Contents

Introduction **1**

1. Surrogate modeling **5**

1.1. Introduction and state of the art 5

1.2. Statistical approach based on linear regression 9

1.3. Artificial neural networks 12

1.3.1. Artificial neural network design and training process 14

1.3.2. Multilayer perceptron networks 20

1.3.3. Nonlinear autoregressive networks with exogenous inputs . 21

1.3.4. Long-short term memory networks 24

1.3.5. Convolutional neural networks 28

1.3.6. Physics-informed neural networks 31

2. Climate change **37**

2.1. Introduction 37

2.2. Historical data processing 40

2.2.1. Gap filling and interpolation procedures 40

2.2.2. Meteorological and groundwater drought indices 41

2.3. Future climate projections 46

2.3.1. Downscaling and bias correction 47

2.3.2. Future meteorological drought indices 49

3. Applications **51**

3.1. Impact of climate change on groundwater resources 52

3.1.1. State of the art 53

3.1.2. Study area and available data 57

3.1.3. Future climate projections 63

3.1.4. Statistical approach 64

3.1.5. Comparison of three different artificial neural network techniques 80

3.1.6. Discussion and conclusions 98

3.2. An artificial neural network as a quick tool to assess the effects of climate change and agricultural policies on groundwater 101

3.2.1. Case study 102

3.2.2. Surrogate model: ANN 103

3.2.3. Conclusion and discussion 109

3.3. Artificial neural networks for solving forward and inverse transport problems 110

3.3.1. State of the art 111

3.3.2. Case study 112

3.3.3. Groundwater flow and transport 115

3.3.4. Set up of the ANN 117

3.3.5. Results 125

3.3.6. Discussion and conclusions 135

3.4. Physics-informed neural networks for solving transient unconfined groundwater flow 137

3.4.1. Transient unconfined flow 137

3.4.2. Case study 140

3.4.3. PINN set up 142
3.4.4. Evaluation of the performance 149
3.4.5. Results 150
3.4.6. Discussion and conclusions 161

4. Extra contents **165**

4.1. Identification of the inflow source in a foul sewer system using an artificial neural network as inverse model 166
4.1.1. Case study 167
4.1.2. Set up of the ANN 168
4.1.3. Results 171
4.1.4. Discussion and conclusions 171
4.2. Enhancing user-friendliness: a comprehensive and accessible example of numerical groundwater flow modeling using spreadsheets . . 173
4.2.1. Unconfined two-dimensional groundwater flow in a horizontal plane 174
4.2.2. Unconfined two-dimensional groundwater flow in a vertical cross-section 198
4.2.3. Conclusions and discussion 206

Conclusions **209**

Limitations and future directions 211