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Table 35. Sample of the lexicographic ordered matches per `alpha` equal to $c(1,1,0.000750,0.000750)$.

Id	X1	X2	X3	X4	X5	X6	X7	X8	X9
1	1.3	1.5	1.9	3.5	4.1	**W211**	**Kevlinge_21**	Kevlinge_20	Kevlinge_19
2	5.2	5.2	6.3	6.9	8.3	**W318**	**Tranas**	Teglarod	Kjellstorp_05
3	6.4	13.9	16.9	17.7	18.6	**W185**	**Vasagarden_05**	Nyhus	Halmstad_03
4	7.1	16.8	21.1	24.0	25.8	**W268**	**Vasagarden_05**	Norraby_03	Nyhus
5	7.1	17.3	18.4	20.2	21.9	**W262**	**Vasagarden_05**	Nyhus	Norraby_03
6	8.1	18.0	22.1	25.1	26.8	**W269**	**Vasagarden_05**	Norraby_03	Nyhus
7	8.8	15.2	17.4	24.8	27.8	**W270**	**Oregarden_mfl**	Rodahus_06	Norraby_04
8	9.2	15.5	17.6	24.6	26.4	**W186**	**Oregarden_mfl**	Rodahus_06	Norraby_04
9	9.6	9.7	10.6	12.0	12.3	**W305**	**Kevlinge1012_Torvmosse**	Kevlinge_10	Kevlinge_12
10	10.2	13.7	14.6	14.9	15.0	**W170**	**Godstorp_01**	ostergard	Stettehus_01
11	10.3	35.2	37.7	41.6	43.8	**W181**	**Troskeberg_01**	Oregarden_mfl	Kagerod_04
12	10.4	16.8	19.0	23.2	27.0	**W187**	**Oregarden_mfl**	Rodahus_06	Norraby_04
13	10.6	11.5	13.7	15.7	15.9	**W190**	**Kevlinge_10**	Kevlinge1012_Torvmosse	Kevlinge_12
14	12.3	22.1	26.4	29.3	31.0	**W168**	**Vasagarden_05**	Norraby_03	Nyhus
15	12.4	12.6	13.2	13.3	13.9	**W311**	**Kevlinge_12**	Kevlinge_17	Kevlinge_10
16	12.6	35.5	36.3	36.5	37.3	**W223**	**Hog_12**	Kevlinge_23	Kevlinge_11
17	14.7	27.5	28.3	29.4	29.4	**W231**	**Hog_12**	Kevlinge_23	Kevlinge_11
18	15.5	26.6	27.1	27.8	28.1	**W283**	**Halmstad_14**	Sirekopinge_03	Sirekopinge_01
19	16.7	47.8	64.5	67.4	68.9	**W230**	**Kevlinge_02**	Norraby_06	Kevlinge_22_GRYET
20	17.1	17.1	17.4	18.4	18.6	**W162**	**Bessinge**	Svarvarehus	Vennelund
21	18.4	39.4	51.7	53.2	53.4	**W215**	**Sirekopinge_01_8**	Hog_12	Halmstad_05
22	18.6	23.3	29.2	33.3	35.1	**W264**	**Vasagarden_05**	Norraby_03	Halmstad_05
23	19.4	30.9	38.4	39.6	56.0	**W299**	**Kevlinge_09**	Kevlinge_22_GRYET	Kevlinge_01_GRYET
24	19.5	20.1	22.0	22.6	22.7	**W267**	**Sirekopinge_08**	Sirekopinge_09	Sirekopinge_03
25	19.9	21.7	25.0	25.2	25.7	**W195**	**Kevlinge_18**	Kevlinge_23	Kevlinge_21
26	20.0	51.5	68.2	70.2	71.8	**W229**	**Kevlinge_02**	Norraby_06	Kevlinge_22_GRYET
27	20.1	40.1	43.0	43.8	44.8	**W227**	**Hog_12**	Sirekopinge_01_8	Kevlinge_23
28	20.8	21.0	21.9	22.4	22.8	**W91**	**Bauserod_02**	Bauserod_01	Orod_01
29	20.9	22.7	26.0	26.2	26.7	**W202**	**Kevlinge_18**	Kevlinge_23	Kevlinge_21
30	21.0	21.2	22.0	23.0	23.4	**W12**	**Bauserod_02**	Bauserod_01	Orod_01
31	21.4	21.5	21.8	22.3	23.0	**W45**	**Kagerod_05**	Sonnarp_03	Teckarebol
32	21.6	41.8	42.9	48.1	49.2	**W282**	**Sirekopinge_01_8**	Nyhus	Vasagarden_05
33	22.3	33.5	33.6	43.3	48.3	**W263**	**Norraby_03**	Norraby_06	Vasagarden_05
34	22.4	32.5	53.8	56.8	60.8	**W309**	**Kevlinge_22_GRYET**	Kevlinge_09	Norraby_04
35	23.0	25.7	25.9	26.1	26.8	**W9**	**Vinterhus**	Bauserod_02	Bauserod_01
36	24.6	34.3	44.1	48.4	51.3	**W158**	**Rovegardshus_01**	Vasagarden_05	Norraby_03
37	25.3	27.1	29.2	29.4	35.1	**W254**	**Norraby_05**	Norrlycke_01	Bangstorp_01
38	25.4	25.6	27.8	27.9	28.4	**W2**	**Bauserod_02**	Bauserod_01	Smormolla_01
39	25.8	28.5	28.7	29.0	29.2	**W252**	**Klesinge_03**	Tagarp_12	Tagarp_03
40	26.1	28.3	34.7	35.6	37.0	**W302**	**Norraby_04**	Rodahus_06	Oregarden_mfl

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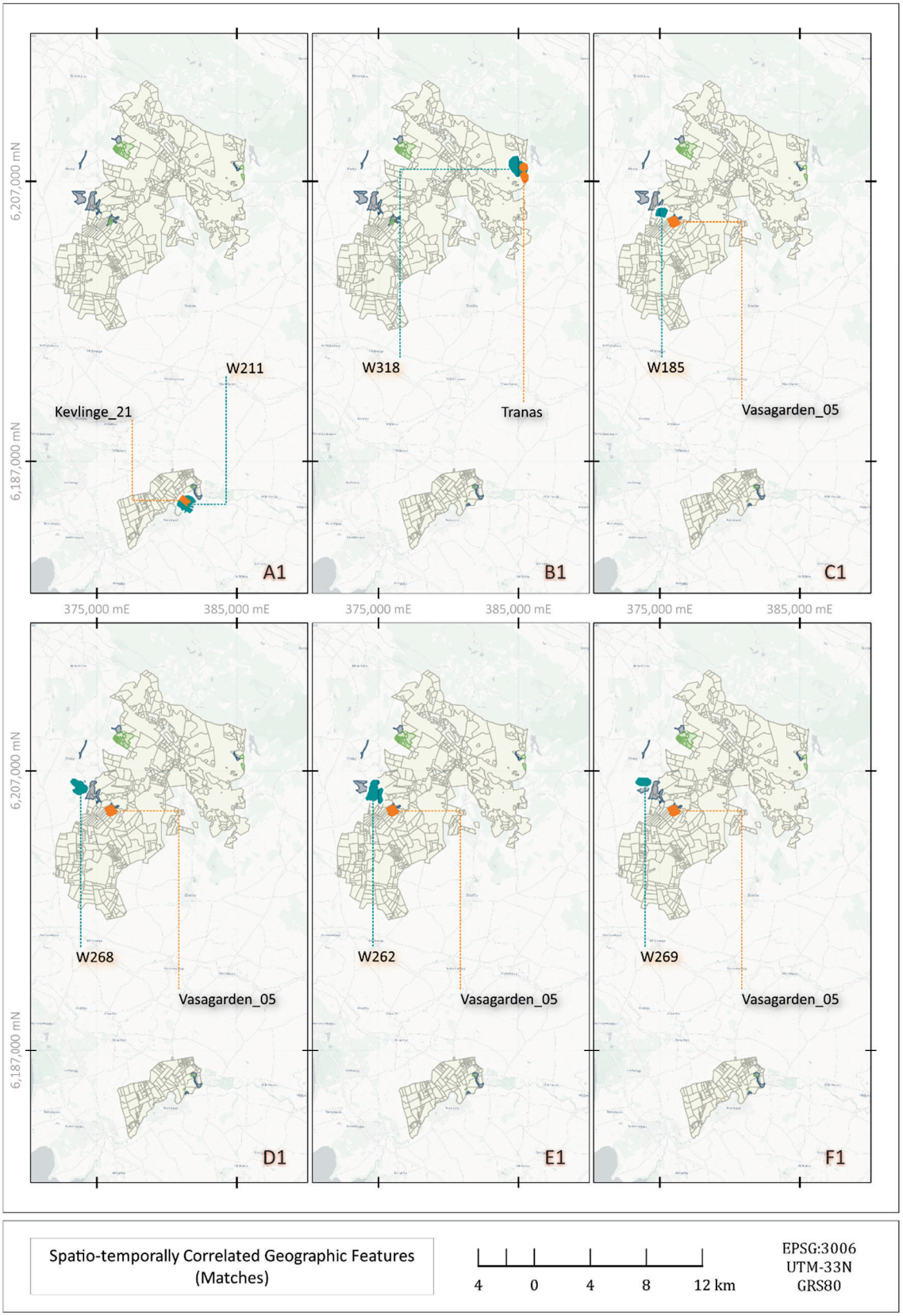


Figure 78. Geographic location of the matches ranked 1st–6th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000750, 0.000750)$.

Some *Property Units* and *Wetlands* have been rescaled to better visualise the geographic matches.

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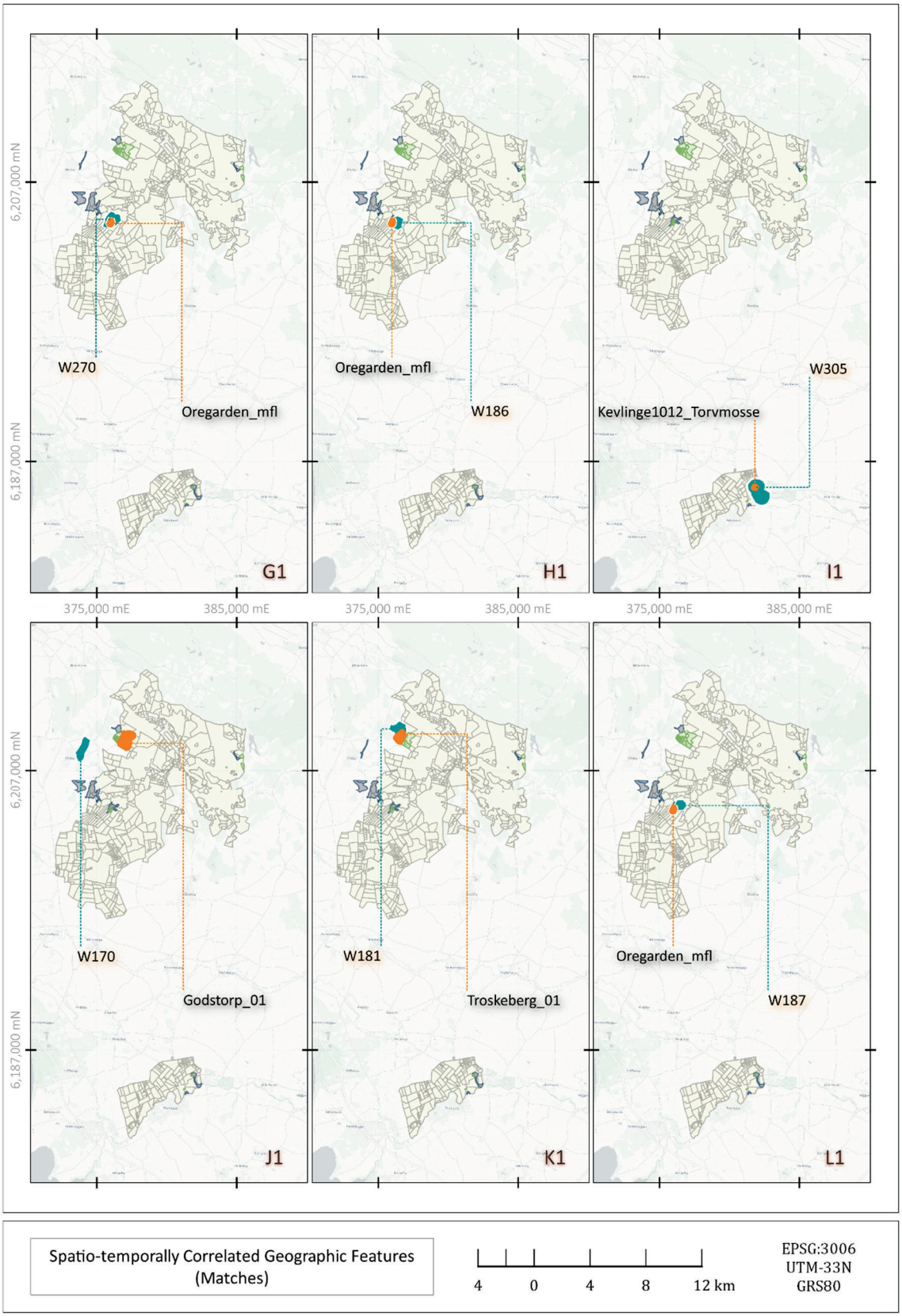


Figure 79. Geographic location of the matches ranked 6th–12th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000750, 0.000750)$.

Some *Property Units* and *Wetlands* have been rescaled to better visualise the geographic matches.

Another interesting fact worthy of note about `alpha <- c('1', '1', '0.000750', '0.000750')` is the first record in Table 35. It can be seen how the 5 property units matched (correlated) with the wetland *W211* have smaller distances (1.3, 1.5, 1.9, 3.5, 4.1) than the first distance of the second ordered wetland (5.2 – *W318*). This shows that this wetland in particular was simultaneously affected by several property units according to the conditions of the modelling exercise. As shown, the model is sensitive enough to identify different potential correlations. Figure 81 shows the spatio-temporal interactions of wetland *W211* and its correlated property units: *Kevlinge_21*, *Kevlinge_20*, *Kevlinge_19*, *Kevlinge_12*, *Kevlinge_17*. A historical reason that could explain this situation is that these neighbouring properties had used this wetland to implement a private irrigation system and after a few years it was drained by overexploitation. Although just speculation, this idea is plausible since the geographical distance between the limits of wetland *W211* and the correlated property units varies between 200 m and 1 km, which is an acceptable distance for an irrigation system. Note how the dates for all dimensions labelled in Figure 81 are equal, this explains the short distances calculated. This case also exemplifies how the setting of the variable `n=5` described in the section 5.6.1.6 is useful to show more or less detail as appropriate in the analysis. All the iterations performed during the proofs of concept have signified `n=5` as a suitable value for setting up any initial analysis scenario, such variable must be greater than 0 and less than or equal to the number of trajectories compared.

5.6.3.1 Time Over Space

A last analytical scenario is presented to show what happens when the temporal dimensions are prioritised over the spatial ones, but not totally prioritised as in the first proof of concept. How can one do this? Since the equilibrium point is $\alpha_i = 0.000734$, then any value greater than 0.000734 will prioritise spatial dimensions whereas any value less than 0.000734 will prioritise temporal ones. For instance, when $\alpha_i = 0.000\mathbf{0}734$ the ratio of time to space is 10 to1, being temporal dimensions ten times more significant than spatial ones. *Values greater than or less than 0.000734 marks the limit for spatio-temporal or temporospatial analysis, respectively*.

To analyse the impact of the increased emphasis on time, we have parameterised and implemented the following analytical scenarios[52]:

[52] As in previous analyses, the whole results are available at the repository of the research[42], check the file *resultsRStudioPConcept03Test05_short.xlsx* and look for the corresponding worksheets.

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```
alpha  <- c('1', '1', '0.000500', '0.000500')              # Test seven
alpha  <- c('1', '1', '0.000375', '0.000375')              # Test eight
alpha  <- c('1', '1', '0.000250', '0.000250')              # Test nine
alpha  <- c('1', '1', '0.0001875', '0.0001875')            # Test ten
alpha  <- c('1', '1', '0.0001250', '0.0001250')            # Test eleven
alpha  <- c('1', '1', '0.00009375', '0.0009375')           # Test twelve
alpha  <- c('1', '1', '0.00006250', '0.0006250')           # Test thirteen
alpha  <- c('1', '1', '0.00003125', '0.0003215')           # Test fourteen

beta   <- 1
M      <- 27

property_units  <- c('auId', 'eDate', 'eDateMax',
                     'x_centroid_prop', 'y_centroid_prop')

wetlands        <- c('wetlandId', 'eDateMin', 'eDateAvg',
                     'x_centroid_wet', 'y_centroid_wet')
```

Table 36 shows the first twelve correlated *Property Units* and *Wetlands* for each test. These results are quite insightful. First, it must be highlighted that the ordered matches are identical from $\alpha_i = 0.000250$ to $\alpha_i = 0.00003125$, this means that any value in-between these `alpha` limits will result in the same geographic matches, at least up to the 12th ordered match (correlated geographic features). This also means that, according to these results, the lowest value in which the balance between space and time is worthy of note is 0.000250, giving us a preliminary complete view of the interval for spatio-temporal evolution of the analysed phenomena $[0.000250, 0.520000]$, above or below this range no changes in matches have been identified up to the 12th ordered correlation. These interval limits point out the sections of Figure 74 in which the ongoing analysis will mainly consider changes either in temporal (< 0.000250) or spatial (> 0.520) dimensions.

One could say that there is no complete evidence to support this statement from the data provided, and it could be true. The lower limit of 0.000250 could be any value between 0.000375 and 0.000250, notice in Table 36 that the first change in the reported matches occur in $\alpha_i = 0.000375$. Nonetheless, Figure 77 shows a clear trend in the averages for 5, 10, 15, and 20 matches. In all four cases the average plots remain constant up to 0.000250, and the plots for 15 and 20 decay to the same spatial average for $\alpha = 0.000375$. From this fact it can be inferred that for the averages up to the 20th ordered match (avg20) there will not be significant changes up to an α_i value of 0.000375, however, 0.000250 is the value which limits the clear trend. Then, the verified lower limit is so far 0.000250. Figure 80 shows the plots with visual noise removed (averages 25 to 50) making this affirmation clearer. These statements are true for the data set analysed and should not be generalised.

It would be necessary to iterate more densely for α_i values in the range $[0.000250; 0.000375]$ to identify the accurate value of the lower limit. After completing this task, we have concluded that the lower limit is 0.0003625. These complementary calculations[53] let us refine the range for spatio-temporal evolution of the analysed phenomena to $[0.0003625, 0.520000]$. When plotting averages derived from the calculations, averages plots for 5, 10, 15, and 20 matches remain constant up to $\alpha_i =$

[53] proof_of_concept_03_lower_limit.RData; resultsRStudioPConceptLowerLimit.xlsx; resultsRStudioPConceptLowerLimitSP.xlsx

0.0003625. A similar implementation could be done to refine upper limit between [0.480; 0.520].

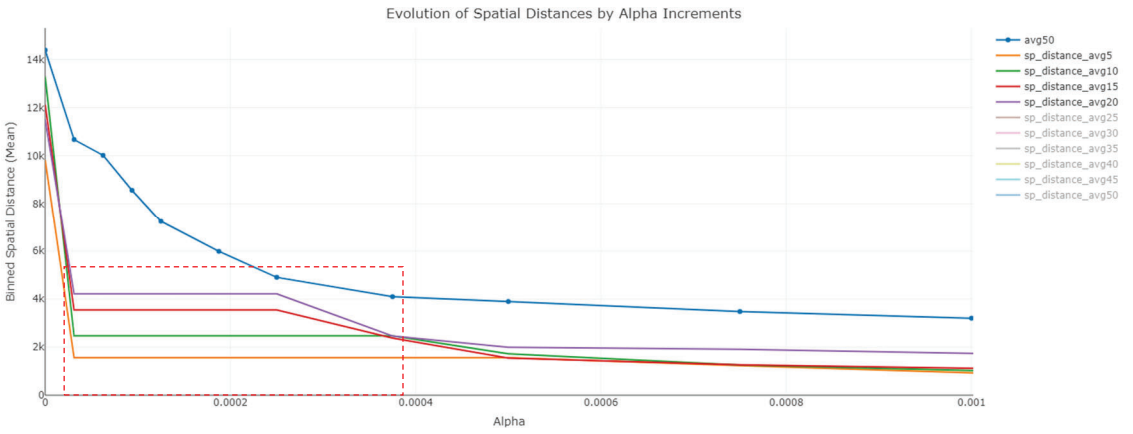


Figure 80. Detailed plots of spatial distance averages: avg5 to avg20.

It is evident how the behaviour of the avg5 to avg20 plots is constant up to 0.000250 and the avg15 to avg20 averages decay and coincide for 0.000375.

The second aspect to highlight from Table 36 is the changes for $0.000375 \leq \alpha_i \leq 0.000750$. Note that for all α_i values the first 6 matches are coincident; there are 8 coincidences between 0.000500 and 0.000375; and 11 matches are equal between 0.000375 and 0.000250. In addition to the fact that these common matches reinforce the aforementioned statement (especially between 0.000375 and 0.000250), we can notice that from $\alpha_i = 0.000500$ onwards there are noticeable changes in the matches, once again pointing to the α_3 and α_4 values where the spatial dimensions start to become more and more significant.

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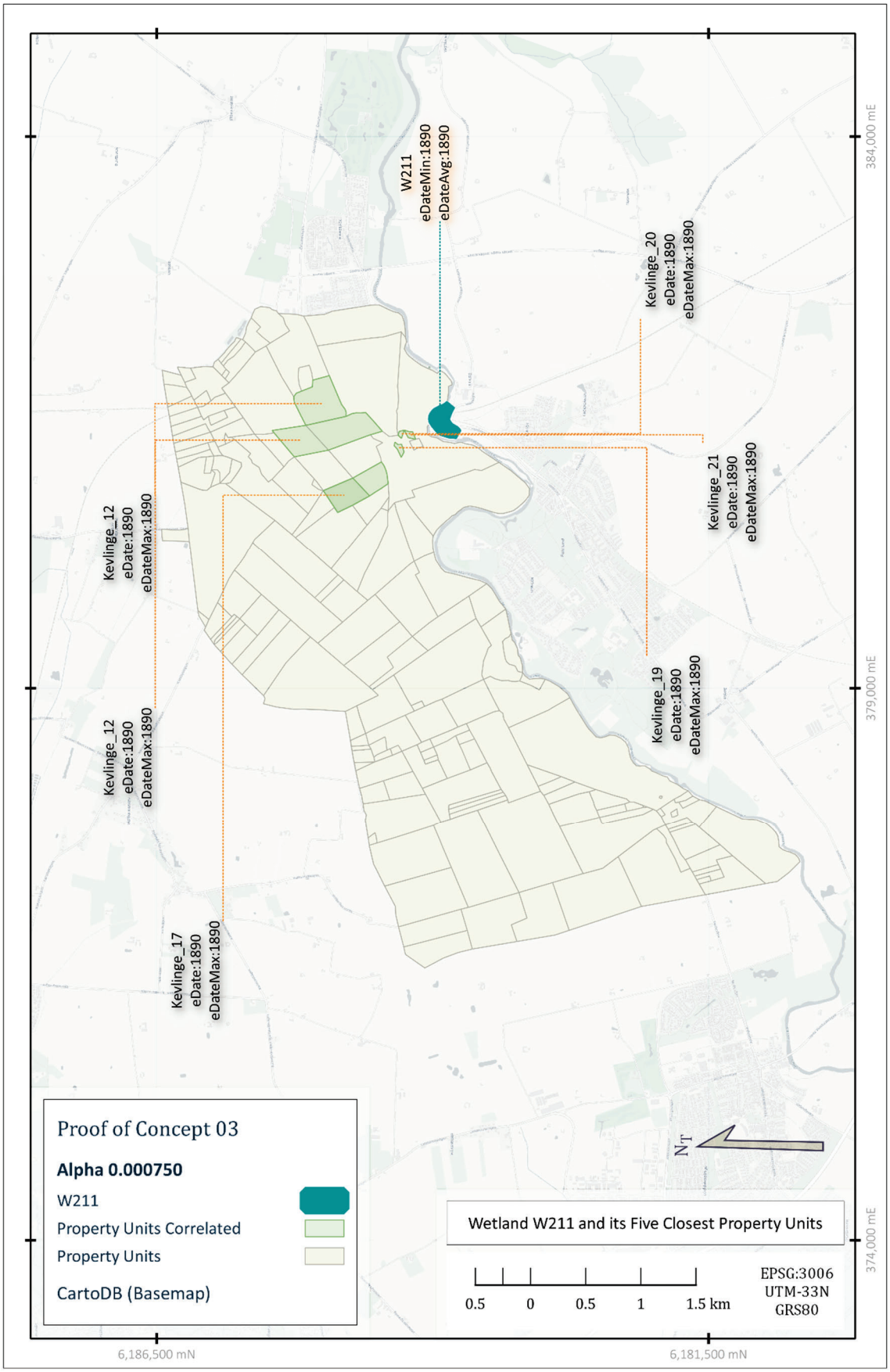


Figure 81. The five closest property units correlated with wetland *W211* for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000750, 0.000750)$.

Table 36. First twelve ordered correlated *Wetlands* and *Property Units* for $\alpha = c(1, 1, \alpha_i, \alpha_i)$.

$(1, 1, 0.000750, 0.000750)$		$(1, 1, 0.000500, 0.000500)$		$(1, 1, 0.000375, 0.000375)$	
X6	**X7**	**X6**	**X7**	**X6**	**X7**
W211	Kevlinge_21	W211	Kevlinge_21	W211	Kevlinge_21
W318	Tranas	W318	Kjellstorp_05	W318	Kjellstorp_05
W185	Vasagarden_05	W185	Vasagarden_05	W185	Vasagarden_05
W268	Vasagarden_05	W268	Vasagarden_05	W268	Vasagarden_05
W262	Vasagarden_05	W262	Vasagarden_05	W262	Vasagarden_05
W269	Vasagarden_05	W269	Vasagarden_05	W269	Vasagarden_05
W270	**Oregarden_mfl**	W170	Godstorp_01	W170	Godstorp_01
W186	Oregarden_mfl	W168	Vasagarden_05	W168	Vasagarden_05
W305	Kevlinge1012_Torvmosse	**W270**	**Oregarden_mfl**	W231	Hog_12
W170	Godstorp_01	W186	Oregarden_mfl	W283	Halmstad_14
W181	Troskeberg_01	W305	Kevlinge1012_Torvmosse	W230	Kevlinge_02
W187	Oregarden_mfl	W181	Troskeberg_01	**W270**	**Oregarden_mfl**
$(1, 1, 0.000250, 0.000250)$		$(1, 1, 0.0001875, 0.0001875)$		$(1, 1, 0.0001250, 0.0001250)$	
X6	**X7**	**X6**	**X7**	**X6**	**X7**
W211	Kevlinge_21	W211	Kevlinge_21	W211	Kevlinge_21
W318	Kjellstorp_05	W318	Kjellstorp_05	W318	Kjellstorp_05
W185	Vasagarden_05	W185	Vasagarden_05	W185	Vasagarden_05
W268	Vasagarden_05	W268	Vasagarden_05	W268	Vasagarden_05
W262	Vasagarden_05	W262	Vasagarden_05	W262	Vasagarden_05
W269	Vasagarden_05	W269	Vasagarden_05	W269	Vasagarden_05
W170	Godstorp_01	W170	Godstorp_01	W170	Godstorp_01
W168	Vasagarden_05	W168	Vasagarden_05	W168	Vasagarden_05
W231	Hog_12	W231	Hog_12	W231	Hog_12
W283	Halmstad_14	W283	Halmstad_14	W283	Halmstad_14
W230	Kevlinge_02	W230	Kevlinge_02	W230	Kevlinge_02
W162	Bessinge	W162	Bessinge	W162	Bessinge
$(1, 1, 0.00009375, 0.00009375)$		$(1, 1, 0.00006250, 0.00006250)$		$(1, 1, 0.00003125, 0.00003125)$	
X6	**X7**	**X6**	**X7**	**X6**	**X7**
W211	Kevlinge_21	W211	Kevlinge_21	W211	Kevlinge_21
W318	Kjellstorp_05	W318	Kjellstorp_05	W318	Kjellstorp_05
W185	Vasagarden_05	W185	Vasagarden_05	W185	Vasagarden_05
W268	Vasagarden_05	W268	Vasagarden_05	W268	Vasagarden_05
W262	Vasagarden_05	W262	Vasagarden_05	W262	Vasagarden_05
W269	Vasagarden_05	W269	Vasagarden_05	W269	Vasagarden_05
W170	Godstorp_01	W170	Godstorp_01	W170	Godstorp_01
W168	Vasagarden_05	W168	Vasagarden_05	W168	Vasagarden_05
W231	Hog_12	W231	Hog_12	W231	Hog_12
W283	Halmstad_14	W283	Halmstad_14	W283	Halmstad_14
W230	Kevlinge_02	W230	Kevlinge_02	W230	Kevlinge_02
W162	Bessinge	W162	Bessinge	W162	Bessinge

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We will now present the results for vector `alpha <- c('1', '1', '0.000375', '0.000375')`, doubling the importance of temporal dimensions by halving the α_i value previously assigned to the spatial dimensions (see Figure 82 and Figure 83). The results are also presented when tripling the importance of time through the vector `alpha <- c('1', '1', '0.000250', '0.000250')` (see Figure 84). It can be noted that doubling or tripling the importance of time has no major effect on the analysis for the first to twelfth records, maps show that only the record 12th changes when comparing both scenarios. Nonetheless, significant changes are identified when compared to the vector vector `alpha <- c('1', '1', '0.000750', '0.000750')`, 7 out of 12 matches are different, showing that when prioritising temporal dimensions results are different and more significant to answer the question posed in page 216.

Figure 83 shows an interesting fact. Note maps V1, W1, and Y1, when doubling the importance of the temporal dimensions ($\alpha_i = 0.000375$) these maps show a contra intuitive behaviour. Despite map Y1 shows that the wetland *W270* and the property unit *Oregarden_mfl* are very close in geographic space (~208 m between centroids), this match is ordered at the position 12th while the geographic features represented in maps V1 and W1 at positions 10th and 11th are significantly further apart (~4.4 and ~5.5 km). This behaviour means that the features correlated in V1 and W1 are closer in time than the ones matched in Y1, and because we are doubling the importance of time, the calculated distance between trajectories $d_{\mathcal{M}}^{(\alpha,\beta)}$ denotes the lower significance of the Euclidean distances for this specific α_i value.

Note also that the same match (*W270-Oregarden_mfl*) is also identified for $\alpha_i = 0.000500$ and $\alpha_i = 0.000750$, however, it is ordered at positions 9th and 7th (see Table 36), becoming more important. This corroborates how the geographic distance becomes more significant while α_i increases (the closer geographically, the more important). On the other hand, the analysed match is no longer classified in the first twelve records when tripling the importance of time ($\alpha_i = 0.000250$), which means that the temporal difference between the dimensions of the wetland *W270* and the property unit *Oregarden_mfl* must be greater than the differences of the first twelve records, actually, it is just 1 year but it results in 0 years for the first twelve records. This also implies that the difference between the distances $d_{\mathcal{M}}^{(\alpha,\beta)}$ are very small, but just enough to classify the relevance of the correlated features.

5.6.4 Conclusions of the Analyses Performed in the Proofs of Concept

We can safely draw some conclusions from our analyses. We implemented three different and complementary modelling scenarios to understand and gain insights into the intertwisted relations of *Wetlands* and *Property Units* across time in the county of Scania in the Kingdom of Sweden. These modelling scenarios have provided the information needed to solve the problem stated earlier: *to identify the most correlated pairs of the type Property Units–Wetlands that represent the evolution of properties versus drainage of wetlands over the period 1801–1914. Is there a correlation between these phenomena over time?*

In response to the question posed, it is possible to affirm that there exist significant correlations between the occurrence and changes in the *Property Units* and the drainage of *Wetlands*. The information gathered from the temporal, spatial, spatio-temporal, and temporospatial analyses has shown solid evidence of this conjecture. This information was derived from calculating the distances between trajectories, i.e., $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i^W, \gamma_i^P)$.

Both the spatial and temporal analyses have shown that there exist geographic features that are very close both in space and time; maps A–L and maps M–Y point to evidence of this (see Figure 69, Figure 70, Figure 71 and Figure 72). However, it was not sufficient to examine these components separately to solve the stated problem and, therefore, different analyses integrating spatial and temporal dimensions were considered by weighing such dimensions through different α_i values. Some of them gave more significance to space ($i.e.\ \alpha_i > 0.000750$), others to time ($i.e.\ \alpha_i < 0.000750$), whereas others equilibrated the weights and, therefore, the significance of the dimensions integrated into the modelling approaches ($e.g.\ \alpha_i = 0.000750$).

During the modelling iterations performed to adjust the significance of each dimension, *the interval [0.00003625; 0.520000] was determined as the range of* α_i *values in which a change in the parameter* `alpha` *represented changes in the identified relationships (matches)*; α_i values less than and greater than such a range voided the significance of the spatial and temporal dimensions, respectively. The break-even point between the dimensions considered in the analysis was determined to be $\alpha_i = \sim 0.000750$. When doubling the significance of the temporal dimensions by considering $\alpha_i = 0.000375$, the response to the question posed arose. It came into view that the property units *Kevlinge_21*; *Kjellstorp_05*; *Vasagarden_05*; *Godstorp_01*; *Hog_12*; *Halmstad_14; Kevlinge_02;* and *Oregarden_mfl* were identified as having affected the surrounding wetlands the most, in particular, *W211*; *W318*; *W185*; *W268*; *W262*; *W269*; *W170*; *W168*; *W231*; *W283*; *W230;* and *W270*. Maps M1–Y1 show these interactions (see Figure 82 and Figure 83). We have listed these correlated geographic features, bearing in mind that only the first twelve ranked records have been systematically visualised throughout the analyses; nonetheless, the complete list of correlations is available at the data repository[42] for this dissertation. In addition, classification for the entire 513 wetlands available in the SEDD data set is provided in the Excel spreadsheet *shortestDist_Full_XY_0.000375*. No temporal correlations were identified for 152 wetlands under the modelling conditions proposed.

At first glance, we can confidently conclude that there exists a temporal correlation between the analysed phenomena because *(i)* the information derived from the analysis (i.e., the descending order of the lowest calculated temporal distances) shows it to be so; and *(ii)* when the above-listed wetlands were manually compared one by one as a visual validation method, it was evident from their *geolifespan* that at least some parts of them had been drained, giving way to new areas of properties, or they were close enough to have been affected by the listed property units. Furthermore, the cartographic compositions show this to be the case, and the parameterisation of the modelling scenario ($\beta = 1, \mathcal{M} = 27, \alpha = \mathrm{c}(1, 1, 0.000375, 0.000375)$) allows this conclusion to be reached.

The final answer could be refined by considering the results derived from the parametric vector $\alpha = \mathrm{c}(1, 1, 0.000500, 0.000500)$; the maps S2–Y2 in Figure 85 show the records ranked in the 7th to 12th positions. Note that the first eight matches are the same for $\alpha_i = 0.000375$ and $\alpha_i = 0.000500$, and, therefore, they coincide with those depicted in Figure 82 (see maps M1–R1). However, when $\alpha = \mathrm{c}(1, 1, 0.000500, 0.000500)$ is applied, and, therefore, the spatial dimensions are slightly prioritised over the temporal ones, the matches ranked 9th to 12th show closer features and more intuitive spatial correlations (see Figure 85, maps U2–Y2). This result is somewhat evident, as we have increased the significance of the spatial dimensions, even if only a little. *This complementary result shows more coherent spatial results*; however, it will depend on the scenario of the application of the results whether that

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can be considered more relevant or significant by giving slightly more importance to time or space. Note that for the two α_i modelling cases, the temporal dimensions remain more significant than the spatial ones.

It should also be underlined that the question could not be exclusively answered by considering the temporal dimensions (as initially expected). In order to ascertain a coherent and logical method for solving the problem, it was necessary to include the spatial dimensions. The reasons for doing so were clarified during the implementation of the third proof of concept, but they can be summed up by considering that the problem faced follows closely the First Law of Geography; the very nature of the analysed phenomena somehow forced us to consider the spatial dimensions to accomplish it. However, it was essential to *keep the temporal nature of the analysis to a maximum by minimising the significance of the spatial variables for as long as possible*; only in this way could we identify significant matches representing the *intertwined temporal evolution* of the *Property Units* and the *Wetlands*. *This is a major characteristic of the modelling framework; its robustness allows one to manage and prioritise the analysed dimensions systematically, prioritising one set of dimensions over others as required*; in the case of the proofs of concept performed, this means prioritising time over space as much as possible or as much as required. Figure 53 to Figure 85 represent in detail the results obtained and the reasoning behind the solution of the problem.

The three proofs of concept have also shown that it would be difficult to answer the question posed with a conventional spatial-centred approach. It may be possible to identify extinct *Wetlands* that existed nearby *Property Units*, but this would not imply a relationship between them beyond geographic distance. *The modelling framework provides the mechanisms to evaluate to which degree the evolution of wetlands and properties is linked and to identify intertwisted changes and correlations at spatial, temporal, and semantic levels*. The temporal-based, spatial-based, temporospatial-based, and spatio-temporal-based analytical approaches have shown that a mixed analytical scenario is required to answer the question posed; not only mixing, but also balancing the participation of the analysed dimensions. *The temporospatial relationships highlighted in maps M1–Y1 (Figure 82 and Figure 83), G2–L2 (Figure 84), and S2–Y2 (Figure 85) could not have been identified by considering only spatial relationships*. Note that for the spatial case, the results of the analyses showed an incremental progression in the Euclidean distances between the centroids taken as reference, as shown in maps M–Y (Figure 71 & Figure 72) and, particularly, in Figure 73. Therefore, the reasoning framework allows the identification of relationships, changes, and correlations that could go unnoticed or would be challenging to evaluate with a conventional spatial-centred approach, as in the case of the *W211–Kevlinge_21* relationship.

Finally, it is worth remarking that despite the weaknesses and inconsistencies of the analysed data set, which were described throughout the analyses (overall, the coarser temporal granularity of the geographic features analysed), *The Cube of Time* — ***Ct***— has proved to be robust and flexible and, overall, appropriate to solve the problem and the question posed.

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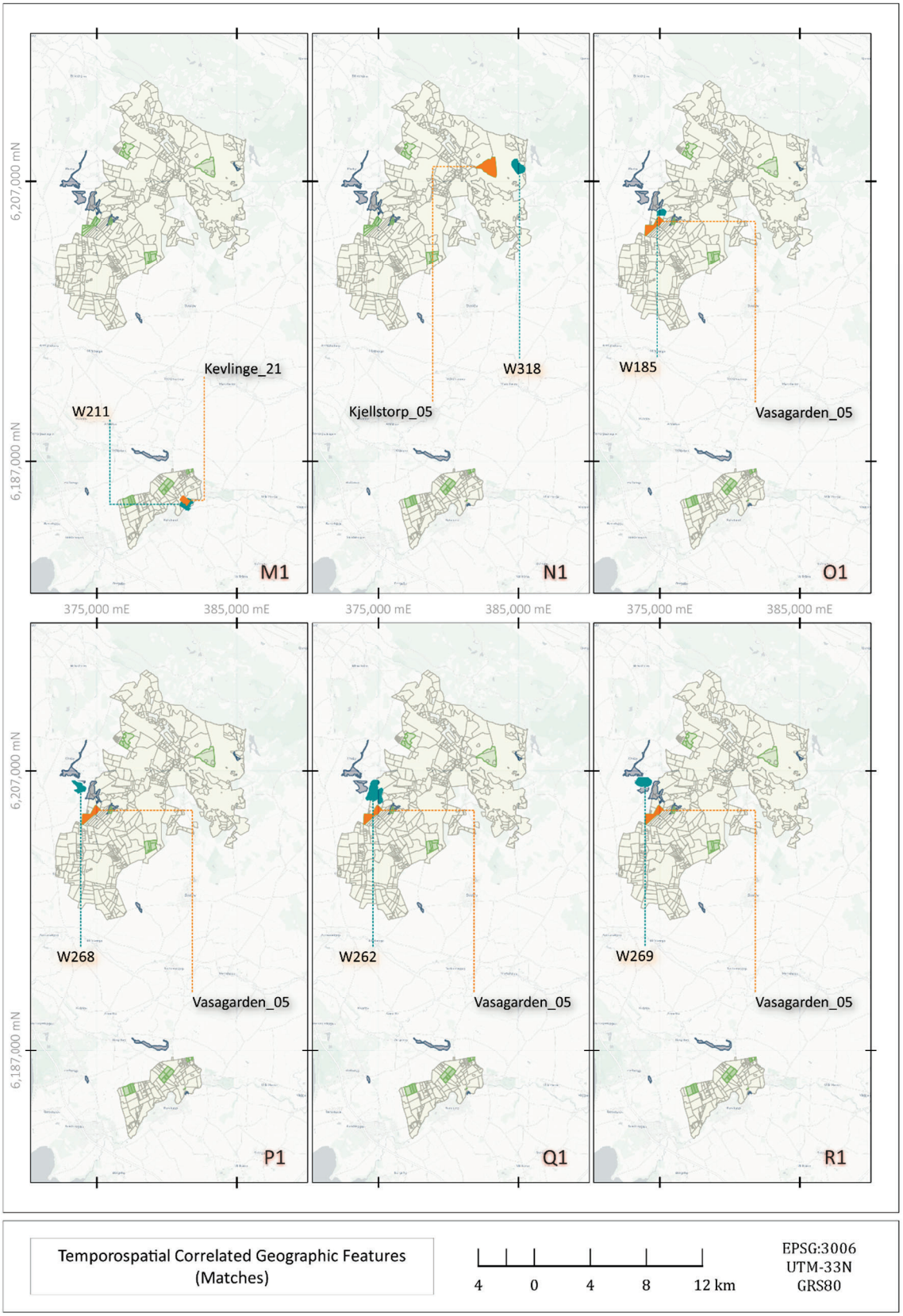


Figure 82. Geographic location of the matches ranked 1st–6th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000375, 0.000375)$.

Some *Property Units* and *Wetlands* have been rescaled to better visualise the geographic matches.

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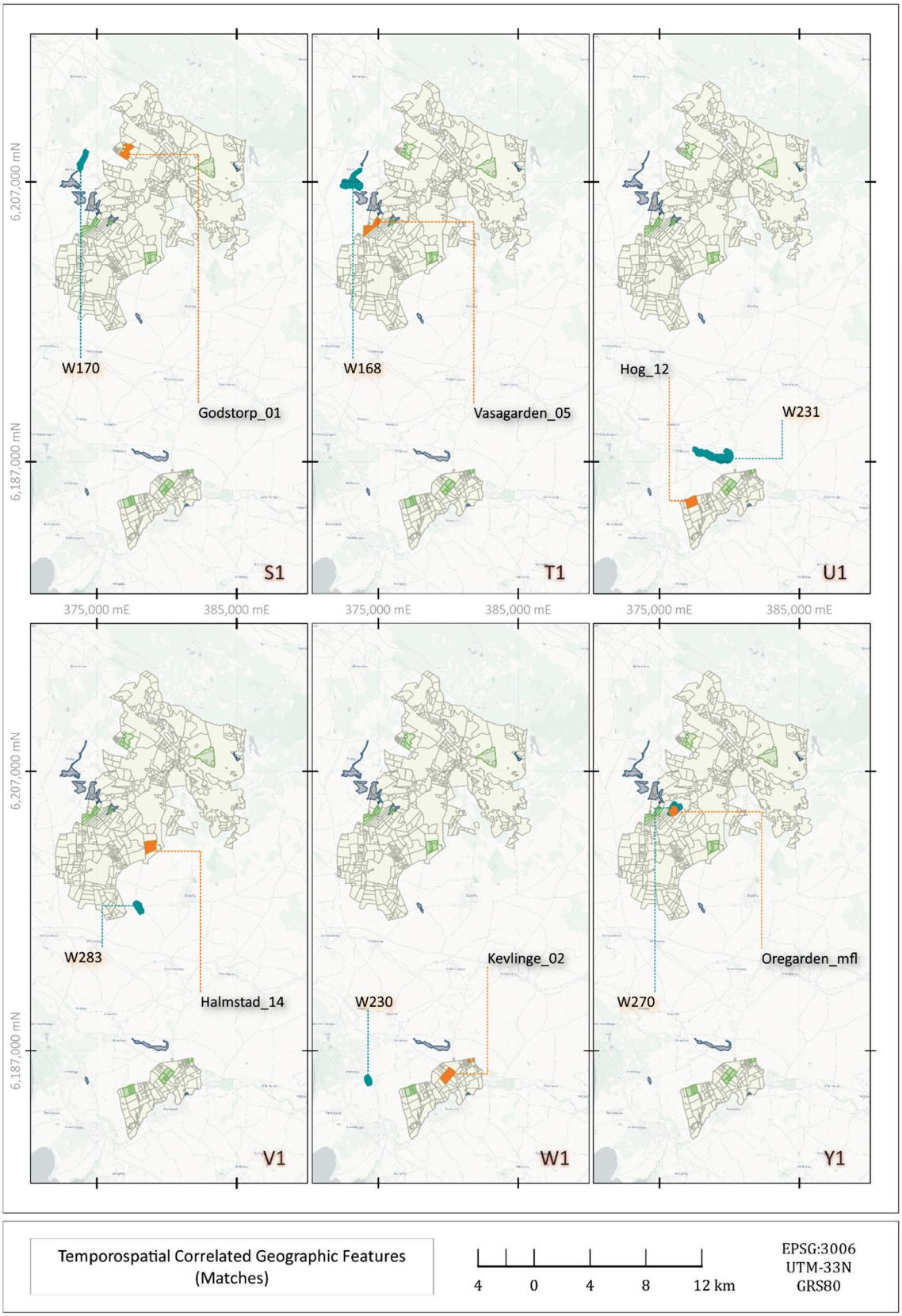


Figure 83. Geographic location of the matches ranked 7th–12th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = \mathrm{c}(1, 1, 0.000375, 0.000375)$.

Some *Property Units* and *Wetlands* have been rescaled to better visualise the geographic matches.

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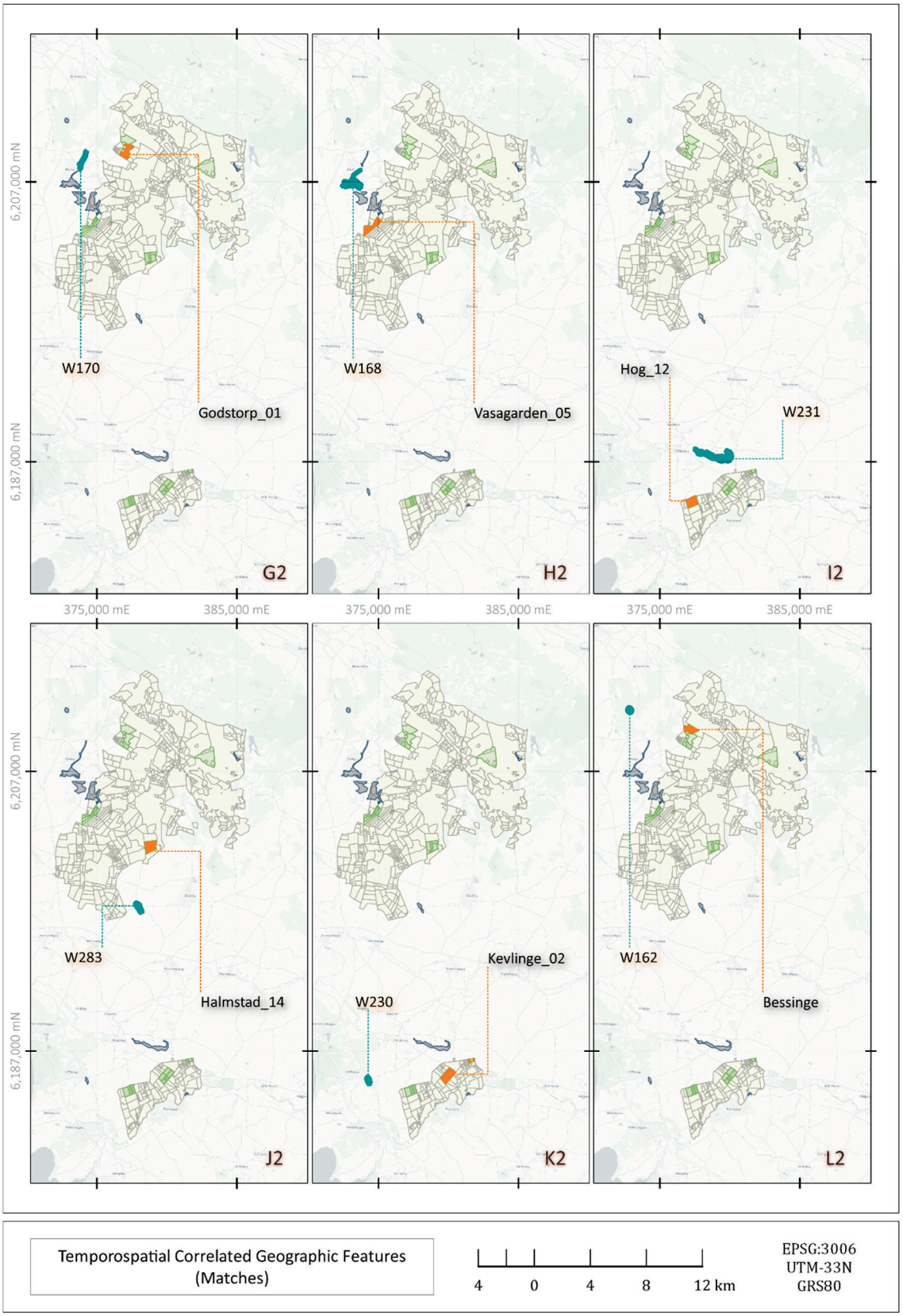


Figure 84. Geographic location of the matches ranked 7th–12th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000250, 0.000250)$.

Note that maps A2–F2 are not represented because the 1st–7th matches are the same as those presented in Figure 82. Some *Property Units* and *Wetlands* have been rescaled to better visualise the matches.

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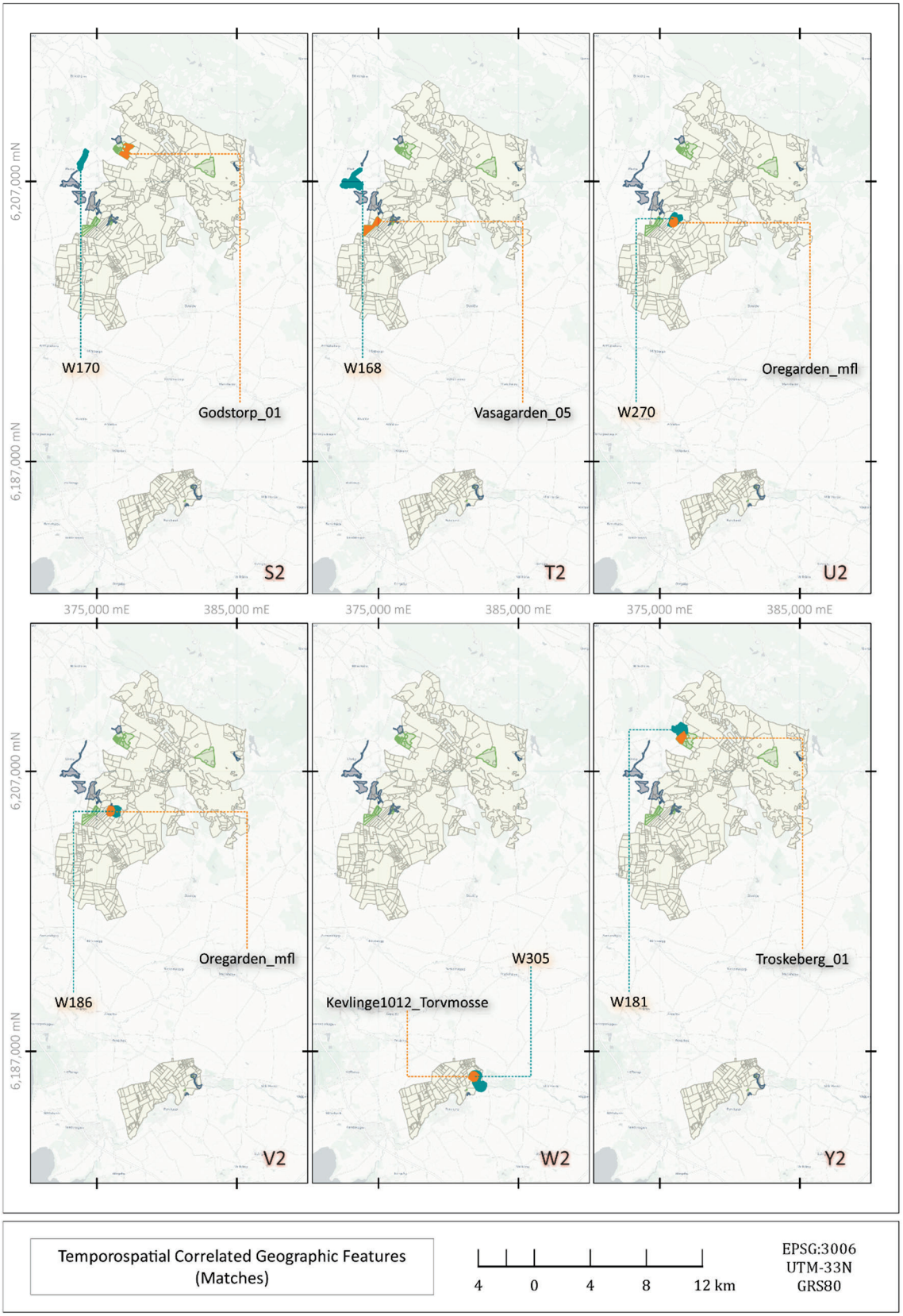


Figure 85. Geographic location of the matches ranked 7th–12th for $\beta = 1$, $\mathcal{M} = 27$ and $\alpha = c(1, 1, 0.000500, 0.000500)$.

Maps M2–R2 are not represented because the 1st–7th matches are the same as those presented in Figure 82. Some *Property Units* and *Wetlands* have been rescaled to better visualise the geographic matches.

5.7 Case Study

Having explained and discussed the foundations and characteristics of the modelling and reasoning framework (***Ct***) through the different tests and experiments, this section discusses a case study to demonstrate its flexibility and robustness by presenting an alternative method for defining trajectories and an example of a second-order analysis through the integration of distances for pattern discovery. We will briefly document a study based on the *health data set of the Capital District of Colombia related to acute respiratory infections during the period 2011–2019*.

5.7.1 Modelling scenario

Acute respiratory infections (ARI) are a group of transmissible diseases that affect the upper and lower respiratory tract and are typically characterised by a course of no more than 20 days. These diseases are caused by microorganisms, such as viruses (e.g., influenza, parainfluenza, adenovirus, rhinovirus, rotavirus, metapneumovirus, bocavirus, and respiratory syncytial virus,) and bacteria(e.g., *Haemophilus influenzae* and *Streptococcus pneumoniae*), which can cause anything from a common cold to pneumonia and in some cases even death. The average incubation period for such illnesses is known to be between 2 and 6 days, and the average infection period from the outbreak of the disease is known to be between 4 and 12 days.

The health data set provided by the Capital District of Colombia reports 4645 cases for the period 2011–2019. It is composed of *136 variables, of which 15 are of a temporal nature*. To obtain insights and a better understanding of the data set and ARI, we sought expert opinion and support: a physician who works in the Epidemiology Department of the District Secretariat of Health in Bogotá D.C. —*DSH*— explained the data entry form to us, the meaning and significance of each variable, and the purpose of data entry with special emphasis on the temporal variables. Considering the nature of the analysed phenomena, and the information gathered from discussions with the physician, the question posed to validate the model through this case study is as follows:

> Given the health data set of the Capital District of Colombia related to ARI-type respiratory conditions during the period 2011–2019, *can spatial or spatio-temporal global patterns be identified by considering temporal dimensions as the core component of the analysis*? What temporal and spatio-temporal patterns can be identified from the different types of dates selected from the data set?

Generally speaking, the monitoring of diseases is carried out from the instant a patient reports the onset of symptoms; this is, the moment when the body starts to show clinical signs. Determining whether the clinical condition is mild or severe depends on the development of symptoms and, with this information, a physician can verify the type of treatment to follow. Mild illness is viral in origin, highly contagious, and of short duration and is usually treated with home isolation and antiviral drugs. In contrast with mild cases, severe illnesses may be viral or bacterial in origin, the onset of symptoms is less than 14 days, and is characterised by shortness of breath. Unlike mild cases, severe illnesses must be treated in hospital and the patient's condition monitored more closely. It should be borne in mind that such descriptions cannot be fully generalised; environmental conditions in a specific area can significantly affect the behaviour of infections. For this case study,

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therefore, we also considered the analytic description provided by the National Institute of Health in Colombia (Instituto Nacional de Salud 2020).

Considering this typical medical behaviour and the expert advice given by the physician who supported this case study, we determined that *five out of the fifteen temporal variables available in the data set were required to answer the question* posed earlier. A brief description of the selected temporal dimensions to be considered is presented below:

1. *Onset of symptomatology* corresponds to the date that the patient reported as the day on which the symptoms of respiratory impairment began (`'fec_ini_si'`).
2. *Date of consultation* corresponds to the date on which the patient attended and was assisted by the health service provider unit (`'fec_con'`).
3. *Date of hospitalisation* corresponds to the date on which the patient in care started hospital treatment because s/he was considered to be at high risk (`'fec_hos'`).
4. *Date of admission to ICU* corresponds to the date on which, despite hospital treatment, the patient's situation showed further complications and it was critical to transfer her/him to an Intensive Care Unit (ICU) (`'fec_ing_uc'`).
5. *Death* is the date on which the patient dies due to respiratory complications resulting from ARI (`'fec_def'`).

As mentioned earlier, *only five out of fifteen temporal dimensions were selected*. The reason for excluding the remaining variables was the scope of the proposed analysis: six dimensions are related to dates for vaccinations, X-rays, and the supply of antibiotics and antivirals (i.e., the specific dates of the applied treatments). Two dates (dimensions) are related to data quality processes. In addition, the dimension notification date (`'fec_not'`) is highly correlated to date of consultation (`'fec_con'`) and would not bring significant changes to the calculation of distances if considered. Finally, the date of birth of patients would be quite significant for specific demographic analyses but is not required if general patterns or behaviours related to the total reported cases are sought. For instance, if the question posed had been related to people over 60 and under 5 years of age (i.e., the populations at most risk), then this dimension would certainly be one of the most relevant to consider, but this was not the case.

Before introducing the rationale behind the analysis, a few details regarding the data wrangling and data exploration performed must be given. As with the proofs of concept, no details will be presented about the ESDA performed for in-depth understanding and gaining insights into the data provided by the District Secretariat of Health. However, *it is important to highlight that a complete normalisation of the data and a thorough data wrangling process were required*, including the elimination of duplicate records which were not trivial to identify (i.e., not simply a matter of identifying duplicate data rows). The most important task carried out was the geocoding of the 4645 cases reported by the Health Secretariat, which was essential to define the analysed trajectories and to be able to exemplify a different methodology of analysis. Nine per cent of the raw records required manual geocoding or refinement. The geocoding services implemented were the Esri ArcGIS Geocoding Service, Google My Maps, and QGIS Geocode Web Service (OpenStreetMap / MMQGIS). As a result, the cleaned data set was composed of 4572 records amenable for analysis, of which 4110 belong to the area of analysis. It is also important to note that *the provided data set was previously anonymised by the DSH*.

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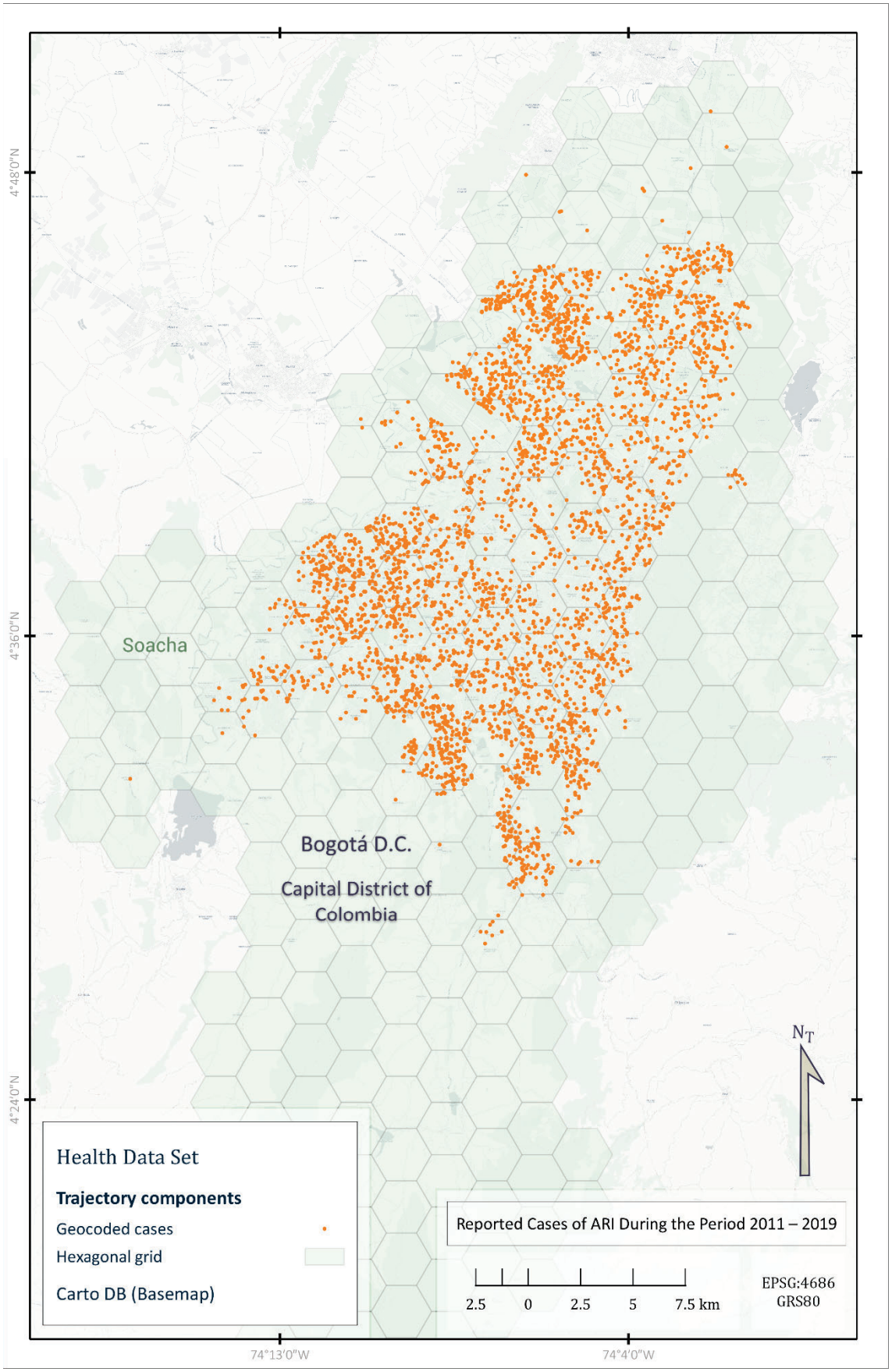


Figure 86. Reported cases of acute respiratory infections (ARI) for the conurbation of Bogotá D.C. and Soacha during the period 2011–2019.

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Following this short introduction to the case study, we will now define the elements to set up and run the model by following the recommendations given in section 5.6.1.

5.7.2 Geographic Framework of Analysis

Strictly speaking, we not only considered the ARI cases in the Capital District of Colombia, but also those reported in the municipality of Soacha, a small town neighbouring Bogotá D.C. The two urban areas share strong socio-economic interaction, so viruses can easily spread between them. In what follows, we will refer to this conurbation simply as Bogotá D.C. or the Capital District. Figure 86 represents the conurbation as a hexagonal grid.

Although the 4645 cases reported in the data set provided by the Health Secretariat correspond to those attended to in the hospitals of the capital city, the geocoded addresses correspond to places of residence. Approximately 10% of the reported cases correspond to people living outside the city, or even abroad. For the case study, we only considered patients who lived in the Capital District, i.e., 4110 cases. As mentioned earlier, the data set provided by the DSH was previously anonymised. In addition, the accuracy of the geocoding process is not sufficient for the exact identification of the reported places of residence.

5.7.3 Justification of the Trajectories and Parameterisation

With regard to the *selection of the temporal dimensions* to be analysed, most of this has been discussed previously. It needs to be clarified, however, that the Health Secretariat's data set records the temporal variables as follows:

```
IRA_fields          <- c('OBJECTID', 'CODIGO', 'localidad', 'fec_not',
'fec_con', 'fec_ini_si', 'fec_hos', 'fec_def', 'fec_nacimi', 'fec_cal_da',
'fec_ajuste', 'fec_fud_hi', 'fec_fud_sp', 'fec_fud_ei', 'fec_tom_ra',
'fec_antib', 'fec_antiv', 'fec_ing_uc')

IRA_fields   <- IRA_fields[c(6, 5, 7, 18, 8, 1, 2)]
```

For the implementation of this case study, we show a different approach to define the trajectories: in contrast with the proofs of concept in which we considered a common ID to integrate the *geolifespans*, for the case study, we apply spatial units to integrate the *Timing Points* that compose each trajectory (see points per hexagon in Figure 86), and note that spatial units operate as spatial indices.

Strictly speaking, from an administrative viewpoint, the option that should be considered as a spatial unit for the definition of the trajectories is one of the administrative planning units into which the Capital District is segmented (e.g., postal codes, localities, or neighbourhoods). This approach might seem reasonable. However, in order to generalise the results and to make them more comprehensible to a broader audience (e.g., those who are not familiar with the administrative boundaries and characteristics of the city), we decided to segment the analysed urban areas through a hexagonal grid. This segmentation guarantees that *the spatial units implemented are equal in area*, which for the purpose of comparison between trajectories is more convenient. Another interesting characteristic of hexagons is that they allow for a *homogeneous segmentation of irregular polygons*, such as the planning units or the whole perimeter of the Capital District. Thus, the hexagonal approach would also allow generalisations to be extended to larger spatial units, such as the city's own administrative units, by recovering their average behaviours; this is without

ruling out that calculations can be made from the beginning for any kind of spatial unit. Figure 86 shows the hexagonal grid and the geocoded ARI cases that compound the trajectories. A total of 107 hexagons contain at least one *Timing Point*, which represents one reported ARI case. Table 37 shows the corresponding trajectory for the hexagon 198 (γ_{Hex}^{198}).

Note that the hexagonal grid is a common and convenient data structure for indexing and analysing spatial data; one of the most extended systems is the *H3 hierarchical geospatial indexing system*, which is mostly used for converting between geographic coordinates and H3 geospatial indexes (see e.g.,Wang, Li, and Zhang 2019, Herrera and Godoy-Faúndez 2021, Melikov *et al.* 2021). Although our hexagonal lattice does not strictly follow the spatial distribution of any of the sixteen (16) levels of spatial granularity that compound the *H3 system*, it is very close in its location and resolution to *level 7*. [54]

The size of the gridded hexagons was defined according to the number of points expected per trajectory. In contrast with the proofs of concept in which the defined trajectories were characterised by a coarse temporal granularity, the ongoing case study is expected to take full advantage of the fine temporal granularity available for the health data set analysed. Therefore, it is expected to have a high number of points per spatial unit of analysis to maximise the number of *Matching Points* between trajectories. This will help to make the distances calculated more significant in terms of temporal relationships. Thus, the selected size (*level 7*) of the hexagonal grid ensures a balance between the number of points per hexagon.

Table 37. *Timing Points* that compound the trajectory γ_{Hex}^{198} for the year 2019.

Timing Point	fec_ini_si	fec_con	fec_hos	fec_ing_uc	fec_def	OBJECTID	CODIGO
1	18033	18035	18035	18036	*NA*	2650	4484
2	18049	18050	18050	18050	*NA*	2672	4514
3	18055	18056	18056	*NA*	*NA*	2679	4522
4	18074	18077	18077	*NA*	*NA*	2694	4540
5	18092	18093	18093	18093	*NA*	4170	4551
6	18136	18136	18140	*NA*	*NA*	3401	4586
7	18172	18172	18172	18172	*NA*	2732	4601
8	18191	18191	18191	18191	*NA*	2745	4617
9	18191	18197	18197	18201	*NA*	2746	4618
10	18213	18213	18213	18213	*NA*	2750	4626

Notice that dates were converted to numbers in order to optimise the distance calculations. The RStudio® platform follows as a reference date the 00:00:00 "UTC" on 1st January 1970, which corresponds to the numeric value 0. Thus, 18033 corresponds to 17th May 2019, representing the number of days since the reference date.

The next step is the parameterisation. The rationale behind the definition of values for parameters α, β and $\mathcal{M}$ is mostly based on technical discussions with the physician who supported this case study. *With regard to the parameter α*, we must consider two points. *First*, since all the selected temporal dimensions share the same units and have equal temporal granularity (i.e., days), the data set dimensions included in the analysis do not need to be rescaled. *Second*, since no date is more important or significant than the others

[54] https://h3geo.org/docs/core-library/restable/

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in the context of the stated problem, all dimensions will be equally weighted. One must keep in mind that, despite equal weights, the first temporal dimension is the most relevant because it is the one selected to identify the *Matching Points*; however, this does not imply a higher significance when calculating distances. Therefore,

$$\alpha = (1,1,1,1,1) \qquad \mathbb{R}^5.$$

The parameter $\mathcal{M}$ depends on the behaviour of the viruses in the urban area of Bogotá D.C. The physician pointed out that the city's own viral circulation should be considered. After data exploration, pneumonia and influenza were identified as the most frequent diseases for the reported period. Respiratory syncytial virus infection (RSV) is the most common in infants, especially for children under the age of 1 year. RSV is the leading cause of death in children under 6 months of age in Bogotá (Instituto Nacional de Salud 2020).

As described above in section 5.7.1, the average *incubation period* for ARI-type illnesses is defined as between 2 and 6 days, and the average *infection period* from the outbreak of the disease is defined as between 4 and 12 days. *These averages are the key elements in defining the parameter* $\mathcal{M}$ and were defined considering the frequency of cases/diseases reported in Bogotá D.C. during the period of analysis. Both the infection and incubation periods are quite important because they can be associated with the spread of the diseases. The parameter $\mathcal{M}$ defines an interval that allows the capture of possible simultaneous infections across the periods analysed. *Virus and bacteria can be transmitted from day zero until full recovery or even further*. Therefore, by considering the two potential periods of transmission or spread, we defined two different $\mathcal{M}$-values that represent the different intervals derived from the average periods (see Figure 87), each value representing a different analysis scenario to be implemented. Thus,

$$\mathcal{M} = 5 \quad \text{and} \quad \mathcal{M} = 10.$$

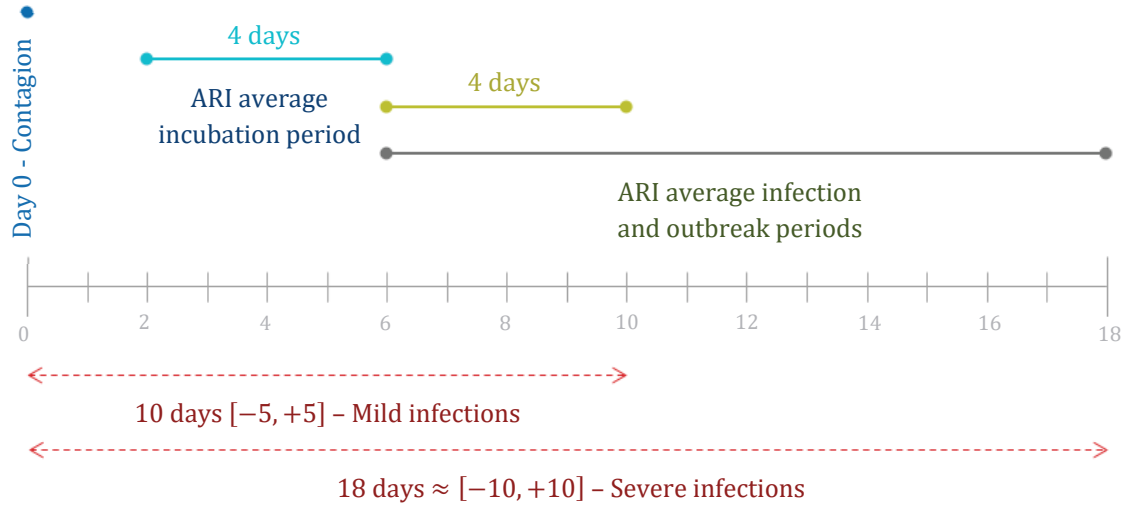


Figure 87. Intervals of the average incubation and infection periods upon which the parameters $\mathcal{M}$ are defined.

The interval for long-term illnesses was extended from 18 days to 20 days to perform scenarios duplicating the values of parameter $\mathcal{M}$. As shown in the conclusion of the analysis, there are no significant differences between $[-9, +9]$ and $[-10, +10]$. The average intervals represented correspond to mild and severe infections, typical of the upper and lower respiratory tract, respectively.

It should be stressed that the parameters $\mathcal{M}$ were defined by considering average standard temporality, i.e., without taking into account the behaviour of diseases in patients under special conditions. For instance, immune-depressed patients can even transmit syncytial virus 4 weeks after they get and feel better. Therefore, it should be emphasised that the incubation and transmission periods referred to are typical and represent patients under average normal conditions. Special conditions such as the presence of immunosuppressants may lead to longer incubation and transmission days and could be considered for another type of analysis.

With regard to the *parameter β*, we will follow the same reasoning that was applied to the different proofs of concept. Considering that we used hexagonal spatial units of analysis to integrate the geocoded punctual ARI cases (i.e., to define the trajectories), the parameter β can help determine the importance of the number of *ARI cases matched per pair of hexagonal units*. A parameter $\beta = 0$ would mean, for instance, that the modelling scenario does not consider the potential differences between hexagons holding only *1 matching case* versus *100 matching cases* (only considering a base distance[55]: averages of $d^{(\alpha)}$, see pp. 203, 204). However, this is a non-reasonable scenario, since a high number of matched ARI cases would represent a stronger potential correlation between the illnesses registered in the two areas being compared (hexagons).[56]

Therefore, to equilibrate this situation and to define the significance of the number of *Matching Points* between hexagonal spatial units when distances $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i,\gamma_j)$ are calculated, *we have defined $\beta = 4$*. One must keep in mind that when the value of parameter β increases, a higher priority is given to distances calculated from a greater number of *Matching Points*. In addition, fixing `beta` and the base distance, the greater the number of matches, the higher the correlation. For instance, a calculated base distance of 40 based on *11 Matching Points* will be equivalent to a base distance of approximately 30 (≅30) based on 5 matches (see explanation on p. 227). In contrast, the same base distance of 40 based on *13 Matching Points* will represent a higher correlation between the linked hexagonal spatial units (lower distance), even if a base distance of 40 is a priori greater than 30, i.e., less correlated. Given $\beta = 4$:

$$\left(40 + \frac{\beta}{11}(40)\right) \cong \left(30 + \frac{\beta}{5}(30)\right)$$

$$\left(40 + \frac{\beta}{13}(40)\right) < \left(30 + \frac{\beta}{5}(30)\right)$$

A complementary discussion of a more robust method of defining parameter β is presented in Annexe A.1 (check it on page 369). By following this new method, the parameter β can be more easily defined by the expression:

$$\beta = \frac{c - a}{\frac{a}{\kappa_1} - \frac{c}{\kappa_2}};$$

[55] $1/\kappa \widehat{\mathcal{D}}_{\mathcal{M}}^{(\alpha)}$ in the algorithm explained in p. 204.

[56] For the whole period of analysis (2011–2019), the min and max number of cases per spatial unit are 1 and 118, respectively; only the 25% of the hexagonal grid that covers the Capital District have at least one ARI case reported (primarily urban area, see Figure 88).

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which, when applied to the data previously exemplified, results in

$$\beta = \frac{30 - 40}{\frac{40}{11} - \frac{30}{5}} \cong 4.$$

Thus, in brief, we have defined the following parametric values for *setting up two different modelling scenarios*, the first representing short-term diseases and the second representing long-term affections, which could also be interpreted as mild and severe impacts, respectively.

```
alpha   <- c(1,1,1,1,1)
beta    <- 4
M       <- 5

alpha   <- c(1,1,1,1,1)
beta    <- 4
M       <- 10
```

5.7.4 Temporal Distances

Once the trajectories have been defined and the parametric values determined, it only remains to apply the **R** functions described in section 5.6.1.5 for the calculation of distances. The ongoing case study has also been implemented through **RStudio®** and the base functions are the same as those applied to the proofs of concept. Such functions are the core component for the implementation of the reasoning framework. Some specific considerations for the implementation of the case study are as follows:

1. We take the reasoning behind the analyses performed in the proofs of concept one step further. Since the aim is not only to find intertwined pairs (*Wetlands* vs. *Property Units*), but also to *identify potential spatio-temporal patterns that describe the behaviour of the ARI cases reported in the entire geographic area of analysis*, an additional operation is required to *integrate the individual calculated distances*. In this case, a *mean field* is considered, specifically, a *mean field distance* (*MFD*) (i.e., a kind of average distance assigned to each hexagonal unit), which is defined by

$$MFD_{\mathrm{Hex}_i}^{(\alpha,\beta)}_{\mathcal{M}} = \frac{1}{\sharp\,\mathcal{A}_i} \sum_{j \in \mathcal{A}_i} d_{\mathcal{M}}^{(\alpha,\beta)}\left(\gamma_{Hex}^{i}, \gamma_{Hex}^{j}\right),$$

   where $\mathcal{A}_i = \{j : Hex_j \sim Hex_i\}$; $Hex_j \sim Hex_i$ indicates that the trajectory j can be linked to the trajectory i through at least one *Matching Point*; and $\sharp\,\mathcal{A}_i$ is the cardinal of the set $\mathcal{A}_i$.

2. Thus, *we will not consider individual but aggregated distances*. Note that to aggregate the paired calculated distances $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i, \gamma_j)$, we could use the *statistical measures of central tendency* and *measures of dispersion and variability*. The choice of any of these measures leads to answering different sorts of questions. For the question posed, we are exemplifying through an *MFD* but it could be another aggregation strategy. In general, aggregation strategies will help to *reveal the potential patterns derived from the behaviours* of the analysed phenomena; in this case, the ARI mean temporal behaviour.

3. In order to validate the effectiveness of our model, the simplest statistical measure was selected (i.e., *mean*); more specifically, an application of the MFD. More advanced analyses could be implemented aggregating the distances by considering other types of measures. However, at this point, we prefer to keep this calculation as simple as possible to avoid "noise" in the analysis of the results presented. In other words, we want to ensure that the patterns identified are justified by the implementation of our modelling proposal and not by the additional calculations derived from the aggregation tasks. Of course, other different approaches can be applied on the basis of the aggregated and individual values, such as K-Means, K-Medians, or hierarchical methods.
4. The patterns can be identified for the whole period of analysis or for shorter periods (e.g., epidemiological weeks[57] or years). During the implementation of the case study, we will consider individual analyses for the *entire data period, as well as for each epidemiological year*. The complete set of calculus is available at the data repository for this dissertation[42].
5. Since the hexagonal grid is a compound of 433 spatial units and each trajectory will be computed against the others, a theoretical total of 187,489 non-symmetric distance calculations are required. Nonetheless, as described above in section 5.6.1.5, `NA` values will reduce these computations.

A total of twenty (20) modelling scenarios were executed: two (2) parameterisations per 9 epidemiological years plus two (2) parameterisations for the full period. The results of the analyses were recorded in 4 distinct Excel workbooks: two for the global analysis (2011–2019) and two for the annual overviews[58]. As in the proofs of concept, four spreadsheets are available for each modelling scenario (*matches_**; *distances_**; *shortestDistances_**; and *shortestDistancesByColumn_**). The results of the calculated distances between trajectories and the integrated values per spatial unit (MFD) are available for downloading at the data repository[42] for this dissertation. The raw data that the trajectories comprise, and part of the data derived from intermediate processes, are also available for retrieval as *RData* workspaces.

Finally, it must be highlighted that although only the MFD of the calculated distances will be considered for the ongoing analysis, the **R** functions of the modelling and reasoning framework also provide the full set of usual statistical measures: *standard deviation; median; Q1; Q3; IQR; min; and max*. These integrated values could be considered for other analytical scenarios and cartographic representations.

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[57] According to the World Health Organisation, an epidemiological week, commonly referred to as an epi week, "is simply a standardized method of counting weeks to allow for the comparison of data year after year". "The first epi week of the year ends, by definition, on the first Saturday of January, as long as it falls at least four days into the month. Each epi week begins on a Sunday and ends on a Saturday". "The Weekly Epidemiological Record (WER) serves as an essential instrument for the rapid and accurate dissemination of epidemiological information on cases and outbreaks of diseases under the International Health Regulations and on other communicable diseases of public health importance, including emerging or re-emerging infections". This approach helps to compare epidemiological data globally. See https://www.who.int/publications/journals/weekly-epidemiological-record

[58] resultsRStudio-ARIHex-Annual-**M10**B4A1.xlsx resultsRStudio-ARIHex-Annual-**M5**B4A1.xlsx
resultsRStudio-ARIHex-Global-**M10**B4A1.xlsx resultsRStudio-ARIHex-Global-**M5**B4A1.xlsx

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5.7.5 Analysis of Results

Figure 88 to Figure 93 show the results of the ARI case study. First of all, we can confidently state that *the modelling framework is able to identify spatial patterns by considering temporal dimensions as the core component of the analysis*. The temporal dimensions have been central at the processing level, whereas the impacts on the spatial and semantics dimensions are considered when analysing the emerging patterns. This means that not only spatial and spatio-temporal patterns can be identified, but also semantic ones; *in this case study, these patterns related to mild and severe acute respiratory infections*. The analysis performed has demonstrated the robustness and flexibility of the modelling and reasoning framework. Let us now present some specific details of each result.

The cartographic representations in Figure 88 and Figure 89 show the *mean field* of the calculated temporal distances by considering averages from each spatial unit of analysis to the whole set of remaining units, i.e., $MFD_{\mathrm{Hex}_i}{}_{\mathcal{M}}^{(\alpha,\beta)}$. So, if different hexagonal spatial units are represented in the same class (see map legends), it means that their mean temporal behaviours linked to ARI cases are similar, more specifically, *spatial units have similar mean field correlation*. Note that although spatially represented, the identified patterns are temporal, more precisely, the identified clusters have revealed the zones with similar *mean field temporal correlations* for the ARI cases reported across the different areas of the capital city of Colombia during the period 2011–2019. The *five temporal dimensions* selected to calculate temporal correlations have clearly uncovered the global spatial patterns, represented as coloured clusters. The identified correlations could be categorised into high, medium, and low: *high* considering the classes with the smallest distances (i.e., dark brown in colour) and *low* for the classes in blueish tones (the greatest distances).

Figure 88 represents the results for the modelling scenario based on the parameterisation $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$. This map clearly shows that during the period 2011–2019 the urban area of Bogotá D.C. concentrates different but structured mean temporal behaviours. It is also noted that there exist areas of the city that certainly have some common characteristics and behaviours in addition to their mean field temporal behaviour. For instance, the clearest pattern is seen when comparing the central area with the peripheral zones of the city; the contrast between the high MFD correlation of the inner spatial units and the very low correlation at the outskirts of the city is quite evident. *The suburban areas classified with low correlations have the highest MFD values and are therefore the most differentiated on average from the rest of the city*. This means that the temporal behaviour of ARI cases is *quite different between the inner city and its boundaries* (dark brown vs. blueish tones). Other geographic areas such as the airport, large urban parks, or protected zones such as the urban wetlands also show a similar behaviour represented in the cartographic representations (white in colour); this last fact is significant about the quality of the results because this class has integrated areas that are known to be mostly uninhabited.

As a complementary point of view, Figure 89 shows the results for the modelling scenario based on the parameterisation $\mathcal{M} = \mathbf{5}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$. Keeping in mind the nature of parameters $\mathcal{M} = \mathbf{5}$ versus $\mathcal{M} = \mathbf{10}$, one could complement the analysis of the results by differentiating the mild and severe cases (see Figure 87). At first glance, when comparing the classification of the spatial units between Figure 88 and Figure 89, despite a few differences, we can state that the identified spatial patterns are equal, mainly if the *high*,

medium, and *low* categorisation is applied. Thus, this second modelling scenario shows that when considering the *mean field temporal correlation* to identify spatial patterns, there is no evident difference between the mild and severe cases registered, i.e., between long- and short-term ARI cases. Apparently, the temporal behaviour of such cases is quite similar irrespective of the different number of *Matching Points* identified per each modelling scenario: 131,206 ($\mathcal{M} = \mathbf{5}$) versus 190,958 ($\mathcal{M} = \mathbf{10}$). Therefore, another possible explanation for this similar behaviour is that most of the cases reported in the data set can be classified as mild. Additional analyses should be applied to validate this claim, for instance, by splitting the data set considering mild illnesses on the one hand and severe illnesses on the other. However, considering the results described above, we can hypothesise that no major differences would be found in a complementary analysis.

Although spatial patterns have been identified and there exist common characteristics, we cannot assert what causes their configuration; more detailed analyses would be required to determine causality. In any case, this is not the question being answered. Possible viewpoints for a deeper analysis are the concentrations of particulate matter in the atmosphere ($PM_{2.5}$ or PM_{10}) due to the presence of industrial areas, the density of fibreglass, cement and concrete factories, the high presence of freight transport, and the use of firewood, amongst other sources of particulate matter that could be measured and modelled. Some studies have claimed to find positive associations between an increase in the number of hospitalisations and exposure to high concentrations of $PM_{2.5}$ (e.g., Gobbo César *et al.* 2016). One could even consider sociocultural or socio-economic factors affecting changes in $PM_{2.5}$ and PM_{10} concentrations. Nonetheless, this causality analysis is far beyond this case study. What is possible to state from a quick visual exploration is that the two areas of the city known to have the strongest industrial activity were classified in the high correlation clusters (dark brown in colour). This second result also validates the first ARI analytical case study and, therefore, the feasibility of the proposed model. It is worth mentioning that the physician who supported this analysis checked the maps, interpreted the patterns discovered, and, according to her medical and epidemiological knowledge, found them reasonable, especially the atypical behaviours represented in the outskirts of the city; her feedback was fundamental in the development of this case study.

At this point, we must remark that *although we have considered a spatial index (hexagons), the global urban patterns were extracted from the five temporal dimensions analysed*; the spatial index only helped to organise the data as trajectories and, subsequently, to represent the calculated distances through maps. Thus, the modelling framework and the concept of mean field temporal correlation based on the distances $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i, \gamma_j)$ applied to uncover spatial patterns can be presented as a novel approach in the field of spatio-temporal analysis. To the best of our knowledge, this analytical approach does not yet exist, at least in the models referenced in the *Time*Bliography. We have shown that the set of abstract mathematical definitions allows the identification of temporal and semantic patterns not including spatial dimensions as part of the analysis, i.e., as elements of the analysed trajectories.

Another complementary viewpoint could be considered if the same reasoning from the proofs of concept were applied to the ARI case study; in this scenario, it would be possible to identify the urban areas with the highest temporal similarity considering the reported ARI cases. However, this would be a *unitary analysis*, representing pairs of hexagons, and

would not allow for the recognition of general or global patterns describing the behaviour of ARI across the city. This sort of analysis would be related to a question such as: *Which areas of the city have the highest temporal correlation?* To identify correlations between the areas represented by the hexagons, local analysis could be implemented, for instance, by implementing any type of Spatial Weights Matrix, $\mathcal{W}$, such as the ones based on contiguity (see Siabato and Guzmán-Manrique 2019). It is well known that in order to have a complete picture of the behaviour of a phenomenon in an analysed area, it is necessary to implement local and global analyses. Note that in applying a more conventional spatial analysis scenario, one could pose a question of the type: *Which times show the highest spatial correlations or autocorrelations?*

In addition, to validate the robustness of the modelling and reasoning framework, we implemented *supplementary analyses considering epidemiological years individually*. The entire health data set was segmented into nine subsets and then processed following the steps described above. A total of eighteen (18) modelling scenarios ($2\ parameterisations \times 9\ years$) were executed and the most significant results discussed herein. The first characteristic to highlight is that the yearly maps do not visualise the same number of hexagons as the two general maps. This characteristic allows identification of the areas in which no cases were reported for that particular year (Figure 90 and Figure 91 show this behaviour). Most of these areas coincide with the restricted or protected zones described earlier, such as the toponym *Airport* in Figure 91.

Another interesting comparison can be made between the cartographic representations in Figure 92 and Figure 93, which show the analyses performed for the maximum and minimum numbers of cases annually reported. Whereas 872 cases were reported in 2013, only 265 were registered in 2019; we will not discuss the reasons for this large difference here. However, what is noteworthy is the different behaviours of these two years. On the one hand, the 2013 analysis result (Figure 92) also allows identification of MFD clusters for the city's industrial areas. In addition, the behaviours previously identified in the urban peripheries are also observed in this individual analysis. These results are consistent with the global analysis (2011–2019) performed. In contrast, the results for the year 2019 (Figure 93) can be interpreted as random, not to mention that most of the spatial units of analysis are identified as very poorly correlated (blueish tones). It can also be observed that near the city's central area, there exists a very different behaviour to that identified in the general averages (see Figure 88 and Figure 89). We do not consider this behaviour an inconsistency in the model; as it emerged, *no insights can be extracted without representative data*. It seems that 265 cases may not be a representative sample from which to extract the expected spatial patterns or identify a temporal-data structure. However, when analysing the year 2012, for which 281 cases were reported, a well-known and recognisable urban cluster of maximum concentration of particulate matter was retrieved (see Figure 91 southwestern), so more extensive analyses are required to extract conclusions from the size of the analysed sample.

Finally, we would like to highlight that according to the cases reported by the District Secretariat of Health of Bogotá D.C., 2016 and 2018 were *peak years* for ARI-type infections. The analysis carried out for each of these years also *identified clusters in the southern and*

northern areas of the city. This identified and confirmed the annual patterns previously reported by the Health Secretariat.[59]

Regarding the classification method applied to the cartographic representations in Figure 88 to Figure 93, it is worth mentioning some clarifications and specifying why each map has its own Jenks intervals. It should be remembered that the Jenks classification method defines classes on the basis of variance: maximising it between classes and minimising it for each class. The cartographic representations in Figure 88 to Figure 93 visualise the distances calculated through seven classes using the same criterion (i.e., Jenks) and are, therefore, comparable between them from a classification point of view. On the other hand, to make them comparable in terms of the magnitude of the calculated distance (i.e., temporal correlation), it is necessary to apply some normalisation method to all the resulting distance groups (e.g., one per epidemiological year) because, as mentioned above (see p. 208), the concept of distance defined in this research is dimensionless $\left(d_{\mathcal{M}}^{(\alpha,\beta)}\right)$. A set of representations using the normalisation method $(d_i - d_{min}) \,/\, (d_{max} - d_{min})$ is available in Annexe A.4; these normalised representations correspond to the parameterisation $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

To conclude this analysis, we must recognise that this has been a bare evaluation. We have been able to answer the question posed, but other issues remain open, most of which are related to causality and the reasons for the concentration of ARI cases. *The results described have simply shown that there exists an MFD correlation with spatial structure*. The analysis of ARIs —acute respiratory infections— is of general interest since they are amongst the leading causes of death globally, particularly in developing countries. The World Health Organisation has pointed out that death rates are highly correlated with effective early interventions in high-risk age groups (below 5 and above 60 years old in Bogotá D.C.). Therefore, any useful analytical approach in this direction would be of help in preventing millions of deaths worldwide; a follow-up project derived from this case study would be worth the effort and time. For instance, for the specific case of Bogotá D.C., the behaviour of wet periods and the thermal variability patterns should be considered. It is well-known that the periods of highest rainfall in the city are April–May–June and September–October–November, months in which local ARI cases increase in frequency because they are usually associated with periods of the highest humidity. These characteristics suggest, for instance, that it may be better to analyse the data by quarters rather than by epidemiological years. Another aspect that could be of interest is the evolution of industries over time and their potential correlation with ARI cases. The urbanisation processes in Bogotá D.C. have been intensive during the last two decades, and the resulting changes have significantly affected the relocation of emission points for gases, particulate matter, and other types of pollutants.

[59] https://saludata.saludcapital.gov.co/osb/index.php/datos-de-salud/enfermedades-trasmisibles/canal-endemico-ira/
http://www.saludcapital.gov.co/Paginas2/Bolet%C3%ADn-Epidemiol%C3%B3gico-Distrital.aspx

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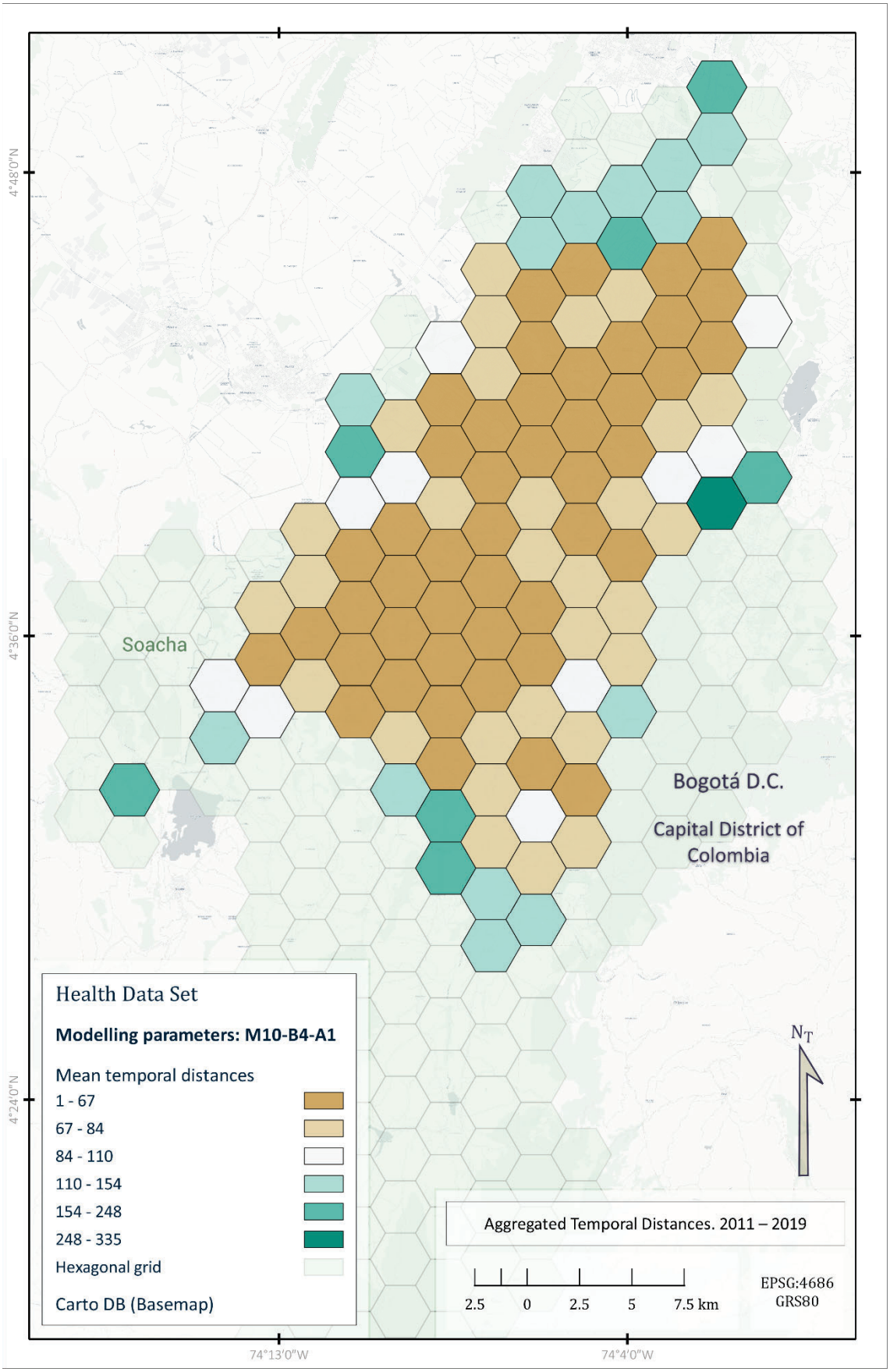


Figure 88. Spatial behaviour of the mean temporal distances calculated per spatial unit: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = c(1, 1, 1, 1, 1)$. Period 2011–2019.

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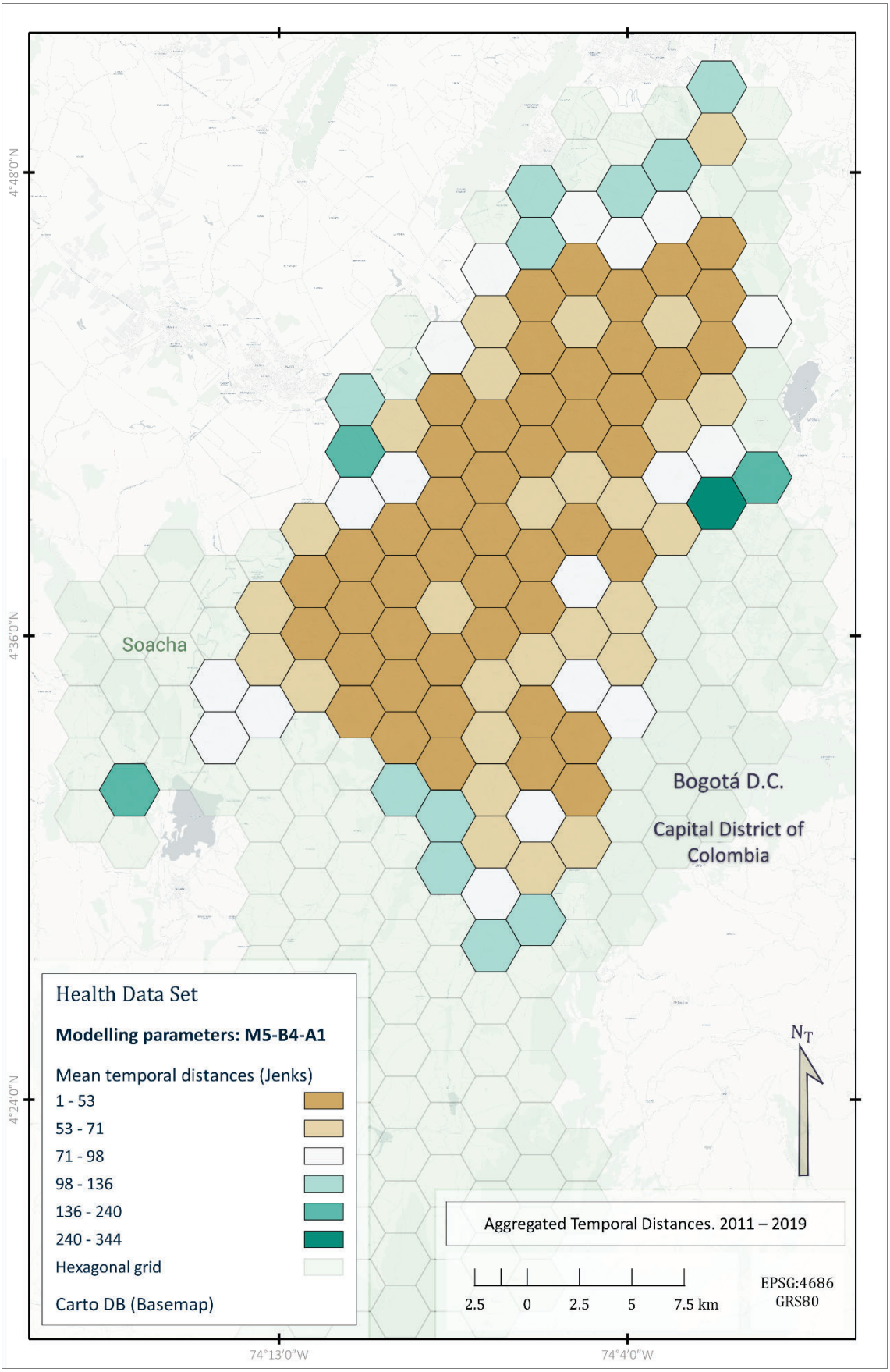


Figure 89. Spatial behaviour of the mean temporal distances calculated per spatial unit: $\mathcal{M} = \mathbf{5}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$. Period 2011–2019.

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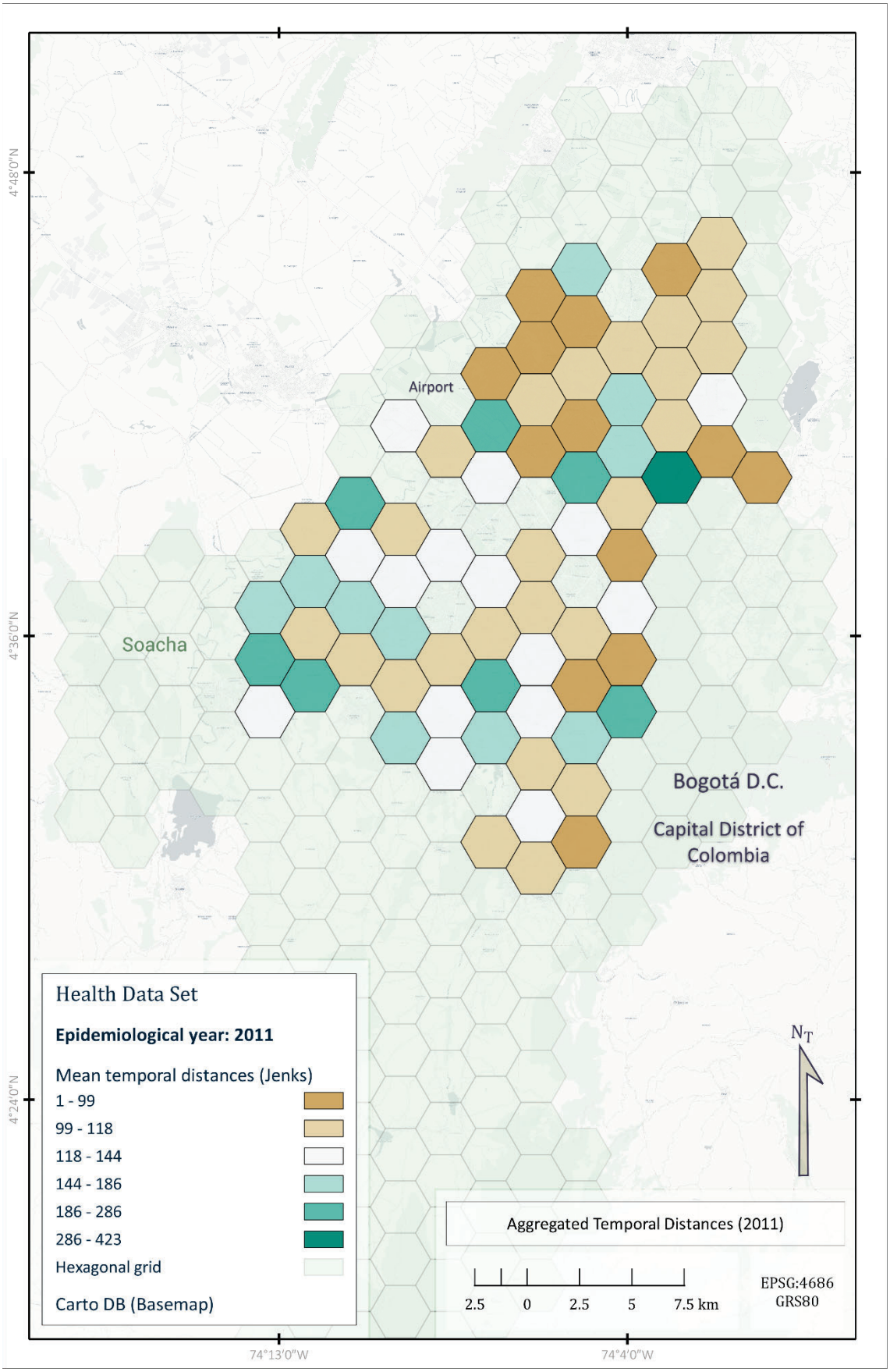


Figure 90. Spatial behaviour of the mean temporal distances for the epidemiological year 2011: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

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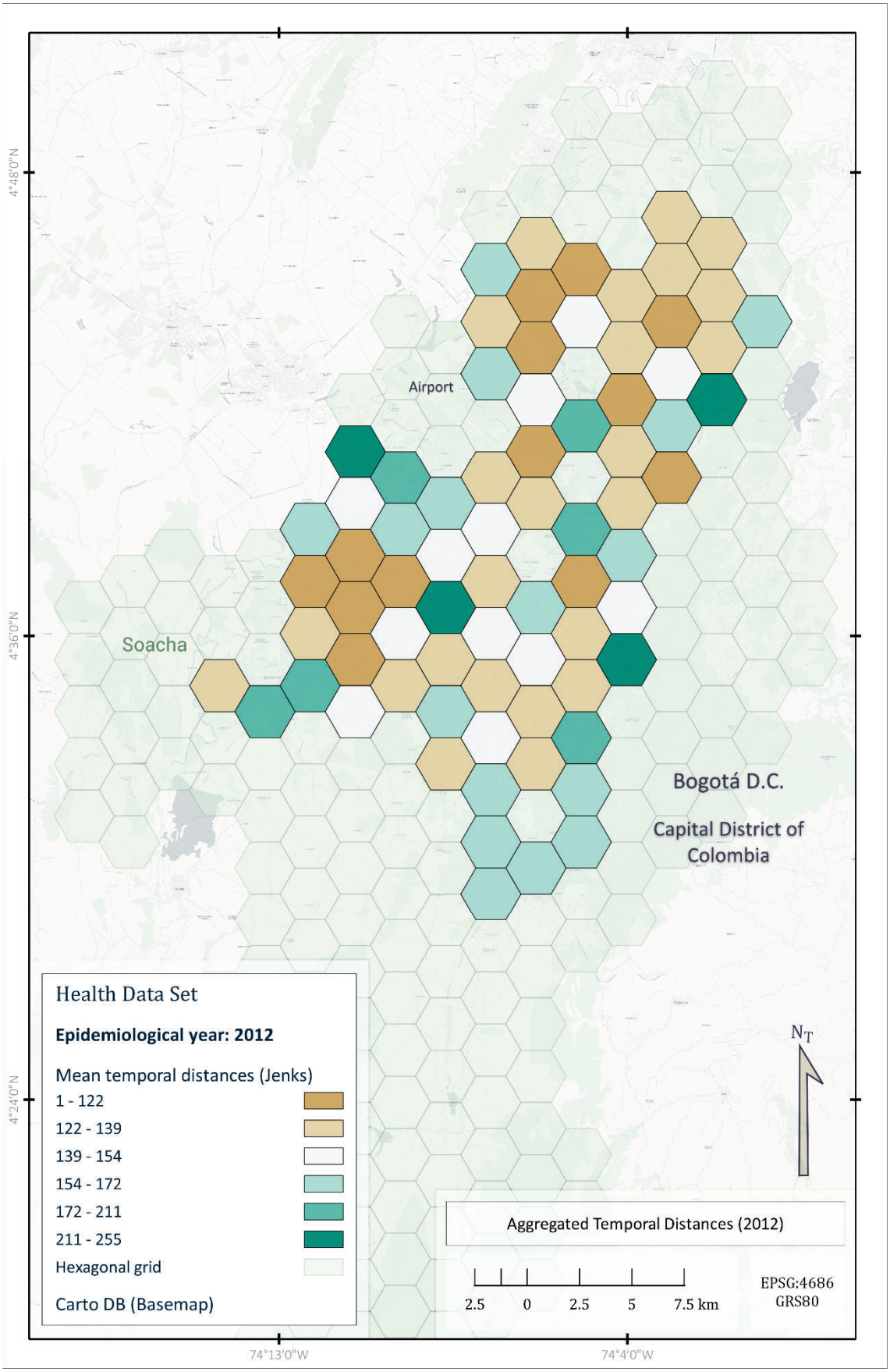


Figure 91. Spatial behaviour of the mean temporal distances for the epidemiological year 2012: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

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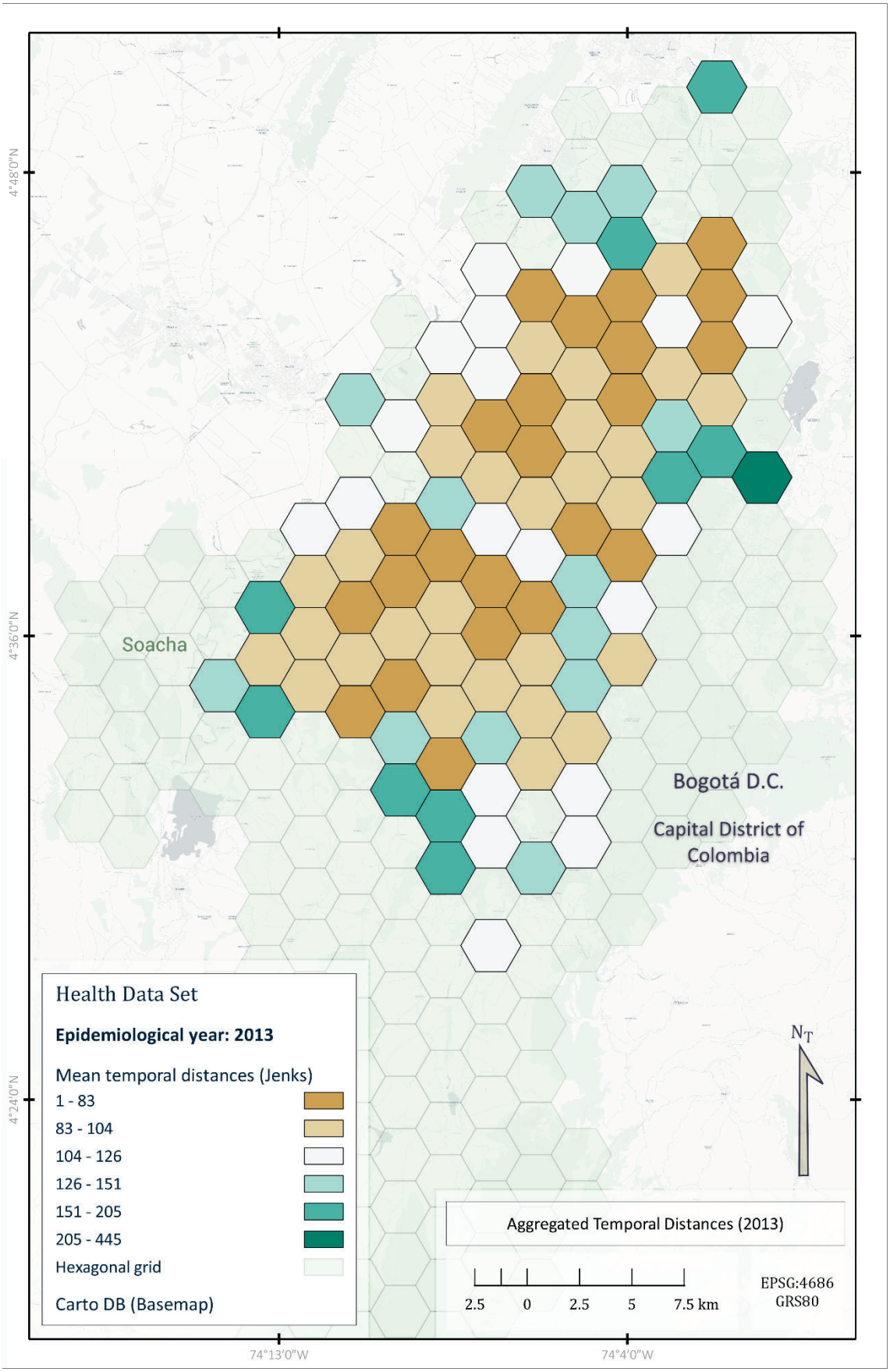


Figure 92. Spatial behaviour of the mean temporal distances for the epidemiological year **2013**: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

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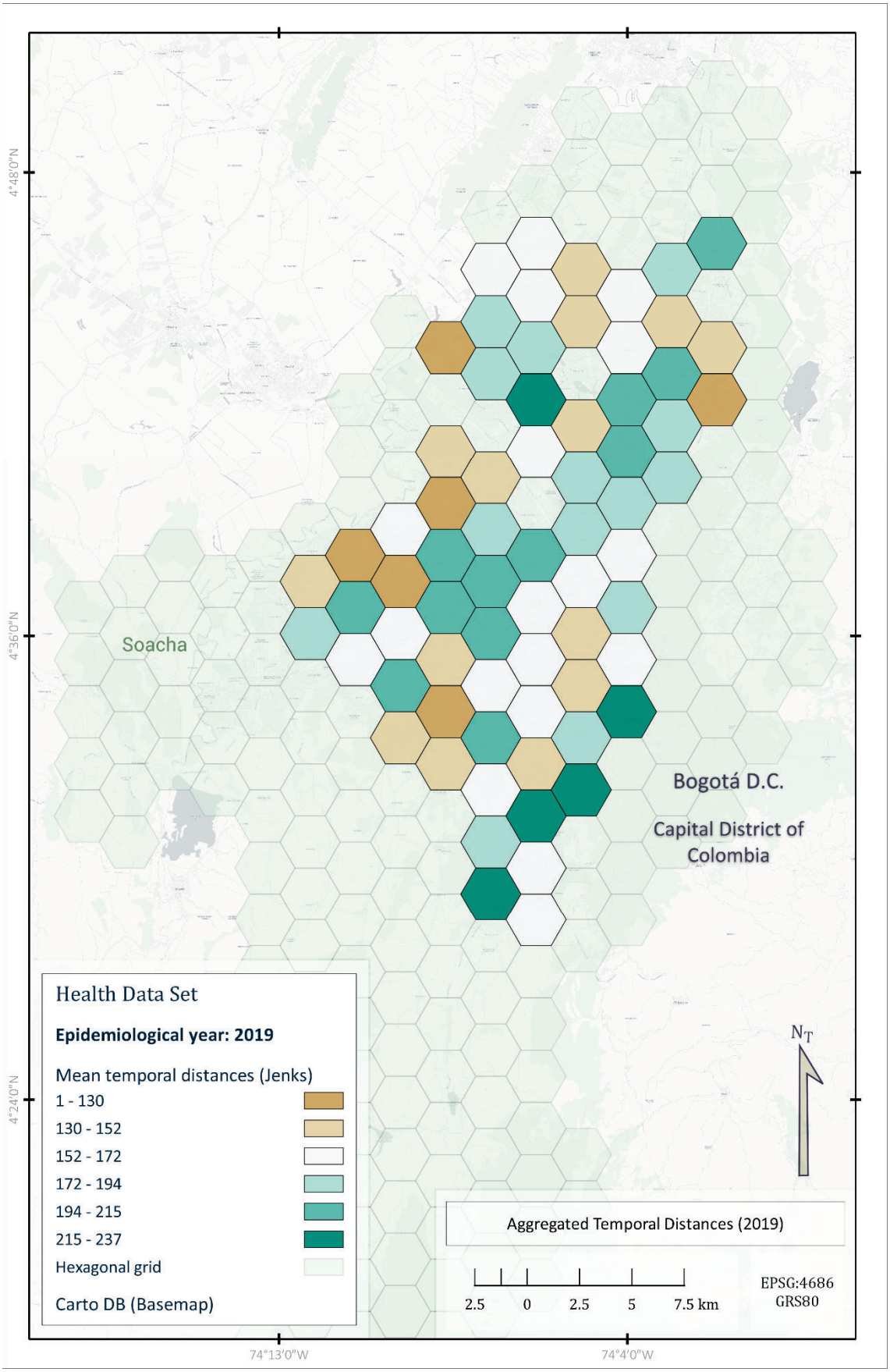


Figure 93. Spatial behaviour of the mean temporal distances for the epidemiological year 2019: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

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5.8 Final Highlights of the Modelling Framework

After discussing the results of the analyses, we now present some final remarks that will help to further clarify the nature of the modelling and reasoning framework (***Ct***). We have shown that there is no single way to solve a stated problem, and that the robustness and flexibility of the reasoning framework allow one to propose various modelling scenarios to address a question from different perspectives. The flexibility is based upon the freedom to model the parameters $\alpha, \beta,$ and $\mathcal{M}$ as required, as well as to define different kinds of trajectory γ according to the problem at hand. Of course, a suitable selection of the modelled dimensions is also a key factor in obtaining meaningful results. *It is the interaction of the parameters and the way the trajectories are defined that will ensure the model answers the questions posed*.

The flexibility to define different types of trajectory is a central component of this proposal. For instance, for the proofs of concept, we considered different scenarios with `'eDate', 'eDateMax', 'eDateMin',` and `'eDateAvg'`, as well as the spatial dimensions to establish the set of trajectories capable of answering the question stated, although other dimensions could have been selected if a different question had been asked. This is the idea underlying the ARI case study; as shown, only five temporal dimensions were selected of the fifteen available. If a different question had been posed, for instance, to establish where in the city the *ARI-related deaths* show the highest temporal correlations, then one would have to consider a different dimensional order by prioritising `'fec_def'` as the first dimension of the trajectories γ_{Hex_i}; thus reframing the ARI case study through a different dimensional vector composed of **`'fec_def'`**, `'fec_hos', 'fec_ing_uc',` and `'fec_ini_si'`. *Changes in the dimensions lead to the definition of different trajectories and by extension to the definition of different modelling scenarios*. As shown, trajectories are determined for a specific problem and can be defined on the basis of alphanumeric criteria, spatial criteria, or a mixture of the two.

A set of proofs of concept (*Wetlands* vs. *Property Units*) was implemented to demonstrate the functionality and effectiveness of the model, but it could have been any other set of proofs. As discussed in section 5.6.1.7, dimensions of any nature could be integrated in the analyses: temporal, geographic coordinates, tonnes of wheat, water table, temperature, gross national product, respiratory diseases, amongst others. Any sort of dimension that can be ordered and quantitatively compared can be integrated into the model to propose even richer analytical scenarios. ***Ct*** is certainly a very robust and flexible reasoning analytical framework.

For instance, the proposed proofs of concept focused on the evolution of *Property Units* and *Wetlands*, but it would also have been possible to compare the evolution and effects between *Property Units* to determine which of them gave way to others, which ones increased their areas significantly, and which were embraced. Since the analysed SEDD data set has two different geographic layers comprising *geolifespans*, it was decided to take advantage of this characteristic; there is no particular reason for pursuing the proofs by considering these geographic features. Another analytical scenario could also consider a land use layer. One could think of integrating the results of the previous example (encompassing and disengagement of plots) and linking them to answer questions related to extensive farming. This could be done, for example, by filtering out some type or types of crops to determine whether several farms (*Property Units*) joined together to create areas

of extensive farming that focused on particular agricultural products, a common practice over the last two centuries in many parts of the world (mainly in mid-latitude and desert regions). It would be worthwhile to explore this scenario by using other data sets, such as those for the evolution of farms and crops. *The challenge in answering all these questions lies in how the trajectories are defined and how the parameters are calibrated*.

As shown, α_i *weights* also play a key role. Tens of iterations were implemented during the proofs of concept to demonstrate how α_i weights affect the results even when analysing the same set of trajectories. It was found that, regardless of whether time and space were always considered, the different `alpha` values assigned to the analysed dimensions changed the results obtained and thus the potential conclusions. The criterion considered in defining the `alpha` values during the proofs of concept was to prioritise time as much as possible without significantly affecting spatial coherence. It is not a matter of choosing ad hoc α_i weights that lead to an expected response or represent the best-fit scenario. If considering another type of analysis relating *Wetlands* and *Property Units*, then different weights to those determined in the proofs of concept could be defined or required. Each distinct research question posed led to different analysis scenarios and thus to a range of parameterisation values, all based on the flexibility of the modelling proposal, as shown in the implementation of the ARI case study for which a fixed `alpha` vector with weights equal to 1 was defined. We also demonstrated that the assigned `alpha` values would also depend on the magnitudes of the dimensions analysed and the rescaling tasks required.

It is essential always to bear in mind that the mathematical definitions on which the model relies are said to be inscribed in the Euclidean space $\mathbb{R}^n$. This implies that it is possible to implement different types of *n*-dimensional analyses. *One can compare n dimensions for a single geographic feature or between multiple layers*. As described throughout the proofs of concept, the single restriction is that the trajectories on which the calculation of the distance $d_{\mathcal{M}}^{(\alpha,\beta)}$ will be based always have an identical number of dimensions so that they can be properly compared. This is also true for the `alpha` vector.

As noted throughout the analyses, *data quality and granularity will also play an important role* in the analysis scenarios to be considered: *the finer the granularity of the dimensions analysed, the more accurate the outputs of the analyses*. This characteristic is highly significant when comparing trajectories and defining the *Matching Points*. With a greater number of *Timing Points* per trajectory, better comparisons can be made by more precisely identifying the common segments between the analysed trajectories and then calculating more refined correlations between the geographical phenomena analysed. This has been shown in the different results analysed. Note that the data set on which the ARI case study was based has a richer temporal granularity than the SEDD data set and, therefore, a generalisation for the whole city of Bogotá was achieved. *One of the most innovative components of the model is the way in which common segments between trajectories are identified*.

The order of the dimensions that the trajectories comprise is also of critical importance in the analyses. Throughout the proofs of concept and the case study, the high relevance of the first dimension has been emphasised as the basis for identifying the *Matching Points*, and consequently for defining the order of the components considered to calculate the distances $d_{\mathcal{M}}^{(\alpha,\beta)}$. However, the order of the subsequent dimensions also has a significant

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effect on the results of the calculated distances and the results in the modelling scenarios. The order of importance of the dimensions is reduced from 1 to *n*. For instance, the spatial coordinates of the centroids were integrated in the second proof of concept, the third dimension incorporated corresponded to the *X*-coordinate, and the fourth to the *Y*-coordinate. *What would happen if this order were interchanged?* Since the defined trajectories are sorted in lexicographical order, having the *X*-coordinate as the third dimension has a critical effect on the results: by prioritising it in this position of the dimensional vector, one is saying that the east-west behaviour of the analysed phenomena is more important than their north-south behaviour; the opposite would be the case if the *Y*-coordinate were to be prioritised as the third dimension. This behaviour was demonstrated in the different iterations performed during the analyses: Table 36 shows the match *W34-Kevlinge_21* as the strongest correlation in all scenarios; nonetheless, when prioritising the *Y*-coordinate as the third dimension of the trajectories, this match did not appear amongst the first twelve ranked relations and in most of the cases the second match took its place (*W318-Kjellstorp_05*) as the most significant. However, this was not the situation in the ARI case study, which shows that in data sets with very high granularity, the importance of the lexicographical order is reduced. Note that it is enough to have high granularity in the first dimension of the trajectories for this to be true.

The order of the dimensions can also be seen as a way of considering the isotropic or anisotropic behaviour of the analysed geographic features, a fundamental element in spatial statistics and geographical analysis. A predominant geographical trend identified in the analysed phenomena could be considered by positioning the corresponding spatial dimension before the other when defining the trajectories. This principle can be applied to assign the relevance of dimensions in any kind of analysis performed through ***Ct***.

As with other elements discussed through the proofs of concept and the case study, whether or not to consider a specific order in the dimensions will be derived from the Exploratory Spatial Data Analysis (ESDA). For instance, the specific case of anisotropic behaviours in the proofs of concept would be determined from a trend analysis. It must be recognised that the described behaviour was quite evident because of the low granularity of the SEDD data set. In some cases, the temporal dimensions (first and second columns) were equal, i.e., all the *Timing Points* had the same dates, so the order of the trajectories depended upon the spatial dimensions (see Table 38), for which the granularity was a lot finer than for the temporal dimensions.

Table 38. Example of a trajectory primarily ordered by the third dimension.

Timing Point	auId	eDate	eDateMax	x_centroid_prop	y_centroid_prop
1	Tagarp_03	1856	1856	372362	6199630
2	Tagarp_03	1864	1864	372167.3	6199713
3	Tagarp_03	1882	1864	372140.2	6199927
4	Tagarp_03	1915	1914	**372140.2**	6199927
5	Tagarp_03	1915	1914	**372149.6**	6199475
6	Tagarp_03	1915	1914	**372165.7**	6200011
7	Tagarp_03	1915	1914	**372175.2**	6199724
8	Tagarp_03	1915	1914	**372472**	6199593
9	Tagarp_03	1915	1914	**372722.6**	6199582

The last conceptual element to emphasise is the concept of the proximity between *Timing Points*. *Which Timing Points are far and which are near?* This concept relies entirely on the modelling parameter $\mathcal{M}$. During the proofs of concept, two examples were described to relate geological phenomena and cadastral phenomena, showing that what might seem to be a far-fetched period of analysis in one might not be significant at all in the other. Parameter $\mathcal{M}$ and the relationships identified between *Timing Points* are clearly linked to the nature of the analysed phenomena. The window of the type $[-\mathcal{M} \cdots + \mathcal{M}]$ bounds the limits of the *Matching Points* and, consequently, the elements on which the distance between trajectories and analyses will be based. Afterwards, the relevance and strength of these matches are defined by parameter β. While α was the most important parameter in the proofs of concept, $\mathcal{M}$ was the most relevant for the ARI case study and the one that allowed us to find results that reflected the behaviour of the illnesses in the conurbation analysed. As shown, *the parameter $\mathcal{M}$ allowed us to differentiate between mild and severe ARI cases*.

Although the modelling and reasoning framework (***Ct***) is computationally expensive (in terms of CPU and memory allocation) to process the required **R** functions that calculate the distances, the mathematical definitions allow trajectories of any type and size to be compared. The high computational cost is compensated for by *(i)* flexibility in defining different trajectories and *(ii)* the multiple analysis scenarios that can be posed for the same data set through the modelling parameters and trajectories. The **R** package {furrr} has been implemented to parallelise procedures and reduce processing times (`purrr::map()` and `furrr::future_map()`).

Finally, it is clear that emphasis has been placed on temporal, spatial, spatio-temporal, and temporospatial analyses, but any other analytical scenario, namely socio-economic, sociocultural, socioecological, biogeographic, medical, or demographic, could be implemented; all of them also incorporating or excluding temporal, spatial, and even semantical dimensions according to the requirements established by a specific posed problem. *The versality of our proposal is based on the abstract nature of the stated mathematical definitions, which can be applied to any quantitative-pro-ordered sort of dimension*. The proximity between trajectories is the core concept for defining which of the analysed elements (e.g., geographic features) are more or less strongly correlated. One must keep in mind that in the case of analysing trajectories of the same phenomena (e.g., property units vs. property units), we could not state correlation but a kind of autocorrelation.

The ideas discussed in this section are extended and generalised in the concluding chapter.

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Chapter 6 condenses the main contributions of the research. We present the most significant characteristics of the reasoning framework and critically discuss its advantages and potential for improvement. In addition, new ideas and perspectives to extend the framework are discussed.

Chapter 6

General Conclusion and Future Works

"What, then is time? If no one asks me, I know; but if I want to explain it to a questioner, I don't know."

St. Augustine of Hippo – (Confessiones XI, XIV)

6 General Conclusion and Future Works

Chapter 6

This chapter presents a final discussion regarding the main contributions of the research from the methodological, conceptual, and logical points of view, as well as the characteristics, advantages, and potential for improvement of the reasoning and modelling proposal. A discussion and critical analysis of the answers to the scientific questions stated are also presented. Finally, ideas and new perspectives and scenarios to extend the modelling and reasoning framework are discussed.

6.1 Overview

This dissertation aimed to formalise and develop a reasoning and modelling framework to analyse the dynamic nature of geographic phenomena. To achieve this objective, the fundamental concept underlying and guiding the research is as follows: *changing the current focus and modelling perspective* on spatio-temporal analysis *by developing a new reasoning approach* that allows *the temporal component to be prioritised over the spatial one* will assist in *more naturally revealing temporal and non-temporal patterns* that help to *describe the dynamic relationships and nature* of geographic and non-geographic phenomena, thus *providing alternative capabilities for temporal and spatio-temporal reasoning and modelling.*

Five main tasks were completed in order to document, propose, and formalise the framework: *(i)* first, a comprehensive and thorough survey that presents an overview of the main achievements of spatio-temporal modelling in the field of geographical information science (*GISci*); *(ii)* the development and implementation of an online bibliography on temporal GIS as an interactive, up-to-date, and comprehensive resource for surveying previous and recent work in the field; *(iii)* the formalisation of a set of abstract mathematical concepts that allows the extraction and analysis of the dynamic behaviour of different sorts of phenomena from a novel perspective; *(iv)* the description of a general framework for the reasoning, modelling, and analysis of dynamic phenomena mainly described by geographic events and processes; and *(v)* the programming of a set of **R** functions to implement and validate the proposed framework and its components. Figure 94 presents an integrated overview of the tasks performed. The infographic summarises the main elements developed in each task and shows the links between them, starting on the left and moving anti-clockwise.

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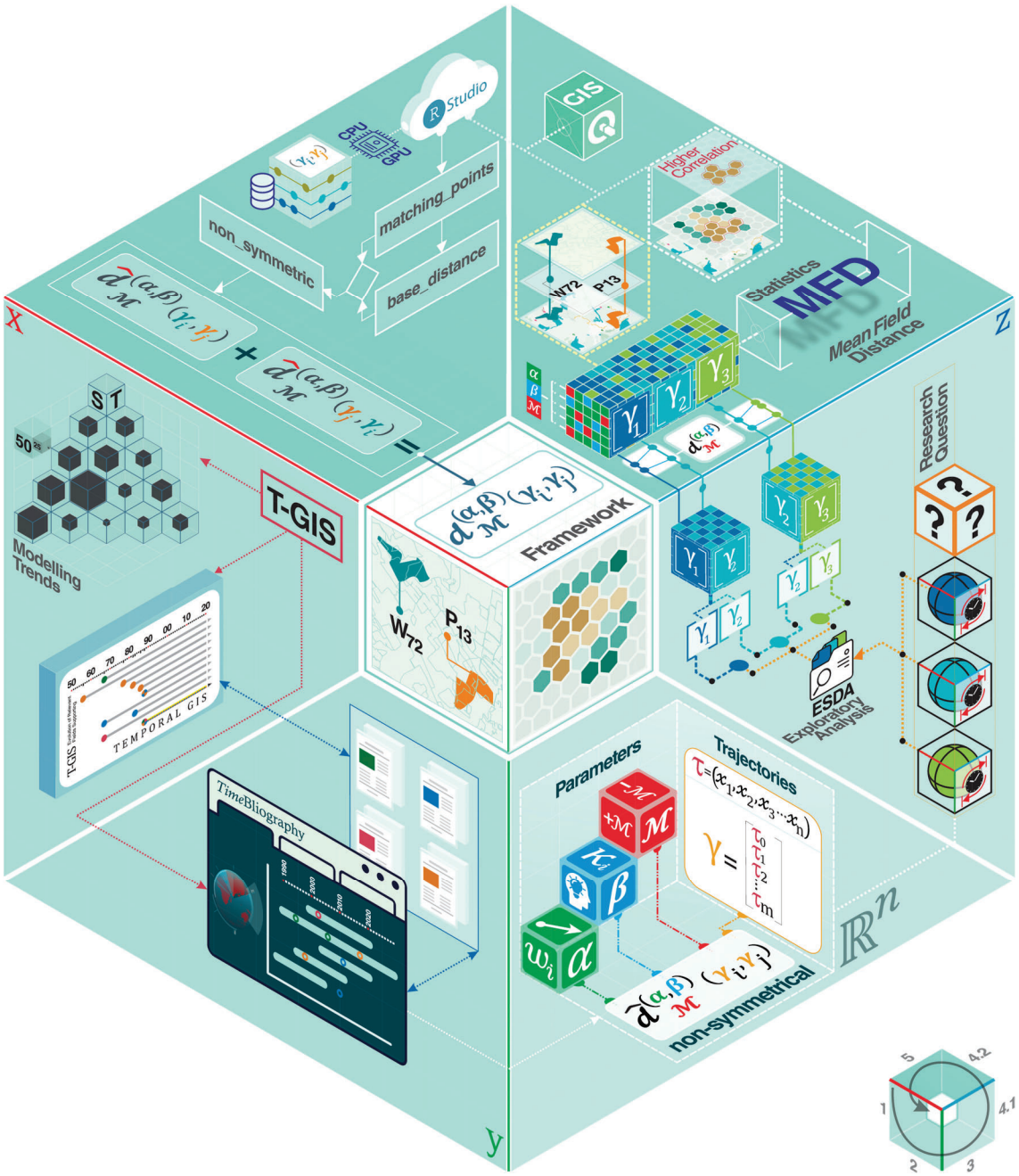


Figure 94. Overview of the modelling and reasoning framework for the analysis of dynamic phenomena.

For the ***first task***, we reviewed and documented over 1600 articles, from which 200+ modelling proposals were analysed and described (50 of them deeply analysed). The surveyed models are listed in section 3.6, and the main bibliographic resources have been described in section 4.2. A relevant result from this documentary analysis is the proposed *taxonomy that classifies the spatio-temporal modelling trends* that have arisen over the last thirty-five years; fourteen general trends were acknowledged (see Figure 38). This classification made it possible to identify that the dominant trend in the modelling of dynamic geographic phenomena is object-orientation, followed by event-, process-, and moving-objects–based modelling trends. Both *the analytical results and modelling contributions of this dissertation can be classified as event-based and process-based trends*. Nonetheless, the proposed abstract mathematical concepts can be extended to moving-

objects modelling scenarios, particularly when required to analyse interactions between highly dynamic objects. Figure 95 summarises a historical and contemporary overview of the topics analysed throughout the survey; blueish tones highlight the core components of the documentary analysis. In addition to the survey published in *ACM Computing Surveys* (Siabato *et al.* 2018), which also includes an extensive historical supplement (see Appendices A–F in greenish tones), two complementary articles were published presenting further modelling insights and an annotated bibliography related to T-GIS (Siabato, Claramunt, and Bernabé-Poveda 2013; Siabato, Claramunt, and Camossi 2017). *The survey as well as the derived articles are considered a solid contribution to the literature in this field because of the thoroughness with which the different analyses were carried out*. The academic community had acknowledged the value of the contributions derived from the survey by citing these results over 60 times by July 2022.

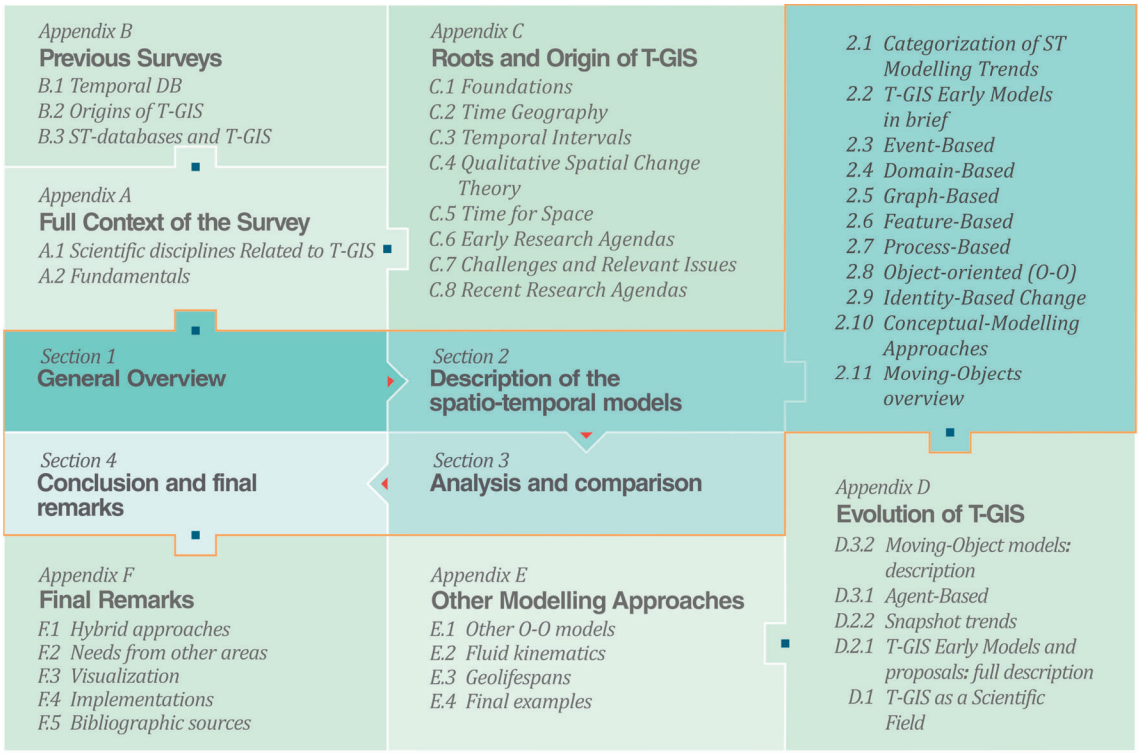


Figure 95. Conceptual map of the topics discussed in the survey.

Source: Siabato *et al*. (2018).

The ***second task*** was related to the programming and deployment of the *Time*Bliography. Given the extensive effort that went into the elaboration of the survey and the thousands of bibliographic references harvested and documented from academic databases (see Table 17), *Time*Bliography is the means we found to share our work and provide researchers and postgraduate students interested in diving into spatio-temporal modelling and the development of temporal GIS with an interactive, up-to-date, and comprehensive resource for surveying previous and recent work in the fields. This online resource has been updated on a regular basis since its publication. Over 2300 references had been classified and made available for browsing by January 2022. A strong characteristic of the online application is that it not only references specific spatio-temporal modelling works, but also research from related fields, such as temporal databases, data

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mining, and time geography, amongst other categories described in Table 18. The full description of this contribution was published in Siabato *et al*. (2014) and the online resource is openly available at http://spaceandtime.wsiabato.info. It is worth noting that this is not a simple ordered list of references, but an interactive application in which published works are fully described and related to each other and linked to the original sources for additional metadata. Figure 96 presents an overview of the number of visits by country of the *Time*Bliography website, showing the global impact of this academic resource.

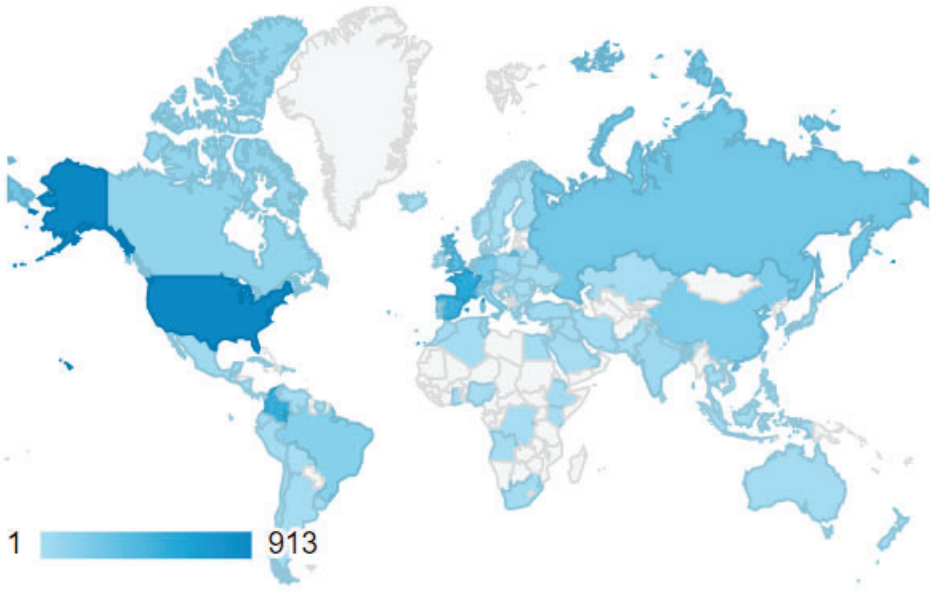


Figure 96. *Time*Bliography's website activity worldwide.

Source: Google Analytics, 2013–2021.

The following tasks were undertaken to compile the scientific and original contribution of this dissertation. We have provided a novel, flexible, and robust framework to model and analyse the dynamic nature of geographic and non-geographic phenomena. Although we have focused on geographic scenarios, from our perspective, the most relevant aspect of *the proposed reasoning and modelling framework is that it is flexible and robust enough to implement all sorts of analytical scenarios*: economic, ecological, biological, financial, demographic, environmental, amongst others. Figure 97 graphically summarises part of the conceptual contributions.

Grounded in the *GISci* object-based ontology, the ***third task*** was focused on the definition and formalisation of *a set of abstract mathematical concepts* that allows the modelling and analysis of the dynamic characteristics of geographic and non-geographic phenomena from a novel perspective: *by giving different levels of importance to the temporal, spatial, and semantic components of geographic data during analysis and treating them as independent or integrated modelling dimensions through the notion of the distance between trajectories*. Although the starting hypothesis of the research suggested developing a model that prioritises time over space, it was clear by the end of the research that the modelling framework allows the prioritising, weighting, and pondering of any of the modelling components and the analysed dimensions, and does not exclusively treat time as the

principal component. To achieve this aim, we proposed a groundbreaking approach to compare the evolution of paired phenomena by applying the concepts of *trajectory*, *partial similarity*, and *distance*. Let us highlight below a few details of each concept.

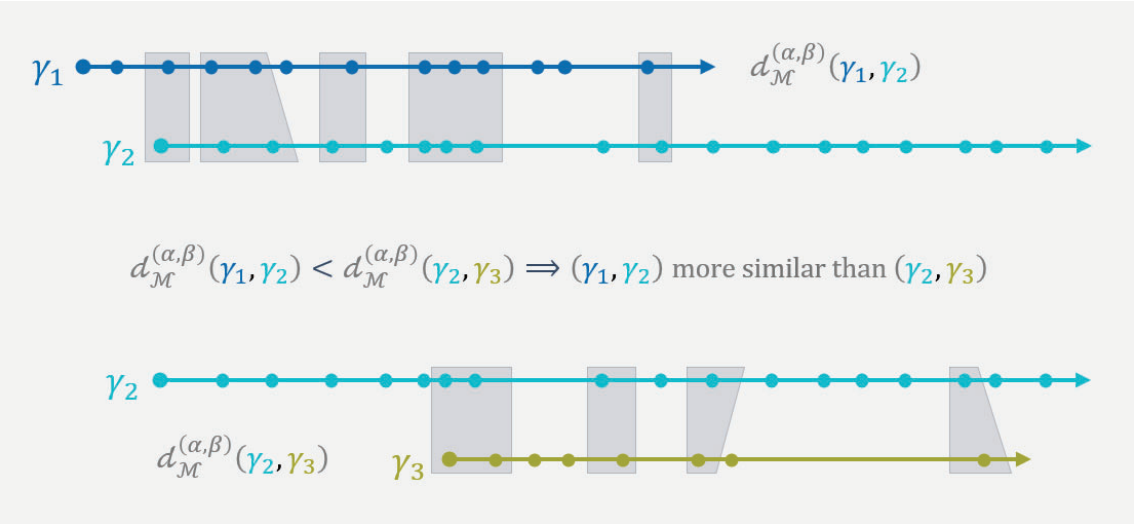


Figure 97. Representation of *Timing Points* (events), trajectories (processes), and partial common segments (comparison between trajectories).

First, the *notion of trajectory* has been a fundamental concept of this research, as it allows the modelling and analysis of the intertwisted and dynamic behaviours of the analysed phenomena based on the so-called events in the *GISci* literature. Although the *Timing Points* that a trajectory comprises represent the *events* of change in a given phenomenon, a trajectory itself represents the *process* of such a modelled phenomenon. For this reason, we have stated that *the spatio-temporal modelling trends in which this research is framed are event-based and process-based*. Figure 97 outlines these concepts.

As trajectories γ are defined in the $\mathbb{R}^n$ Euclidean space, any number and any type of dimension (temporal, spatial, and/or semantic) can be included in the analyses implemented in *The Cube of Time* (***Ct***). As discussed throughout the dissertation, *any sort of dimension that can be ordered and quantitatively compared and operated can be integrated into our modelling framework*, thus providing rich flexibility for implementing general analytical scenarios. γ must comprise *interval- and ratio-type variables*. As any kind of dimension can be incorporated, we have shown that it is necessary to indicate clearly how they are defined, or which trajectory concept is the most suitable to answer the question(s) posed in the analysis (e.g., *geolifespans* or a spatial index). This task goes beyond the mere implementation of the framework, as it requires detailed reasoning in order for the trajectories to be a true representation the modelled phenomenon. From a mathematical point of view, the concept of trajectory is broad and general and offers a lot of flexibility when solving a problem. Since trajectory γ is an abstract object, it can be implemented as needed, and the framework can then be applied to compare these implementations by calculating the distances between them. The heavy reasoning work is consequently in the definition of the trajectories, as shown in the implementation of the proofs of concept and the case study. Therefore, the reasoning problem mainly lies in the definition/implementation of the trajectories because they are and represent the way in

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which the problem is interpreted in terms of the abstract reasoning framework; in other words, *trajectories are the mechanism by which the analysed phenomena are incorporated into the proposed modelling and reasoning framework*.

With regard to the concept of *partial similarity*, we must remark that an essential characteristic when comparing the evolution of two interrelated geographic phenomena is that although some of the events of these phenomena are expected to affect each other, not all the changes (events) in one phenomenon are necessarily related to the others, i.e., *phenomena are related by partial interactions*. Hence, it was essential to define and implement a measure of comparison that reflects this natural/geographic behaviour; the proposed correlation distance $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i,\gamma_j)$ identifies and integrates close events between phenomena by developing *a novel partial match similarity measure*. We should think of close events as those components of the trajectories that find similarity on the basis of the modelling parameters $\alpha, \beta,$ and $\mathcal{M}$ determined for a proposed analysis scenario. The *mathematical method defined to compare trajectories*, and on which the partial similarity measure is founded, is also presented as a specific and innovative contribution of this research (see Figure 97). We elaborate on this idea later below.

Finally, the abstract mathematical framework was completed by applying a *general and broad concept of distance*. In particular, a *pseudosemimetric* was implemented to measure the difference between trajectories γ defined in the Euclidean space $\mathbb{R}^n$. Although the rigorous concept of *metric* was considered during the research, we focused on the implementation of a pseudosemimetric because it is the type of measure of distance that suits the nature of partial and independent interactions between the analysed dynamic phenomena. In a nutshell, the model was designed to identify correlations based on *partial comparisons* performed through a sound and robust definition of the distance between trajectories: $d_{\mathcal{M}}^{(\alpha,\beta)}(\gamma_i,\gamma_j)$.

As an overview of the third task and by integrating the three underlying concepts, we can conclude that *trajectories* are compared by applying a measure based on *partial similarity* and then determining their level of correlation based on the calculated *distance.* To apply and interpret the results, we have stated that *the smaller the distance, the higher the correlation between the evolution of the analysed phenomena*.

In addition to these concepts, it is worth noting how the research fits into the general problem of similarity studied in other domains. The problem of defining similarity between trajectories is quite general and has been widely studied (see Stevens 2011, Su *et al.* 2020 for further details), and different methods have been proposed to determine the level of similarity between trajectories (e.g., PAA, DTW, PDTW, LCSS, EDR, and ERP).[60] In this research, we did not detail the concept of similarity nor did we explicitly compare existing notions of similarity with the one proposed; nonetheless, it is important to note that the proposed method also represents, to some extent, *an advance in the state of the art of similarity-based metrics*, especially *in terms of how partial segments are related and their level of similarity is calculated*. One characteristic is that most existing methods compare complete trajectories, and *our method compares partial trajectories*. Moreover, *existing*

[60] Piecewise Aggregate Approximation (PAA); Dynamic Time Warping (DTW); Piecewise Dynamic Time Warping (PDTW); Longest Common SubSequence (LCSS); Edit Distance on Real Sequence (EDR); Edit Distance with Real Penalty (ERP).

methods for partial comparisons usually calculate similarity by *counting coincidences between trajectories*; in our approach, *we instead consider the number of matches (i.e., points that are close enough depending on the parameter $\mathcal{M}$) and the distances between them*, giving more or less importance (weight) to matches that are closer or further apart (i.e., the closer, the better). Another critical aspect of the proposed metric is that neither repeated events nor repeated matches are considered. To achieve these characteristics, the parameter `beta` interpolates the priority between the number of matches and the distances between close points. If `beta` goes to infinite, only the number of matches will be considered (in practice, this happens when `beta` is large). In contrast, when `beta` tends to zero, only the distances will be considered, and the number of matches will become irrelevant. Therefore, as shown in several sections of the dissertation, `beta` represents the relevance of the number of matches when calculating $d_{\mathcal{M}}^{(\alpha,\beta)}$. *This key concept is a new approach in trajectory distance measures*. Thus, one of the innovative components of the modelling proposal is the way in which partial segments between trajectories are identified and measured, not only the metric itself.

Task four focused on two implementation aspects: *(i)* showing how the parameters $\alpha, \beta,$ and $\mathcal{M}$ are determined, and *(ii)* showing how trajectories γ are defined in order to calculate distances subsequently. These are the most crucial aspects in the *implementation of our modelling framework* to any analytical scenario. As shown throughout the three proofs of concept and the ARI case study, *it is the interaction of the modelling parameters and the way the trajectories are defined that will ensure the framework answers the questions posed and solves the problem modelled*.

Based on two different data sets (Scanian Economic Demographic Database —SEDD— and acute respiratory infections —ARI—), we have described four analytical scenarios and implemented tens of modelling approaches to show *how the abstract mathematical definitions must be understood and may be implemented to create diverse modelling and reasoning scenarios that allow for the analyses of different sorts of dynamic phenomena*. The implementation of these approaches has demonstrated the flexibility and robustness of the mathematical definitions presented in task three. During the implementation of the modelling approaches, we identified and realised some of the limitations of the modelling framework and thus devised the alternatives discussed in the following section. In addition to these potential improvements, we have been able to show that *the mathematical definitions do indeed succeed in extracting some insights regarding the dynamic behaviour and interactions derived from two or more geographic objects*. Furthermore, we have shown that global and local patterns and behaviours can also be extracted by implementing such complementary and derived techniques as the *mean field distance* (*MFD*).

Although many different or alternative questions and analytical scenarios could be posed from the data sets handled in this research (and even from others), the four case studies provided have clarified the nature of the modelling parameters $(\alpha, \beta, \mathcal{M})$ and different ways of thinking about trajectories (γ). *The proposed framework allows the examination of different perspectives and opens up new research areas or avenues for data exploration and reasoning*. For instance, during an analytical scenario that considers spatial and temporal dimensions, one could use the parameter `alpha` to ponder purely temporal or purely spatial analytical scenarios, in addition to any of the transitions between them from temporospatial to spatio-temporal analysis; as shown through the implementation of the 40+ analytical

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modelling scenarios performed in the proof of concept 03. Complementary, the parameter $\mathcal{M}$ is used to identify the *Matching Points* with which the distances are calculated, considering, for instance, the maximum spatial distances, expected temporary periods of affection and interaction, or the temporal ranges of infection and contagion, amongst other criteria needed to model a stated problem. As explained several times in the dissertation, the role of $\mathcal{M}$ is complemented by the parameter `beta`, which defines the extent of the significance of the number of *Matching Points* between trajectories and allows the equilibration of distances and matches, this being a differentiating factor between our method and the existing ones, as referenced in task three. The proofs of concept implemented have shown that *the modelling parameters are flexible and allow the incorporation of the expert criterion*; however, it must be recognised that the parameter `beta` depends very much on expert judgement and requires new alternatives that allow it to be less subjective.

In conjunction with parameters, trajectories γ complete the inputs to calculate the distances and define the level of correlation between them. *The trajectories that were defined throughout the different modelling scenarios considering geolifespans or by using geospatial indices such as the H3 system are just two examples of possible methods that can be applied*. As described during the implementations, administrative units that differ from countries or cities could be another alternative to define different sorts of trajectories that will lead to or be adapted to various types of analysis. As has been seen, trajectories are determined for a specific problem and can be defined on the basis of alphanumeric criteria, spatial criteria, or a mixture of the two; the concept of trajectory is sufficiently flexible to fit different application scenarios and contexts. *That various analytical scenarios will require different sorts of trajectories*, this is a fundamental idea in our research proposal. Despite the method implemented, what is relevant to keep in mind when defining trajectories is that they must represent dynamicity or evolution in terms of spatial and semantic change or temporal chronology.

Finally, ***task five*** was focused on programming the **R** functions that allow the implementation of the mathematical definitions and the analytical scenarios. Five core functions were programmed to implement the theoretical framework and make it available to analyse dynamic phenomena. The whole framework is available in **RStudio** Cloud.[61] The analysed data sets and the results of each modelling scenario are fully available in the repository of this research[42]. *RData* workspaces containing raw trajectories and some intermediate processes are also available and open.

The five tasks described above led to cartographic representations and to the results obtained from the proofs of concept and the case study. These results have revealed significant behaviours that characterise the dynamic nature of the analysed phenomena (property units, wetlands, and acute respiratory infections). In the proofs of concept, despite the restrictions of the data set regarding temporal granularity, *a set of property units were identified that are potentially related to wetlands drainage*; the causality criteria are part of a more in-depth discussion. On the other hand, based on the analysis carried out with the data set provided by the District Secretariat of Health of Bogotá D.C., it was demonstrated from the MFD analysis that *the reported cases of ARI have mean temporal*

[61] The project is available at https://rstudio.cloud/spaces/162542/project/2768547, we are planning to create a GitHub repository in the near future.

structure and conform to clusters that are related to the known industrial pollution hotspots in the city of Bogotá D.C., as well as to the reported peak years of infection. The structure found in the city outskirts and the inner city was particularly significant in the description of the behaviour of the diseases analysed. *These results have helped to validate the robustness of the modelling proposal*.

6.2 Critical Discussion

As anticipated, the definition of the reasoning and modelling framework and its implementation have shown both advantages and potential for enrichment, the latter providing room for improvement and opportunities for future work. Amongst the advantages, we would like to highlight the following:

1. First, and once again, the *flexibility* of the framework. The defined abstract mathematical concepts can be applied to any sort of *n-dimensional analysis* in which the phenomena under analysis involve evolution. The reasoning framework is broad and general enough to be applied to any kind of analytical scenario. The ARI case study and the analysis of correlation between the evolution of *property units* and the drainage of *wetlands* are just two examples of the framework's potential.
2. The modelling parameters α, β, and $\mathcal{M}$ are also flexible enough to be adapted to any application scenario or context. As in any analytical scenario, the expert criterion is a cornerstone in defining a model and interpreting the results. The modelling parameters allow the introduction of expert criteria to differentiate modelling scenarios at various levels of analysis or requirements.
3. The *robustness* of the abstract mathematical definitions: this characteristic has been demonstrated by extracting information from the SEDD data set, in spite of its coarse temporal granularity. We have shown that the modelling framework performs well under limited or tough conditions.
4. Another advantage worth remarking upon is that *different methods* (either spatial or alphanumerical) can be considered *to define the set of trajectories to be computed*. The dynamic attributes of the analysed dimensions can be structured by applying distinct methods, thus opening different analytical scenarios for the same data set. As mentioned above, the distinct structures used to define trajectories lead to different analytical scenarios and procedures.
5. The way in which paired trajectories/distances are stored and the computational *data structure implemented to register the results*, (i.e., data frames of individual (γ_i, γ_j) calculations) provide a wide range of possibilities to integrate results and visualise more complex analysis. The mean field distance (MFD) is just one of the possible ways to discover general behaviours by integrating results. Furthermore, potential methods for the integration of the individual calculated measures open up a wide arena for new research, both in *local and global spatio-temporal and temporal analysis*.
6. The novel method proposed for calculating the *partial match similarity measure* has two notable advantages. First, it focuses on the similarities between segments of the analysed trajectories, as required for our modelling approach. Second, it considers

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not only the number of matches, but also distance; the method allows interpolation between considering only matches and only distances.

7. Last but not least, the results obtained and the proposed framework and processes are *reproducible* and *replicable*. With regard to reproducibility, the SEDD and ARI data sets are available for download at the data repository of this research[42]; by following the methods proposed throughout the dissertation, anyone will be able to reproduce results consistent with those presented in our research. Furthermore, although replicability is a more complex characteristic, we are sufficiently confident in the robustness of the abstract mathematical definitions provided for them to be applied across studies aimed at answering similar modelling questions related to the correlated evolution of phenomena and to obtain consistent results; as emphasised in bullets 1, 2, and 3, the mathematical definitions are flexible and robust.

With regard to potential for enrichment, the implementation of both the proofs of concept and the case study has revealed some possible extensions, modifications, and improvements in the reasoning and modelling phases. What follows describes the shortcomings identified and proposes or suggests alternatives to overcome them all, without seeking to imply that the model as it stands does not adequately address the questions posed.

1. First, when implementing the analysis related to the ARI cases, two different modelling scenarios were proposed: one for mild cases and one for severe infections. The parameters $\mathcal{M} = 10$ and $\mathcal{M} = 5$ were considered to represent the corresponding modelling scenarios and implement the analyses. However, these values represented incubation and infection periods as symmetric intervals $[-\mathcal{M}, +\mathcal{M}]$, even if such periods were different. Considering Figure 87, more reasonable intervals for the parameter $\mathcal{M}$ that better represent the modelling scenarios could be $[-6, +4]$ for mild cases and $[-6, +12]$ for severe cases. Therefore, a practical improvement for the reasoning framework is that the *parameter $\mathcal{M}$ be more flexible and become $\mathcal{M}^{\pm} = [\mathcal{M}^{-}, \mathcal{M}^{+}]$, thus providing independent upper and lower limits for the parametric window by which the Matching Points are identified*. A non-symmetrical $\mathcal{M}^{\pm}$ interval will allow the variations of analysed phenomena to be considered more naturally and appropriately.

2. During the analysis of the SEDD and the implementation of the second proof of concept, the integration of the spatial dimensions made it clear that large differences in the magnitude of the dimensions linked to the analysis can become significant in the results. For instance, when the maximum differences between the temporal and spatial dimensions were determined [48] & [49] and the ratio of the upper limits was estimated at ~265 to 1, this large difference led to the different viewpoints discussed in the second and third proofs of concept (sections 5.6.2 and 5.6.3).

   Nonetheless, from a broader perspective, it could be useful to *consider different $\mathcal{M}$ intervals for each linked dimension*. We have repeatedly stated throughout the dissertation that the most important analysed dimension is the first one, since it is the one from which *Matching Points* are identified. However, when integrating dimensions of a different nature, such as time and space, selecting matches by considering different criteria can be more refined and intuitive. For instance, for the

second proof of concept, we could base the identification of *Matching Points* not only on a maximum temporal difference of 27 years ($\mathcal{M} = 27$), but also by considering the geographic distance between *property units* and *wetlands* (e.g., not more than 1500 metres apart); thereby redefining parameter $\mathcal{M}$ to a vector of the kind $\mathcal{M} = (27, 1500)$. If the $\mathbb{R}^4$ modelling scenario presented in the second proof were taken up again (see section 5.6.2), and a new modelling condition were assumed to be to exclude those *property units* and *wetlands* that are more than 1500 metres apart both in the north-south and east-west directions, then the parameter $\mathcal{M}$ should be redefined as $\mathcal{M} = (27, \texttt{NA}, 1500, 1500)$. The `NA` value meaning that the corresponding dimension will not be related to the identification of *Matching Points*, in the example, the second temporal dimension.

This is a noteworthy improvement because it reduces the extreme dependence of the model on the first dimension and allows other dimensions to participate in the identification of *Matching Points*. Note that a parametric vector of the type $\mathcal{M} = (27, \texttt{NA}, \texttt{NA}, \texttt{NA})$ is equivalent to the modelling scenario presented in the second proof of concept.

The counterpart of this improvement is that it may be inappropriate to apply it in certain scenarios, since a larger number of conditions can significantly reduce the number of *Matching Points,* thus limiting the representativeness of the calculated distances. Therefore, using a parametric vector $\mathcal{M}$ that considers multiple dimensions would be convenient and logical only in data sets rich in reported entries and events.

Note: the implementation of the new characteristics suggested for the parameter $\mathcal{M}$ require slight modifications in the **R** function `matched_timing_points(·)`. By integrating suggestions 1 and 2, the modified parameter must be redefined as $\mathcal{M}^{\pm} = \left(\mathcal{M}_1^{\pm}, \mathcal{M}_2^{\pm}, \dots, \mathcal{M}_n^{\pm}\right)$. This new parametric vector must follow the same restrictions defined for the parameter `alpha` regarding the number of dimensions of the analysed trajectories, being the homologous case of $\alpha_i = 0$ that of $\mathcal{M}_i^{\pm} = \texttt{NA}$.

3. The multiple definitions and descriptions provided for the *parameter β* throughout the dissertation are very *reliant on the expert criterion*. Although the expert knows the modelled phenomenon, s/he does not really know a priori the required distances/matches to be considered in order to tune the parameter β and should, therefore, count upon initial support to create a preliminary informed criterion. A more structured method considering the very nature of the analysed data would be desirable, thus reducing the potential for misinterpretation by experts. To advance in this method, we briefly *outline a complementary proposal to redefine the parameter `beta` from the distributions* of the calculated distances and the number of matches κ assuming the initial parameter $\beta = 0$. Such a method is described in Annexe A.1.

4. It should also be noted that in its current definition, *the framework applies preferably to dynamic phenomena described through many events*; its application becomes more feasible when there is richness along the trajectories to be analysed. Analysing data sets with phenomena whose dynamicity is poorly recorded may lead to erroneous conclusions, or at least require more discerning analysis of the results. Nonetheless,

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we must highlight once again that the model performs well under tough conditions, as shown through the SEDD analysis with coarser temporal resolution.

5. Another shortcoming of the proposed metric is that it does not provide absolute measures of correlation, so the *interpretation and comparison between different phenomena are not possible*. Comparing a correlation value from one experiment to another would be meaningless, mainly because of the different magnitudes of the dimensions. Therefore, normalisation options, such as the *z-score*, or reducing the measures to specific ranges, for example $[-1, +1]$, should be explored to overcome this drawback.

Finally, although flexibility is indeed a key asset of the modelling approach, a critical question is to identify the easiest way of defining the parameters α, β, and $\mathcal{M}$ by minimising subjectivity. The initial modelling conditions might have a substantial impact on the outputs when applied, and thus additional control methods should be considered and defined; some examples of such methods are the improvements presented above for refining the parameters β and $\mathcal{M}$. In this way, by considering the proposed improvements, the model could be upgraded by fixing $\mathcal{M}^{\pm} = \left(\mathcal{M}_1^{\pm}, \mathcal{M}_2^{\pm}, \dots, \mathcal{M}_n^{\pm}\right)$; $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_n)$, and $\beta \geq 0$, thus the *temporal distance* $\boldsymbol{d}_{\mathcal{M}^{\pm}}^{(\boldsymbol{\alpha},\boldsymbol{\beta})}$ between trajectories γ_1 and γ_2 could be redefined as:

$$\boldsymbol{d}_{\mathcal{M}^{\pm}}^{(\alpha,\beta)}(\boldsymbol{\gamma_1}, \boldsymbol{\gamma_2}) = \widehat{\boldsymbol{d}}_{\mathcal{M}^{\pm}}^{(\alpha,\beta)}(\boldsymbol{\gamma_1}, \boldsymbol{\gamma_2}) + \widehat{\boldsymbol{d}}_{\mathcal{M}^{\pm}}^{(\alpha,\beta)}(\boldsymbol{\gamma_2}, \boldsymbol{\gamma_1}).$$

As stated, room for improvement and complements is significant and still open.

To conclude this discussion, we can state that *given the advantages, and having acknowledge the limitations, we are confident in the robustness and power of the proposed model and consider that it can be applied to multiple analytical scenarios that need to take into account the dynamicity of the analysed phenomena.* The results of this research offer room for applications to general and different domains, such as those mentioned above. From the socio-economic, sociocultural, and socioecological perspectives, one could relate rural and urban demographic behaviours to interactions with protected areas, changes in land use, alterations in pollutant concentrations, deforestation, and even phenomena associated with climate change. When considering a demographic viewpoint, evolution in the location and density of human beings could be an interesting scenario to explore. The possible results of these demographic analyses could become part of more complex scenarios by integrating them as new dimensions to the aforementioned socio-perspectives. A biogeographic point of view is also interesting; we could analyse, for instance, the interactions of species in nature by using global navigation satellite system (GNSS) tracks and changes in natural ground cover or land cover, in order to understand the nutritional and feeding patterns of the species analysed. From an environmental perspective, the ARI case study could be enriched by integrating new data sets related to PM_{10} and $PM_{2.5}$ in order to better correlate particle emissions and respiratory illnesses. From a medical perspective, physiological studies are also feasible. For instance, it could be possible to analyse runners' tracks in combination with spatial location (3D), temperature, and biometric data (e.g., heart rate, oxygen saturation rate) to determine how the athletes' performance and health might be related to differences in altitude and temperature changes.

As these examples show, the prospects for applying and implementing the proposed modelling and reasoning framework in different domains are promising.

6.3 Future Works

Future works can be classified into middle- and long-term tasks. Middle-term tasks relate to specific improvements to make the proposed modelling framework more flexible and accessible, and long-term tasks concern additional modules and components to enrich the structure, modelling, and analysis of dynamic phenomena. Amongst the tasks that should initially be considered are:

1. To develop a sound definition for the new description of the parameter `beta` based on the outline provided in Annexe A.1. A comprehensive statistical analysis must be carried out to detail the suggested process.
2. To develop an {**R** package} that generalises access to the analytical framework and the defined methods. This proposed package should integrate the **R** functions described throughout the dissertation and provide new tools and methods to support the definition of trajectories.
3. Related to the previous task, the **R** functions need to be optimised. Although parallelisation methods and procedures have been considered through the package {furrr}, given the potentially enormous number of trajectories derived from the analysed data sets, future implementations based on the framework can still be computationally expensive in terms of CPU and memory allocation. Therefore, new performance improvements need to be explored and implemented. It might even be worth exploring other analytical environments, such as *NumPy*, as probably better options to process big data sets. One could even go a step further and explore more advanced scenarios, such as computing the required processes on GPUs or, more specifically, implementing parallelism tasks on the CUDA platform; or perhaps both of these options, when considering that the calculations performed in the framework are mostly matrix-based. Benchmarking of results and performance will be necessary.
4. A robust characteristic of the modelling framework is that it is possible to compare n-dimensions for a single geographic feature or between paired layers, thus providing a clear connection to analytical scenarios based on *spatial autocorrelation* and *spatial correlation* (see Siabato and Guzmán-Manrique 2019). Therefore, ESDA methods and tools could be extended by exploring robust connections between our mathematical definitions and other autocorrelation and correlation formalisations. A first step in this direction could be, for instance, implementing distinct types of Spatial Weights Matrices $\mathcal{W}$ such as the ones based on contiguity, or even defining new $\mathcal{W}$ structures based on the proposed concept of distance and similarity.
5. Throughout the dissertation, the potential limitations of the model when processing *data sets with coarser granularity* have been mentioned several times. Although the model is robust and it has been shown that this type of data can be processed, this problem needs to be considered in greater depth. Low granularity and scalar uncertainties (both spatial and temporal) are data characteristics that have not

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explicitly been faced. However, it must be noted that given the abstract definitions of the model, these limitations should *be analysed for each modelling scenario and each analysed data set*, since each one will have its own characteristics and limitations.

6. The *implementation of new case studies* is highly recommended. New opportunities to improve the modelling framework could be realised by implementing new case studies and modelling scenarios, allowing adjustment, modification, and reinforcement. New improvements would also allow a broader generalisation of the **R** package proposed. Each case study can be considered as an independent study; therefore, new cases are expected to support MSc projects in the various fields described earlier as part of future perspectives.

7. Finally, it would be worthwhile to compare our novel partial match similarity measure with other types of measure across trajectories, in order to assess its advantages and potential drawbacks more objectively.

With regard to long-term tasks, a wide arena for new research has been opened up. In considering that this dissertation is framed in the research line entitled *Metamodel for the Integration of Temporal and Geosemantic Components into Geographic Information* (see section 1.2), opportunities for future work are extensive and most remain open. The overall aim of the proposed research line is to enrich geographic data with temporal and geosemantic components to improve the spatio-temporal analysis and reasoning of dynamic geographic phenomena. As a whole, the research proposes a three-tier process: one for the enrichment of geographic data; one for the analysis and reasoning of dynamic events; and the third for visualisation processes (see Figure 98). In the overall scheme of things, we propose integrating three new components (layers) into the core of geographic data structure (semantic-temporal, geosemantic, and incremental spatio-temporal) and a set of tools for retrieving, visualising, and exploiting such structures in GIS. To do so, we propose the following tasks:

8. Two models (*temporal* and spatial-incremental) to enrich and describe the dynamic nature of GI and to supply temporal and spatio-temporal analysis capabilities. This dissertation has developed the temporal model.

9. Three new data-structure components for enriching geographic data: semantic-temporal, geosemantic, and incremental spatio-temporal. We consider that the lack of semantic and temporal components in the current geographic data structures is one of the reasons for spatio-temporal analysis being complex and non-generalisable. These new structures will allow integration of the dynamic nature and semantics of phenomena into GI. The new components will describe the meaning and temporal aspects of the stored data, enabling the user and the system to more naturally interact with them (Natural Language Interaction). The third data structure will allow the integration of spatio-temporal structures to incrementally register the changes that occur in geographic features, not only their geometries, but also their meaning (semantics).

10. Two semantic engines that take full advantage of the enriched geographic data: a Semantic Engine of Temporal Expressions (SEoTE) and a Spatio-temporal Semantic Engine (STing). Once the enriched geographic data are ready, it will be necessary to

deploy a set of methods for exploiting them. Part of these methods are the semantic engines, which can directly interact with both the data and the user to identify temporal and semantic expressions, capitalising fully on the enriched data. Note that the SEoTE is focused on temporal expressions, whereas the STing is focused on geographic references with temporal scope.

11. A set of elements and tools to visualise spatio-temporal information. This task includes the definition of rules for the interaction of any stored data set and a design to be implemented with geographic and temporal mark-up languages. An example of these tools has already been developed and published in Mackenzie *et al*. (2017).
12. The overall goal of these tasks is to enhance geographic data, making them more intelligent and flexible, and to provide GIS with semantic tools that enable robust system interactions with user and data (User ←→ System ←→ Data). Machine learning (deep learning) and other types of AI will play a significant role in future works.[62]
13. Finally, as we suggested in the justification of *The Cube of Time* in question 18 (p. 51), we have concluded from the proofs of concept and the case study that causality criteria are part of a more in-depth discussion. We will explore the possibility of integrating the notion of *temporal distance* derived from this research with the *correlation distance* presented by Székely, Rizzo, and Bakirov (2007). This integration will provide temporal and spatio-temporal reasoning and analysis with the robustness of correlation distance to analyse linearly and non-linearly correlated geographic phenomena, and provide correlation distance with spatial, temporal, and semantic capabilities.

To conclude this dissertation, Figure 98 shows a graphical description of the whole research line and highlights in orange the focus of this dissertation: *the temporal model*. As can be seen, *this thesis is just the beginning of a complete plan to make temporal and spatio-temporal reasoning and analysis more efficient and feasible.*

[62] A broader description is available at Siabato and Manso-Callejo (2011a) and Siabato, Manso-Callejo, and Martins (2012)

III

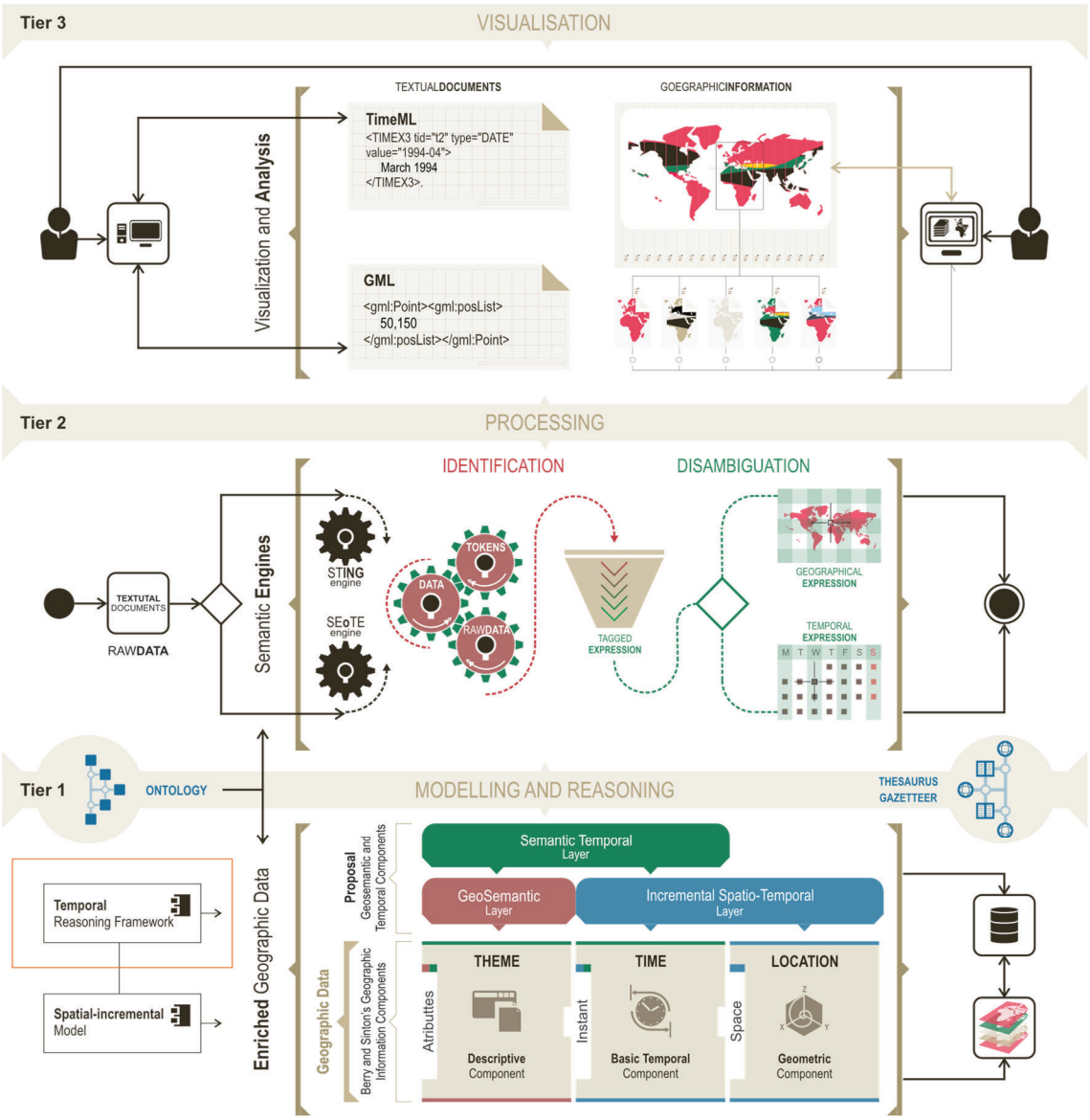


Figure 98. Three-tier overview of the future works of the research.

6.4 Derived Publications

Finally, we would like to list the publications derived from and related to this dissertation and the general research project:

Journal Articles

Siabato, Willington; Christophe Claramunt; Sergio Ilarri; Miguel Ángel Manso-Callejo. 2018. "A Survey of Modelling Trends in Temporal GIS." *ACM Computing Surveys* 51 (2):30. doi: 10.1145/3141772.

Siabato, Willington. 2018. "Sobre la evolución de la información geográfica: las bodas de oro de los SIG." *Cuadernos de Geografía: Revista Colombiana de Geografía* 27 (1):1-9. doi: 10.15446/rcdg.v27n1.69500.

Siabato, Willington; Christophe Claramunt; Elena Camossi. 2017. "An Annotated Bibliography on Spatio-temporal Modelling Trends." *International Journal of Earth and Environmental Science* 2 (2):135. doi: 10.15344/2456-351X/2017/135.

Mackenzie, Kierin; Willington Siabato; Femke Reitsma; Christophe Claramunt. 2017. "Spatio-temporal visualisation and data exploration of traditional ecological knowledge/indigenous knowledge." *Conservation & Society* 15 (1):41-58. doi: 10.4103/0972-4923.201391.

Siabato, Willington; Christophe Claramunt; Miguel Ángel Manso-Callejo; Miguel Ángel Bernabé-Poveda. 2014. "*Time*Bliography: A Dynamic and Online Bibliography on Temporal GIS." *Transactions in GIS* 18 (6):799-816. doi: 10.1111/tgis.12080.

Siabato, Willington; Christophe Claramunt; Miguel Ángel Bernabé-Poveda. 2013. "An Interactive Bibliography on Temporal GIS." *Journal of Spatial Information Science* 7:99-101. doi: 10.5311/JOSIS.2013.7.153.

Guerrero Nieto, Marta; María José García Rodriguez; Adolfo Urrutia Zambrana; Willington Siabato; Miguel Ángel Bernabé. 2010. "Incorporating TimeML into a GIS." *International Journal of Computational Linguistics and Applications -IJCLA-* 1 (1-2):269-283.

Martins, Bruno; Hugo Manguinhas; José Borbinha; Willington Siabato. 2009. "A geo-temporal information extraction service for processing descriptive metadata in digital libraries." *e-Perimetron. International web journal on sciences and technologies affined to history of cartography and maps* 4 (1):25-37.

Manguinhas, Hugo; Bruno Martins; José Borbinha; Willington Siabato. 2009. "The DIGMAP Geo-Temporal Web Gazetteer Service." *e-Perimetron. International web journal on sciences and technologies affined to history of cartography and maps* 4 (1):9-24.

Book Section

Siabato, Willington; Miguel Ángel Manso-Callejo. 2011. Integration of Temporal and Semantic Components into the Geographic Information through Mark-Up Languages. Part I: Definition. In *Computational Science and Its Applications - ICCSA 2011*, edited by B. Murgante; O. Gervasi; A. Iglesias; D. Taniar and B. O. Apduhan. Berlin - Germany: Springer Verlag. doi: 10.1007/978-3-642-21928-3_28.

Conference Proceedings

Siabato, Willington; Freddy Hernández-Romero. 2021. Searching dynamic (non-)geographical correlations through non-continuous similarity between trajectories. Paper read at the *XVIII Ciclo Anual de Conferencias del Departamento de Geografía. La geografía y las geotecnologías en la gestión de pandemias y riesgos socioambientales*, Oct. 15th - Nov. 12th 2019, at Bogotá D.C. - Colombia.

Siabato, Willington. 2019. Métodos de dependencia lineal y no lineal para el análisis espacial. Paper read at the *XVI Ciclo Anual de Conferencias del Departamento de Geografía. La expresión regional del cambio ambiental global*, 21-22 Octubre de 2019, at Bogotá D.C. - Colombia.

Siabato, Willington; Miguel Ángel Manso-Callejo; Bruno Martins. 2012. Integration of Temporal and Semantic Components into the Geographic Information. Part II: Methodology. Paper read at the *1st AGILE PhD School*, March 13-14 2012, at Aanchen - Germany.

Siabato, Willington; Miguel Ángel Manso-Callejo. 2011. Proposal for the Management of temporal and semantic components of Geographic Information. Paper read at the *International Symposium on Spatial-Temporal Analysis and Data Mining - STDM 2011*, July 18-19 2011, at London-UK.

Guerrero Nieto, Marta; María José García Rodriguez; Adolfo Urrutia Zambrana; Willington Siabato; Miguel Ángel Bernabé. 2010. Incorporating TimeML into a GIS. Paper read at the *11th International Conference on Intelligent Text Processing and Computational Linguistics*, March 21-27 2010.

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Siabato, Willington; Lucio Colaiacomo. 2008. Proposal for Storing Dynamic Geographical Information Based on GML. Paper read at the *International Congress on Geomatic & Surveying Engineering*, February 18-21 2008, at Valencia - España.

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Siabato, Willington; Lucio Colaiacomo. 2007. Generation of Geographic Dynamic Information Storage Based on GML. Paper read at the *GeoWeb 2007 Conference - From Mashups to Infrastructure*, July 23-27 2007, at Vancouver - Canada.

Electronic Source

Siabato, Willington; Christophe Claramunt; Miguel Ángel Manso-Callejo. 2013. *Time*Bliography*. A Dynamic and Online Bibliography upon Space and Time in GIS* [Online]. Universidad Politécnica de Madrid - French Naval Academy Research Institute, 2013/03/30 [cited 30/03/2022]. Available from http://spaceandtime.wsiabato.info.

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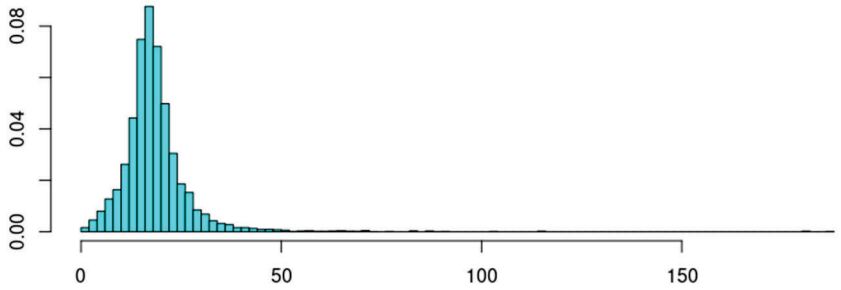
Zheni, Donia; Ali Frihida; Henda Ben Ghezala; Christophe Claramunt. 2009. A Semantic Approach for the Modeling of Trajectories in Space and Time. In *Advances in Conceptual Modeling - Challenging Perspectives*, edited by C. A. Heuser and G. Pernul. Berlin - Germany: Springer Verlag. doi: 10.1007/978-3-642-04947-7_41.

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Annexes

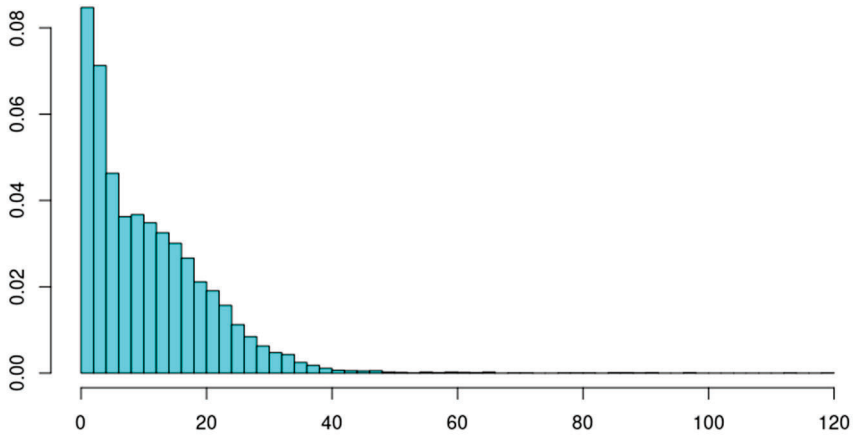
A.1 Redefinition of the Parameter `Beta` (β)

It has been stated that the parameter `beta` is needed to relate or make equivalent a small distance with few matches to a large distance with many matches. Thus, a logical question derived from this statement might be: *what is or should be understood by small and large distances, and by few and many matches?* One way to give a structured answer to these questions is to consider the *distribution of the non-symmetric distances calculated in the analysis, initially assuming that the number of matches does not matter*, i.e., $\left(\hat{d}_{\mathcal{M}}^{(\alpha,\beta=0)}\right)$.



$min = 1$ $max = 187$ $\overline{x}_d = 18.35594$ $sd_d = 9.325647$

(a) Distribution of the *distances* $\hat{d}_{\mathcal{M}}^{(\alpha,\beta=0)}$ between the paired trajectories (n = 9,179)



$min = 1$ $max = 118$ $\overline{x}_\kappa = 10.4019$ $sd_\kappa = 9.654155$

(b) Distribution of the *number of matches* κ (n = 190,958) per paired trajectories (n = 9,179)

Figure 99. Base distributions and statistics to redefine the parameter `beta` for the ARI case study.

To exemplify this concept, the ARI case study will be reconsidered. *First*, a preliminary implementation of a modelling scenario considering $\beta = 0$ must be executed. By following the reasoning discussed in section 5.7.3, the complete parameterisation is listed below. The modelling results are available at the data repository for the dissertation[42].

```
alpha   <- c(1,1,1,1,1)
beta    <- 0
M       <- 10
```

Second, after running the base model, one should identify the distributions of the calculated distances and the number of matches κ per pair of trajectories (γ_i, γ_j). For the ARI case study, these values correspond to the distances and matches between the paired hexagonal spatial units. Figure 99 shows the resulting distributions, which are the core element for redefining the parameter `beta`.

Figure 99a represents a total of 9179 effective distances calculated and the corresponding paired γ_i, γ_j matches identified, which are computed from the period 2011–2019. These distributions and their basic statistics ($\overline{x}$ and sd) are the data needed to calculate a new parameter `beta`, redefined by the expression:

$$\beta = \frac{c - a}{\frac{a}{\kappa_1} - \frac{c}{\kappa_2}};$$

where a, c, κ_1 *and* κ_2 *correspond to small and large distances, and few and many matches, respectively*. Note that this new expression is derived from the equivalence already discussed in section 5.6.1.2 (see p. 227):

$$a\left(1 + \frac{\beta}{\kappa_1}\right) = c\left(1 + \frac{\beta}{\kappa_2}\right).$$

Third, to quantify a, c, κ_1 and κ_2, we will consider the resulting distributions, their mean values ($\overline{x}_d$ and $\overline{x}_\kappa$), and their standard deviations (sd_d and sd_κ) operated as follows:

$$a = \overline{x}_d - (z_1 \cdot sd_d)$$
$$c = \overline{x}_d + (z_1 \cdot sd_d)$$
$$\kappa_1 = \overline{x}_\kappa - (z_2 \cdot sd_\kappa)$$
$$\kappa_2 = \overline{x}_\kappa + (z_2 \cdot sd_\kappa)$$

In this way, *the expert opinion is now restricted to determining the number of standard deviations* (z_1 and z_2) that should be considered to quantify a, c, κ_1 *and* κ_2. If applying this alternative proposal to the ARI case study, the reasoning is as follows. Let us assume that the medical expert opinion suggested two different scenarios: one considering $\frac{3}{4}sd$ and the other $\frac{7}{8}sd$. In these scenarios, the corresponding parameters `beta` will be calculated by:

β considering $\frac{3}{4}sd$	β considering $\frac{7}{8}sd$
$\beta = \frac{25.35017525 - 11.36170475}{\frac{11.36170475}{3.16128375} - \frac{25.35017525}{17.64251625}};$ $\beta = 6.484741088$	$\beta = \frac{26.51588113 - 10.19599888}{\frac{10.19599888}{1.954514375} - \frac{26.51588113}{18.84928563}};$ $\beta = 4.283535793$

By following the previous explanations of the parameter `beta` (see pp. 206, 227), calculations for $\beta = 4.283535793$ would be homologous to that of an expert opinion indicating that a distance of $\cong 10$ based on $\cong 2$ matches is equivalent to that of $\cong 26$ based on $\cong 18$ matches. As shown, the resulting `beta` value is very close to the one proposed in the ARI case study (4); however, a definition starting from the distributions and considering a measure based on standard deviations is a more robust and comprehensible method. *It will be easier for the expert to express his/her opinion in terms of standard deviations than from distances/matches working in tandem*. Standard deviation is indeed a better method to define what should be understood by small and large distances. Note that for the exemplified calculations, z_1 and z_2 have been considered equal, but they could be different, representing separate intervals for distances (z_1) and matches (z_2). Each distribution could have its own properties.

In some cases, depending on the type of data distributions, expressing equivalences between the measures (distances vs. matches) in terms of standard deviations could be inaccurate, so other alternatives to articulate such relations in terms of percentages of the distribution could be required. This alternative demands a more profound discussion that will be part of future works. Based on Figure 99, although the 9179 calculated distances do not perfectly fit a normal distribution,[63] we could a priori state that distances between 1 and 35 follow a normal distribution ($\bar{x}_d = 17.30059$; $\tilde{x}_d = 17.1062$; $sd_d = 5.74699$) —see Figure 100— whereas the number of matches follow a Pareto distribution. Deeper analysis considering the type of distribution obtained from the calculations can be a first step in this future work.

Last, once the value or values of `beta` have been determined, new modelling scenarios must be run to consider them. Note that different `beta` values can be determined if the expert considers two or more options for standard deviations, such as one for local analyses and another for global views.

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Anderson-Darling normality test:	A = 423.5,	p-value < 2.2e-16.
Cramer-von Mises normality test:	W = 75.688,	p-value = 7.37e-10
Lilliefors (Kolmogorov-Smirnov) normality test:	D = 0.15399,	p-value < 2.2e-16
Pearson chi-square normality test:	P = 3831.3,	p-value < 2.2e-16

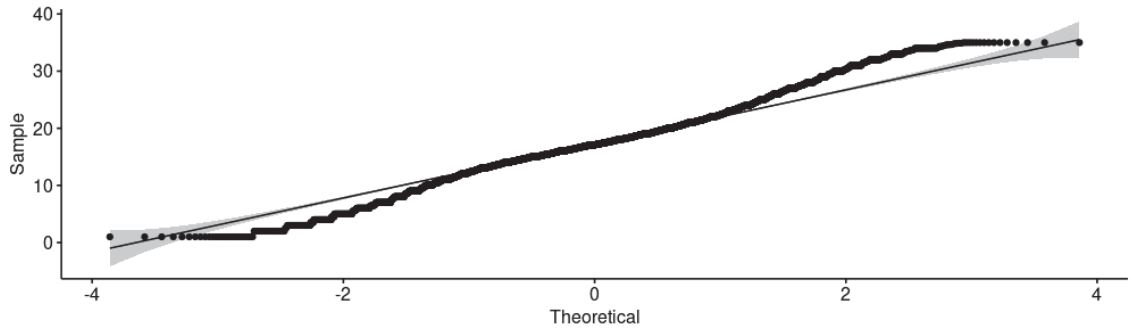


Figure 100. QQPlot representing distances between 1 and 35 for the ARI case study.

Another interesting aspect of this method is that each analysed period can have its own parameter `beta` depending on the resulting distribution. It should be stressed that in the example given, the entire period of analysis was considered (2011–2019), but a different parameter `beta` could also be determined for each epidemiological year[57] or any other period analysed. *Thus, the parameter `beta` is now defined as a function of the number of standard deviations*.

A.2 Algorithm for the definition of non-symmetric distances

Algorithm 1: Definition of $\hat{d}_M^{(\alpha,\beta)}(\gamma_1, \gamma_2)$.

Input : Two trajectories γ_1 and γ_2,
one vector $\alpha = (\alpha_1, \cdots, \alpha_n)$ of non-negative real numbers,
$\beta \geq 0$,
$M \geq 0$.

Output: $\hat{d}_M^{(\alpha,\beta)}(\gamma_1, \gamma_2)$.

$D \leftarrow 0$;
$I \leftarrow -1$;
$j \leftarrow -1$;
$\kappa \leftarrow 0$;
while $j \in \{-1, 0, 1, \cdots, n-1\}$ & $I \in \{-1, 0, 1, \cdots, m-1\}$ **do**
  $j \leftarrow j + 1$;
  Choose in $\{\tilde{x}_{I+1}, \cdots, \tilde{x}_m\}$ the nearest element to x_j, said to be $\tilde{x}_{I+J}$, that is, J is the position of $\tilde{x}_{I+J}$ in $\{\tilde{x}_{I+1}, \cdots, \tilde{x}_m\}$. In the case of a tie, choose the minimum index;
  if $|x_j - \tilde{x}_{I+J}| \leq M$ **then**
    $D \leftarrow D + d^{(\alpha)}((x_j, y_j, z_j), (\tilde{x}_{I+J}, \tilde{y}_{I+J}, \tilde{z}_{I+J}))$;
    $I \leftarrow I + J$;
    $\kappa \leftarrow \kappa + 1$;
  else
end
if $\kappa \neq 0$ **then**
  return $\frac{1+\frac{\beta}{\kappa}}{\kappa}\ D$;
else
  return ∞
end

A.3 Main definitions related to the SEDD data set

Table 39. Description of the Fields in the layer *Property Units*.

Attribute	Description
PuId	"Property unit identifier created by the authors. This identifier establishes links on the property unit level between the geographic data and the individuals in the SEDD (cf. section 'Links to the Scanian Economic Demographic Database (SEDD)'."
AuId	"Address unit identifier created by the authors. This identifier establishes links on the address unit level between the geographic data and the individuals in the SEDD (cf. section 'Links to the Scanian Economic Demographic Database (SEDD)'."
sDate	"Start date of the object (usually only the year)."
eDate	"End date of the object (usually only the year)."
sDateMin	"The earliest start date (usually only the year), which represents an uncertainty interval of the object's lifeline. That is, the object may exist as early as indicated in this attribute."
eDateMax	"The latest end date (usually only the year), which represents an uncertainty interval of the object's lifeline. That is, the object may exist as late as indicated in this attribute."
obsDate	"Date of observation (=date of the map from which the object was digitized) (usually only the year)."
notePU	"Comments made about the property unit when it was digitized (sometimes a transcription of a text part in the map document or cadastral dossier). This information is primarily relevant if the property units were to be improved or changed."
noteTimEst	"Comments about the lifeline estimation of the property unit/object. This information is primarily relevant if the lifeline estimation were to be improved."
Parish	"The parish that the property unit belongs to."
parishCode	"National parish codes from Statistics Sweden (SCB)."
addrName	"Address name (e.g., 'Hög')."
addrCode	"Address number (e.g., 04)."
addrLetter	"Address part (e.g., 'B' or '1')."

Source: Hedefalk, Svensson, and Harrie (2017, p. 8).

Table 40. Description of the Fields in the layer *Wetlands* structured as object-lifelines.

Attribute	Description
wetlandId	"Unique identifier of the wetland. The same identifier is assigned to those overlapping historical and modern wetland polygons that represent the same wetland (but with different geometric shapes because of, e.g., drainage). Created by the authors."
sDateMin	"The earliest start date (usually only the year), which represents an uncertainty interval of the object's lifeline. That is, the object may exist as early as indicated in this attribute."
sDate	"Specific start date (usually only the year). Almost always used when a joint drainage unit explicitly determines the start date of a modern wetland. E.g., a wetland was partially drained in 1889, and an overlapping, smaller, wetland can be observed in the modern data, this wetland is assigned the start date of 1890.That is, we assume that at this point in time, the modern wetland got its present geometric shape. The value '9999' indicates that the wetland [starts] within the interval that is defined by the sDateMin and sDateMax."
sDateAvg	"An approximate start date for the wetlands observed in the modern data (usually only the year). Calculated as sDateMin +(eDateMin − sDateMin)/2. E.g., if a wetland observed in the modern data can earliest start in 1821, and earliest end at 2007 (the year it was digitized), its sDateAvg=1914."
sDateMax	"The latest possible start date. Most often the year when the wetland was observed in the map."
eDateMin	"The earliest possible end date (usually only the year), which represents an uncertainty interval of the object's lifeline. That is, the object exists to at least the date indicated in this attribute. This date [corresponds] often to the observation in the map. E.g., if a wetland was digitized from the MTSM map in 1820, eDateMin is set to 1820."
eDate	"A specific date which most often indicate the year when a joint drainage was carried out on the wetland (usually only the year). The value '9999' means that no joint drainage has been observed and that the wetland therefore stops to exist within the interval eDateMin and eDateMax."
eDateAvg	"Used mostly for the historical wetlands observed in the 1820 MTSM map (usually only the year). Calculated as: sDateMax +(eDateMin − sDateMax)/2. If eDate is a specific date, eDateAvg is assigned the value of eDate."
eDateMax	"The latest possible end date (usually only the year). The value '9999' is used for the wetlands observed in the modern data and means 'and onwards' (i.e., it still [exists] and we do not know when it will stop existing)."
obsDate	"Date of observation (=date of the map from which the wetland was digitized) (usually only the year)."

Source: Hedefalk, Svensson, and Harrie (2017, p. 9).

A.4 Normalised maps of the ARI case study

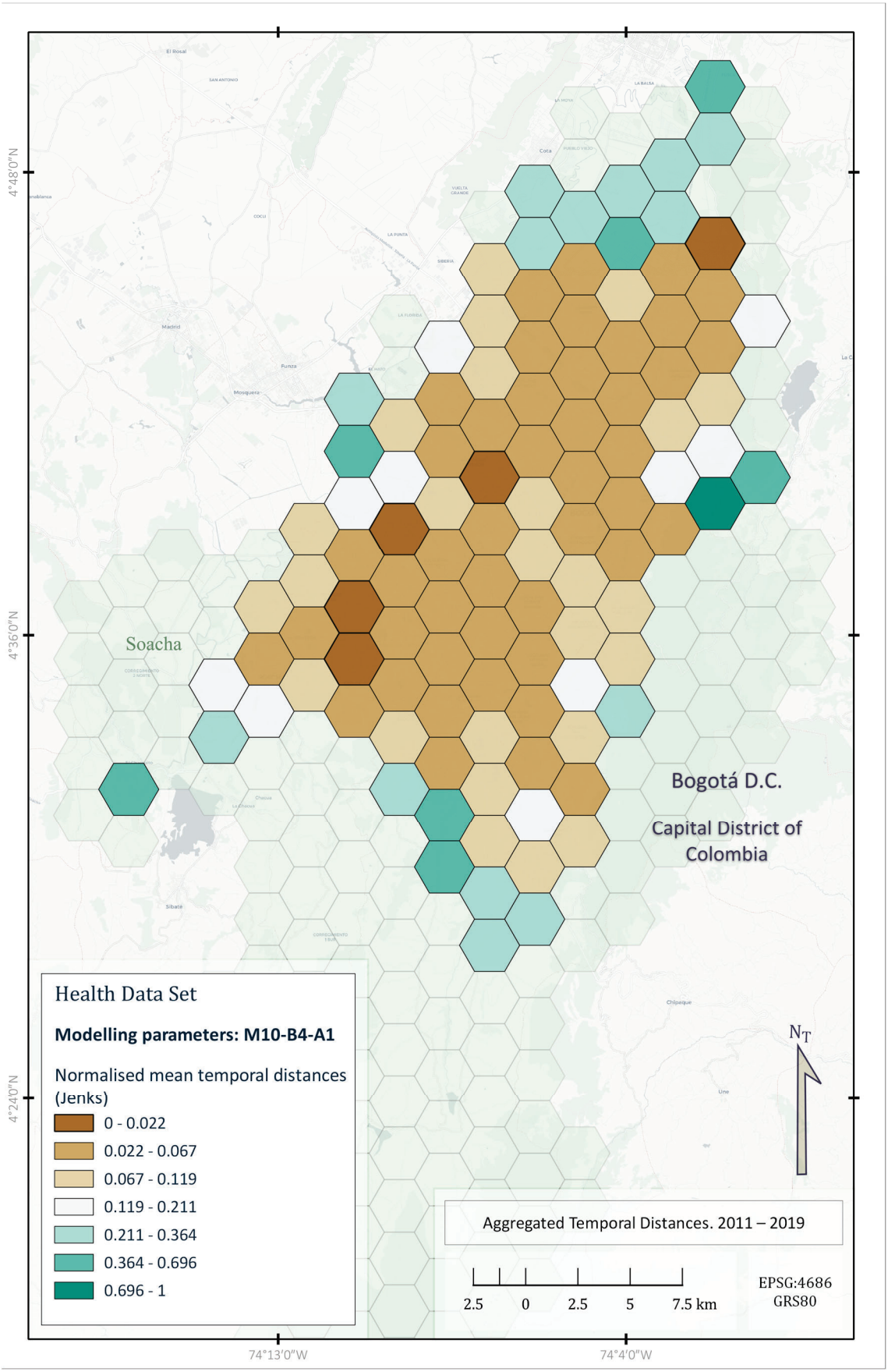


Figure 101. Normalised mean temporal distances calculated per spatial unit: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = c(1, 1, 1, 1, 1)$. Period **2011–2019**.

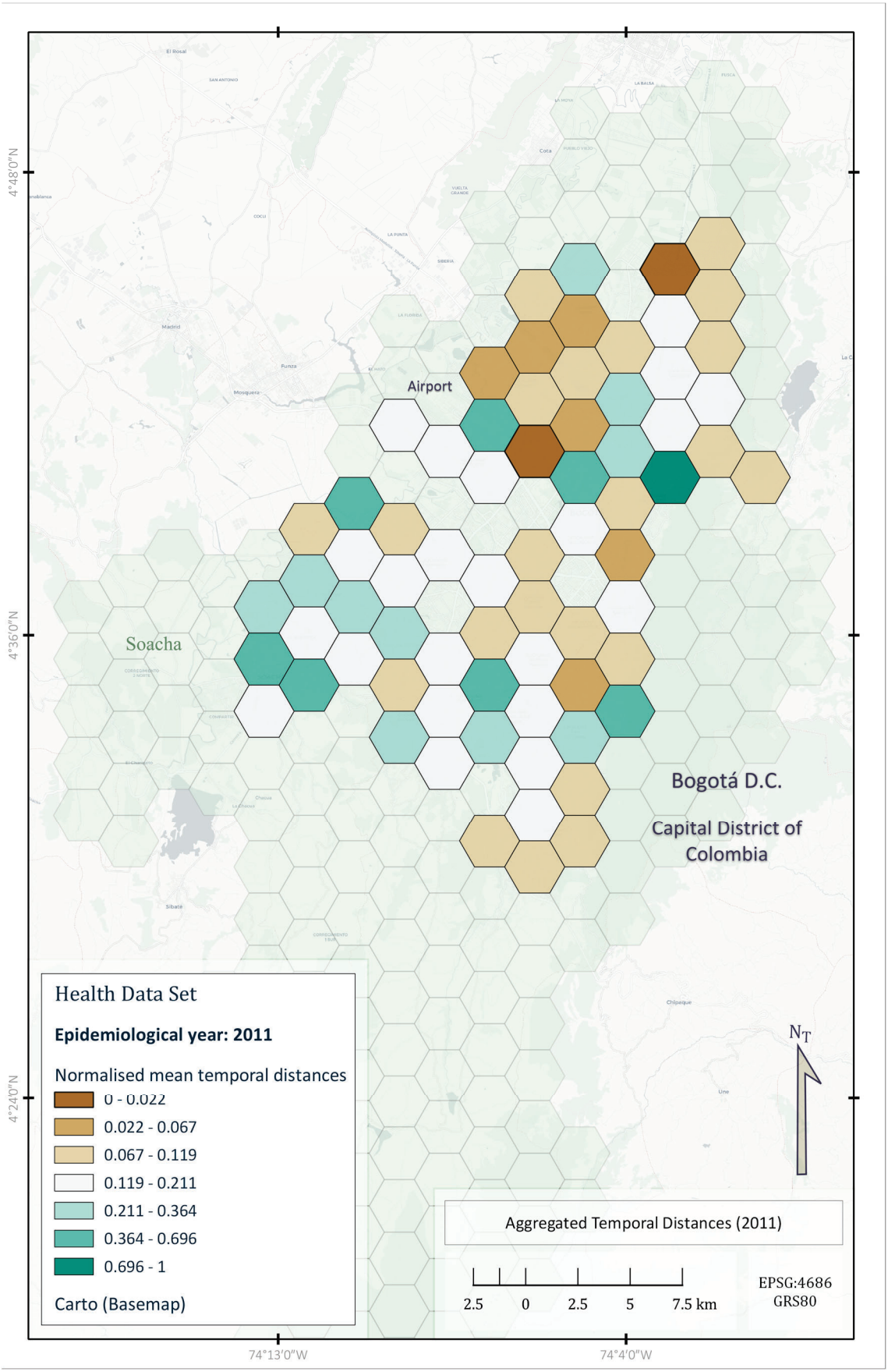


Figure 102. Normalised mean temporal distances for the epidemiological year **2011**: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

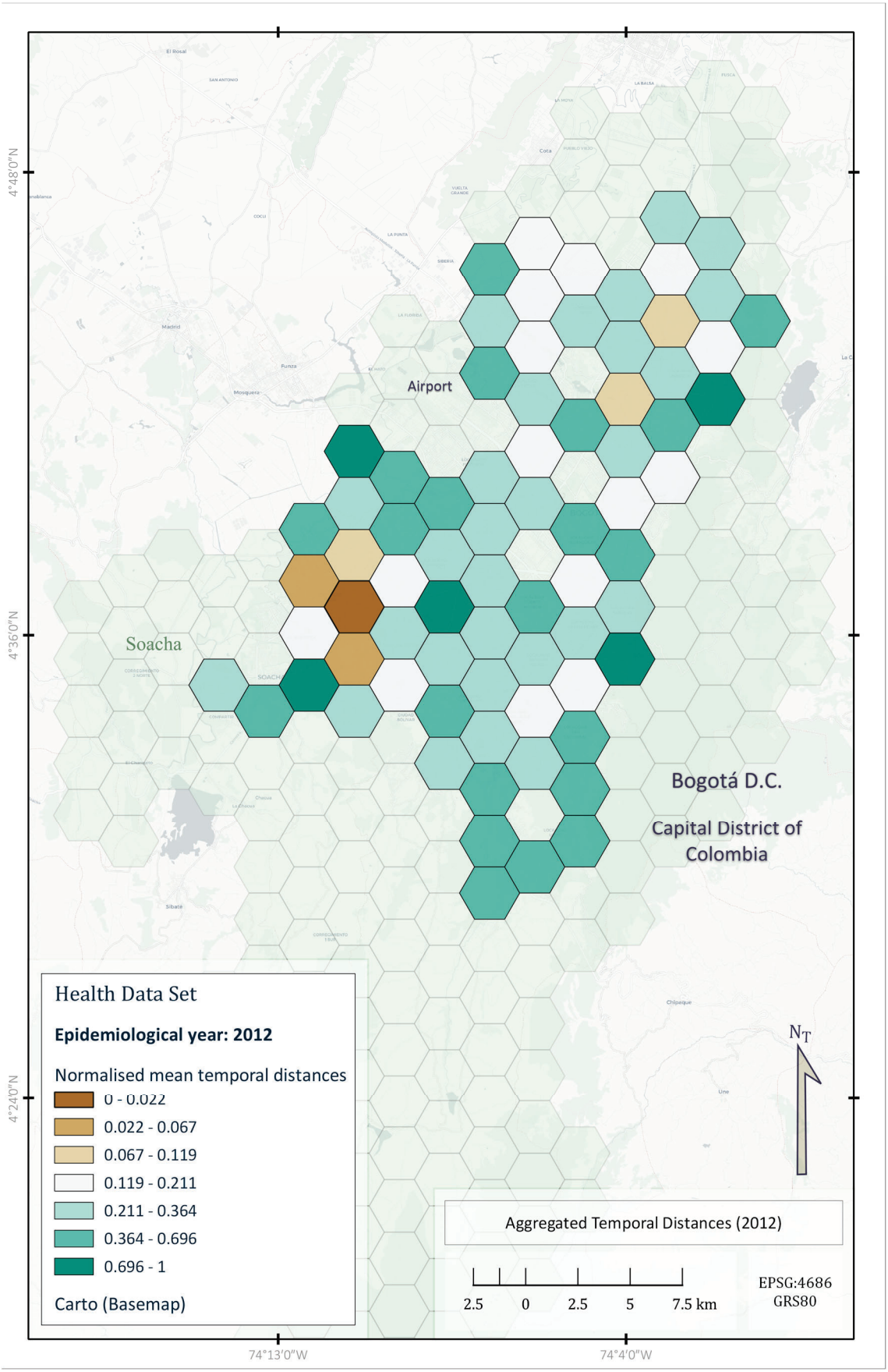


Figure 103. Normalised mean temporal distances for the epidemiological year **2012**: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

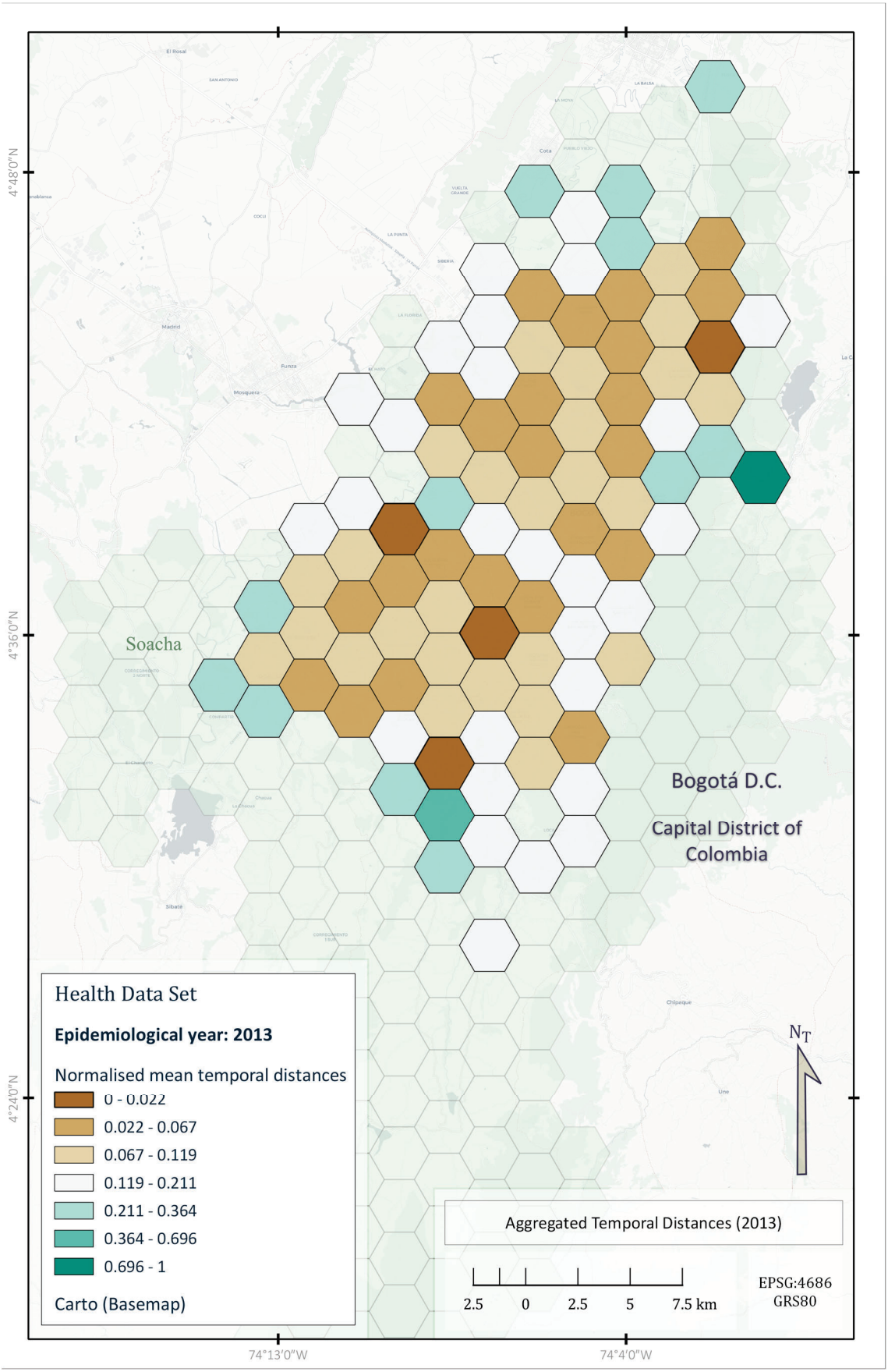


Figure 104. Normalised mean temporal distances for the epidemiological year **2013**: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

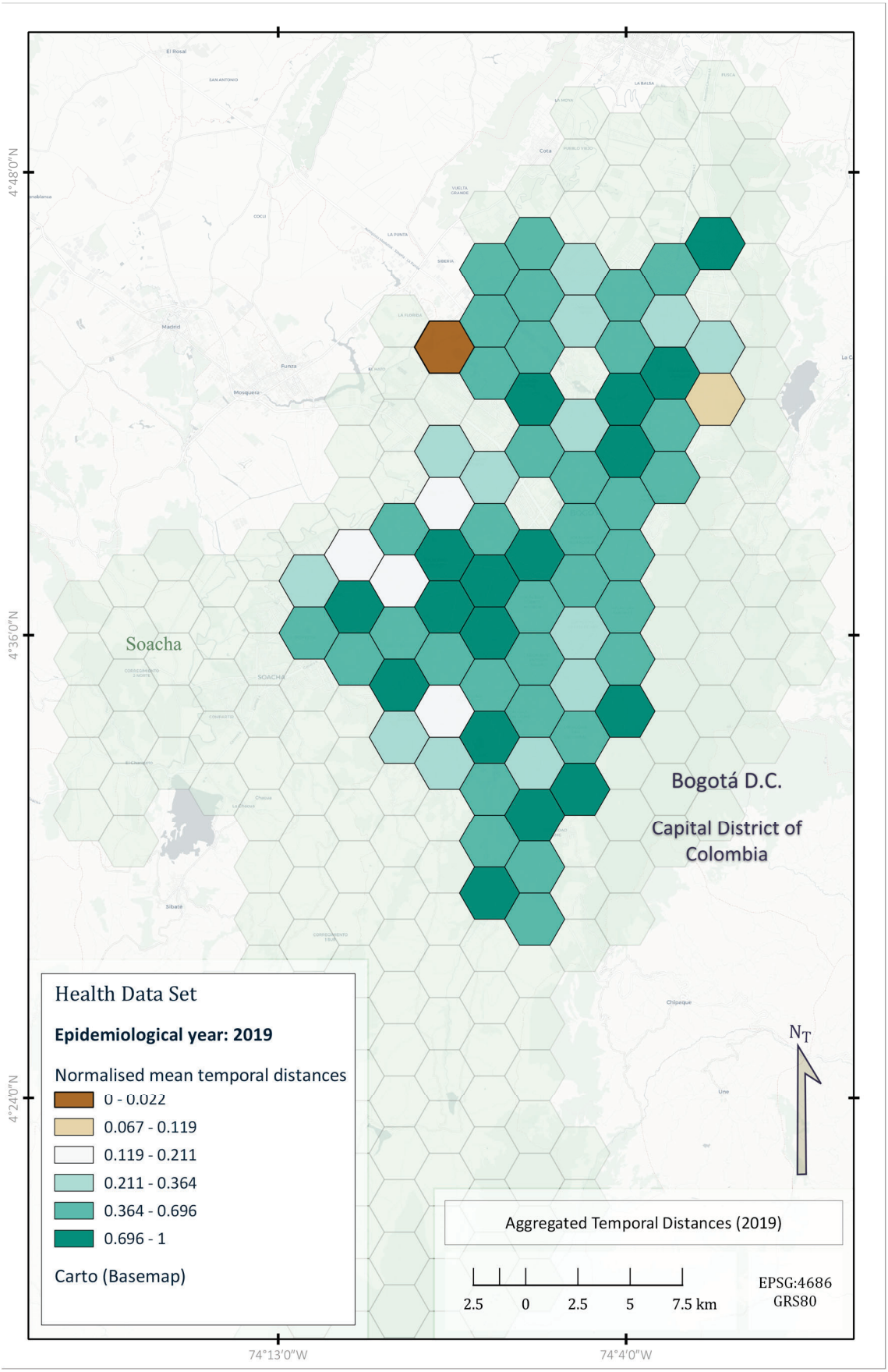


Figure 105. Normalised mean temporal distances for the epidemiological year 2019: $\mathcal{M} = \mathbf{10}$, $\beta = 4$, and $\alpha = \mathrm{c}(1, 1, 1, 1, 1)$.

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Willington Siabato