

Data-driven decision management of urban underground infrastructure through groundwater-level time-series cluster analysis: the case of Milan (Italy)

Davide Sartirana^{1*}, Marco Rotiroti¹, Tullia Bonomi¹, Mattia De Amicis¹, Veronica Nava¹, Letizia Fumagalli¹ and Chiara Zanotti¹

¹Department of Earth and Environmental Sciences, University of Milano-Bicocca, Piazza Della Scienza 1, 20126 Milan, Italy

*corresponding author: d.sartirana1@campus.unimib.it

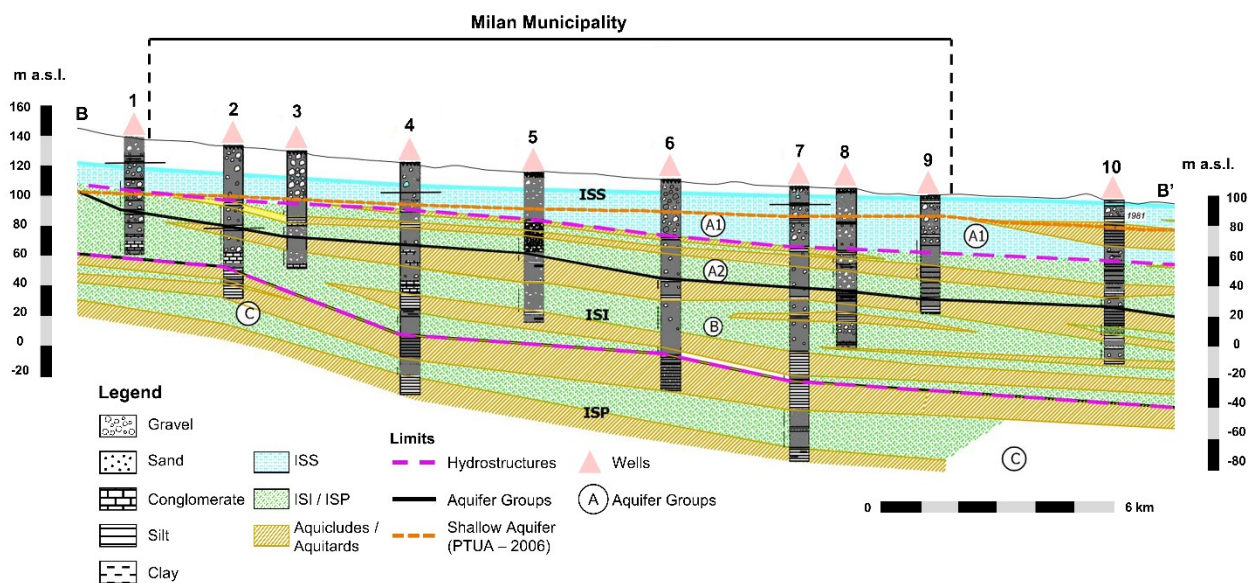


Figure S1 Geological profile of N-S cross section BB' of the study area, modified from Regione Lombardia (2016). The aquifer group classification from Regione Lombardia & ENI (2002) is also provided. For its location see Fig. 1b of the main article.

Table S1 List and main features of the underground car parks located in the study area. Modified from Sartirana et al., (2020).

Name	X	Y	Bottom (m a.s.l.)	Depth (m)	Area ×10 ³ (m ²)	Volume ×10 ³ (m ³)	No. of floors	Management Area (MA)
Accursio	1511485.84	5037744	115.6	14	4.55	63.7	4	1
Alghero	1517701.21	5039071.93	122.72	5	2.12	10.6	1	1
Balla	1507957.48	5037820.27	125.58	8	2.65	21.2	2	1
Betti	1508980.61	5037640.25	123.7	8	5.69	45.52	2	1
Bicocca P7	1516646.62	5040339.49	122.1	11	5.67	62.37	3	1
Bicocca P8	1516524.32	5040512.1	125.5	8	6.67	53.36	2	1
Capecelatro/Pessano	1509901.6	5035738.05	116.35	8	5.05	40.4	2	1
Carafa/Conte Verde	1513936.49	5038952.12	120.2	11	3.3	36.3	3	1
Caroli/Ricordo	1518666.43	5039557.39	121.53	8	3.77	30.16	2	1
Cechov	1509386.56	5037414.7	122.54	8	2.92	23.36	2	1
Cervi/Assietta	1512373.32	5040363.31	130.11	8	8.05	64.4	2	1
Cilea 100	1508047.52	5038263.79	126.83	8	4.37	34.96	2	1
De Lemene	1510760.32	5037758.24	120.6	8	2.29	18.32	2	1
Don Calabria	1518778.05	5038369.45	116.85	8	6.4	51.2	2	1
Emo	1519036.29	5039190.67	116.23	11	2.76	30.36	3	1
Gandhi/Perlasca	1509948.41	5039335.56	128.2	8	4.31	34.48	2	1
Govone	1513118.71	5037348.35	110.19	17	1.6	27.2	5	1
Grado	1517211.36	5038640.95	118.77	8	1.68	13.44	2	1
Graf/De Pisis Ovest	1511107.75	5039909.65	128.9	8	5.94	47.52	2	1
Lampugnano	1510040.4	5037101.23	119.85	8	3.78	30.24	2	1
Marmolada	1515157.07	5040349.03	124.4	11	3.36	36.96	3	1
Monte Baldo	1509381.09	5035753.2	117.22	8	3.1	24.8	2	1
Muttoni/Quarenghi	1508615.77	5038295.25	124.8	8	3.99	31.92	2	1
Ojetti	1508659.3	5037949.88	124.16	8	7.03	56.24	2	1
Osculati/Camerino	1513331.39	5040348.89	125.14	11	0.45	4.95	3	1
Populonia/Valassina	1514806.27	5038597.8	117.68	11	8.68	95.48	3	1
Prinetti/Vida	1517828	5038383.33	114.2	11	3.25	35.75	3	1
Riccione	1511829.45	5038646.35	120.95	11	1.91	21.01	3	1
Salmoiraghi/Stuparich	1511149.64	5036736.65	115.37	11	1.76	19.36	3	1
San Giusto/Val Poschiavina	1509526.06	5035796.61	116.7	8	5.56	44.48	2	1
Sarca/Nota	1516176.66	5040017.4	123.99	8	4.4	35.2	2	1
Suzzani	1516380.56	5041573.99	129.85	8	3.56	28.48	2	1
Toce/Boltraffio	1514529.35	5037668.46	115.33	11	4.55	50.05	3	1
Trechi	1513908.66	5041439.14	132.14	8	3.97	31.76	2	1
Veglia/Caserta	1515284.04	5038813.26	120.9	8	22.28	178.24	2	1
Adda	1515464.18	5036660.94	102	20	0.81	16.2	6	2
Ampere/Compagni	1517683.2	5036345.61	104.5	14	2	28	4	2
Arduino	1511809.5	5036030.75	112.9	11	5.67	62.37	3	2
Aretusa Nord	1510747.39	5034988.54	110.75	11	4.39	48.29	3	2
Bazzini	1517651.24	5036632.32	102.2	17	1.49	25.33	5	2
Benedetto Marcello	1516454.72	5036654.51	106.53	14	3.05	42.7	4	2
Carducci Olona	1513474.33	5034278.09	101.2	17	3.42	58.14	5	2
Caterina da Forlì	1510989.9	5034176.92	108.97	11	10.35	113.85	3	2
Cesariano	1513865.34	5036150.32	111.5	11	4.54	49.94	3	2
Ciclamini/Margherite	1510019.19	5033551.32	111.5	8	3	24	2	2
Correggio Est	1511974.14	5035341.08	107.81	14	1.03	14.42	4	2
Correggio Ovest	1511678.6	5035067.69	106.95	14	2.75	38.5	4	2
Costa/Loreto	1517106.55	5037054.09	106.9	14	1.97	27.58	4	2
Dateo Nord	1516955.54	5035034.03	99.8	17	1.94	32.98	5	2
Dateo Sud	1516957.23	5034929.13	102.8	14	2.11	29.54	4	2
Donati/Redaelli	1511197.3	5033370.38	110.01	8	9.53	76.24	2	2
Etiopia	1511542.85	5033877.47	111.66	8	0.5	4	2	2
Fratelli Bandiera	1516496.72	5035290.1	103.5	14	2.81	39.34	4	2
Giotto	1512438.45	5034963.95	107.05	14	4.49	62.86	4	2
Giulio Cesare	1512187.46	5035610.15	109.2	14	4.42	61.88	4	2
Gramsci	1513200.91	5036501.03	110.2	14	4.3	60.2	4	2

Leoncavallo	1517547.2	5037482.89	108	14	2.54	35.56	4	2
Leone XIII	1512812.29	5035699.34	115.35	8	7.4	59.2	2	2
Lucerna	1509342.34	5033909.07	113.39	8	4	32	2	2
Majno	1516086.23	5035424.18	101.86	17	2.05	34.85	5	2
Manuzio	1515710.27	5036192.81	103.56	17	2.27	38.59	5	2
Mascagni	1515904.86	5034781.4	102.2	14	4.63	64.82	4	2
Meda	1515131.95	5034864.81	102.85	17	2.1	35.7	5	2
Moisè Loria/Stromboli	1512434.29	5033912.51	101.5	17	3	51	5	2
Moscova	1514917.58	5035995.65	107	14	7.32	102.48	4	2
Murani	1518374.85	5035559.21	101.6	14	3.38	47.32	4	2
Novelli	1517153.81	5035275.21	103.2	14	1.17	16.38	4	2
Numa Pompilio	1513243.7	5034106.03	100.7	17	4.07	69.19	5	2
Ozanam	1516616.28	5036350.75	105.63	14	4.6	64.4	4	2
Piazza Diaz	1514880.39	5034351.4	108.5	11	2.4	26.4	3	2
Po	1512348.88	5034312	105.2	14	6.87	96.18	4	2
Puccini	1514101.89	5034899.19	101.33	20	1.68	33.6	6	2
Quinto Alpini	1513084.57	5035409.12	106.47	14	1.66	23.24	4	2
Rio de Janeiro	1517488.23	5035637.66	105.7	11	2.27	24.97	3	2
Rio de Janeiro/Andrea del Sarto	1517491.64	5035532.08	105.7	11	2.64	29.04	3	2
Risorgimento nord	1516498.3	5035017.14	96.9	20	1.43	28.6	6	2
Risorgimento Sud	1516499.64	5034923.53	102.8	14	2.11	29.54	4	2
Romagnoli/Bertieri	1511511.74	5033526.2	107.34	11	2.11	23.21	3	2
Rossetti	1512698.19	5035485.92	115.2	8	2.88	23.04	2	2
Sammartini/Lunigiana	1516147.13	5037407.22	112.3	11	3.49	38.39	3	2
Sant'Ambrogio	1513731.23	5034447.5	102	17	7.41	125.97	5	2
Savona Tolstoj	1511916.99	5032900.45	110.67	5	1.08	5.4	1	2
Solera Mantegazza	1514289.66	5035843.73	107.85	14	2.92	40.88	4	2
Tommasco	1513068.3	5035131	103.89	17	3.15	53.55	5	2
Viganò	1514835.34	5036556.91	110.61	14	2.19	30.66	4	2
Vittor Pisani	1515730.82	5036618.21	107.58	14	8.78	122.92	4	2
Volontari	1513298.55	5035839.73	108.8	14	1.3	18.2	4	2
Washington/Piemonte	1512111.32	5034808.26	100.35	20	3.02	60.4	6	2
XXV Aprile	1514631.9	5036394.43	105.2	17	5.07	86.19	5	2
Avezana	1517873.99	5031883.54	98.07	11	2.04	22.44	3	3
Bacchiglione/Scheiwiller	1517383.43	5032344.39	99.9	11	3.35	36.85	3	3
Balilla/Zamenhof	1514313.08	5032513.11	105.66	8	2.4	19.2	2	3
Bellosio/Facchinetti	1518953.76	5034267.33	102.46	8	3.71	29.68	2	3
Bibbiena/Centro Civico	1514421.51	5032437.4	105.65	8	3.86	30.88	2	3
Bordighera/Alzaia Naviglio Pavese	1513648.26	5031674.16	102.56	11	3.32	36.52	3	3
Cardinal Ferrari	1515081.96	5033637	101.53	14	2.24	31.36	4	3
Cascina Bianca	1511998.82	5030521.49	106.2	5	7.88	39.4	1	3
Ciceri Visconti	1517277.28	5033481.59	101.47	11	4.16	45.76	3	3
Conca del Naviglio	1513941.04	5033547.63	101.92	14	2.43	34.02	4	3
Dalmazia	1519045.11	5033905.82	101.75	8	2.09	16.72	2	3
De Nicola/San Vigilio	1512532.53	5030898.81	106.46	5	4.78	23.9	1	3
De Pretis/San Vigilio	1512459.32	5030669.99	106.4	5	4.52	22.6	1	3
De Pretis/Voltri	1512075.33	5030908.4	106.89	5	4.73	23.65	1	3
Erculea	1514865.99	5033973.05	100.91	17	1.3	22.1	5	3
Feltrinelli	1519489.16	5031024.34	101.83	5	8.3	41.5	1	3
Giulio Romano	1515724.46	5032803.81	96.45	17	2.48	42.16	5	3
Isimbardi	1514186.97	5031007.03	102.9	8	2.64	21.12	2	3
Maffei	1516394.56	5033918.6	100.9	14	3.41	47.74	4	3
Manusardi	1514024.89	5033138.81	100.25	14	2.12	29.68	4	3
Menotti Serrati	1520604.48	5032025.48	98.94	5	7.5	37.5	1	3
Monte Popera/Piana	1519440.96	5031185.9	101.12	5	2.8	14	1	3
Monte Velino/Cadibona	1517855.23	5033358.26	102.83	8	7.05	56.4	2	3
Montemartini/Fabio Massimo	1517890.62	5031451.16	101.38	8	7.16	57.28	2	3
Pavia	1513972.07	5032693.29	99.84	14	3.38	47.32	4	3
Sabotino	1515789.26	5033114.62	96.91	17	2.47	41.99	5	3
San Barnaba	1515498.62	5034024.26	105.4	11	7.45	81.95	3	3
Spaventa/Meda	1513944.73	5031872.92	104.44	8	5.46	43.68	2	3
Trani/Malipiero/Mecenate	1519146.89	5033450.12	100.1	8	5.92	47.36	2	3

Vittadini	1515207.46	5032910.41	99.23	14	3.63	50.82	4	3
Betulle Est	1506526.35	5033273.32	118.01	5	4.6	23	1	4
Betulle Ovest	1506298.21	5033348.3	118.2	5	2.49	12.45	1	4
Broggini	1507415.46	5034706.6	119.07	5	2.17	10.85	1	4
Nikolajevka	1508333.19	5033698.32	113.4	8	4.64	37.12	2	4
Silla	1505988.25	5037819.83	131.3	5	5.82	29.1	1	4
Valsesia Est	1507716.77	5033575.94	116.45	5	3.42	17.1	1	4
Valsesia Ovest	1507604.98	5033515.39	116.6	5	1.96	9.8	1	4
Total parks: 126						5,157		

Time-series reversal points: R Script

#Packages uploading

library(imputeTS) #to be used for interpolating time-series missing values

library(utils) # to export the final list of identified reversal points for each monitoring well (MW)

#Data loading (.csv format)

db<-read.table("MWs_dataset.csv", header=T, sep=";", dec=",") #file setting: the first column contains Date; the remaining columns contain MWs time-series; each row contains the MWs observations at a given Date

#Set Date

db\$Date<-as.Date(db\$Date,format = c("%d/%m/%Y")) # set Date column in Date format

#Interpolating Missing Values

db_notNA<-na_interpolation(db) #Create a new database linearly interpolating missing values

#Reversal Points Identification

results <- NULL #Initialize results

count <- 1

for (i in 1:ncol(db_notNA)){ #for is used to set a cycle, thus iterating the procedure for all the MWs

sel_db<-(db_notNA[,i]) #select columns

ts_db<-ts(sel_db, start=2005, frequency=2) #set data as time-series

stl_db<-stl(ts_db, s.window="periodic") #Decompose a time series into seasonal, trend and irregular components using loess

trend_db<-stl_db\$time.series[, "trend"] #Analyse only the trend component

shape_smooth <- diff(sign(diff(trend_db, na.pad = T))) #Determine the sign of the difference between successive couples of data

index_smooth<-which(shape_smooth!=0,arr.ind = T)+1 #Determine the position of reversal points

results[[count]] <- index_smooth

names(results)[[count]] <- names(db_notNA)[i]

count <- count + 1

print(results)

}

capture.output(print(results), file = "Identified_ReversalPoints.txt") #Export a .txt file containing all the identified Reversal Points for each MW

Table S2 Summary of groundwater reversal points (RPs) for the analysed monitoring wells (MWs) in the study area. GW stands for groundwater.

MW	Location	GW Min.	GW Max.	GW Loc. Max.	GW Loc. Min.	No. of RPs
MW1	Downtown	sep-07	mar-12	sep-12	sep-14	6
MW2	East	mar-07	NCI	NCI	mar-18	8
MW3	North	sep-07	sep-11	sep-12	sep-15	4
MW4	North	mar-08	sep-11	sep-12	sep-15	4
MW5	North	sep-07	sep-11	sep-12	mar-15	6
MW6	North	mar-08	sep-11	sep-12	mar-15	4
MW7	South	sep-07	NCI	NCI	sep-14	10
MW8	Downtown	sep-07	sep-11	sep-12	mar-15	7
MW9	East	sep-06	mar-11	mar-12	mar-15	6
MW10	South	mar-07	NCI	NCI	sep-16	7
MW11	East	sep-07	sep-11	sep-12	mar-15	4
MW12	East	sep-06	mar-11	mar-12	sep-15	7
MW13	West	mar-07	mar-11	sep-12	sep-14	4
MW14	East	sep-06	NCI	NCI	mar-14	10
MW15	East	mar-07	sep-11	mar-12	sep-15	8
MW16	South	NCI	NCI	NCI	NCI	8
MW17	South	sep-07	mar-10	mar-12	sep-14	9
MW18	South	mar-07	NCI	NCI	mar-14	8
MW19	North	mar-08	sep-11	sep-12	mar-15	4
MW20	West	mar-07	NCI	NCI	sep-13	10
MW21	South	mar-07	NCI	NCI	sep-14	9
MW22	North	mar-07	sep-11	sep-12	sep-14	6
MW23	Downtown	sep-06	sep-11	sep-12	mar-15	7
MW24	North	sep-07	sep-11	sep-12	mar-15	4
MW25	Downtown	NCI	NCI	NCI	mar-14	8
MW26	Downtown	mar-07	NCI	NCI	sep-14	10
MW27	South	mar-07	NCI	NCI	mar-14	11
MW28	South	mar-07	NCI	NCI	mar-15	11
MW29	North	mar-08	sep-11	sep-12	mar-15	6
MW30	North	mar-07	sep-11	sep-12	mar-15	6
MW31	Downtown	mar-07	NCI	NCI	mar-15	10
MW32	Downtown	mar-07	NCI	NCI	sep-14	6
MW33	East	mar-07	mar-11	mar-12	mar-15	7
MW34	North	mar-08	sep-11	sep-12	mar-15	4
MW35	East	sep-06	mar-11	sep-12	NCI	10
MW36	South	NCI	NCI	NCI	NCI	10
MW37	West	NCI	NCI	NCI	NCI	10
MW38	North	mar-07	NCI	NCI	mar-14	7
MW39	West	sep-06	NCI	NCI	mar-14	10
MW40	West	NCI	NCI	NCI	NCI	8
MW41	North	sep-07	sep-11	sep-12	mar-15	9
MW42	Downtown	mar-07	NCI	NCI	mar-14	7
MW43	West	NCI	NCI	NCI	NCI	13
MW44	East	sep-06	NCI	NCI	sep-14	7
MW45	West	NCI	NCI	NCI	NCI	14
MW46	Downtown	sep-06	sep-09	mar-12	mar-15	8
MW47	East	mar-07	mar-11	mar-12	sep-15	6
MW48	North	sep-07	sep-11	sep-12	mar-15	4
MW49	South	NCI	sep-09	mar-11	mar-15	9
MW50	East	mar-07	mar-11	sep-12	sep-18	6
MW51	Downtown	sep-07	sep-11	sep-12	sep-14	6
MW52	Downtown	sep-07	sep-11	sep-12	sep-14	4
MW53	Downtown	mar-06	mar-11	sep-11	sep-16	6
MW54	North	mar-08	sep-11	sep-12	mar-15	4
MW55	North	sep-07	sep-11	sep-12	sep-15	4
MW56	North	sep-07	sep-11	sep-12	mar-15	6
MW57	East	sep-07	sep-11	mar-12	sep-15	5
MW58	West	sep-07	mar-11	sep-12	sep-14	8
MW59	Downtown	sep-07	mar-11	sep-12	mar-15	8
MW60	Downtown	sep-07	mar-11	sep-12	mar-15	9
MW61	Downtown	sep-07	sep-11	sep-12	sep-15	10

MW62	Downtown	sep-07	sep-11	sep-12	mar-16	6
MW63	East	mar-07	sep-11	mar-12	sep-16	8
MW64	North	mar-08	sep-11	sep-12	mar-15	4
MW65	North	sep-07	sep-11	mar-12	mar-15	6
MW66	South	sep-07	mar-12	mar-13	sep-14	8
MW67	Downtown	sep-07	sep-11	sep-12	mar-15	7
MW68	Downtown	sep-07	sep-11	sep-12	mar-15	6
MW69	Downtown	sep-07	sep-11	sep-12	mar-16	10
MW70	South	sep-07	mar-12	sep-12	mar-15	8
MW71	South	sep-07	sep-11	mar-12	sep-15	6
MW72	South	mar-07	NCI	NCI	sep-15	9
MW73	Downtown	mar-07	NCI	NCI	mar-15	6
MW74	Downtown	mar-07	sep-09	sep-10	mar-15	6
MW75	West	sep-06	NCI	NCI	sep-15	14
MW76	North	mar-07	sep-11	sep-12	mar-15	4
MW77	Downtown	mar-07	sep-11	sep-12	mar-15	6
MW78	Downtown	sep-07	sep-11	sep-12	mar-15	6
MW79	Downtown	sep-07	sep-11	sep-12	sep-14	6
MW80	West	sep-07	mar-11	sep-12	mar-15	8
MW81	West	mar-08	sep-11	sep-12	mar-14	10
MW82	North	sep-07	sep-11	sep-12	sep-14	4
MW83	North	sep-07	sep-11	sep-12	mar-15	4
MW84	North	mar-08	mar-12	sep-12	mar-15	4
MW85	North	mar-08	mar-12	sep-12	mar-15	6
MW86	Downtown	sep-07	sep-11	sep-12	sep-15	7
MW87	South	mar-07	sep-11	sep-12	sep-15	7
MW88	East	mar-06	NCI	NCI	NCI	10
MW89	North	sep-07	sep-11	sep-12	sep-14	4
MW90	West	mar-06	NCI	NCI	NCI	7
MW91	North	mar-08	sep-11	sep-12	mar-15	4
MW92	North	sep-07	sep-11	sep-12	mar-15	4
MW93	West	mar-06	NCI	NCI	NCI	9
MW94	West	sep-07	mar-11	mar-12	mar-14	6
MW95	North	sep-07	sep-11	sep-12	sep-15	4

*NCI stands for Not Clearly Identifiable.

ESM References

Regione Lombardia (2016) Piano di Tutela ed Uso delle Acque (PTUA) [Water Protection and Use Plan (PTUA)]

Regione Lombardia & ENI Divisione AGIP (2002) Geologia degli acquiferi Padani della Regione Lombardia [Geology of the Padan aquifers of the Lombardy Region]. S.EL.CA

Sartirana D, Rotiroti M, Zanotti C, Bonomi T, Fumagalli L, De Amicis M, 2020. A 3D geodatabase for urban underground infrastructures: implementation and application to groundwater management in Milan metropolitan area. ISPRS Int. J. Geo-Information 9. <https://doi.org/10.3390/ijgi9100609>