MODELLING SPATIOTEMPORAL VARIABILITY OF WATER TABLE DEPTHS MONITORING DATA

PROF. DR. RODRIGO LILLA MANZIONE

UNESP – SÃO PAULO STATE UNIVERSITY

CAMPUS OF OURINHOS

OUTLINE

- GEOSTATISCAL APPROACHES FOR SPATIO-TEMPORAL DATA
- COVARIANCE MODELS
- MONITORING NETWORK FOR WATER TABLE DEPTHS
- PRELIMINARY RESULTS
- CONCLUSIONS
- FUTURE STUDIES

INTRODUCTION

GROUNDWATER MONITORING DATA ARE PARTICULARLY INTERESTING WHEN ANALYSING AQUIFER CHARACTERISTICS BECAUSE CAN REVEAL NOT ONLY TEMPORAL PATTERNS BUT ALSO SPATIAL DISTRIBUTIONS AND VARIATION OVER TIME IF COLLECTED IN A GEOSPATIAL NETWORK.

FROM SPATIAL AND TEMPORAL CORRELATIONS, IT IS POSSIBLE TO PREDICT VALUES AT POINTS FROM NEIGHBOURING OBSERVATIONS AND MAKE PREDICTIONS IN BETWEEN OBSERVATION TIMES.

SPATIO-TEMPORAL INTERPOLATION CAN POTENTIALLY PROVIDE MORE ACCURATE PREDICTIONS THAN SPATIAL INTERPOLATION BECAUSE OBSERVATIONS TAKEN AT OTHER TIMES CAN BE INCLUDED.

SPATIO-TEMPORAL GEOSTATISTICS

KYRIAKIDIS & JOURNEL (1999) DEFINE TWO MAJOR CONCEPTUAL VIEWPOINTS FOR MODELING OF SPATIOTEMPORAL DISTRIBUTIONS VIA SPATIAL STATISTICS TOOLS EXTENDED TO INCLUDE THE ADDITIONAL TIME DIMENSION:

A SINGLE SPATIOTEMPORAL RF MODEL $Z(\mathbf{U}, T)$, TYPICALLY DECOMPOSED INTO A TREND COMPONENT MODELING SOME ''AVERAGE'' SMOOTH VARIABILITY OF THE SPATIOTEMPORAL PROCESS $Z(\mathbf{U}, T)$, AND A STATIONARY RESIDUAL COMPONENT MODELING HIGHER FREQUENCY FLUCTUATIONS AROUND THAT TREND IN BOTH SPACE AND TIME.

MULTIPLE VECTORS OF RFS OR VECTORS OF TS. TWO MODEL SUBCLASSES CAN THEN BE DEFINED. MODELS IN THE FIRST SUBCLASS TREAT THE SPATIOTEMPORAL RF $Z(\mathbf{U}, T)$ AS A COLLECTION OF A FINITE NUMBER T OF TEMPORALLY CORRELATED SPACE RFS $\mathbf{Z}(\mathbf{U})$, WHILE MODELS IN THE SECOND SUBCLASS VIEW THE RF $Z(\mathbf{U}, T)$ AS A COLLECTION OF A FINITE NUMBER N OF SPATIALLY CORRELATED TS $\mathbf{Z}(T)$.

SPATIO-TEMPORAL COVARIANCE MODELS

ESTIMATING AND MODELLING THE CORRELATION OF A SPACE-TIME PROCESS IS FUNDAMENTAL TO GEOSTATISTICAL ANALYSIS, SINCE ONLY IF THE CORRELATION MODEL IS APPROPRIATE FOR THE VARIABLE UNDER STUDY CAN THE SUBSEQUENT ESTIMATION AND/OR SIMULATION RESULTS BE RELIED ON (DE IACO, 2010).

IN PRACTICE IT IS CUSTOMARY TO PROPOSE A MODEL AND TEST ITS PERMISSIBILITY USING ONE OF A SET OF BASIC MODELS THAT ARE KNOWN TO BE PERMISSIBLE.

THAT IS A RELATIVELY STRAIGHTFORWARD PRACTICE IN MODELLING SPATIAL (OR TEMPORAL) VARIOGRAMS AS THERE ARE MANY SUCH MODELS IN COMMON USE AND THESE MODELS MAY BE COMBINED LINEARLY TO FORM COMPLEX MODELS.

SPATIOTEMPORAL COVARIANCE MODELS

- SEPARABLE/LINEAR MODEL (ROUHANI & HALL, 1989)
- PRODUCT MODEL (DE CESARE ET AL., 2001)
- PRODUCT-SUM MODEL (DE IACO ET AL., 2001)
- METRIC MODEL (DIMITRAKOPOULOS & LUO, 1994; SOARES & PEREIRA; 2007).
- CRESSIE-HUANG MODEL (CRESSIE & HUANG, 1999),
- GNEITING MODELS (GNEITING, 2002),
- INTEGRATED PRODUCT MODEL AND MIXTURE MODELS (DE IACO ET AL., 2002A)
- INTEGRATED PRODUCT-SUM MODEL (DE IACO ET AL., 2002B)
- NON-SEPARABLE SPATIOTEMPORAL COVARIANCE MODELS (KOLOVOS ET AL., 2004; STEIN, 2005; PORCU ET AL., 2008; RODRIGUES & DIGGLE, 2010).

COVARIANCE MODELS – NOTION OF SEPARABILITY

A *SEPARABLE* SPACE–TIME COVARIANCE FUNCTION CONSIDERS THE SPATIOTEMPORAL PROCESS AS THE JOINT PROCESS OF TWO INDEPENDENT PROCESSES, ONE THAT OCCURS IN SPACE AND ANOTHER THAT OCCURS IN TIME, RESULTING IN A PURELY SPATIAL COMPONENT AND A PURELY TEMPORAL COMPONENT.

HOWEVER, WE DO NOT OBSERVE REALISATIONS OF THE TWO SEPARATE PROCESSES, ONLY THE JOINT PROCESS.

SEPARABILITY IS RESTRICTIVE AND OFTEN REQUIRES UNREALISTIC ASSUMPTIONS.

COVARIANCE MODELS

IN THIS STUDY WE TESTED THREE ST COVARIANCE MODELS:

- SEPARABLE
- PRODUCT-SUM
- METRIC

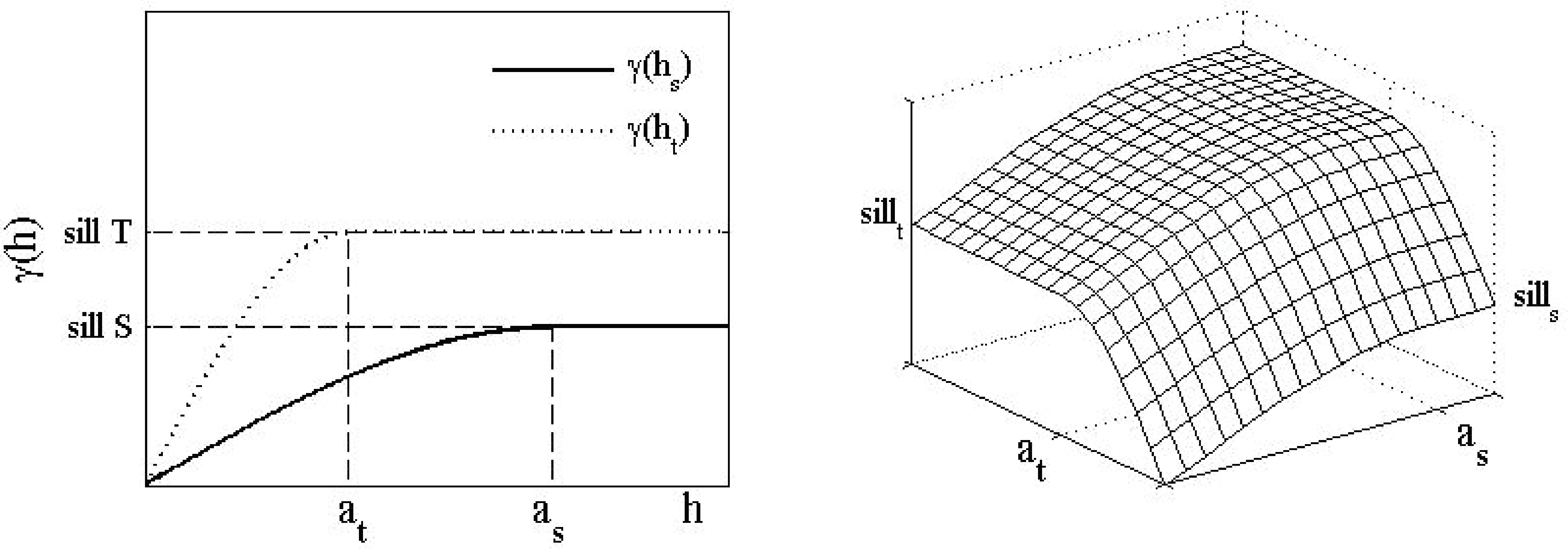
SEPARABLE

$$C_{st}(h_s, h_t) = C_s(h_s) + C_t(h_t)$$

$C_s(h_s)$ SPATIAL COVARIANCE AND $C_t(h_t)$ TEMPORAL COVARIANCE SIMPLE ADDED

FOR THIS MODEL, COVARIANCE MATRICES OF CERTAIN CONFIGURATIONS OF SPATIOTEMPORAL DATA ARE SINGULAR (MYERS & JOURNEL, 1990; ROUHANI & MYERS, 1990).

THIS MEANS THIS COVARIANCE FUNCTION IS ONLY POSITIVE SEMI-DEFINITE AND IS UNSATISFACTORY FOR OPTIMAL PREDICTION.



Example of separable model, semivariograms in (omnidirectional) spatial and temporal directions (left) and spatiotemporal semivariogram (right).
SOURCE: Denham (2012)

PRODUCT-SUM

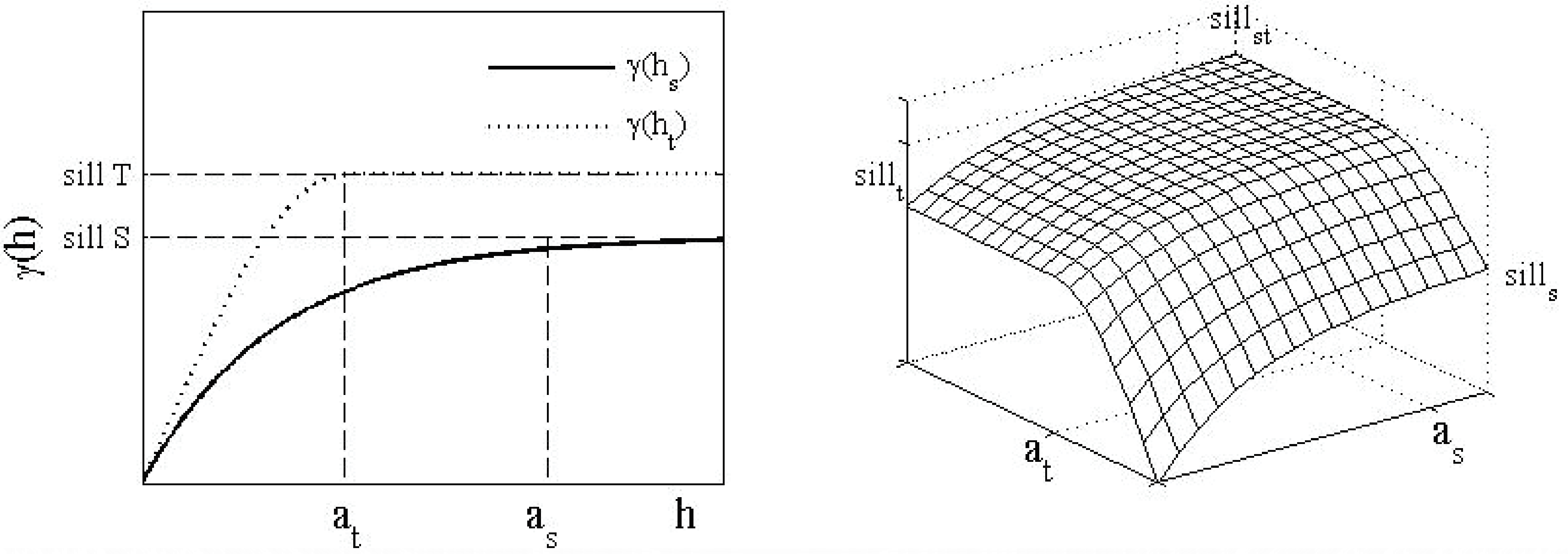
$$C_{st}\ (h_s; h_t) = k_1 C_s\ (h_s) C_t(h_t) + k_2 C_s(h_{s)} + k_3 C_3(h_t)$$

$$\gamma_{st}(h_s; h_t) = [k_2 + k_1 C_t(0)]\, \gamma_s(h_s) + [k_3 +\ k_1 C_s(0)]\, \gamma_t(h_t) -\ k_1 \gamma_s(h_s)\, \gamma_t(h_t)$$

C_s AND C_t ARE COVARIANCE FUNCTIONS AND γ_sAND γ_t ARE THE CORRESPONDENT VARIOGRAM FUNCTIONS.

$C_{st}(0)$ IS THE γ_{st} SILL, BEING $C_s(0)$ AND $C_t(0)$ THE γ_sAND γ_t SILLS.

BY DEFINITION, $\gamma_{st}\ (0{,}0) =\ \gamma_s(0) =\ \gamma_t = 0.$



Example of product-sum model, marginal (omnidirectional) spatial and temporal semivariograms (left) and spatiotemporal semivariogram (right).
SOURCE: Denham (2012)

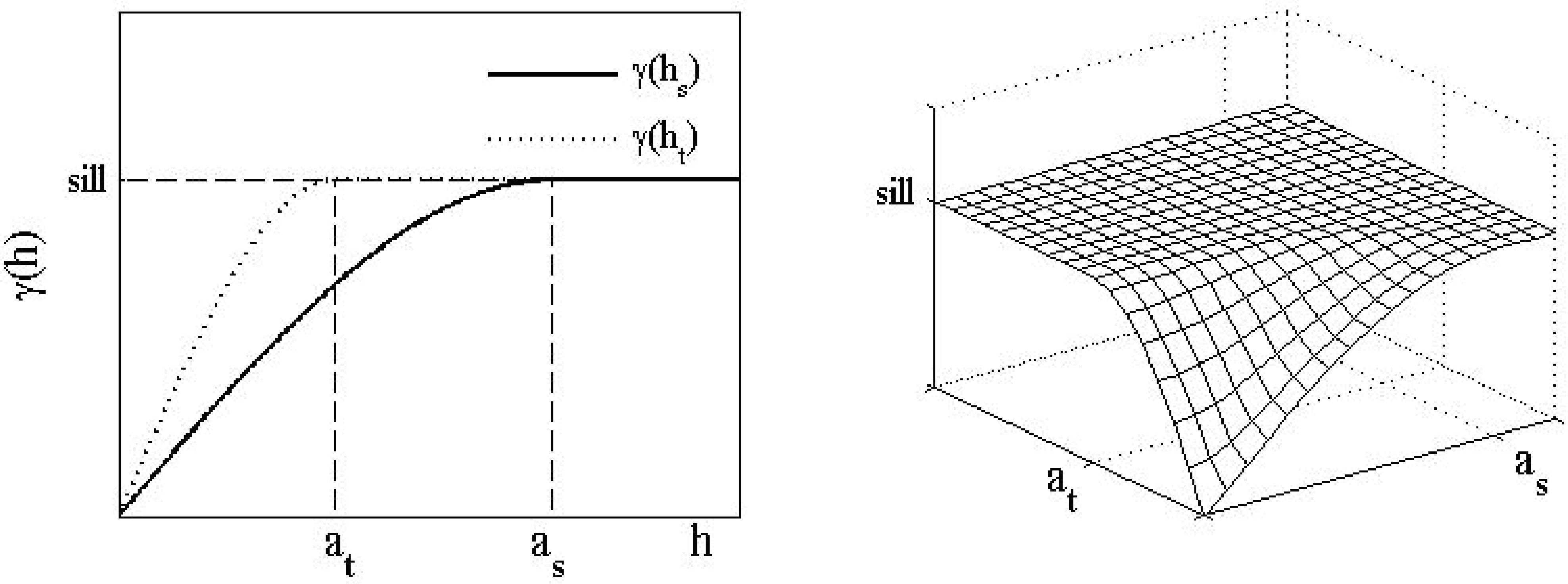
METRIC

$$C_{st}(h_s, h_{t)} = C(a^2|h_s|^2 + b^2 h_t^2)$$

COEFFICIENTS *A; B ∈ R* .

IN THE EQUATION, THE SAME MODEL IS ASSUMED FOR BOTH SPATIAL AND TEMPORAL COVARIANCE, WITH POSSIBLE CHANGES IN THE RANGE.

THIS MODEL CAN BE REALISED AS A SPATIAL COVARIANCE MODEL WITH AN EXTRA DIMENSION (AND ANISOTROPY RATIO) TO CONSIDER THE TEMPORAL DIMENSION.



Example of metric model, semivariograms in (omnidirectional) spatial and temporal directions (left) and spatiotemporal semivariogram (right).
SOURCE: Denham (2012)

STUDY AREA AND DATA SET

SANTA BARBARA ECOLOGICAL STATION (EECSB)

MONITORING WATER TABLE DEPTHS FROM SEPTEMBER 2014 TO AUGUST 2016

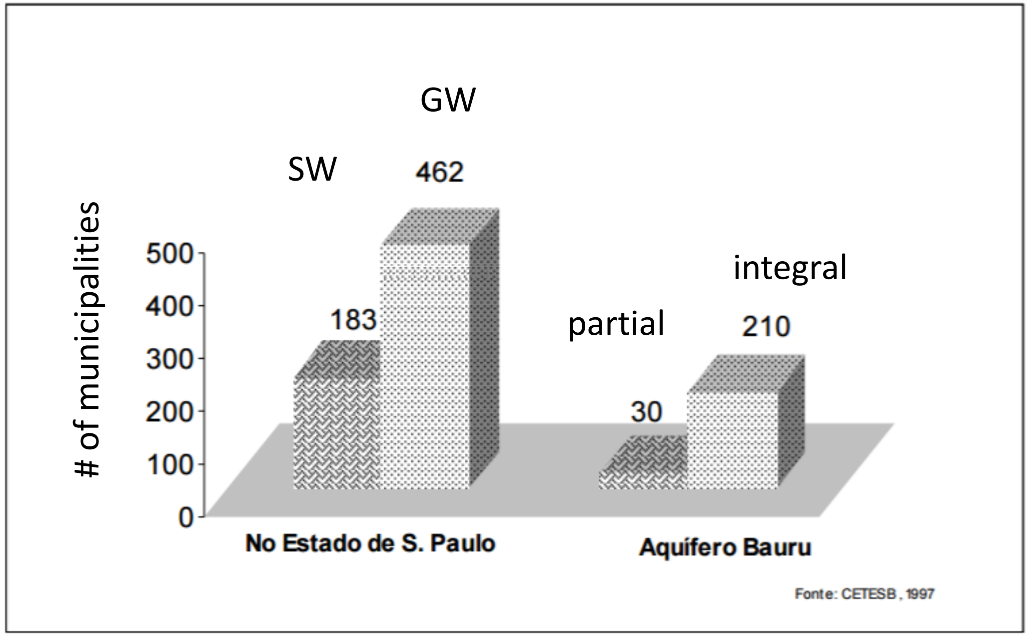
BAURU AQUIFER SYSTEM

65 WELLS

GSTAT ROUTINES IN R (PEBESMA & GRÄLER, 2016; GRÄLER ET AL., 2016)

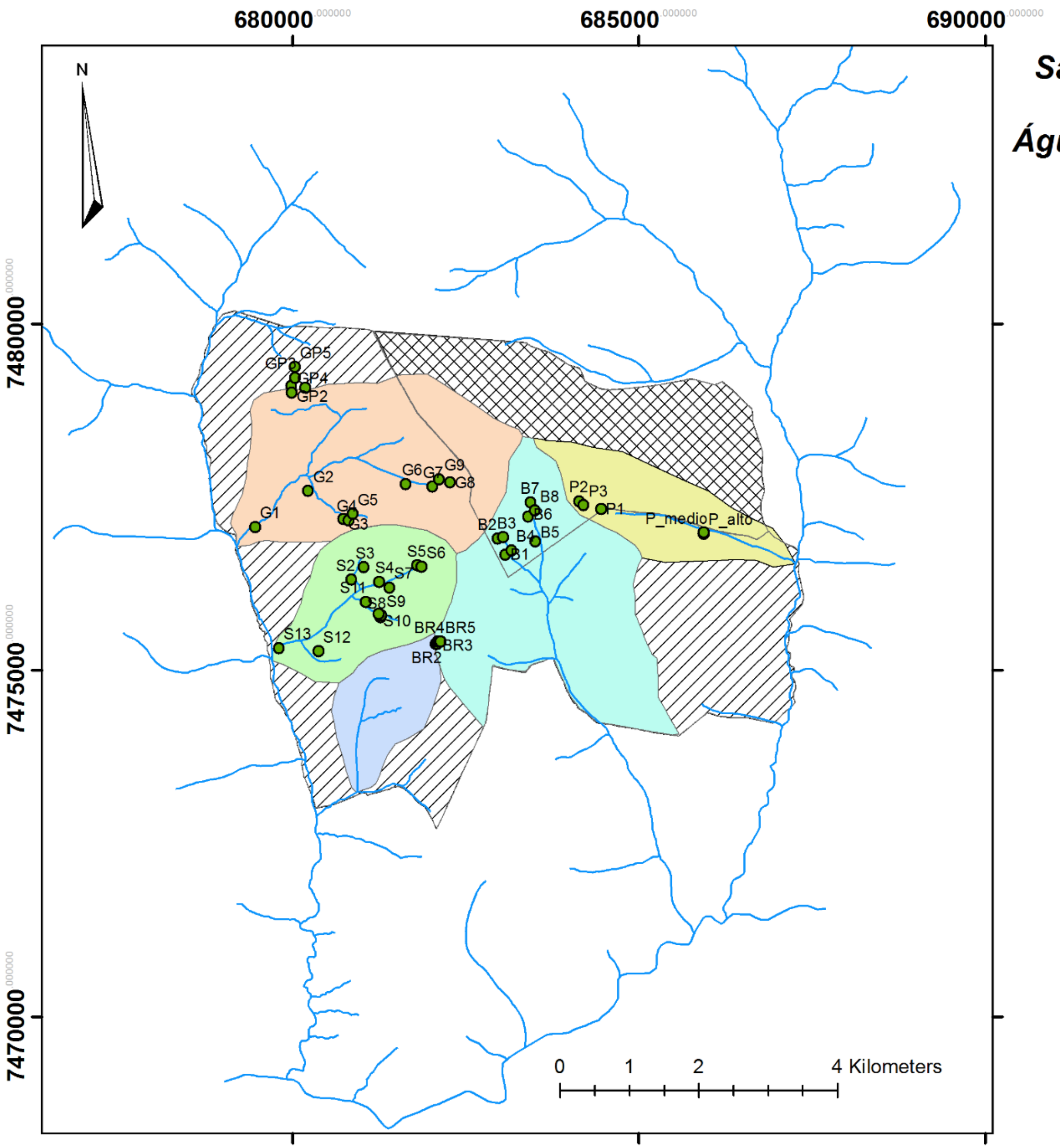

Aguas de Santa Barbara
BAS
Sao Paulo state
Brazil
0
1.150
2.300
Kilometers

BAURU AQUIFER SYSTEM (BAS)



COMPARISON AMONG THE NUMBER OF CITIES THAT USE SUPERFICIAL AND UNDERGROUND WATER FOR PUBLIC PROVISIONING IN THE SÃO PAULO STATE AND AMONG THE CITIES THAT USE, PARTIAL OR INTEGRALLY, UNDERGROUND WATER OF THE BAURU AQUIFER SYSTEM (CETESB, 1997).

Santa Bárbara Ecological Station (EEcSB)
Águas de Santa Bárbara - SP, Brazil



- Wells
- Drainage
- EEcSB
- SB State Forrest

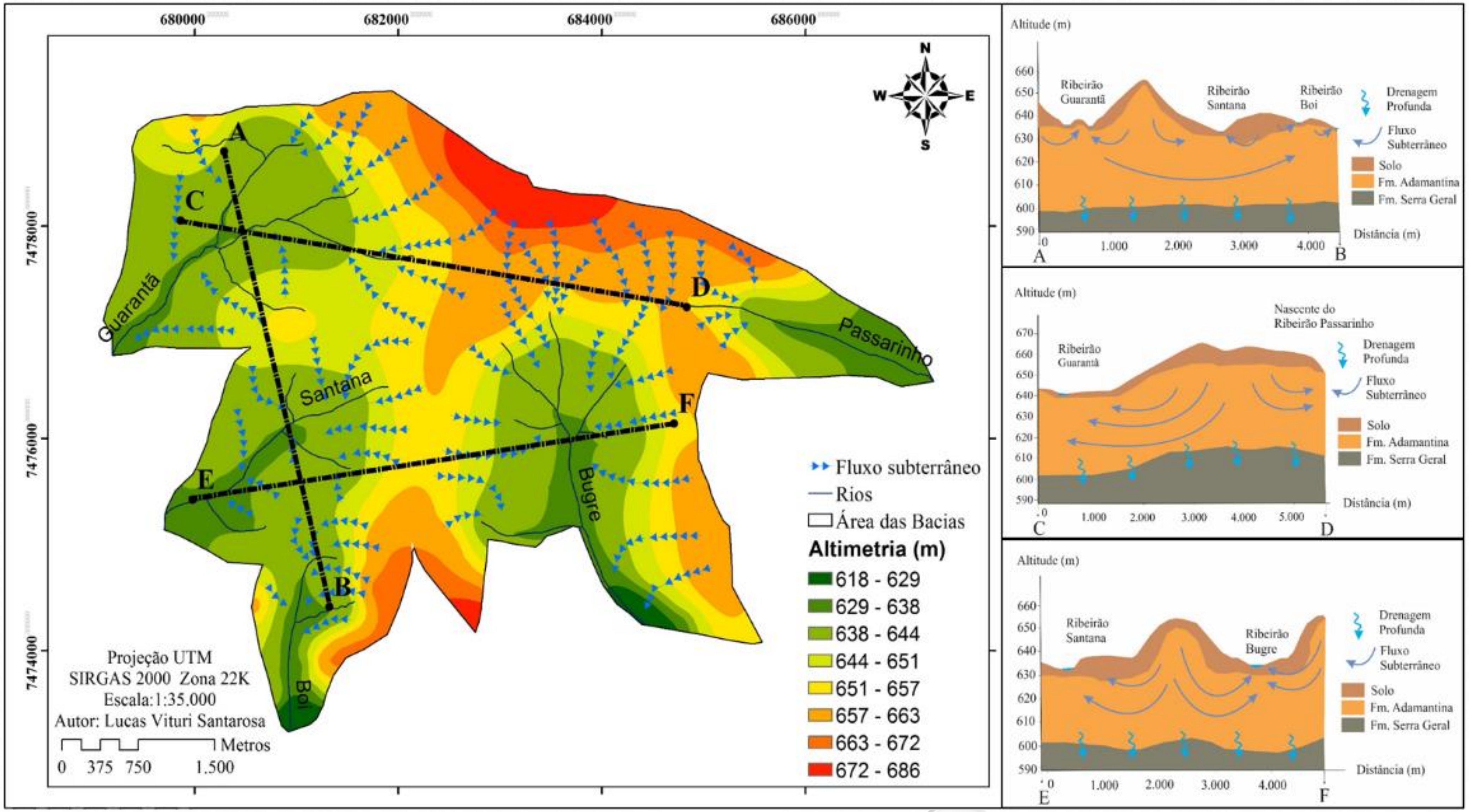
Watersheds

- Boi
- Santana
- Passarinho
- Gurarantã
- Bugre

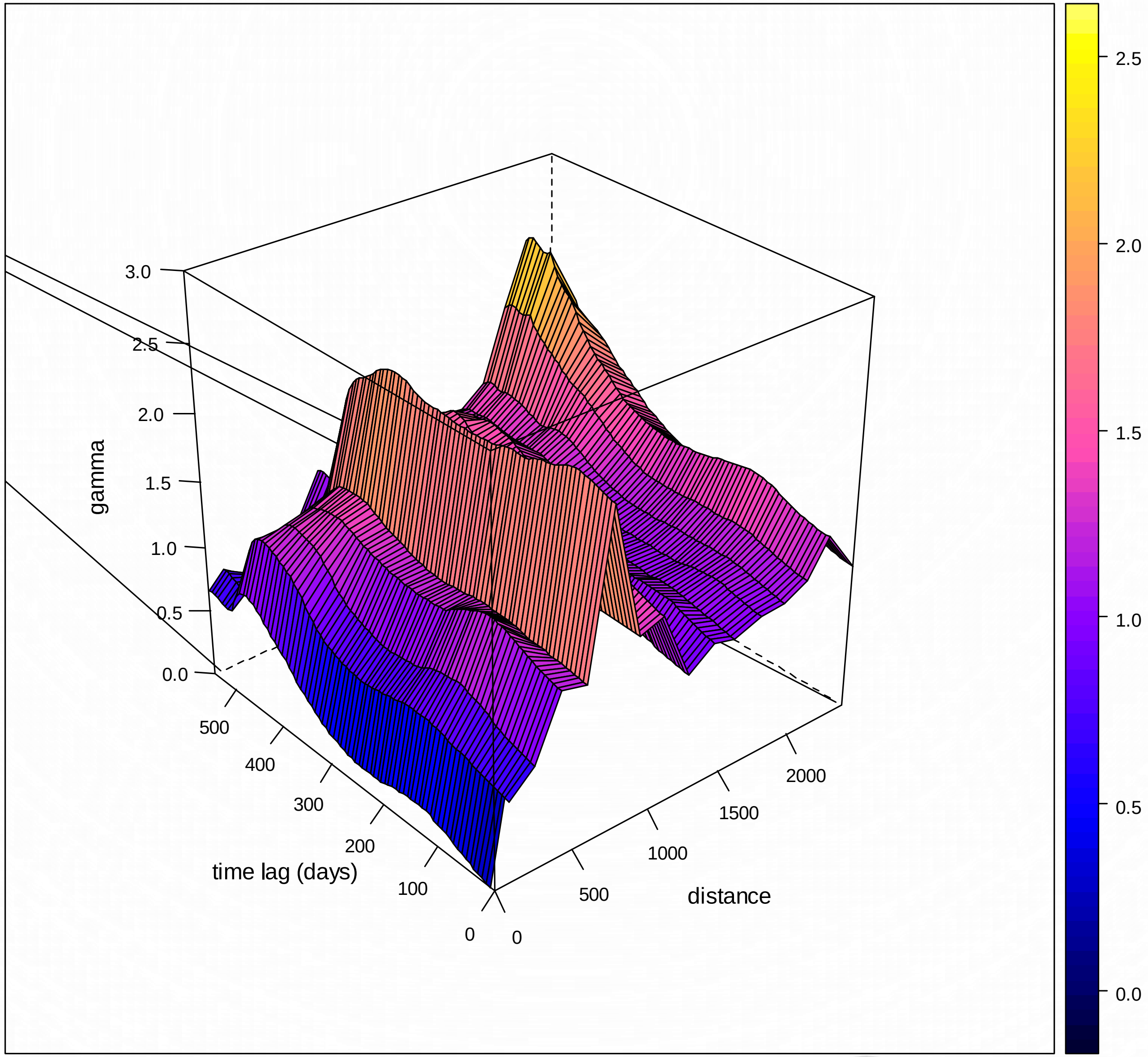
Projection UTM
Datum: SIRGAS 2000
Zone 22 k (51°W)

Autor: Prof. Dr. Rodrigo Lilla Manzione
UNESP/Ourinhos

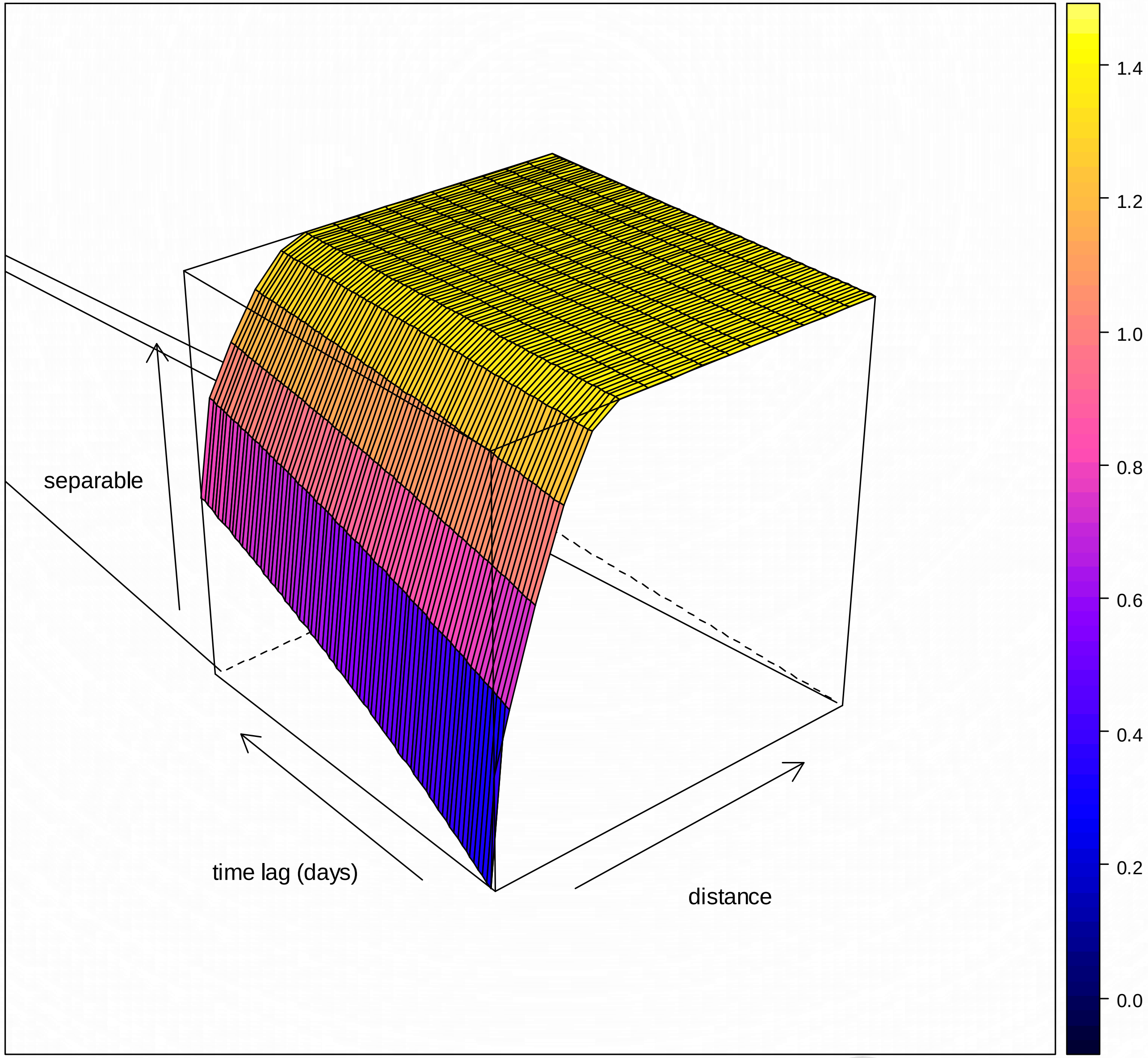
LAB
Laboratório de Hidrologia e Hidrogeologia Operacional H2O



680000
682000
684000
686000
7478000
7476000
7474000
N
S
W
E
A
B
C
D
E
F
Guarantã
Santana
Passarinho
Bugre
Boi
Fluxo subterrâneo
Rios
Área das Bacias
Altimetria (m)
618 - 629
629 - 638
638 - 644
644 - 651
651 - 657
657 - 663
663 - 672
672 - 686
Projeção UTM
SIRGAS 2000 Zona 22K
Escala:1:35.000
Autor: Lucas Vituri Santarosa
Metros
0 375 750 1.500
Altitude (m)
Ribeirão Guarantã
Ribeirão Santana
Ribeirão Boi
Drenagem Profunda
Fluxo Subterrâneo
Solo
Fm. Adamantina
Fm. Serra Geral
Distância (m)
Nascente do Ribeirão Passarinho
Ribeirão Bugre



gamma
3.0
2.5
2.0
1.5
1.0
0.5
0.0
time lag (days)
500
400
300
200
100
0
distance
0
500
1000
1500
2000
2.5
2.0
1.5
1.0
0.5
0.0

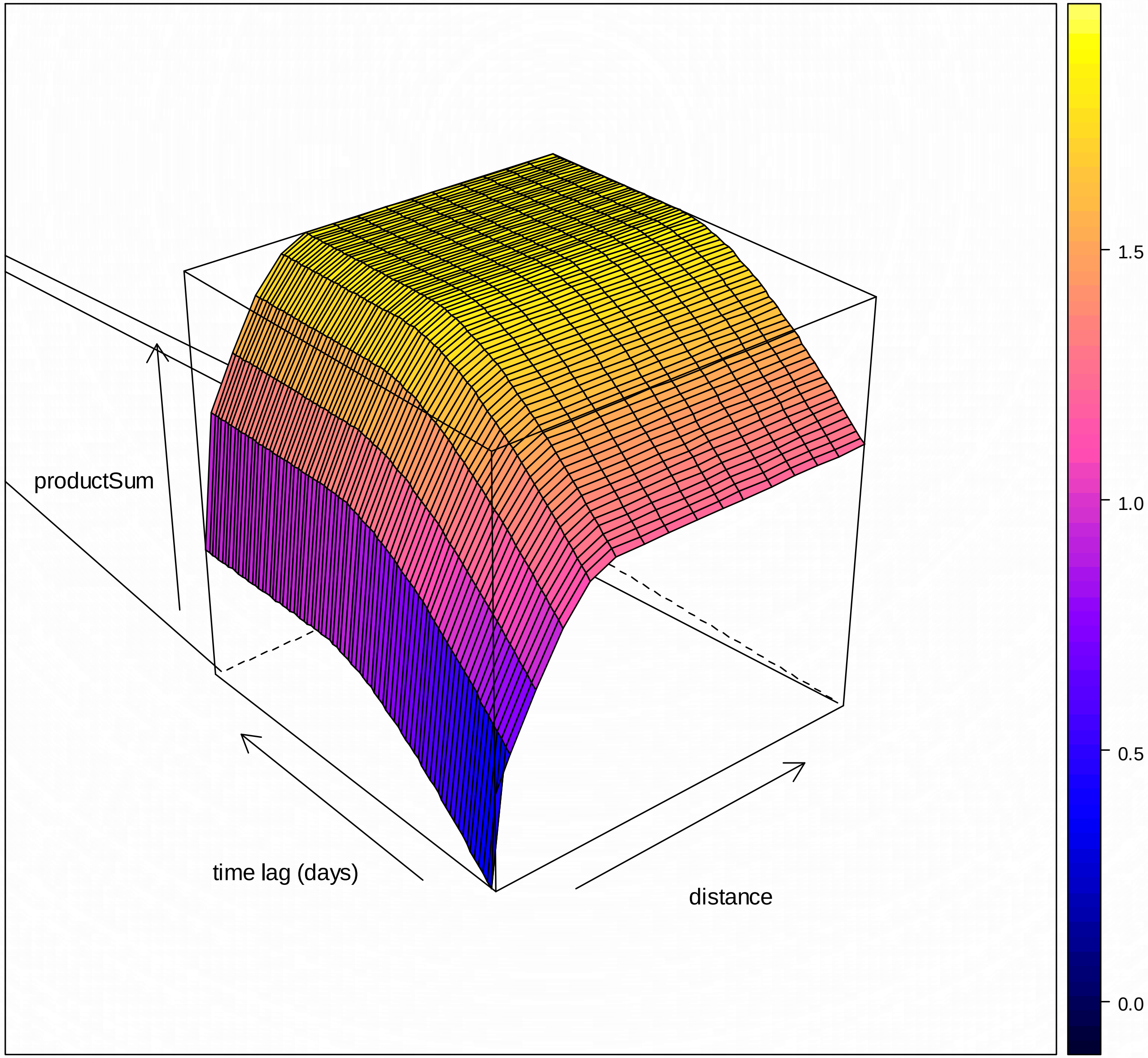


"separable",

space=vgm(0.9,"Sph", 750, 0.1),

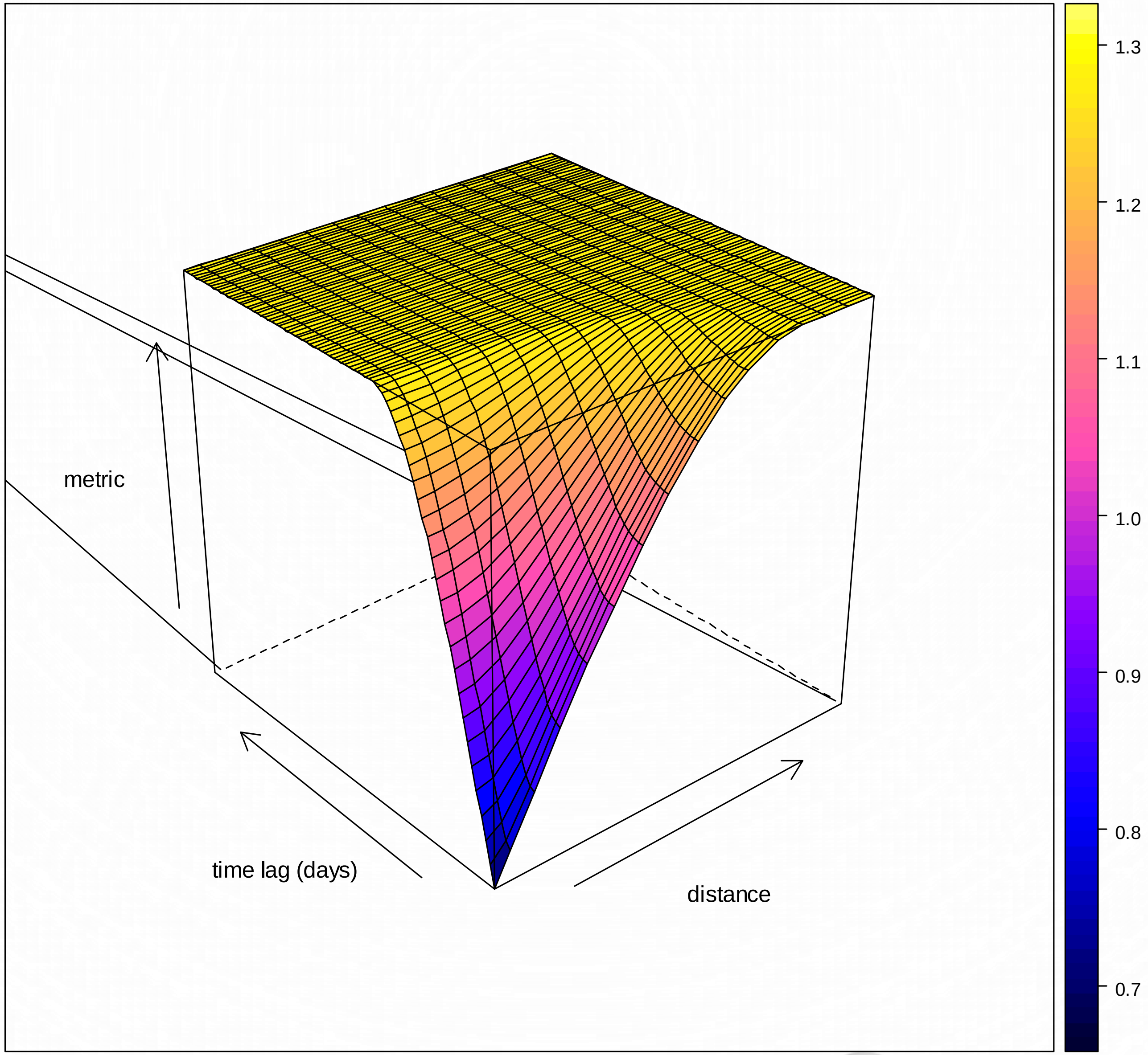
time =vgm(0.8,"Exp", 150, 0.2),

sill=2



"productSum",

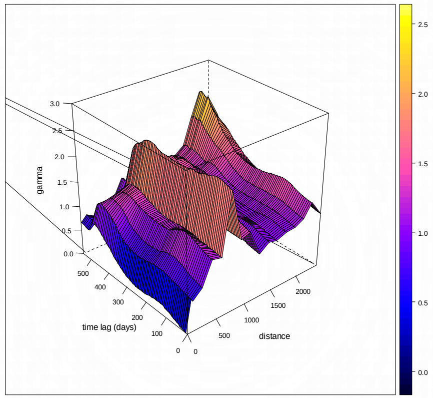
```
space = vgm(1.2, "Sph", 750, 0.1),
time = vgm(0.8, "Sph", 320, 0.0),
k = 2)
```

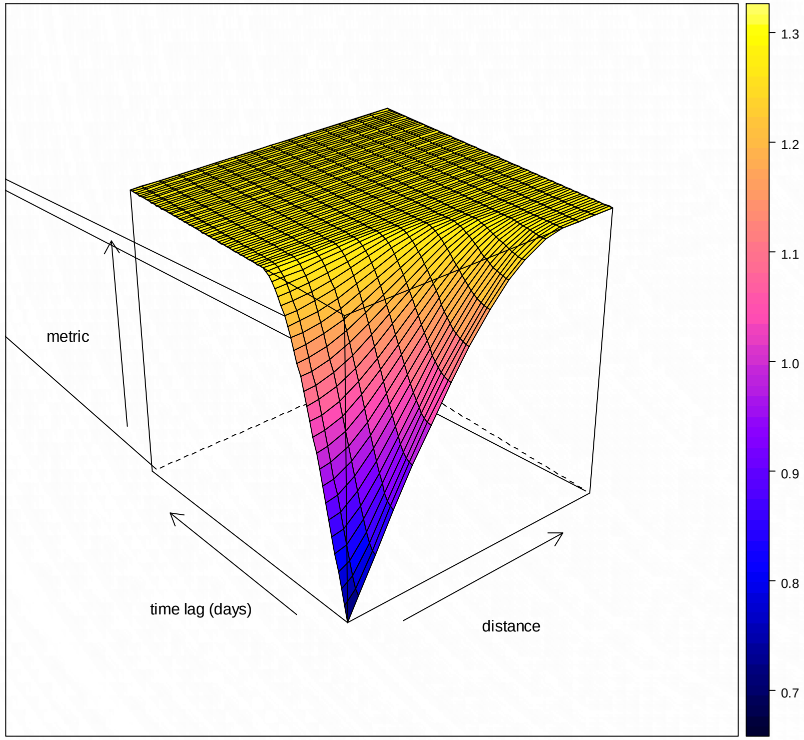


"metric",

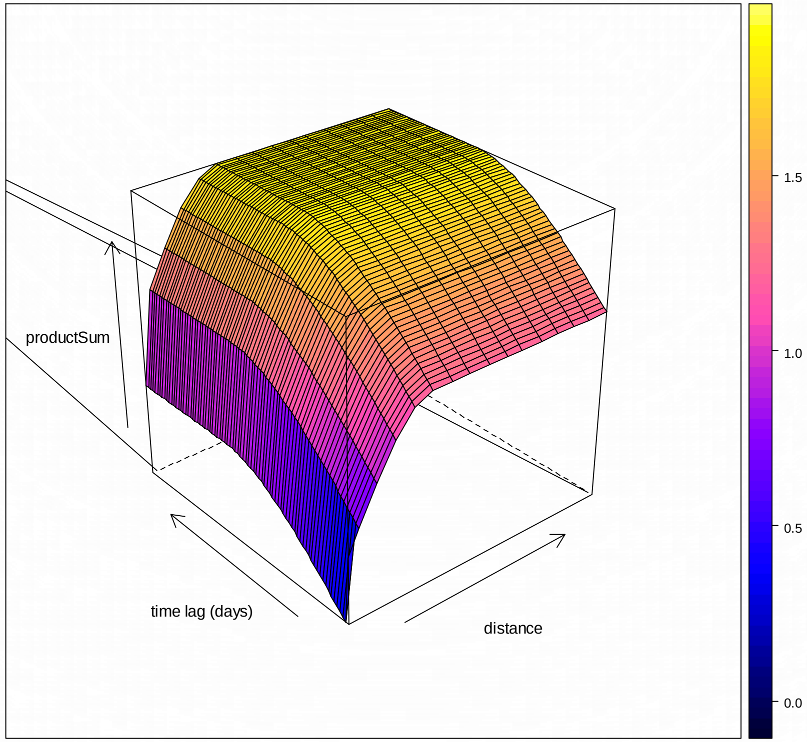
joint=vgm(1.7,"Sph", 950, 0.2),

stAni=10)

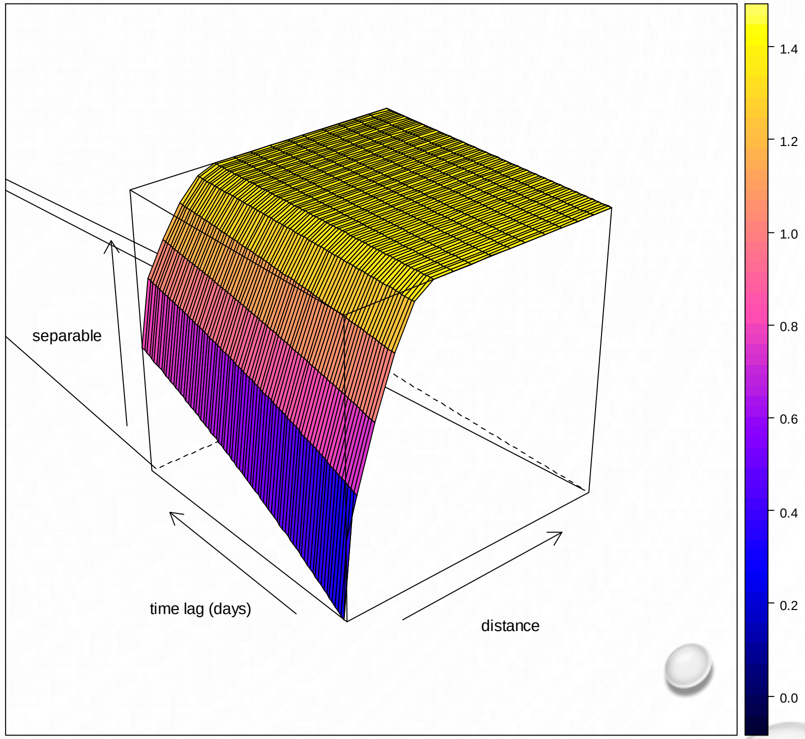




SEPARABLE



PRODUCT-SUM



METRIC

FINAL REMARKS – CONCLUSIONS

ST VARIABILITY

NETWORK

PRODUCT-SUM

FAST RESPONSE

FINAL REMARKS – CONCLUSIONS

GROUNDWATER MANAGEMENT AND PLANNING

MONITORING STRATEGIES

MANAGED AQUIFER RECHARGE

REMEDIATION PLANS

FINAL REMARKS – NEXT STEPS

INCREASE TS LENGTH

INCREASE OBSERVATION POINTS VIA GEOSTATISTICAL OPTIMIZATION

TEST OTHER MODELS

TEST SEPARABILITY

ST INTERPOLATION OF WATER TABLE DEPTHS

REFERENCES

CRESSIE, N.; HUANG, H. C. (1999). CLASSES OF NONSEPARABLE, SPATIO-TEMPORAL STATIONARY COVARIANCE FUNCTIONS. *JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION, 94*, 1330-1340.

DE CESARE, L.; MYERS, D. E.; POSA, D. (2001) ESTIMATING AND MODELING SPACE-TIME CORRELATION STRUCTURES. *STATISTICS AND PROBABILITY LETTERS, 51*, 9-14.

DE IACO, S.; MYERS, D. E.; POSA, D. (2001). SPACE-TIME ANALYSIS USING A GENERAL PRODUCT-SUM MODEL. *STATISTICS AND PROBABILITY LETTERS, 52*, 21-28.

DE IACO, S.; MYERS, D. E.; POSA, D. (2002A) NONSEPARABLE SPACE-TIME COVARIANCE MODELS: SOME PARAMETRIC FAMILIES. *MATHEMATICAL GEOLOGY, 34*, 23-42.

DE IACO, S.; MYERS, D. E.; POSA, D. (2002B) SPACE-TIME VARIOGRAMS AND A FUNCTIONAL FORM FOR TOTAL AIR POLLUTION MEASUREMENTS. *COMPUTATIONAL STATISTICS AND DATA ANALYSIS, 41*, 311-328.

DE IACO, S. (2010) SPACE-TIME CORRELATION ANALYSIS: A COMPARATIVE STUDY. *JOURNAL OF APPLIED STATISTICS, 37*, 1027-1041.

DENHAM, A. (2012) GEOSTATISTICAL SPATIOTEMPORAL MODELLING WITH APPLICATION TO THE WESTERN KING PRAWN OF THE SHARK BAY MANAGED PRAWN FISHERY. PHD THESIS (EDITH COWAN UNIVERSITY)

DIMITRAKOPOULOS, R.; LUO, X. (1994) SPATIOTEMPORAL MODELLING: COVARIANCES AND ORDINARY KRIGING SYSTEMS *GEOSTATISTICS FOR THE NEXT CENTURY* (PP. 88-93).

GNEITING, T. (2002) NONSEPARABLE, STATIONARY COVARIANCE FUNCTIONS FOR SPACE-TIME DATA. *JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION, 97*, 590-600.

GRÄLER, B.; PEBESMA, E. J.; HEUVELINK, G. M. B. *SPATIO-TEMPORAL GEOSTATISTICS USING GSTAT.* IFGI: INSTITUTE FOR GEOINFORMATICS UNIVERSITY OF MÜNSTER. AVAIABLE AT: <HTTPS://CRAN.R-PROJECT.ORG/WEB/PACKAGES/GSTAT/VIGNETTES/SPATIO-TEMPORAL-KRIGING.PDF>. ACCESS: SEP. 08, 2016.

REFERENCES

KOLOVOS, A.; CHRISTAKOS, G.; HRISTOPULOS, D. T.; SERRE, M. L. (2004) METHODS FOR GENERATING NON-SEPARABLE SPATIOTEMPORAL COVARIANCE MODELS WITH POTENTIAL ENVIRONMENTAL APPLICATIONS. *ADVANCES IN WATER RESOURCES, 27*, 815-830.

KYRIAKIDIS, P. C.; JOURNEL, A. G. (1999) GEOSTATISTICAL SPACE-TIME MODELS: A REVIEW. *MATHEMATICAL GEOLOGY, 31*(6), 651-684.

MYERS, D. E.; JOURNEL, A. (1990) VARIOGRAMS WITH ZONAL ANISOTROPIES AND NONINVERTIBLE KRIGING SYSTEMS. *MATHEMATICAL GEOLOGY, 22*, 779-785.

PEBESMA, E. J.; GRÄLER, B. INTRODUCTION TO SPATIO-TEMPORAL VARIOGRAPHY. IFGI: INSTITUTE FOR GEOINFORMATICS UNIVERSITY OF MÜNSTER. AVAIABLE AT: <HTTPS://CRAN.R-PROJECT.ORG/WEB/PACKAGES/GSTAT/VIGNETTES/ST.PDF>. ACCESS: MAY 08, 2016.

PORCU, E.; MATEU, J.; SAURA, F. (2008) NEW CLASSES OF COVARIANCE AND SPECTRAL DENSITY FUNCTIONS FOR SPATIO-TEMPORAL MODELLING. *STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT, 22*(SUPPLEMENT 1), 65-79.

RODRIGUES, A.; DIGGLE, P. J. (2010) A CLASS OF CONVOLUTION-BASED MODELS FOR SPATIO-TEMPORAL PROCESSES WITH NON-SEPARABLE COVARIANCE STRUCTURE. *SCANDINAVIAN JOURNAL OF STATISTICS, 37*, 553-567.

ROUHANI, S.; HALL, T. J. (1989) SPACE-TIME KRIGING OF GROUNDWATER DATA. IN M. ARMSTRONG (ED.), *GEOSTATISTICS: PROCEEDINGS OF THE THIRD INTERNATIONAL GEOSTATISTICS CONGRESS, SEPTEMBER 5-9, 1988, AVIGNON, FRANCE* (VOL. 2, PP. 639-650). DORDRECHT, BOSTON: KLUWER ACADEMIC PUBLISHERS.

ROUHANI, S.; MYERS, D. E. (1990) PROBLEMS IN SPACE-TIME KRIGING OF HYDROGEOLOGICAL DATA. *MATHEMATICAL GEOLOGY*, 611-623.

SOARES, A.; PEREIRA, M. J. (2007) SPACE-TIME MODELLING OF AIR QUALITY FOR ENVIRONMENTAL-RISK MAPS: A CASE STUDY IN SOUTH PORTUGAL. *COMPUTERS & GEOSCIENCES, 33*, 1327-1336.

STEIN, M. L. (2005) SPACE-TIME COVARIANCE FUNCTIONS. *JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION, 100*, 310-321.

THANK YOU FOR YOUR ATTENTION

RLMANZIONE@GMAIL.COM