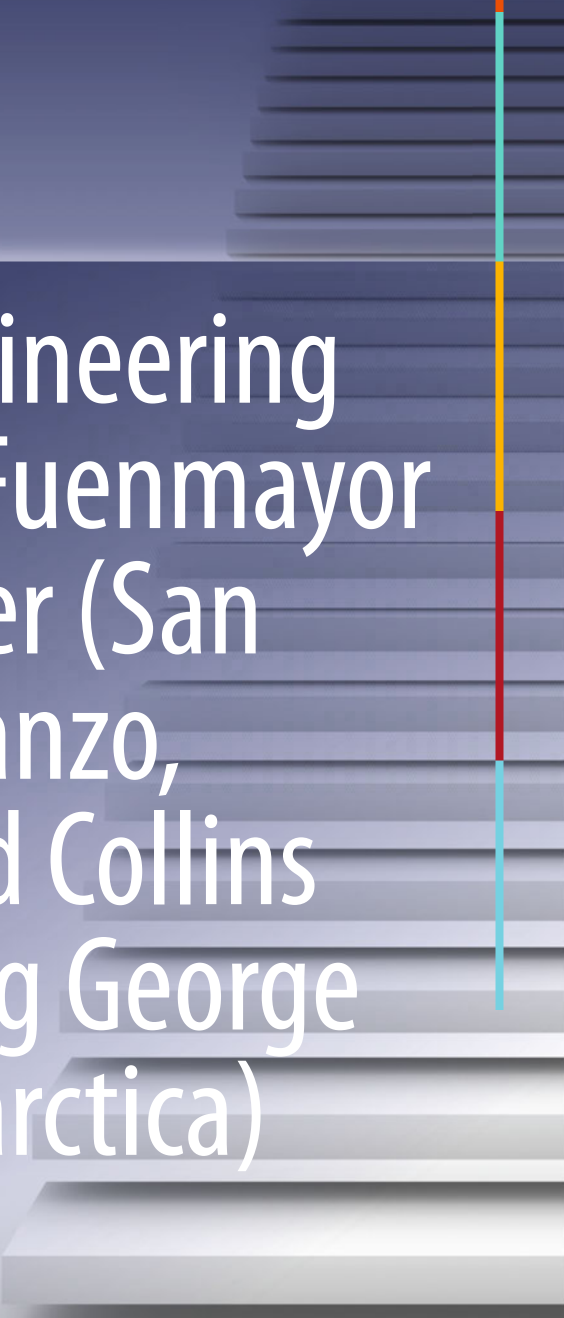
Springer Theses
Recognizing Outstanding Ph.D. Research

David Chinarro

System Engineering Applied to Fuenmayor Karst Aquifer (San Julián de Banzo, Huesca) and Collins Glacier (King George Island, Antarctica)



Springer

Springer Theses

Recognizing Outstanding Ph.D. Research

Aims and Scope

The series "Springer Theses" brings together a selection of the very best Ph.D. theses from around the world and across the physical sciences. Nominated and endorsed by two recognized specialists, each published volume has been selected for its scientific excellence and the high impact of its contents for the pertinent field of research. For greater accessibility to non-specialists, the published versions include an extended introduction, as well as a foreword by the student's supervisor explaining the special relevance of the work for the field. As a whole, the series will provide a valuable resource both for newcomers to the research fields described, and for other scientists seeking detailed background information on special questions. Finally, it provides an accredited documentation of the valuable contributions made by today's younger generation of scientists.

Theses are accepted into the series by invited nomination only and must fulfill all of the following criteria

- They must be written in good English.
- The topic should fall within the confines of Chemistry, Physics, Earth Sciences, Engineering and related interdisciplinary fields such as Materials, Nanoscience, Chemical Engineering, Complex Systems and Biophysics.
- The work reported in the thesis must represent a significant scientific advance.
- If the thesis includes previously published material, permission to reproduce this must be gained from the respective copyright holder.
- They must have been examined and passed during the 12 months prior to nomination.
- Each thesis should include a foreword by the supervisor outlining the significance of its content.
- The theses should have a clearly defined structure including an introduction accessible to scientists not expert in that particular field.

More information about this series at http://www.springer.com/series/8790

David Chinarro

System Engineering Applied to Fuenmayor Karst Aquifer (San Julián de Banzo, Huesca) and Collins Glacier (King George Island, Antarctica)

Doctoral Thesis accepted by
the University of Zaragoza, Spain

Springer

Author
Dr. David Chinarro
Polytechnic School
San Jorge University
Zaragoza
Spain

Supervisors
Prof. José L. Villarroel
Department of Computer and Systems Engineering
University of Zaragoza, Group of Technologies in Harsh Environments (GTE)
Zaragoza
Spain

Prof. José A. Cuchí
Department of Agricultural Sciences and Natural Habitats, Polytechnic School of Huesca
University of Zaragoza
Huesca
Spain

ISSN 2190-5053 ISSN 2190-5061 (electronic)
ISBN 978-3-319-08857-0 ISBN 978-3-319-08858-7 (eBook)
DOI 10.1007/978-3-319-08858-7

Library of Congress Control Number: 2014943252

Springer Cham Heidelberg New York Dordrecht London

© Springer International Publishing Switzerland 2014
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Parts of this thesis have been published in the following journal articles:

- **Application of Wavelet Correlation Analysis to the Karst Spring of Fuenmayor. San Julian de Banzo, Huesca, Spain (2011).**
  Authors: David Chinarro, José L. Villarroel and José A. Cuchí.
  Chapter in book: *Advances in Research in Karst Media. Series: Environmental Earth Sciences*.
  Authors: Carrasco, Francisco; Durán Valsero, Juan José; LaMoreaux, James W. (Eds.).
  Publisher: Springer. 1st Edition, 2011, ISBN 978-3-642-12485-3.
- **Wavelet analysis of Fuenmayor karst spring, San Julián de Banzo, Huesca, Spain (2011 and 2012).**
  Authors: D. Chinarro, J. L. Villarroel and J. A. Cuchí.
  Journal: Environmental Earth Sciences ISSN: 1866-6299, doi: 10.1007/s12665-011-1351-y, September 17, 2011. 13 pages.
  Reprinted: April 2012, ISSN 1866-6280, 2012, Volume 65, Number 8, pages 2231–2243.
- **Linear System Techniques Applied to the Fuenmayor Karst Spring, Huesca (Spain) (2013).**
  Authors: J. A. Cuchí, D. Chinarro and J. L. Villarroel.
  Journal : Environmental Earth Sciences.
- **Application of wavelet correlation analysis to the karst spring of Fuenmayor. San Julián de Banzo, Huesca, Spain (2010).**
  Authors: D. Chinarro, J. A. Cuchi and J. L. Villarroel.
  Congress: 4th International Symposium on Karst (ISKA-2010). Málaga, Spain, April 2010.
- **Polar glacier, the eyewitness of the climate change.**
  Author: D. Chinarro, J. L. Villarroel and J. A. Cuchi, C. Dominguez and A. Eraso (2012).
  Congress: International Geography Congress, IGC COLOGNE 2012, Germany, August 2012.
- **Climate change scenarios for temperature and precipitation in Aragón (Spain) (2013).**
  Authors: J. Ribalaygua and M. R. Pino and J. Pórtoles and E. Roldán and E. Gaitán and D. Chinarro and L. Torres
  Journal: Science of Total Environment.
- **A Study of the Relationship between Weather Variables and Electric Power Demand inside a Smart Grid/Smart World Framework (2012).**
  Authors: Luis Hernández, Carlos Baladrón, Javier M. Aguiar, Lorena Calavia, Belén Carro, Antonio Sánchez-Esguevillas, Diane J. Cook, David Chinarro and Jorge Gómez.
  Journal: Sensors 2012, 12, 11571-11591; doi:10.3390/s120911571. ISSN 1424-8220.

- **A Multi-Agent-System Architecture for Smart Grid Management and Forecasting of Energy Demand in Virtual Power Plants (2013).**
  Authors: Luis Hernández, Carlos Baladrón, Javier M. Aguiar, Belén Carro, Antonio Sánchez-Esguevillas, Jaime Lloret, David Chinarro, Jorge J. Gómez, Diane Cook.
  Journal = IEEE Communications, volume 51, No. 1, pages 106–114.
- **Modelos matemáticos aplicados al Acuífero de Fuenmayor (Sierra de Guara) (2010).**
  Authors: David Chinarro. Proceeding semminar: Aguas Subterráneas. IV Jornada. Ciclo sobre residuos. Published by Fundación Genes y Gentes (2010), page: 57–66.
- **Avances en localización, comunicaciones TTE y geofísica aplicables a cavidades de interésturístico (2010).**
  Authors: Ayuso, N; Bataller, V; Aisa, J; Cabrero, S; Chinarro, D; Cuchi, JA; Larma, R; Lera, F; Mediano, A; Molina, P; Muñoz, A; Tardioli, D; Sicignano, D; Viñals, V; Villarroel.
  Congress: III Congreso Español de Cuevas Turísticas (CUEVATUR 2010). Aracena (Huelva), 4–6 Noviembre, 2010. Published by J.J. Durán y F. Carrasco (Eds.), Cuevas: Patrimonio, Naturaleza, Cultura y Turismo, pp. 363–370, Madrid, Asociación de Cuevas Turísticas Españolas. ISBN: 978-84-614-4630-8. EAN: 9788461446308.
- **Sistemic Analysis of Karst Springs. Application to Fuenmayor spring (San Julián de Banzo, Huesca)**
  Authors: José Luis Villarroel and David Chinarro.
  Institution: Estudios Altoaragoneses, Diputación de Huesca. Report (2009–2010).

I lovingly dedicate this thesis to my wife, who always stood by me in all my difficult duties; to my children, to encourage them in the adventure of acquiring and sharing new skills; to my parents, who instilled me the endeavor in the study from an early age

Supervisors' Foreword

System engineering is typically defined as an art and science to create principles, identify methodologies, and establish models, with the purpose of deriving knowledge on controlling and managing the operation of complex-engineered systems. Similarly, a natural system can be categorized as complex, because of the difficulty in identifying and quantifying all information involved in its behavior, in terms of establishing all constraints and variables involved in the system, and accurately quantifying the temporal and spatial parameters. David Chinarro's thesis tackles fundamental questions posed in two natural systems, viz, a karst aquifer system and a glacier system, on the basis of transferability of system engineering methodology and from an exclusively hydrological outlook. This work has been developed in a high-tech research group, the I3A institute at the University of Zaragoza, where we carry out a set of projects by applying computing and communication technologies to groundwater, nivology, and geology. The guidance of this thesis by two mentors has allowed for it to be developed in a multidisciplinary way, due to complementary profiles from an engineer and a hydrogeologist.

Identification techniques, developed to represent typical engineering artificial systems through linear and nonlinear models, can be applied in the study of natural systems, where coupling effects between climate and hydrosphere occur. This thesis proposes enhanced methods to meet the new requirements in identification fields, innovating analysis and identification strategies to determine models that better represent the peculiarities of the two particular systems. One study specifically aims to estimate the mutual influence between precipitation and discharge of a karst aquifer, which is situated near Spanish Pyrenees mountains. Another, using the same data-driven models, deals with the implications of air temperature in a glacier melting, specifically, as it manifests itself in the stream drainage of Collins glacier, King George island, Antarctica. In this regard, special tools, such as those based on wavelet transform, have been considered in the preparing and analysis of time series, such as smoothing of signals, sampling frequency, coherence levels, and data abnormality detection. Through parametric and nonparametric identification processes, the author tries to identify models that best represent the internal dynamics of the system by iterative testings, where models are systematically checked against monitorized data, with an efficiency criterion given. The best obtained solution, in the assessment of results drawn from dealt cases, has been found among the model structures in blocks.

This thesis is meant to be a formal statement of engineering system identification methodology, mainly through nonlinear approaches, in the context of aquifer systems, which improves in many cases the results of karst hydrology. Remarkable results are derived from the characterization of Fuenmayor spring response and its correlation with precipitation, under the assumption of a linear system to be complemented with identification methods based on nonlinear techniques. Important findings such as a transfer function reduced to five parameters may describe properly the hydrologic behavior of this karst system under linear assumption. A Hammerstein–Wiener model approach presents a high efficiency value that exceeds the results obtained by the linear models using the same efficiency criterion. Likewise, approaches proposed for Antarctica's glaciology, through wavelet analysis and runoff models, scarcely appear in the literature, and can reveal essential information when it is not possible to clarify the all physics governing the system. The wavelet coherence density is used to estimate the boundaries of the Seasonal Effective Core (SEC), the period when the glacier discharge responds in a coherent way to temperature. For each year, an acceptably coherent sampling period is used as refined data for the identification process of the glacial system. Linear parametric identification was applied to each SEC. Nevertheless, it is demonstrated that nonlinearities present in glacier behavior are due to the phase change of water, a fact revealed by Hammerstein–Wiener structures used to define models with greater efficiency. Moreover, two different types of glacier dynamics have been discovered depending on the annual cycle and the SEC average temperature.

Therefore, system engineering techniques based on black-box identification, as a well-developed scientific procedure, are very useful tools to characterize the hydrological response of a karstic system discharge and to model the response of glacier stream to melting processes or climate variations.

Zaragoza, February 2014

José L. Villarroel
José A. Cuchí

Acknowledgments

It is very difficult to express in words the great gratitude I feel for who helped me to bring to fruition this work.

First, I would like to thank my two supervisors, Dr. Villarroel and Dr. Cuchí, because of their mentoring work, rich technical discussions and excellent guidance during the thesis development. Their wise advices and long experience have really contributed to the best findings of this work. Also, I would like to recognize the learnt lessons from lecturers of postgraduate and doctoral courses of University of Zaragoza, Group of Technologies in Hostile Environments (GTE) and Engineering Research Institute of Aragon (I3A).

Some individuals and entities have selflessly supported me and provided the necessary data to perform the exposed analysis. Dr. Adolfo Eraso and Dr. Carmen Dominguez, from GLACKMA foundation (Glaciers, CrioKarst and Environment), have supplied long-time series from glacier sensoring obtained under harsh conditions. Dr. Bartolome Andreo has outstandingly assessed and recommended the findings of this thesis, regarding it deserves an international dissemination. I must recognize the contribution of several Antartic bases: the Bellingshausen Russian base, former Jubany Station-Dallmann laboratory, Uruguayan Artigas base and Chilean Capitania del Puerto Bahía Fildes, for the meteorology data supply and logistical support. Also, thanks to authorities of *Natural Park of Sierra and Canyons of Guara* for granting access permissions to the Fuenmayor aquifer enclosure and its surrounding.

Gratefulness to managers and officials of San Jorge University, who have allowed me to participate and lead international research projects with a notorious impact on certain issues of the current thesis. Likewise, to some of my colleagues for their help and encouragement.

Contents

Symbols

Lists of symbols used in this paper with a brief description.

$\mu S/cm\,25\,^{\circ}\mathrm{C}$	Micro-Siemens per centimetre. Conductivity unit
θ	Parameters vector
$u_n(t)$	Discrete time series for the input of system
$y_n(t)$	Discrete time series for the output of system
$\hat{y_n}(t)$	Estimate value of $y_n(t)$
f*(x)	Complex conjugate of function f(x)
$\mathscr{F}\{u(t)\}$	Fourier transform of u(t)
$\widetilde{\mathscr{F}}\{u(t)\}$	Discrete Time Fourier Transform of u(t)
$\hat{f}(\omega)$	Fourier transform of the function f in the frequency domain
$\widetilde{f}(\tau,\omega)$	Wavelet transform of the function f in the time-frequency space
$\mathscr{G}_{\psi,s,\tau}\{u(t)\}$	Wavelet power spectrum of u(t) with wavelet family ψ
$\mathscr{H}\mathscr{W}_{f_{1,[nl]};f_{2,[nl]};f_{3,[nl]}}$	Hammerstein–Wiener model of u(t) and y(t)
$L^2(\mathbb{R})$	Set of all square integrable functions in the Hilbert space
$(f \otimes g)(t)$	Convolution of two function f(t) and g(t)
$(f * g)(t)$	Correlation of two function f(t) and g(t)
$\mathscr{L}\{y(t)\}$	Laplace transforms of y(t)
$\mathscr{W}_{\psi,s,\tau}\{u(t)\}$	Continuous Wavelet Transform of u(t) with wavelet family ψ
$\mathscr{P}_{\psi,s,\tau}\{u(t)\}$	Wavelet power spectrum of u(t) with wavelet family ψ
$\mathscr{C}_{\psi,s,\tau}\{u(t),y(t)\}$	Wavelet coherence spectrum
$\Gamma_{\psi}[f(t),g(t)]_{\tau}$	Coherence Average Function
σ_y^2	Variance of $y(n)$
C_y^k	Autocovariance of $y(n)$ with lag k
r_y	Autocorrelation of $y(n)$

Acronyms

Lists of abbreviations used in this chapter with a brief description.

AAO	Antarctic Oscillation
ACF	Autocorrelation function
ACVF	Autocovariance, or covariance of the signal
AIC	Akaike Information Criterion
ANN	Artificial neural networks
AR	Auto Regressive
ARIMA	Autoregressive integrated moving average
ARMA	Autoregressive-moving-average
ARMAX	ARMA with exogenous inputs model
BJ	Box–Jenkins Model
CAF	Coherence average function
CCM	Collins Coalescent Model
CWT	Continuous Wavelet Transform
CWS	Wavelet coherence spectrum
DDF	Degree-day factor
DDM	Data-driven model
DOF	Degree of Freedom
DSP	Digital Signal Processing
DTFT	Discrete Time Fourier Transform
DWT	Discrete Wavelet Transformation
EBM	Energy balance model
ECV	Essential Climate Variables
EOF	Empirical orthogonal functions
FIR	Finite Impulse Response
FFT	Fast Fourier Transform
FKS	Fuenmayor Karst System
GCM	Global circulation model
GLACKMA	Fundation for the study of glaciers, cryokarst and environment

GHG	Greenhouse gases
TIM	Temperature-index model
IIR	Infinite Impulse Response
ICSU	International Council for Science
IPCC	Intergovernmental Panel on Climate Change
KGI	King George Island
K–L	Kullback and Leibler information
LTI	Linear and Time Invariant
MIMO	Multiple Input–Multiple Output
MRA	Multiresolution analysis
MSLP	Mean Sea Level Pressure
NaN	Denomination for missing, or non-finite value
NLS	Non Linear Squares
NHS	Natural Hydrological system
OE	Output Error Model
ODE	Ordinary differential equations
PDF	Probability Density Function
PDE	Partial differential equations
PSD	Power spectral Density
SAM	Southern Annular Mode
SCAF	Smoothed Coherence Average Function
SISO	Single input-single output
STFT	Short-time Fourier Transform
SNR	Signal to noise ratio
TPH	Transition Period Head
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	US Geological Survey
WFT	Windowed Fourier Transformation
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organitation
WPS	Wavelet power spectrum
XWS	Cross wavelet spectrum