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David Chinarro

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



**Springer**

David Chinarro

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

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the University of Zaragoza, Spain

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- **Sistemic Analysis of Karst Springs. Application to Fuenmayor spring (San Julián de Banzo, Huesca)**

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*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

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# Symbols

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

$\mu S/cm$	Micro-Siemens per centimetre. Conductivity unit
$\theta$	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 $f(x)$
$\mathcal{F}\{u(t)\}$	Fourier transform of $u(t)$
$\widetilde{\mathcal{F}}\{u(t)\}$	Discrete Time Fourier Transform of $u(t)$
$\hat{f}(\omega)$	Fourier transform of the function $f$ in the frequency domain
$\tilde{f}(\tau, \omega)$	Wavelet transform of the function $f$ in the time-frequency space
$\mathcal{G}_{\psi,s,\tau}\{u(t)\}$	Wavelet power spectrum of $u(t)$ with wavelet family $\psi$
$\mathcal{HW}_{f_1,[n],f_2,[n],f_3,[n]}$	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 $g(t)$
$\mathcal{L}\{y(t)\}$	Laplace transforms of $y(t)$
$\mathcal{W}_{\psi,s,\tau}\{u(t)\}$	Continuous Wavelet Transform of $u(t)$ with wavelet family $\psi$
$\mathcal{P}_{\psi,s,\tau}\{u(t)\}$	Wavelet power spectrum of $u(t)$ with wavelet family $\psi$
$\mathcal{C}_{\psi,s,\tau}\{u(t), y(t)\}$	Wavelet coherence spectrum
$\Gamma_{\psi}[f(t), g(t)]_{\tau}$	Coherence Average Function
$\sigma_y^2$	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 Organisation
WPS	Wavelet power spectrum
XWS	Cross wavelet spectrum

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