Nat Hazards
DOI 10.1007/s11069-009-9417-9

ORIGINAL PAPER

The tropical storm Noel and its effects on the territory of the Dominican Republic

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Received: 9 November 2008 / Accepted: 17 June 2009

Abstract In the period between the end of October and the beginning of November 2007, the Dominican Republic was hit by the tropical storm Noel, then turned into hurricane in its movement toward the Californian coasts. The passage of Noel was accompanied by huge precipitation especially in the south-western part of the country. In some areas, the rainfall registered in 6 days exceeded 700 mm, i.e., more than two-thirds of the mean annual precipitation. The return periods calculated for this rainfall event vary greatly from region to region: while they locally reach 200 years, such as in San José de Ocoa (50 km west of Santo Domingo), in other areas, as for instance in the territory of the capital Santo Domingo, return periods do not exceed 20 years. The tropical storm caused huge damage both in terms of human victims and economic losses, related to diffused inundations and landslide phenomena, which may be attributed only partially to the exceptionality of the event. As a matter of fact, in many regions, the inadequate answer of the territory—widely characterized by serious problems of land degradation and an almost complete lack of territorial planning—appears to be the major responsible for the occurred negative effects. The impact assessment, based on the calculation of an Impact Index, confirms this statement.

Keywords Tropical storm Noel · Storm impact · Geomorphologic hazard · Land management · Dominican Republic

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Abbreviations

CODOCAFE	Consejo Dominicano del Café (Dominican Coffee Council)
ECLAC	Economic Commission for Latin America and the Caribbean
GEF	Global Environment Facility
INDRHI	Instituto Nacional de Recursos Hidráulicos (National Hydraulic Resources Institute of the Dominican Republic)
IPCC	Intergovernamental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
ONAMET	Oficina Nacional de Meteorología (National Meteorological Office of the Dominican Republic)
SEMARENA	Secreataría de Estado de Medio Ambiente y Recursos Naturales (Ministry of Environment of the Dominican Republic)
SGP	Small Grants Programme
UNDP	United Nations Development Programme
WFP	World Food Programme

1 Introduction

Between the end of October and the beginning of November 2007, the territory of the Dominican Republic (Fig. 1) was affected by the passage of the tropical storm Noel, which caused heavy precipitation all over the country, especially in the southern and south-western part of it.

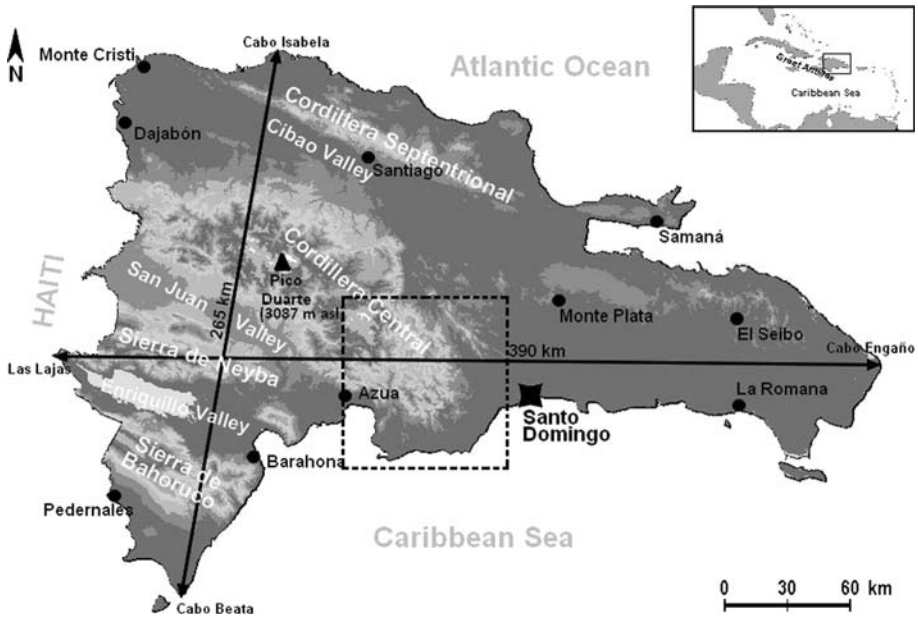


Fig. 1 Location and main physiographic features of the Dominican Republic. The *rectangle* identifies the study area

After the phase of emergency, various programs of disaster recovery were started in the country. According to a medium-term perspective, actions related to such programs try to guarantee the survival of rural communities, seriously challenged by the destruction of crops, agricultural lands and infrastructures, first of all those related to communication. Programs such as the Small Grants Programme (SGP/GEF/UNDP) and the Food for Work by the WFP (World Food Programme) are trying to create the conditions for an efficient recovery of rural communities, highly exposed to land abandonment and consequent increase of emigration toward urban areas, as already observed only a few days after the storm.

This study presents a general characterization of the storm and a first evaluation of its impact on the territory of the Dominican Republic. Given the large extent of the Dominican territory, the investigation on storm effects was necessarily limited to some minor, most impacted, areas. Therefore, attention was focused on the Nizao and Haina hydrographical basins, located in the central-southern sector of the Dominican Republic (Fig. 1), where very high amounts of rainfall and the hugest damage were registered. The results of the analysis of the effects of the storm within the two hydrographic basins, which are characterized by areas of high socio-economic and strategic importance, are presented, and implications in terms of land management are discussed.

The Dominican Republic is located in the Caribbean region between 17°36′ and 19°58′ of latitude North and between 68°19′ and 72°01′ of longitude West, and belongs, as Jamaica, Cuba, Haiti and Porto Rico, to the Great Antilles (Fig. 1). It is part of the Hispaniola island, occupying its eastern portion and about two-thirds of its surface, while the western portion is occupied by Haiti (26,100 km^2). The Dominican territory has an area of about 48,400 km^2 and maximum east–west and north–south extensions of 390 and 265 km, respectively (Marcano 2007). Its external perimeter is 1,963 km, 1,575 km of which is represented by its coasts, while 488 km refers to the border with the adjacent state of Haiti.

The physiographic structure of the Hispaniola island is strongly controlled by the presence of young mountainous structures. The main mountain chains and valleys are frequently controlled by active fault systems with a prevalent NE–SW orientation (Mann et al. 1990, 1995), evolving under the control of the complex dynamics of Caribbean tectonics (Lewis 1980; Burke et al. 1984; DeMets et al. 1990). The island is characterized by four main mountain chains: from NE to SW, the Cordillera Septentrional, the Cordillera Central, the Sierra de Neyba and the Sierra de Bahoruco, where the highest peaks of the Antilles are located (in the Cordillera Central, Pico Duarte and La Pelona reach 3,087 and 3,085 m, respectively). These mountain chains are separated by three major NW–SE oriented tectonic depressions, which are occupied by the Cibao valley, the San Juan valley and the Enriquillo valley (Fig. 1).

From a geological point of view, the Dominican territory is characterized by the following main rocks: volcanic and metamorphic Cretaceous rocks, intrusive Cretaceous and Tertiary rocks and sedimentary rocks of Cretaceous to Pleistocene age (Toloczyki and Ramírez 1991). Sedimentary successions deformed by compressive tectonics widely crop out in the Sierra de Neyba and Sierra de Bahoruco areas, while volcanic and metamorphic rocks constitute the bulk of the Cordillera Central (Toloczyki and Ramírez 1991). Beneath the influence of the Dominican climate (see paragraph 3), outcropping rocks are affected by intensive meteoric weathering, which produces a thick soil-regolith cover.

2 Main geological–environmental features of the Haina and Nizao hydrographic basins

The Haina and Nizao hydrographic basins were selected to investigate in detail the ground effects produced by the passage of the storm Noel. These basins are located in the south-eastern portion of the Cordillera Central (Fig. 1), which hosts most of the physiographic and morphodynamic environments, which typically characterize the central-southern sector of the Dominican Republic. The selected basins are of fifth order, and they are characterized by an area of 564 and 1,036 km^2 and an average altitude of 330 and 809 m asl, respectively.

Starting from elevations up to 2,000 m asl, typical for the northern and north-western portions of the Nizao basin (Fig. 2), the Haina and Nizao rivers reach the Caribbean Sea crossing a wide hilly-mountainous region. Major peaks are Loma El Pinchón (2,354 m), Loma de la Piedra de Manuel (2,600 m), Loma Alto de la Bandera (2,842 m) and Alto de la Lechuguilla (2,540 m) in the North, and Alto de la Lechuga (2,400 m) and Loma de los Chivos (2,073 m) in the Northwest.

Hilly-mountainous to high-mountainous terrains largely dominate in the Nizao basin (nearly 78%), while they are very limited in the Haina basin (4%). The latter, in fact, is characterized primarily by a coastal to hilly-territory located beneath 500 m asl (about 76.5%) and secondarily by hilly-mountainous terrains (19.5%).

About one-third and two-thirds of the Nizao and Haina basins respectively are characterized by slope gradients less than 10 degrees, and about 93 and 98.4% respectively by slope gradients less than 30 degrees (Table 1). Only the Nizao basin shows an appreciable percentage (about 6.8%) of areas with slopes exceeding 30 degrees. The latter are concentrated within the northern portion and part of the central portion of the basin where volcanic and sedimentary rocks crop out. Within the remaining central portion of the basin, instead, where granitic rocks are typical, valley incisions are characterized by less steep

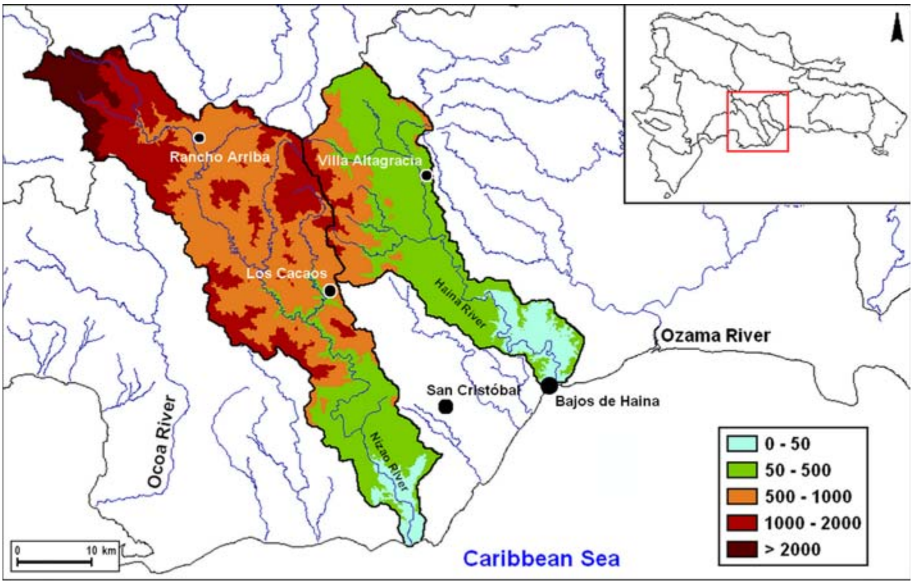


Fig. 2 Location and altitudinal characteristics of the Nizao and Haina hydrographical basins

Table 1 Morphologic-altitudinal and slope features of the Haina and Nizao hydrographic basins

Morphologic units and relative altitudinal limits (m asl)	NIZAO (%)	HAINA (%)	Slope classes (°)	NIZAO (%)	HAINA (%)
Alluvial and coastal plains (≤50)	3.98	13.35	≤ 10	32.37	61.94
Hilly terrains (50 ÷ 500)	18.14	63.18	10 ÷ 20	38.63	24.41
Hilly-mountainous terrains (500 ÷ 1,000)	43.68	19.45	20 ÷ 30	22.22	12.01
Mountainous terrains (1,000 ÷ 2,000)	27.26	4.02	30 ÷ 40	6.11	1.62
High-mountainous terrains (>2,000)	6.94	0.00	>40	0.67	0.02

flanks, generally under 20 degrees. In the Haina basin, the areas with the highest local relief and the steepest slopes are limited to its western and north-western portions, while the remaining zones are prevalently hilly or flat.

Within the headwater portions of the two basins, narrow valleys dominate that are drained by steep, entrenched, cascading, step-pool streams characterized by a torrential regime. Within the middle-upper basin portions, valley incisions are generally larger, and streams are partially unconfined and characterized by a braided to sinuous (Rancho Arriba) and, finally, meandering pattern (Villa Altagracia) where floodplains locally reach 2 km of width. The lower basin portions are characterized by coastal and alluvial plains stretching up to 15 km from the coastline and streams having a typical meandering channel pattern.

On the basis of main course lengths of 77 and 133 km, respectively, a corrivation period of 14.5 and 13.8 h was estimated for the Haina and Nizao basin, respectively, by applying the Giandotti method (Giandotti 1934, 1940).

The hilly to mountainous portions of the two basins slopes are characterized by more or less thick soil-regolith mantles, which are highly unstable, especially where man has removed the original forest cover for cultivations during the last centuries. According to the land use map of the Dominican Republic, cultivated lands are in fact very widespread, occupying 43% of the territory in the Haina basin. Coffee is largely cultivated, especially in the headwater sectors of the two basins. In the high-mountainous zone of the Nizao basin, forests prevail.

Rural population is typically distributed in permanent villages, which are composed of the most internal areas of about one hundred families living in wooden and zinc houses. Maintenance of this population is based on subsistence farming, consisting in clearing small migratory farms of short cycle products (conuco, as this practice is locally called). This type of farming, typical in mountainous steep-sloped areas, is characterized by low productivity and causes a progressive land degradation. Cleared lands guarantee the sustenance of a family of peasants only for a few months. In fact, rapid soil loss due to accelerated erosion by running waters and mass wasting affect extensively the scarcely protected slopes, causing lands to turn rapidly unproductive and obliging the peasant to deforest nearby areas and repeat the same cycle.

It is important to point out that in the San Cristóbal Province, which occupies the major part of the Haina hydrographical basin and almost half of the Nizao basin, the average population density is about 420 inhabitants/km^2, according to the National Statistical Office. Some of the biggest urban centers, such as the town of Los Cacaos (7,494 inhabitants according to the last population census by the National Statistical Office), are located in inter-mountainous valleys at stream confluences.

The two hydrographical basins are very important also from an infrastructural and industrial point of view and strategic in terms of water supply for one of the most populous zones of the Dominican Republic (INDRHI 2006) as the Haina-Manoguayabo drainage system provides 25% of the water supplied to the capital, according to a study carried out in 2004 for the Aqueduct Corporation of Santo Domingo.

The road network, which connects the biggest urban centers of the country, develops along the main water courses. Within the middle course of the Haina river, the Autopista Duarte, the highway, which connects Santo Domingo to Santiago, the second urban center of the Dominican Republic, runs along the valley floor.

The coastal and alluvial plains, characterized by high fertility, show the highest concentration of anthropic activities (mechanized intensive agriculture, industries, etc.) and elevated population densities that reach 5,000 inhabitants/km^2 in the area of Bajos de Haina.

One of the biggest industrial poles of the country is located at the Haina river mouth, which is characterized by artificial banks to protect the populous urban and industrial pole. In this area, adjacent to the capital Santo Domingo, more than 100 industries can be found, ranging from manufacturing to chemical, metallurgic and pharmaceutical industries, in addition to electric power plants and the Dominican oil refinery. In 2006, this industrial pole, known as Bajos de Haina, was listed among the ten most contaminated sites in the world (Caravanos and Fuller 2006), because of its very high environmental lead concentrations, caused by a company recycling car batteries.

3 Climatic features of the Dominican Republic

Following the classification of Köppen (1936), the climate of the Dominican Republic can be referred to class A (tropical rainy climates), which is characterized by monthly mean air temperatures above 18°C and annual mean rainfall amounts, which exceed annual evapotranspiration.

At a more detailed scale, the climate of the Dominican Republic appears strongly influenced by its orography and hydrography, which are responsible for the high environmental diversity not only between coastal areas and the internal hilly-mountainous zones, but also between regions located at similar altitudes in different parts of the country.

According to Cocco Quezada (2001), the Hispaniola island is under the influence of the North-Atlantic anticyclone, regulator of trade winds, and of the humid oceanic tropical air masses, which, due to the perturbation by summer tropical waves, are responsible for a great part of precipitation in the country. During winter, fronts and vaguadas, (the latter corresponds to the Spanish name for an elongated barometric depression between two anticyclones), are responsible for important precipitation during this season.

On the basis of these considerations, Cocco Quezada (2001) elaborated a climate classification for the Dominican Republic based on the following climatic periods: a period of frontal activity from November to April; a period of convective activity from May to July, characterized by a reinforcement of eastern winds, which causes an intense convection and the development of huge clouds and consequent thunderstorms and electric storms; a period of tropical activity from August to October, characterized by abundant precipitation. These three periods are accompanied by two short transition periods: the first one in the second half of April, when the passage from frontal to convective activity occurs, and the second one in the second half of November, when the cyclonic activity is progressively replaced by the frontal one.

This type of classification allows to explain the reduction of precipitation in the northern coastal plains, the presence of summer precipitation in the south of the country and the occurrence of seasonal drought periods in different parts of the country. The weather and climate of the island are highly influenced by the presence of mountain chains aligned perpendicularly to the prevalent eastern currents. Their presence causes a remarkable difference in mean annual rainfall between the areas located northeast and southwest of the Cordillera Central, respectively. The first, in fact, are characterized by rainfall amounts exceeding 2,000 mm, while the second receives very modest totals of 350–400 mm, denoting conditions of arid environment (Köppen category BShw, warm arid steppe climate). Following the Köppen classification, in the country all the three subcategories of climate A are present: Af (tropical rain forest climate), typical of the Samaná peninsula, the Cordillera Oriental, the Los Haitises karstic zone, the low Yuna valley and, partially, the Cordillera Septentrional and the Sierra de Bahoruco; Am (tropical monsoon climate), which can be identified in the area of Cabrera, Cotuí, El Seibo, Monte Plata, San Cristóbal, Villa Altagracia, Villa Riva, Yamasá and Yásica; Aw (tropical wet and dry or savanna climate) typical for the Santo Domingo province. Finally, in the zone of Constanza valley and within the highest mountainous areas, the climate category Cf (wet temperate climate) can be recognized (Marcano 2007).

The analysis of the spatial distribution of some of the main climatic parameters, such as air temperature and precipitation, allowed to define, as shown in Fig. 3, the Bagnouls–Gaussen and Peguy diagrams for the weather stations, which represent the main climatic regions of the country. In particular, the Bagnouls–Gaussen diagram (Gaussen and Bagnouls 1957; Bagnouls and Gaussen 1953) shows the relation between average monthly rainfall amounts (in mm) and relative air temperatures (in °C) calculated for the 30-year period 1971–2000 for the considered weather stations. The diagram allows to define a dry period when the amount of average monthly precipitation is lower than the double of the monthly mean temperature. The Peguy diagram (Peguy 1970) is based on the representation of segments, which join the monthly average values of air temperature and precipitation. Four sectors (C = Cold months; T = Temperate months; H = Hot months; D = Dry months) are identified as the intersection of three straight lines: $y = 1.71x$; $y = 13.3x$; and $y = -19x + 485.7$.

The presented diagrams evidence a gradual reduction of precipitation from east to west. For the eastern zones, even though a typical reduction of precipitation is clearly evident during winter and spring, no arid period can be identified. The western zones, instead, are characterized by a more or less pronounced aridity. In particular, within the south-western sector (Barahona), aridity characterizes the periods from December to February and from July to August, while it extends for the whole summer period (May–September) within the north-western sector showing similarities to Mediterranean climate (Monte Cristi).

Typical elements of temperate climate appear in mountainous zones (Constanza), where the elevation causes a considerable reduction of mean annual air temperature. As a matter of fact, the mean annual air temperature, which is about 26°C for the country as a whole, at altitudes above 1,200 m in some areas of the Cordigliera Central drops down to less than 18°C. Figure 4 shows the spatial distribution of mean annual precipitation (A) and that of annual minimum and maximum temperatures (B and C) for the 30-year period 1971–2000.

The Dominican territory is characterized by a further important climatic aspect as it belongs to the latitudinal zone interested by atmospheric phenomena known as tropical cyclones.

Cyclones typically originate during summer when the warming of the oceanic surface is maximum, from the beginning of June until the end of November in the Atlantic (Landsea 1993). Initially, cyclones move westwards, under the driving force of the easterlies that flow at the latitudes where the cyclones take origin (between 5 and 30°), and then they

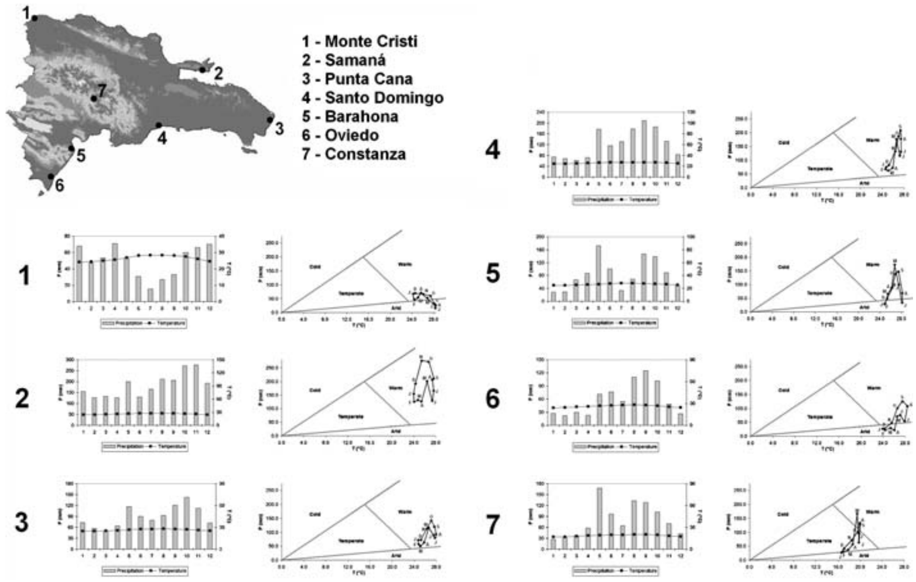


Fig. 3 Thermo-pluviometric diagrams of some stations in the country: Bagnolus-Gaussen on the *left*; Peguy on the *right*

move slowly toward the poles. A lot of cyclones turn far enough from the Equator reaching, at mid latitudes, areas dominated by western winds, which cause an inversion in the direction of cyclones, which consequently move eastward (MetOffice 2008). According to data from NOAA, the trajectory of a cyclone has a typical evolution depending on the month of the year. In Fig. 5, the typical trajectories for June, July, August and September are shown.

4 Dynamics and evolution of the storm

According to the Saffir–Simpson scale (Simpson and Riehl 1981), which classifies tropical cyclones in relation to their intensity, Noel reaches the category of Hurricane 1, hitting the Dominican territory as a tropical storm.

As described in Brown (2007), the development of the tropical cyclone Noel took its origin from a tropical wave, which left the western coasts of Africa on October 16th. During the following 7 days, the wave moved westwards across the eastern Atlantic without showing any element of organization. On October 22nd, it reached the Lesser Antilles as tropical wave. From that moment on, it started its interaction with a superficial low pressure situated northward of Leeward Islands and with an upper-level trough extending south-westward from the Atlantic Ocean to the eastern portion of the Caribbean Sea. On October 23rd, this interaction caused the development of a low pressure area at 280 km ENE of northern Leeward Islands. Then, the new baric minimum moved slowly westward, producing disorganized electric activity in the following 2 days, while upper-level strong west winds inhibited further development. On October 25th, the low pressure area turned west-south-westward, moving over the Virgin Islands and passing near the south-eastern coast of Puerto Rico on October 26th. On October 27th, the upper-level west

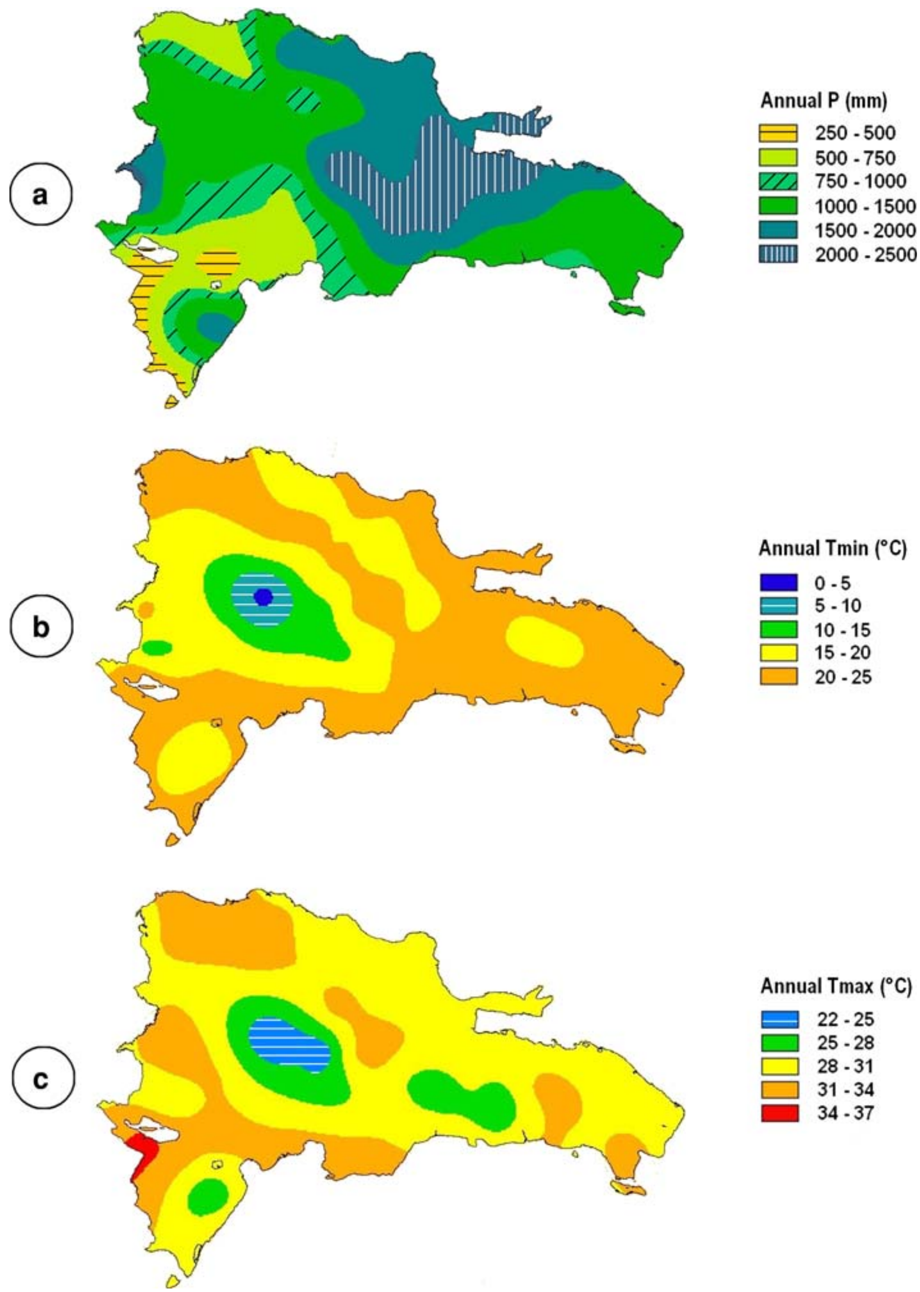


Fig. 4 Territorial distribution of mean annual precipitation (**a**), mean annual minimum temperature (**b**) and mean annual maximum temperature (**c**) (reference period 1971–2000)

winds started to decrease, allowing convection to develop. An increase in the level of organization, occurred on October 27th around midnight, caused the phenomenon to convert in a tropical depression, about 340 km SSE of Port-Au-Prince.

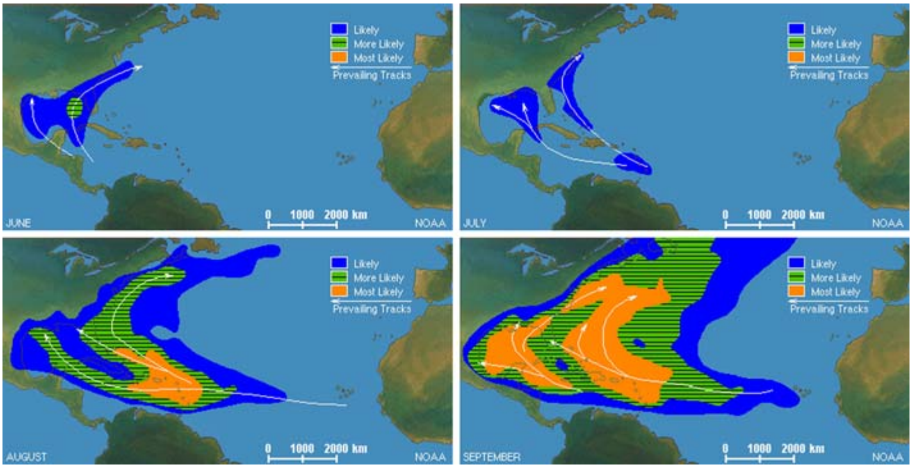


Fig. 5 Prevailing tracks of tropical cyclones from June to September in the Atlantic ocean (from NOAA modified)

After its formation, the depression moved north-westwards. Convection continued to increase, and typical banding features became evident from the early morning hours of October 28th, when the phenomenon reached the category of tropical storm. Thereafter, Noel continued to strengthen, reaching 6 h later an intensity of 50 knots (92.6 km/h). On October 29th, following its north-western trajectory toward the southern coast of Haiti, the interaction with mountainous terrain caused the disruption of the low-level circulation. Consequently, wind velocity dropped to 45 knots (83.3 km/h).

The organization of the storm considerably reduced during its passage along the western coast of Haiti. In its westward movement, the phenomenon regained strength passing over the western Atlantic reaching an intensity of 50 knots (92.6 km/h) along the northern coast of eastern Cuba. The storm remained over the Cuban territory for about 30 h, during which it slightly reduced its intensity. The following passage over the ocean at north of Cuba, accompanied by a progressive increase in convection, caused the storm to strengthen progressively since it reached the category of hurricane on November 2nd, at north-west of the Bahamas. Continuing its trajectory northwards, the hurricane progressively weakened, and finally it merged with another extratropical low near the coasts of Greenland. Figure 6 shows the evolution of the tropical storm during its passage over the Dominican territory.

A synthesis of the geophysical parameters of the storm is reported in Table 2. The maximum rainfall (about 1,000 mm) occurred in the territory of Hispaniola.

5 Intensity of the storm event

The passage of the tropical storm Noel over the territory of the Dominican Republic (Fig. 6) caused heavy and persistent rainfall. Even though the cyclone was centered over Haiti, its highly asymmetric structure provoked the most of precipitation to occur east of it. More than wind intensity, the abundant rainfalls caused the most of impacts, even though in Barahona and surrounding areas (SW of the country), winds up to 60 knots (111.1 km/h) were registered (Brown 2007).

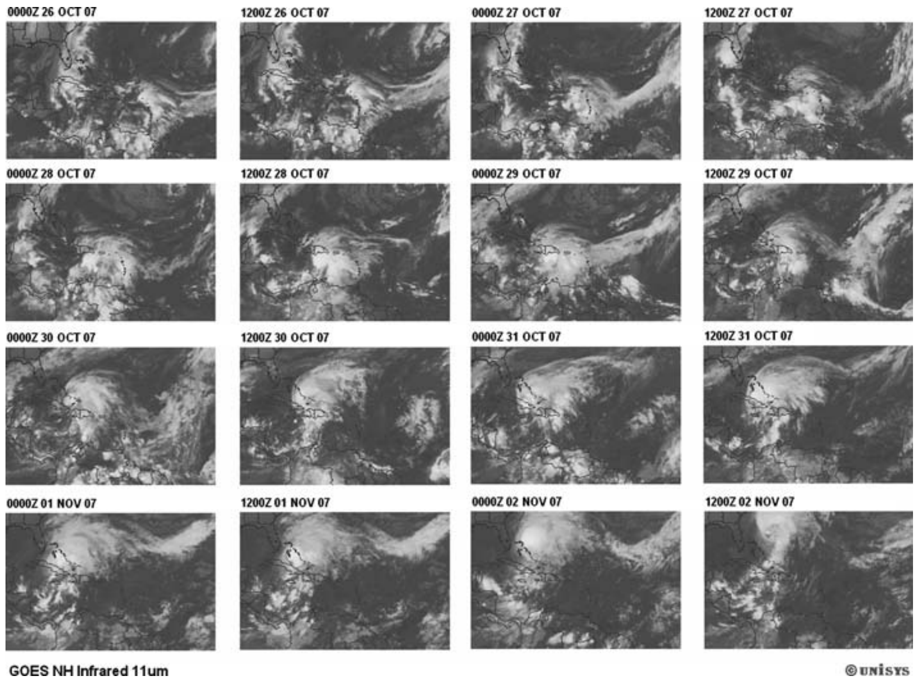


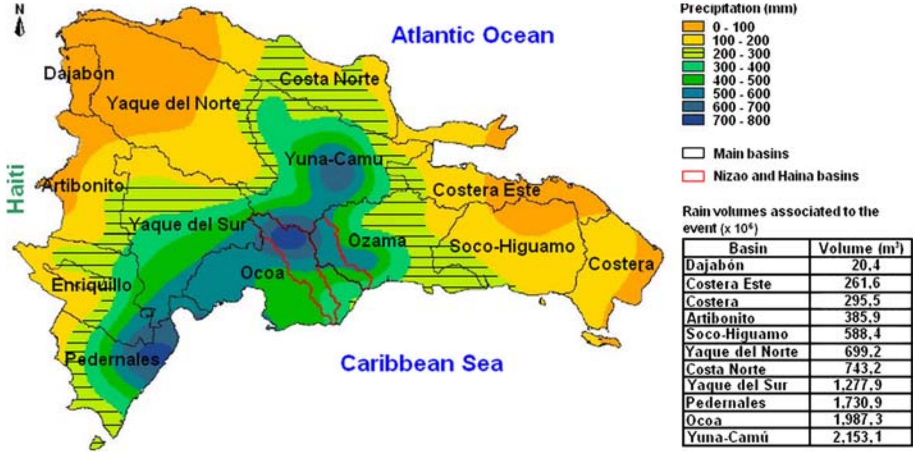
Fig. 6 Evolution of the tropical cyclone Noel (*source*: UNISYS 2008)

Table 2 Geophysical parameters of the storm (according to Brown 2007)

Parameter	Phenomenon category				
	Low (L)	Tropical depression (TD)	Tropical storm (TS)	Hurricane cat.1 (H1)	Extratropical cyclone (E)
Duration (hours)	96	12	108	24	72
Track length (km)	1,356	79	1,676	778	3,883
Land track length (km)	2 (Puerto Rico)	0	458 (Haiti, Cuba, The Bahamas)	0	947 (Canada, Greenland)
Velocity (km/h)	14	7	16	32	54
Minimum pressure (mbar)	1,004	1,002	992	980	965
Maximum wind speed (m/s)	13	15	28	36	39

The meteorological reconstruction of the storm event was carried out using data registered by the National Meteorological Office (ONAMET) and the National Hydraulic Resources Institute (INDRHI).

The spatial distribution of precipitation associated with the event (Fig. 7) shows that, coherently with the storm trajectory, the most of rainfall occurred in the south and southwest of the country. In particular, the Cordillera Central acted as a barrier, causing differences in precipitation up to 500–600 mm between the southern and the northern flank of the mountain chain.



Basin	Volume (m^3)
Dajabón	20.4
Costera Este	261.6
Costera	295.5
Artibonito	385.9
Soco-Higuamo	588.4
Yaque del Norte	699.2
Costa Norte	743.2
Yaque del Sur	1,277.9
Pedernales	1,730.9
Ocoa	1,987.3
Yuna-Camú	2,153.1

Fig. 7 Distribution of precipitation and rain volumes in the main hydrographic basins from October 26th to November 1st 2007

Confronting monthly precipitation occurred in the Dominican territory during 2007 with the mean values (normal) registered during the 30-year period 1971–2000 (Fig. 8), two main anomalies can be evidenced: the central and southern weather stations registered monthly precipitation inferior or equal to the normal, while the northern stations show a very inhomogeneous distribution of their rainfall amounts, significantly higher than the normal in the majority of months, separated by one or more months with precipitations similar to considerably lower than the normal (Arroyo Barril and Sabana de la Mar stations). Deviations of total average rainfall amounts and those registered during 2007, calculated as percentage of [(total precipitation 2007−average annual precipitation)/average annual precipitation], produce a typical zonation of the Dominican territory (Fig. 8), which highlights the zones that were characterized in 2007 by an excess (over all the central sector) and by a deficit of total annual rainfall (the north-western and eastern sectors) with respect to the normal.

From a general point of view, a strong reduction of monthly rainfall in 2007 can be observed for February, which is one of the driest months. On the other hand, October 2007 was definitely more rainy than the average (Fig. 9). Most of the stations (see for example Fig. 8) registered daily values mostly beneath the normal during the weeks, which preceded the storm and a maximum of precipitation at the end of October, during the passage of the tropical storm. Throughout the whole national territory, the precipitation registered during this month presents positive percentages of deviation from the normal, with values from 20% up to five times higher than the average (Rancho Arriba station).

In order to estimate the return periods of the storm event, total precipitation in 24 h and 6 days respectively, were compared with the historical series of Santo Domingo, Barahona, Constanza, San José de Ocoa and San Cristóbal, applying the First Type Gumbel distribution (Gumbel 1958), with a percentage of available data generally around 80%. Data from the stations of Villa Altagracia and Rancho Arriba were excluded from the analysis because of their high percentage of no data. Performance of the chi-square test has shown that data are distributed according to the First Type Gumbel distribution, at a confidence level of 95%.

The obtained results (Table 3) show that the storm cannot be defined as exceptional in relation to daily rainfall amounts, as the calculated return periods are very short and only

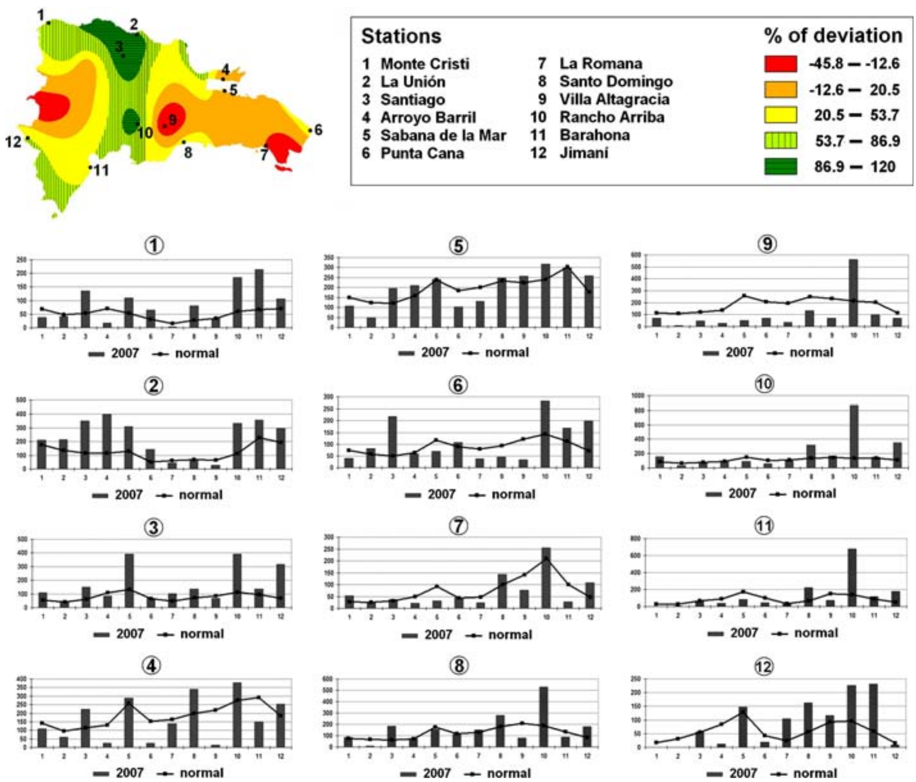


Fig. 8 Trend of precipitation in 2007 and comparison with the average of the period 1971–2000 for some stations of ONAMET network. Deviation was calculated as described in the text of the article

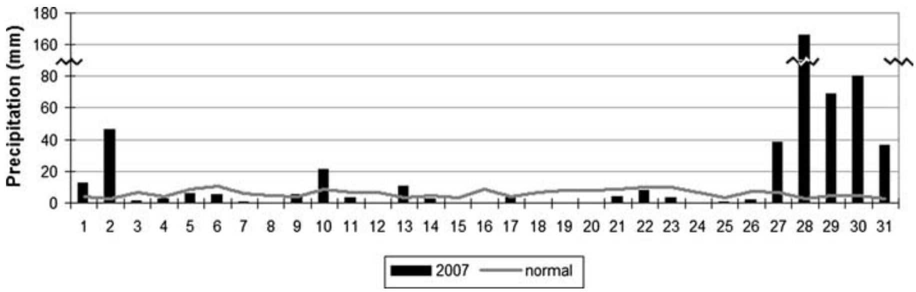


Fig. 9 Precipitation in October 2007 and comparison with the average of the period 1971–2000 for the Santo Domingo station

locally exceed 20 years (21.7 years for San José de Ocoa). On the contrary, the persistence of rainfall can be defined as significant: the return periods calculated for the 6-day period, for three of the five analyzed stations exceed 50 years, reaching about 207 years in San José de Ocoa, a town located in an internal zone on the southern slope of the Cordillera Central at 475 m asl. Coherently with the dynamics of the storm event, which was characterized by an asymmetric structure centered above Haiti and extending eastward, return periods decrease considerably for the stations situated in the eastern portion of the country.

Table 3 Maximum daily rainfall and rainfall amounts in the 6-day period registered during the storm and relative return periods for the stations of San Cristóbal, Santo Domingo, Constanza, Barahona and San José de Ocoa

Station	Altitude (m asl)	Total rainfall (mm)	Date	Return period (years)	Total rainfall (mm)	Period	Return period (years)
SAN CRISTÓBAL	44	124.4	29/10/2007	2.2	357.4	28/10/2007–2/11/2007	9.8
SANTO DOMINGO	14	166.2	28/10/2007	4.2	394.3	27/10/2007–1/11/2007	18.7
CONSTANZA	1,164	95.2	29/10/2007	3.5	305.4	25/10/2007–30/10/2007	52.6
BARAHONA	10	216.2	29/10/2007	5.5	683.5	28/10/2007–2/11/2007	72.4
SAN JOSÉ DE OCOA	475	175.0	28/10/2007	21.7	496.1	25/10/2007–30/10/2007	206.9

6 Main ground effects

According to an ECLAC report, the passage of the tropical storm Noel in the Dominican territory caused 87 victims, while 48 persons resulted missing. More than 3,000 houses were completely destroyed and other 16,000 were damaged, and about 79,000 people remained in shelters for more than 2 weeks after the event. Two days after the passage of the storm, the President of the Dominican Republic, on the basis of first evaluations of the occurred devastation, declared the state of emergency in the country.

According to the same report, agriculture, the most damaged sector, was practically kneeled down: first estimates report total damages exceeding 100 million dollars. Low scale and subsistence agriculture were the most affected, with heavy social consequences in particular for the most vulnerable components of the population. Musaceae (bananas and planes) and coffee were the most damaged crops. Damages to coffee are estimated in about 6 million dollars by CODOCAFE, the main Dominican institution supporting coffee cultivation.

Relevant damages were registered in the following provinces: the National District, Santo Domingo, Barahona, San Pedro de Macorís, San Cristóbal, Santiago, Sánchez Ramírez, Duarte, Samaná, Azua, Independencia, Peravia, Pedernales, La Vega and Monte Cristi. The San Cristóbal and San José de Ocoa provinces, in whose territories the Haina and Nizao basins are located, were among the most affected areas.

Most of the ground effects produced by the tropical storm were caused by rainfall and consequent phenomena of river flooding and mass wasting. Only the south-western part of the country and the Barahona province in particular were affected in a significant manner by the action of winds (reaching up to 111 km/h), which caused huge damage to agriculture, infrastructures and rural structures (mainly wooden and zinc houses).

Even though data on peak discharge of rivers during the event are not available, the observed ground effects suggest that peak discharge was considerable. An indicative estimation was obtained through the application of the rational equation method (Kuichling 1889), which relates peak discharge to the drainage area, rainfall intensity and runoff coefficient, the latter being based on catchment slope, land-use and hydrologic features of soils, according to the following equation:

$$Q = ciA$$

where Q is the peak discharge, c is the rational method runoff coefficient, function of the soil type and drainage basin slope, i is the rainfall intensity, A is the drainage area.

The results show peak discharges at the river mouth around 1,500 and 2,000 m^3/s for the Haina and Nizao basins, respectively. Flooding affected the valley floors and alluvial coastal plains to a greater extent. Its destructive effects were related both to the inundation of land by water and to the erosion by flowing waters along river channels and within floodplain areas. It involved wide areas pertaining to the municipalities of Rancho Arriba, Los Cacaos and Yaguate in the Nizao basin and those of Villa Altagracia and Haina in the Haina basin. The municipality of Villa Altagracia, where more than 30 people died in the inter-mountainous valley of El Duey, had the highest number of victims. Here, entire rural communities living along the river channels and within the floodplain areas (Fig. 10a–d) pertaining to the confluence area of El Duey and Arroyo Grande rivers (both tributaries of the Haina river) were destroyed by the flood (Fig. 10e), which surprised people during sleep. This flood, as involved people afterwards referred, was the biggest one ever observed in this area during the last 70 years.

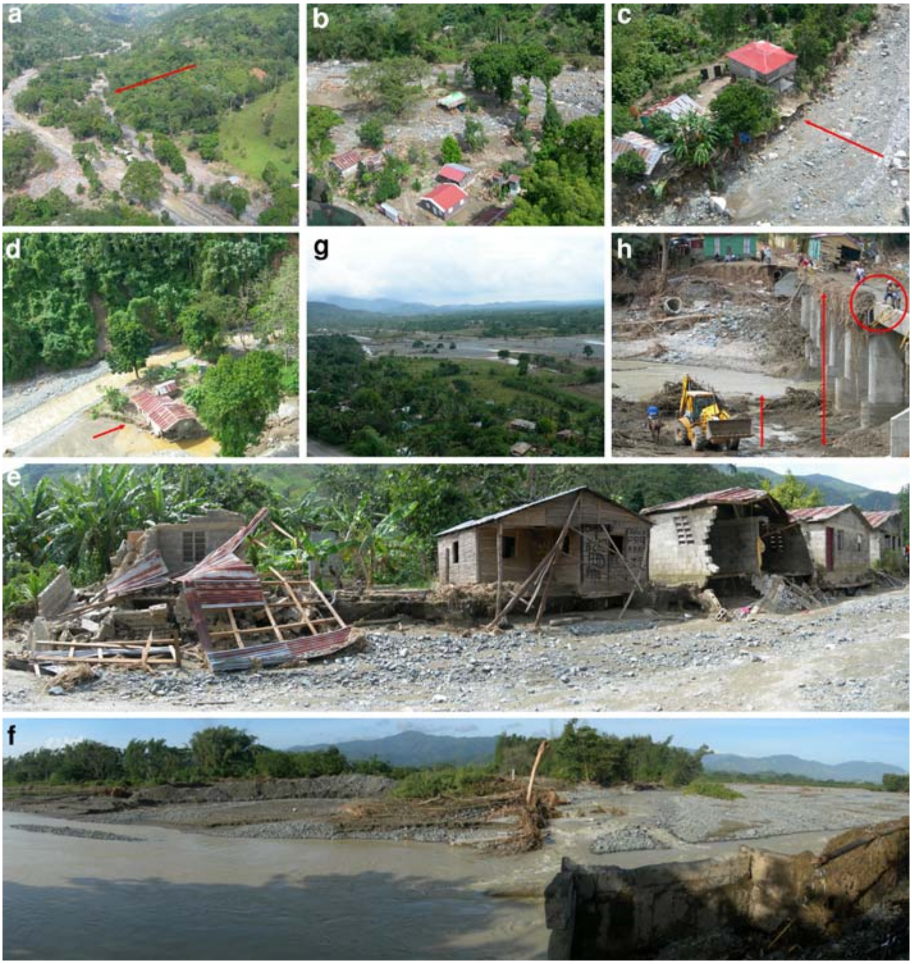


Fig. 10 Impacts of stream erosion on anthropic structures provoked by the flood during the passage of the tropical storm Noel. Note that within the surveyed fluvial reaches the damaged houses are located or on the flood plain or within the active channel (**a**–**e**); flood effects related to elevated hydrometric levels during the storm event: the collapse of the bridge on the Haina river within the Villa Altagracia municipality (**f**); a view from the Duarte highway, locally reached by the flood (**g**); evidence of the elevated hydrometric level reached by the Mahomita river within the town of Los Cacaos, San Cristóbal province (**h**)

Many roads and communication infrastructures were severely affected by flooding. In particular, flooding caused the collapse of a lot of bridges (Fig. 10f), while a stretch of the Duarte highway was inundated by water and closed to transit of vehicles for various hours (Fig. 10g). In the area where the Basima river joins the Haina river, water flow inundated large portions of the floodplain and reactivated abandoned river channels (Fig. 10g).

Also in urban centers, flooding caused huge damage as for example in the town of Los Cacaos (San Cristóbal Province), located in the medium sector of the Nizao basin along the middle course of the Mahomita river, whose hydrometric level locally rose more than 6 m (Fig. 10h). In this specific case, it is important to put in evidence the inadequate technique,

Fig. 11 Steep, mainly deforested, slopes affected by diffuse shallow earth-slides and earthflows triggered by the rainfall during the storm event (**a**–**c**); evidence of huge debris flow impacts within the town of Los Cacaos (San Cristóbal) (**d**): rock and earthfalls occurred on very steep slopes along road cuts (**e**, **f**) and triggered by stream undercutting (**g**), respectively

which was adopted to build the bridge: short spans are not adequate for this kind of river, which is characterized by significant solid loads and very variable flows.

Landslides occurred prevalently in the hilly-mountainous and mountainous zones of the Haina and Nizao basins. The main types of movement were represented by slides, flows and falls.

Debris flows and mudflows typically involved the soil and regolith mantles of steep slopes (generally exceeding 30°) and affected mostly slopes, which had undergone recent denudation due to the clearing of the original forest cover (Fig. 11a–c). In the investigated basins, such flows produced a high negative impact on agriculture, based prevalently on coffee. As a matter of fact, damage consisted not only in the loss of production, related to the occurrence of the storm during the harvesting season, but also in the extensive land degradation generated by soil loss or its burial due to debris accumulation.

Flows caused also the collapse of bridges and the interruption of accesses to built-up areas with up to thousands of inhabitants. For example, the town of Los Cacaos was accessible only by helicopter for more than 15 days. Entire suburbs of the town were buried by debris flows (Fig. 11d), which descended from the mountainous territory surrounding the town and in particular from the La Cañada del Café hydrographical basin where highly weathered igneous rocks are outcropping.

Landslides of minor dimensions but widely diffused were rock and earthfalls which typically occurred along scarps characterized by excessive steepness due to artificial cuts (for instance road cuts, Fig. 11e, f) or river undercutting during the event (Fig. 11g).

Field surveys carried out 3 months after the event in the areas, which were most affected by landslides, revealed that the zones of depletion appeared still completely bare and practically unmodified with respect to the morphology they showed immediately after the storm, highlighting long periods necessary for reconstituting again the vegetation cover and reaching, consequently, an amelioration of present slope conditions.

An evaluation of the potential damage caused by the storm was carried out applying the Impact Index (Palmieri et al. 2006), according to the following equation:

$$I = 0.9178 + 0.0030L + 0.0012D$$

where I is the Impact Index, L (in km) is the land track of the storm, D (in kg/s^3) = $C_D V\rho$, being C_D the surface drag coefficient (in the case of strong winds C_D can be related to the surface wind speed V by means of $C_D = (0.94 + 0.034V)10^{-3}$), V the surface wind speed and ρ the air density near the surface.

The Impact Index of the tropical storm, considering an air density of 0.9 kg/m^3, is estimated in 2.34, which represents a relatively low value (Palmieri et al. 2006).

7 Discussions and conclusions

On October 29th 2007, the Dominican Republic was hit by the Tropical Storm Noel, which caused huge precipitation all over the country and strong winds in the South West of the national territory.

The storm can be considered as an exceptional event as to the persistence of rainfall in the considered 6-day period, for which recurrence periods of 50 to over 200 years could be calculated in various provinces.

The collected data evidence that the main impacts on the population were provoked by landslides and flooding, which accompanied the storm event.

The hugest socio-economic consequences involved rural communities, which were affected very strongly by the interruption or destruction of communication infrastructures and by the loss of a lot of foodstuffs and agricultural products. This created during the weeks, which followed the storm event a very critic situation in relation to the fulfillment of alimentary needs of the local population.

Zones where recuperation appears the most critic are those affected by landslides. In particular, the complete removal of the vegetation cover makes very difficult, at least in the short to medium-term period, the rehabilitation of agricultural parcels.

However, the analysis of ground effects, specifically the investigation carried out in the Nizao and Haina basins, points out that the registered damage only partially may be justified by the exceptionality of the event. Frequently, as stressed for natural hazards also by Pielke et al. (2008) for other countries, human and economic losses are strongly related to an inadequate or inexistent territorial planning. In the examined case of the Dominican Republic, the low value of the calculated Impact Index of the storm confirms this statement.

In the Dominican Republic, the absence of a territorial plan, together with the elevated state of poverty of a large number of people, causes human settlements to be located typically in areas, which are easily accessible and cultivable on one hand, but exposed, on the other hand, to elevated geomorphologic hazard and related risk due to flooding and slope degradation. The latter, in particular, is highly accentuated by inefficient and harmful agriculture practices, based on clearing small migratory farms of short-cycle products, which still constitutes the most frequent agricultural technique in many areas.

Within the main urban areas of the country, represented by Santo Domingo and Santiago de los Caballeros, entire popular suburbs (barrios) lie along large rivers, such as the Ozama (Santo Domingo) and the Yaque del Norte (Santiago). These suburbs were among the most damaged by the tropical storm Noel.

The exposed considerations highlight two main aspects, which can be generalized: first of all, events as the described one that are normally defined as natural disasters should better be defined as "manmade" disasters, as the provoked damage largely depends on the high vulnerability of the territorial system and its inadequate response to the event. Secondly, such "manmade" disasters are typically characterized by a significant nonhomogeneity in the distribution and entity of social consequences, as major human and economic losses mostly affect the poorest and consequently most vulnerable people.

On the basis of what has been discussed until now, the development of a policy of territory management based on an adequate planning appears of primary importance for the Dominican Republic. In order to reach this objective, it is necessary to work at various levels:

1. Scientific research, which improves basic and specific knowledge on the Dominican territory, as a fundamental instrument to evaluate any land use alternative;
2. Planning, which guarantees the possibility of identifying the most sustainable land use, limiting risks related to natural phenomena to which the Dominican territory is exposed;
3. A direct action involving local rural population, which focuses on the improvement of living conditions and the spreading of a culture of respect and protection of the environment. Poverty and lack of alternatives, together with ignorance about the consequences, also economic, of environmental degradation, represent one of the main causes for the high environmental vulnerability, which characterizes the country, as well as a big barrier to human development.

The above listed points represent important elements in order to guarantee the sustainable development and security of any territory, but are particularly essential in a country like the Dominican Republic, which is exposed to extreme meteorological events such as tropical cyclones.

Furthermore, as the Dominican Republic is located on an island, it is particularly vulnerable to climate change (SEMARENA 2004), which, according to recent studies (IPCC 2007) is expected to cause an increase in frequency of meteorological extreme events. As a consequence, a correct territory planning can be considered the main action for adaptation to climate change.

The present work creates the base for further studies. In particular, the investigations in progress aim to characterize climate trends in the Dominican Republic territory, estimating potential territory responses to the most likely future projections. The final objective is to provide decision makers with information useful in orienting land use planning, coherently with environmental characteristics of the Dominican territory, toward a sustainability in a medium to long perspective.

Acknowledgments The authors gratefully acknowledge the precious collaboration of: Ing. Noris Araujo, Prof. Ludovico Brancaccio, Ing. Gloria Ceballos, Ing. Roberto Gaudio, Ing. Santiago Muñoz, Ing. Alberto Sánchez and Mr. Hugo Segura.

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