Receiving water body quality assessment: an integrated mathematical approach applied to an Italian case study

Angela Candela, Gabriele Freni, Giorgio Mannina and Gaspare Viviani

ABSTRACT

This study presents a basin-scale approach to the analysis of receiving water body quality considering both point and non-point pollution sources. In particular, this paper describes an extensive data gathering campaign carried out in the Nocella catchment, which is an agricultural and semi-urbanised basin located in Sicily, Italy. Two sewer systems, two wastewater treatment plants and a river reach were monitored during both dry and wet weather periods. A mathematical model of the entire integrated system was also created. Specifically, a detailed modelling approach was developed by employing three well known models: Storm Water Management Model, GPS-X and Soil and Water Assessment Tool. The study proposed a comprehensive modelling approach to analyse the importance of diffuse and concentrated polluting sources on receiving water quality. The study demonstrated that point pollution loads can be more influential during wet periods by an order of magnitude compared with the dry weather period. In the long term, diffuse and point pollution sources were demonstrated to affect river quality and they have both to be considered. The use of the proposed integrated model-based approach may support water managers in decision making about which strategies should be preferred with the aim of water quality preservation.

Key words | non-point pollution sources, point pollution sources, river water quality modelling, river water quality monitoring, urban drainage-integrated modelling

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INTRODUCTION

The inherent complexity of natural systems requires tools that can analyse the whole system in a simplified way without neglecting the most important physical phenomena. Numerical modelling is one of these tools, even if there are many interconnected elements in the rural and urban areas of the river basin. New computational capabilities becoming available year after year support the development of new approaches that can analyse both the quality and quantity of water in an entire river basin, including elements such as: a sewer system (SS), waste-water treatment plant (WWTP), a rural catchment (RC) and a receiving water body (RWB). As reported by Devesa *et al.* (2009), the management of these units has been rarely considered in an integrated way where the relationships between the SS, WWTP, RWB and other ancillary infrastructures (i.e. storage tanks) are accounted for, rather these elements are typically considered as individual systems.

In the past decade, the need for an integrated approach has attracted an increasing amount of attention from local, national and European Authorities, who have established progressively more restrictive regulations. In particular, the European Union Water Framework Directive (EU WFD), established in 2000 (European Union 2000) defined the river basin as the reference territorial management unit. The directive calls for integrated catchment management to achieve 'good ecological status' for all natural water bodies in a specified time frame, a goal that involves the reduction of pollution loads by eliminating and/or treating non-point and point sources.

Modelling plays a central role in the analysis of catchment-sized water bodies as it can help to evaluate current

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water resources, identify pollution sources, evaluate alternative management policies, and dictate sustainable water allocation among various stakeholders. Many models have been developed to simulate water quality and quantity on both field and basin scales, and various studies have investigated the role of models in the implementation of water-related policies, such as the EU WFD (Dørge & Windolf 2003).

Three main classes of integrated approach are typically applied to rural semi-urbanised basins (Candela *et al.* 2009).

1. Urban-integrated models: designed for the evaluation of point pollution.
2. River basin-integrated models: designed for the assessment of non-point pollution.
3. Fully integrated modelling approaches: these provide a detailed representation of both point and non-point sources of pollution.

Previous studies have been primarily based on models that analyse point pollution sources and estimate non-point sources in a simplified way (urban-integrated models) or vice versa (river basin-integrated models). A large effort was carried out for developing urban-integrated models facing difficulties in interconnecting differently modelled systems and reducing the inbalance between the available data and the number of model parameters (Vanrolleghem *et al.* 1999; Schütze *et al.* 2002; Mannina 2005; Vanrolleghem *et al.* 2005; Reussner *et al.* 2009). The problem of integrating these models with natural and RC models was not taken into account and the flow and polluting loads from those areas are normally considered in a simplified, and often aggregated, manner.

Conversely, river basin-integrated models were developed separately mainly looking at nutrients and sediments from rural areas and analysing urban areas in a very simplified way. The efforts to model non-point nutrient losses within catchments have intensified in recent years given the need to incorporate the WFD and the recognition that the amelioration of point source inputs alone is not sufficient to deliver the required reductions in nutrient pressures to ensure good ecological status (Wade *et al.* 2002; Boorman 2003; Neal *et al.* 2005). However, non-point sources can be difficult to evaluate since they are strongly influenced by climatic conditions, as well as the geomorphological, lithological and pedological properties of the area. In the literature there are many studies on such issues associated with non-point sources (Haycock & Muscutt 1995; Arheimer *et al.* 2004). There is a general consensus that agriculture is the main non-point source of nutrients for a given body of water (Rekolainen *et al.* 1999; Sharpley *et al.* 1999), due to the high percentage of land covered by crops in most watersheds and the heavy use of fertilisers in modern intensive farming (Garnier *et al.* 1999). The complexity of the physical phenomenon, the involvement of a wide range of physical and chemical parameters, the need to generate results in different areas and the cost of the field campaigns require models that are capable of reproducing and predicting environmental impacts so that mitigation measures can be devised (Saloranta *et al.* 2003).

The WFD requires the integration of modelling experience and tools in order to couple the effects of point and non-point pollution sources (Horn *et al.* 2004). Separate analyses of point and non-point pollution sources do not allow for the in-depth analysis requested by the WFD, but the adoption of fully integrated modelling approaches have drawbacks associated with efforts to monitor, control, and access information by the different entities in a catchment. Several works in the literature highlight the same problems associated with developing an integrated modelling tool (Achleitner *et al.* 2007; Dorner *et al.* 2007; Letcher *et al.* 2007; Xu *et al.* 2007; Benedetti *et al.* 2008).

The main issues associated with integrating efforts in a catchment include the following.

- The responsibilities for planning and managing SSs, WWTP and water bodies are split between different authorities in most European countries (Fronteau *et al.* 1997).
- The models for the different sub-systems have been developed independently. Thus, different concepts, model approaches and different state variables have been used to describe processes in the different sub-systems, inhibiting efforts to link the models together (Rauch *et al.* 2003).
- The data requirements increase dramatically with the inclusion of more and more sub-systems. Usually, only key parameters are calibrated while default values are used for the other parameters. The uncertainties in these estimations are propagated through the integrated

models since each downstream model uses the outputs of the upstream model as an input (Freni *et al*. 2009, 2011).

- The complexity of a given model introduces uncertainties in the modelling process that, sometimes, are not clearly identifiable and assessable (Mannina & Viviani 2010).
- Such approaches are usually computationally demanding, often requiring the definition of specific *ad hoc* models able to improve such aspects (Fu *et al*. 2010).
- System complexity take as a consequence difficulties in the definition of reliable parameters values; such a consideration took to the investigation of probabilistic models giving the advantages of not focusing on single deterministic values of the parameters and of providing probabilities associated to specific model responses (Benedetti *et al*. 2010).

Fully integrated modelling approaches that consider both point and non-point sources in a detailed and satisfactory way have, as far as the authors know, been rarely applied as a result of the various challenges discussed above. Therefore, there is a lack of integrated modelling tools that consider all four sub-systems of a catchment (SS, WWTP, RC and RWB).

The aim of this study was to understand the impact of point and non-point polluting sources on RWB quality state, to investigate if integrated modelling approaches have to consider both polluting sources or if common simplifications proposed in literature can be applied.

In order to reach the aim of the study, a complex rural, semi-urbanised catchment was considered and an extensive monitoring programme was carried out to collect data from SSs, wastewater treatment plants and a river reach during both dry and wet weather periods. In this study a combination of detailed/commercial models (Figure 1) were assembled and applied to the experimental case study in order to evaluate the reliability of such modelling tools and which had the most widespread availability and applicability. First, the SS was simulated by means of the Storm Water Management Model (SWMM) in order to simulate the quantity and quality of the water in the sewer networks. The WWTP processes were simulated by means of GPS-X software. Both of the systems were analysed on a sub-hourly scale in order to provide a detailed analysis of the propagation of urban pollution to the receiver. Finally, the

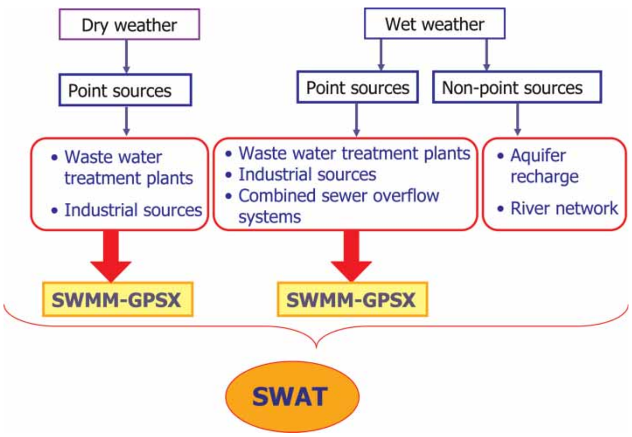

Figure 1 | Schematic diagram showing the integrated modelling approach.

Soil and Water Assessment Tool (SWAT) was applied to analyse and quantify the pollution dynamics of the basin considering the distribution and transformation of the pollution delivered from the urban areas.

METHODS

As discussed above, the entire water system of the basin was modelled by using different models for each system component: for the SS, WWTP and RWB we used SWMM, GPS-X and SWAT, respectively. SWMM (5.018 version) was used to simulate the urban drainage network; this model allows the user to select different mathematical models to describe the runoff formation and propagation in SS (Huber 2001). Also, different solvers for the resulting equations can be chosen according to the peculiarities of a given case study. A distributed 'non-linear reservoir' was adopted to simulate the surface runoff, taking into account the surface storage, as an initial hydrological loss, and the infiltration phenomena using the Horton equation. Rainfall–runoff routing was solved by coupling the continuity equation with the Manning equation, thereby obtaining a non-linear reservoir scheme. This approach is used separately on the pervious and impervious parts of the system, with the only difference being that infiltration is not applied to the impervious part of the catchment. The runoff delivered by the two parts of the catchment is routed to the drainage system.

The complete one-dimensional De Saint Venant equations were used to simulate the propagation into the SS by adopting an iterative explicit mathematical solver. A water quality module was used to simulate the build-up and wash-off of pollutants from the catchment surfaces, where the build-up was simulated by an exponential function (Alley & Smith 1981) and the solid wash-off, caused by overland flow during a storm event, was simulated using the formulas proposed by Jewell & Adrian (1978). The propagation of pollutants in the drainage system was simulated with a simple transfer function that accounts for the water flow velocity but neglects sediment transport and pollutant transformations in the sewer pipes (Campisano *et al.* 2004, 2006; Freni *et al.* 2010a).

The WWTPs were simulated with the GPS-X software (Hydromantis 2003). More specifically, such software is designed to simulate several WWTP processes; it was made by packages that implement different mathematical models to simulate the WWTP units. The models employed to simulate the WWTP included the Activated Sludge Model No. 1 (ASM1) for the biological processes (Henze *et al.* 2000), and the model by Takács *et al.* (1991) to simulate the physical processes of the secondary clarifier. In particular, the biological processes that were accounted for included the growth and decay of biomass, the ammonification of organic nitrogen and the hydrolysis of particulate organic matter. The Monod relationship was used to describe the growth rate of both heterotrophic and autotrophic organisms (Meltcalf & Eddy 2003). The chemical oxygen demand (COD) was used to define the carbonaceous material as it provides a link between electron equivalents in the organic substrate, the biomass and the oxygen utilised. Furthermore, mass balances can be formulated in terms of the COD. The carbonaceous material in the ASM1 model is divided into biodegradable COD, non-biodegradable COD (inert material) and biomass. In ASM1, the COD is subdivided based on (i) solubility, (ii) biodegradability, (iii) biodegradation rate and (iv) viability (biomass).

One of the physical processes that were taken into account was the solid sedimentation in the clarifier. According to the model proposed by Takács *et al.* (1991), the settler is divided into several layers and the mass balances between the layers were used to evaluate the profile of the solids throughout the settler. The clarifier models were based on settling functions, which evaluate the settling velocity of the particles, which depends on the concentration of the solid. Four types of settling were considered (Takács *et al.* 1991): discrete particle settling (the solids settle as individual entities), flocculent particle settling (typical for primary clarifiers and for the upper layers of secondary settlers), hindered settling (where inter-particle forces hinder the settling process), and compression settling (where the mass of the particles was compressed).

The SWAT model (Arnold *et al.* 1993, 1998; Neitsch *et al.* 2001) has been used in order to simulate both the qualitative and quantitative terms of hydrological balances on a catchment scale. It is a spatially continuous hydrological model that operates on a daily time step on a catchment scale, developed by the Agricultural Research Service at the US Department of Agriculture (USDA). Its purpose is to simulate the water, sediment and chemical yields of large river basins and determine the possible impacts of land use, climate changes and watershed management. SWAT can also handle the discharges of point sources (Neitsch *et al.* 2001).

SWAT has been used in Europe for several applications (Krysanova *et al.* 1999; Eckhardt *et al.* 2002; Grizzetti *et al.* 2003); many of these applications are summarised by Gassman *et al.* (2007). Some applications included predicting the transport of sediments and nutrients during water routing in Mediterranean areas (Bouraoui *et al.* 2005). Moreover, the impacts of forestry and agricultural activities on water quality and quantity have been analysed. Also, water budgets at the regional scale have been evaluated to provide insight into the relative importance of different flow components.

In SWAT, the catchment is divided into multiple subbasins, which are then further sub-divided into hydrological response units (HRUs). These units consist of homogeneous land use, land management and the soil's characteristics.

The hydrologic model was based on the water balance equation of the soil profile where the simulated processes include precipitation, infiltration, surface runoff, evapotranspiration, lateral flow and percolation. The soil profile was represented by 10 soil layers, a shallow aquifer and a deep aquifer. When the field capacity was exceeded in a given layer, the water was routed to the lower soil layer. If this layer was already saturated, a lateral flow occurs. From the bottom soil layer, percolation goes into the shallow and deep aquifers and the shallow unconfined aquifer contributes to the return flow.

The surface runoff model has been analysed by the Soil Conservation Service (SCS) curve number. The peak runoff is an indicator of the erosive power of a storm and is used to predict sediment loss. The sediment yield in SWAT was estimated with the modified soil loss equation, which was developed by Williams & Berndt (1977), using the surface runoff, peak flow rate, soil erosion, crop management, erosion control practice and slope length and steepness factors.

The uptake of nitrogen and phosphorus by plants was estimated using a supply and demand approach. A simplified EPIC model (Williams *et al.* 1983) was selected for the present application to simulate crop growth using unique sets of parameters for each crop, the natural vegetation (i.e. forest, grass, pasture) was also considered. Nitrogen and phosphorus can be lost in both particulate and dissolved forms. For this study, ArcView SWAT (AV-SWAT) (Neitsch *et al.* 2001) was adopted with the ArcView interface (Di Luzio *et al.* 2002).

The models were applied sequentially from the most upstream (simulating SS) to the RWB, using the output of one model to feed the downstream one as input. Particular care was given to the conversion between different sets of variables concerning water quality because SWMM and SWAT simulates total COD concentrations while GPS-X requires different fractions of the total COD (soluble, settleable, easily biodegradable, etc.); these fractions were assessed on the basis of a default COD fraction in the WWTP model. The RWB sub-model was fed considering the total COD and BOD calculated as output from GPS-X (for the WWTP output) and SWMM (for the CSO output).

THE CASE STUDY AND THE MONITORING CAMPAIGN

The Nocella catchment, which has an area of 99 km^2, is an agricultural and urbanised catchment located in the north-western part of Sicily, Italy (Figure 2). It receives approximately 750 mm of precipitation annually and 27% of this annual total is discharged (the mean annual runoff is 200 mm). The study was focused on the northern sub-catchment of Nocella basin (shaded in Figure 2), which has an area of

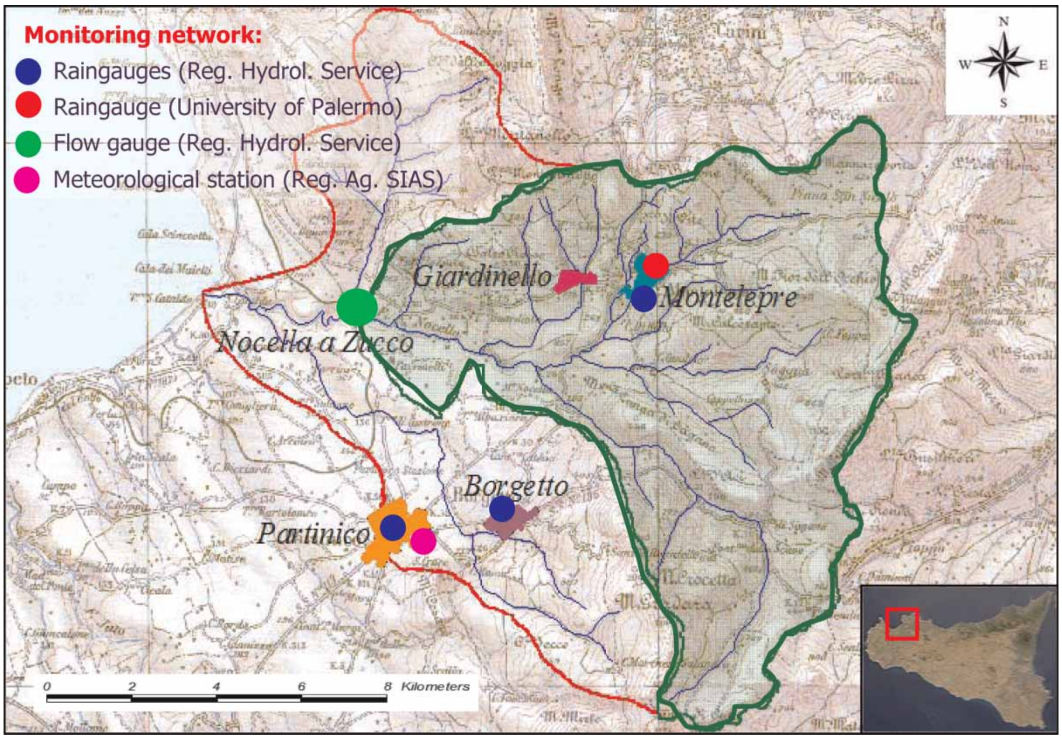

Figure 2 | Nocella catchment.

59 km^2 and is delimited downstream by a flow gauge station named 'Nocella a Zucco'.

The digital elevation model (DEM) used for this study was characterised by 20×20 m cells (Figure 3(a)). The area was assumed to be geologically homogeneous, the dominant rock type is limestone, which is covered with calcareous soils. The lithological composition is mainly provided by calcareous formations (Figure 3(b)). The climate is Mediterranean with hot, dry summers and a rainy winter season from October to April. The hydrological response of this basin is dominated by long dry seasons followed by wet periods. Also, there is a slow hydrological response because runoff is also present at the basin outlet during dry periods. Moreover, using remotely captured Landsat satellite images, the land cover map was obtained for the catchment based on the CORINE Land Cover Project 2000 (Figure 3(c)).

Regarding the inventory of point and non-point pollutants sources, the river receives waste- and stormwater from two urban areas drained by combined sewers and non-point source pollutants from agricultural cropland and zoo-technical farms. In particular, the Nocella River receives waste- and stormwater from the Montelepre catchment, which has a surface equal to 70 ha, and the Giardinello catchment, which has a surface of 45 ha and is drained by combined sewers. Both of these urban areas are characterised by concrete sewer pipes with steep slopes. The Montelepre sewer is characterised by circular and oval-shaped pipes with maximum dimensions equal to 100×150 cm. The SS serves 7,000 inhabitants and it is characterised by an average dry weather flow equal to 12.5 L/s and an average dry weather biochemical oxygen demand (BOD) concentration of 223 mg/L. The Giardinello sewer is characterised by circular pipes with a maximum diameter of 80 cm. The population served is about 2,000 inhabitants with an average dry weather flow equal to 2.5 L/s and an average dry weather BOD concentration of 420 mg/L. Each SS is connected to a WWTP that is protected by combined sewer overflow (CSO) devices. The WWTPs are characterised by simplified activated sludge processes with preliminary mechanical treatment units, an activated sludge tank and a final circular settler. Table 1 gives detailed specifications of the WWTPs.

Rainfall was monitored by four rain gauges that were distributed over the catchment (Figure 2): the Montelepre rain gauge is operated by Palermo University and it is characterised by a 0.1 mm tipping bucket and a temporal resolution of 1 min; the other three rain gauges (Partinico, Montelepre and Romitello) are operated by the Regional Hydrological Service and are characterised by 0.2 mm tipping buckets and temporal resolutions of 15 min.

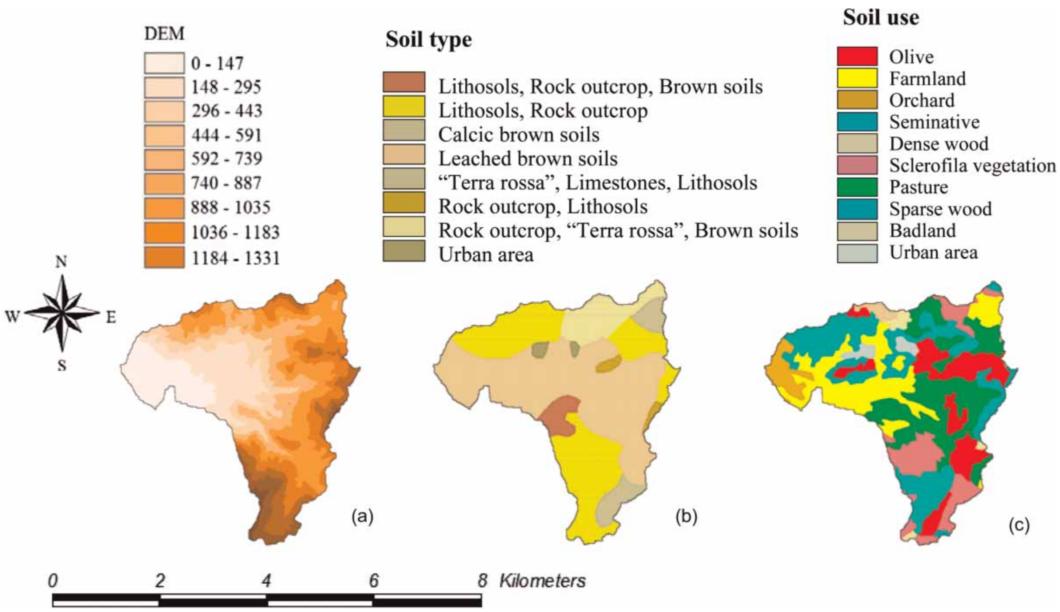

Figure 3 | DEM, soil type and land use maps for the Nocella catchment.

Table 1 | WWTPs characteristics

	Unit	Giardinello	Montelepre
Dry weather influent flow	m^3/h	45	9
Wet weather influent flow	m^3/h	112	27
Mixed liquor suspended solids	$kgVSS/m^3$	2.5	3
Returned activated sludge recirculation	m^3/h	45	9
Activated sludge tank volume	m^3	328	668
Settler volume	m^3	46	231

The flow gauge 'Nocella a Zucco', located at the basin outlet (Figure 2), is characterised by an ultrasonic level gauge, with a temporal resolution of 15 min, that is operated by the Regional Hydrological Service. The instrumentation was integrated by Palermo University by installing an area-velocity probe that provided the water level and velocity with 1 min temporal resolution and an automatic 24-bottle water quality sampler. Also, the daily maximum/minimum air temperature, mean values of the wind speed, solar radiation and relative humidity were recorded at one meteorological station, Partinico, located near the catchment and operated by the regional agency SIAS (Servizio Informativo Agrometeorologico Siciliano) (Figure 2).

Each urban drainage system (SS, CSO and WWTP) was monitored by equipping the different systems with *ad hoc* instruments. More specifically, flow measurements were recorded using area-velocity probes with a 1 min temporal resolution, which provided the inflow and outflow volumes for each element in the system. Water quality sampling was performed by automatic 24-bottle water quality samplers and grab sampling; the pollutant loads and treatment efficiencies were then defined. Dry weather automatic sampling was performed on hourly time steps; the wet weather samples were taken every 15 min for the urban drainage systems and every 20 min in the river. This delay accounts for the hydraulic distance between the urban areas and 'Nocella a Zucco' station (18 km downstream from the Montelepre WWTP and 15 km downstream from the Giardinello WWTP), which was expected to dilute and reduce the polluted load coming from the urban areas. Monitored water quality parameters that were measured include the total suspended solids (TSS), BOD, COD, ammonia nitrogen ($N\text{-}NH_4$), total Kjeldahl nitrogen, phosphorus (P) and, for the river sample, the dissolved oxygen.

The monitoring campaign started in December 2006 and is still in progress (Freni *et al.* 2010b). Rainfall and discharge monitoring has been carried out continuously, while water quality measurements have been taken during specific periods.

- Dry weather water sampling has been performed in five one-day campaigns on 13 April 2007, 10 May 2007, 1 June 2007, 14 February 2008 and 24 March 2008. For each campaign, 24 h samples were taken each day in the monitored cross-sections of the urban drainage system and the river.
- Seven rainfall events were monitored between April 2007 and May 2008, as shown in Table 2. For these events, 24 bottle samplers were automatically activated by the Montelepre rain gauge to start sampling immediately at the beginning of the rainfall event, with the exception of the sampler located at the basin closing cross-section, which was programmed to start sampling 20 min after the beginning of the rainfall event in order to take into account the natural catchment concentration time.

The water quality parameters that were monitored include the pH, electrical conductivity, BOD, COD, ammonia nitrogen, nitrite plus nitrate, nitrogen, suspended solids, total phosphorus and ortho-phosphate, which can be used to describe the physical, chemical and microbiological characteristics of the river water.

MODEL APPLICATION AND RESULT DISCUSSION

As discussed above, the SWMM and GPS-X models were used to define the point pollution sources of the urban drainage system, CSOs and WWTP outflows.

Assuming that the catchment geometry (area, average slope, catchment average width) and impervious area were known and not subjected to calibration, each sub-catchment was fully characterised by seven calibrated parameters. The water quality module was defined by four parameters for each type of land use, while the propagation through the sewer was fully defined by the pipe roughness, which could be defined for each pipe.

Table 2 | Main features of monitored rainfall events

	Event 1 21/04/07	Event 2 02/06/07	Event 3 05/03/08	Event 4 06/03/08	Event 5 24/03/08	Event 6 27/04/08	Event 7 03/05/08	Dry Weather
Rainfall duration (min)	260	780	1,080	630	190	130	350	–
Rainfall volume (mm)	8.3	18.4	7.2	17.6	36.8	23.0	19.2	–
Rainfall max. intensity (mm/h)	13.6	8.8	5.6	12.3	36.4	45.0	18.2	–
Rainfall av. intensity (mm/h)	2.0	1.6	0.4	1.6	12.2	11.1	6.2	–
ADWP (h)	1,268	642	260	8	485	79	135	–
SS No. of water quality data points	48	48	48	24	42	40	36	48
CSO No. of water quality data points	48	48	48	24	34	38	40	48
WWTP No. of water quality data points	24	24	24	12	24	48	24	144
RWB No. of water quality data points	72	108	108	48	48	64	72	72

SWMM is a distributed model and the parameters were calibrated in a lumped way by assuming that the parameters listed above were constant in each urban area. This simplification depends on the availability of a single measuring station for each urban area. Each urban area was characterised by seven hydrologic parameters, one hydraulic parameter for the drainage system and four parameters for the water quality (Table 3). These parameters were initially subjected to sensitivity analysis, where the ranges of the parameters were determined using the literature (Huber 2001).

The model proved to be largely insensitive to infiltration parameters and such parameters were not calibrated in subsequent tests. The sensitive parameters were calibrated using the available data set and maximising the Nash–Sutcliffe criterion (Nash & Sutcliffe 1970). The water quantity modules were calibrated first and then fixed as the water quality modules were calibrated. No validation steps were performed due to the small available dataset. In all of the SWMM simulations, 1 min time steps were used for the runoff generation and water quality processes on the catchment surface, while the flow propagation in the SS was analysed with a time step of 5 s to account for the faster temporal variability of dynamic processes in a sewer during flood propagation.

Table 3 | SWMM parameters subjected to sensitivity analysis (against sewer outflow BOD concentration): underlined parameters have been fixed to average values because the model is marginally sensitive to their variation

		Montelepre		Giardinello	
Parameter	**Sensitivity variation range**	**Sensitivity**	**Calibrated value**	**Sensitivity**	**Calibrated value**
Imp. area roughness (Manning)	0.01–0.03	0.45	0.022	0.55	0.018
Perv. area roughness (Manning)	0.02–0.1	0.22	0.035	0.17	0.038
Imp. area surface storage (mm)	0.1–2	0.36	0.8	0.42	0.6
Perv. area surface storage (mm)	0.5–4	0.12	2.1	0.23	2.5
Initial infiltration rate [mm/h]	*40–100*	*0.03*	*70*	*0.07*	*70*
Equilibrium infiltration rate [mm/h]	*8–25*	*0.02*	*15*	*0.04*	*15*
Infiltration decay constant [day^{-1}]	*0.001–0.05*	*0.01*	*0.02*	*0.02*	*0.02*
Sewer pipe roughness (Manning)	0.01–0.03	0.48	0.018	0.41	0.015
Unit accumulation rate [kg/(ha * d)]	0.5–12	0.56	5.2	0.35	8.5
Dispersion parameter (day^{-1})	0.05–0.8	0.31	0.18	0.32	0.25
Wash-off coefficient (mm^{-1})	0.01–2	0.38	0.55	0.42	0.67
Wash-off factor (h)	0.5–2.5	0.31	1.05	0.24	1.12

For the GPS-X, the models were first evaluated with dry-weather data and then verified with data gathered during the rain events. The model parameters were calibrated in three steps: a sensitivity analysis, trial and error calibration and mathematical optimisation. The sensitivity analysis was performed for all of the model parameters (19) in order to evaluate the most sensitive parameters. The initial set of parameters was determined using the values reported in the literature (Henze *et al.* 2000) at 20 °C. Then, a trial and error model calibration step was performed with a visual assessment of the curves of the measured and simulated values. Finally, mathematical optimisation was used to improve the agreement between the modelled and simulated values.

A good fit between the measured and simulated concentrations was obtained after modifying four of the 19 ASM1 parameters. Table 4 gives a list of the model coefficients that were adjusted during the calibration of the model. More specifically, using the kinetic and stoichiometric parameters by GPS-X, the following parameters were modified: the maximum heterotrophic growth rate, μ_H was increased from 3.2 to 6 day^{-1}, the heterotrophic decay rate was lowered from 0.6 to 0.3 day^{-1} and the heterotrophic yield was increased from 0.66 to 0.81. Such variations to

Table 4 | Modified ASM1 parameters for calibration (defaults have been used for parameters where calibrated values are missing)

Parameters	Symbol	Unit	Default value in GPS-X	Calibrated for Giardinello	Calibrated for Montelepre
Stoichiometric					
Heterotrophic yield	Y_H	–	0.666	0.80	0.80
N content of active het. biomass	i_{BH}	gN/gCOD	0.068		
N content of products from het. biomass	i_{PH}	gN/gCOD	0.068		
Fraction of het. biomass yielding particulate products	f_{PH}	–	0.08		
Autotrophic yield	Y_A	–	0.15	0.15	0.12
N content of active aut. biomass	i_{BA}	gN/gCOD	0.068		
N content of products from het. biomass	i_{PA}	gN/gCOD	0.068		
Fraction of aut. biomass yielding particulate products	f_{PA}	–	0.08		
Kinetic					
Max. het. growth rate	μ_H	1/day	3.2	6.0	6.0
Half saturation coefficient	K_{SH}	gCOD/m^3	5		
Het. decay rate	b_H	1/day	0.62	0.3	0.3
Anoxic hydrolysis factor	η_h	–	0.37		
Anoxic growth factor	η_g	–	1		
Max. hydrolysis rate	k_h	1/day	2.81		
Hydrolysis half sat. coeff.	K_x	–	0.15		
Ammonification rate	k_a	m^3/gCOD/day	0.016		
Max. aut. growth rate	μ_A	1/day	0.75	0.4	0.4
Half saturation coefficient	K_{NA}	gN/m^3	1		
Aut. decay rate	b_A	1/day	0.04	0.04	0.075
Switching functions					
Aerobic/anoxic growth	K_{OH}	g O_2/m^3	0.2		
Ammonia limit	K_{NH}	gN/m^3	0.05		
Nitrate limit	K_{NO}	gN/m^3	1		

the model parameters values were most likely caused by high content discharges of industrial wastewater. Nevertheless, the values of the parameters remained within the ranges reported in the literature (Henze *et al.* 2000).

The COD, TSS, $N\text{-}NH_4$ and BOD effluent concentrations were also considered and the GPS-X simulations employed a time step of 5 min.

The basic map inputs needed by the comprehensive SWAT model include the DEM, soil map, land-use/cover map, hydrographical map (stream lines) and climate information, which are shown in Figure 3.

All of the soil sample data sets for the Nocella catchment were used to derive the values for the physical–chemical parameters in the SWAT database, including: the land use group, depth of horizon, percentage of sand, silt, clay, organic carbon, bulk density, saturated hydraulic conductivity and water content. In addition, the interface included the following parameters: the land usage, soil type, weather, groundwater attributes, water use and management, soil chemistry, stream water quality and simulation period.

The basin was divided into seven sub-basins, and each of these were further divided into HRUs or lumped areas in a sub-basin, consisting of unique combinations of land usage, soil type and management (Neitsch *et al.* 2001), as required by the model.

The SWAT model was calibrated during the period from September 1998 to August 2001 using the daily discharge measurements collected at the 'Nocella a Zucco' station. For the same period and in the same river cross-section, water quality measurements were taken every month where the total nitrogen and phosphorus concentrations were recorded. This data collection was performed on a monthly basis, except in the summer when the discharge in the torrents stops. First, the water volume and flow rate were calibrated, followed by the nutrient quantities. Then the model was verified using the meteorological and quality field data collected from 1 September 2006 to 31 August 31 2008.

The climatic data was recorded on a daily basis, including: the precipitation rates, maximum/minimum air temperatures, mean values of the wind speed, solar radiation and relative humidity. More specifically, Thiessen polygons were used to evaluate the influence of each station on each particular sub-basin. Given the climatic features of the areas studied, the presence of a long dry season with an absence of stream flow surely affects the hydrological analysis. For this reason, the reference period of the annual analysis was chosen to include the rainy season, starting on 1 September of year N and ending on 31 August of year $N+1$.

The uncertainty in the model parameters, which were used in the subsequent calibration process, was assessed by performing a sensitivity analysis in order to reduce the number of parameters that influenced the model's predictions, the majority of the performance optimisation parameters were flow related. The sensitivity analysis was implemented for all of the 34 SWAT parameters that influenced the land and routing phase of the hydrological cycle. These parameters are identified in Table 5, along with their Monte Carlo sensitivity ranges and maximum efficiency values. The sensitivity analysis generated 10,000 uniform random sets of parameters and simulated the model using the sum of squared errors as a basic likelihood measure, following the Nash & Sutcliffe (1970) efficiency criterion. Since none of the field data parameters was available for the catchment studied, the sensitivity parameters were chosen according to suggestions in the literature (Bouraoui *et al.* 2005; Gikas *et al.* 2006). For the non-point source modelling, only information about the land usage was available. A simplification of the land management was thus established using 10 main classes. Moreover, the default values provided by the SWAT crop database (Arnold *et al.* 1998) were used. As mentioned previously, two WWTPs are present on the catchment (Montelepre and Giardinello) that treat the wastewater for a population of about 12,000 people. Since no field data of the time series of discharges and nutrient loads were available for the calibration period of these point sources, synthetic data from the previously calibrated models, that is, SWMM and GPS-X, was used as the input for the SWAT propagation model.

The model's calibration results were used to evaluate the agreement between the model and the measured data. Then, the calibrated models were used for evaluating the affects of the point and non-point pollution sources on the river quality.

Figures 4 and 5 show calibration examples for the Montelepre and Giardinello urban drainage systems for the

Table 5 | SWAT parameters used for sensitivity analysis

Parameter	Sensitivity range	Calibrated values
SURLAG – surface runoff lag coefficient	0–4	2
CN_2 – SCS runoff Curve Number	60 ÷ 75	63
CH_K_1 – hydrologic conductivity into the channels (mm h^{-1})	0 ÷ 150	150
ALPHA_BF – baseflow factor for bank storage (days)	0–1	0.5
SOL_BD – Moist bulk density (g cm^{-3})	1–10	6
RCHRG_DP – deep aquifer percolation fraction	0–1	0.05
SMFMX – maximum melt factor (°C^{-1} day^{-1})	0–10	6
SMFMN – minimum melt factor (mm °C^{-1} day^{-1})	0–10	6.5
SOL_Z – depth from soil surface to bottom of layer (mm)	1–20	10
GWQMN – min. depth of water in soil for baseflow to occur (mm)	0 ÷ 5,000	0
GW_DELAY – Groundwater delay time (days)	0–50	6
CH_N – manning *n* for the main channel	0–20	10
SOL_AWC – available water capacity (mmH_2O/mm soil)	0.10 ÷ 0.30	0.22
SHALLST initial depth of water in the shallow aquifer (mm)	0.5–6,000	0.7
ESCO – soil evaporation compensation factor	0 ÷ 1	0
OV_N – Manning *n* for overland flow	0–20	15
SOL_ZMX maximum routing depth of soil profile (mm)	0.001–3,000	20
LAT_TTIME – lateral flow travel time (days)	0–20	3
SOL_K – saturated hydraulic conducibility (mm h^{-1})	0.1 ÷ 0.2	0.16
GW_REVAP – groundwater revap coefficient	0.02 ÷ 0.2	0.02
DDRAIN – Depth to subsurface drain (mm)	0–1,000	25
EPCO – plant uptake compensation factor	0–1	0.2
TDRAIN – time to drain soil to field capacity (h)	0–84	24
EVRCH Reach evaporation adjustment factor	0–1	1
SOL_ALB moist soil albedo	1–40	30
GDRAIN drain tile lag time (h)	0–1,000	1
BLAI maximum potential leaf area index	1–100	30
REVAPMN threshold depth of water for 'revap' or percolation to occur (mm)	0–500	1
ALPHA_BNK baseflow factor for bank storage (days)	0–1	0.1

rainfall event on 9 August 2008: the figures show a good agreement between modelled water flows and the measurements at the SS outlet even for a multiple peak event, which is usually harder to be calibrated; also, the BOD concentrations were accurately modelled. There was only minor agreement for the WWTP outflow, but the model is still adequate for practical applications. The graphs demonstrate the damping capacity of WWTPs, which performed well even when the inflow polluting loads were varying, as during rainfall events. The graphs show also that WWTPs return to stationary treatment conditions within a few hours of the end of the rainfall event. Such a result is likely to be due to the small size of the WWTPs that are indeed more flexible to inflow dynamic variation. The computed flows and pollution loads were input into the SWAT propagation model.

A comparison of the observed values and the values predicted by SWAT are shown for the calibration period, in terms of the flow rate, in Figure 6(a).

In general, the growth and recession curves of the hydrographs were correctly reproduced by the model, confirming that the hydrological response of the catchment is mainly due to the subsurface flows. Furthermore, simulations of the peak discharges agreed with the timing of the events, but the magnitudes were underestimated. These magnitudes strongly depend on non-linearities in the soil surface caused by the long dry periods of low-yielding ephemeral catchments; also, after wet periods, even large inputs of rainfall may produce little or no response at the catchment outlet. In addition, the results suggest that the daily precipitation is not able to accurately predict runoff

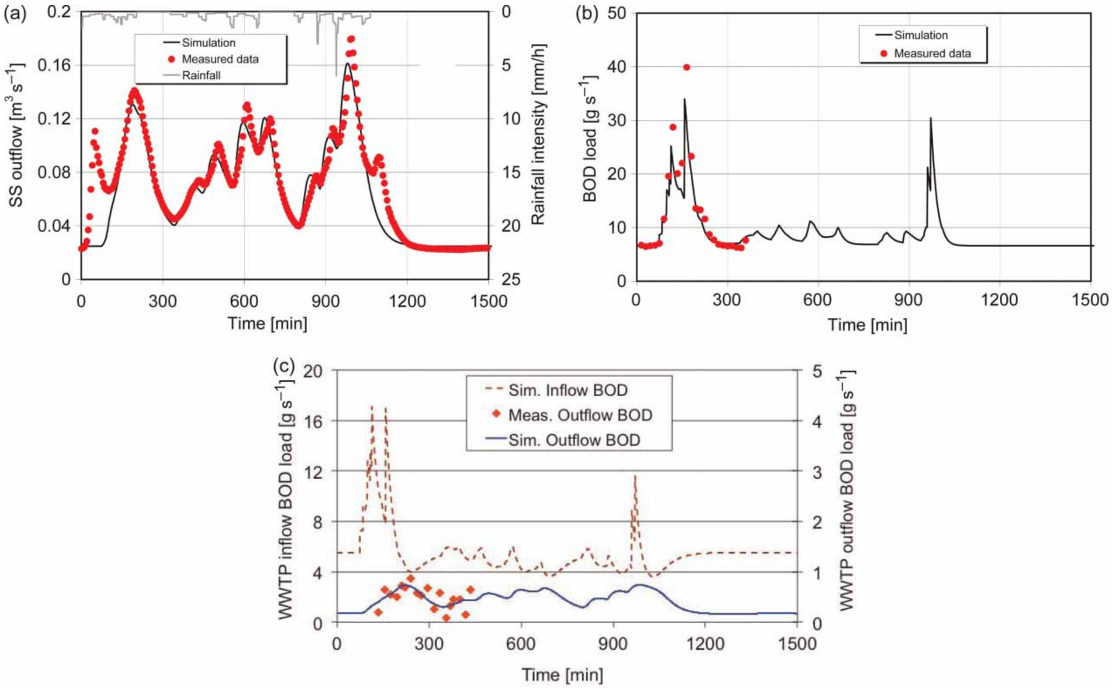

Figure 4 | Results of SWMM calibration for Montelepre urban drainage network (event 05/03/08): (a) comparison between measured and simulated flows at the SS outflow; (b) comparison between simulated and measured BOD concentrations at the SS outflow.

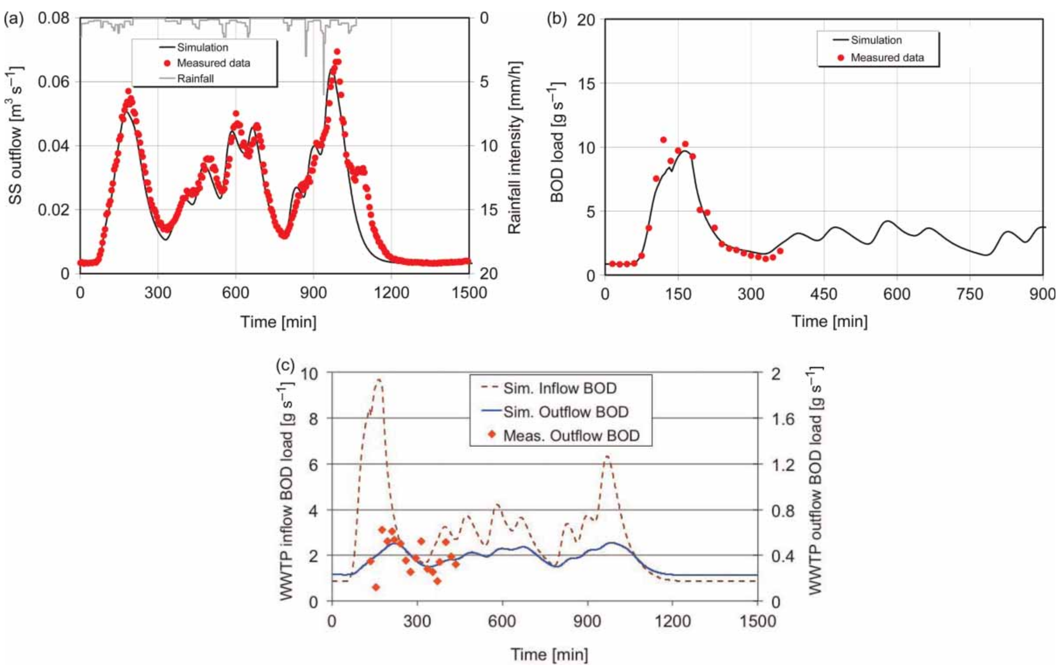

Figure 5 | Results of SWMM calibration for Giardinello urban drainage network (event 05/03/08): (a) comparison between measured and simulated flows at the SS outflow; (b) comparison between simulated and measured BOD concentrations at the SS outflow.

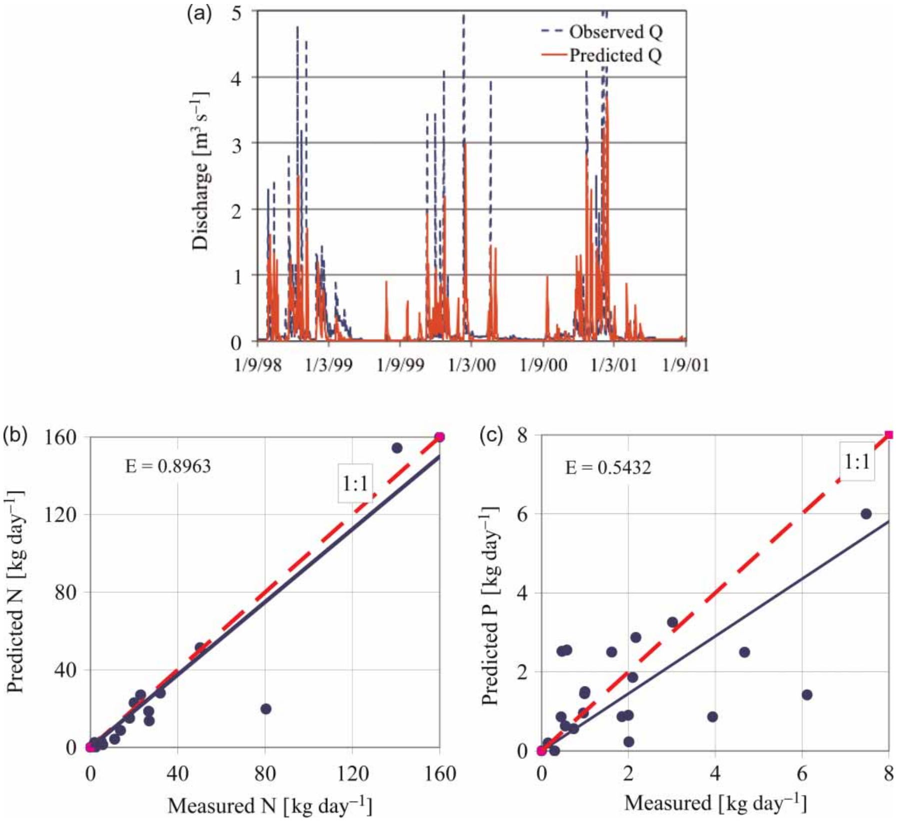

Figure 6 | Model calibration: scattergramms at Nocella a Zucco station.

events (Bouraoui *et al.* 2005). In many Mediterranean countries, runoff is generated by intense rainfall events. Conan *et al.* (2003) applied SWAT to a Spanish Mediterranean catchment and found that the quality of the precipitation data is of primary importance when modelling the peak runoff. Indeed, rain the intensity plays a key role in runoff generation in those semi-arid areas.

Scatter plots of the total nitrogen and phosphorus concentrations are reported in Figure 6(b) and (c). As shown by the figures, the model's predictions are in the range of the measured values; generally, an underestimation of the peak flows explains the underestimation of the corresponding nitrogen and phosphorus peaks. The correlation between the model and measurements for the volume is acceptable. Also, while the Nash–Sutcliffe efficiency coefficient is not high (0.43), it is positive and agrees with the values previously reported in semi-arid catchments (Candela *et al.* 2009). The correlations are better for the nitrogen and phosphorus discharges, reaching 0.54 and 0.89, respectively.

As discussed above, the model was verified using meteorological and quality field data collected from 1 September 2006 to 31 August 2008. The input model parameters used for this verification were those found during the calibration for both the point and non-point pollutants sources, as summarised in Tables 3–5.

The predicted daily discharges and total nitrogen and phosphorous concentrations are compared with the measured values in Figure 7(a)–(c). It is difficult to assess the ability of the model to determine the nutrient concentrations, as they were not systematically measured during the entire simulation period. Nonetheless, the model's predictions are in the ranges of the measured values, in general. It is notable that the total nitrogen discharge increased during the autumn–winter and decreased during the late spring–summer period, which is characterised by a small flow in the channels.

The Nash–Sutcliffe efficiency value could not be generated for the hydrological predictions because during the

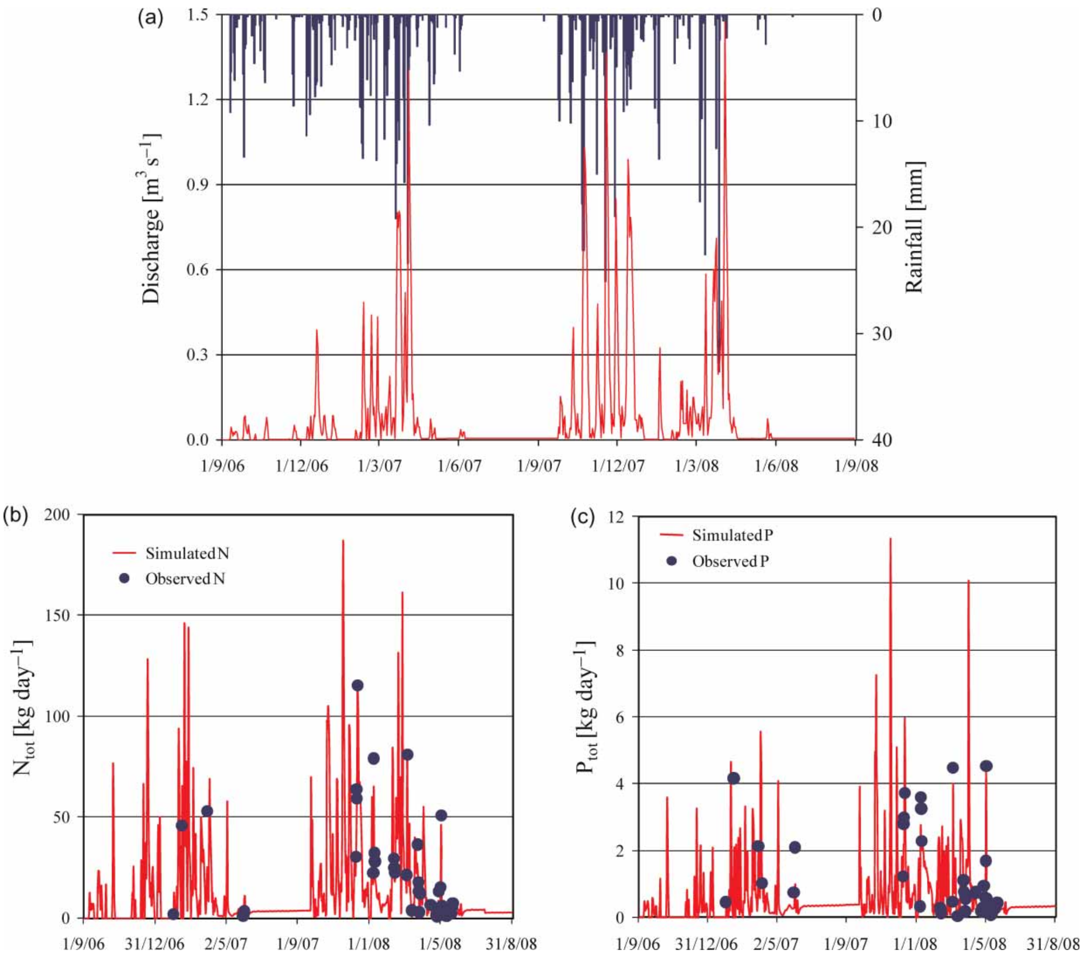

Figure 7 | (a) Predicted daily discharge, (b) measured and predicted total nitrogen and (c) total phosphorus at the Nocella a Zucco outlet.

period of measurement (September 2006–August 2008), there were no observed discharge values at the Nocella a Zucco gauging station.

Figure 8(a) and (b) show a comparison between the pollution contributions of urban areas and of the natural catchment in terms of the water volumes and nutrients for both of the considered hydrological years. As shown in Table 6, the mean annual outflow volume from the Nocella basin was equal to 9.10 Mm^3 in the analysed period.

As expected, a large part of the total volume for both of the hydrological years is generated by natural catchments, as opposed to urban areas. However, this is not always the case for the nutrient loads. In terms of total nitrogen and phosphorus polluting loads, the mean yearly polluting masses discharged by the RWB during the analysed period was equal to 92.2 for N and 1.5 for P. The contribution from urban areas was modest (17% for the N and 50% for the P) and, although it is smaller than the contribution from the natural catchment, it cannot be neglected when considering the pollution of the natural water body. Large nutrient loads from urban areas, especially phosphorus, can result in simplified WWTP architectures without the presence of specifically oriented treatment processes. In terms of the nitrogen content, natural areas provide more than 85% of the total polluting load in the RWB. It is likely that the nitrogen load mainly depends on agricultural inputs due to the intensive cropping in the region. Moreover, the contributions from the different sources to the total load of the river depend on the

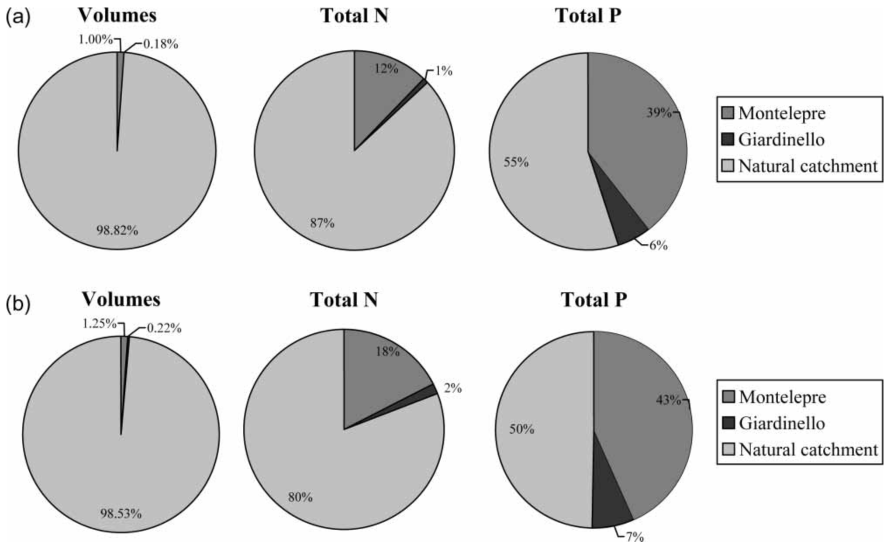

Figure 8 | Comparison between volumes and nutrient contributions of urban and natural areas (a) for the hydrological year 2006/07 and (b) for the hydrological year 2007/08.

Table 6 | Comparison between volumes and nutrient contributions of urban and natural areas for the hydrological year 2006/07 and 2007/08

	2006/07			2007/08			Mean value		
	Vol. (Mm^3)	N_{tot} (tons)	P_{tot} (tons)	Vol. (Mm^3)	N_{tot} (tons)	P_{tot} (tons)	Vol. (Mm^3)	N_{tot} (tons)	P_{tot} (tons)
Urban areas	1.13	12.20	0.63	1.43	18.98	0.98	1.28	15.54	0.75
Natural areas	7.84	75.36	0.63	7.80	77.88	0.78	7.82	76.62	0.71
Total area	8.97	87.56	1.26	9.23	96.76	1.66	9.10	92.16	1.46

inputs and on the ability of the basin to remove nitrogen during its transport from land to water.

CONCLUSION

An integrated river-basin scale modelling approach, including non-point sources and multiple urban areas, was evaluated. In particular, this paper explored the application of an integrated urban drainage model to a complex integrated catchment that is characterised by two urban areas and a natural catchment. Each urban area is served by combined SSs and a WWTP. The application entailed the implementation of extensive monitoring, which required data collection for the two urban drainage systems and the RWB. The proposed model was capable of reproducing processes within and between different sub-systems of the river basin, including urban areas with SSs and CSOs, WWTPs as well as runoff and pollutants from agricultural and natural areas.

The model's results can be summarised as follows.

- In this study the performance of the SWAT model was explored. The model was calibrated and then validated, obtaining satisfactory performance. The estimation of loads from non-point sources was difficult due to limited data availability. Thus, it was only possible to include constant non-point pollution concentrations. In spite of these limitations, the model gave a good prediction of the dynamic of flow generation and was able to predict the range of nutrient concentrations in the surface water.
- The obtained results emphasise the necessity of such an integrated model approach; the integration of the SWAT model with the SWMM and GPS-X models can greatly contribute to the improvement of flow simulations and, consequently, the prediction of nutrient and sediment losses on a catchment scale.

- The contributions from urban areas to the polluting loads received by the RWB are important, especially in terms of the shock impact of intermittent urban drainage discharges of untreated sewage.
- This study demonstrates that point and non-point pollution sources have to be analysed contiguously, because they affect both the short-term RWB water quality (during or immediately after the rainfall event when the shock polluting impact off urban areas is relevant) and the long-term RWB water quality (the inter-event time when non-point sources still release pollution loads and urban areas contribute WWTP dry weather discharges).

The proposed model is a promising tool for the investigation of water quality problems and the interactions between different sub-systems on a river basin scale. Indeed, the use of this integrated model-based approach may support water managers in decision-making about which are good control strategies in scenario analysis by allowing the simulation of different alternatives and choosing the one that better fits the manager's primary objectives.

The results provided in this study are naturally dependent on the specific case study and they should be confirmed by other applications; nevertheless, they provide a useful insight into pollution propagation in river basins.

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