Contents

1 General context 29
1.1 Motivation and objectives 29
1.2 Legislation on groundwater nitrate pollution 31
1.3 Thesis organization 36
2 Modeling policies for nitrate pollution abatement. State of the art. 39
2.1 Economics and policies of nitrate pollution control 39
2.1.1 Introduction. Efficient allocation of pollution. 39
2.1.2 Policies for agricultural pollution control 40
2.1.3 Economic analysis of agricultural nonpoint pollution. 41
2.2 Modeling of nitrate abatement policies. 42
2.3 Stochastic analysis of groundwater pollution: incorporating parameter uncertainty into decision making. 43
3 Groundwater nitrate pollution. Bio-physico-chemical processes. 47
3.1 Nitrogen cycle 47
3.2 Agriculture as a source of groundwater pollution 50
3.2.1 Soil-crop system 50
3.2.2 Water and nitrogen percolation 52
3.3 Nitrogen movement in groundwater 53
4 Hydroeconomic modeling framework 57
4.1 Deterministic management model 57
4.1.1 Pollutant Response Matrix Method 59
4.1.2 Agronomic simulation 61
4.2 Illustrative example. Synthetic case study application 68
4.2.1 Case study description 68
4.2.2 Pollutant concentration response matrix and breakthrough curves 70
4.2.3 Scenario 0. No nitrate standard 72
4.2.4 Scenario 1. Variable fertilizer application 74
4.2.5 Scenario 2. Constant fertilizer application 78
4.2.6 Scenario 3. Recovery from pollution 80
4.2.7 Scenario 4. Constant fertilizer application with initial pollution 86
4.2.8 Discussion 88
5 Real case study: The Salobral-Los Llanos aquifer 91
5.1 Overview of study area 91
5.2 Agronomic modeling 100
5.3 Groundwater flow modeling 101
5.4 Groundwater nitrate transport modeling 105
5.5 Hydro-economic management model 108
5.5.1 Concentration response matrix 108
5.5.2 Scenarios 114
5.6 Fertilizer tax 127
6 Stochastic modeling framework 131
6.1 Stochastic modeling framework 131
6.1.1 Monte Carlo simulation with pre-assumed (“true”) parameter field 132
6.1.2 Monte Carlo optimization 132
6.1.3 Multiple realizations or stacking management model 133
6.1.4 Mixed-integer stochastic optimization model with predefined reliability 134
6.2 Synthetic case study 136
6.2.1 Simulation of conductivity fields 137
6.2.2 Pollutant concentration response matrices 138
6.2.3 Monte Carlo simulation with pre-assumed (“true”) parameter field 138
6.2.4 Monte Carlo optimization 140
6.2.5 Multiple realizations or stacking management model 140
6.2.6 Mixed-integer stochastic model with predefined reliability 143
6.3 Discussion 147
7 Conclusions, limitations and future research 149
7.1 Summary and conclusions 149
7.2 Limitations and recommendations for future research 151
References 153
Appendix A. Crop yield and nitrate leaching functions. El Salobral-Los Llanos Case Study 167

Appendix B. Groundwater flow model calibration. El Salobral-Los Llanos case study 179
Appendix C. Unitary nitrate concentration curves. El Salobral-Los Llanos case study. 187
Appendix D. Farming costs. El Salobral-Los Llanos case study. 199

List of Figures

Figure 3.1 Nitrogen cycle 48
Figure 4.1 Flowchart describing the modeling framework 59
Figure 4.2 Response matrix configuration 61
Figure 4.3 Processes taken into account in EPIC 65
Figure 4.4 Groundwater system configuration 68
Figure 4.5 Breakthrough curves for the control sites 71
Figure 4.6 Breakthrough curves. Scenario 0 73
Figure 4.7 Total fertilizer application for different planning horizons. Scenario 1 74
Figure 4.8 Spatial and temporal reduction fertilizer application. Scenario 1 76
Figure 4.9 Breakthrough curves. Scenario 1 77
Figure 4.10 Comparison between scenario 1 and 2 79
Figure 4.11 Breakthrough curves. Scenario 2 81
Figure 4.12 Breakthrough curves considering an initial concentration of 55 mg/l. 82
Figure 4.13 Comparison between scenario 1 and 3 83
Figure 4.14 Breakthrough curves. Scenario 3 (20 years recovery time) 84
Figure 4.15 Total fertilizer application for different recovery times. 40 management periods. Scenario 3 85
Figure 4.16 Breakthrough curves for different recovery times. Scenario 3 86
Figure 4.17 Optimal fertilizer application considering a 3% discount rate 88
Figure 5.1 Aquifer location 93
Figure 5.2 El Salobral- Los llanos domain 93
Figure 5.3. Mean temperature 94
Figure 5.4. Precipitation 95
Figure 5.5 Geologic Map and Cross Section 96
Figure 5.6. Main crops in the study area (2004) 97
Figure 5.7. Groundwater nitrate concentrations. 99
Figure 5.8 Piezometric head for 1975 103
Figure 5.9 Observation well location 105
Figure 5.10 Observed vs calculated heads. Well 682 105
Figure 5.11 Crops area in 1982 106
Figure 5.12 Crops areas in 1989 107
Figure 5.13 Calculated nitrate concentrations. 2005 108
Figure 5.14 Administrative areas for irrigation management 109
Figure 5.15 Discretization of administrative areas 109
Figure 5.16 Crop type subdivision 110
Figure 5.17 Control sites location 111
Figure 5.18 Unitary concentration time curves for crop area 8c 112
Figure 5.19 Concentration time curves for dry-land 112
Figure 5.20 Background nitrate concentration derived from the initial nitrate concentration at the control well 113
Figure 5.21 Concentration time curves for the current fertilizer application. Scenario 1 116
Figure 5.22 Concentration time curves for the fertilizer application that yields the maximum benefits. Scenario 2 117
Figure 5.23 Concentration time curves for the maximum allowed fertilizer application. Scenario 3 118
Figure 5.24 Allocation of fertilizer reduction. Recovery time 2015 121
Figure 5.25 Concentration time curves for the optimal fertilizer application. Recovery time 2015 121
Figure 5.26 Concentration time curves by superposition vs simulated. Recovery time 2015 122
Figure 5.27 Allocation of fertilizer reduction. Recovery time 2021 124

Figure 5.28 Concentration time curves for the optimal fertilizer application. 2021 124
Figure 5.29. Concentration time curves for different scenarios at control site “El Salobral”. 126
Figure 5.30. Concentration time curves for different scenarios at control site “Sondeo 8”. 127
Figure 5.31 Maximum nitrate concentration achieved with different fertilizer price and total benefits 128
Figure 6.1 K field for realization #1 and variances of 15 (left) and 60 (right) 137
Figure 6.2 Frequency distribution and univariate statistics for all K realizations and variances of 15 (left) and 60 (right). 138
Figure 6.3 Reliability (probability of not exceeding the maximum nitrate concentration) of the optimal fertilizer application for realization 14 with variances of 15 and 60 139
Figure 6.4 Probability distribution of the mean fertilizer application, case 1 140
Figure 6.5 Maximum nitrate concentration vs. reliability of not exceeding the nitrate concentration (post Monte Carlo simulation) 142
Figure 6.6 Mean reliability (post Monte Carlo simulation) vs. stack size 143
Figure 6.7 Probability of not exceeding the nitrate concentration for different reliability levels (case 2). 144
Figure 6.8 Reliability vs upper value of maximum nitrate concentrations 144
Figure 6.9 Trade-off between reliability and benefits. 145
Figure 6.10 Comparison between the solutions of the different formulations 146

List of Tables:

Table 4.1 Production and leaching functions coefficients 69
Table 4.2 Sources, crops and irrigation 69
Table 4.3 Maximum nitrate concentrations for maximum benefits. Scenario 0 72
Table 4.4 Fertilizer application that maximizes the total net benefits 74
Table 4.5 Constant fertilizer application. Scenario 2 78
Table 4.6 Percentage of fertilizer reduction. Scenario 2 78
Table 4.7 Net annual average benefits and total fertilizer application average for Scenario 1 and 2 80
Table 4.8 Benefits for different recovery times. 40 years planning horizon. Scenario 3 85
Table 4.9 Net annual benefits average and total fertilizer application average for Scenario 3 and 4. 40 year planning horizon 86
Table 4.10 Fertilizer application. Scenario 4. 20 management periods 87
Table 4.11 Fertilizer application and fertilizer reduction for the case where the concentration recharge is below 50 mg/l 87
Table 5.1 Soil characterization 95
Table 5.2. Main crops and cultivated area for year 2005 98
Table 5.3. Irrigation for the main crops 2005 98
Table 5.4 Production functions 101
Table 5.5 Leaching functions 101
Table 5.6 Hydraulic parameters 103
Table 5.7 Nitrate leaching 107
Table 5.8 Crop areas 110
Table 5.9 Crop, irrigation and prices 114
Table 5.10. Fertilizer application and nitrate leaching. Scenario 1 115
Table 5.11. Fertilizer application and nitrate leaching. Scenario 2 117
Table 5.12. Reference values for maximum nitrate fertilizer application (kg/ha) (DOCM, 2007) 118
Table 5.13 Optimal fertilizer application. Recovery time 2015 120
Table 5.14 Optimal fertilizer application. Recovery time 2021 123
Table 5.15. Comparison among scenarios. 125
Table 6.1 Percentage of spatial fertilizer reduction for different levels of reliability 146

10