

## Laboratoire de Génie Civil et d'Ingénierie Environnementale

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To whom it may concern  
COLCIENCIAS programmes  
Bogota, Colombia

Villeurbanne, France, 6 March 2013

### Certification of invitation, programme length and language requirements

I undersigned, Jean-Luc Bertrand-Krajewski, professor at LGCIE (Laboratory of Civil and Environmental Engineering), INSA Lyon, France, have the pleasure to invite Santiago Sandoval Arenas, with ID 1020723493, from Bogota, Colombia, to work under my supervision for a PhD thesis in my laboratory, on the topic "On-line continuous monitoring and data validation in urban drainage and sewer systems", which we discussed and agreed together as being of great mutual interest. The PhD thesis will last 3 years, tentatively from May 2013 to May 2016.

Hereby I inform COLCIENCIAS that his PhD thesis will be written in English. As required by the Doctoral School MEGA (Mechanics, Energetics, Civil Engineering and Acoustics), the thesis will include an extended summary in French: I thus will ask Santiago Sandoval to attend a French course at INSA during his studies. Learning French will also be very useful for his daily life in France.

Sincerely yours,

Pr. Jean-Luc Bertrand-Krajewski

Jean-Luc BERTRAND-KRAJEWSKI  
Directeur adjoint  
LGCIE-INSA LYON





**Rapport de soutenance d'une thèse de doctorat  
de l'Université de Lyon  
opérée au sein de l'INSA LYON**

Arrêté du 25 mai 2016 fixant le cadre national de la formation et les modalités conduisant à la délivrance du diplôme national de doctorat

**Présentée par M SANDOVAL Santiago** à Villeurbanne, le 05/12/2017

Sur le sujet de thèse : « REVISITING STORMWATER QUALITY CONCEPTUAL MODELS IN A LARGE URBAN CATCHMENT: ONLINE MEASUREMENTS, UNCERTAINTIES IN DATA AND MODELS »

On December 5<sup>th</sup>, 2017, Mr. Santiago Sandoval has defended his Doctoral thesis on « *Revisiting storm water quality conceptual models in a large urban catchment: online measurements, uncertainties in data and models* ». His 45 min presentation was made in English.

The jury has highlighted the great quality of the presentation which was clear, well-structured and very pleasant. In particular, the candidate made relevant choices to present his main contributions in a simple and instructive way. No doubt, the candidate could be an excellent teacher.

The jury has also appreciated the quality and the impressive amount of work done by Santiago Sandoval and, according to all the members of the jury, his important contribution to the different aspects he addressed in the work (sampling procedure, data validation, proposal to revisit conceptual model in the field of urban hydrology).

The answers to the questions were also pertinent. With modesty and enthusiasm, Mr Sandoval has proven his scientific maturity, his pleasure and skill for scientific discussion.

After deliberation, the jury has unanimously congratulated Mr. Santiago Sandoval for his excellent work and pronounced his admission to the degree of Doctor of INSA Lyon - France.

| Civilité | Nom                | Prénom   | Signature |
|----------|--------------------|----------|-----------|
| M.       | CLEMENS            | François |           |
| M.       | TORRES             | Andres   |           |
| MME      | BONHOMME           | Céline   |           |
| MME      | VIKLANDER          | Marla    |           |
| M.       | RENARD             | Benjamin |           |
| MME      | BARRAUD            | Sylvie   |           |
| M.       | BERTRAND-KRAJEWSKI | Jean-Luc |           |

\*Le président signe le rapport de soutenance, qui est contresigné par l'ensemble des membres du jury présent à la soutenance.

\*\*L'original signé de ce document doit être transmis au département FEDORA, INSA LYON

TH0251-F04-Rapport\_Soutenance

Vu, collationné et certifié conforme  
à l'original qui nous a été présenté

Document destiné aux autorités étrangères  
Pour la Colombie

PARIS, le 23 MAI 2025

Pour la Maire de Paris et par délégation  
Le fonctionnaire de la Mairie du 14<sup>e</sup> arrondissement  
BILON Eva

***Traducción oficial de un documento escrito en francés, debidamente sellado por María Luisa Molano Vásquez, traductora e intérprete oficial según decreto 0332 del 28 abril 1997 del Ministerio de la Justicia de la República de Colombia.***

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## **República Francesa**

**Ministerio de la Enseñanza Superior, la Investigación y la Innovación**

## **Universidad de Lyon**

### **Doctorado**

Considerando el Código de Educación, especialmente sus artículos L.612-7; L.613-1, D.613-3 y D.613-6;

Considerando el Código de la Investigación, especialmente su artículo L.412-1;

Considerando el Decreto No. 2015-127 del 5 de febrero del 2015 que trata sobre la aprobación de los estatutos de la comunidad de universidades y establecimientos “Universidad de Lyon”

Considerando la Resolución del 10 de junio del 2016 que acredita a la comunidad de universidades y establecimientos Universidad de Lyon para la expedición de diplomas nacionales ;

Considerando los documentos justificativos del señor **SANDOVAL ARENAS Santiago** nacido el 13 de abril de 1987 en Bogotá (Colombia) para su inscripción al doctorado;

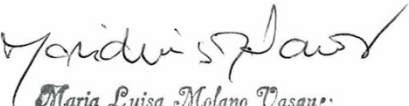
Considerando las actas del jurado que certifican que el interesado ha hecho una sustentación el 5 de diciembre del 2017 de una tesis que trata sobre el siguiente tema:

**“Revisiting stormwater quality conceptual models in a large urban catchment: Online measurements, uncertain in data and models » (SIC)**

preparada en el seno de nuestra Escuela Doctoral Mega de Lyon (Mecánica, energética, ingeniería civil, acústica) ante un jurado presidido por la señora BARRAUD Sylvie (INSA de Lyon) (profesora y compuesto por:

A. TORRES (PUJ, Pontificia Universidad Javeriana) (profesor, señor VIKLANDER (LULEA University of Technology), B. RENARD INSTEAD Lyon (CR), JL. BERTRAND-KRAJEWSKI (INSA de Lyon) (profesor) F. CLEMENS (TU DELFT) (profesor), C. BONHOMME (Escuela de Obras, ParisTech)(HDR)

Considerando la deliberación del jurado;

  
MARÍA LUISA MOLANO VÁSQUEZ  
TRADUCTORA E INTERPRETE OFICIAL  
FRANCS - ESPAÑOL - FRANCES  
RESOLUCION 0332 MINJUSTICIA 1997

El diploma de **Doctorado en Ingeniería civil**  
preparado en el seno del Instituto nacional de ciencias aplicadas de Lyon  
le es otorgado al señor SANDOVAL ARENAS Santiago

A título del **año universitario 2017**  
y le confiere el **Grado de Doctor**,  
Para ejercer con todos sus derechos y prerrogativas que le son vinculados.

Hecho el 5 de marzo del 2018.

El titular - firma ilegible

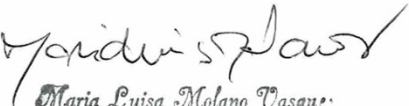
El Presidente de la COMUE  
Firma ilegible – Khaled BOUABDALLAH  
Sello: Universidad de Lyon

El director de INSA de Lyon  
Firma ilegible – Eric MAURINCOMME  
Sello: Instituto nacional de ciencias aplicadas de Lyon

El Rector de la Academia – Canciller de Universidades  
Firma ilegible - Marie-Daniele CAMPION  
Sello: Academia \* Rector

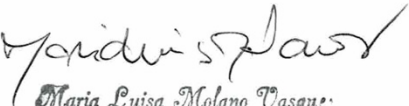
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Sello: Ciudad de Lyon (Rhône-France)  
Alcaldía de la Tercera localidad  
Certifica como conforme el original destinado únicamente a las autoridades  
extranjeras.  
Para Colombia  
Lyon, el 4 de febrero del 2019  
Por el Alcalde y por delegación  
El funcionario comunal  
Firma ilegible  
Sello: República francesa \* Alcaldía de Lyon

  
*Maria Luisa Molano Vasquez*  
TRADUCTORA E INTERPRETE OFICIAL  
FRANCS - ESPAÑOL - FRANCES  
RESOLUCION 0332 MINJUSTICIA 1997

|                                                                                                                                                                                                                                                      |                                                         |                                                             |  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------------|--|
| <b>APOSTILLA</b>                                                                                                                                                                                                                                     |                                                         |                                                             |  |
| (Convención de La Haya del 5 de octubre de 1961)                                                                                                                                                                                                     |                                                         |                                                             |  |
| <b>1.</b>                                                                                                                                                                                                                                            | <b>República francesa</b>                               |                                                             |  |
| <b>El presente acto público</b>                                                                                                                                                                                                                      |                                                         |                                                             |  |
| <b>2.</b>                                                                                                                                                                                                                                            | Ha sido firmado por :                                   | <b>Marylene. BRON</b>                                       |  |
| <b>3.</b>                                                                                                                                                                                                                                            | Actuando en calidad de:                                 | Funcionario municipal                                       |  |
| <b>4.</b>                                                                                                                                                                                                                                            | Lleva el sello /estampilla de:                          | TerceranLocalidad de la alcaldía de Lyon                    |  |
| <b>CERTIFICADO</b>                                                                                                                                                                                                                                   |                                                         |                                                             |  |
| <b>5.</b>                                                                                                                                                                                                                                            | En:                                                     | Paris                                                       |  |
| <b>5.</b>                                                                                                                                                                                                                                            | El:                                                     | 4 de febrero de 2019                                        |  |
| <b>6.</b>                                                                                                                                                                                                                                            | El Procurador general ante la Corte de justicia de Lyon |                                                             |  |
| <b>8.</b>                                                                                                                                                                                                                                            | Bajo el Numero:                                         | <b>1 0 1 8</b>                                              |  |
| <b>9.</b>                                                                                                                                                                                                                                            | Sello redondo:<br>Corte de apelación de Lyon            | Firma ilegible<br>Monique LABELLI<br>Primer abogado general |  |
| <p><i>Advertencia: La apostilla confirma solamente la autenticidad de la firma, del sello o de las estampillas del documento. Ello no significa que el contenido del documento sea correcto o que la República Francesa apruebe su contenido</i></p> |                                                         |                                                             |  |

***Esta es una traducción conforme al original, de la que se guarda copia en los archivos del traductor para verificación – Hecho en Bogotá el 21 de junio de 2025.***

  
 Maria Luisa Molano Vasquez  
 TRADUCTORA E INTERPRETE OFICIAL  
 FRANCES - ESPAÑOL - FRANCES  
 RESOLUCION 0332 MINJUSTICIA 1997

**R É P U B L I Q U E F R A N Ç A I S E**  
Ministère de l'Enseignement supérieur, de la Recherche et de l'Innovation  
**UNIVERSITE DE LYON**  
**DOCTORAT**

Vu le code de l'éducation, notamment ses articles L.612-7, L.613-1, D.613-3 et D.613-6 ;

Vu le code de la recherche, notamment son article L. 412-1 ;

Vu le décret n°2015-127 du 5 février 2015 portant approbation des statuts de la communauté d'universités et établissements "Université de Lyon"

Vu l'arrêté du 10 juin 2016 accordant la communauté d'universités et établissements Université de Lyon en vue de la délivrance de diplômes nationaux

Vu les pièces justificatives produites par M. SANDOVAL ARENAS Santiago

né(e) le 13/04/1987 à BOGOTA (COLOMBIE)

en vue de son inscription en doctorat ;

Vu le procès-verbal du jury attestant que l'intéressé(e) a soutenu, le 05 décembre 2017 une thèse portant sur le sujet suivant :

**REVISITING STORMWATER QUALITY CONCEPTUAL MODELS IN A LARGE URBAN CATCHMENT: ONLINE MEASUREMENTS, UNCERTAINTIES IN DATA AND MODELS**

préparée au sein de l'école doctorale MEGA DE LYON (MÉCANIQUE, ÉNERGÉTIQUE, GÉNIE CIVIL, ACOUSTIQUE)

devant un jury présidé par Mme BARRAUD SYLVIE (INSA DE LYON) (Prof) et composé de :

A. TORRES (PUJ. PONTIFICIA UNIVERSIDAD JAVERIANA) (Prof), M. VIKLANDER (LULEA UNIVERSITY OF TECHNOLOGY) (Prof), B. RENARD (IRSTEA LYON) (CR), JL. BERTRAND-KRAJEWSKI (INSA DE LYON) (Prof), F. CLEMENS (TU DELFT) (Prof), C. BONHOMME (ECOLE DES PONTS, PARISTECH) (HDR)

Vu la délibération du jury :

Le diplôme de DOCTORAT en GÉNIE CIVIL

préparé au sein de l'Institut National des Sciences Appliquées de Lyon

est délivré à M. SANDOVAL ARENAS Santiago

au titre de l'année universitaire 2017

et confère le grade de docteur,

pour en jouir avec les droits et prérogatives qui y sont attachés.

Fait le 05 mars 2018

Le titulaire

*Santiago Sandoval*

Le président de la COMUE

Khaled BOUABDALAH

Le directeur de l'INSA de LYON

Eric Maurincompine

Le Recteur d'Académie  
Chancelier des universités



N° INSALYO 12401172

Marie-Danièle Carpi 2617-121

**VILLE DE LYON (Rhône-France)**  
MAIRIE DU 3<sup>e</sup> Arrondissement  
Certifié conforme à l'original et destiné  
uniquement aux autorités étrangères.  
**POUR LA CELEBRATION**

LYON, le **04 FEV 2018**

LE MAIRE DE LYON



Pour le Maire et par délégation  
L'agent communal

*Philippe Borel*



N°d'ordre NNT : 2017LYSEI089

**THESE de DOCTORAT DE L'UNIVERSITE DE LYON**  
opérée au sein de  
**INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE LYON**

**Ecole Doctorale EDA162**  
**MECANIQUE, ENERGETIQUE, GENIE CIVIL, ACOUSTIQUE**

**Spécialité : Génie Civil**

Soutenue publiquement le 10/10/2017, par :  
**Santiago SANDOVAL**

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**REVISITING STORMWATER QUALITY CONCEPTUAL  
MODELS IN A LARGE URBAN CATCHMENT: ONLINE  
MEASUREMENTS, UNCERTAINTIES IN DATA AND  
MODELS**

**Révision des modèles conceptuels de qualité des  
eaux pluviales sur un grand bassin versant urbain :  
mesures en continue, incertitudes sur les données et  
les modèles**

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Devant le jury composé de :

BARRAUD, Sylvie

INSA LYON

Présidente

CLEMENS, François  
TORRES, Andres  
BONHOMME, Céline  
VIKLANDER, Maria  
RENARD, Benjamin

TU DELF  
PONTIFICIA UNIVERSIDAD JAVERIANA  
ECOLE DES PONTS – PARISTECH  
LULEA UNIVERSITY OF TECHNOLOGY  
IRSTEA LYON

Rapporteur  
Rapporteur  
Examinatrice  
Examinatrice  
Examinateur

BERTRAND-KRAJEWSKI, Jean-Luc

INSA LYON

Directeur de thèse

## ABSTRACT

Total Suspended Solids (TSS) stormwater models in urban drainage systems are often required for scientific, legal, environmental and operational reasons. However, these TSS stormwater traditional model structures have been widely questioned, especially when reproducing data from online measurements at the outlet of large urban catchments. In this thesis, three potential limitations of traditional TSS stormwater models are analyzed in a 185 ha urban catchment (Chassieu, Lyon, France), by means of 365 rainfall events monitored online: a) uncertainties in TSS data due to field conditions (data acquisition and validation); b) uncertainties in hydrological models and rainfall measurements and c) uncertainties in the stormwater quality model structures. These aspects are investigated in six separate contributions, whose principal results can be summarized as follows:

a) TSS data acquisition and validation: (i) four sampling strategies during rainfall events are simulated and evaluated by means of online TSS and flow rate measurements. Recommended sampling time intervals are of 5 min, with average sampling errors between 7 % and 20 % and uncertainties in sampling errors of about 5 %, depending on the sampling interval; (ii) the probability of underestimating the cross section mean TSS concentration is estimated by two methodologies: Simplified Method (SM) and Time Series Method (TSM). TSM shows more realistic TSS underestimations (about 39 %) than SM (about 269 %). A power law describing the TSS as a function of flow rate is revealed, including higher variances of TSS for higher flow rates.

b) Hydrological models and rainfall measurements: (iii) a parameter estimation strategy is proposed for conceptual rainfall-runoff models by analysing the variability of the optimal parameters obtained by single-event (SE) Bayesian calibrations, based on clusters and graphs representations. The results are compared to traditional Bayesian calibrations obtained by SE and multi-event (ME) approaches. The new strategy shows better performances than for SE and ME in terms of accuracy and precision in validation. A single model structure might be able to reproduce at least two different hydrological conditions for the studied urban catchment; (iv) a methodology aimed to calculate “mean” areal rainfall estimation is proposed, based on the same hydrological model and flow rate data. Rainfall estimations by multiplying factors over constant-length time window and rainfall zero records filled with a reverse model show the most satisfactory results compared to further rainfall estimation models.

c) Stormwater TSS pollutograph modelling: (v) the modelling performance of the traditional Rating Curve (RC) model is superior to different linear Transfer Function models (TFs), especially in terms of parsimony and precision of the simulations. No relation between the rainfall corrections or hydrological conditions defined in (iii) and (iv) with performances of RC and linear Transfer Functions (TFs) could be established. Statistical tests strengthen that the occurrence of events not representable by the RC model in time presents a random distribution (independent of the antecedent dry weather period); (vi) a Bayesian reconstruction method of virtual state variables indicates that potential missing processes in the RC description are hardly interpretable in terms of a unique virtual available mass over the catchment that is decreasing over time, as assumed by a great number of traditional models.



## FOLIO ADMINISTRATIF

### THESE DE L'UNIVERSITE DE LYON OPEREE AU SEIN DE L'INSA LYON

NOM : SANDOVAL

DATE de SOUTENANCE : 05/12/2017

Prénoms : Santiago

TITRE : REVISITING STORMWATER QUALITY CONCEPTUAL MODELS IN A LARGE URBAN CATCHMENT: ONLINE MEASUREMENTS, UNCERTAINTIES IN DATA AND MODELS

NATURE : Doctorat

Numéro d'ordre : 2017LYSEI089

Ecole doctorale : MEGA DE LYON (MECANIQUE, ENERGETIQUE, GENIE CIVIL, ACOUSTIQUE) - ED162

Spécialité : Génie Civil

#### RESUME :

Different hypotheses about traditional Total Suspended Solids (TSS) stormwater models from data validation and hydrological concepts have been revisited in a 185 French urban catchment, including online data from 365 rainfall events. Four sampling strategies during rainfall events are simulated and compared to online monitoring. Recommended sampling time intervals are of 5 min, with average sampling errors between 7 % and 20 % and uncertainties in sampling errors of about 5 %, depending on the sampling interval. The probability of underestimating the cross section mean TSS concentration in the sewer system is estimated by two methodologies, where one shows more realistic TSS underestimations (about 39 %). A power law describing the TSS as a function of flow rate is revealed. In the hydrological context, a parameter estimation strategy is proposed by analyzing the variability of parameters obtained by event-based Bayesian calibrations, based on clusters and graphs representations. A single model structure might be able to reproduce at least two different hydrological conditions. A methodology aimed to calculate "mean" areal rainfall estimation is proposed, based on a hydrological model and flow rate data. Regarding TSS modelling, the performance indicators of the traditional Rating Curve (RC) model are superior to different transfer Functions (TFs), with flow rate, rainfall or "mean" areal rainfall as the model input. The potential missing representation of an essential process in the RC model is found to be independent of antecedent dry weather period. A Bayesian reconstruction method indicates that a potential missing process in the RC description is hardly interpretable in terms of a unique state of virtual available mass over the catchment that is decreasing over time, as assumed by a great number of traditional models. Furthermore, the reconstructed processes are highly unrepeatable regarding their shape, besides having a low transferability to other rainfall events.

MOTS-CLÉS: Bayesian method, conceptual modelling, conditional probability, clustering, error models, identifiability, parameters variability

Laboratoire (s) de recherche : Laboratoire DEEP (Déchets Eaux Environnement Pollutions)

Directeur de thèse: Jean-Luc BERTRAND-KRAJEWSKI

Président de jury : Sylvie BARRAUD

Composition du jury :

|                              |                                      |                    |
|------------------------------|--------------------------------------|--------------------|
| BARRAUD, Sylvie              | INSA Lyon                            | Présidente         |
| CLEMENS, François            | TU DELFT                             | Rapporteur         |
| TORRES, Andres               | PUJ Pontificia Universidad Javeriana | Rapporteur         |
| BONHOMME, Céline             | Ecole des ponts – Paristech          | Examinatrice       |
| VIKLANDER, Maria             | Lulea University of Technology       | Examinatrice       |
| RENARD, Benjamin             | IRSTEA LYON                          | Examinateur        |
| BERTRAND-KRAJEWSKI, Jean-Luc | INSA Lyon                            | Directeur de thèse |