

Basin	base	Wm	Wd	Wp	b	dmax	dmin	perc	exp
RECA	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
RESS	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
REBR	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
REVR	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
REMP	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
REPV	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0
RESU	0.00	230	200	-	0.01	0.70	0.06	0.00	2.0

<u>Legend:</u>

base basic flow (m^3/s)
Wm mean field capacity of the soil (mm)
Wd threshold value for drainage calculation (mm)
Wp threshold value for percolation calculation (mm)
b exponent of the field capacity spatial distribution curve
dmax maximum drainage value (mm)
dmin drainage value for linear contribute (mm)
perc maximum percolation value(mm)
exp drainage curve exponent

Table 7.22 - Calibration parameters used in the soil moisture component

7.3.1.4. The parabolic transfer parameters

The calibration of the transfer module entails identifying the diffusivity and celerity values which most faithfully reproduce the correspondence between the measured and calculated peak discharge values. This search is performed on the basis of physical and hydrological considerations (estimation of concentration times); the use of an automatic calibration method is avoided as it does not always lead to sets of physically interpretable parameters. Table 7.23 lists the final parameters used in the Reno.

	HILLSLOPE			CHANNEL (diffuse)			CHANNEL (upstream)		
Basin	celerity (m/s)	diffusivity (m^2/s)	lenght (m)	celerity (m/s)	diffusivity (m^2/s)	lenght (m)	celerity (m/s)	diffusivity (m^2/s)	lenght (m)
RECA	1	300	5000	1.5	2000	28000	----	-----	-----
RESS	1	300	1000	1.5	2000	40000	1.7	2000	14000
REVR	1	300	1000	1.5	2000	30000	1.7	2000	25000
REBR	1	300	1000	1.5	2000	5000	1.7	2000	34000
RESU	1	300	1000	1.5	2000	17000	1.7	2000	24000
REPV	1	300	1000	1.5	2000	13000	1.7	2000	28000
REMP	1	300	1000	1.5	2000	17000	1.7	2000	30000

Table 7.23 Parameters relevant to the parabolic transfer module.

7.3.2 Results of the calibration of the rainfall-runoff model

In order to calibrate the rainfall-runoff model, the period of available data (1st February 1990 - 31st December 1992) was divided into two parts:

- the first part was used to determine the model's basic parameters;

- the second set of data was used to test the validity of the previously determined parameters.

The first period identified as the calibration period extends from 1st February 1990 to 31st December 1990, while the model validation period covers the remaining period up to 31st December 1992.

It must also be stated that, although the Reno basin closed at Casalecchio was divided into 7 sub-basins, it was possible to compare the discharges generated by the model with the measured values only for the closing section of the entire basin, where both hydrometer measurements and the rating curve required to translate the levels into discharge were available. Hydrometer measurements for the other sub-basins are not available at the present time, except for the Vergato closing section where level measurements are available but not the rating curve.

Accordingly, the comparison between the measured discharge values and the model-generated values was conducted only for the Casalecchio section which subtends the entire upland basin.

Judgements as to the accuracy of the model calibration are based on a visual comparison between the reconstructed runoff data sets and the corresponding measured sets, assisted by an estimation of the determination coefficient (CD), the correlation coefficient (CC), and the explained variance (VS), calculated using the following formulas:

$$CD = 1 - \frac{\sum \varepsilon_{i^2}}{\sum (Qs_i - \mu s)^2}$$

$$CC = \sqrt{CD}$$

$$VS = 1 - \frac{\sum (\varepsilon_i - \mu\varepsilon)^2}{\sum (Qs_i - \mu s)^2}$$

where:

$\varepsilon_i = Qs_i - Qc_i$

Qs_i = discharge measured at the i-th time;

Qc_i = discharge calculated at the i-th time;

μ_s = mean measured discharge;

μ_ε = mean error.

The flow output from the model are shown in Figures 7.15 (February-May 1990) and 7.16 (June-December 1990) with regard to the calibration period, in Figures 7.17 and 7.18 for the 1991 validation period, and in Figures 7.19 and 7.20 for the 1992 validation period. Figure 7.21 shows the model results for the flood period in 1990.

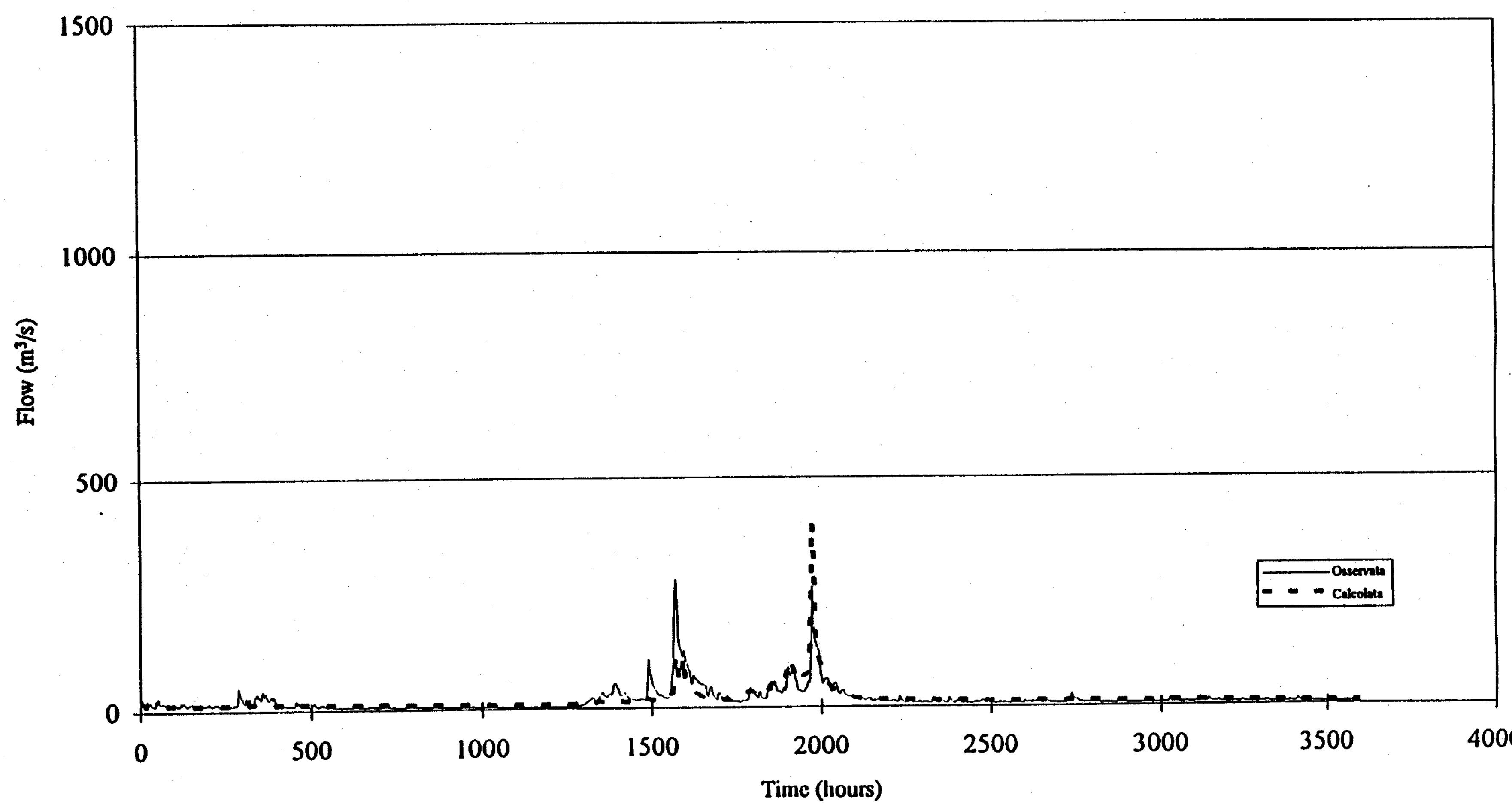


Figure 7.15 - Observed and computed hourly discharges at Casalecchio weir, during the calibration period February-May, 1990.

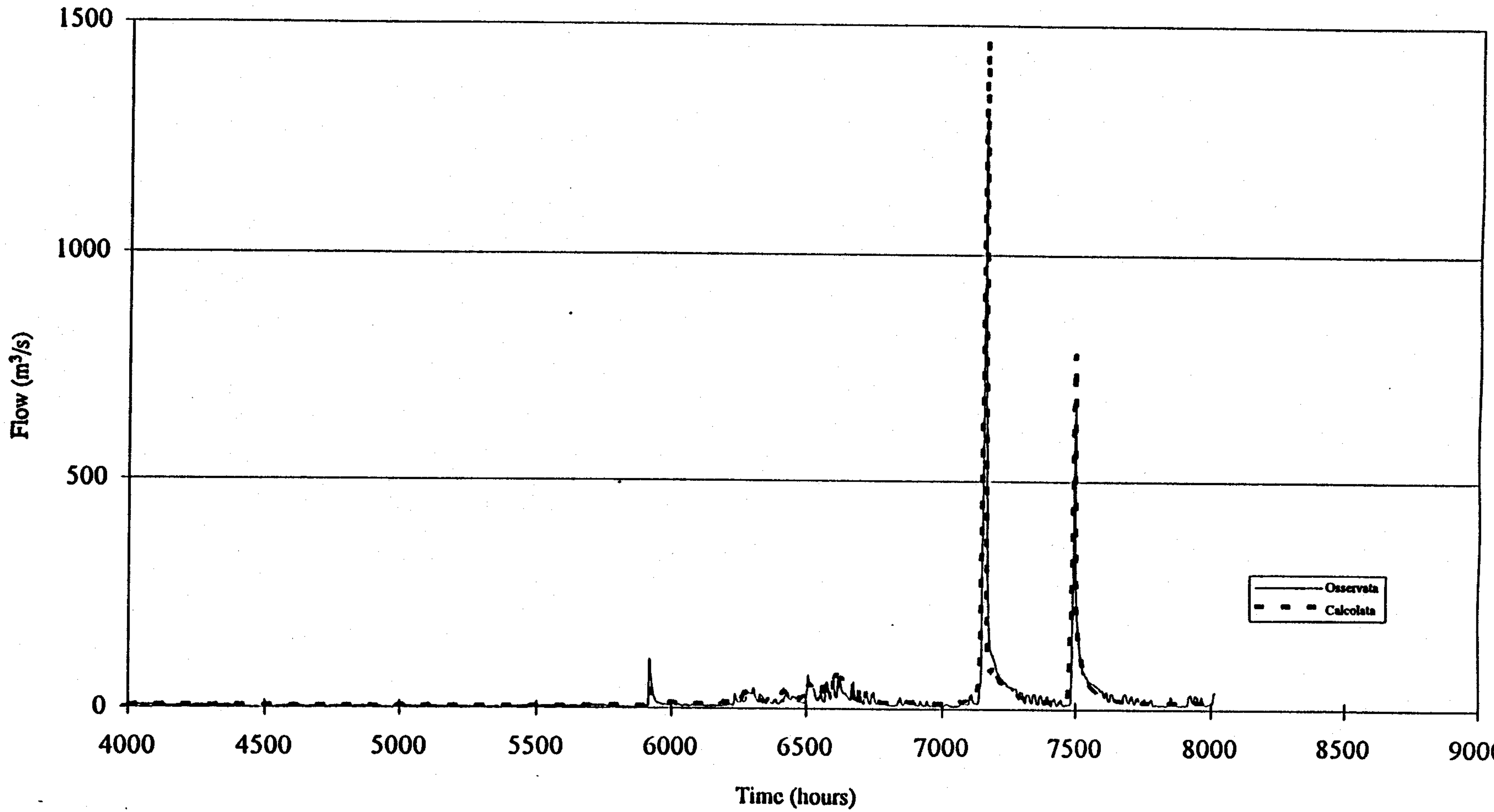


Figure 7.16 - Observed and computed hourly discharges at Casalecchio weir, during the calibration period June-December, 1990.

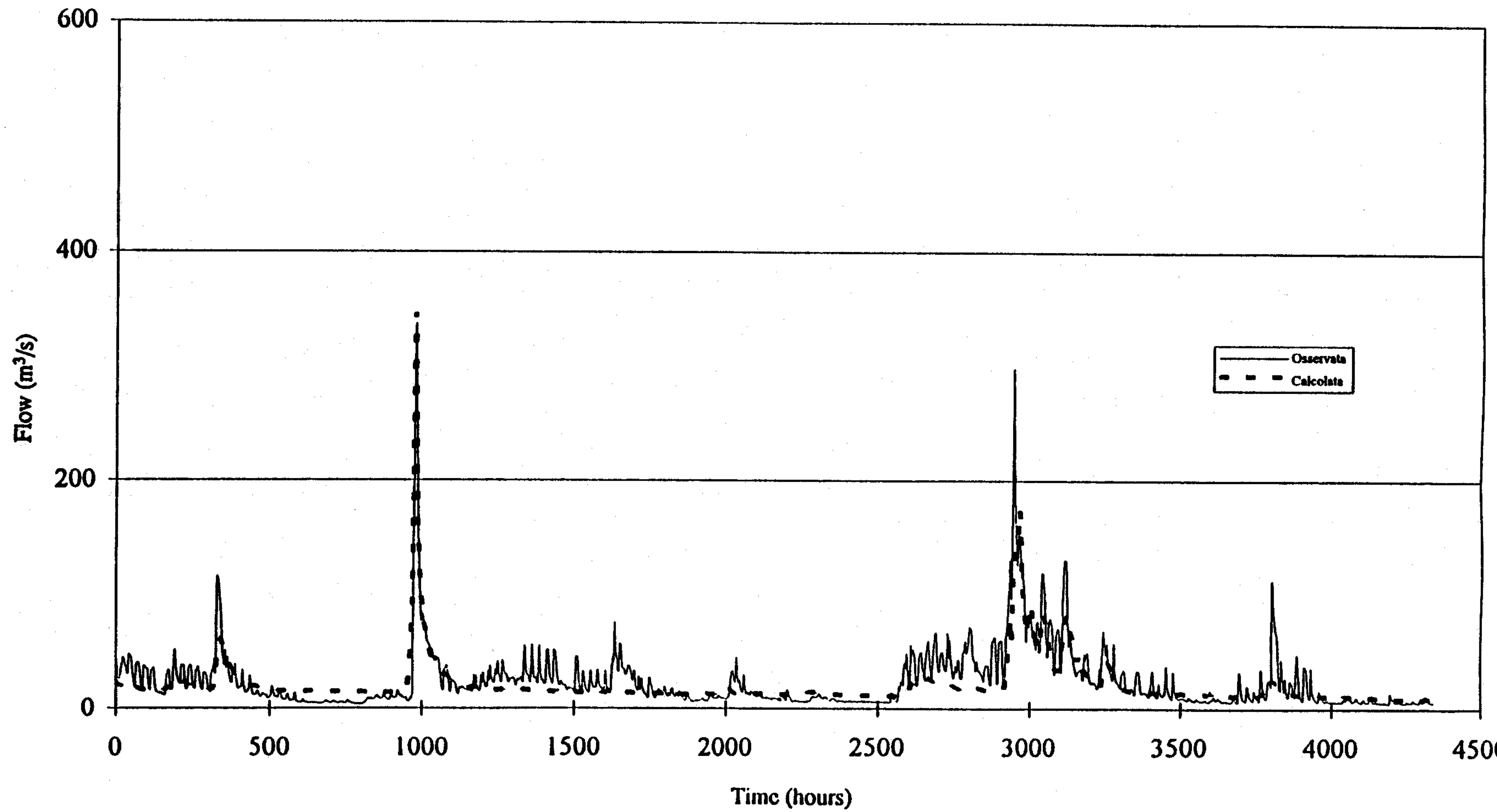


Figure 7.17 - Observed and computed hourly discharges at Casalecchio weir, during the validation period January-June, 1991

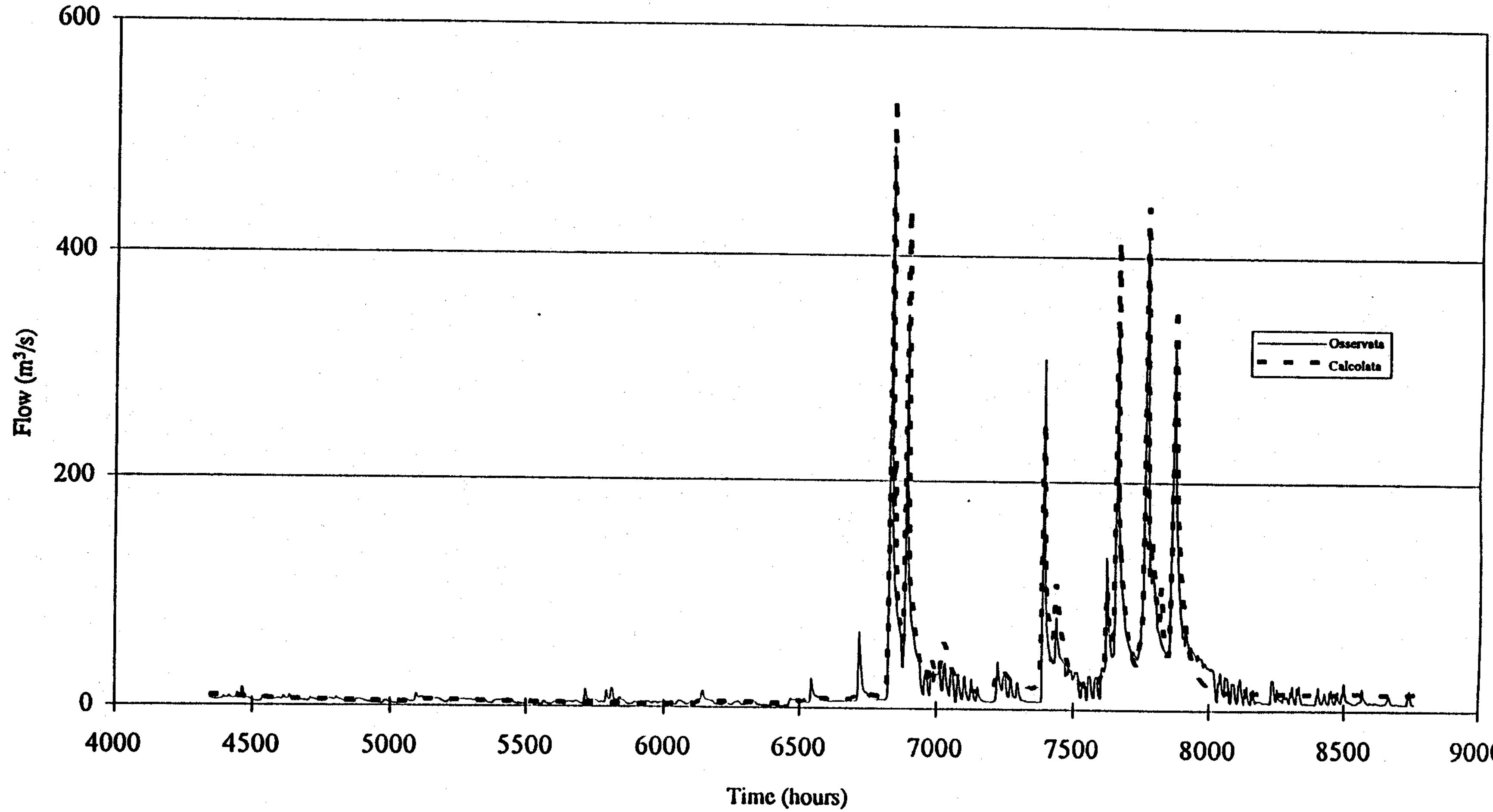


Figure 7.18 - Observed and computed hourly discharges at Casalecchio weir, during the validation period July-December, 1991.

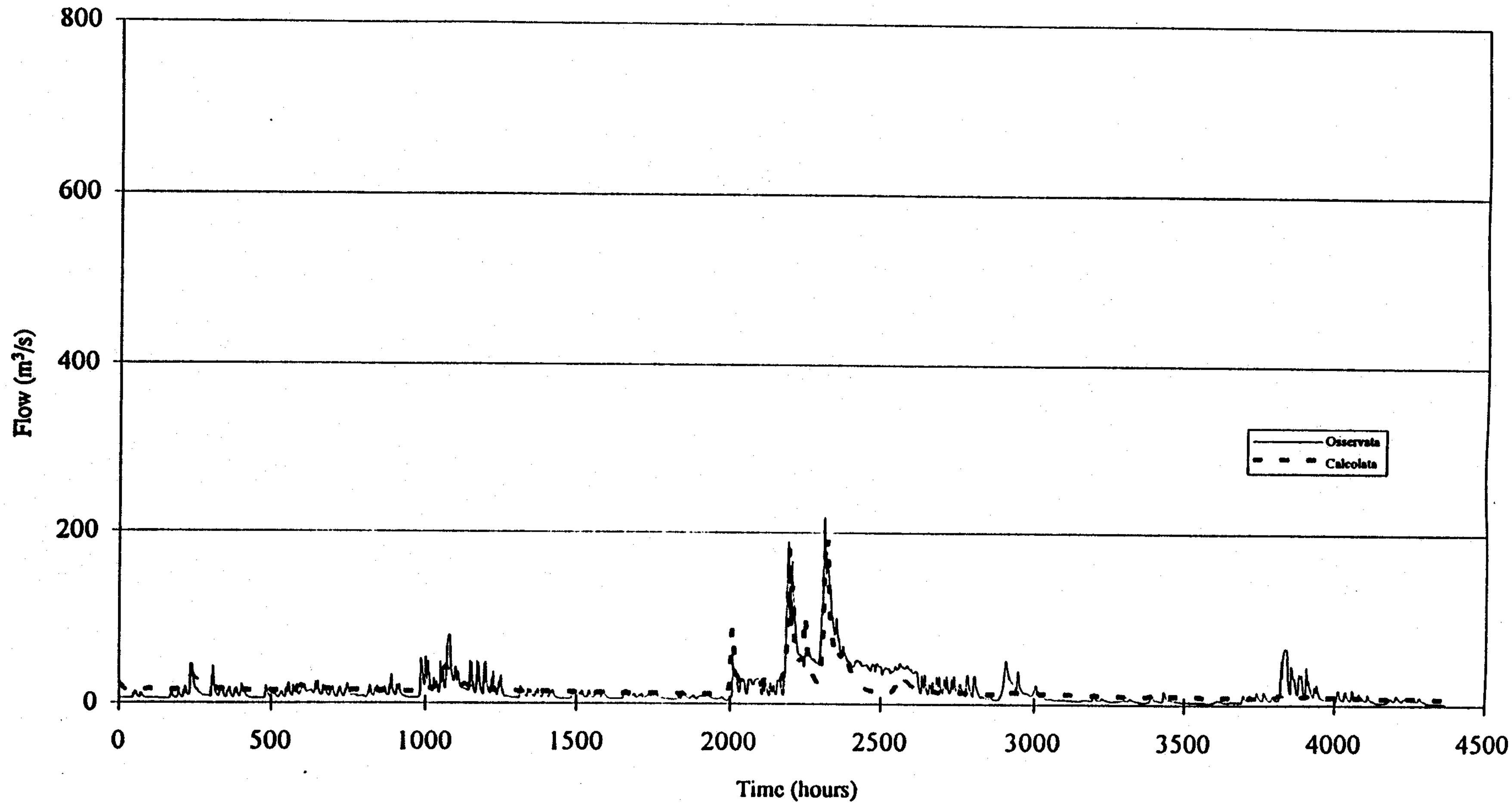


Figure 7.19 - Observed and computed hourly discharges at Casalecchio weir, during the validation period January-June, 1992.

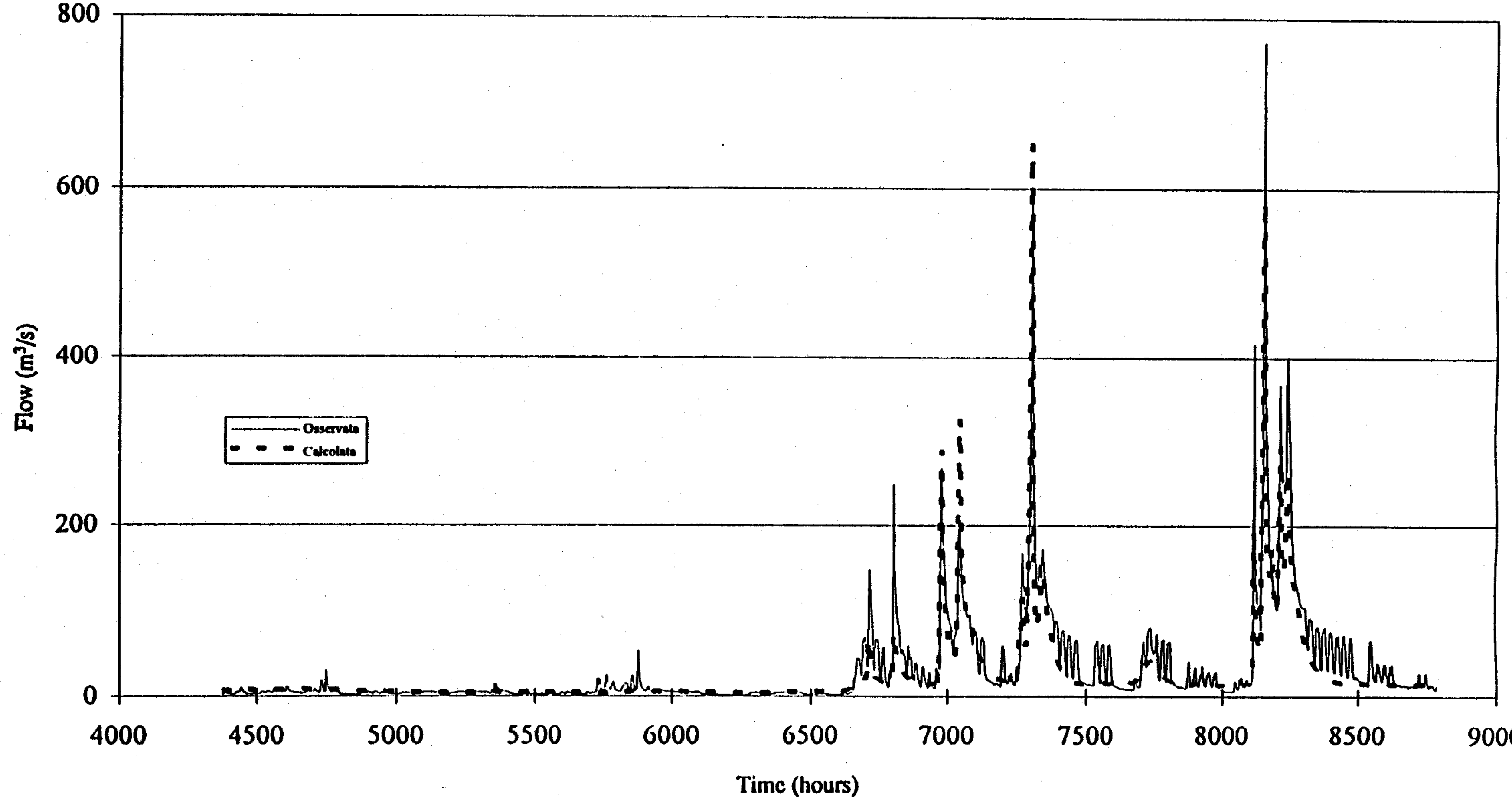


Figure 7.20 - Observed and computed hourly discharges at Casalecchio weir, during the validation period July-December, 1992.

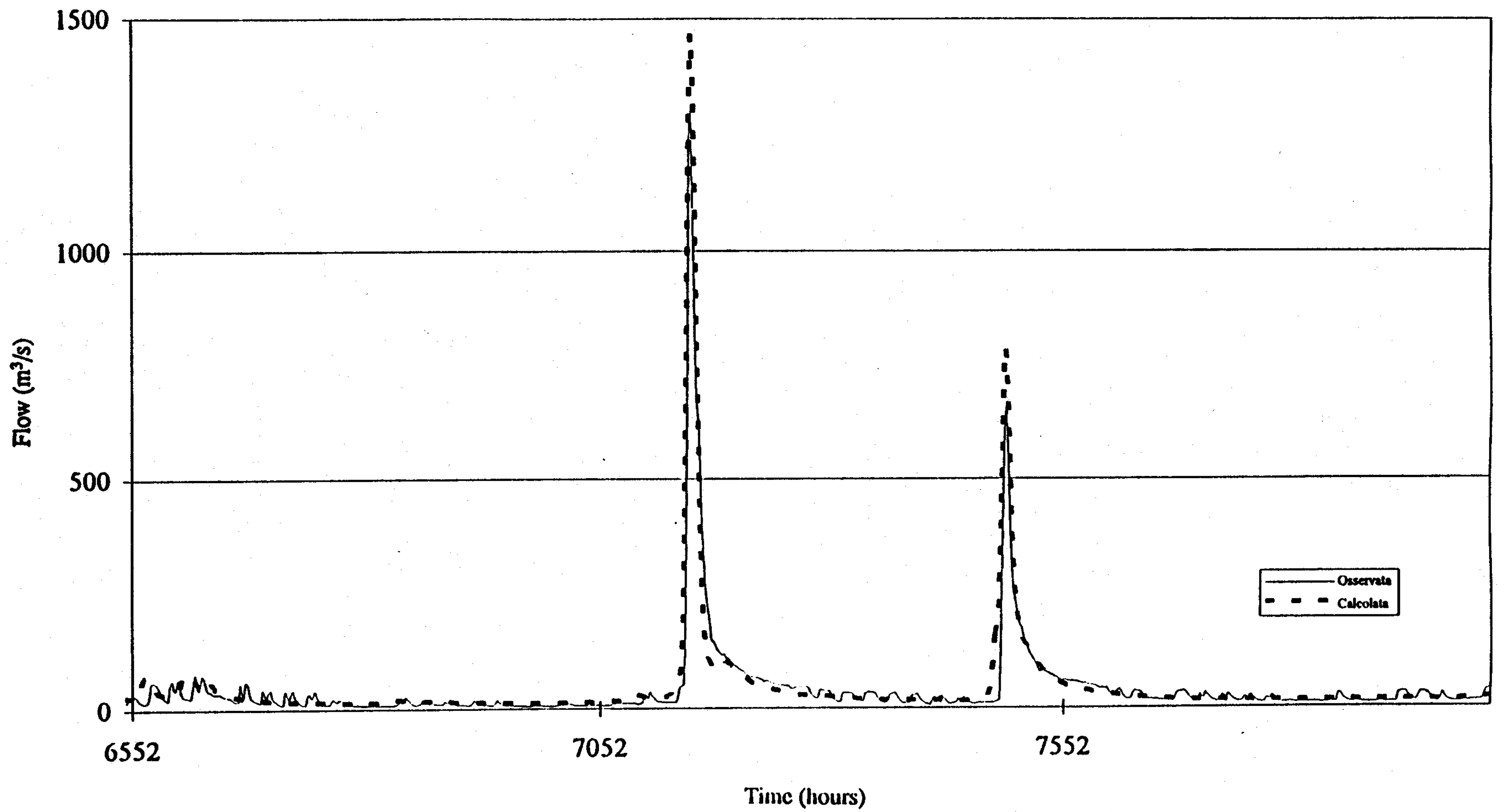


Figure 7.21 - Observed and computed hourly discharges at Casalecchio weir, during the flood event of November-December, 1990

Table 7.24 shows the statistics of results at Casalecchio.

Period	Historical mean (m^3/s)	Computed mean (m^3/s)	CD	VS	CC
Febbr.-Dic. 1990	17.59	18.49	0.8629	0.8632	0.9289
Gen.-Dic. 1991	22.39	22.34	0.8132	0.8132	0.9018
Gen.-Dic. 1992	24.51	20.92	0.8378	0.8438	0.9153

Table 7.24 - Statistical comparison of results

7.4 THE REAL TIME FLOOD ROUTING MODEL

7.4.1. Calibration of the flood routing model

The Parabolic and Backwater (PAB) flood routing model used takes into account the discharge arriving from the upland basin (Casalecchio section) and the lateral tributaries (Samoggia, Idice, Sillaro) between the Casalecchio section and the Bastia bridge. In any case, with regard to the simulations performed, the discharge values from the tributaries were found to be negligible when compared with the upland basin discharge.

Figure 7.22 shows the channel section between Casalecchio and the Bastia bridge and the input data used in the PAB model.

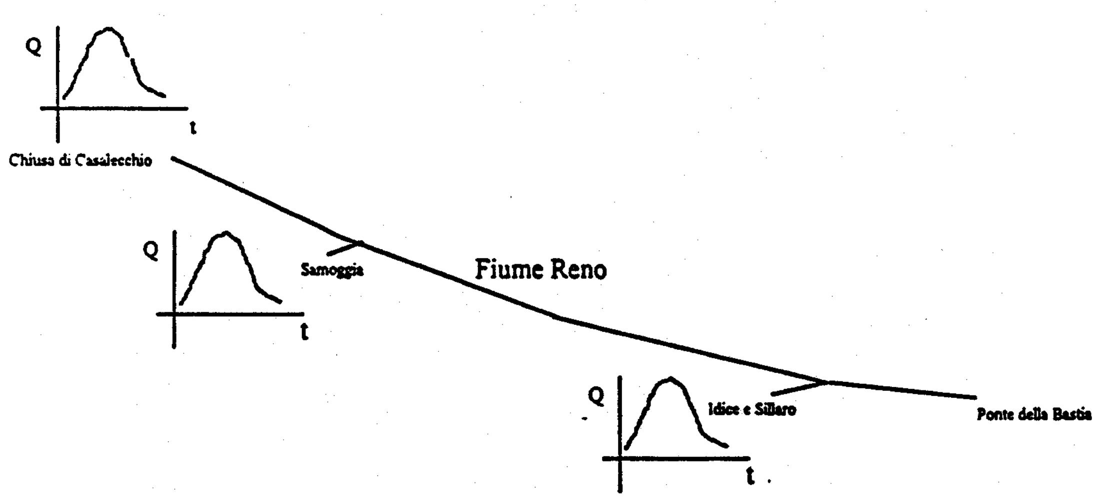


Figure 7.22 - Sketch of the Reno River for flood modelling

7.4.2 Analysis and reconstruction of flood profiles

After displaying and verifying all the available sections the channel bed and flood plain limits were defined for each of them. The roughness values were calibrated using the flood routing model on the assumption of steady flow. Specifically, two floods were used:

- the first flood, of 263 hours duration, extends from 09:00 hours on 7th October 1991 to 18:00 hours on 17th October 1991; the roughness values were calibrated on this first flood;

- the second flood, of 168 hours duration, extends from 00:00 hours on 22nd November 1990 to 24:00 hours on 28th November 1990; this flood was used to validate the roughness values calculated on the first flood.

It should be pointed out immediately that during this second flood event, which proved to be extremely dangerous following the breach of a bank, a series of operations which are not schematised in the model used were performed, starting at 06:00 hours on 26th November, using the hydraulic structures installed on the Reno river. Specifically, after this time, corresponding to computation hour 102, flow in the Reno was interrupted at Panfilia by the total closure of the "Opera Reno" sluice-gates and, consequently, the Napoleonic Channel was put into operation. As a result of this, after hour 102 the model's results are clearly at variance with the level measurements.

Table 7.25 shows the correspondence between the codes of the sections used and the level gauging sites and points of confluence between the Casalecchio weir and the Bastia bridge.

Section	Measurement section at confluence
RENO-001	Bastia
RENO-002	Confl. Idice e Sillaro
RENB-068	Gallo
RENB-117	Dosso
RENB-131	Cento
RENB-140	Confl. Samoggia
CASA-006	Casalecchio

Table 7.25 - Correspondence between sections and significant features along the Reno.

7.4.2.1 Flood routing model calibration process

The first stage in the calibration process entailed the preparation of the model input data as represented by the discharges arriving from both the upstream basin and the lateral tributaries.

The calibration period, as we have said, encompasses the flood event which occurred from 09:00 hours on 7th October 1991 to 18:00 hours on 17th October 1991, for a total of 263 hours.

The maximum discharge recorded during the flood event at the Weir at Casalecchio was approximately 500 m^3/s, with a maximum level of 1.57 m above gauge zero.

The input hydrographs are set out in Figure 7.23 and they show that, in this case too, the discharge values of the tributaries are negligible when compared with the flood peak value for the upstream discharge. Specifically, the estimated flood peak discharge for the Samoggia tributary was approximately 11 m^3/s, while the flood peak discharge of the Idice and Sillaro tributaries was approximately 28 m^3/s. The flood hydrographs for the tributaries were obtained using a simple kinematic model which schematises the propagation along the tributaries from the upland sections, comprising the Calcara section for the Samoggia, the Pizzocalvo section for the Idice and the Castel S. Pietro section for the Sillaro, sections for which the respective rating curves were available.

The rating curve of the Reno at Bastia, supplied by the Hydrographic and Marigraphic Office in Bologna, was taken to be valid as the downstream condition for the wave propagation along the Reno.

The results of the calibration are set out in Figures 7.24 - 7.33 which show the results obtained with the model and the observed results for the level measuring stations at Casalecchio, Cento, Dosso, Gallo and Bastia respectively. Table 7.26 lists the sections usedand next to them the relevant roughness coefficient values according to Manning; as can be seen, this coefficient was kept constant except at the Casalecchio weir.

It will be noted that in the Cento, Dosso and Gallo sections there is a recession of the flood wave, calculated using the available and now unfortunately obsolete cross sections, which is considerably slower than the recession actually recorded. This signifies the occurrence of a considerable increase in the mean slope of the channel bed which is not reproduced in the available geometrical data.

With respect to the Bastia section there is also a problem connected with both the validity of the rating curve and the calculation of the arrival times of the inflows from the tributaries which in some way affect their reliability, albeit not to a high degree in percentage terms.

In accordance with the available geometry, the calibrated model is nevertheless already able to furnish general indications on floodability, since the effects listed above, which are magnified during the recession phase, are more modest in scale during the backwater phase and around the flood peak zone.

7.4.2.2. Validation of the flood routing model

The model's validation period encompasses the flood that occurred from 00:00 hours on 22nd November 1990 to 24:00 hours on 28th November 1990, for a total of 248 hours. The maximum discharge recorded during the flood event at the weir at Casalecchio was approximately 1300 m^3/s, with a maximum level of 2.55 m above gauge zero. The flood event permitted verification of the model's validity for the range of discharge values corresponding to the highest flood event return periods.

The input hydrographs are shown in Figure 7.34. The flood peak discharge of the Samoggia tributary is approximately 41 m^3/s, while the flood peak discharge of the Idice and Sillaro is approximately 120 m^3/s. The results of the validation are shown in Figures 7.35 - 7.44 which summarise the results obtained with the model and make a comparison with the results observed at the level measuring stations of Casalecchio, Cento, Dosso, Gallo and Bastia respectively. Once more, it should be borne in mind that the model used here does not take account, after hour 102, of the operations performed on the Reno and that after this hour, therefore, the results obtained are not reliable. As can be seen in Figures 7.35-7.44, during verification there is still excellent correspondence of the results up until the 102nd simulation hour, after which the closing of the gates and the opening of the Napoleonic Channel substantially modify the natural flow.

Section Number	Section Code	Section Type	Manning Roughness Coefficient (main channel)	Manning Roughness Coefficient (berms)
1	RENO-001	I	0.0751	0.0751
2	RENO-002	A	0.0751	0.0751
3	RENO-003	0	0.0751	0.0751
4	RENO-004	0	0.0751	0.0751
5	RENO-005	0	0.0751	0.0751
6	RENO-006	0	0.0751	0.0751
7	RENO-007	0	0.0751	0.0751
8	RENO-008	0	0.0751	0.0751
8	RENB-008	S	0.0751	0.0751
9	RENO-009	0	0.0751	0.0751
10	RENO-010	R	0.0751	0.0751
11	RENO-011	0	0.0751	0.0751
12	RENO-012	0	0.0751	0.0751
13	RENO-013	0	0.0751	0.0751
14	RENO-014	0	0.0751	0.0751
15	RENO-015	R	0.0751	0.0751
16	RENO-016	0	0.0751	0.0751
17	RENO-017	0	0.0751	0.0751
18	RENO-018	0	0.0751	0.0751
19	RENO-019	0	0.0751	0.0751
20	RENO-020	R	0.0751	0.0751
21	RENO-021	0	0.0751	0.0751
22	RENO-022	0	0.0751	0.0751
23	RENO-023	0	0.0751	0.0751
24	RENO-024	0	0.0751	0.0751
25	RENO-025	R	0.0751	0.0751
26	RENO-026	0	0.0751	0.0751
27	RENO-027	0	0.0751	0.0751
28	RENO-028	0	0.0751	0.0751
29	RENO-029	0	0.0751	0.0751
30	RENO-030	R	0.0751	0.0751
31	RENO-031	0	0.0751	0.0751
32	RENO-032	0	0.0751	0.0751
33	RENO-033	0	0.0751	0.0751
34	RENO-034	0	0.0751	0.0751
35	RENO-035	R	0.0751	0.0751
36	RENO-036	0	0.0751	0.0751
37	RENO-037	0	0.0751	0.0751
38	RENO-038	0	0.0751	0.0751
39	RENO-039	0	0.0751	0.0751
40	RENO-040	R	0.0751	0.0751

Table 7.26 - Manning's roughness coefficients (continued)

Section Number	Section Code	Section Type	Manning Roughness Coefficient (main channel)	Manning Roughness Coefficient (berms)
41	RENO-041	0	0.0751	0.0751
42	RENO-042	0	0.0751	0.0751
43	RENO-043	0	0.0751	0.0751
44	RENO-044	0	0.0751	0.0751
45	RENO-045	R	0.0751	0.0751
46	RENO-046	0	0.0751	0.0751
47	RENO-047	0	0.0751	0.0751
48	RENO-048	0	0.0751	0.0751
49	RENO-049	0	0.0751	0.0751
50	RENO-050	R	0.0751	0.0751
51	RENO-051	0	0.0751	0.0751
52	RENO-052	0	0.0751	0.0751
53	RENO-053	0	0.0751	0.0751
54	RENO-054	0	0.0751	0.0751
55	RENO-055	R	0.0751	0.0751
56	RENO-056	0	0.0751	0.0751
57	RENO-057	0	0.0751	0.0751
58	RENO-058	0	0.0751	0.0751
59	RENO-059	0	0.0751	0.0751
60	RENO-060	R	0.0751	0.0751
61	RENO-061	0	0.0751	0.0751
62	RENO-062	0	0.0751	0.0751
63	RENO-063	0	0.0751	0.0751
64	RENO-064	0	0.0751	0.0751
65	RENO-065	R	0.0751	0.0751
66	RENO-066	0	0.0751	0.0751
67	RENO-067	0	0.0751	0.0751
68	RENO-068	0	0.0751	0.0751
68	RENB-068	S	0.0751	0.0751
69	RENO-069	0	0.0751	0.0751
70	RENO-070	R	0.0751	0.0751
71	RENO-071	0	0.0751	0.0751
72	RENO-072	0	0.0751	0.0751
73	RENO-073	0	0.0751	0.0751
74	RENO-074	0	0.0751	0.0751
75	RENO-075	R	0.0751	0.0751
76	RENO-076	0	0.0751	0.0751
77	RENO-077	0	0.0751	0.0751
78	RENO-078	0	0.0751	0.0751
79	RENO-079	0	0.0751	0.0751
80	RENO-080	R	0.0751	0.0751

Table 7.26 - Manning's roughness coefficients (continued)

Section Number	Section Code	Section Type	Manning Roughness Coefficient (main channel)	Manning Roughness Coefficient (berms)
81	RENO-081	0	0.0751	0.0751
82	RENO-082	0	0.0751	0.0751
83	RENO-083	0	0.0751	0.0751
84	RENO-084	0	0.0751	0.0751
85	RENO-085	R	0.0751	0.0751
86	RENO-086	0	0.0751	0.0751
87	RENO-087	0	0.0751	0.0751
88	RENO-088	0	0.0751	0.0751
89	RENO-089	0	0.0751	0.0751
90	RENO-090	R	0.0751	0.0751
91	RENO-091	0	0.0751	0.0751
92	RENO-092	0	0.0751	0.0751
93	RENO-093	0	0.0751	0.0751
94	RENO-094	0	0.0751	0.0751
95	RENO-095	R	0.0751	0.0751
96	RENO-096	0	0.0751	0.0751
97	RENO-097	0	0.0751	0.0751
98	RENO-098	0	0.0751	0.0751
99	RENO-099	0	0.0751	0.0751
100	RENO-100	R	0.0751	0.0751
101	RENO-101	0	0.0751	0.0751
102	RENO-102	0	0.0751	0.0751
103	RENO-103	0	0.0751	0.0751
104	RENO-104	0	0.0751	0.0751
105	RENO-105	R	0.0751	0.0751
106	RENO-106	S	0.0751	0.0751
107	RENO-107	0	0.0751	0.0751
108	RENO-108	0	0.0751	0.0751
109	RENO-109	0	0.0751	0.0751
110	RENO-110	R	0.0751	0.0751
111	RENO-111	0	0.0751	0.0751
112	RENO-112	0	0.0751	0.0751
113	RENO-113	0	0.0751	0.0751
114	RENO-114	0	0.0751	0.0751
115	RENO-115	R	0.0751	0.0751
116	RENO-116	0	0.0751	0.0751
117	RENO-117	0	0.0751	0.0751
117	RENB-117	S	0.0751	0.0751
118	RENO-118	0	0.0751	0.0751
119	RENO-119	0	0.0751	0.0751
120	RENO-120	R	0.0751	0.0751

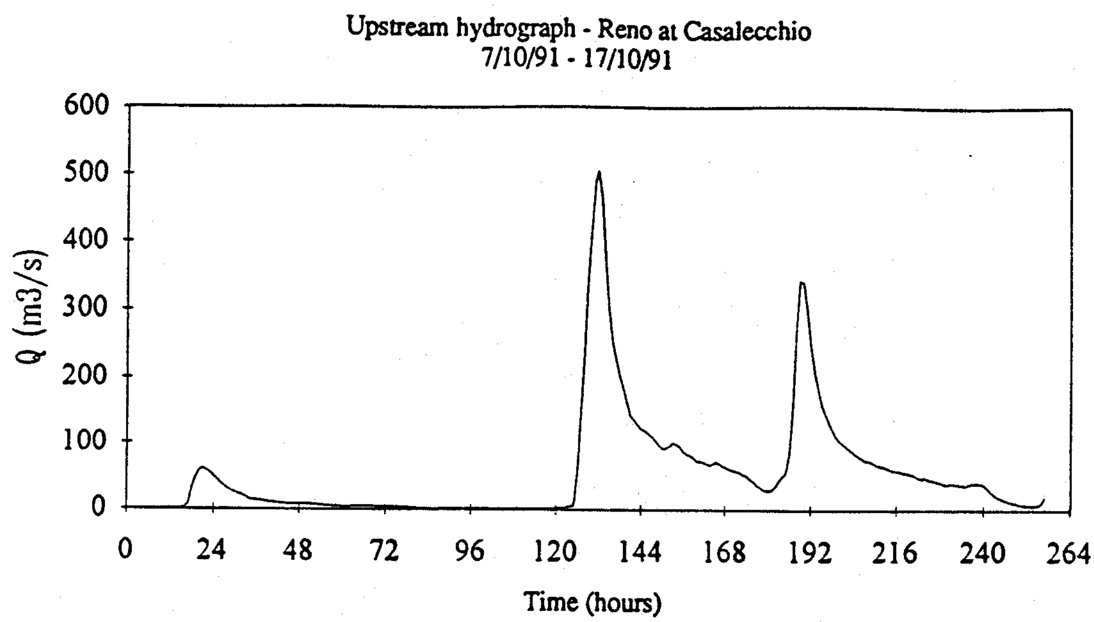
Table 7.26 - Manning's roughness coefficients (continued)

Section Number	Section Code	Section Type	Manning Roughness Coefficient (main channel)	Manning Roughness Coefficient (berms)
121	RENO-121	0	0.0751	0.0751
122	RENO-122	0	0.0751	0.0751
123	RENO-123	0	0.0751	0.0751
124	RENO-124	0	0.0751	0.0751
125	RENO-125	R	0.0751	0.0751
126	RENO-126	0	0.0751	0.0751
127	RENO-127	0	0.0751	0.0751
128	RENO-128	0	0.0751	0.0751
129	RENO-129	0	0.0751	0.0751
130	RENO-130	R	0.0751	0.0751
131	RENO-131	0	0.0751	0.0751
131	RENB-131	S	0.0751	0.0751
132	RENO-132	0	0.0751	0.0751
133	RENO-133	0	0.0751	0.0751
134	RENO-134	0	0.0751	0.0751
135	RENO-135	R	0.0751	0.0751
136	RENO-136	0	0.0751	0.0751
137	RENO-137	0	0.0751	0.0751
138	RENO-138	0	0.0751	0.0751
139	RENO-139	0	0.0751	0.0751
140	RENO-140	A	0.0751	0.0751
141	RENO-141	0	0.0751	0.0751
142	RENO-142	0	0.0751	0.0751
143	RENO-143	0	0.0751	0.0751
144	RENO-144	0	0.0751	0.0751
145	RENO-145	R	0.0751	0.0751
146	RENO-146	0	0.0751	0.0751
147	RENO-147	0	0.0751	0.0751
148	RENO-148	0	0.0751	0.0751
149	RENO-149	0	0.0751	0.0751
150	RENO-150	R	0.0751	0.0751
151	RENO-151	0	0.0751	0.0751
152	RENO-152	0	0.0751	0.0751
153	RENO-153	0	0.0751	0.0751
154	RENO-154	0	0.0751	0.0751
155	RENO-155	R	0.0751	0.0751
156	RENO-156	0	0.0751	0.0751
157	RENO-157	0	0.0751	0.0751
158	RENO-158	0	0.0751	0.0751
159	RENO-159	0	0.0751	0.0751
160	RENO-160	R	0.0751	0.0751
161	RENO-161	0	0.0751	0.0751

Table 7.26 - Manning's roughness coefficients (continued)

Section Number	Section Code	Section Type	Manning Roughness Coefficient (main channel)	Manning Roughness Coefficient (berms)
162	RENO-162	0	0.0751	0.0751
163	RENO-163	0	0.0751	0.0751
164	RENO-164	0	0.0751	0.0751
165	RENO-165	R	0.0751	0.0751
166	RENO-166	0	0.0751	0.0751
167	RENO-167	0	0.0751	0.0751
168	RENO-168	0	0.0751	0.0751
169	RENO-169	0	0.0751	0.0751
170	RENO-170	R	0.0751	0.0751
171	RENO-171	0	0.0751	0.0751
172	RENO-172	0	0.0751	0.0751
173	RENO-173	0	0.0751	0.0751
174	RENO-174	0	0.0751	0.0751
175	RENO-175	R	0.0751	0.0751
176	RENO-176	0	0.0751	0.0751
177	RENO-177	0	0.0751	0.0751
178	RENO-178	0	0.0751	0.0751
179	RENO-179	0	0.0751	0.0751
180	RENO-180	R	0.0751	0.0751
181	RENO-181	0	0.0751	0.0751
182	RENO-182	0	0.0751	0.0751
183	RENO-183	0	0.0751	0.0751
184	RENO-184	0	0.0751	0.0751
185	RENO-185	R	0.0751	0.0751
186	RENO-186	0	0.0751	0.0751
187	RENO-187	0	0.0751	0.0751
188	RENO-188	0	0.0751	0.0751
189	RENO-189	0	0.0751	0.0751
190	RENO-190	R	0.0751	0.0751
191	RENO-191	0	0.0751	0.0751
192	RENO-192	0	0.0751	0.0751
193	RENO-193	0	0.0751	0.0751
194	RENO-194	0	0.0751	0.0751
195	RENO-195	R	0.0751	0.0751
196	RENO-196	0	0.0751	0.0751
196	RENB-196	S	0.0751	0.0751
197	RENO-197	0	0.0751	0.0751
198	RENO-198	0	0.0751	0.0751
199	CASA-001	0	0.025	0.025
200	CASA-002	0	0.013	0.013
201	CASA-003	0	0.013	0.013
202	CASA-004	0	0.013	0.013
203	CASA-005	0	0.013	0.013
204	CASA-006	I	0.013	0.013

Table 7.26 - Manning's roughness coefficients



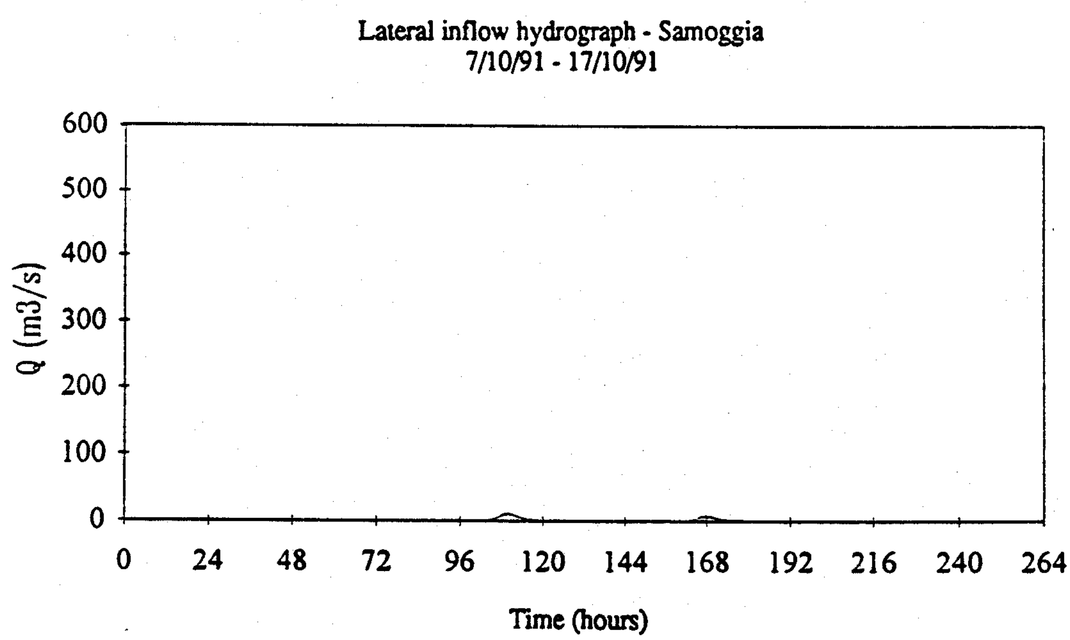
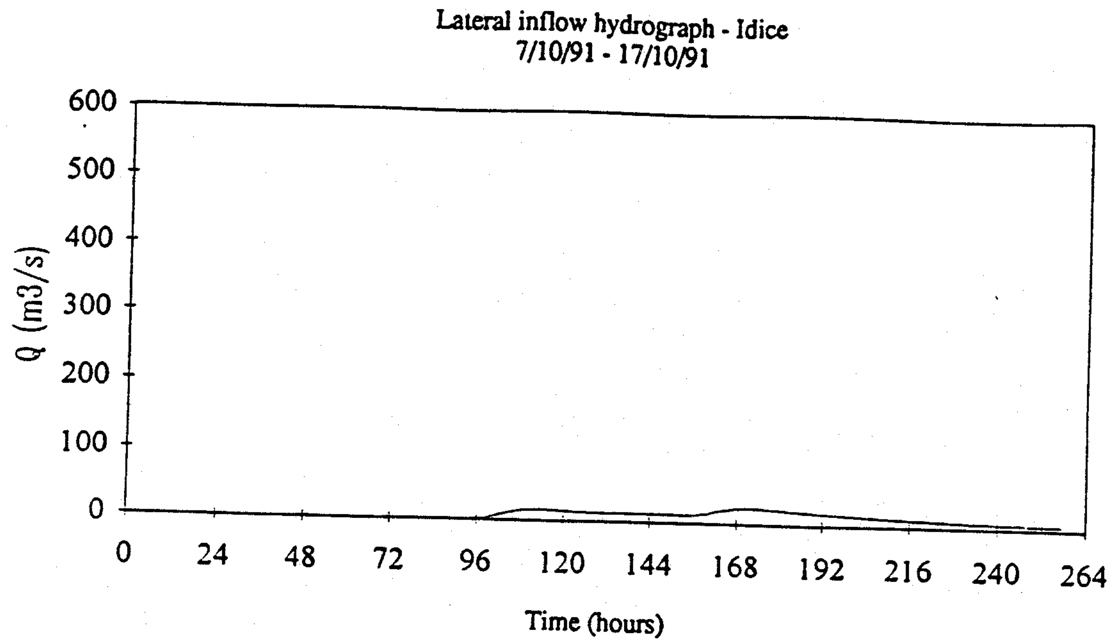


Figure 7.23 - Inflow hydrographs used in PAB for the flood wave of October 1991 (Calibration period)



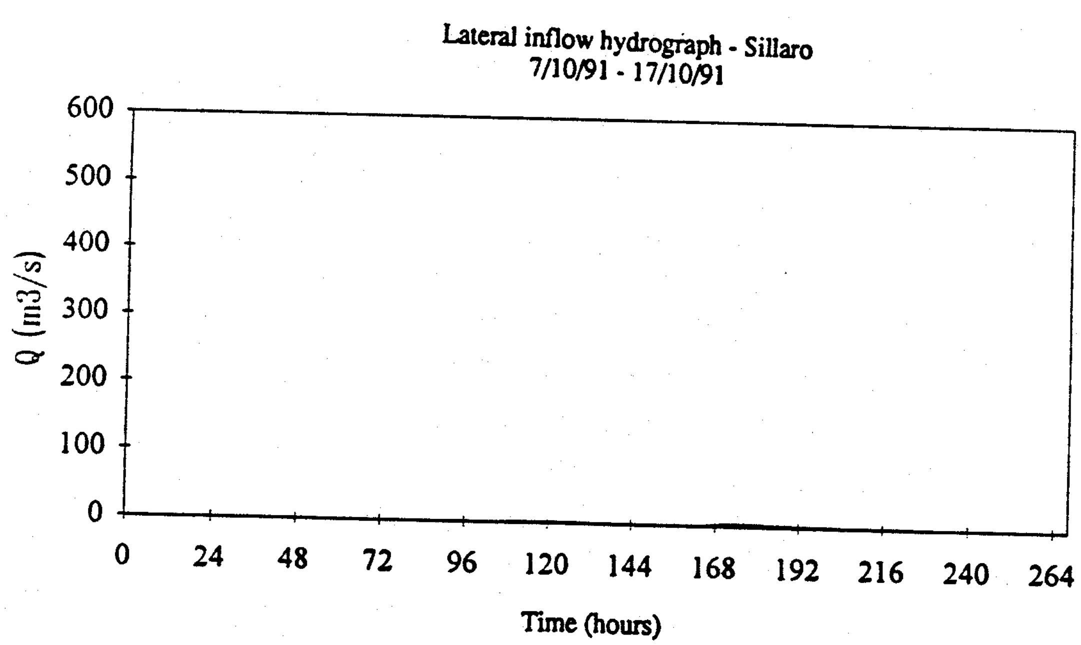


Figure 7.23 - Inflow hydrographs used in PAB for the flood wave of October 1991 (Calibration period)

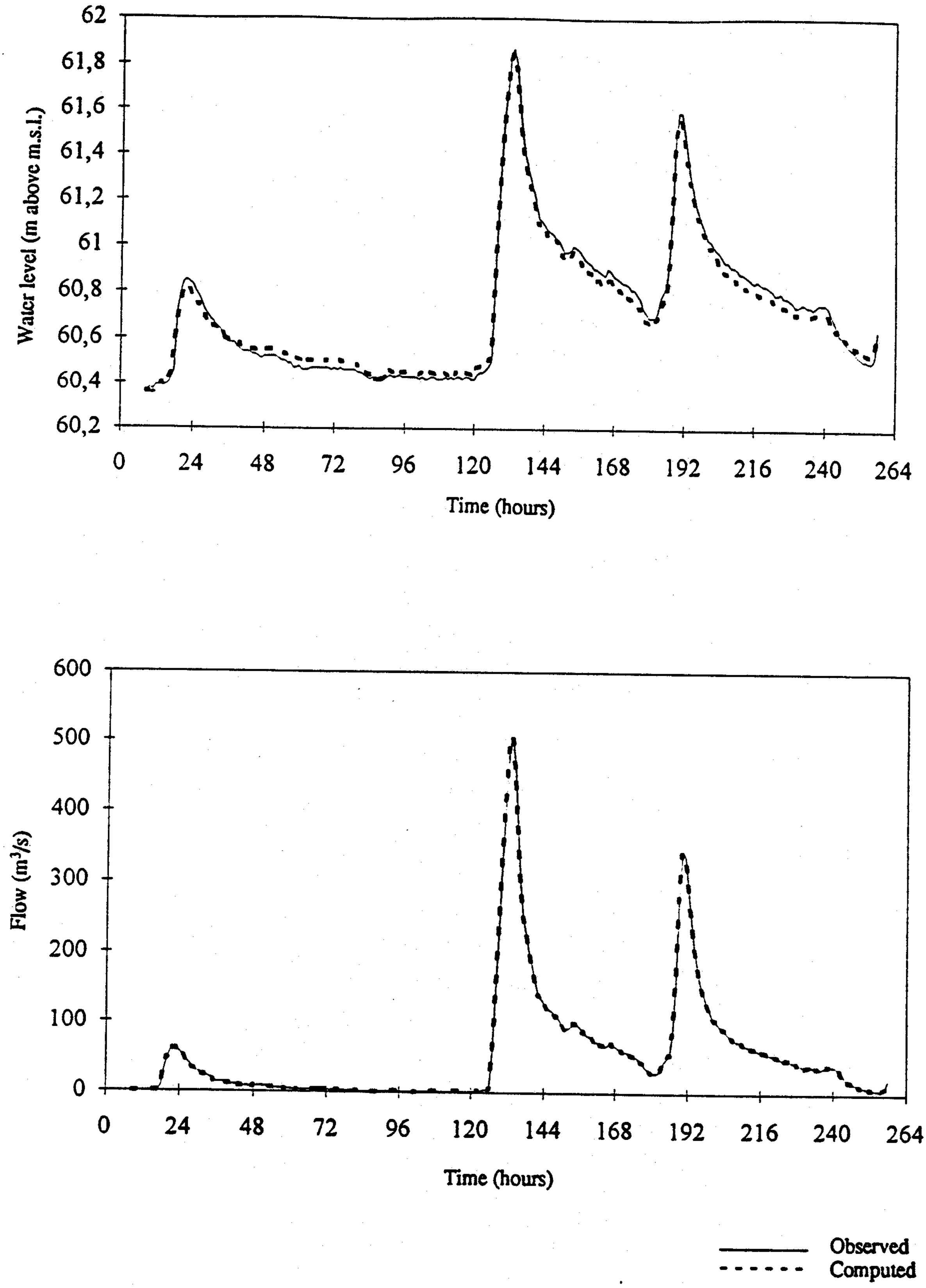


Figure 7.24 - Simulation of the flood wave of October 1991 at Casalecchio weir.

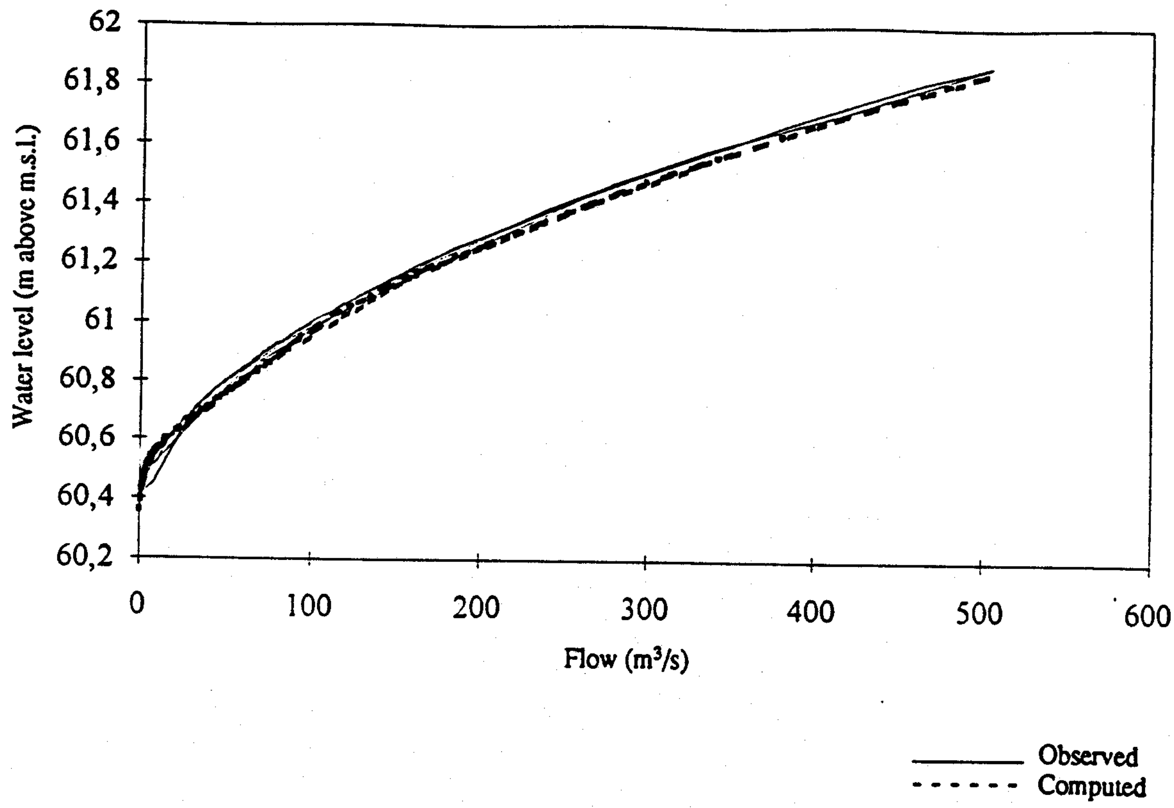


Figure 7.25 - Rating curve reconstructed using the simulation model for the flood-wave of October 1991 at the Casalecchio weir, showing the expected one-to-one correspondence.

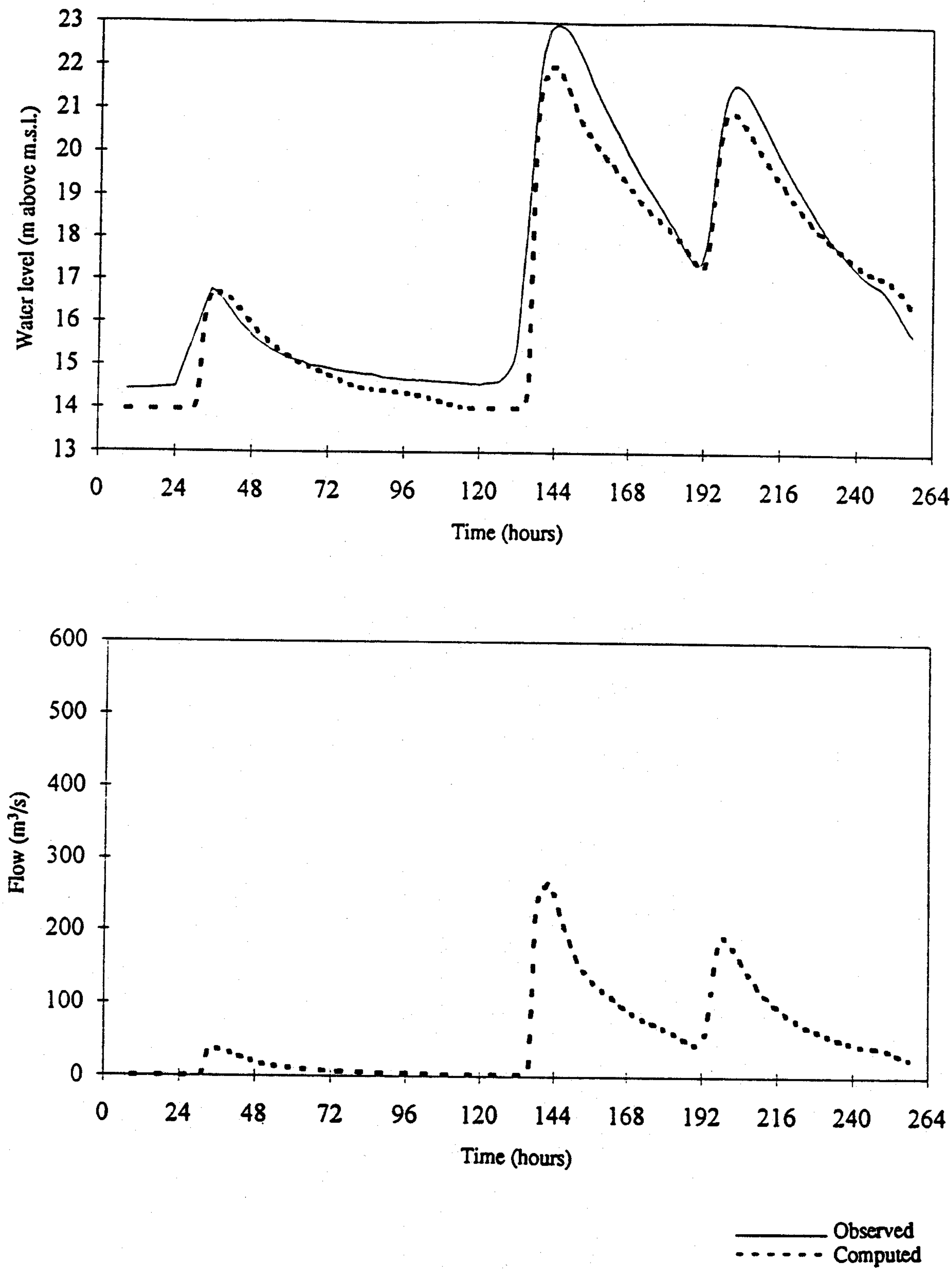


Figure 7.26 - Reconstruction using the simulation model, of the flood hydrograph of October 1991 at the Cento cross-section.

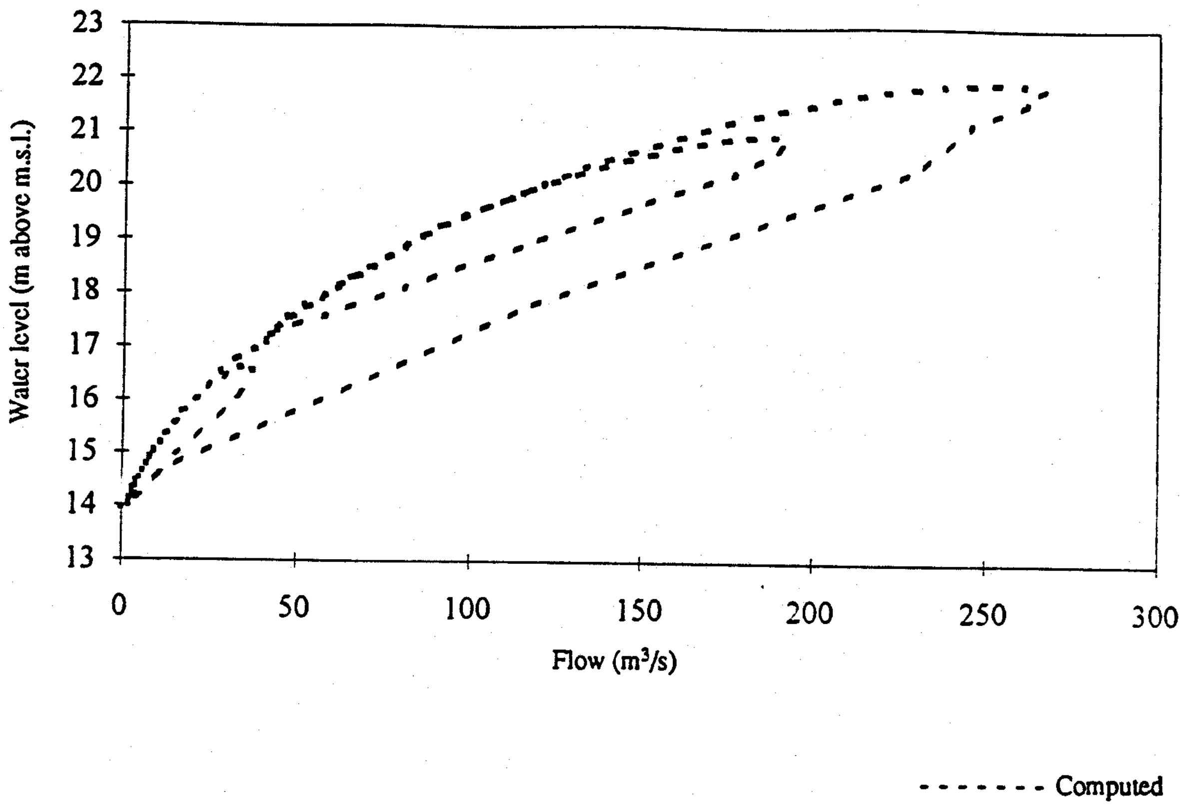


Figure 7.27 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of October 1991 at the (uncontrolled) Cento cross-section showing the expected open loop.

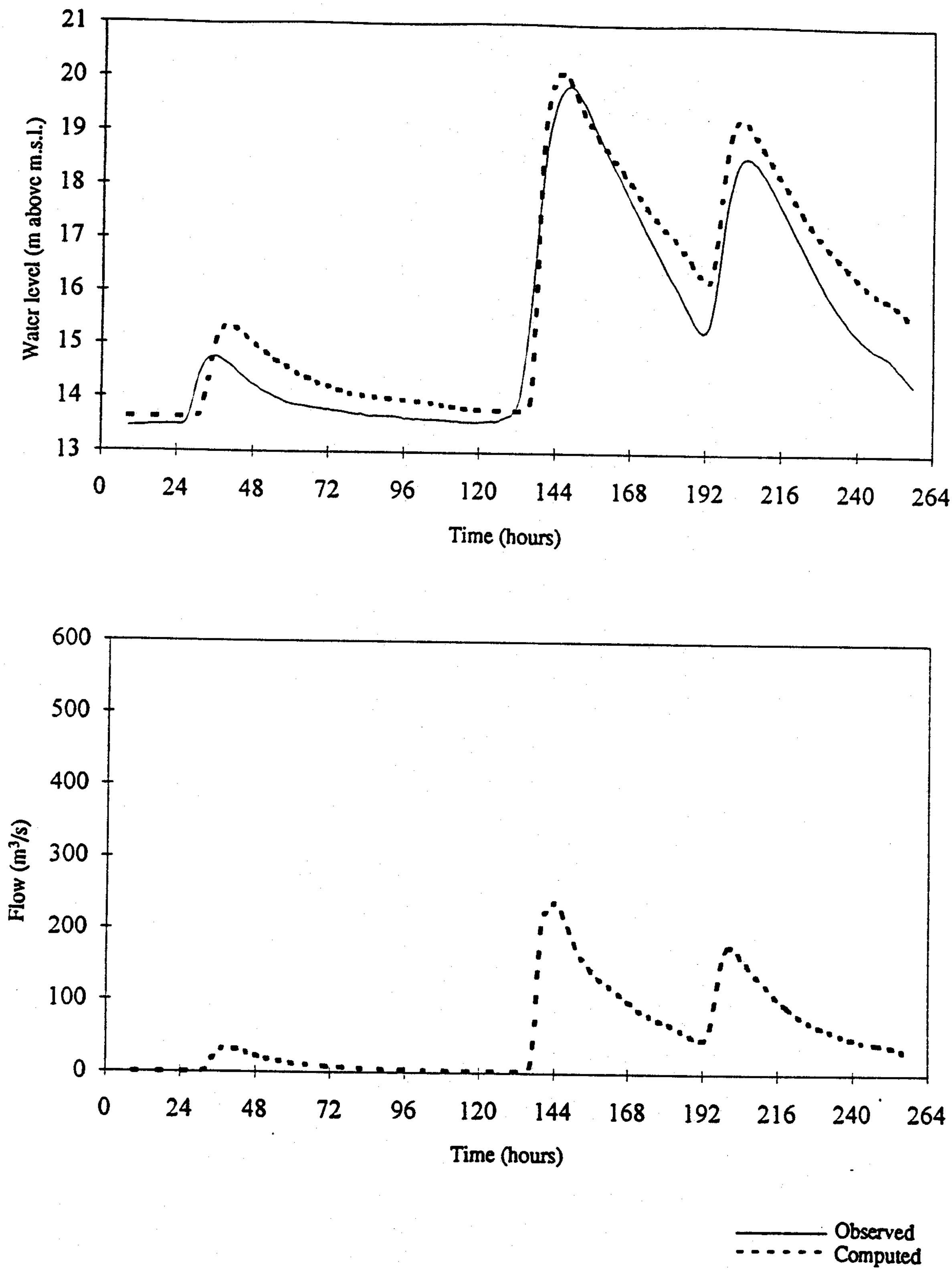


Figure 7.28 - Reconstruction using the simulation model, of the flood hydrograph of October 1991 at the Dosso cross-section.

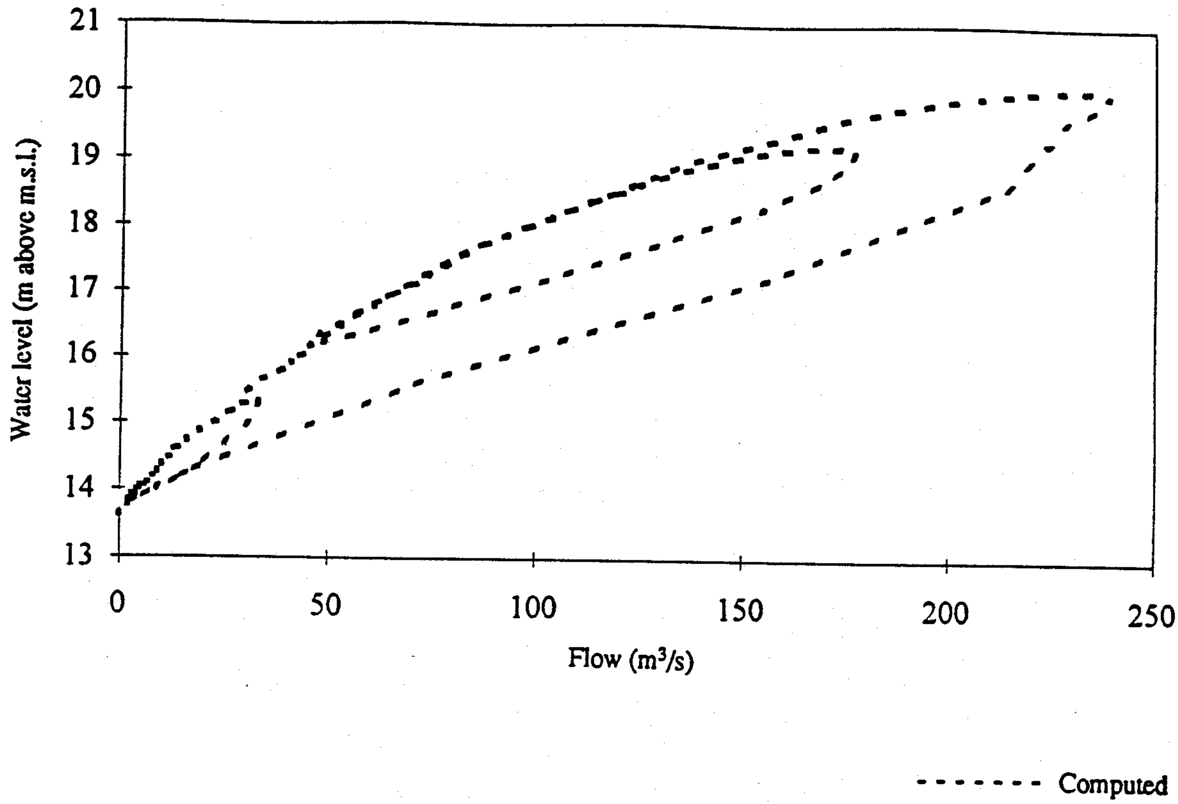


Figure 7.29 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of October 1991 at the (uncontrolled) Dosso cross-section showing the expected open loop.

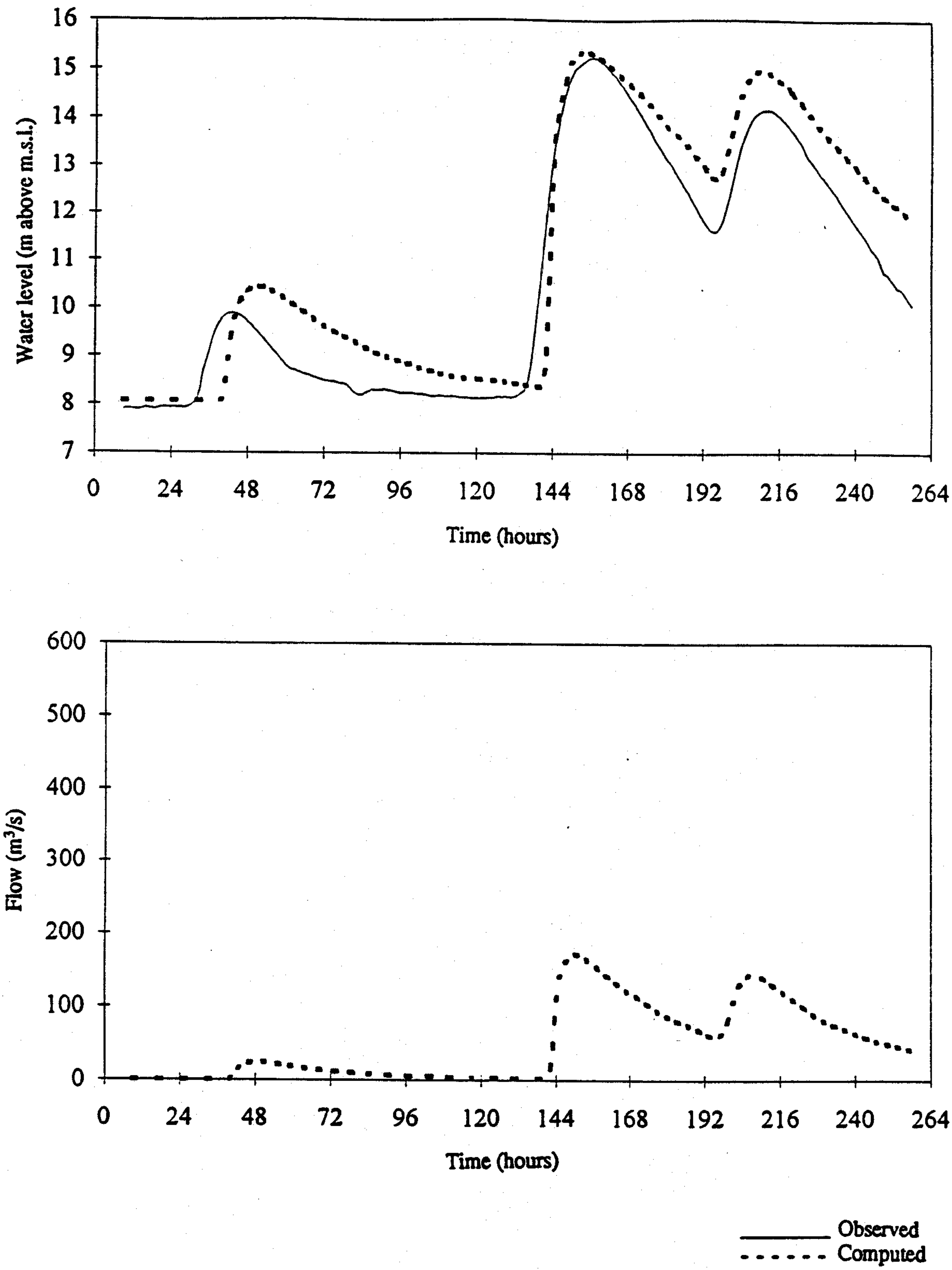


Figure 7.30 - Reconstruction using the simulation model, of the flood hydrograph of October 1991 at the Gallo cross-section.

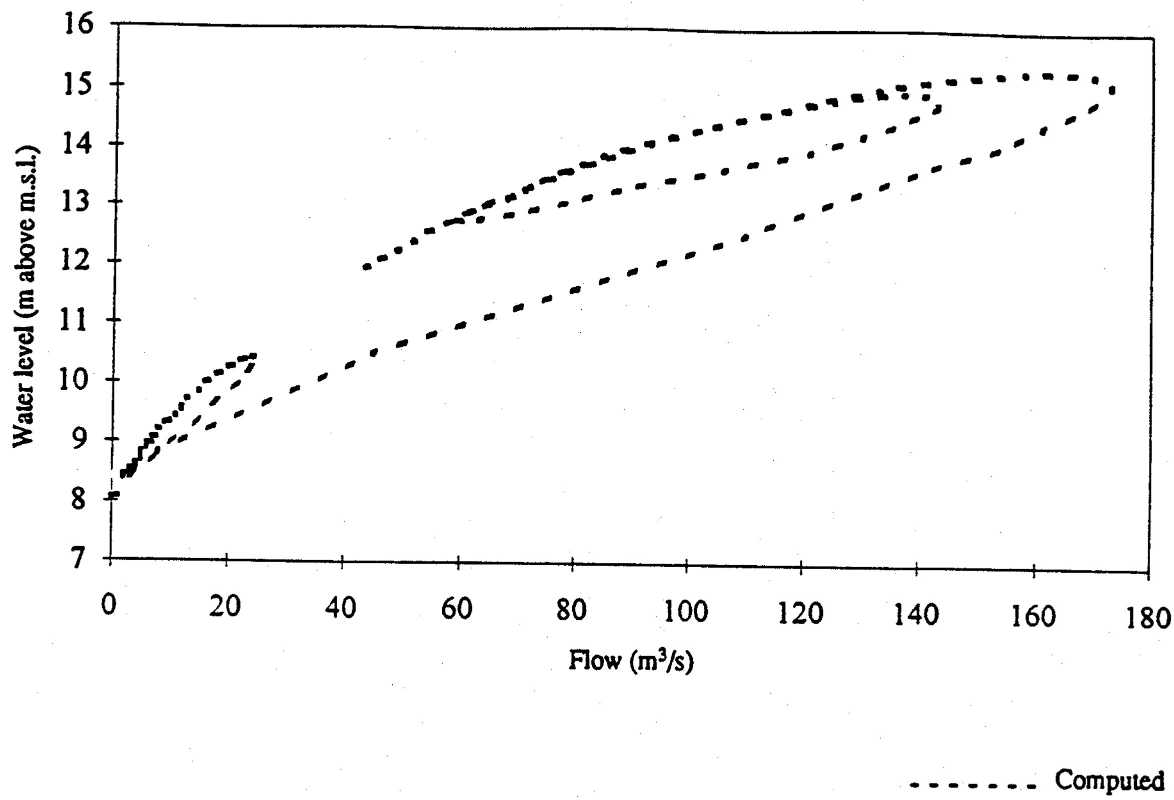


Figure 7.31 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of October 1991 at the (uncontrolled) Gallo cross-section showing the expected open loop.

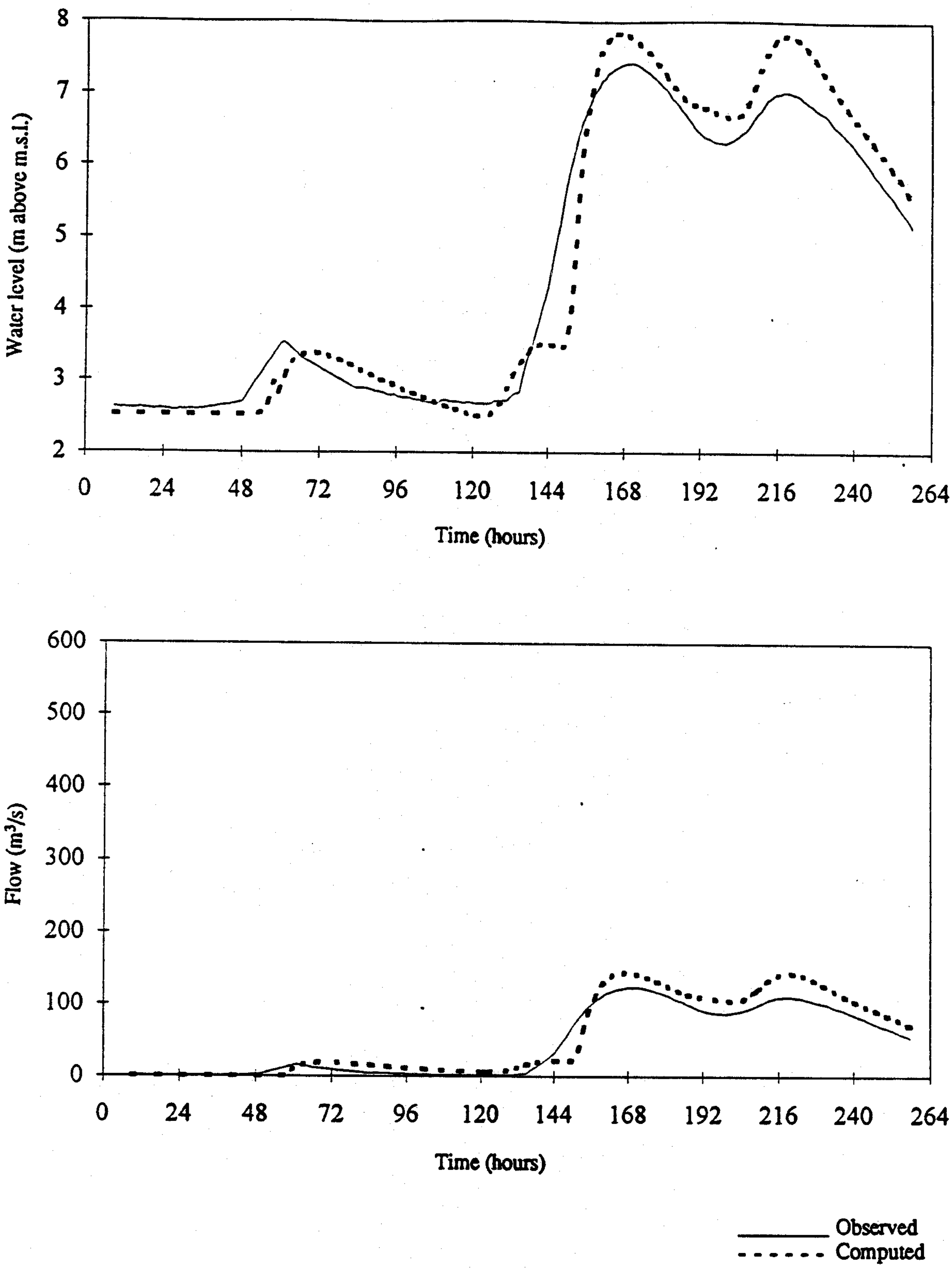


Figure 7.32 - Reconstruction using the simulation model, of the flood hydrograph of October 1991 at the Bastia cross-section.

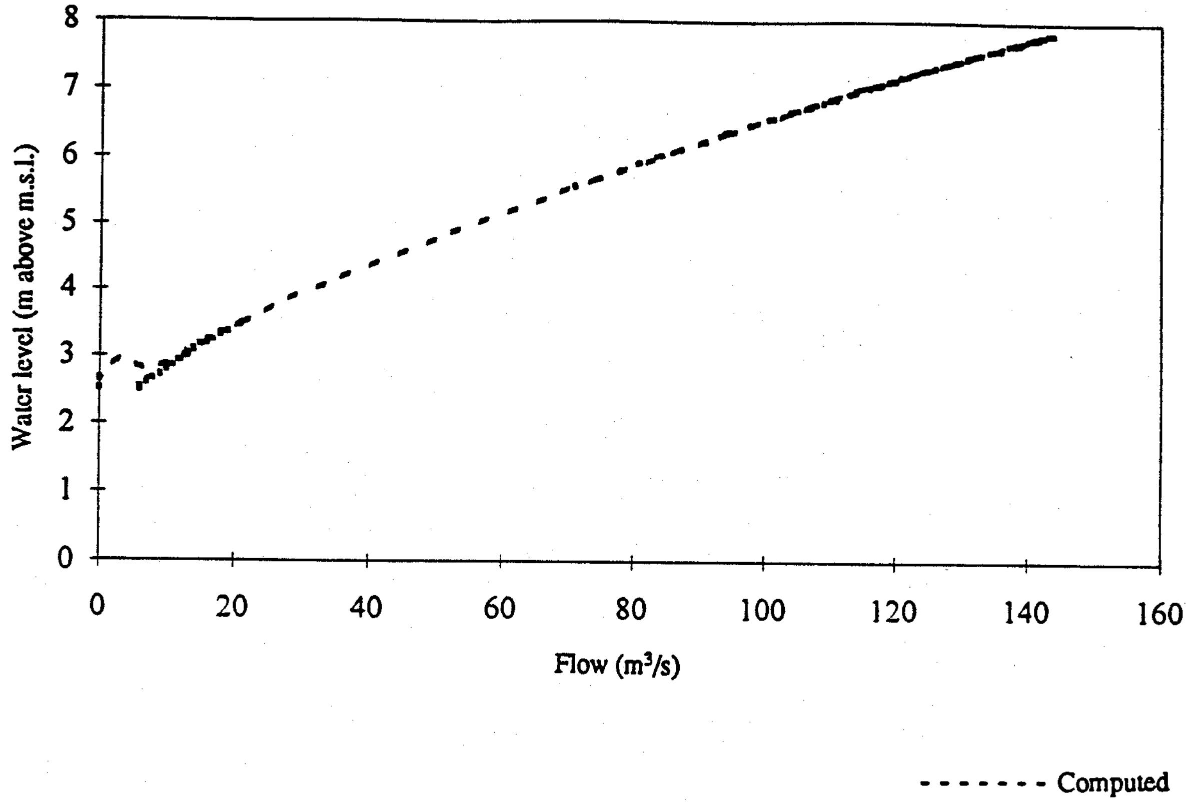
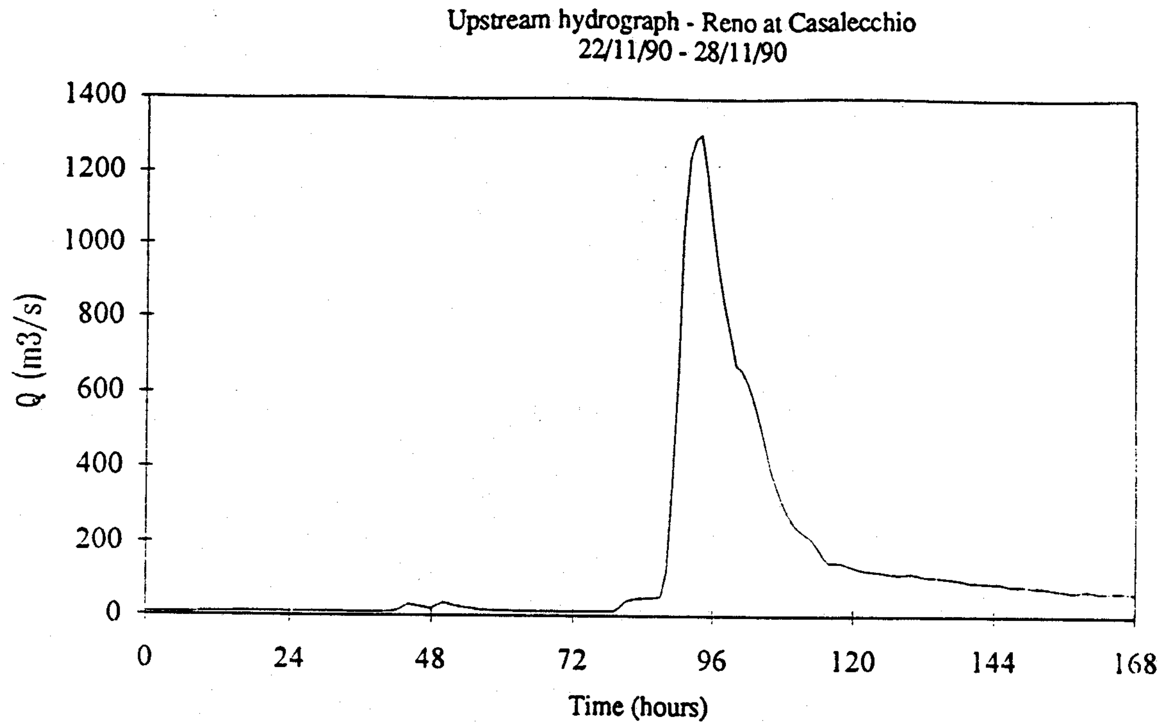


Figure 7.33 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of October 1991 at the Bastia weir, showing the expected one-to-one correspondence.



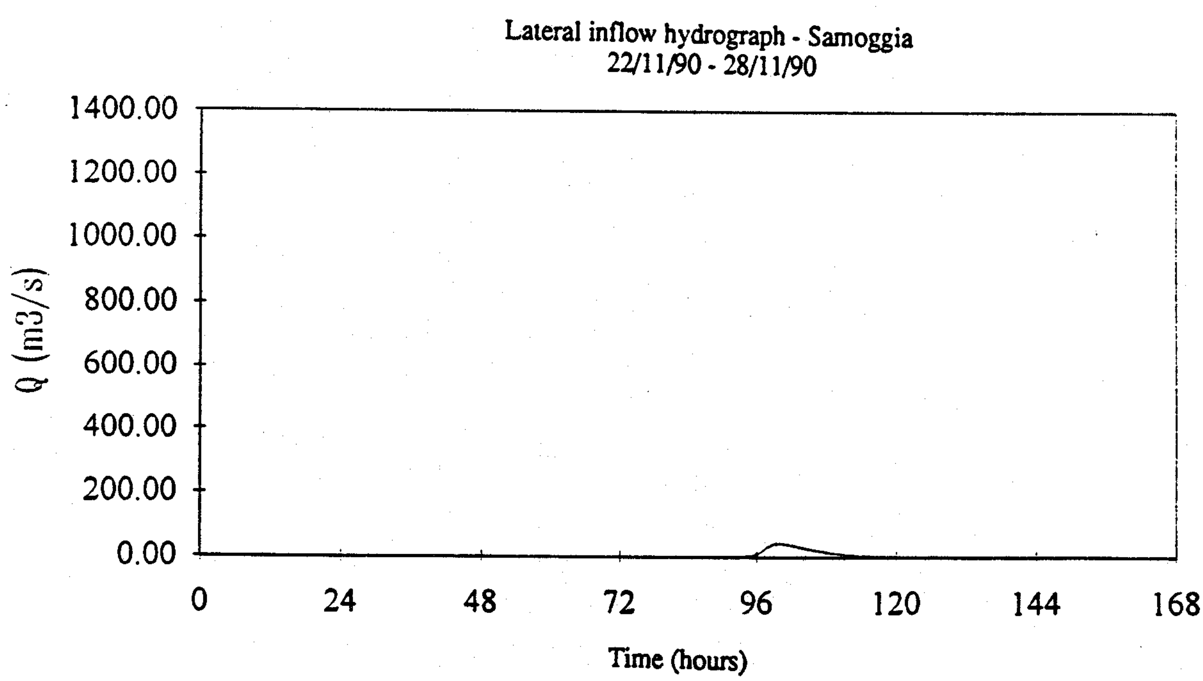
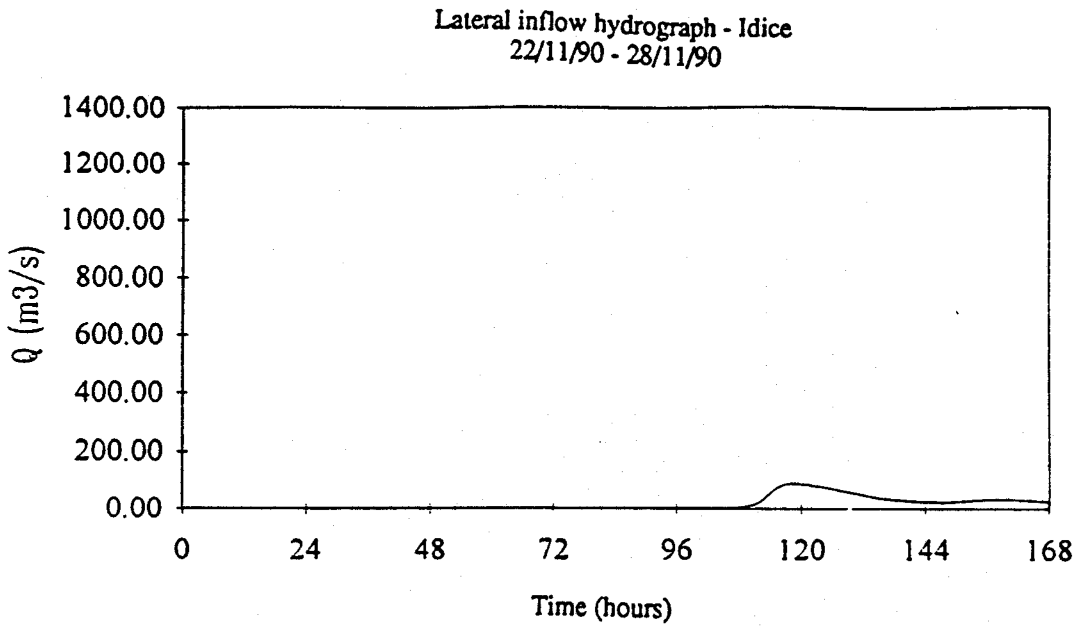


Figure 7.34 - Inflow hydrographs used in PAB for the flood wave of November 1990 (Validation period)



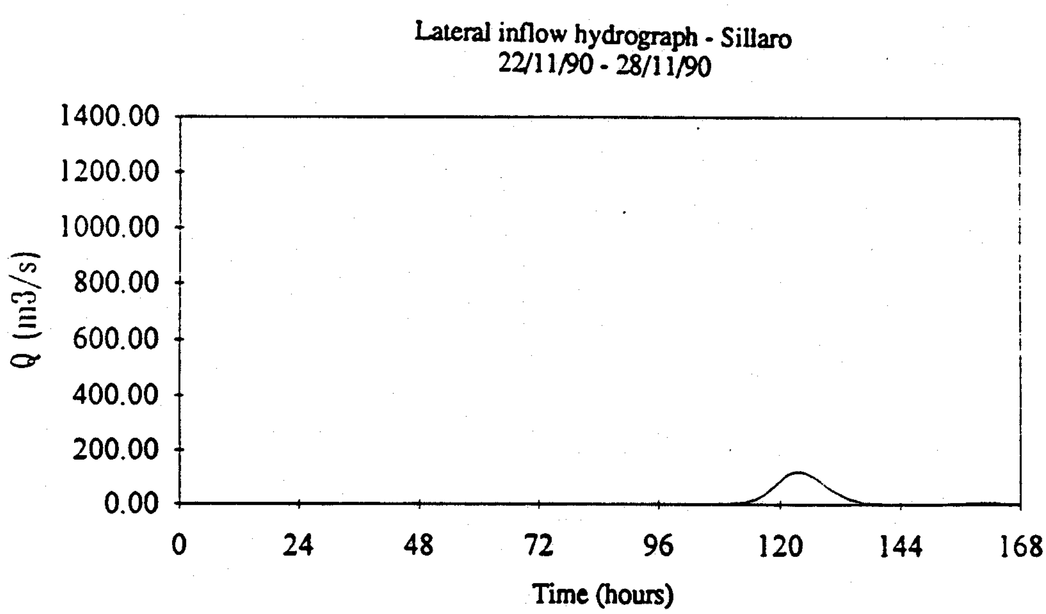


Figure 7.34 - Inflow hydrographs used in PAB for the flood wave of November 1990 (Validation period)

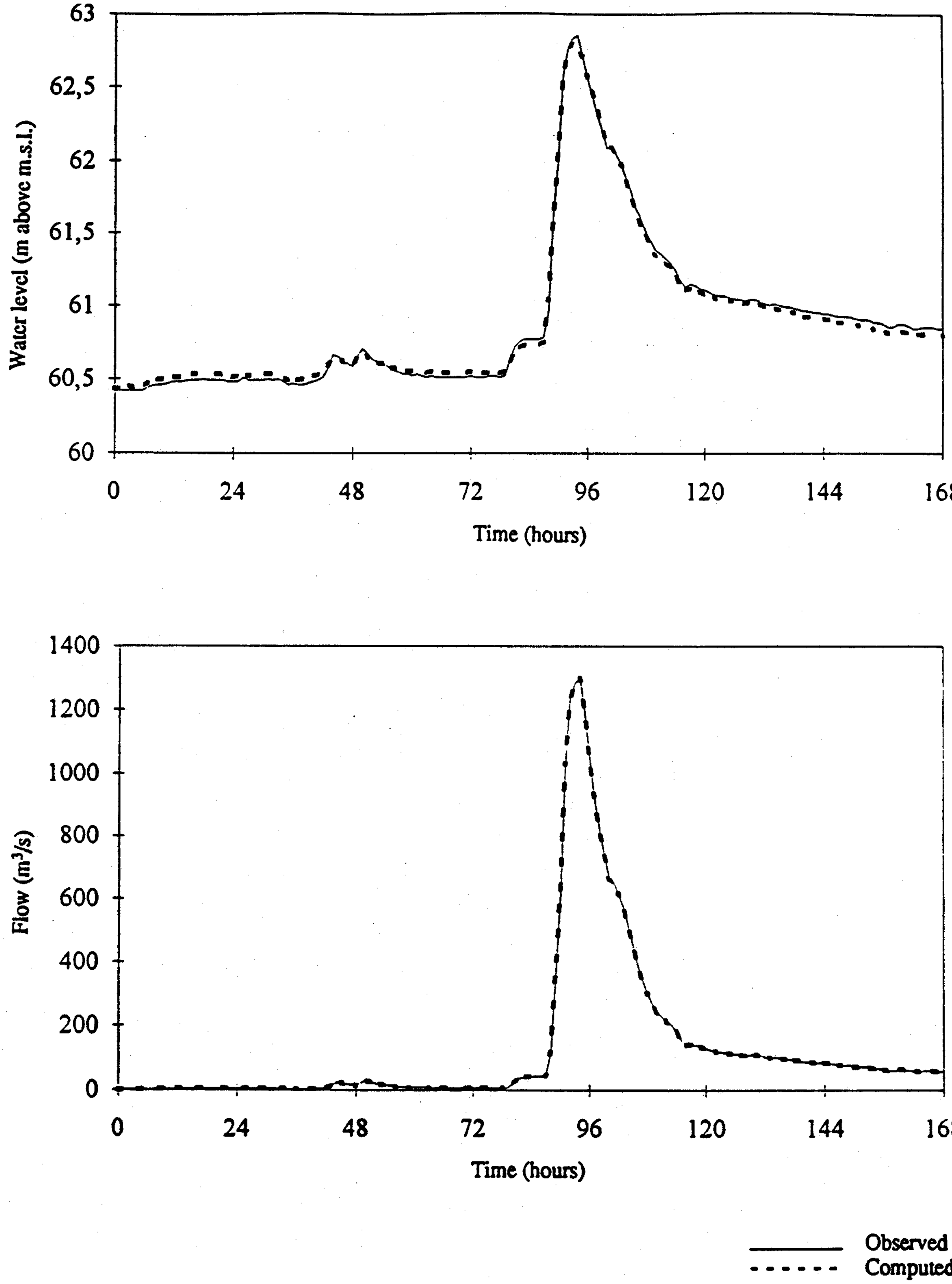


Figure 7.35 - Reconstruction using the simulation model, of the flood hydrograph of November 1990 at the Casalecchio cross-section.

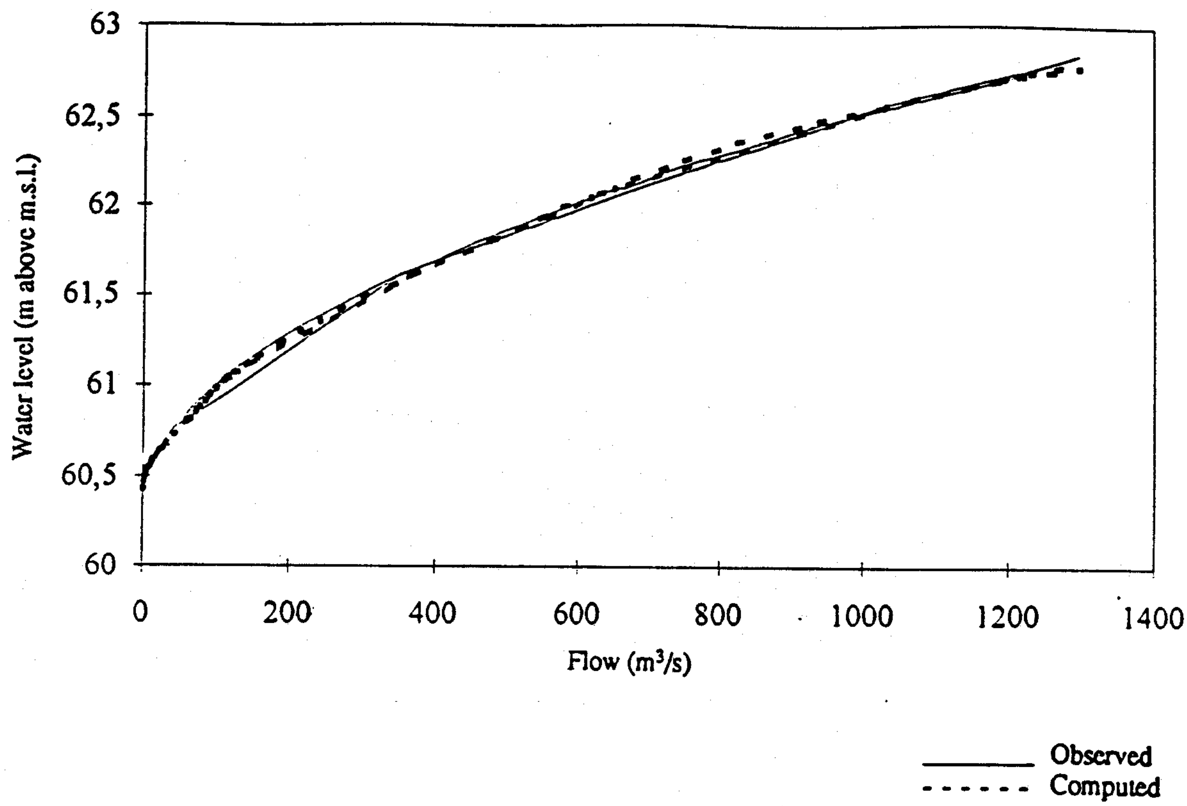


Figure 7.36 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of November 1990 at the Casalecchio weir, showing the expected one-to-one correspondence.

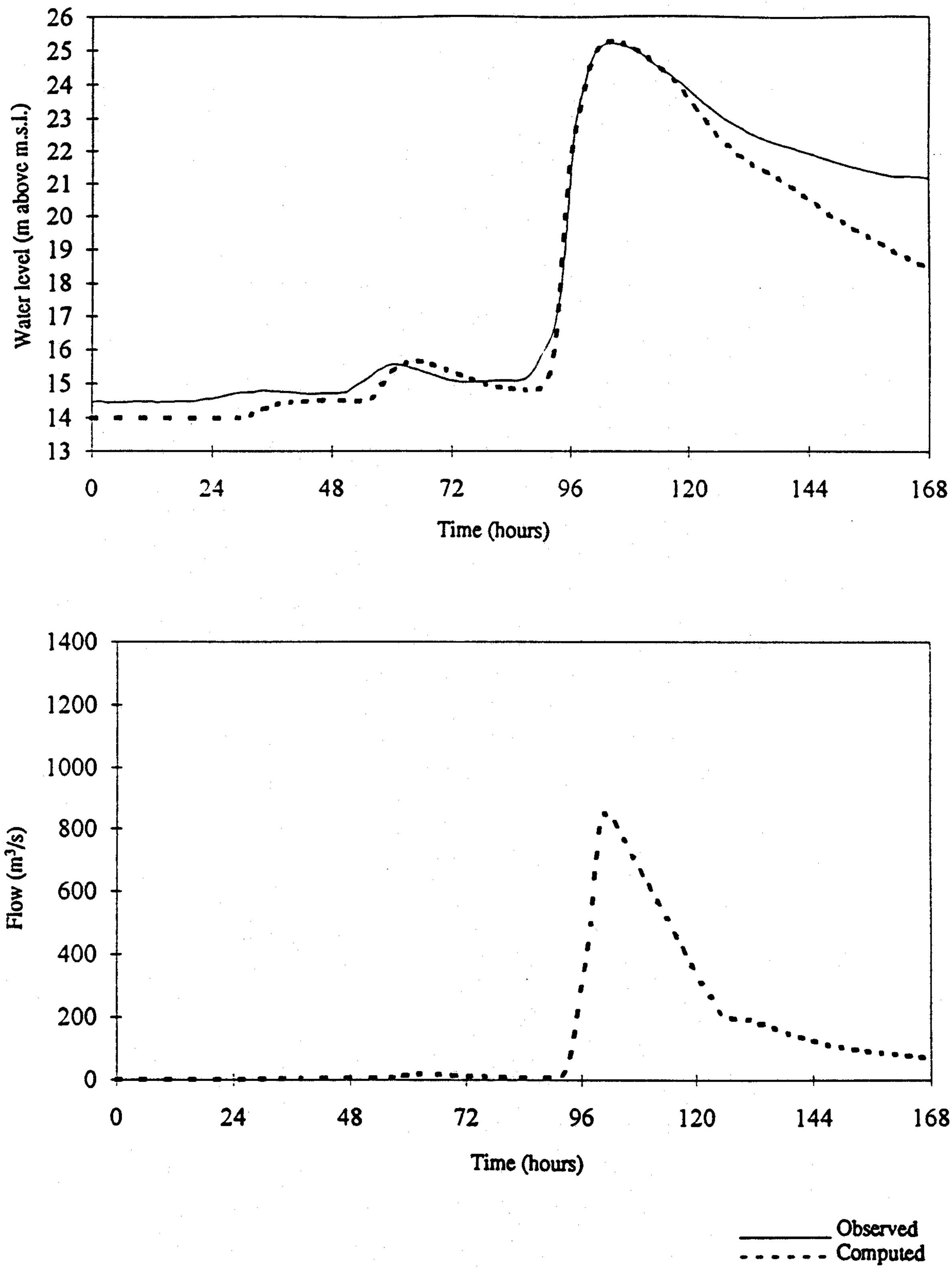


Figure 7.37 - Reconstruction using the simulation model, of the flood hydrograph of November 1990 at the Cento cross-section.

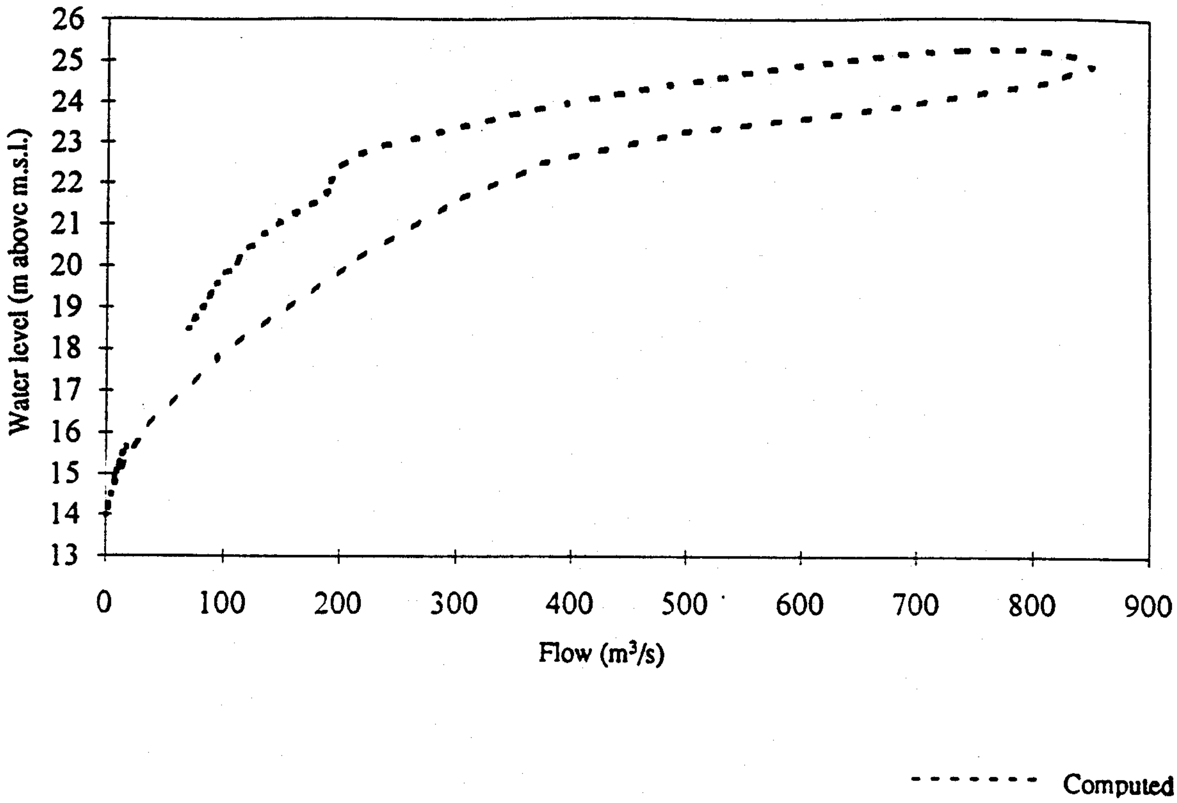


Figure 7.38 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of November 1990 at the (uncontrolled) Cento cross section showing the expected open loop.

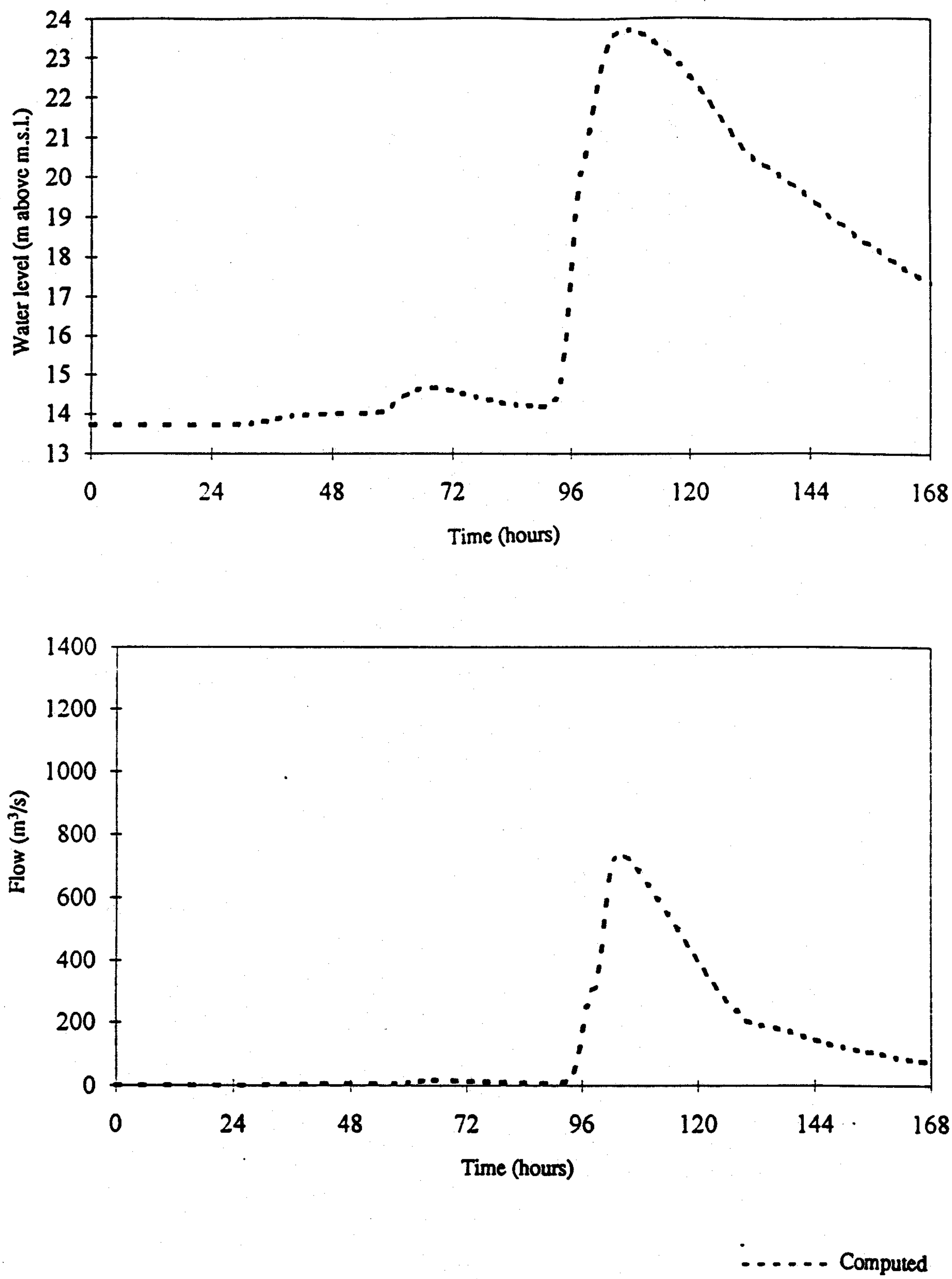


Figure 7.39 - Reconstruction using the simulation model, of the flood hydrograph of November 1990 at the Dosso cross-section.

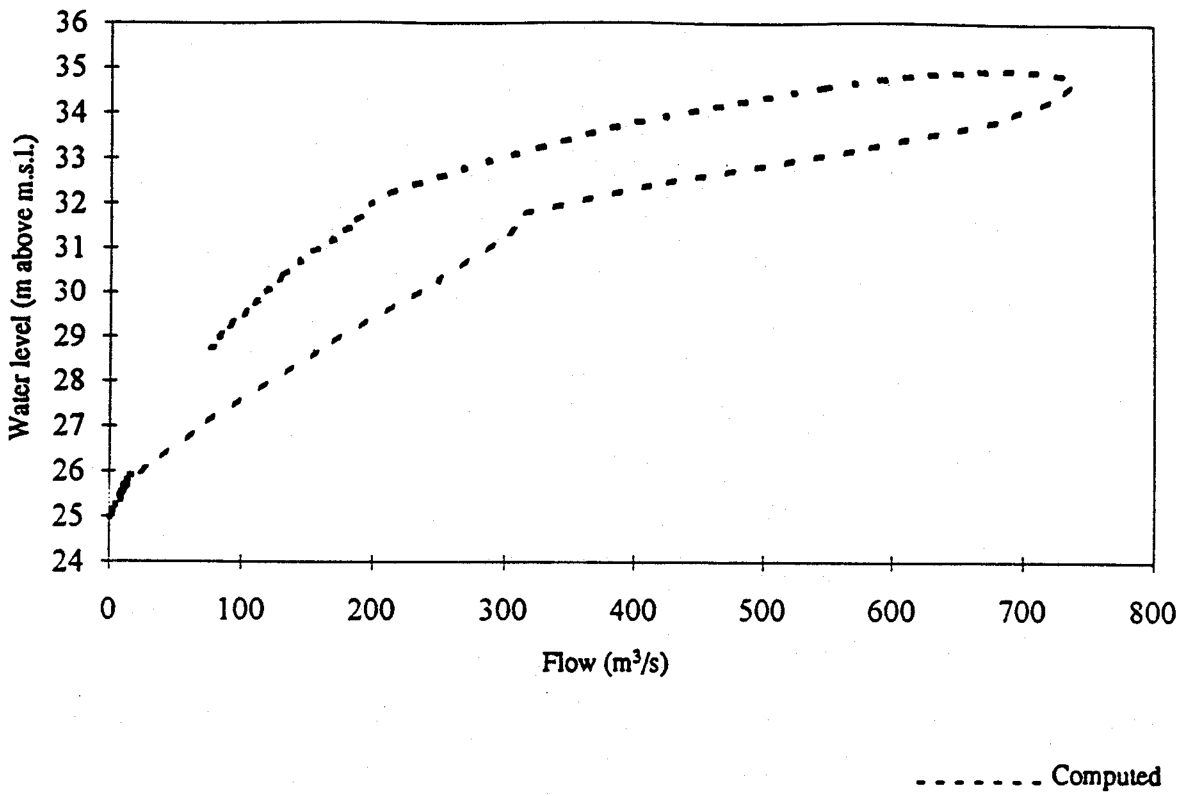


Figure 7.40 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of November 1990 at the (uncontrolled) Dosso cross section showing the expected open loop.

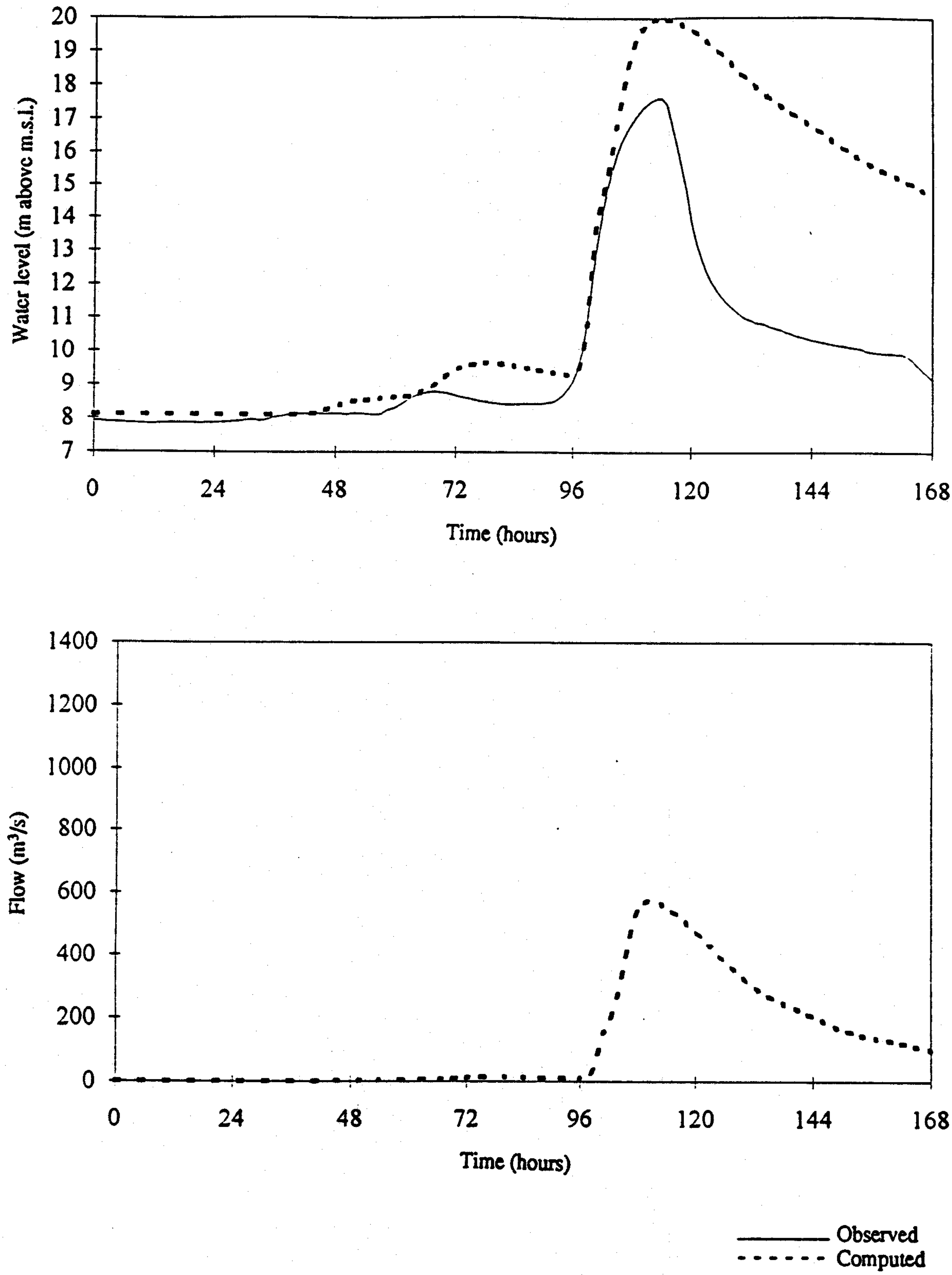


Figure 7.41 - Reconstruction using the simulation model, of the flood hydrograph of November 1990 at the Gallo cross-section.

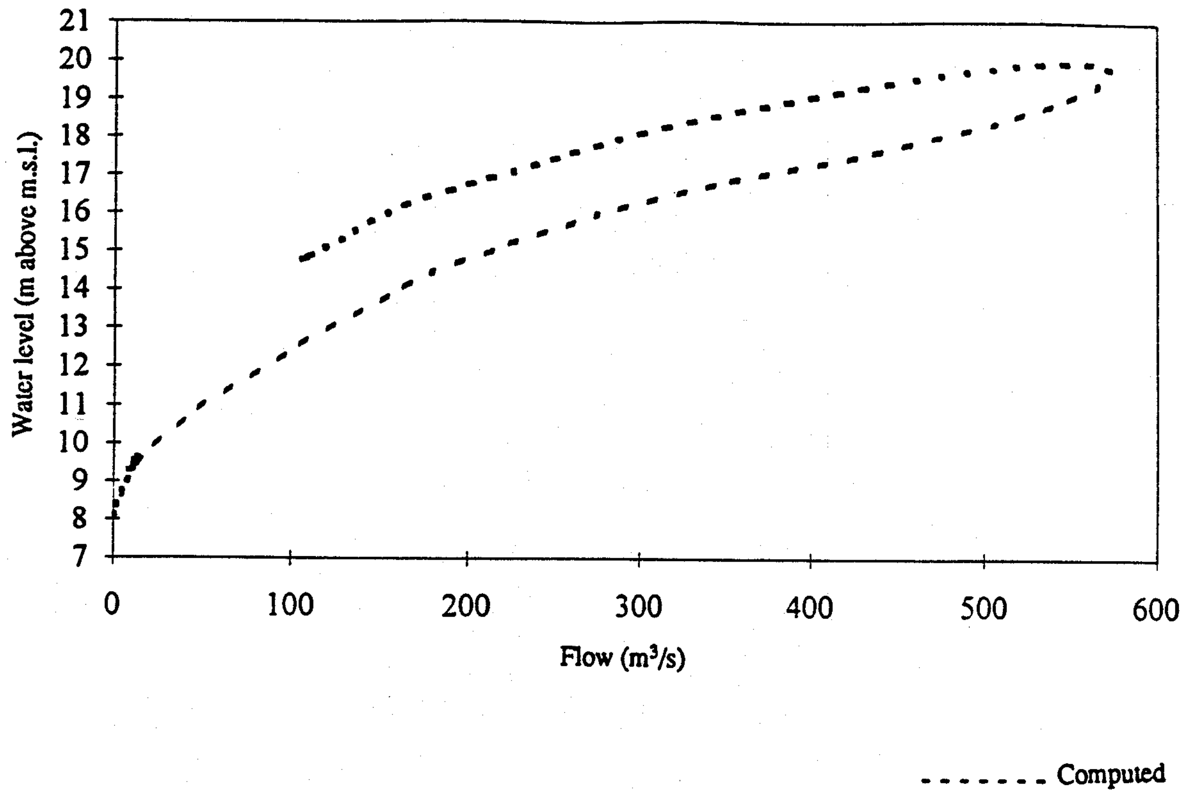
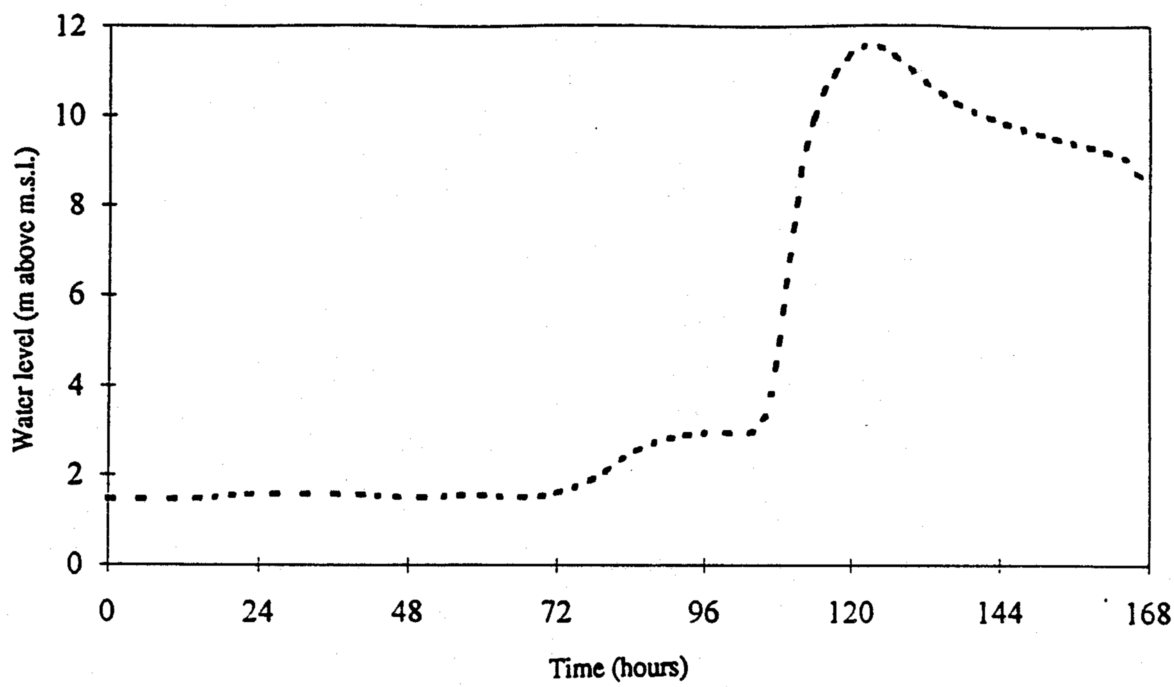


Figure 7.42 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of November 1990 at the (uncontrolled) Gallo cross section showing the expected open loop.



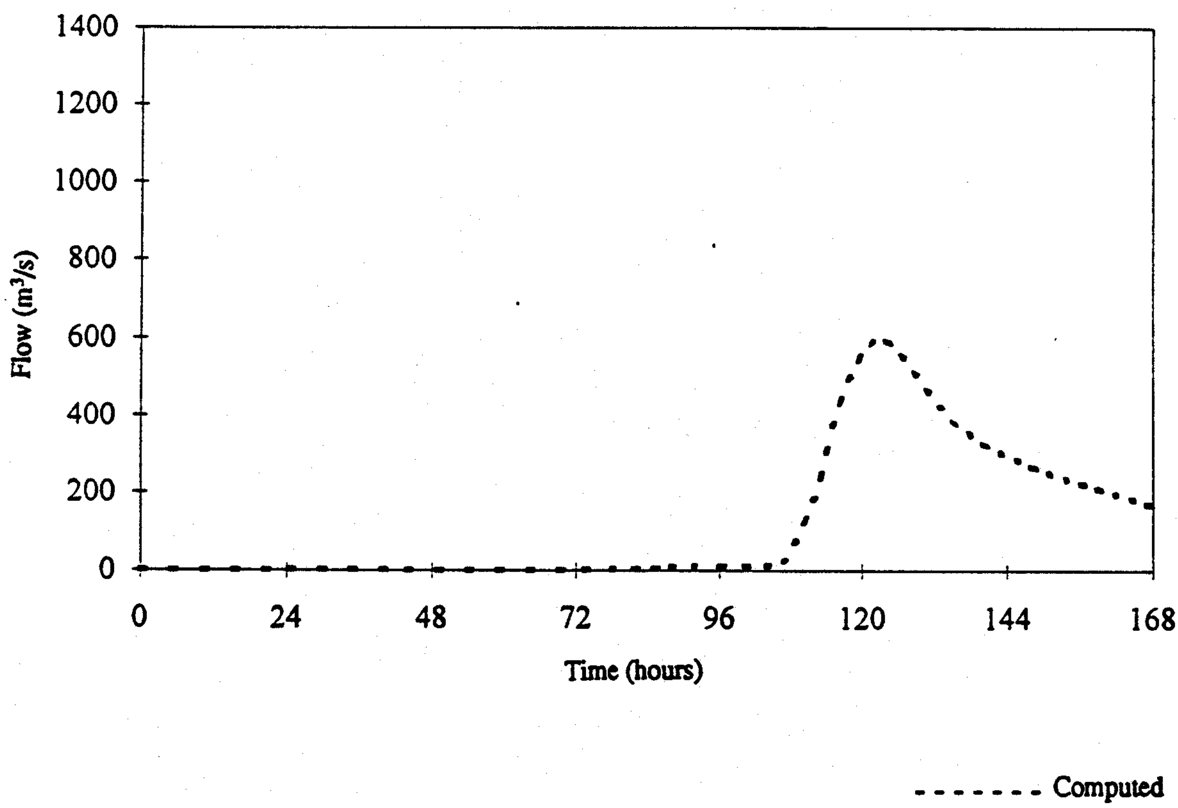


Figure 7.43 - Reconstruction using the simulation model, of the flood hydrograph of November 1990 at the Bastia cross-section.

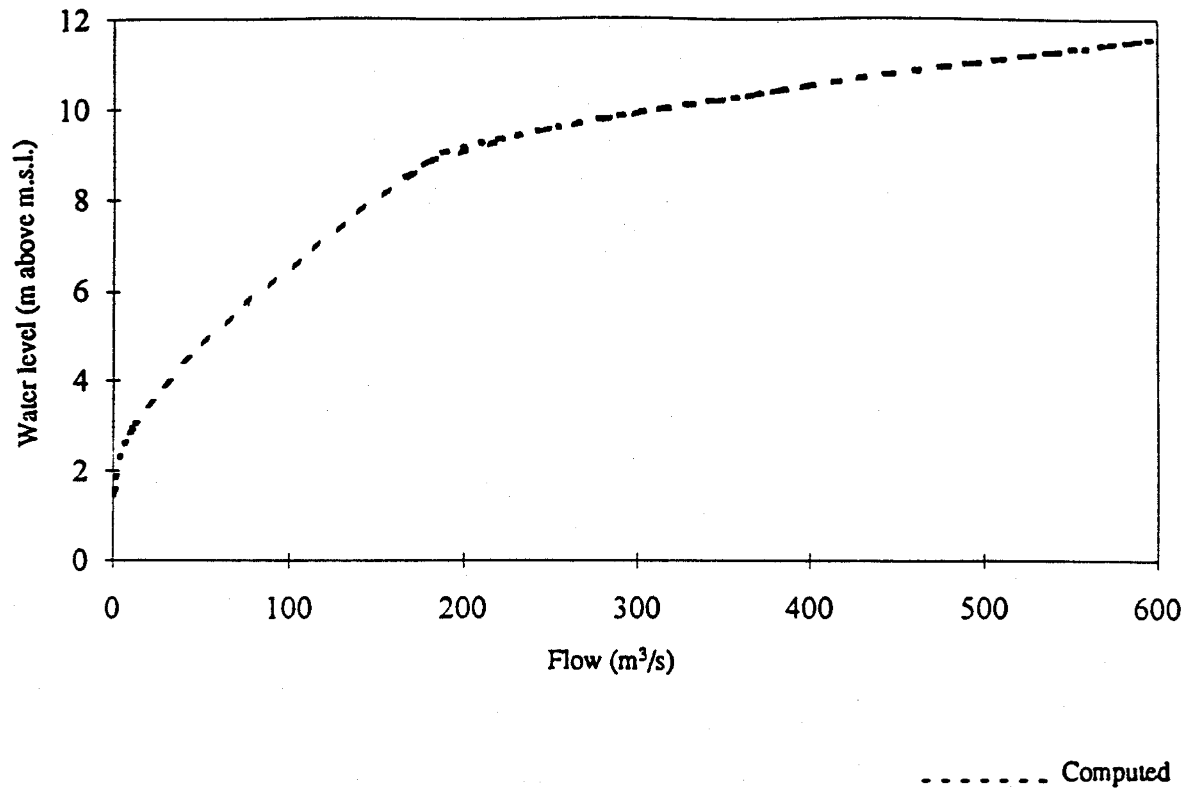


Figure 7.44 - Loop rating curve, reconstructed using the simulation model, for the flood-wave of November 1990 at the Bastia weir, showing the expected one-to-one correspondence.

7.5 THE EXPERIMENT ON THE USE OF LAM PRECIPITATION FORECASTS

One of the major problems in flood forecasting is to establish the time horizon needed for effectively organizing and implementing actions in real time. From the literature on finds that in the case of flash floods no intervention can reduce the actual damages if the forcasting lead time is less than six to eight hours, mainly due to organization problems. This is true if a Manual of Procedures is available which reflects previous analysis and in-depth knowledge of the system under control as well as of the organization (or of the organizations) that will take the responsibility of leading the interventions. To be on the safe side, when the procedure are not completely certain, it is convenient to assume twelve hours as the lead time at which a quantitative flood forecast is needed.

This results in a need for subdividing rivers into three main categories:

- Large rivers for which a flood in the downstream sections can be forecast for the next 12 hours, only by measuring the flow at upstream sections.
- Intermediate rivers where reliable forecasts 12 hours in advance can be provided if rainfall is measured up to the present time (this would include "nowcasting").
- Small rivers for which, due to their very small concentration time, forecasts 12 hours in advance can only be attained if reliable quantitative rainfall forecasts are available for the next 6 to 12 hours.

Within the frame of AFORISM an experiment was conducted in order to verify the possibility of using the rainfall forecasts provided by the Limited Area Model which is now operational in Emilia-Romagna (LAMBO) instead of using statistical extrapolations of the precipitation field based on stochastic precipitation modelling, as described in Chapter 2. It was performed on the basin of the Reno river downstream of Casalecchio, which is a combination of the second and third categories listed above.

Every six hours, starting from November 24, 1990, 24 hours long rainfall sequences were issued by the Servizio Meteorologico Regionale-Emilia Romagna (SMR-ER), sampled at one hour time step and located at the nodes of the LAM schematization grid, whose element size is 10 km. The precipitation data were then combined in order to provide an estimate of the average rainfall forecast over a specific sub-catchment relevant to the ARNO rainfall-runoff model representation.

A comparison of these precipitation estimates with the areal precipitation obtained from the ground-based raingauge network, revealed a very low degree of correspondence, particularly in terms of actual precipitation depth. It was therefore decided to use the first 12 hours of forecast for computing an amplification factor to be applied to the next 12 hours, by comparing the LAM forecasted values with the corresponding areal precipitation values obtained on the basis of the raingauge measurements. This resulted in a delay of 12 hours before using the SMR-ER forecasts. This is a reasonable approach considering that atmospheric models, such as LAMBO require at least 6 hours of warm-up, so that the first 6 hours forecasts are generally of a lower quality than the second set. In practice, every 6 hours at the issue of a forecast, the areal precipitation cumulated over 12 hours was compared with the corresponding value obtained using the raingauges in the last 12 hours, by matching the time sequences, and thus obtaining a volume ratio which was then used to amplify (or reduce) the extrapolated values.

This procedure led to a noticeable improvement in the precipitation forecasts, as can be seen in Figures 7.45 to 7.51 relevant to the different sub-catchement in which the Reno river upstream Casalecchio was subdivided. In each figure the observed values (dots) are compared with the forecasts issued every six hours. As one can see, although well centered in time, the forecasts were still very low when compared to the observed. In particular one should notice the large difference in subcatchment REBR where a forecast of 5 mm/hr of rain badly underestimates the ground observed maximum intensity of 24 mm/hr.

The same pattern can then be observed in the forecasted flows at Casalecchio (Figures 7.52 to 7.58), where the flows are based on routing the ERSA predicted rainfalls and are generally underestimated. In particular one should observe Figures 7.53 and 7.54 in which the rapid increase in flow is not captured when the SMR-ER forecasts are used. Proceeding onwards from Figure 7.55 it appears that the rainfall has practically stopped and therefore all the forecasts are correct, because now the rainfall-runoff model is in zero-input response mode.

From this experiment, although limited to only one case and given the cost of the LAM runs, one may conclude that there is a potential in the use of LAM precipitation forecasts, provided that a better post-processing treatment is used instead of the very simple approach adopted in the AFORISM project. It is important to emphasize the fact that the timing of the large intensities as well as the shape of the hyetographs is well described by the LAM model outputs, while the intensities are still underestimated to too great an extent to be really useful at the level of accurancy required by an operational real-time flood forecasting system.

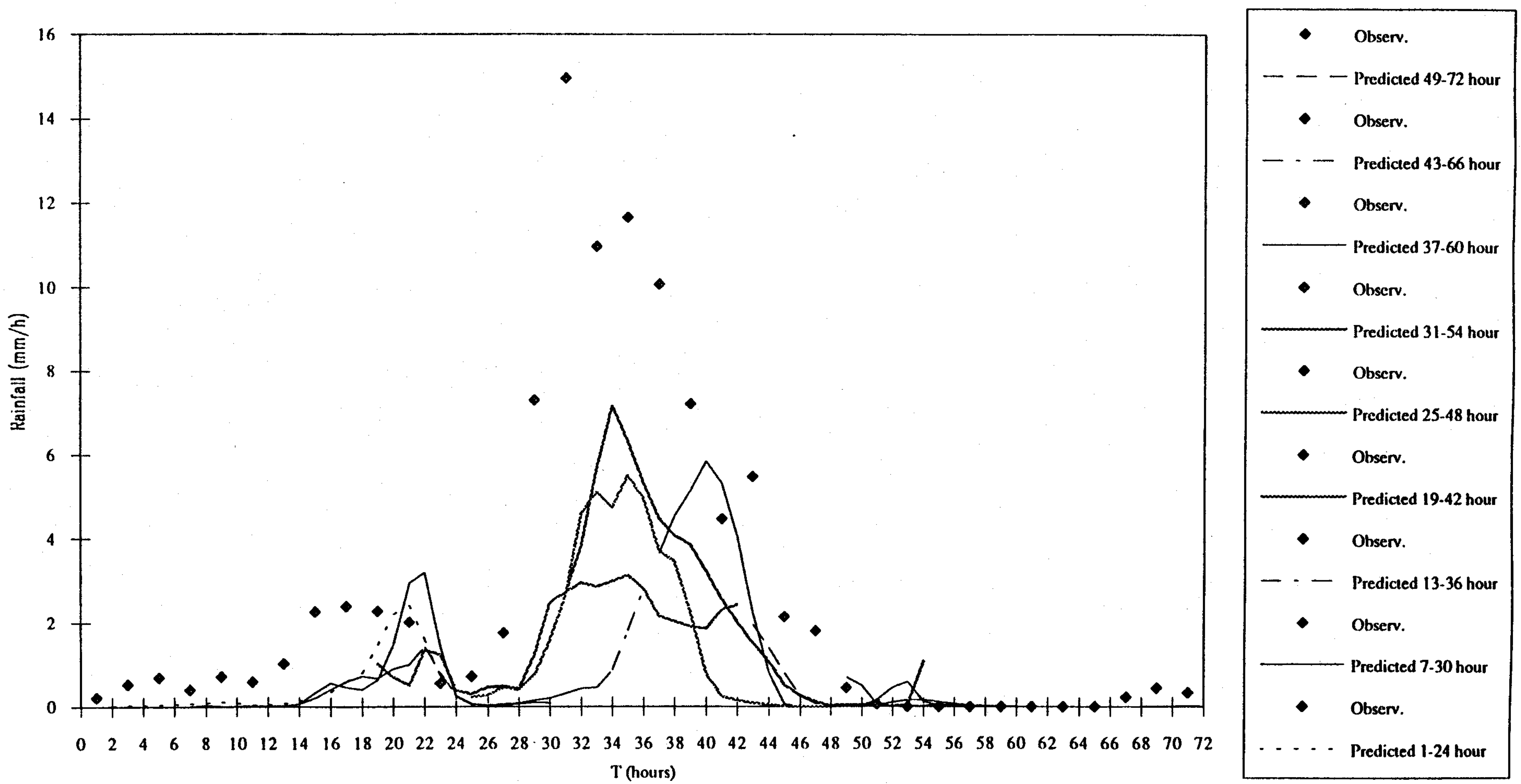


Figure 7.45 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin REMP.

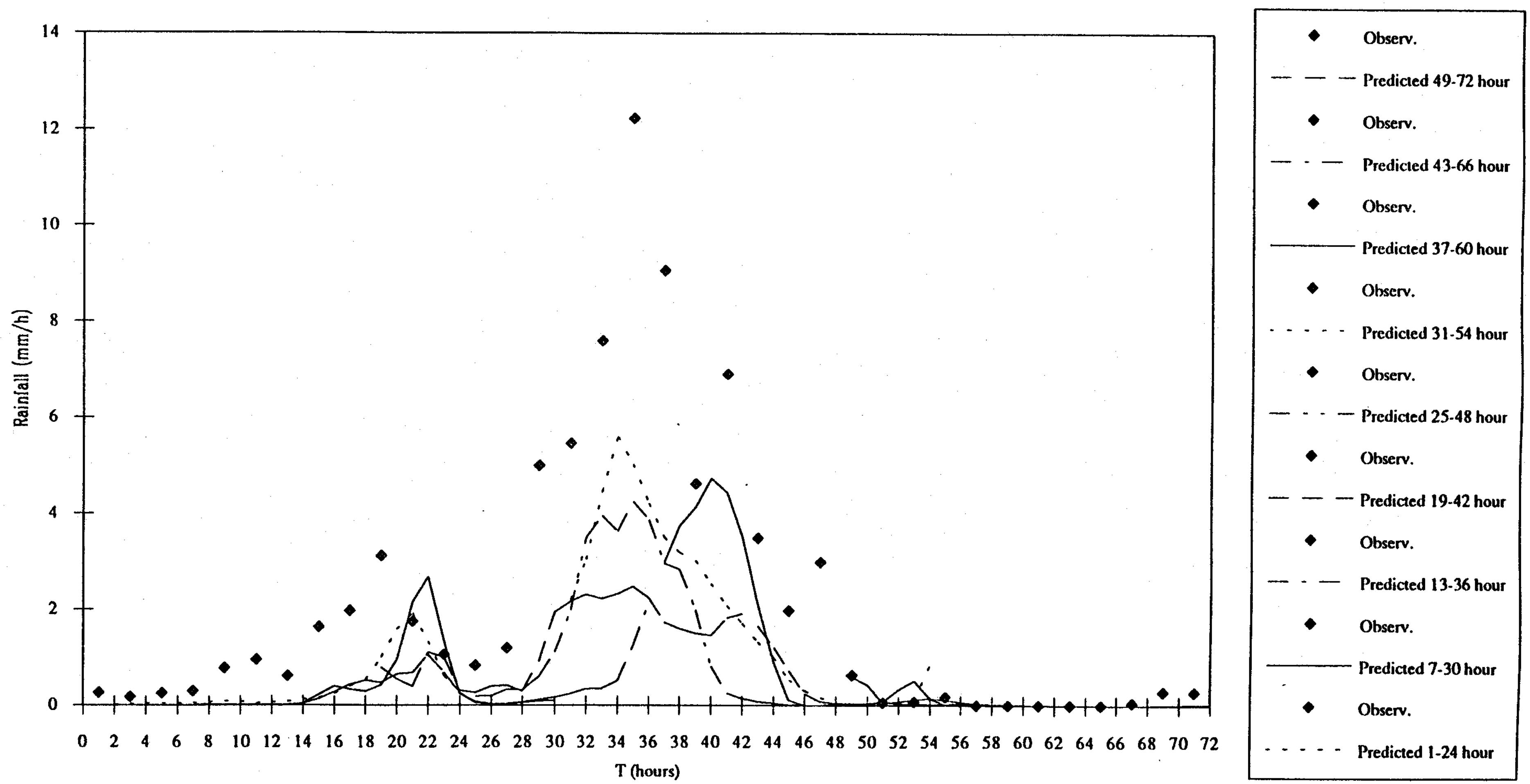


Figure 7.46 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin REPV.

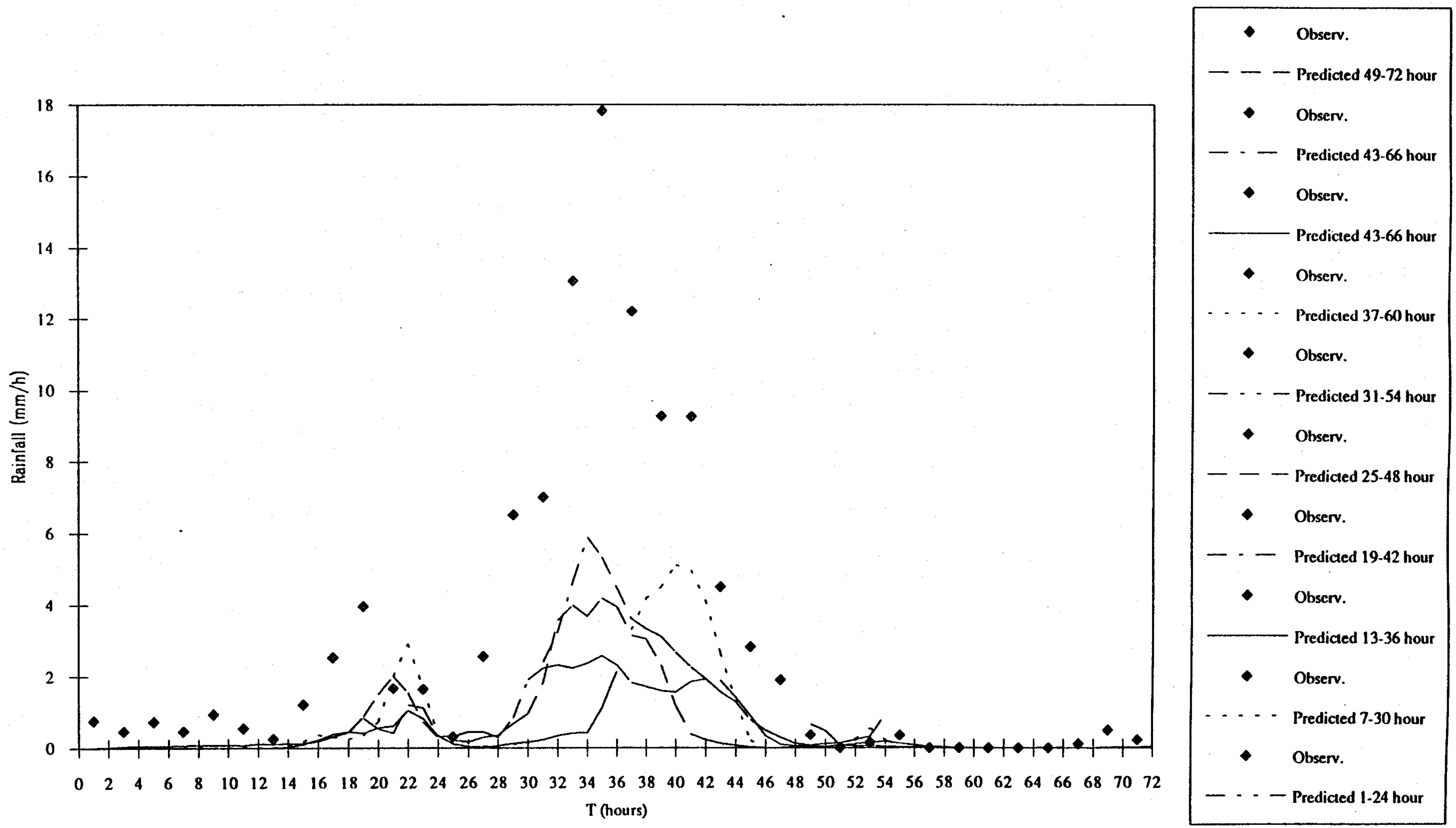


Figure 7.47 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin RESU.

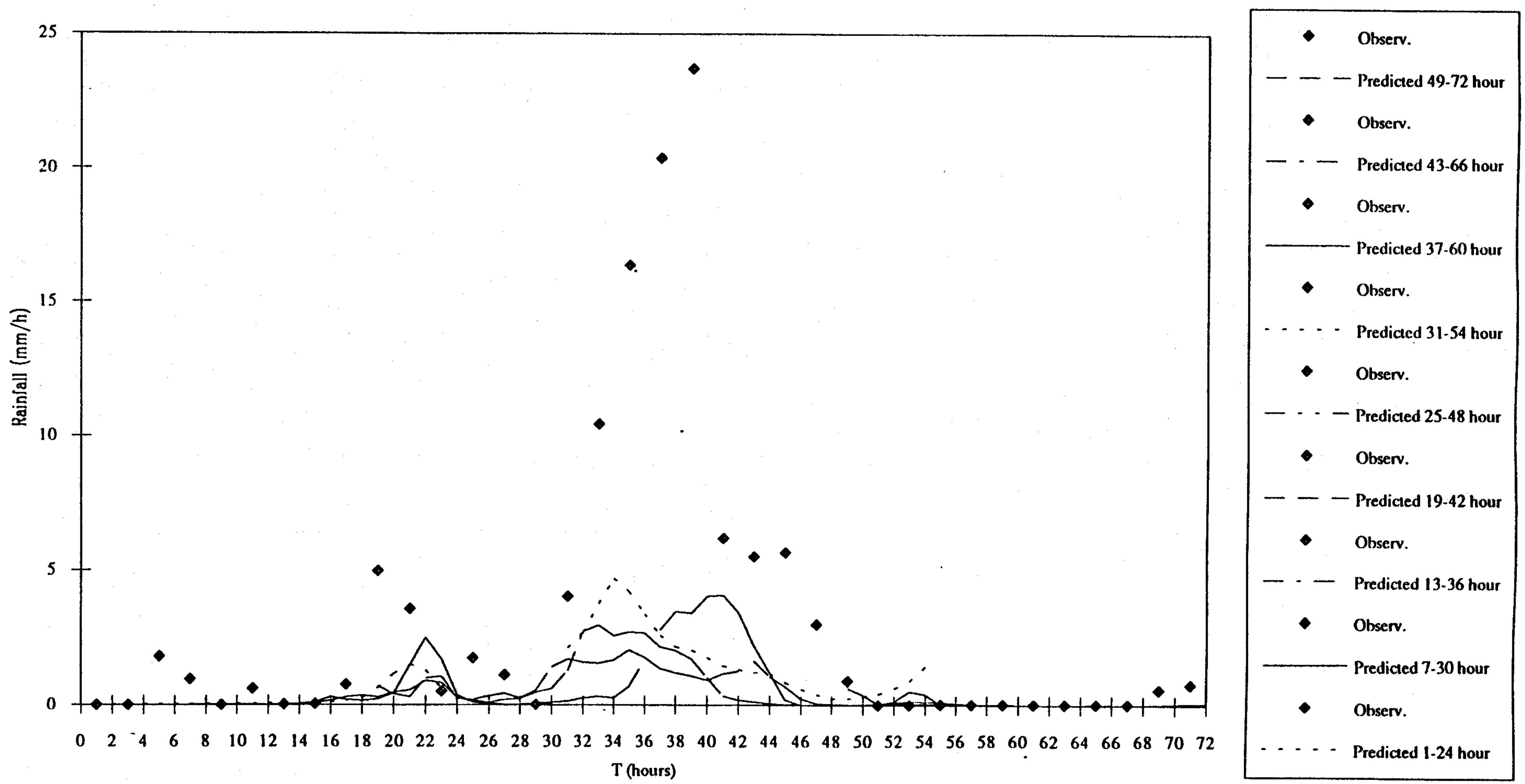


Figure 7.48 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin REBR.

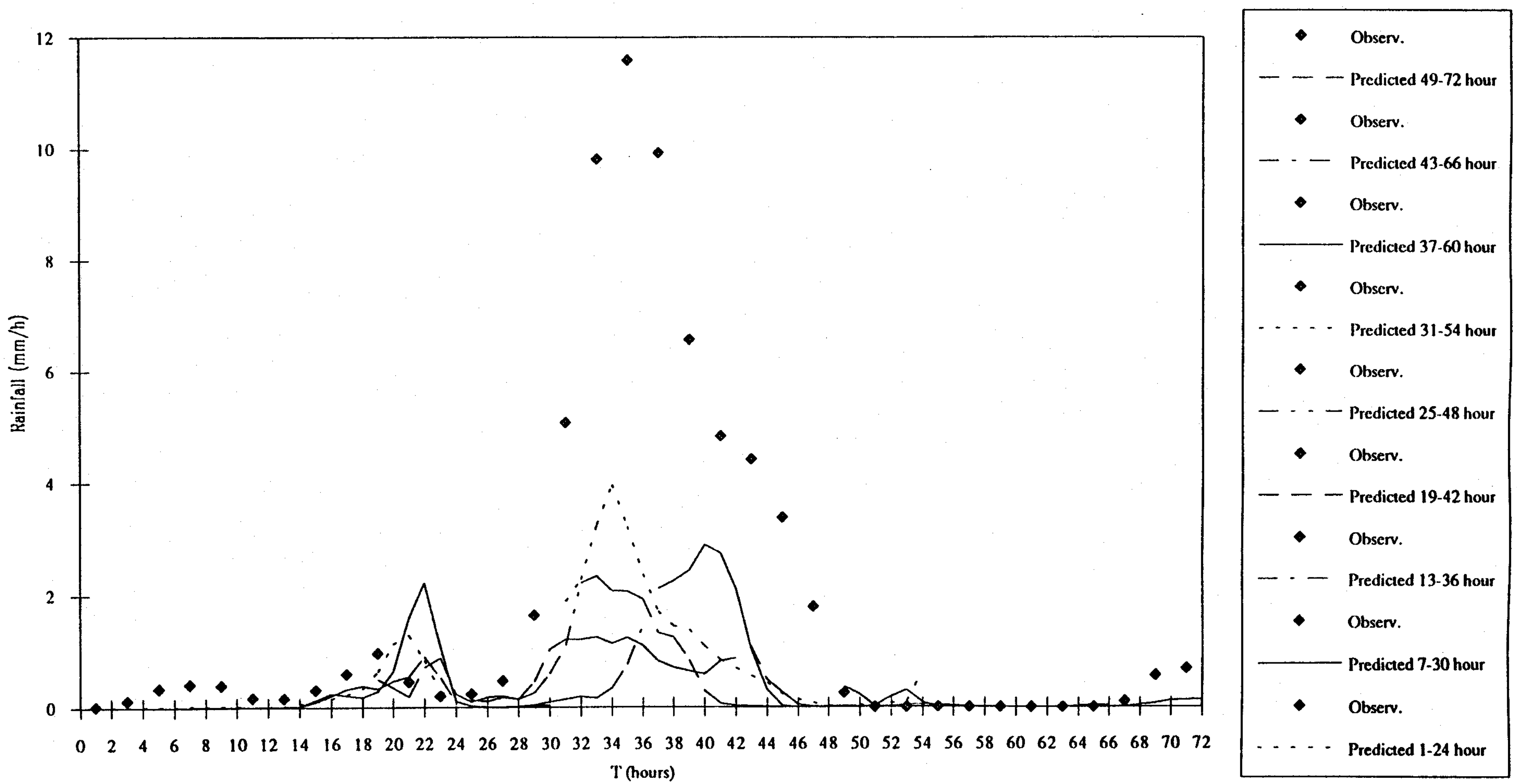


Figure 7.49 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin REVR.

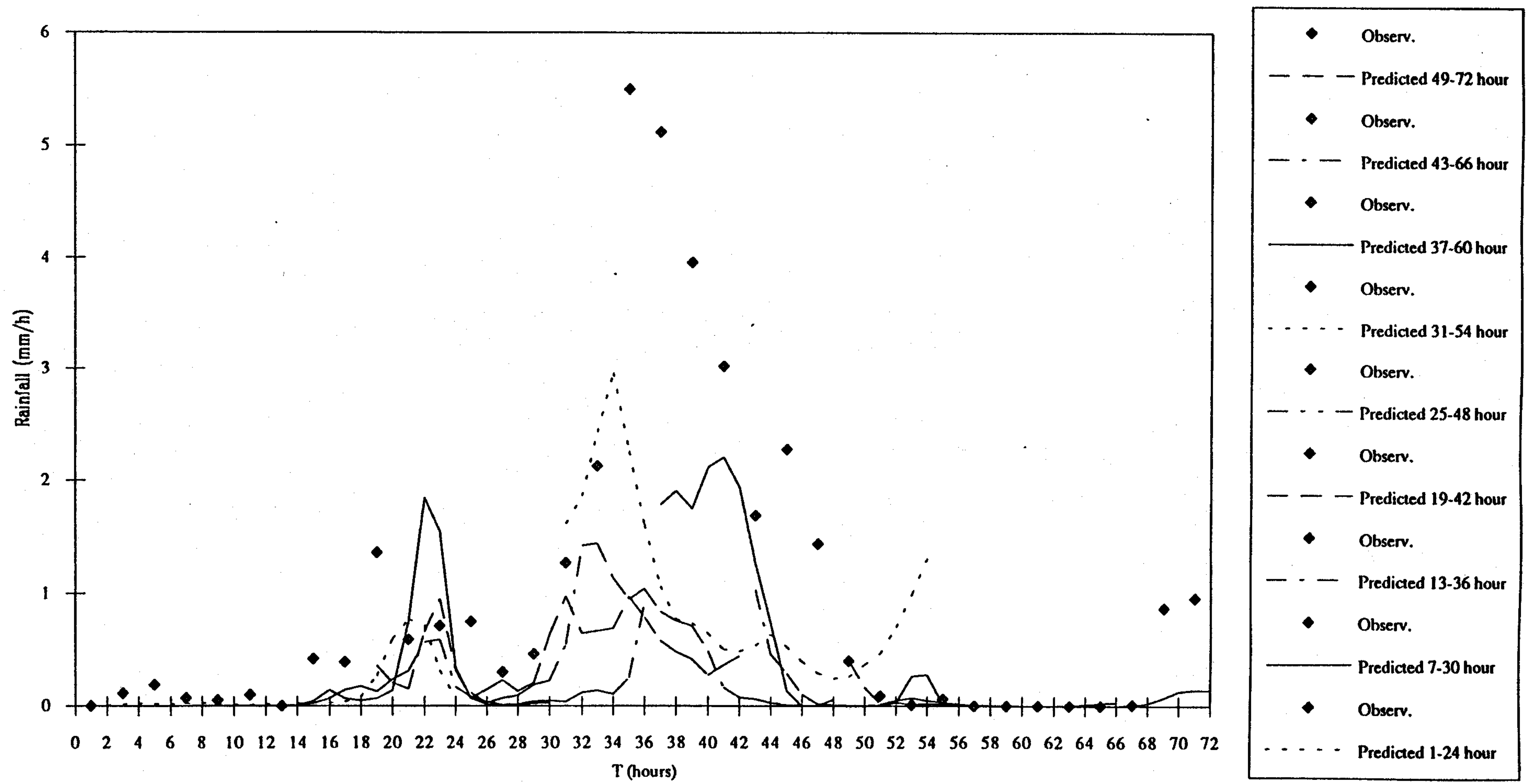


Figure 7.50 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin RESS.

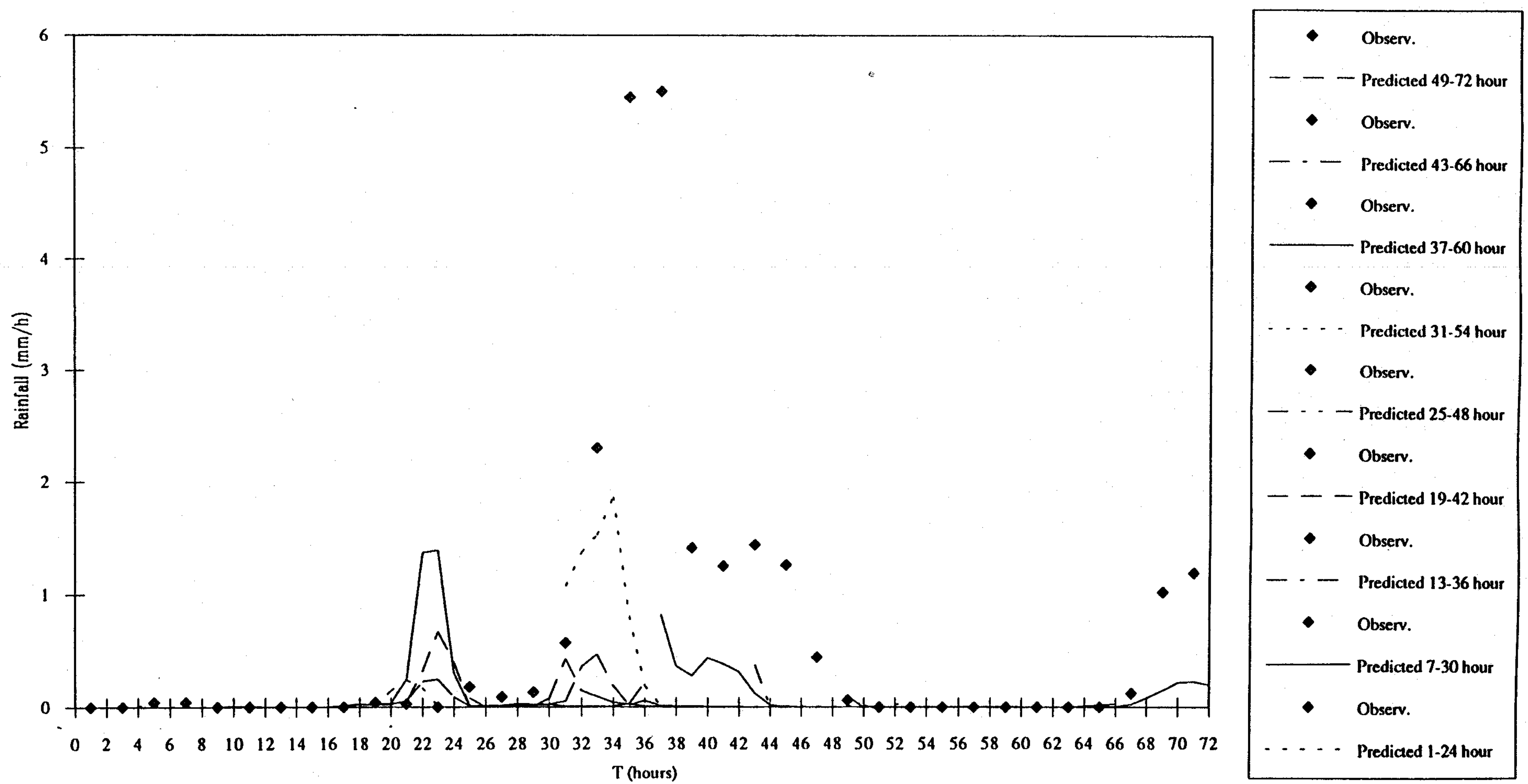


Figure 7.51 24-hour average rainfall forecasts for the 1990 event issued by SMR-ER at successive 6 hour intervals for sub-basin RECA.

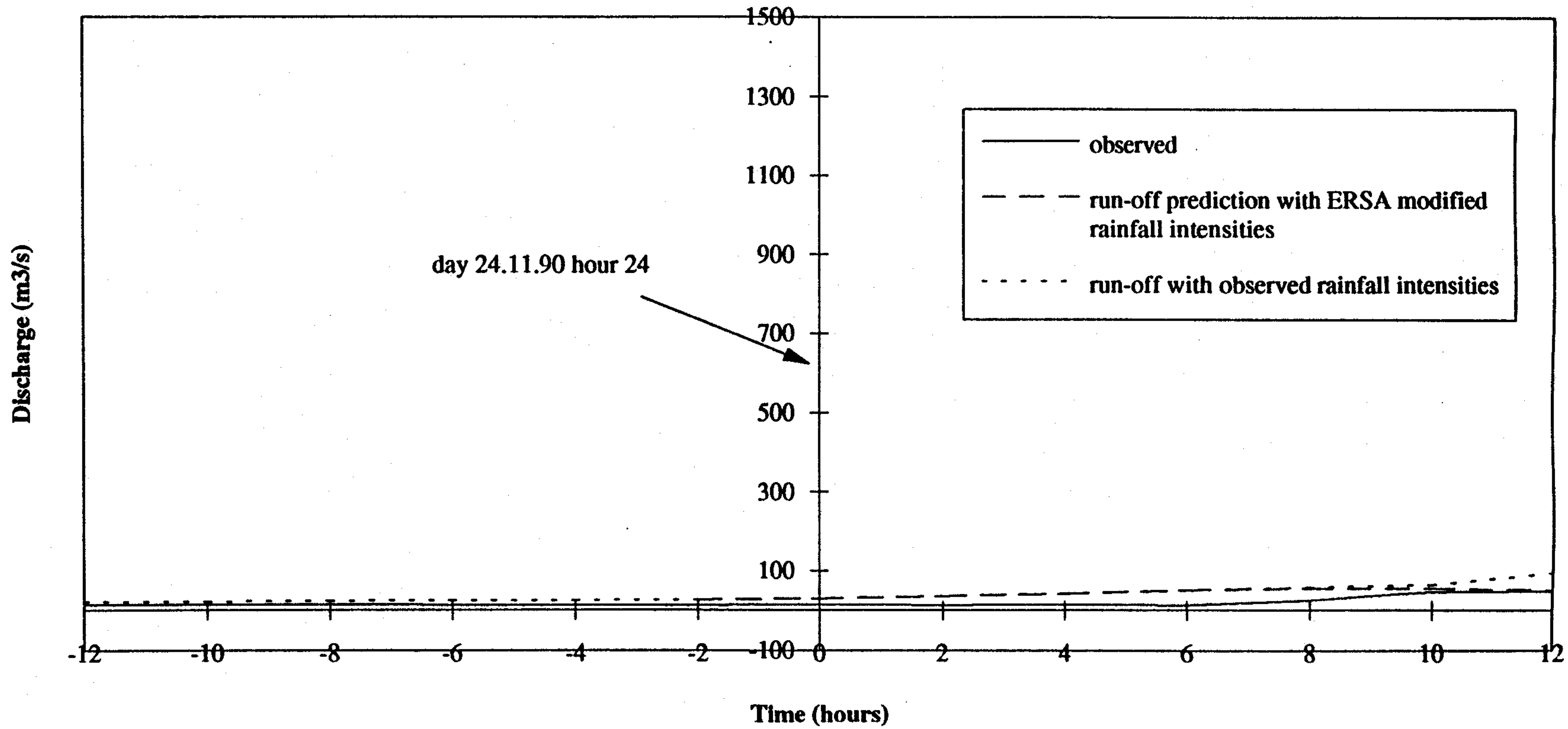


Figure 7.52 - Comparison between observed flows at Casalecchio

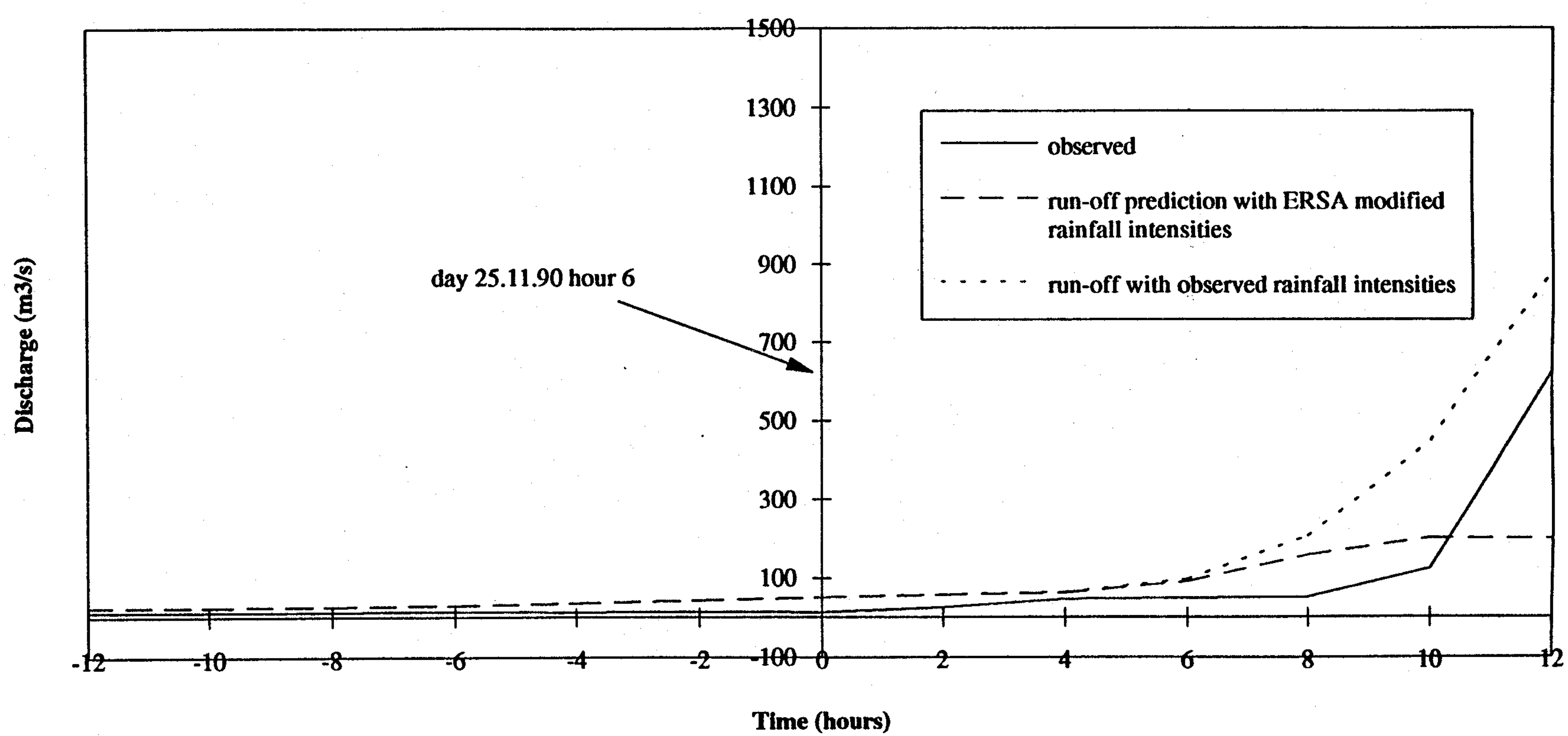


Figure 7.53 - Comparison between observed flows at Casalecchio

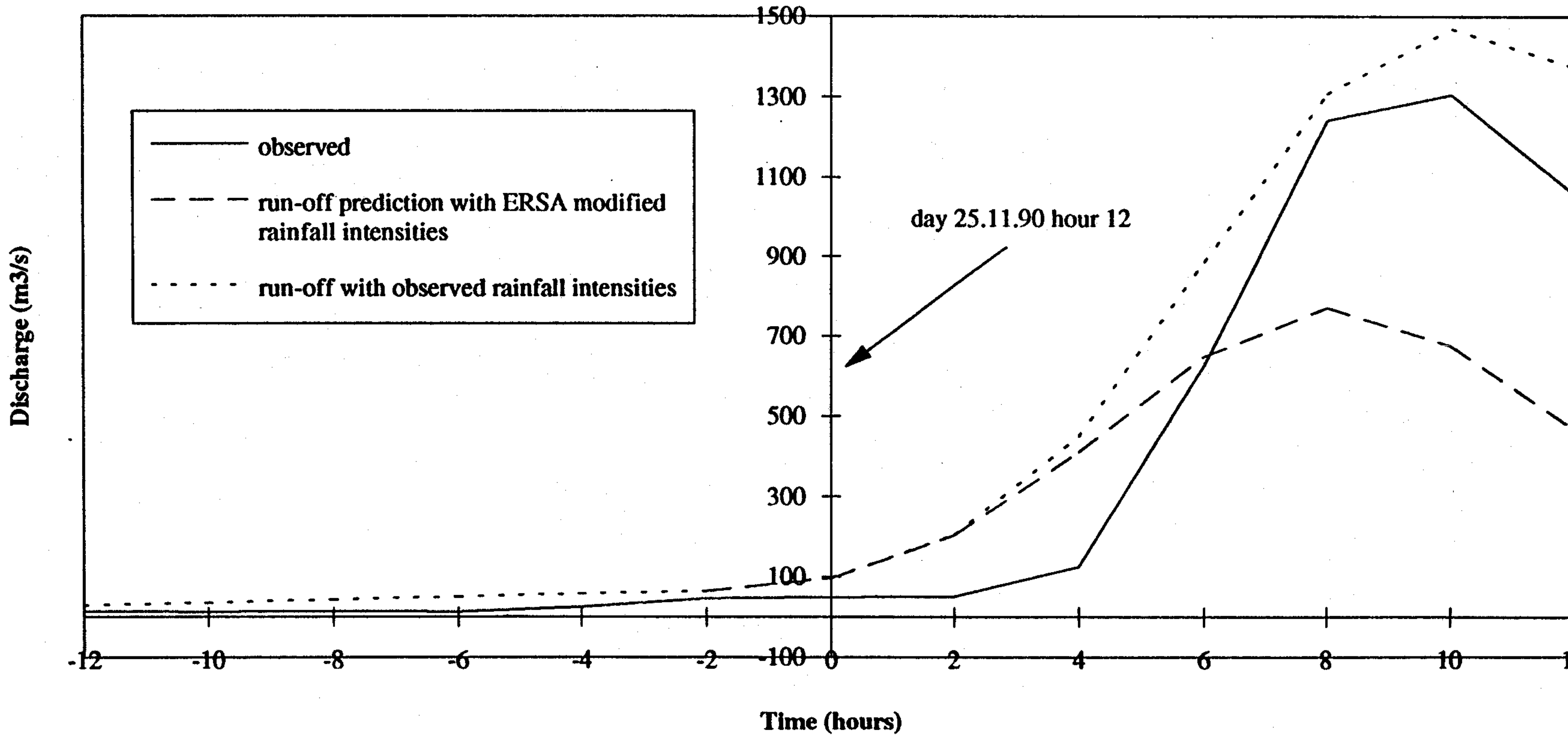


Figure 7.54 - Comparison between observed flows at Casalecchio

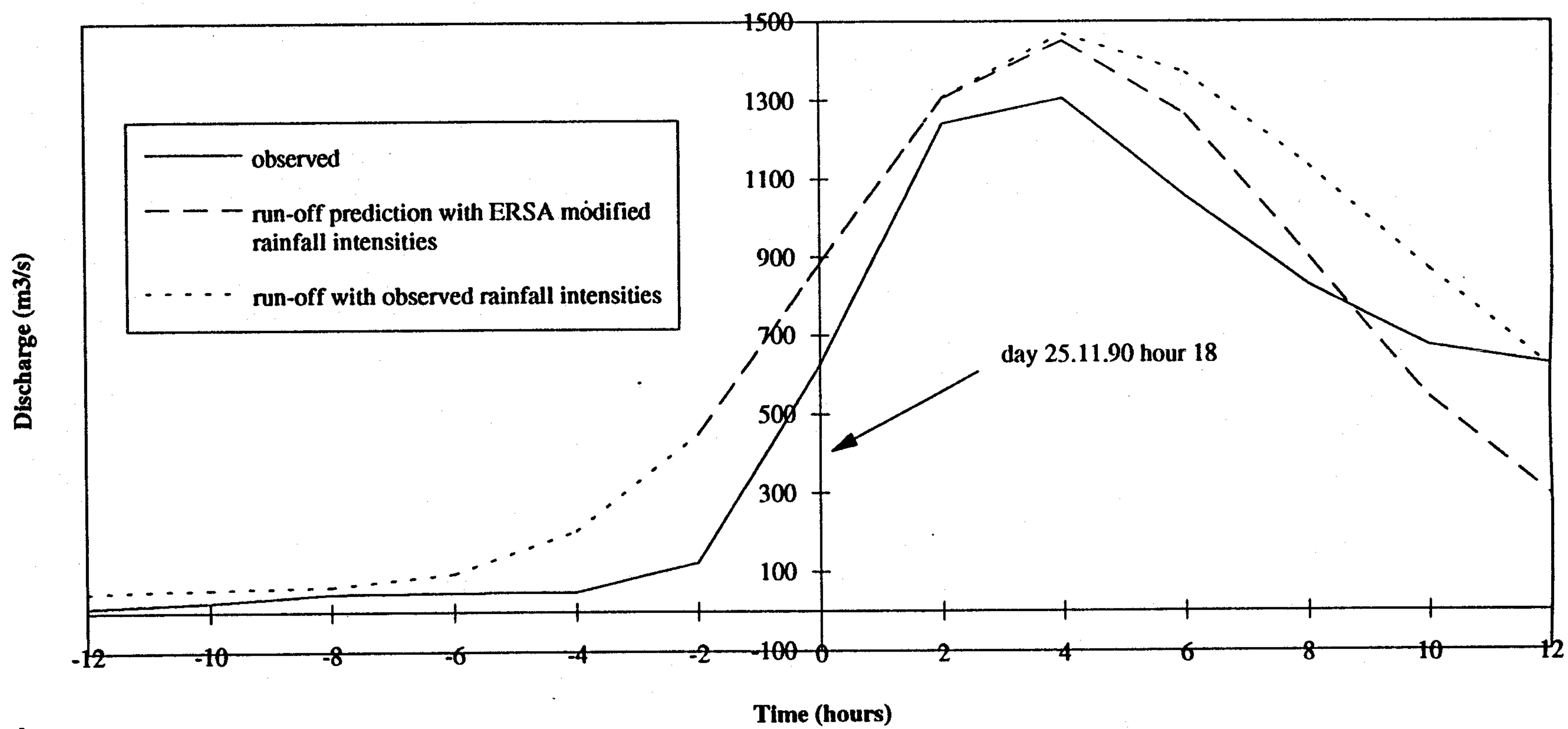


Figure 7.55 - Comparison between observed flows at Casalecchio

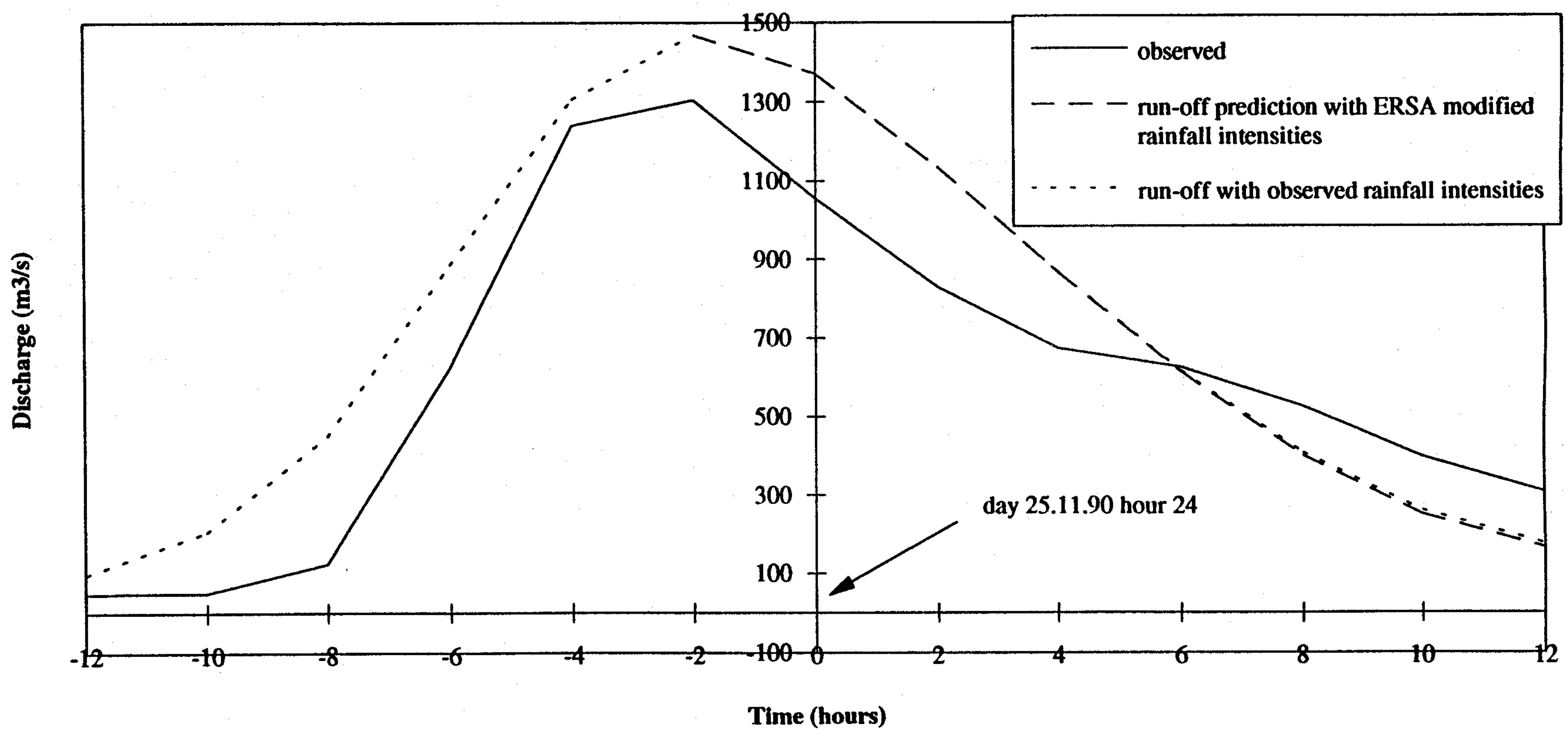


Figure 7.56 - Comparison between observed flows at Casalecchio

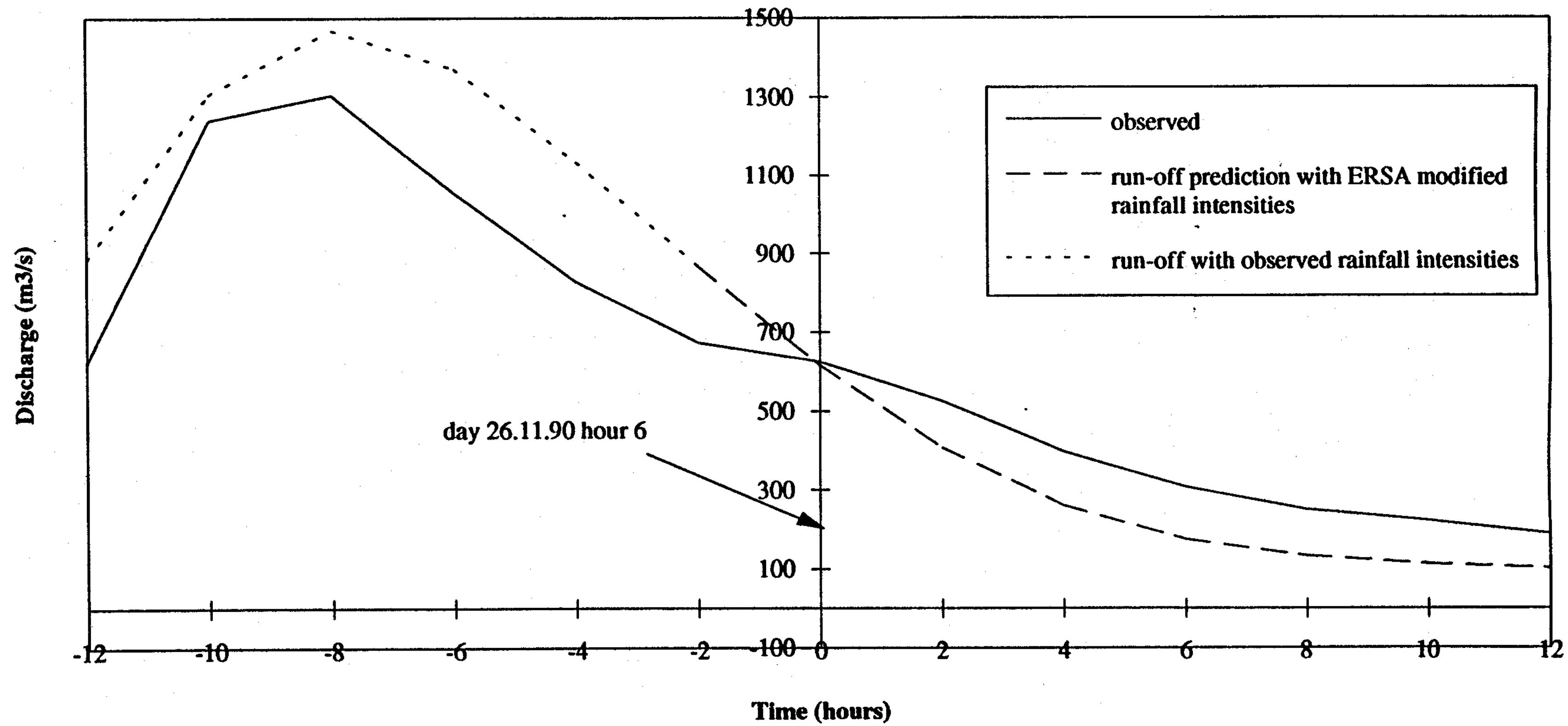


Figure 7.57 - Comparison between observed flows at Casalecchio

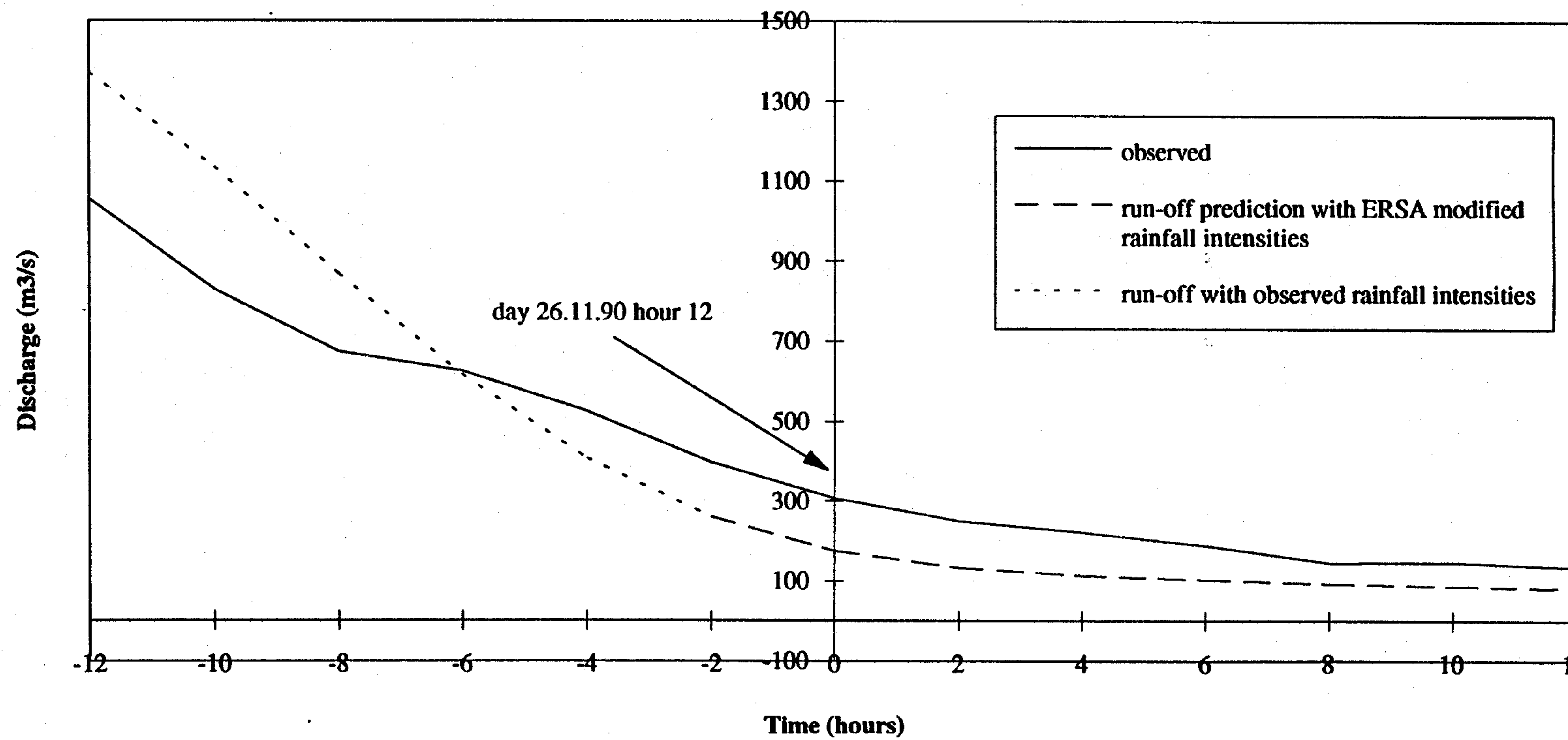


Figure 7.58 - Comparison between observed flows at Casalecchio

7.6 THE FLOOD-PLAIN INUNDATION MODEL

As explained in Chapters 5 and 6, a flood inundation model is generally required for the planning of real time actions to be taken in case of severe flooding. In this section the application of the quasi two-dimensional model, based upon the Integrated Finite Differences approach is performed in order to emulate the effect of the November 1990 flooding, which affected the area on the right bank of the river Reno at Bosco, between S. Vincenzo and Malalbergo. The actual flood event is described, followed by a description of the model's estimate of the extent of inundation.

7.6.1 The meteorological event

On 25th and 26th November 1990 there occurred a major flood in the Reno river, occasioned by precipitation caused by low pressure over the Ligurian Sea and by the presence of strong south-westerly winds, which led to particularly heavy precipitation on the Tuscany side of the Apennines and on the Emilia side close to the ridge; at the same time, ordinary rainfall events were reported on the hillside and plain areas of the Reno basin. The contributions to the flood of the Samoggia and Sillaro tributaries, whose catchment basin does not extend to the Tuscany-Emilia Apennine ridge, proved negligible. The Idice too, although its catchment basin lies on the ridge but in a more marginal area, was not subject to intense flooding.

7.6.2 The flood

On 25th November, in the upland reach of the river, the flood wave caused modest flooding at Porretta on the side overlooking the river, while other cases of limited flooding were reported at Marzabotto and Pontecchio Marconi.

That same day the flood wave passed the weir at Casalecchio, the outlet of the upland basin, where its maximum level of 2.55 m, corresponding to a flood peak discharge of approximately 1410 m^3/s, was recorded at 22:00 hours.

Thus, on 25th November 1990, the flood was relatively steep at Casalecchio and resulted in a short duration flood hydrograph which had a volume of 87.350 million m^3 that passed in 72 hours.

The following day the flood peak travelled to the plain section where the river has a highly raised bed and where in the past its levees have been breached several times (the most recent being the breaches at Passo del Gallo in 1949 and 1951, and the breach at Castel Campeggi in 1966).

At 06:00 hours on 26th November the flood peak travelled past the hydrometric station at Cento, which lies 33.4 km from the weir at Casalecchio, recording a maximum level of 8.72 m.

The Reno Flood Channel was pressed into service at 06:00 hours on the same day; at 17:00 hours at the Opera di Reno weir the gates were completely closed following the alarm raised by the Civil Defence Authority in response to the occurrence of a seepage point on the right bank of the Reno near the village of Bosco in the municipality of Galliera (the siphon grew in the following hours, causing the collapse of the levee and resulting flooding). As a result of these manoeuvres the levels in the Napoleonic Channel at S. Agostino rose abruptly with the passage of the discharge which initially amounted to approximately 300 m^3/s, rising from below 8.00 m a.s.l. to an elevation of 9 m a.s.l. recorded at 6:30 hours on 26th November, and thereafter remaining above 10.00 m a.s.l. from 10:00 hours on 26th to about 12:30 hours on the following day.

The operation of the Napoleonic Channel was assisted by the trend in the levels of the Po at Palantone; in fact the flood in the Po follows about one day behind the Reno flood wave.

On the following days the gauge levels in the Po decreased rapidly as a result of a marked improvement in the meteorological conditions which recorded modest and sporadic rainfall.

In spite of this, the weir at Opera di Reno remained completely closed until the morning of 4th December so that the levee repair work could be carried out. At 10:00 hours that same morning the discharge of the Flood Channel waters into the Po ceased; by that time the waters were, moreover, relatively low.

7.6.3 The breach

The peak flood generated by the meteorological events occurring in the upland basin passed Casalecchio (upstream reach outlet section) in the late evening of 25th November 1990; in 72 hours it conveyed 87.350 million m^3 of water. On 26th November the flood peak reached Cento (33.4 km downstream) at 06:00 hours, at the time when the Napoleonic Channel was put into operation: at 17:00 hours the Channel was functioning at full capacity as the gates of the Opera Reno had been completely closed as a result of the first signs of levee collapse further downstream.

Before the cut-off, in the reach downstream of the Opera Reno weir, the gauge level remained constant with a discharge of 650 m^3/s.

At approximately 16:30 hours on 26th November, a seepage point was observed in the countryside close to the right levee of the Reno at Bosco between S. Vincenzo and Malalbergo, at the point where a SNAM pipeline passes under the river bed - 3 metres (+13.5 m a.s.l.) above the natural ground level in front of it (+10.5 m a.s.l.) - while at the same time, a sink hole was observed in the berm, at the toe of the bank of the main levee.

The amount of seepage was such as to thwart the attempts made at around 17:30 hours to place an impermeable sheet over the fault in the berm, as it was dragged away into the countryside by the water through the breach that had been made in the levee. At the start of the breach the water surface, at an elevation of +18.54 m a.s.l., covered the high berms by approximately 50 cm, remaining 2.68 m below the top of the main levee and 8 m above external ground level. A powerful bentonite diaphragm wall already in place at the internal foot of the levee was crushed and the resulting blocks - in some cases over one metre in size - were scattered over the surrounding countryside to a distance of about 200 m.

At approximately 20:00 hours the levee collapsed and the gas pipeline was visible through the fault that had been formed. The rip-rap, consisting of limestone blocks lining the original main channel from the bottom (+7.46 m a.s.l.) to elevation +12.40 m a.s.l., was partially broken up on top (perhaps to a depth of at least 1 m, probably reaching elevation +11.40/+11.00 m as a result); however, it basically withstood, preserving the profile of the Reno channel for at least a further 3/4 m in depth (the fact that this protection largely withstood the force of the outgoing water, remaining in its original configuration, allowed the complete outflow of the discharge in the stream from the time that this elevation was reached, thereby limiting the flood volumes; in addition, given the topography of the countryside surrounding the breach, the ballast prevented part of the flood volumes from returning to the river channel through the breach in the levee).

The discharge flowed into the countryside and, at around 02:00 hours on 27th November, the berm also collapsed completely. The breach expanded to its final configuration, measuring 28.00 m in width on the levee axis and corresponding to a volume of approximately 19,600 m^3 of entrained material.

The levee repair works were started as early as the morning of the 27th; the chief difficulties were connected with the roads, since the Basso Reno local road which runs along the foot of the levee on the right bank of the Reno was partially flooded, and the section of road next to the breach had been entirely swept away.

Since, following the closure of the weir at Opera Reno, the stream was confined to the main channel, it was possible to repair the levee on the axis of the old structure in very short space of time.

The SNAM gas pipeline remained in its original configuration.

At 11:00 hours on 27th November, a fall in the water level and the completion of the repair work stopped the flow from the breach, which had reached a length of 24-28 m and a volume of 19,600 m^3 of fines (clayey-silty material). Indications of the maximum water level reached in the flood basin, obviously with variable head depending on the natural topography, as measured on tree trunks, the sides of buildings and in relation to the top of the Riolo levee, point to an average elevation of +12.60-12.70 m a.s.l. in Regional Technical Map terms; however, nothing is known unfortunately of the intermediate level stages during the event itself, of the real morphology of the water surface elevation and of the timing of the maximum level reached in the flood basinn.

Even though the cartographic method used to determine the elevations is clearly insufficient, in view of the minimal differences in elevation and the great distances involved, it is nevertheless possible to identify, in hydrometric-behavioural terms, at least three sub-areas inside the flood basin. In the western part of the basin, the water, held back by the motorway embankment and forced to siphon through the S. Prospero Drainage Channel and under the A13 overpass, is at least 90-100 cm higher than in the eastern part (between the motorway and Malalbergo); but in the same western section it is probable that the Ponte Bosco road - elevation +12.20 (Technical Regional Map) - 400 m west of the breach in the levee, momentarily performed a similar function - on a smaller scale - to that of the motorway bank: only after it had been topped by the breach waters could the western portion of the basin be flooded.

In order to facilitate the drainage of the flood water, that same day (the 27th), as soon as the flow from the breach had ceased, the Riolo drainage channel level was cut into upstream of the motorway embankment and, on 28th November, at another point downstream.

On 29th and 30th November the drainage of the basin was completed.

At 10:00 hours on 4th December, the Napoleonic Channel was put out of service and the flow was restored to the repaired bed of the Reno. Because of both the adverse local weather conditions and the hours of darkness, there is no direct photographic record of the development of the flood event: all of the pictures consulted (amateur videos and photographs, etc.) date from the early morning of 27th November.

Out of a total flood event duration of 15-18 hours, the breach outlet itself was in operation for approximately 10 hours, recording a peak discharge of 195 m^3/s: 3 to 4 million m^3 of liquid escaped from the ordinary bed, spreading over 400 hectares of land and depositing approximately 150,000 m^3 of sediment. In the absence of man-made structures and manoeuvres, from a breach outlet of 34 m, 50 million m^3 of water with a peak discharge of 570 m^3/s would have flowed out of the Reno bed, leaving a volume of sediment that it is impossible to calculate with any precision.

7.6.4 The damage

The flooded area was bounded in the south by the levees of the Riolo drainage channel, in the east by the A13 motorway embankment and in the west by the Bassa local road; the total extent of the flood zone was 400 ha and the estimated flood water volume was between 3 and 4 million m^3. The phenomenon seems relatively modest when compared with the two flood events that occurred in November 1949 and February 1951 at Passo del Gallo, about 5.00 km downstream of the breach, during which the flooded areas extended over 6,000 and 12,000 hectares respectively.

The land next to the breach, which stands at about 11.00 m a.s.l., is bounded in the east by the A13 motorway embankments, in the west by the Ponte Bosco road which runs parallel to the motorway whose edge is 12.20 m a.s.l., and lastly in the south by the banks of the Riolo drainage channel which are over 13.00 m a.s.l. in the area in front of the breach. The volumes that flowed into the countryside through the breach first spread through this section, flooding approximately 120 ha and flowing slowly eastwards through the Laribali local road underpass and then spreading towards Malalbergo. After it exceeded a height of approximately 12.20 m a.s.l., the water that flooded this section topped the Ponte Bosco road in the west, flooding the land between the Ponte Bosco road in the east and the Bassa local road in the west which contained the waters.

Because of the limited volumes that flowed through the motorway underpass, in the east only the first few houses in the village of Malalbergo were affected by the flood, while in the west no significant built-up areas (S. Vincenzo and S. Venanzio) were affected.

Because the flow of water into the countryside through the fault formed in the levee of the Reno river had ceased by the early hours of the morning of 27th November, it was decided to cut the embankments of the Riolo drainage channel immediately upstream of the C‡ Bianca local road to facilitate the outflow of the water which had flooded the land between the A13 motorway in the east and the Ponte Bosco road in the west; on the following day two cuts were made on the Laribali road, the first immediately to the east of the motorway overpass and the second close to the village of Malalbergo, in order to allow the dead water in the countryside to flow through the Riolo drainage channel.

The damage caused was estimated by the District Authorities to be in the region of Lire 2.250 billion for farming, Lire 0.250 billion for private property, Lire 0.400 billion for the drainage system and Lire 2,200 for public works (for a total of Lire 5,100 billion).

7.6.5 Application of the Model to the Galliera Breach

Using the two dimensional integrated finite difference model described previously in Chapter 5, it was possible to simulate the November 1990 flood event which encompassed the land adjoining the right bank of the river Reno, at Bosco, between the municipalities of S. Vincenzo and Malalbergo. The flooded area reached an extent of approximately 6 km^2 and was bounded in the north by the banks of the river Reno, in the east by the local road joining the villages of Malalbergo and Gallo, in the south by the levees of the Scolo Riolo drainage channel and, lastly, in the west by the Bassa local road linking S. Vincenzo with Poggio Renatico.

The area is traversed in a south-west/north-east direction by the A13 motorway embankment, by the Casa Bianca local road and by the Ponte Bosco road; the area also includes many secondary roads and footpaths which join the smaller hamlets and border the various farm holdings. For the purposes of hydraulic simulation, however, these latter features were not introduced in the scheme of the perimeter, since they were not believed to create obstacles to the overland flow of the flood. As a result, the area under study was divided into four sub-domains.

For each of the four elements a computerised map was constructed by digitisation. This allows a connection to be made between the cartographic data and the computer data, preserving the position of each object in relation to an absolute reference system. The information accordingly remains "geo referenced", i.e. provided with a geographical reference, according to the x and y coordinates of the topographic network.

In the case under study, the cartographic base was provided by Regional Technical Maps scale 1:5000, while the digitisation was performed using AutoCad. Figure7.59 shows the elevetaion of the ground.

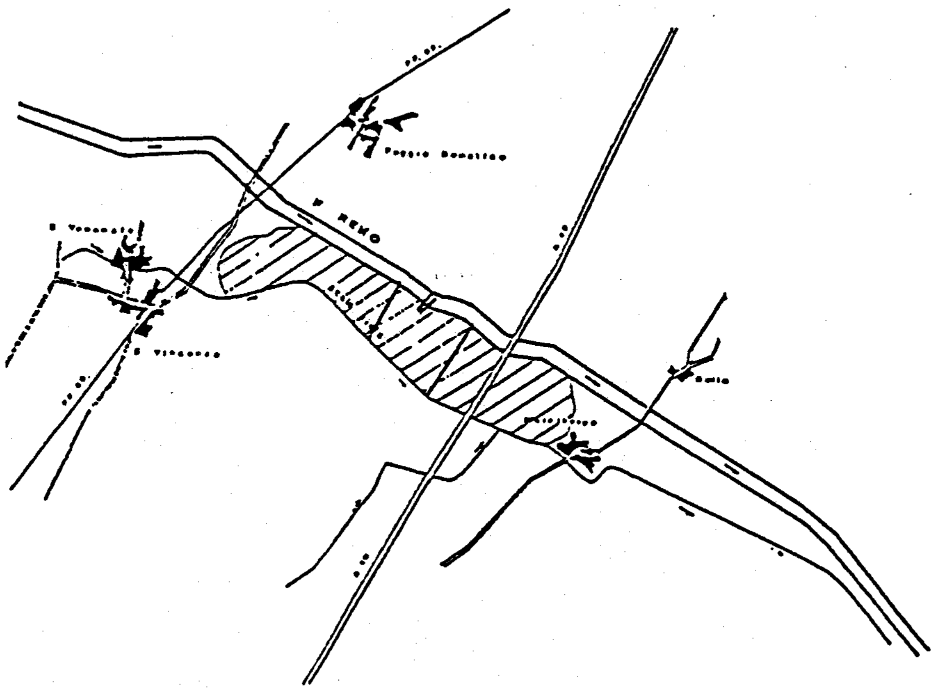


Figure 7.59 - Plan of the area and its division into super-elements

Developing semi-automatic procedures it was then possible to discretise the hydraulic domain: a first phase of TIN (Triangular Irregular Network) construction, performed using an automatic triangle generating program was followed by a second stage entailing the delineation of Thiessen polygons and deriving the set of geometrical characteristics associated with them (specifically, the distance between the nodes in the domain, the associated interface width and the area of each polygon). Using this method it was possible to discretise the focus area according to a scheme commensurate with the hydraulic model, respecting both the topography of the area and all the rules governing the construction of the TIN and the polygons as described above.

Fig. 7.60 shows the division of the domain according to the TIN schematisation, on the basis of which the Digital Elevation Model (DEM) used to represent the area (Fig. 7.61) was obtained.

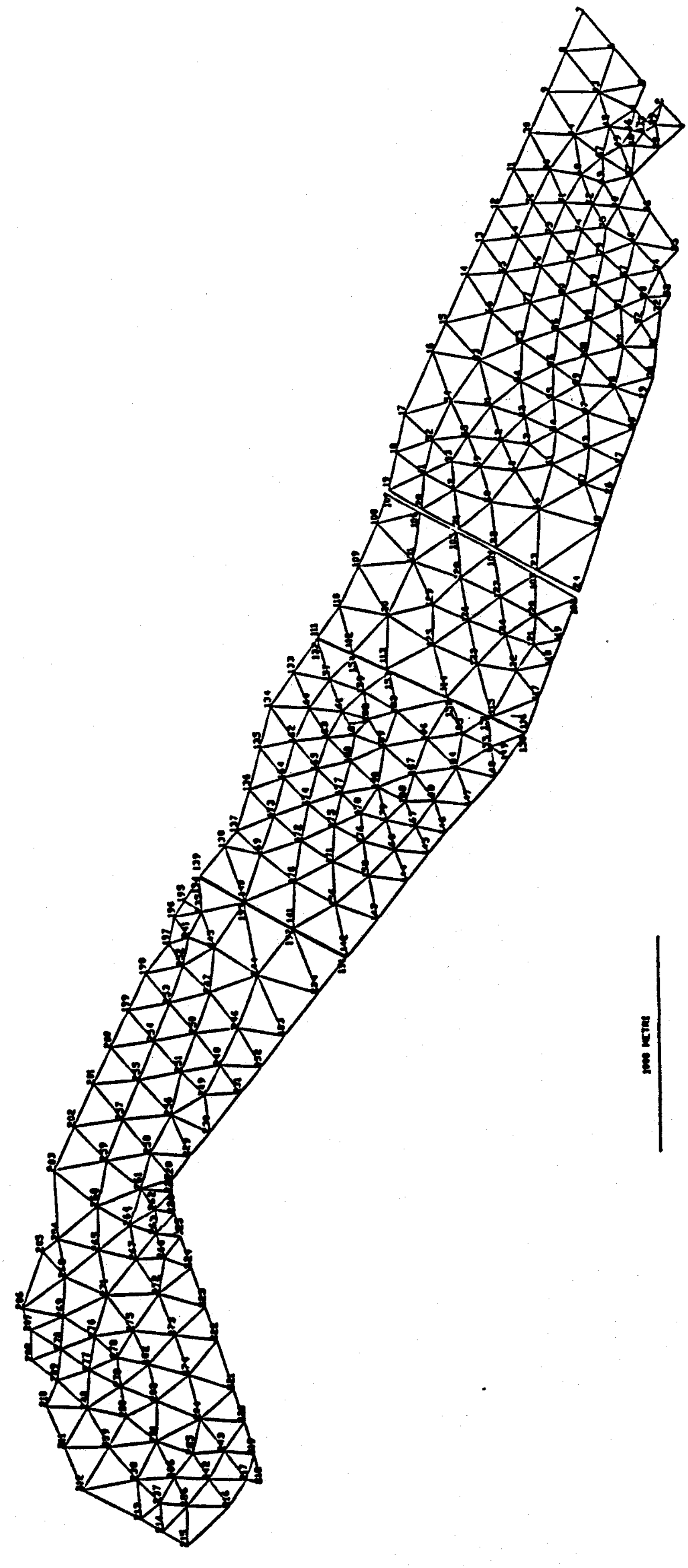


Figure 7.60 - Division of the domain of the region subject to flooding using a Triangular Irregular Network (TIN).

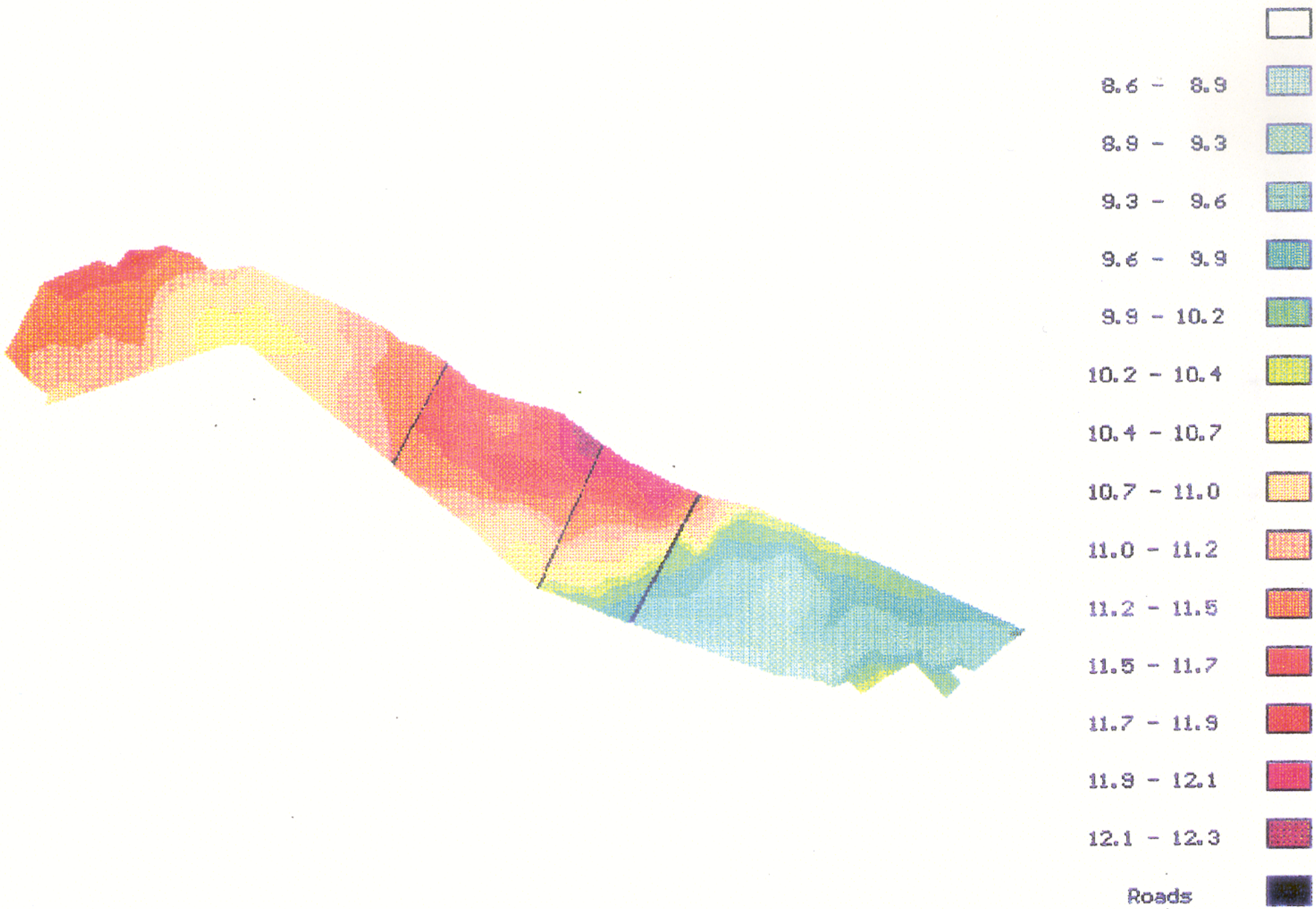


Figure 7.61 - Digital elevation model of the region subject to flooding showing the ground levels.

In addition to the geometrical characteristics, it was necessary to add to the starting data the schematisation of the hydraulic peculiarities of the area and the event, as represented by:

- Roughness of the soil at ground level: A Manning's n value of 0.10 was assumed for the flood plane.This value may seem rather high, but it takes account of the presence of the numerous obstacles present in the area, including farm footpaths, minor roads, areas with dense vegetation (fruit orchards, vineyards, etc.), farm buildings and other structures. Given the homogeneity of the area, a single value was assigned to the whole area under study.

  The possibility was also discussed of using a variable roughness coefficient according to the water surface elevation in relation to the ground, but given the volume of water that flooded the countryside, and the high velocity of the flow, this option was rejected.

- S. Prospero drainage channel. This is a minor drainage channel which runs parallel to the Scolo Riolo channel situated between ground level and the Laribali road which flanks the Riolo. In spite of its small size and limited hydraulic capacity, this channel acquired great importance during the 1990 flood event, in that it was the only point of connection between the areas of land situated to the west and east respectively of the motorway embankment; the water that flooded the land to the west of the A13 motorway flowed along the S. Prospero channel, through the underpass and on towards Malalbergo.

  During the simulation, in the absence of detailed information, the channel section was taken to be of regular rectangular shape, with a width b=3.00 m and height h=2.00 m; the slope was assumed to be i=0.3% and the roughness coefficient inside the channel was n=0.025.

- Breach hydrograph. The set of data relating to the development of the breach and the associated volumes that flooded the plain, shown in Figure 7.62, was obtained on the basis of the gauge data recorded at the Casalecchio weir, the flood of November 1990 was simulated on a model for a river reach of approximately 91.260 km between the weir at Casalecchio and Bastia, in order to reconstruct the real flood event.

The one-dimensional model used to represent the propagation of the flood wave in the Reno, provides for the use of two different computational schemes: the kinematic model and the model with integration of the De Saint Venant flow equations. The system's boundary conditions are the discharge hydrograph upstream and the rating curve downstream. The starting conditions can either be borrowed from an earlier simulation or constructed "internally" by the model.

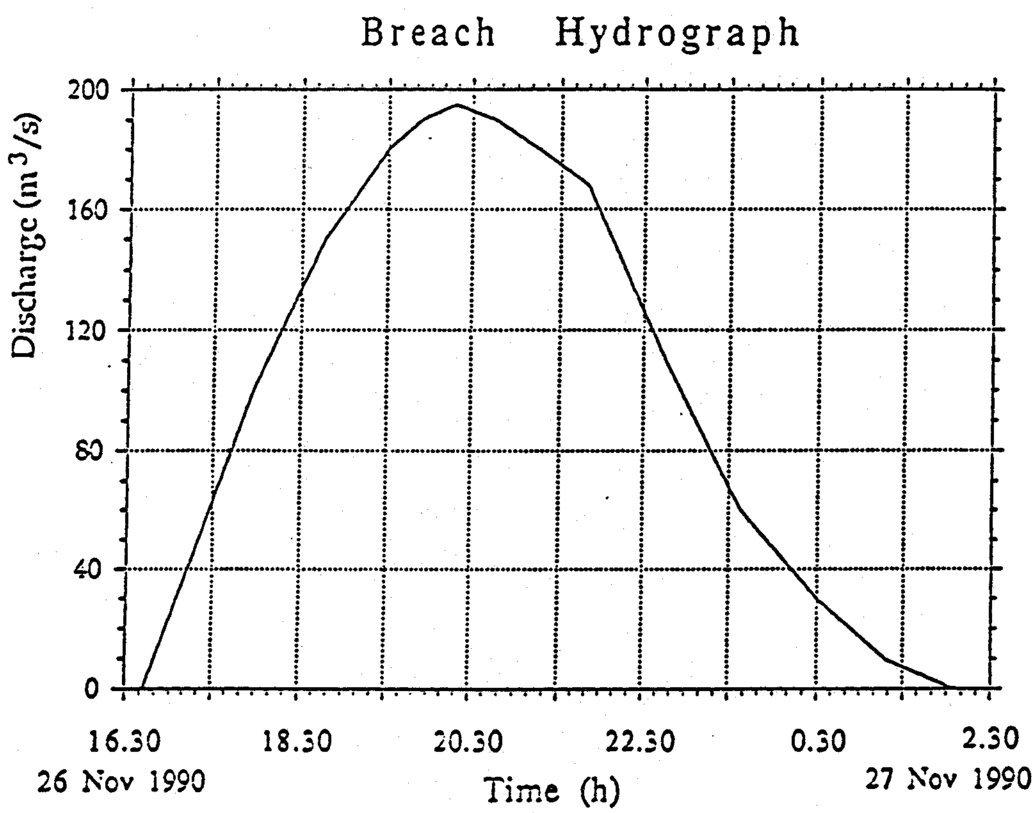


Figure 7.62 - The breach hydrograph

7.6.6 Salient features of the event

Below is a summary of the salient moments in the development of the flood event:

26/11/90	16:30 hours	start of siphoning at the right levee of the river Reno, at Bosco
	20:30 hours	peak time, corresponding to a peak discharge in the breach $Q_{max} = 195\ m^3/s$
27/11/90	02:30 hours	end of flow from the breach to ground level

Total flood volumes: Vol=3.4 10E6 m^3/s

Using the geometrical and hydraulic data described above, the event was simulated on the hydraulic model presented: the start time of the simulation coincides with the siphoning reported at 16:30 hours on 26/11/90, while the simulation ends at 12:30 hours on 27/11/90, giving a total simulation time of 19 hours. The time step used was 30 seconds, while the tolerances used with regard to the water levels and the discharge quantities were 1.10E-5 and 1.1E-3 respectively.

Using the results of the hydraulic model it was possible to follow the unfolding of the event, observing variations in the water surface elevation in each polygon, the discharge exchanges and the flow velocities for each time step in the simulation.

7.6.7 Space-time development of the flood event

The numerical results obtained by applying the integrated finite difference model were displayed at successive time intervals using the IDRISI Geographical Information Sistem so as to have an overall picture of the flood in terms of both space and time.

The most significant graphical printouts were chosen and, when viewed in sequence, they give a precise idea as to the development of the event (Figures 7.63 - 7.70).

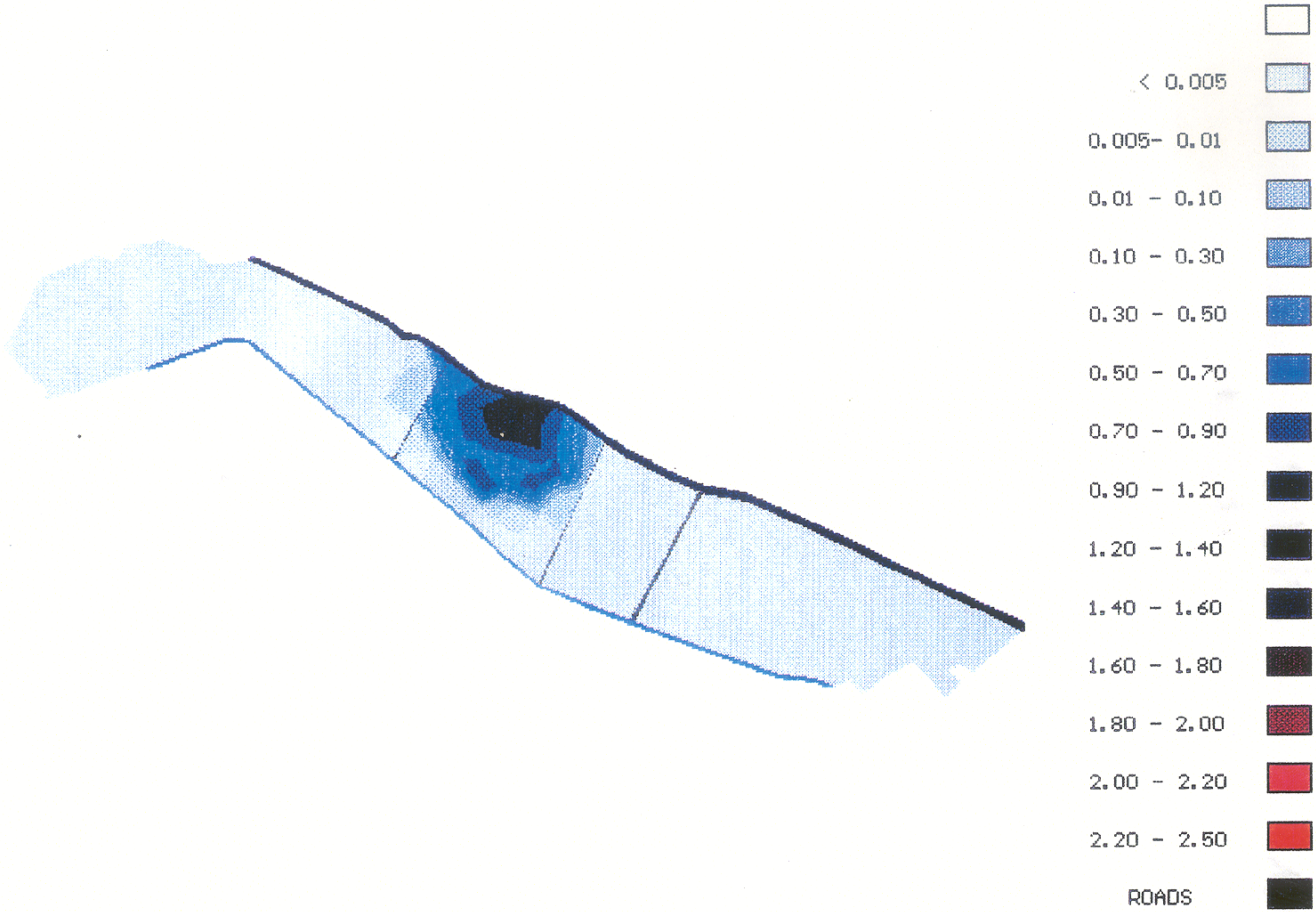


Figure 7.64 - Simulation of flood plain inundation. Depths of water in metres.
Date: 26 November 1990. Time: $18^h\ 30'$

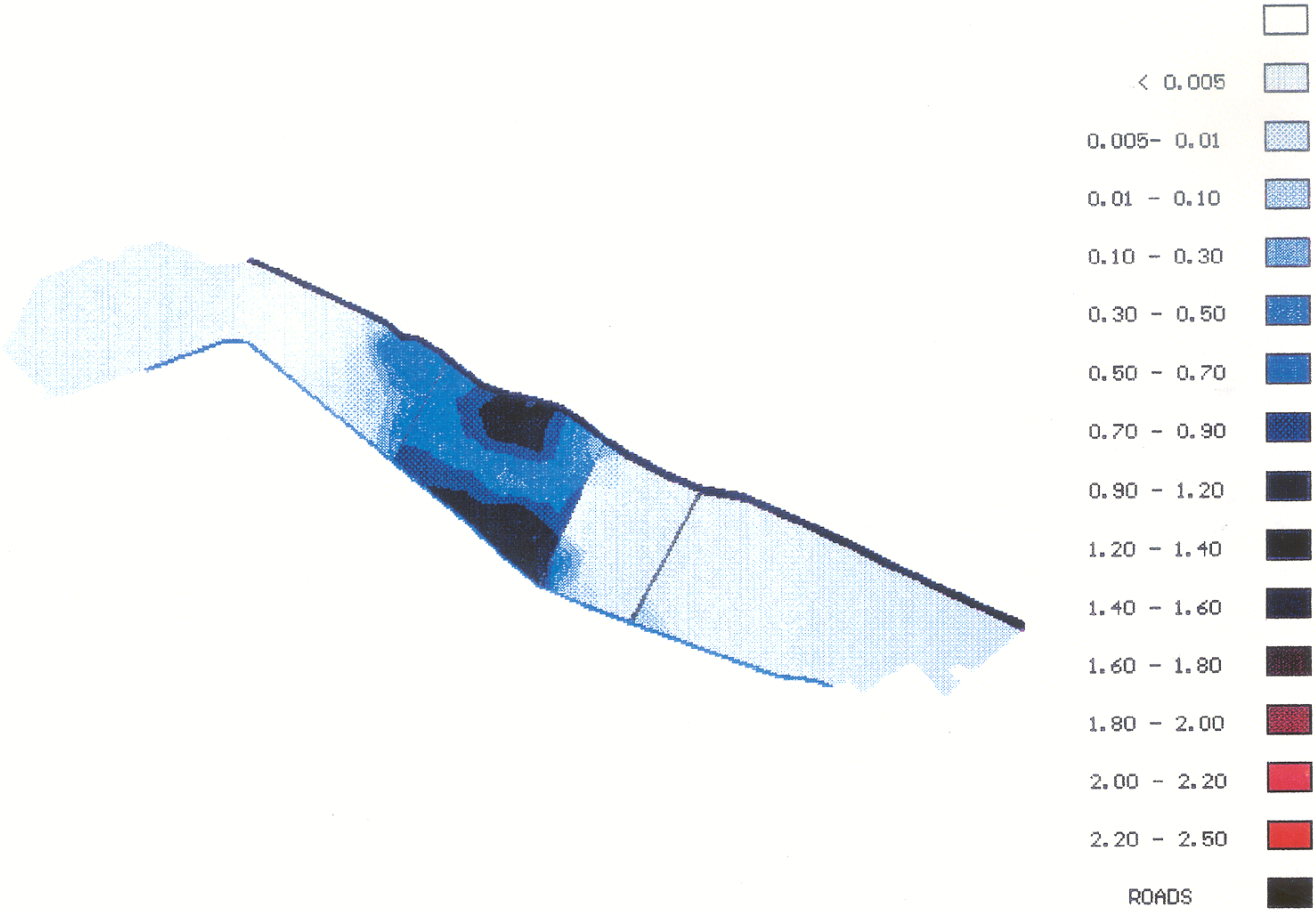


Figure 7.65 - Simulation of flood plain inundation. Depths of water in metres. Date: 26 November 1990. Time: $19^h 30'$

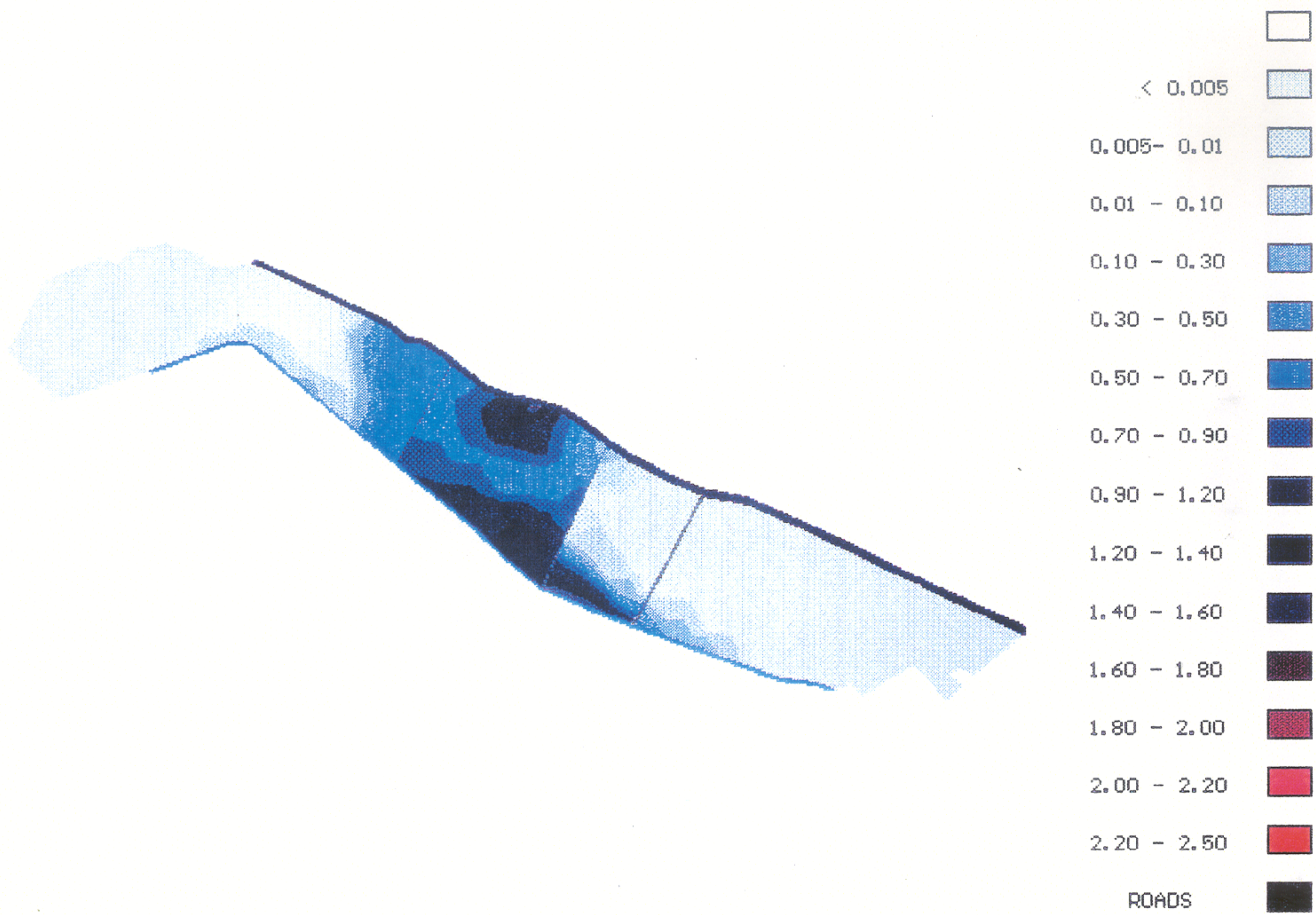


Figure 7.66 - Simulation of flood plain inundation. Depths of water in metres. Date: 26 November 1990. Time: $20^h 00'$

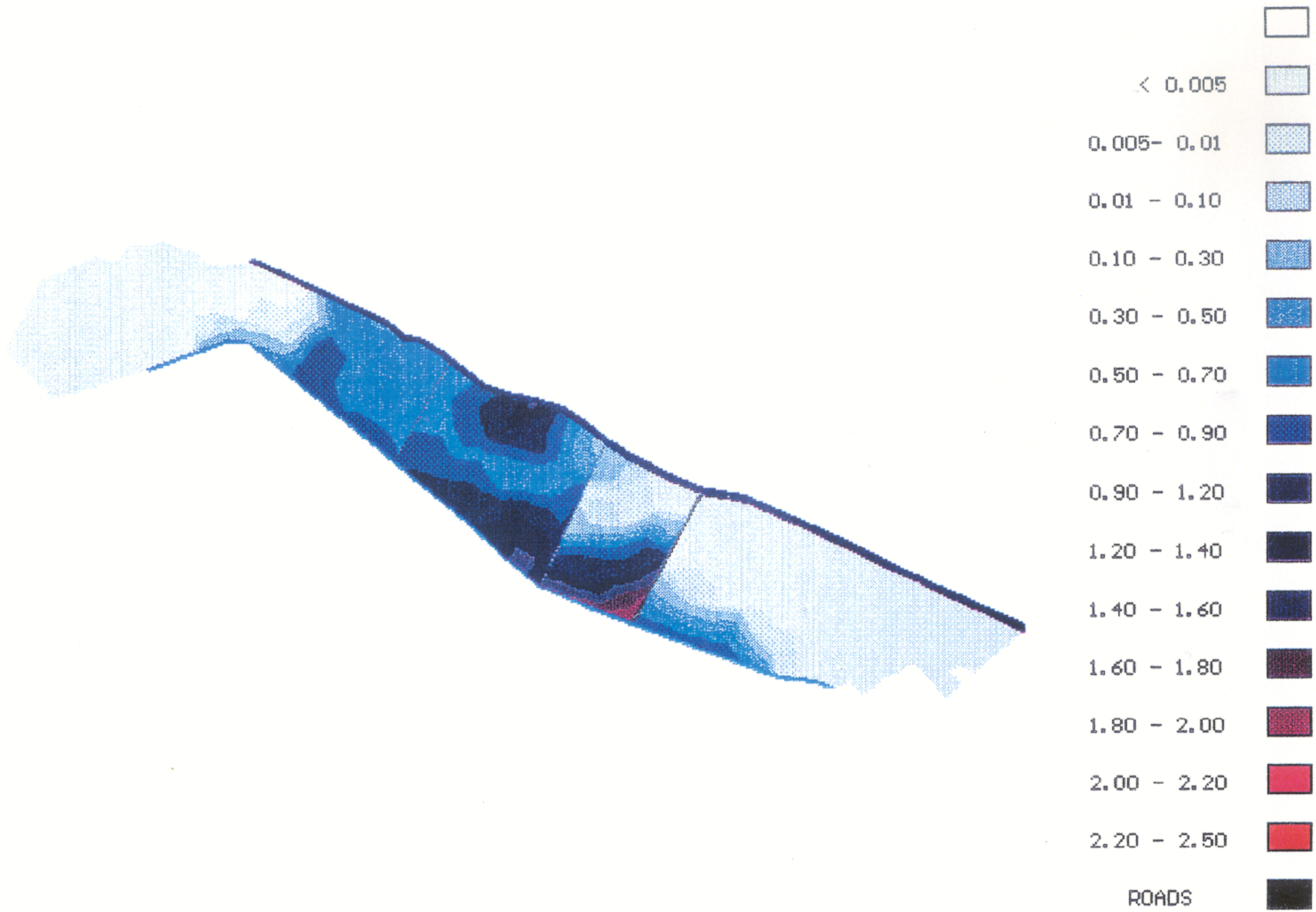


Figure 7.67 - Simulation of flood plain inundation. Depths of water in metres. Date: 26 November 1990. Time: $21^h 00'$

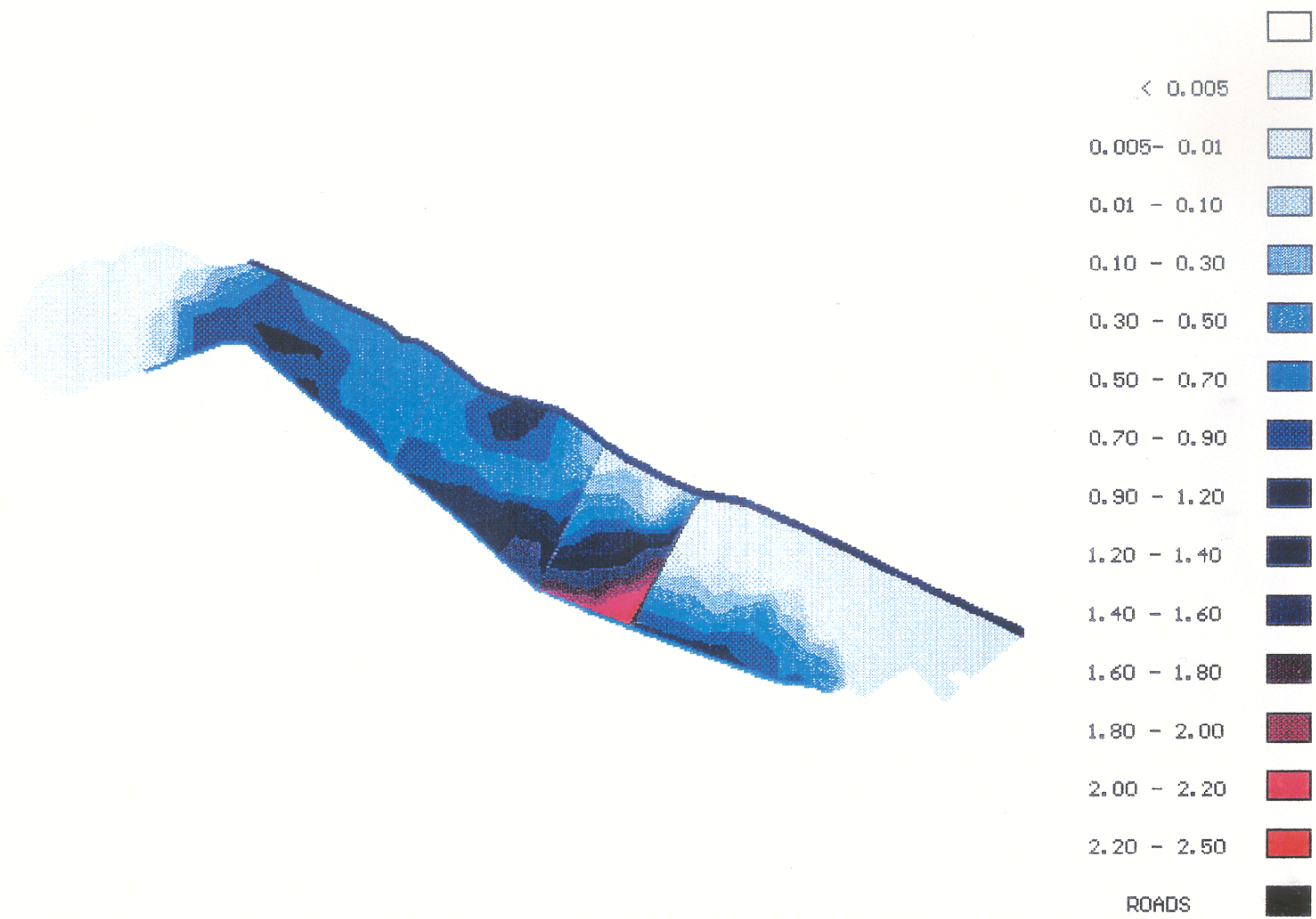


Figure 7.68 - Simulation of flood plain inundation. Depths of water in metres.
Date: 26 November 1990. Time: $22^h 30'$

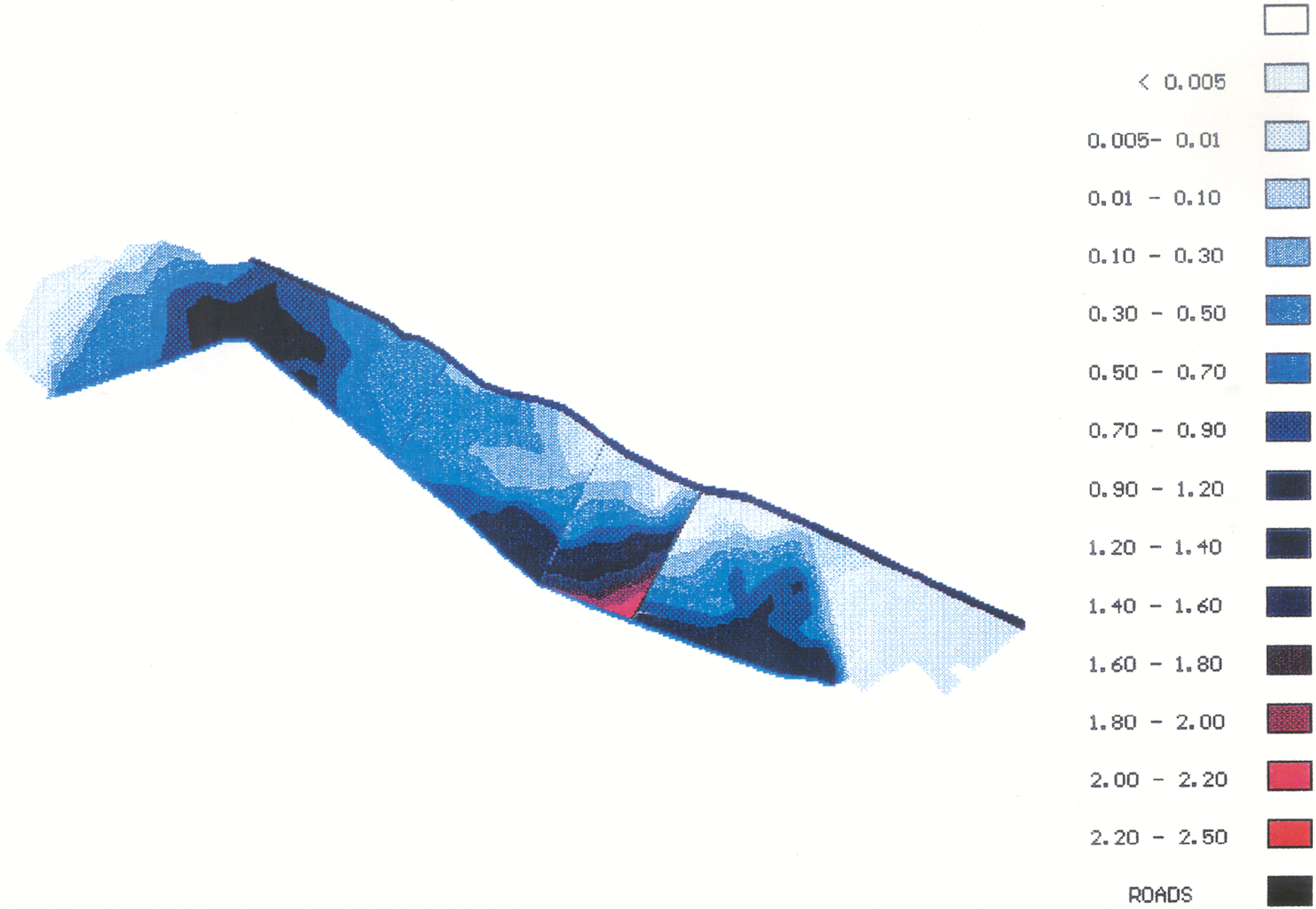


Figure 7.69 - Simulation of flood plain inundation. Depths of water in metres.
Date: 27 November 1990. Time: $04^h 00'$

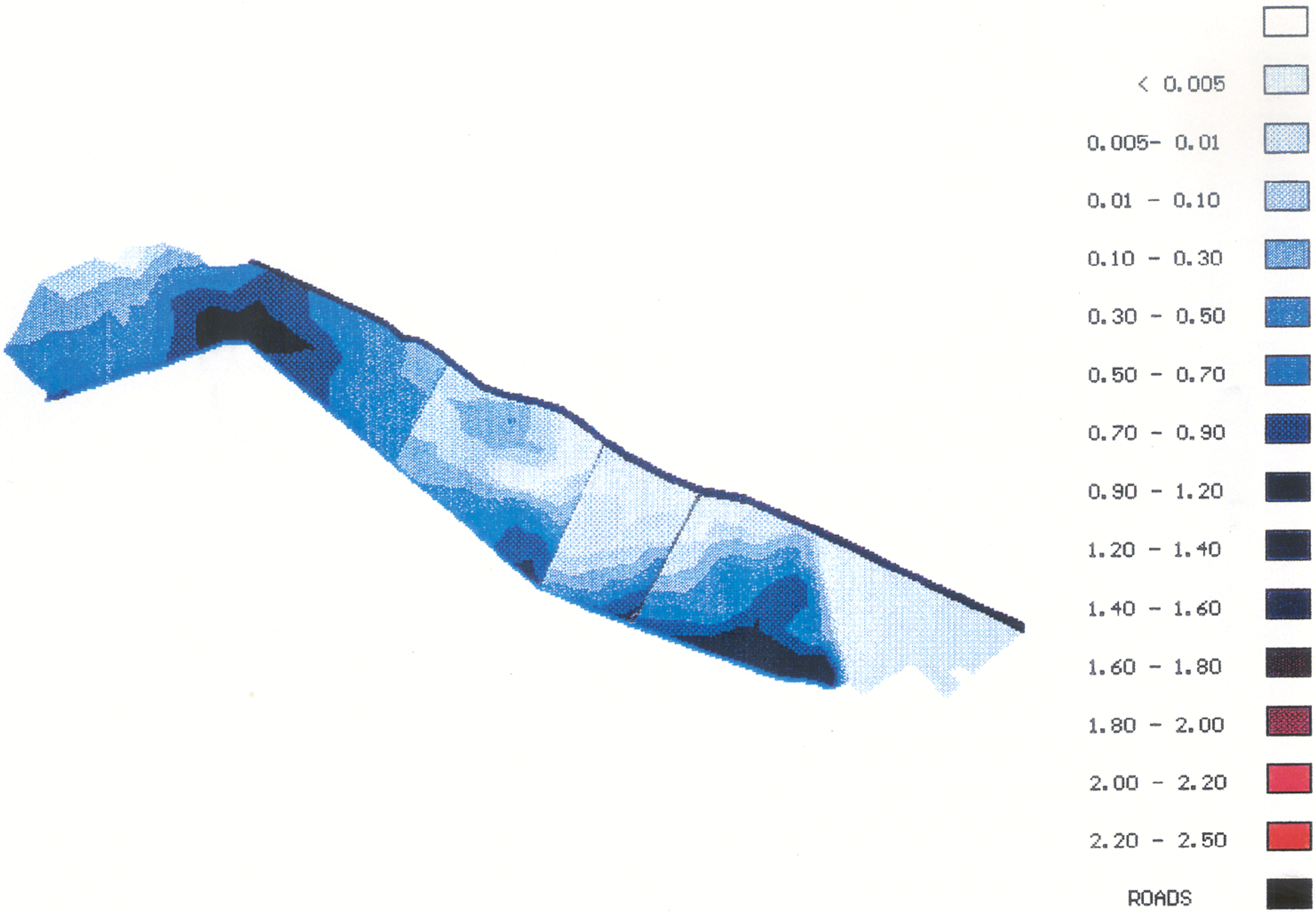


Figure 7.70 - Simulation of flood plain inundation. Depths of water in metres. Date: 27 November 1990. Time: $09^h 30'$

The breach develops between the local roads of Casa Bianca and Ponte Bosco and affects an area at an elevation of 11.50 m a.s.l.

On the left-hand side of the breach the elevations, next to the Casa Bianca local road, are approximately 12.50-12.90 m a.s.l., while to the right of the breach the bottom elevation is 11.50 m a.s.l. In fact at 17:30 hours the trend in the model's draughts signals the widespread flooding of the plain. The waters spread on one side in a southerly direction as far as the San Prospero drainage channel, and on the other to the west as far as the Ponte Bosco road, which at 18:30 hours has already been overtopped: the areas to the east of the breach, where the land elevations are higher, escape the flood waters.

At 19:00 hours the waters reach the San Prospero drainage channel and at node 144 (see annexed Nodes Chart) the levees of the channel are overtopped: there is a flow discharge from plain to channel of approximately 0.5 m^3/s, while all the other connections with the channel do not show exchanges in discharge.

Half an hour later the situation is clearer: a discharge of 180 m^3/s is flowing from the breach to the plain and at 19:30 hours the breach has already discharged a volume of approximately 1 million m^3 of water into the area in question. Zone A is completely flooded (see annexes to identify the areas in which the focus area has been divided). The nodes next to the channel have draughts in the region of one metre and from node 143 to node 150 the waters are flowing towards the channel with discharges of 0.5 m^3/s from node 143, to 5 m^3/s from node 148 to the channel.

Next to the Casa Bianca local road (node 150) there is a discharge of 2 m^3/s from node 150 to the channel and a discharge of 11 m^3/s which overtops the road from node 150 to node 116. The flow on the road continues as far as connection 158-114 where we have discharges of 5 m^3/s. At node 116 the flow is still from plain to channel with a discharge of 0.5 m^3/s, while at nodes 117 and 118 the level in the channel tops the levees and the water starts to flow into the countryside with an average discharge of 1 m^3/s. The channel then overflows at node 24 also (the bottom elevations here are 9 m a.s.l.) with a discharge of 5 m^3/s.

On the west side of the breach the Ponte Bosco local road is completely submerged by a flow which propagates from zone A to zone B with a maximum discharge of 14 m^3/s at the junction between nodes 140-193.

At 20:00 hours the water flows constantly from zone A to zone B, overtopping the road; at the same time the channel starts to release discharge from node 225 to node 234 with a peak of 2.2 m^3/s at node 231 (the level in the channel has risen because of the mass of water that has been discharged from zone A where the breach was formed; part of the water flows downstream and part flows back upstream). To the east of the breach the waters also cover the higher areas, so that at node 132 the levels overtop the Casa Bianca local road and zone C starts to be filled from upstream also. The motorway is situated at elevation +3-+5 m above ground level and will never be swamped by the waters; at 21:00 hours a large accumulation of liquid is in fact observed in zone C close to the motorway with draughts in the region of 2 m and more.

At the nodes next to the drainage channel, in zone C, the discharge from the channel to the plain at the connections with nodes 116, 117 and 118 is 0.1 m^3/s. Close to this node, towards the motorway, there will be a reversal in the direction of the discharge, which at nodes 119 and 102 is 10 and 25 m^3/s respectively from plain to channel; this discharge then passes through the channel and enters zone D with discharges ranging from 24 m^3/s arriving at node 24 to discharges of 0.8 m^3/s at node 28. In zone B the channel continues to discharge water into nodes 191 to 225.

At 22:30 hours the volume of water in the area under study is approximately 2.5 million m^3.

The Ponte Bosco local road is still completely submerged by a discharge flowing from zone A to zone B; the water tends to build up close to the drainage channel where the ground elevations are lower. In the southernmost part of zone A, large quantities of water are accumulating because the channel is now full (the maximum exchange discharge between plain and channel is at node 144, with the passage of 4 m^3/s, while next to the Casa Bianca local road the plain nodes discharge increasingly smaller volumes so that, between node 149 and 150 there is a reversal in the direction of discharge and the channel, at node 150, discharges 0.6 m^3/s into the plain).

In zone C the channel discharges as far as node 117, then the direction of flow is reversed again and at nodes 119 and 102 the plain discharges an average of 20 m^3/s.

Zone D is increasingly affected by the flow arriving from the channel as far as node 28. The flow then changes direction and node 29 discharges 1.2 m^3/s as far as node 31, which discharges 3 m^3/s.

At 02:30 on 27th November the breach is closed and the volume of water that has flooded the area under study begins to run off slowly.

At 04:00 hours in the morning the waters move towards the south, next to the channel, where the bottom elevations are lower. Nodes 142 to 145 no longer exchange discharge with the channel, while nodes 146 to 150 discharge an average of 0.6 m^3/s into the channel. Zone C is also being depleted and, apart from node 116 which receives water, all the nodes discharge up to node 102, which conveys 25 m^3/s into the channel. In zone D water continues to arrive from the channel and spreads according to the orography of the ground. It can be seen that the propagation of the water is interrupted due to the presence of the obstacle presented by the road which runs past the village of Malalbergo. In zone B there are virtually no more exchanges of discharge either with the channel or with the nodes in zone A. The water thus tends to gather principally where the bottom elevations are lower and the water surface is consistently horizontal. The movement of liquid is also limited in zone C, and here too the water surface is practically horizontal. In zone D the waters pass beyond the road close to Malalbergo with limited discharge exchanges.

At 09:30 hours in the morning zone D continues to receive water from the channel in steadily smaller quantities from nodes close to the motorway, then from node 28 to node 33 discharges of as much as 10 m^3/s are released. Zone C is emptying through nodes 118 to 102, and zone A is also emptying through nodes 148, 149 and 150. The same is happening through nodes 228 to 231 in zone B, with average discharges of 0.5 m^3/s.

In the morning of 27th November the area flooded by the waters is still partly submerged and the largest draughts are found in the most depressed areas next to the San Prospero drainage channel, which continues to release discharge as it is the only path of outflow for the waters in the flood zones.

7.7 CONCLUSIONS AND RECOMMENDATIONS

The research work carried out within the frame work of this section aimed at demonstrating the feasibility of the setting up of a comprehensive flood forecasting system as advocated by the AFORISM project. One has to realize that the mathematical models described in the different sections of this report can only be set in an operational form if: (i) sufficient appropriate data describing the system under control are available , (ii) the suite of programs needed to link the measurement of rain to the forecast of runoff at the sections of interest, can be provided in automatic and extremely simplified form, obviating the necessity for continuous operator intervention.

The chapter shows the large amount of work needed to set up real time flood forecasting system and highlights, as part of the feasibility study, the gaps in data and more generally in knowledge. The calibration of all of the models cannot be considered entirely successful, for the various reasons listed below, but has given the opportunity to define the pitfalls in the available information and the priorities for the collection of new data, which was started immediately after the completion of AFORISM.

The major limitations in the calibration of the different models are:

i) The precipitation network is not homogeneous. Some of the stations are telemetering automatic stations and information from several others was digitized from charts, with possible errors both in quantity and timing.

ii) The rating curves, particularly those in the plain, need additional measurements and updating due to the large amount of subsidence that has lowered the averge elevation of the bed by approximately 2 m in the last 50 years.

iii) Today, the geometrical description of the river bed differs from the available measurements due to land subsidence and the routed discharges were not consistent with it.

On the positive side it has been shown that when the data are available, it is possible to set up a system that can reliably predict the flows and the possible future levels. This has given to the Regional Authorities, and in particular to the Reno River Authority the necesary framework within which to start a wide campaign for data collection aimed at setting up the operational real time forecasting system.

At the same time the Reno River Authority initiated the basic work aimed at establishing the sensitivity to hazard of the different flood prone areas, based upon the quasi two-dimensional model developed within the frame of AFORISM. This was in conjunction with the real time use of the operational flood forecasting system, which will require the setting up of Manuals of Procedure for the practical implementation of the different intervention scenarios.

Finally the Reno River experiment clearly showed that the rainfall forecasts provided by the Limited Area Models, although not yet of the required quality, are a promising tool for extending to 12 hours the flood forecasts in small or steep catchments characterized by very short concentration times.