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Simulation by the IPTM-CS model of pesticides found in surface water and groundwater of the Fucino Plain, Italy

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Abstract The agricultural area of the Fucino Plain, Italy, has recently had a transition to intensive agriculture characterized by increased horticultural production with a double or sometimes a triple harvest, and accompanied by high water demand and wide use of pesticides. Water sampling conducted in 2004 and 2006 showed the presence of pesticides, mainly Linuron, Dicloran and Carbaryl. By taking into account pesticide application, irrigation practice, rainfall, evapotranspiration and soil characteristics, mathematical simulations were conducted using the IPTM-CS pesticide transport model. The aim of the simulations is to verify if measured pesticide concentrations agree with a conceptual model based on the amount of pesticide application and its transport into the water system by runoff or infiltration. Simulations of Linuron, the use of which has been banned in Italy since 2005, showed a higher persistence. This pesticide is mobilized partly by runoff, while infiltration rates allow its transport to shallow groundwater in concentrations up to the limits specified by law.

Key words mathematical models; pesticides; runoff; unsaturated zone; groundwater pollution; Italy

INTRODUCTION

The agricultural area of the Fucino Plain, central Italy, has been studied in the last ten years from hydrological, hydrogeological, and agricultural points of view (Burri & Petitta, 1998, 2004; Petitta *et al.*, 2005, 2006), in order to develop a management model which could be applied by decision-makers and public authorities who are interested in the growing economy of this agricultural region. During the past 15 years, traditional farm crops, comprising mostly wheat, potatoes and sugar beet, have been replaced progressively with more profitable horticultural crops. This transition to intensive agriculture, characterized by a double and sometimes triple harvest, has been accompanied by high water demand and by wide use of pesticides, which have been found in surface water and groundwater during seasonal surveys in 2004 and 2006.

There is a need to clarify whether surface runoff and/or infiltration processes allow pesticides to reach canals and groundwater and if there is an accumulation of pesticides either in soil or in groundwater. Due to the lack of field data for several parameters influencing the process of migration of pesticides in soil and water, simulations were conducted to test if the measured concentrations of pesticides are consistent with infiltration through the soil and/or surface runoff, taking into account agricultural practices, climatic conditions, and soil characteristics. The IPTM model, derived from the physically-based analytical model of Hantush & Mariño (1996), was used with a new Windows-based interface (IPTM-CS) for the simulations. This is a hybrid time-continuous and space-discrete semi-discrete model, which takes advantage of both analytical and numerical methods. The model is able to deal with physical and biochemical processes related to one-dimensional vertical water flow and three-phase pesticide transport in the vadose zone (separated into a root zone and in a deep vadose zone), where a complete mixing is assumed (Chu & Mariño, 2004, 2007).

The long-term goal of this research is to develop a new integrated management model for both irrigation and pesticide use in the Fucino Plain. In this paper, a preliminary conceptual model of the transport and fate of pesticides in the Plain is developed from simulation results.

HYDROGEOLOGICAL SETTING AND PESTICIDE USE

The Fucino Plain (200 km^2 in area) was the largest lake in central Italy, totally reclaimed in the 1800s for agricultural purposes, with an extent of 130 km^2 (Fig. 1). The fractured and karstified carbonate aquifers surrounding the Plain are drained at their boundaries by high-discharge springs and streambed springs, which ensure steady discharges even during the dry season (Burri & Petitta, 2004). The aquifer of the Plain, which has an extremely variable permeability, is supplied in part by groundwater seepage from the carbonate ridges and in part by direct infiltration from precipitation. The long-term water balance of the Plain shows 700 mm/year of precipitation, 450 mm/year of evapotranspiration, and consequently 250 mm/year of water excess in the October–March period (Burri & Petitta, 2004). As a consequence, crop irrigation was based on a sustainable use of surface water and, increasingly, groundwater through the 1980s. During the past 15 years, the concurrence of natural causes (low precipitation and aquifer recharge accompanied by a decrease in discharge from springs) and of anthropogenic factors (increased pumping and water requirements for irrigation) have caused a significant water shortage in the summer (Burri & Petitta, 2004). The transition from water abundance to water scarcity, coupled with an incorrect perception of water inexhaustibility, was responsible for a slow response to the signs of water and environmental imbalance in the water–man–agriculture system in the Fucino Plain. After the recent transition to an intensive agriculture, the decreasing discharge in the canals nullifies the dilution of the pollutants circulating in surface waters, which are mainly residues of fertilizers (Petitta *et al.*, 2005) and pesticides. In this framework, surveys conducted on both surface water and groundwater have shown the presence of pesticides (Table 1), mainly Linuron, Dicloran, and Carbaryl, with concentrations ranging from 2.8 to 0.02 μg/L in surface water, and from 0.5 to 0.03 μg/L in groundwater in 2004 (Ruggieri *et al.*, 2005). In 2006, only Linuron and Dicloran were found in surface waters; concentrations ranged from a maximum value greater than 13 μg/L to values of 0.03 μg/L, which confirmed, in particular, the occurrence of high levels of Linuron.

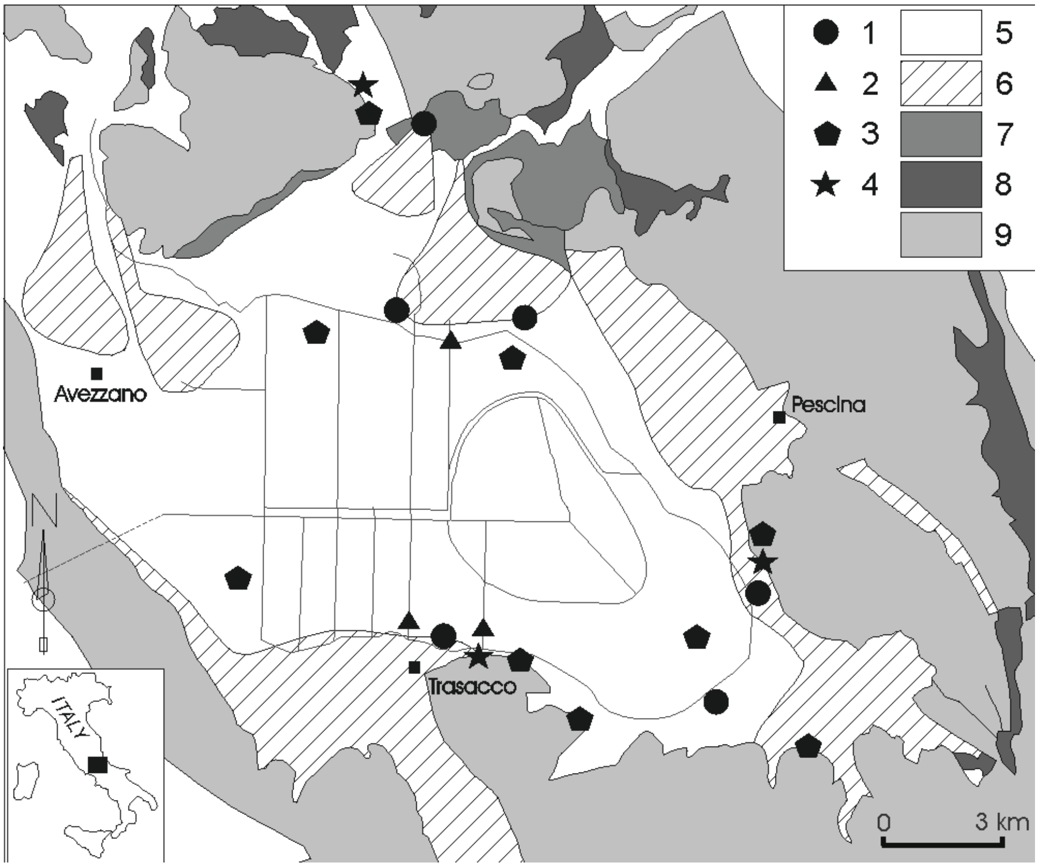

Fig. 1 Hydrological setting of the Fucino Plain. Main network of artificial canals is shown by black thin lines. 1: main springs; 2: main streambed springs; 3: public irrigation wells; 4: drinking water wells; 5: Plain aquifer, corresponding to the agricultural area; 6: fan and detrital deposits connecting carbonate aquifers to the plain aquifer; 7: ancient alluvial deposits (aquitard); 8: terrigenous deposits (regional aquiclude); 9: carbonate aquifers (recharge area of springs).

Table 1 Measured pesticide concentrations in water samples (35 samples in 2004, 20 samples in 2006). n.f.: not found.

Pesticide (in μg/L)		6/2004	9/2004	4/2006	6/2006	9/2006
Linuron	max.	2.81	0.07	11.02	13.13	0.17
	average	0.43	0.04	1.18	1.72	0.1
	min.	0.03	0.03	0.21	0.3	0.07
	occurrence	86%	20%	85%	100%	44%
Dicloran	max.	0.65	0.14	2.33	-	0.56
	average	0.15	0.05	0.46	0.08	0.08
	min.	0.02	0.02	0.03	-	0.06
	occurrence	17%	34%	35%	5%	38%
Carbaryl	max.	-	0.40	n.f.	n.f.	n.f.
	average	0.04	0.13	n.f	n.f	n.f
	min.	-	0.04	n.f.	n.f.	n.f.
	occurrence	3%	12%	-	-	-

Concentrations of pollutants are frequently higher than threshold values (0.1 μg/L in groundwater and surface water for human use) allowed by Italian law and European Union Directives (European Union, 1991, 2000; Gazzetta Ufficiale, 1999). As observed in 2004 and 2006, the pesticide occurrence in waters follows a seasonal cycle, with high concentration in late spring and early summer, due to the application in April, followed by a decrease (September) and by the total absence in winter. In groundwater, a seasonal cycle is not evident, due partly to the unsaturated zone transit time, but mainly to the dilution of infiltrating waters containing pesticides with groundwater coming from surrounding carbonate aquifers, where pesticides are absent.

In order to evaluate parameters required by the IPTM-CS model, data were collected by field and laboratory experiments (Petitta & Mariño, 2007), supplemented by reference data included in the latest software version. Simulations were conducted for a 10 000 m^2 study area under potato, which is the most common crop in the Plain, and represents 23% of the agricultural land use in the last 15 years (Burri & Petitta, 2004). Information related to field pesticide use and irrigation practices was obtained directly by interviews with farmers. Simulations were conducted for the herbicide Linuron, the herbicide most commonly found in waters, and considered one application at the beginning of April with a concentration of 1 kg/ha. The pesticide application is assumed to be instantaneous and under-canopy because it is applied mainly in non-growing periods, as pre-treatment or as pre-harvest.

Statistical data on pesticide use in the region show an average of 3 kg/ha during the last decade, with a rate of 0.5 kg/ha of herbicide in the Plain (Istat, 2004). Based on the amount of pesticides sold in the Plain in 2004, in relation to the area cultivated with potatoes, the application of Linuron is about 0.4 kg/ha. The amount of 1 kg/ha used in simulations is in relatively good agreement with these data and could be adopted as reference value for the potato crops.

Simulations were undertaken for the period 2001–2006 years, using a daily time step, in order to test if the concentration values measured in 2004 and 2006, both in surface waters and groundwater, agree with the proposed conceptual model. Effective precipitation was evaluated from daily precipitation values and daily evapotranspiration (Mintz & Walker, 1993). The permeability coefficient adopted for the soil was 1×10^{-5} m/s, both in the root and deep vadose zones, which reflects a sandy loam soil, with a runoff curve number of 86. The thickness of the root zone was assumed to vary between 30 and 70 cm, in order to test its influence on pesticide transport towards groundwater. For the first year simulated, initial pesticide concentration was considered to be zero, while for following years the concentration in the soil was that calculated at the end of the previous year.

SIMULATED INFILTRATION AND GROUNDWATER OCCURRENCE

Infiltration is responsible for pesticide migration through soil in recharged water and, consequently, for its occurrence in groundwater. Where the root zone is thin (30 cm), pesticide concentrations remain under the legal limit (0.1 μg/L) in the vadose zone at depths greater than 1 m, while between 0.5 and 1 m below the ground surface, simulated values of Linuron show levels around the limit allowed by law (Fig. 2). This

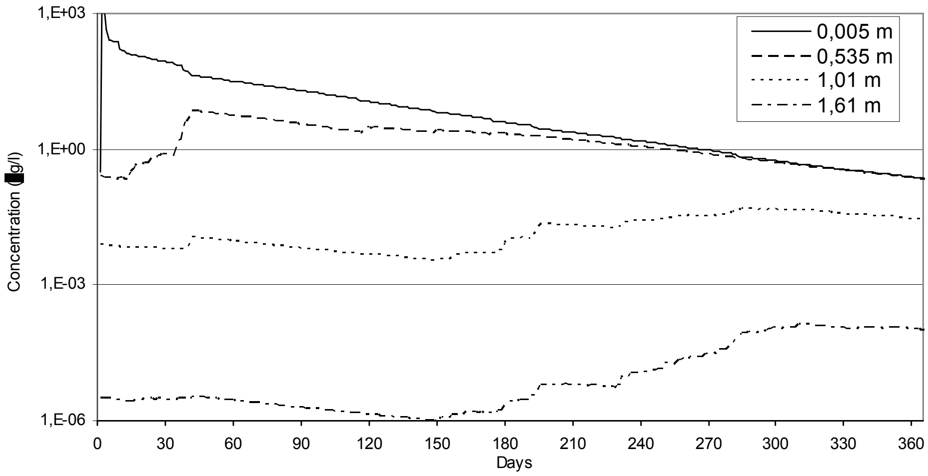

Fig. 2. Linuron concentration over time at various depths, in a sandy loam soil with a 30 cm root zone (year 2002–2003, starting from 1 April).

means that where the water table is located close to the surface, the migration of the contaminant to groundwater is possible throughout the year. In fact, recharge water from rainfall affects Linuron concentration in the soil sometimes during spring (May) and mainly in the autumn (October–January), and moves the pesticide from the root zone to the deep vadose zone and also below the groundwater.

However, natural oscillation of the water table has also to be considered. The water table reaches its highest level at the end of the recharge period, which corresponds with a high migration rate of the contaminant. In addition, a water table rise can contribute not only to the leaching of the contaminant arriving from the vadose zone, but to the dissolution of pesticide contained into the soil region newly involved in the saturated zone. This situation increases the risk of groundwater pollution, due to the combination of high vulnerability (water table close to the surface) and high hazard (high concentration of pesticide in the unsaturated zone, which is available for transport in groundwater).

In addition, a process involving small amounts of accumulation, depending on rainfall quantity and distribution in different years, has been observed in the study period. This happens particularly at a depth of 1 m (Fig. 2), where the final concentration at the end of the year is higher than the starting value. This process is more marked at deeper levels, and at 1.61 m below the ground surface, simulations suggest final concentrations are two orders of magnitude higher than the starting value. However, concentration at this depth is very low and cannot cause significant pollution.

A change in root zone thickness has a large influence on the infiltration process and consequently on the contaminant transport into groundwater. By increasing root zone thickness in simulations, significant differences in Linuron concentration were found (Fig. 3). Employing a 30-cm root zone, simulated pesticide concentration values at 1 m depth were approximately 0.1 µg/L, while with a 70-cm root zone, peak values were about 0.001 µg/L. In the latter case, the risk of contamination of groundwater is clearly very limited. Consequently, to assess the groundwater vulnerability, it is necessary not only to consider the total thickness of the unsaturated zone, but also to evaluate the root zone thickness.

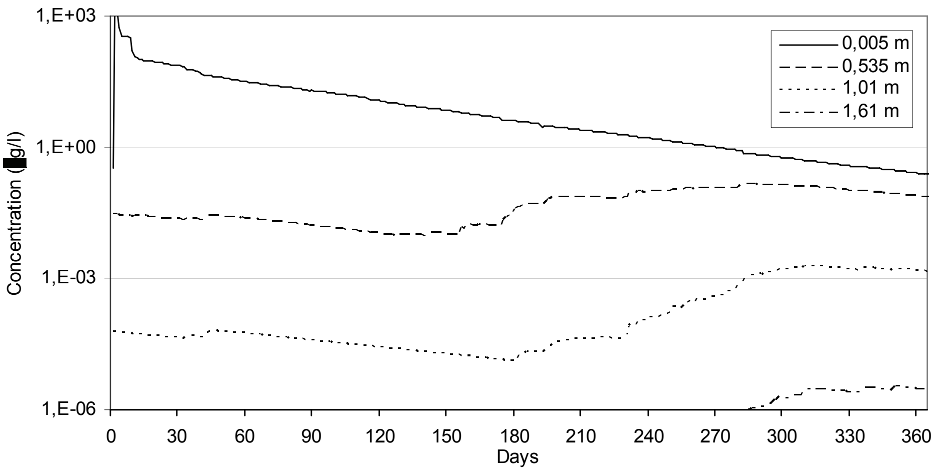

Fig. 3. Linuron concentration over time at various depths, in a sandy loam soil with 70 cm root zone (year 2002–2003, starting from 1 April).

Finally, simulations were conducted to evaluate the role of the irrigation process during summer. No significant changes in the contaminant concentration at different depths were found, showing the small importance of this factor in the transport of Linuron.

SIMULATED RUNOFF AND SURFACE WATER CONCENTRATION

Linuron can reach groundwater in significant concentrations only in specific and limited situations. Pesticides are found more frequently and in higher concentrations in surface waters than in groundwater, and contaminant transport is more easily accomplished by runoff processes in the surface hydrological network.

In order to evaluate the role of transport in surface runoff, simulations, employing a 30-cm root zone, were conducted to take into account the runoff generated by rainfall. Pesticide runoff is prevalent during rainfall events following pesticide application (2 April) but this gradually decreases during the year, depending on the amount of effective rainfall (Figs 4 and 5). Large differences in the amount of pesticide transported in surface runoff were simulated in different periods. During 2001–2004 no more than 2 g/ha of Linuron were mobilized by single rainfall events, while in 2004–2006 peaks of 10 g/ha were registered. The reason for these differences lies in the different distribution of rainfall immediately after pesticide application. Thus, when discrete rainfall events occur a few days after Linuron application, the runoff of the contaminant is greatly enhanced and high concentrations are observed in surface waters. In contrast, scarce or zero rainfall immediately after application favours the decay process and low concentrations of Linuron remain on the ground surface and the amount available to be transported during subsequent precipitation events is small.

A significant amount of pesticide may also be mobilized from the soil during autumn, when runoff increases. At this time, the amount of pesticide runoff is not as high as in late spring, but pesticide can be moved to the canals of the Plain by the abundant runoff. The soil saturation can influence the runoff process, as evident for

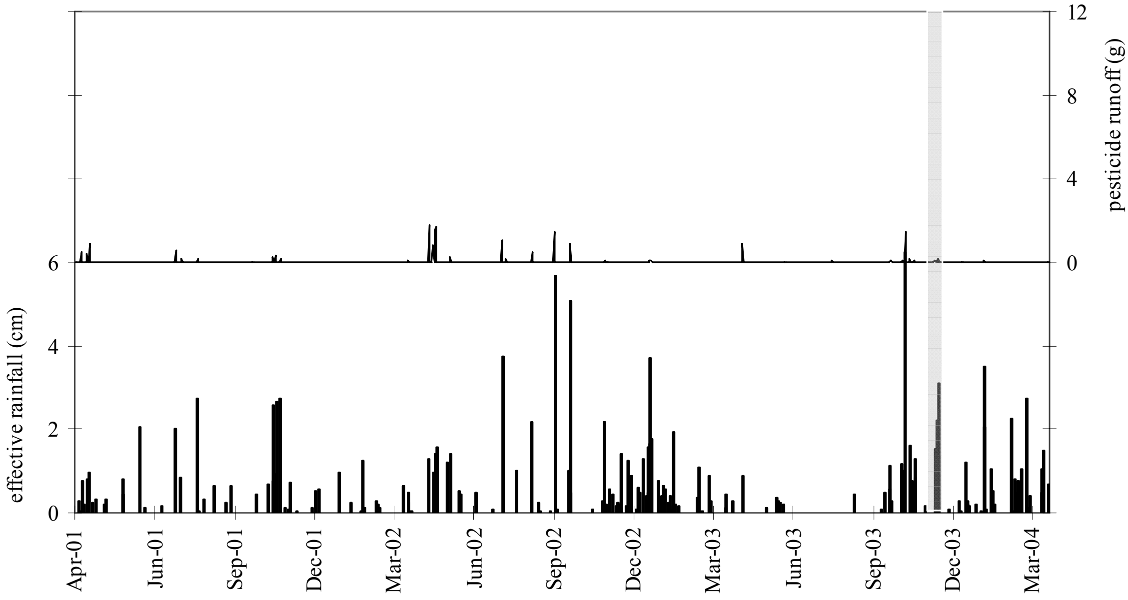

Fig. 4 Comparison between effective rainfall (rainfall minus evapotranspiration) and simulated pesticide runoff (2001–04). Grey area indicates the sampling period (see Table 2). The effects of doubling irrigation in June and July are simulated.

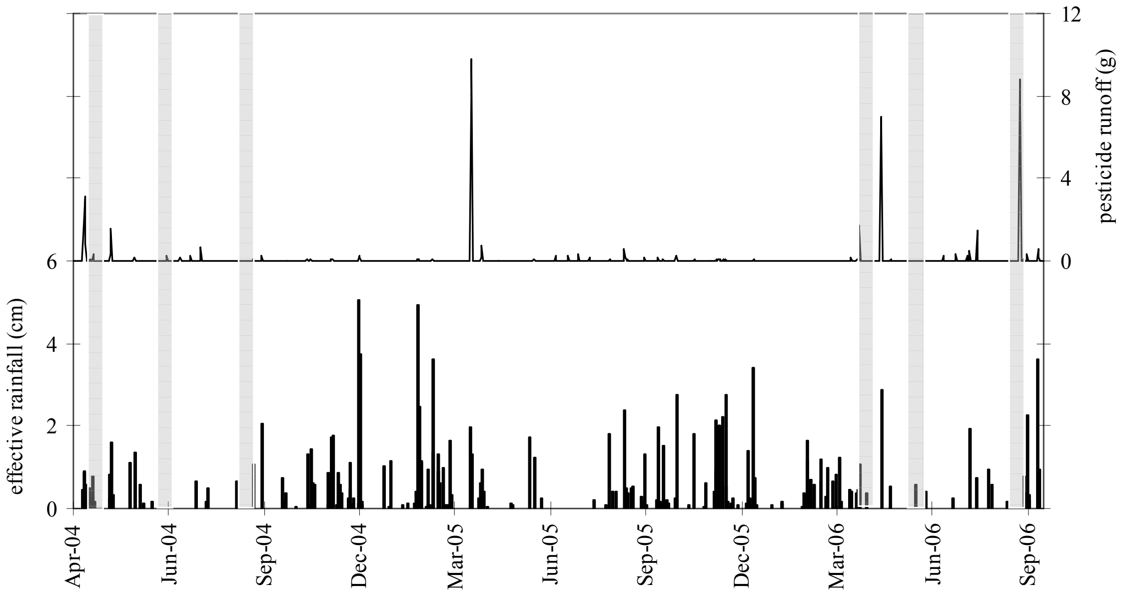

Fig. 5. Comparison between effective rainfall (rainfall minus evapotranspiration) and simulated pesticide runoff (2004–06). Grey areas indicate the sampling periods (see Table 2). The effects of doubling irrigation in June and July are simulated.

September 2006. In this case, rainfall events in September cause high pesticide runoff, because effective rainfall was absent during the summer and pesticide was available on the ground due to the low saturation of the soil.

Pesticide runoff is strongly influenced by irrigation practice and this factor was investigated by simulating the effects of a doubling in the irrigation rate reported by

Table 2 Comparison between simulated and measured Linuron concentrations in surface waters. Simulated values have been obtained considering the average runoff over 15 days (one week before and one week after sampling).

Sampling day	Pesticide runoff (g/ha)	Total pesticide runoff (g/d)	Discharge of water runoff (m^3/d)	Pesticide concentration (μg/L): Simulated	Measured
23/09/2006	0.74	162.8	172 800	0.94	0.07
15/06/2006	0	0	216 000	0.00	1.72
26/04/2006	7.004	1540.9	259 200	5.94	0.57
14/09/2004	0.068	14.9	233 280	0.06	0.04
30/06/2004	0.218	48.0	300 240	0.16	0.43
20/04/2004	0.175	38.4	345 600	0.11	0
01/12/2003	0.15	33.0	328 320	0.10	0

farmers (Figs 4 and 5). Results show for the period 2001–2004 that summer pesticide runoff is limited at the declared rates of irrigation (Fig. 4), but significant pesticide runoff occurred for June and July in simulations where the higher rates of irrigation were included. The simulated Linuron runoff was compared with pesticide concentrations found in surface waters during 2004 and 2006 surveys (Figs 4 and 5) taking into account the dilution provided by the different discharge levels in the canals. Of course, it was impossible to evaluate with high precision the time and amount of pesticide use on fields across the entire Plain; and sampling during surveys could not be representative of runoff generated by the same rainfall event in a study area of 200 km^2.

In order take into account possible shifts in actual pesticide application by farmers and the transit time of runoff waters into the Plain, simulations considered average conditions for 15-day periods (7-days before and after sampling). Simulation results (Table 2) are in good accordance with those from monitoring, especially for the summer and autumn of 2004. The model shows some discrepancies for 2006 surveys, where simulated values are higher than observed in two cases, and lower for June. Nevertheless, it can be confirmed that the conceptual model is consistent with simulations. Furthermore, despite of some discrepancies, the seasonal trends are the same for simulated and measured values, suggesting it is possible to replicate successfully the pesticide and water cycles of the Plain.

CONCLUSIONS

A preliminary conceptual model of the transport and fate of pesticides in the Fucino Plain has been implemented and validated by simulation using the IPTM-CS model. Preliminary attempts to simulate the pesticide Linuron in a sandy loam soil under potato cultivation, agreed with a conceptual model where pesticide transport occurs as a result of runoff and infiltration.

The infiltration process appears to be influenced mainly by root thickness, and contamination of groundwater occurs in the Plain only where the water table is very close to the ground surface (1 m below ground). Surveys results confirm that the threshold concentrations of Linuron may occur in groundwater through contributions from the unsaturated zone, in vulnerable areas.

Contaminant runoff can be considered largely dependent on single rainfall events and also on irrigation practice. Concentrations of Linuron found in surface waters are comparable with those simulated, especially when the difficulties of reproducing a process influenced by daily events are taken into account.

Simulations by the IPTM-CS model allowed the development of a conceptual model for pesticide transport in the Fucino Plain, which indicates that after Linuron application in early spring, contaminant runoff is prevalent until summer, when rainfall and high rates of irrigation may also facilitate pesticide runoff into surface waters. In autumn and winter, infiltration processes are prevalent and a water table rise may cause the occurrence of pesticide in shallow groundwater in concentrations higher than those permitted by law.

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