ESCUELA POLITÉCNICA SUPERIOR DE ÁVILA
DEPARTAMENTO DE INGENIERÍA CARTOGRÁFICA Y DEL TERRENO
ÁREA DE INGENIERÍA HIDRÁULICA

TESIS DOCTORAL

MENCIÓN INTERNACIONAL

ANÁLISIS DEL COMPORTAMIENTO HIDRODINÁMICO FLUVIAL MEDIANTE RAZONAMIENTO CAUSAL Y VISIÓN ARTIFICIAL

Santiago Zazo del Dedo

Ávila, Marzo de 2017

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MENCIÓN INTERNACIONAL

Tesis Doctoral, por compendio de artículos/publicaciones, para optar al Grado de Doctor por la Universidad de Salamanca y la Universidad de Vigo

Programa de Doctorado interuniversitario en Geotecnologías aplicadas a la Construcción, Energía e Industria

Doctorando
Santiago Zazo del Dedo

DIRECTORES

Dr. José Luís Molina González Dr. Pablo Rodríguez Gonzálvez

Ávila, Marzo de 2017

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“La Naturaleza nos es hostil porque no la conocemos: ...”

“... Escuchar sus latidos íntimos con el fervor de apasionada curiosidad, equivale a descifrar sus secretos: ...”.

Santiago Ramón y Cajal

A mis padres, herman@s,

y a Mari Cruz …

Agradecimientos

"*Que la realidad supere a la ficción"*, y "*yo soy yo y mis circunstancias*" [1], son dos frases que resumen el porqué de esta Tesis Doctoral. Inicialmente, como estudiante universitario no imaginé que mis pasos pudieran llevarme donde hoy me encuentro. Sin embargo, y en gran medida, la *"casualidad"* y más tarde la *"causalidad"* han propiciado que lo que un día fue un sueño sea hoy una realidad, fruto de mis circunstancias, del sacrificio y del esfuerzo de estos últimos años.

A la casualidad, y no puede imaginarse cuanto, que el año 2011 hizo que mis pasos se cruzarán con los de los Doctores José Luis Molina González y Pablo Rodríguez Gonzálvez; primero como compañeros docentes en la Universidad de Salamanca y luego como Directores de esta Tesis. A ambos mi agradecimiento por la confianza depositada en mí y su esfuerzo. Gracias por guiarme, por abrirme esta puerta al Conocimiento, por enseñarme e iniciarme, como *maestros*, en lo que es Investigar y lo que es un Investigador. Mi agradecimiento por las horas vividas y las compartidas de análisis, de pruebas, de ensayos y de discusiones. Gracias por vuestros consejos y orientaciones, y sobre todo por hacer posible esta Tesis.

Por otro lado, agradecer al catedrático de la Universidad de Salamanca, Doctor Diego González Aguilera, haberme dado la oportunidad de integrarme en su reconocido Grupo de Investigación TIDOP (http://tidop.usal.es), como Investigador predoctoral, y poner a mi disposición todos los medios que he necesitado, además de su apoyo personal y la colaboración de su equipo humano. Agradecer también al Doctor David Hernández López, del Instituto de Desarrollo Regional de la Universidad de Castilla-La Mancha, los medios puestos al servicio de esta Tesis, así como sus aportaciones.

Al Departamento de Ingeniería Civil y Arquitectura, de la Universidad de Beira Interior (Covilhã, Portugal), en especial a su Directora, Dra. Cristina María Sena Fael, por la oportunidad brindada de realizar una estancia internacional y permitirme investigar con ellos en el ámbito de Hidráulica Fluvial, en su Laboratorio de Hidráulica.

1. José Ortega y Gasset. Meditaciones del Quijote, 1914.

A mis profesores, compañeros y amigos, que de un modo u otro, desde mis inicios en la vida académica universitaria, primero en mis estudios de Ingenierías Técnicas, y más tarde en los de Grado y Máster, me han ayudado a que este camino se haya podido recorrer.

A mi buen amigo Fernando de Lorenzo Velasco por su buen hacer y disposición.

Finalmente a mis padres, Basi y Santiago, por darme unos valores y una educación, y a mi hermano Jorge Juan, por vuestro apoyo incondicional no sólo durante estos años de Doctorado. Y a ti, Mari Cruz, mi pareja en especial. Por tu ánimo constante, por estar ahí en los momento difíciles, por creer en mí y en este reto, por la comprensión de mis ausencias en cuerpo y en mente, por hacer fácil lo difícil.

A tod@s, mi agradecimiento por hacer "*que la realidad supere a la ficción*".

Santiago Zazo del Dedo

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TIPOLOGÍA DE TESIS

TÍTULO / *TITLE*

Análisis del comportamiento Hidrodinámico Fluvial mediante Razonamiento Causal y Visión Artificial.

Analysis of the Hydrodynamic Fluvial behaviour through Causal Reasoning and Artificial Vision

MODALIDAD / *FORMAT*

Tesis Doctoral por compendio de artículos/publicaciones, con Mención Internacional.

Doctoral Thesis as a compentidum of articles/publications, with International Mention.

PROGRAMA DE DOCTORADO / *PhD. PROGRAM*

Geotecnologías aplicadas a la Construcción, Energía e Industria, regulado por el R.D. 99/2011. Programa de Doctorado interuniversitario, propuesto por las Universidades de Salamanca y Vigo, España.

Geotechnologies applied to Construction, Energy and Industry, according to R.D. 99/2011. Interuniversity Doctorate Program, proposed by the Universities of Salamanca and Vigo, Spain.

Esta Tesis Doctoral, redactada en la modalidad de compendio de artículos/publicaciones, está compuesta por tres artículos de investigación, previamente aceptados y publicados en prestigiosas revistas científicas internacionales de impacto (sujetas a evaluación crítica mediante revisiones anónimas, por pares expertos internacionales, de reconocida trayectoria), en el ámbito de la Gestión de Recursos Hídricos, la Hidrología, y la Hidráulica Fluvial; siendo todas ellas indexadas en las bases de datos Journal Citation Report (JCR) y SCImago Journal Rank (SJR), en los cuartiles primero (Q1) y segundo (Q2):

1. **Innovative Analysis of Runoff Temporal Behavior through Bayesian Networks**

   José Luis Molina, Santiago Zazo, Pablo Rodríguez-Gonzálvez, Diego González-Aguilera

   Area of Hydraulic Engineering, Land and Cartographic Engineering Department, High Polytechnic School of Avila, University of Salamanca, Av. de los Hornos Caleros, 50, Ávila 05003, Spain.

   Water, October 2016

   DOI:10.3390/w8110484

2. **Analysis of flood modeling through innovative geomatic methods**

   Santiago Zazo, José-Luis Molina, Pablo Rodríguez-Gonzálvez

   Salamanca University, High Polytechnic School of Engineering, Ávila. Area of Hydraulic Engineering, Av. de los Hornos Caleros, 50, 05003 Ávila, Spain.

   Journal of Hydrology, March 2015

   DOI.org/10.1016/j.jhydrol.2015.03.011

3. **Flood analysis supported by low-cost geometric modelling**

   S. Zazo[a], P. Rodríguez-Gonzálvez[a], J.-L. Molina[a], D. Hernández-López[b], D. González-Aguilera[a]

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   b Institute for Regional Development (IDR), University of Castilla-La Mancha. Campus Universitario s/n, 02071, Albacete, Spain.

   River Research and Applications, October 2016

   DOI: 10.1002/rra.3113

ANÁLISIS DEL COMPORTAMIENTO HIDRODINÁMICO FLUVIAL MEDIANTE RAZONAMIENTO CAUSAL Y VISIÓN ARTIFICIAL

Tesis Doctoral presentada por Santiago Zazo del Dedo

INFORME DE LOS DIRECTORES DE TESIS

Esta Tesis Doctoral, titulada "Análisis del comportamiento Hidrodinámico Fluvial mediante Razonamiento Causal y Visión Artificial", presentada por D. Santiago Zazo del Dedo, se enmarca en una nueva línea de investigación puesta en marcha por el Grupo de Investigación reconocido TIDOP (http://tidop.usal.es) de la Universidad de Salamanca. Dicha línea aspira a conseguir la hibridación de dos disciplinas muy lejanas hasta la actualidad, la Modelización de Recursos Hídricos y la Geomática. El objetivo final es el de mejorar el conocimiento de la interacción hidrológica-hidráulica, dentro de una gestión sostenible y segura de los recursos hídricos de una cuenca.

Esta nueva línea de investigación aborda el problema de la creciente no-estacionalidad en los procesos hidrológicos-hidráulicos desde una doble componente hidrológica e hidráulica-geomática; aplicando el Razonamiento Causal, mediante la inferencia bayesiana, al estudio del comportamiento de las series temporales de aportaciones; y la Visión Artificial, a través de los algoritmos SfM (*Structure from Motion*) para la generación de modelos digitales 3D, al servicio de la hidrodinámica e hidráulica fluvial.

A nivel hidrológico, la creciente demanda de recursos hídricos así como una mayor necesidad de fiabilidad en su evaluación y predicción, además de los avances en el campo de la Informática, está posibilitando la aparición de planteamientos innovadores en la hidrología estocástica basados en la Inteligencia Artificial. Estos nuevos enfoques resultan especialmente útiles en el análisis de sistemas complejos no-lineales naturales, como la gestión de los recursos hídricos de una cuenca, y donde no se tiene un conocimiento completo sobre las relaciones e interdependencias que en ellos subyacen.

Por otro lado, la planificación y gestión sostenible y segura de los recursos hídricos de una cuenca no debe abordarse sólo desde diferentes escenarios hidrológicos y un conocimiento en profundidad de los recursos; una representación detallada del entorno físico resulta esencial, dada además su influencia en la determinación de las variables hidráulicas que definen el comportamiento del flujo, por ejemplo en la evaluación y gestión de los riesgos naturales fluviales. Esta dependencia del modelado 3D del terreno de la hidráulica fluvial, está llevando también a una creciente necesidad de datos topográficos de calidad, y donde la Visión Artificial se demuestra como una interesante alternativa para este propósito.

En este contexto, esta Tesis aborda de una manera novedosa este doble reto global, proporcionando un marco metodológico de actuación que mejora el conocimiento de ambas componentes hidrológica e hidráulica-geomática, con importantes implicaciones a nivel social, en lo que a medidas de adaptación frente a las nuevas realidades hidrológicas derivadas del Calentamiento Global se refiere. En este sentido, se ha llevado a cabo una adecuada revisión del Estado del Arte; y además los casos de estudios propuestos presentan características de alto interés para la línea de investigación donde se enmarca esta Tesis Doctoral.

Por otra parte, el hecho de que la Tesis se redacte en la modalidad de compendio de artículos/publicaciones, aporta un valor añadido a las investigaciones desarrolladas, dado que han tenido que pasar un proceso de revisión y evaluación crítica anónimas externas, por pares independientes de reconocido prestigio en sus ámbitos de conocimiento, antes de ser publicadas en las revistas científicas internacionales indexadas, con altos factores de impacto (cuartiles Q1 y Q2) en las bases de datos Journal Citation Report (JCR) y SCImago Journal Rank (SJR).

Las nuevas contribuciones científicas y los resultados originales que esta Tesis Doctoral aporta se centran en:

- Una evaluación dinámica de la dependencia temporal de las series hidrológicas de aportaciones, mediante el Razonamiento Causal, que permite disponer de un indicador de la dependencia a medio plazo, frente a los planteamiento clásicos a corto plazo (mediante correlogramas) y a largo plazo (a través del coeficiente de Hurst).

- Materialización del análisis de dependencia temporal en la hidrología fluvial, mediante la evaluación cuantitativa de dependencias e independencias de flujo.
- La propuesta metodológica para la generación de modelos geométricos de muy bajo coste e incluso de coste reducido, precisos y detallados, para su aplicación en el ámbito de la Hidrodinámica y la Hidráulica Fluvial, obtenidos mediante técnicas de Visión Artificial.
- Dos nuevas propuestas metodológicas para la evaluación de la componente estrictamente métrica de la incertidumbre asociada a la modelización de la hidráulica y debida a la influencia del modelo 3D del terreno. La primera desde un punto de vista metrológico, y la segunda mediante estimadores robustos.

Por último, la Tesis finaliza con un apartado de Conclusiones y Líneas Futuras de Investigación en el que se detalla las principales aportaciones realizadas y se plantean las futuras investigaciones a desarrollar en esta nueva línea, que aúna la Hidrología y la Hidráulica-Geomática.

Por todo lo anteriormente expuesto, los Directores de esta Tesis Doctoral, consideran que ésta es apta para su presentación y defensa en acto público, en la modalidad de “Compendio de artículos/publicaciones”, además de optar a la “Mención Internacional”, ya que se cumplen todos los requerimientos establecidos, a tal efecto, por la Universidad de Salamanca.

Para que así conste, firman este certificado, en Ávila a 31 de marzo de 2017.

Dr. José Luis Molina González Dr. Pablo Rodríguez Gonzálvez

ANALYSIS OF THE HYDRODYNAMIC FLUVIAL BEHAVIOUR THROUGH CAUSAL REASONING AND ARTIFICIAL VISION

Doctoral Thesis presented by Santiago Zazo del Dedo

INTERNATIONAL SUPERVISORS' REPORTS REGARDING

THE DOCTORAL THESIS

Assessment reports that support the Doctoral Thesis which are signed by Doctors of a non-Spanish Institution

REPORT 1

Prof. Dragan Savic (FREng, FICE, FCIWEM). Director of the Centre for Water Systems. University of Exeter.

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REPORT 2

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30th March 2017

TO WHOM IT MAY CONCERN

Dear Sir/Madam,

Re: External report on PhD thesis "Analysis of the hydrodynamic fluvial behaviour through causal reasoning and artificial vision" by Santiago Zazo del Dedo.

The candidate has carried some interesting work and impressive work on a new methodology for improving understanding of both hydrological and hydraulic behaviour within river catchments. The methodology utilises a hybrid approach by linking two main disciplines, namely water resource modelling (stochastic hydrology) and geomatic approaches. The complex problems have also been tackled using causal reasoning and Bayesian Networks, which have been demonstrated to work well on several cast studies.

The hypothesis that dependency analysis and Bayesian reasoning are able to adequately capture stochastic processes in hydrology and hydromorphology, has been demonstrated on a number of case studies, as evidenced in journal publications. I envisage that this line of research will generate some new ideas and influence the international research community in the near future. The availability of remotely sensed geospatial data and the coupling with fast 3D terrain models provide another interesting research topic.

The quality of the work is high and well up to PhD standard. Some of the work has already been published in top quality journals; much more of the work is also worthy of publication.

Yours sincerely,

Professor Dragan Savic FREng, FICE, FCIWEM

REPORT 2

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TO WHOM IT MAY CONCERN

Our reference
IWSG/JSU/SAK

Date
23 March 2017

Subject
External report on PhD thesis "Analysis of the hydrodynamic fluvial behaviour through causal reasoning and artificial vision" by Santiago Zazo del Dedo.

Dear Sir/Madam,
The doctoral thesis named above seeks to provide a methodological framework to improve the knowledge of both hydrological and hydraulic behaviour within river basins. This has been accomplished through a hybridization approach comprising of water modelling (stochastic hydrology) and geomatic disciplines. Causal reasoning and Bayesian Networks are extensively used and applied to a number of practical problems.

Dependency analysis and Bayesian reasoning was able to adequately capture stochastic processes in hydrology and hydromorphology case studies, and should lead to new insights and research lines in this field, and in other related areas. The integration of geospatial data and the coupling to fast 3D terrain models is a useful advance.

Hydrological behaviour of river reaches as well modelling using temporal dynamic dependency analysis, ad coupled with a Bayesian Network analysis, variability in hydrological regimes is well simulated.
A number of plausible future research lines are proposed. It is proposed that these should be incorporated into larger research programmes in order to allow them to develop into fully mature areas within this field.

Three journal papers have been published as a result of the PhD work. All are in very good quality international peer-reviewed journals (e.g. Journal of Hydrology, Water). This indicates the quality, relevance and impact of the work.

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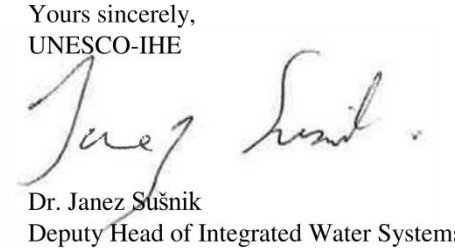
Our reference	Page
MAI/PZA/SAK	2/2

In my opinion, the summary of the PhD thesis, and the three journal papers, indicates that this work is more than suitable to be awarded a doctoral degree.

Yours sincerely,
UNESCO-IHE



Dr. Janez Sušnik
Deputy Head of Integrated Water Systems and Governance Department
Lecturer/Researcher in Water Resources

ANALYSIS OF THE HYDRODYNAMIC FLUVIAL BEHAVIOUR THROUGH CAUSAL REASONING AND ARTIFICIAL VISION

Doctoral Thesis presented by Santiago Zazo del Dedo

INTERNATIONAL RESEARCH STAY. REPORT

University of Beira Interior, Covilhã (Portugal)

Faculty of Engineering - Department of Civil Engineering and Architecture

FACULDADE ENGENHARIA
Departamento de
Engenharia Civil
e Arquitectura

Declaration

Pedro Gabriel de Faria Lapa Barbosa de Almeida, Assistant Professor on the Department of Civil Engineering and Architecture (DECA) at University of Beira Interior (UBI), Covilhã, Portugal, certifies that Santiago Zazo del Dedo, PhD Student, has stayed from September 2016 to February 2017 at University of Beira Interior as a Visiting PhD Student Researcher, coinciding with his doctoral period. During these six months, the student carried out research within the field of Fluvial Hydraulic at the Hydraulic Laboratory, where geomatic methods and solutions based on passive sensors (digital photogrammetry on-demand) on the characterization of the topography of a meandering channel were applied.

Finally, I also would like to express that this research has been productive in terms of the academic activities that have been carried out.

Covilhã, march 1st of 2017

Universidade da Beira Interior
UBI
DECA
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RESUMEN

La alteración de los patrones climáticos y meteorológicos así como su repercusión en el ciclo hidrológico, en gran medida atribuible al fenómeno del Calentamiento Global y puesto de manifiesto en las últimas décadas en numerosos estudios, son una realidad global, con dramáticas consecuencias ambientales, sociales y económicas. Eventos extremos tales como precipitaciones, sequias e inundaciones, resultan cada vez menos "anómalos", y por tanto más recurrentes en el tiempo. Estas nuevas realidades, derivadas de una creciente no-estacionalidad de los procesos hidrológicos e hidráulicos, están provocando una mayor incertidumbre a la hora de modelar y predecir los comportamientos hidrológicos dentro un contexto de gestión sostenible y segura de los recursos hídricos de una cuenca, en el marco del paradigma internacional para la gestión integrada del agua, conocido como "Integrated Water Resources Management" (IWRM).

Por otro lado, como sociedad constatamos que las medidas tomadas por parte de instituciones internacionales y gobiernos para revertir los efectos del Calentamiento Global están teniendo un efecto limitado a corto y medio plazo, como consecuencia de la persistencia de los efectos antropogénicos. Dichas medidas mayoritariamente son de adaptación y mitigación frente a estas nuevas realidades hidrológicas.

Frente a esta situación, se hace necesario disponer de métodos y técnicas de análisis y observación, eficientes en tiempo y coste, que permitan generar modelos predictivos precisos que agilicen el proceso de toma de decisiones en el ámbito fluvial.

Esta Tesis Doctoral, afronta este reto global desde la doble componente hidrológica-geomática y su interdependencia, dado que la cuenca hidrológica se configura como el "medio" donde se pone de manifiesto el "comportamiento" de ésta frente al ciclo hidrológico.

En primer lugar se propone una metodología hidrológica de análisis de las series temporales de aportaciones con el fin de profundizar en el conocimiento de las relaciones de dependencia que explique, más en profundidad, su comportamiento. Esto se ha llevado a cabo a través de un enfoque conjunto mediante técnicas tradicionales, basadas en modelos paramétricos (genéricamente expresados como ARIMA; modelos Autorregresivos Integrados de Medias Móviles) y el Razonamiento Causal mediante Inferencia Bayesiana, en consonancia con las nuevas tendencias de la investigación estocástica hidrológica.

En segundo lugar, se ha evaluado la idoneidad, entre la hidráulica y la geomática, de nuevos modelos 3D, de coste reducido e incluso bajo coste, continuos, detallados y precisos, generados de modo eficiente (tiempo-coste), y aplicables a la Hidrodinámica y la Hidráulica Fluvial. Estos nuevos modelos 3D (basados en la Visión Artificial y fundamentados en la Geometría Epipolar y la Fotogrametría Digital) son obtenidos mediante la aplicación de técnicas SfM (*Structure from Motion*). Por otro lado, se proponen dos nuevos métodos para la evaluación de la incertidumbre altimétrica de los modelos digitales de elevación; el primero fundamentado en un enfoque metrológico mediante una evaluación Tipo A de la incertidumbre, y el segundo en los Estimadores Robustos de la centralidad y la dispersión de los errores.

En definitiva, se pretende ofrecer un marco metodológico, para incrementar el conocimiento sobre el comportamiento hidrológico-hidráulico de la cuenca hidrográfica, encaminado a una gestión más objetiva, sostenible y segura de los recursos hídricos de una cuenca y de los riesgos naturales de origen fluvial.

En esencia, se aspira a conocer para predecir y prevenir.

SUMMARY

The alteration of climatic and meteorological patterns as well as their impact on the hydrological cycle, largely attributable to the phenomenon of Global Warming becomes global reality with dramatic environmental, social and economic consequences. Extrem events such as rainfall, drought and flood, are becoming less "anomalous", and therefore more recurrent in time. These new realities, due to a growing non-stationarity of hydrological and hydraulic processes, are leading to greater uncertainty in modeling and forestcasting the hydrological behavior. Within a context of sustainable and safe management of water resources in a basin, this Doctoral Thesis is framed in the international paradigm of integrated water management known as "Integrated Water Resources Management" (IWRM).

On the other hand, as a global society, we are witnessinghow the measures taken by international institutions and governments to subvert the effects of Climate Change are having a limited effect in the short and medium term, as a consequence of the persistence of the anthropogenic effects. Those measures are largely based on, the adaptation and mitigation against these new hydrological realities.

Given this situation, in order to generate accurate predictive models to facilitate the process of decision making on fluvial field, it is necessary to have time-cost efficient methods and techniques of analysis and observation.

This Doctoral Thesis addresses this global challenge from the double hydrological-geomatic component and its interdependence, given that the hydrological basin is configured as the "medium" where it shows the "behavior" of the hydrological cycle.

First, in order to deepen the knowledge of dependency relationships that explains, more in depth, basins´ behavior, a hydrological analytical methodology, based on runoff time series is proposed. This has been done through a joint approach using traditional techniques, based on parametric models (generically expressed as ARIMA, Integrated Autoregressive Models of Moving Averages) and Causal Reasoning through Bayesian Inference, in line with the new trends in hydrological stochastic research and approaches.

Second, a hybrized methodology, between hydraulics and geomatic is proposed. Geomatic techniques and methods largely comprise new reduced/low cost 3D models, which are continuous, detailed and accurate, efficiently generated (time-cost), and applicable to Hydrodynamics and Fluvial Hydraulics. These new 3D models (based on the Artificial Vision and based on Epipolar Geometry and therefore in Digital Photogrammetry) are obtained through the application of SfM (Structure from Motion) techniques. On the other hand, two new methods for the evaluation of the altimetric uncertainty of the digital elevation models are proposed. The first one is based on a metrological approach through a Type A evaluation of uncertainty, and the second one, based on the Robust Estimators of centrality and the dispersion of errors.

To summarize, this Doctoral Thesis is aimed to provide a methodological framework to improve the knowledge on the hydrological and hydraulic behavior of the river basin. This is done at the highest level by the hybridization of Water Modelling (Stochastic Hydrology) and Geomatic disciplines.

In essence, it is all about knowing for forecasting and preventing.

CAPÍTULO I

Introducción

I.1 ANTECEDENTES

Esta Tesis Doctoral, titulada "*Análisis del comportamiento Hidrodinámico Fluvial mediante Razonamiento Causal y Visión Artificial*", se redacta en cumplimiento de las directrices de la Universidad de Salamanca, en su Reglamento de Doctorado (capítulo II artículo 14.1), sobre elaboración y defensa de la Tesis Doctoral, conforme al Programa de Doctorado interuniversitario en "Geotecnologías aplicadas a la Construcción, Energía e Industria" propuesto por las Universidades de Salamanca y Vigo, España, según el Real Decreto 99/2011, de 28 de enero, por el que se regulan las enseñanzas oficiales de doctorado en España.

De acuerdo al Plan de Investigación presentado en el año académico 2014-15, la modalidad de Tesis Doctoral por compendio de artículos/publicaciones en revistas internacionales especializadas y de prestigio; es conforme a lo establecido por la Comisión de Doctorado, siendo además de aplicación el punto 4 del Procedimiento para la presentación de este tipo de tesis doctorales, de la Comisión de Doctorado y Posgrado de la Universidad de Salamanca, de 15 de febrero de 2013.

I.2 JUSTIFICACIÓN E INTERÉS DE LA INVESTIGACIÓN

Agua y Tierra, como dos de los cuatro elementos fundamentales de la Naturaleza, según la filosofía clásica occidental. Certidumbre y Seguridad, como "estados" a los que los seres humanos aspiramos, individual o colectivamente, y Economía, como variable que condiciona, hoy en día, nuestro proceso de toma de decisiones. Además del deseo humano por el conocimiento [2], y una visión causa-efecto, de hostilidad Natural por su desconocimiento [3], son las ideas fundamentales que subyacen en esta investigación y que han inspirado esta Tesis Doctoral.

2. Aristóteles. Metafísica. "Todos los hombres desean por naturaleza saber".

3. Santiago Ramón y Cajal. Recuerdos de mi vida. Segunda parte. Historia de mi labor científica. Capítulo XXVII. 1917

Profundizar en el conocimiento del binomio "flujo-terreno" (Agua-Tierra), permite prever y prevenir (Certidumbre y Seguridad), dentro de una gestión sostenible y segura de los recursos hídricos de una cuenca. Además, un mayor conocimiento del terreno posibilita una mejor definición de la susceptibilidad y determinación de la vulnerabilidad a las inundaciones fluviales, así como una evaluación más objetiva de este riesgo [4] y de un diseño más eficiente de las soluciones, estructurales y no-estructurales, frente a las inundaciones (Economía).

Por otro lado, los patrones típicos del comportamiento espacio-temporal de los eventos meteorológicos y climáticos están experimentando cambios a nivel local y global. Esto está produciendo modificaciones, cada vez más evidentes, en los procesos hidrológicos (Molina *et al*., 2016). En este sentido eventos extremos, como inundaciones y sequias entre otros, son cada vez más frecuentes en el tiempo (Bogner *et al.*, 2016; Huntington, 2006; Reihan *et al*., 2012; Yang *et al*., 2012).

Estas nuevas "realidades hidrológicas", están produciendo una fuerte presión sobre los recursos hídricos (Chávez Jiménez A, 2012; Merritt *et al*., 2006; Pulido-Velázquez *et al*., 2015), e incrementando la incertidumbre de unos procesos hidrológico-hidráulicos, ya de por sí aleatorios en magnitud y ocurrencia de eventos.

Internacionalmente se está constatando como los efectos de las medidas contra el Calentamiento Global están teniendo un efecto muy limitado en el corto y medio plazo (IPCC, 2014). Esto está llevando a la sociedad a tomar medidas de adaptación y protección (EU Directive, 2007; Zechner *et al*., 2011), donde las consideraciones económicas están muy presentes (Sayers *et al*., 2002). En el caso de España, las inundaciones son la catástrofe natural que mayores daños generan, del orden de 800 millones de euros anuales (MAGRAMA, 2014), estimándose para el periodo 2004-2033 esos daños en 26.000 millones de euros, lo que supondrá aproximadamente 870 millones de euros anualmente (Mateo-Lázaro, 2011).

4. Riesgo: Valoración económica de los daños que pueden causar en un territorio determinado un proceso natural en un periodo de tiempo determinado. Resultado del estudio de diferentes parámetros tales como susceptibilidad, vulnerabilidad, peligrosidad y exposición (coste).

Ante esta situación resulta crucial disponer de metodologías de análisis y técnicas de observación, eficientes en tiempo y coste, entendidas como medidas efectivas de adaptación, que permitan agilizar el proceso de toma de decisiones en el ámbito fluvial, con el objetivo de disponer de recursos hídricos en condiciones de fiabilidad y seguridad, hacia personas, bienes y actividades productivas dependientes de ellos.

Por las razones anteriores, se propone una nueva metodológica para avanzar en el conocimiento hidrológico-hidráulico, derivada de una cada vez mayor no-estacionalidad de los procesos hidrológicos, muy vinculada al fenómeno del Calentamiento Global. (Labat *et al*., 2004; Lepori *et al*., 2015; Praskievicz, 2016)

I.3 HIPÓTESIS DE TRABAJOS

Esta investigación, sobre el comportamiento hidrodinámico de ríos, en su doble vertiente hidrológica y geomática, se fundamenta en la aplicación de nuevos métodos de análisis del comportamiento temporal de las series hidrológicas de aportaciones, y la obtención de novedosos modelos digitales 3D, al servicio de la ingeniería fluvial.

En el contexto anterior se han planteado las siguientes hipótesis diferenciadas:

A nivel hidrológico

- Avanzar en la aplicación de la Inferencia Bayesiana en el contexto de la dependencia-independencia de series temporales de aportaciones.
- Profundizar en el conocimiento de los registros históricos, ya que las razones que explican la creciente variabilidad de los procesos hidrológicos pueden no deberse a causas antropogénicas.
- El terreno es en sí mismo variable, en cuanto a usos del suelo (estacionalidad) y modificaciones de su forma.
- Considerar series temporales de aportaciones, como variable hidrológica de respuesta de la cuenca ante el ciclo hidrológico, en la que está implícitamente la variabilidad del terreno.
- Disponer de series temporales de las aportaciones y del régimen de caudales, elimina la necesidad de generar modelos específicos de precipitación-escorrentía que pueden constituirse en fuente de incertidumbre.

- Aplicar enfoques clásicos en el análisis de series temporales de aportaciones y del régimen de caudales, posibilita la generación de múltiples escenarios equiprobables para la gestión y simulación de procesos hidrológico-hidráulicos.
- La inundación es un mecanismo de respuesta de la cuenca hidrológica producida cuando se excede la capacidad de transporte del cauce fluvial, por eventos hidrológicos extremos o como consecuencia de efectos antropogénicos sobre el propio cauce.

A nivel geomático

- Adquirir información geoespacial mediante sensores activos (emisión de energía), como el LiDAR (*Light Detection and Ranging*) en sus diferentes variantes, supone importantes costes de adquisición, operación y logística.
- Las plataformas aéreas no convencionales tipo multirrotor presentan importantes restricciones en cuanto al tiempo de vuelo, que no tienen los parapentes-trike (ultraligero motorizado de poco peso, baja velocidad y apto para el vuelo tripulado, siglas en inglés *Ultra Light Motor*).
- Las características técnicas (precisiones y resoluciones espaciales) de los productos geomáticos obtenidos a partir de los nuevos enfoques de la Fotogrametría Digital resultan interesantes para su aplicación en el ámbito fluvial.

I.4 OBJETIVOS DE LA INVESTIGACIÓN

El objetivo general de esta Tesis Doctoral, frente al reto de la no-estacionalidad de los procesos hidrológicos-hidráulicos, es doble, aportando unos marcos metodológicos que permitan:

- Un mejor análisis y conocimiento de las dependencias internas en las series hidrológicas temporales de aportaciones, que expliquen su comportamiento mediante el Razonamiento Causal.
- La generación de modelos geométricos continuos, de coste reducido o de bajo coste, precisos y fiables aplicables al campo de la Hidrodinámica y la Hidráulica Fluvial, basados en la Visión Artificial.

Todo ello inspirado en el paradigma internacional IWRM (Biswas, 2004), para una gestión sostenible y segura de los recursos hídricos de una cuenca; y una evaluación más objetiva de los riesgos naturales fluviales mediante un mejor conocimiento del comportamiento hidráulico, definición de la susceptibilidad y determinación de la vulnerabilidad.

Para la consecución de estos objetivos generales se han establecido los siguientes objetivos específicos clasificados de acuerdo a las dos componentes de la investigación:

A nivel hidrológico

- Definir una metodología de análisis dinámica para la dependencia temporal en cuencas hidrológicas no reguladas, partiendo de series temporales de aportaciones-caudales.
- Comprobar sí el Razonamiento Causal, gracias a la propagación de la probabilidad condicionada mediante la inferencia bayesiana, permite evaluar dinámicamente las dependencias temporales.
- Analizar la posibilidad de determinar la dependencia temporal a medio plazo, frente a los enfoques clásicos que proporcionan resultados a corto plazo gracias a los Correlogramas y a largo plazo mediante el Coeficiente de Hurst.

A nivel geomático-hidráulico

- Estudiar la aplicación de las técnicas SfM (*Structure from Motion*, de la Visión Artificial, e inspiradas en la Geometría Epipolar y la Fotogrametría Digital) a la adquisición de información geoespacial, mediante la hibridación de sensores pasivos de coste reducido e incluso bajo coste, embarcados en plataformas aéreas ligeras-alternativas tipo ULM.
- Estudiar la idoneidad de los productos geomáticos resultantes para su aplicación en el campo de la Hidrodinámica y la Hidráulica Fluvial, comparando sus características técnicas con las de productos, más comunes y asentados en la comunidad científica, como el LiDAR.

- Analizar la aplicación de un enfoque metrológico, mediante una evaluación Tipo A de la incertidumbre altimétrica, a los modelos 3D del terreno, como medio para valorar la componente estrictamente métrica de la incertidumbre en la modelización hidráulica.
- Estudiar la aplicación de enfoques alternativos para evaluar la incertidumbre altimétrica en los modelos geométricos fluviales que puedan superar las limitaciones propias de los planteamientos clásicos, basados en la distribución normal.

I.5 ZONAS DE ESTUDIO

El doble enfoque hidrológico-geomático que esta tesis aborda, ha implicado la necesidad de considerar zonas de estudio diferenciadas para ambas componentes del binomio "flujo-terreno". Sin embargo, ambas se enmarcan en el ámbito geográfico de la Cuenca Hidrográfica del río Duero, dada la especial relevancia que ésta tiene en la Península Ibérica, como la de mayor extensión y a su carácter internacional entre España y Portugal [5]

La irregularidad es la característica distintiva de la distribución espacio-temporal de las precipitaciones en España y el origen de la extrema variabilidad de los recursos hídricos (MAGRAMA, 2016). Este hecho ha favorecido acusados periodos de sequías seguidos de importantes inundaciones con significativos impactos (HISPAGUA, 2014).

Por otro lado, la alta variabilidad pluviométrica interanual junto a la elevada desigualdad consecutiva en las precipitaciones, el gradiente positivo de éstas respecto de la latitud así como su asimetría hacia el sur peninsular, con un norte húmedo y un sur seco, han contribuido a acentuar este negativo fenómeno (Martín Vide, 1994).

5. Convenio sobre Cooperación para la Protección y el Aprovechamiento Sostenible de las Aguas de las Cuencas Hidrográficas Hispano-Portuguesas. Firmado en 1998 y en vigor desde el 17 de enero de 2000, conocido como Convenio de Albufeira.

El comportamiento antes indicado se observa también en la parte española de la Cuenca Hidrográfica del Duero. Razón por la que a la hora de seleccionar los casos de estudio, en el ámbito hidrológico de la investigación (ver Capítulo II, Punto II.1), se han tenido en cuenta consideraciones relativas a la situación geográfica, al régimen pluviométrico anual, así como a la disponibilidad de series temporales de aportaciones-caudales en régimen natural, y por tanto en tramos fluviales no regulados. Esta última condición ha supuesto un importante reto en la selección de los casos de estudio, debido a la larga tradición presística española, con más de 2 presas por cada 1.000 Km², derivada de la menor capacidad de retención del suelo en España, estimada en un 9% frente al 34% de los países del norte de Europa (Vallarino *et al*., 2001).

Con las premisas anteriores, se seleccionaron las sub-cuencas hidrológicas de los ríos Porma, en el norte, y Adaja en el sur, ambas, atendiendo a su superficie vertiente, de tipología media (entre 100 y 1.000 Km²), conforme a la clasificación tipo A de ríos, establecida en la Directiva 2000/60/CE del Parlamento Europeo y del Consejo, de 23 de octubre de 2000 (DOCE, 2000), conocida como Directiva Marco del Agua.

Por lo que a la componente geomática respecta, la investigación se ha focalizado en la sub-cuenca del río Adaja (ver Capítulo III, Punto III.1 y III.2) atendiendo a criterios estrictamente logísticos (proximidad al área de estudio). En concreto en la cuenca alta del río Adaja, en un tramo de interés del núcleo de población de El Fresno, municipio de la provincia de Ávila, situado a unos 6,5 Km al sureste de la capital de dicha provincia. En la margen derecha del tramo seleccionado se localizan gran cantidad de edificaciones, instalaciones deportivas, áreas de recreo y servicios esenciales de suministros municipales. Por el contrario en la margen izquierda se ubican de forma dispersas algunas edificaciones y varias explotaciones agropecuarias, resultando el conjunto de interés para la investigación.

I.6 METODOLOGÍA

El hecho de que esta Tesis aborde la problemática expuesta (punto I.2) a través del binomio “flujo-terreno”, mediante la hibridación de dos disciplinas tan diferentes como la Modelización de Recursos Hídricos y la Geomática, y a la vez tan interdependientes desde el punto de vista de la seguridad, hace preciso definir una Metodología General (ver Figura 1) donde se diferencian dos componentes; por un lado la geomática (terreno), y por otro la hidrológica-hidráulica (flujo).

La metodología propuesta se articulada en cinco etapas. Las tres primeras se integran dentro de la componente geomática. La cuarta conforma la componente hidrológica. Por último, se propone una quinta etapa (futura), específicamente de gestión y de apoyo a la decisión, que constata el carácter multidisciplinar y el planteamiento holístico que la gestión de los recursos hídricos impone.

COMPONENTE GEOMÁTICA

La etapa inicial (*Stage-1 Problem Definition*), define las características técnicas exigibles a los productos geomáticos. Aspectos como la extensión de la zona, que puede limitar la utilización de plataformas tipo UAV (*Unmanned Aerial Vehicle*) multirrotor (Hardin y Jensen, 2011; Ortega-Terol *et al*., 2014), condicionantes del flujo tanto en el cauce principal como en la llanura de inundación o dimensiones del thalweg, por ejemplo, son tenidas en cuenta a la hora de determinar las resoluciones espaciales del Modelo Digital de Elevación (DEM, *Digital Elevation Model*) y de la ortoimagen.

A continuación, se procede a la selección del sensor pasivo (conjunto cámara-lente), considerando la resolución espacial máxima del sensor (tamaño del píxel en el sensor), rendimiento de la lente y la distancia focal a emplear, conjugando resolución espacial y proyección sobre el terreno de la imagen. Esto se hace en base a la altura media de vuelo sobre el terreno, considerando las limitaciones legales que pudieran establecerse sobre la plataforma aérea seleccionada. De esta forma se determina el mínimo detalle observable o GSD (*Ground Sampling Distance*). Seguidamente, se planifica el vuelo, teniendo en cuenta los solapes longitudinales y transversales entre imágenes adyacentes, la variación del GSD debida a la orografía del terreno, el tiempo de exposición, los errores estimados en el posicionamiento de la plataforma aérea durante la ejecución del vuelo y la velocidad media de éste.

En la etapa siguiente (*Stage-2 Geometric Model*), se reconstruye el modelo 3D, basado en el procesado fotogramétrico, aplicando técnicas SfM, obteniéndose además la ortofotografía. De un modo semiautomático se llevan a cabo las operaciones de alineación de imágenes, identificación de puntos homólogos, georreferenciación, construcción de la nube de puntos densa, mallado y texturizado. Estas técnicas, frente a los planteamientos de la Fotogrametría Digital clásica o del LiDAR, suponen una menor complejidad.

Por otro lado, como se ha indicado, esta etapa implica la georreferenciación del modelo 3D al sistema legal de coordenadas del área de estudio (en el caso de estudio de esta Tesis: Proyección UTM ETRS89 Huso 30 N). Para esta operación es preciso la determinación de Puntos de Control sobre el Terreno (*Ground Control Points*; GCP) mediante una observación GNSS (*Global Navigation Satellite System*).

La etapa tercera (*Stage-3 Geometric Assessment*) supone la evaluación del modelo geométrico. Es una etapa crucial y en ella se determina su precisión. Hay que tener en cuenta que los errores en la reconstrucción del modelo 3D, se transmiten directamente a los estudios fluviales derivados de éstos (simulaciones hidráulicas, geomorfología fluvial, susceptibilidad a inundaciones, evaluación del riesgo…), influyendo en el grado de fiabilidad y por tanto deben determinarse.

La disponibilidad de datos geoespaciales de calidad, condiciona la verificación. Un primer enfoque es mediante Puntos de Chequeo sobre el terreno (*Check Points*) medidos conjuntamente a los GCPs de la observación GNSS anterior. Otra alternativa sería la verificación frente a datos existentes, por ejemplo LiDAR. Posibilidad que existe en España gracias a la Directiva Europea INSPIRE que establece la Infraestructura de Información Espacial en la Comunidad Europea.

En el contexto de verificación del modelado 3D del terreno, estrictamente métrico, y sin posibilidad de acudir a otras fuentes de referencia, se proponen dos novedosos enfoques. Un primer planteamiento metrológico, mediante una evaluación de la incertidumbre Tipo A (CEM, 2008), sí la condición de normalidad de los errores se cumple. Otro segundo, mediante Estimadores Robustos de la centralidad y la dispersión de los errores (Rodriguez-Gonzalvez *et al*., 2014), cuando no se verifica la distribución gaussiana. Este último enfoque ofrece la ventaja de no precisar un conocimiento previo de la función de distribución de los errores, eliminando la necesidad de la prueba de normalidad y agilizando el proceso.

Verificado el modelo 3D obtenido mediante procesado SfM y confirmada su validez como soporte para la definición del modelo geométrico de las simulaciones hidráulicas, además de determinada su precisión, concluye la parte geomática de la metodología.

COMPONENTE HIDROLÓGICA

La cuarta etapa (*Stage-4 Hydrologic-Hydraulic Processing*) supone la componente hidrológica. Implica la manifestación de la interdependencia de los términos del binomio "flujo-terreno", es decir, el comportamiento hidráulico del flujo en el medio que sirve de apoyo al ciclo hidrológico.

En primer lugar se define y genera el tipo de modelo hidráulico a simular (1D/2D, por ejemplo), las condiciones del flujo, y caudales de estudio. Tras la calibración del modelo, se procede a la obtención de los resultados de las variables hidráulicas y mapas de inundabilidad, con los que definir las zonas de susceptibilidad-peligrosidad y disponer de los datos necesarios para llevar a cabo la gestión de los recursos hídricos de un modo seguro (*Future Stage-5 Water Resources Management*).

Por otro lado, es preciso detallar la propuesta metodológica llevada a cabo sobre series temporales hidrológicas de aportaciones anuales. En este sentido, se propone un enfoque (ver Capítulo II) inspirado en las nuevas tendencias investigadoras en el campo de la hidrología estocástica, combinando un planteamiento tradicional, mediante un modelo paramétrico Autorregresivo de Medias Móviles (*Autoregressive Moving Average*; ARMA), con un nuevo enfoque basado en la Inteligencia Artificial, a través de las Redes Bayesianas (*Bayesian Networks*; BNs). Según se ha puesto de manifiesto en varios estudios y trabajos (Jain y Kumar, 2007; Sang YanFang *et al*., 2013; See y Openshaw, 2000; Zhang, 2003) esta hibridación de técnicas proporciona resultados más precisos a la hora de modelizar sistemas complejos naturales, como es el caso de los recursos hídricos.

Con el fin de poner en valor el potencial analítico de las BNs, a partir de la serie de registros históricos de las aportaciones anuales, se define un modelo ARMA (1,1) parsimonioso y no condicionado, con el que generar Series Sintéticas (SSs) temporales equiprobables. Éstas, de igual longitud que el registro histórico, se obtienen de acuerdo al marco de actuación clásico definido en Salas *et al*., (1980), vigente hoy en día. Además el modelo ARMA (1,1) dota de una mayor libertad al posterior Razonamiento Causal.

La asunción de una distribución gaussiana por parte de los modelos ARMA (Kim y Valdes, 2005; Salas *et al*., 1980), junto con una más que probable sesgada distribución de la probabilidad en los datos hidrológicos (Lee *et al*., 2010), implica que deban aplicarse pruebas de normalidad a la serie histórica y funciones de normalización en el caso de no verificarse la hipótesis de distribución normal. La calidad de las SSs generadas se evalúa mediante la aplicación del Test de Kolmogorov–Smirnov–Lilliefors (Steinskog *et al.*, 2007). De esta forma se comprueba la fiabilidad de las SSs para el Razonamiento Causal.

La característica de las BNs como modelo gráfico probabilístico (Jensen, 1996; Pearl, 1988), posibilita, en modelos complejos, definir estructuras lógicas entre variables de un modo ágil y eficiente. La implementación del Teorema de Bayes mediante las BNs permite la propagación de la probabilidad condicionada y la cuantificación de las relaciones de dependencia-independencia (Castelletti y Soncini-Sessa, 2007). En esta estructura lógica así definida, cada año es considerado como una variable de decisión, calculándose la distribución de probabilidad de cada uno y su propagación en la totalidad del periodo de análisis.

La última fase de la metodología hidrológica comprende un análisis de sensibilidad de los resultados mediante métodos de Teoría de la Información. Se evalúa la Entropía, la Entropía Condicionada y la Información Mutua de cada variable de la estructura lógica definida.

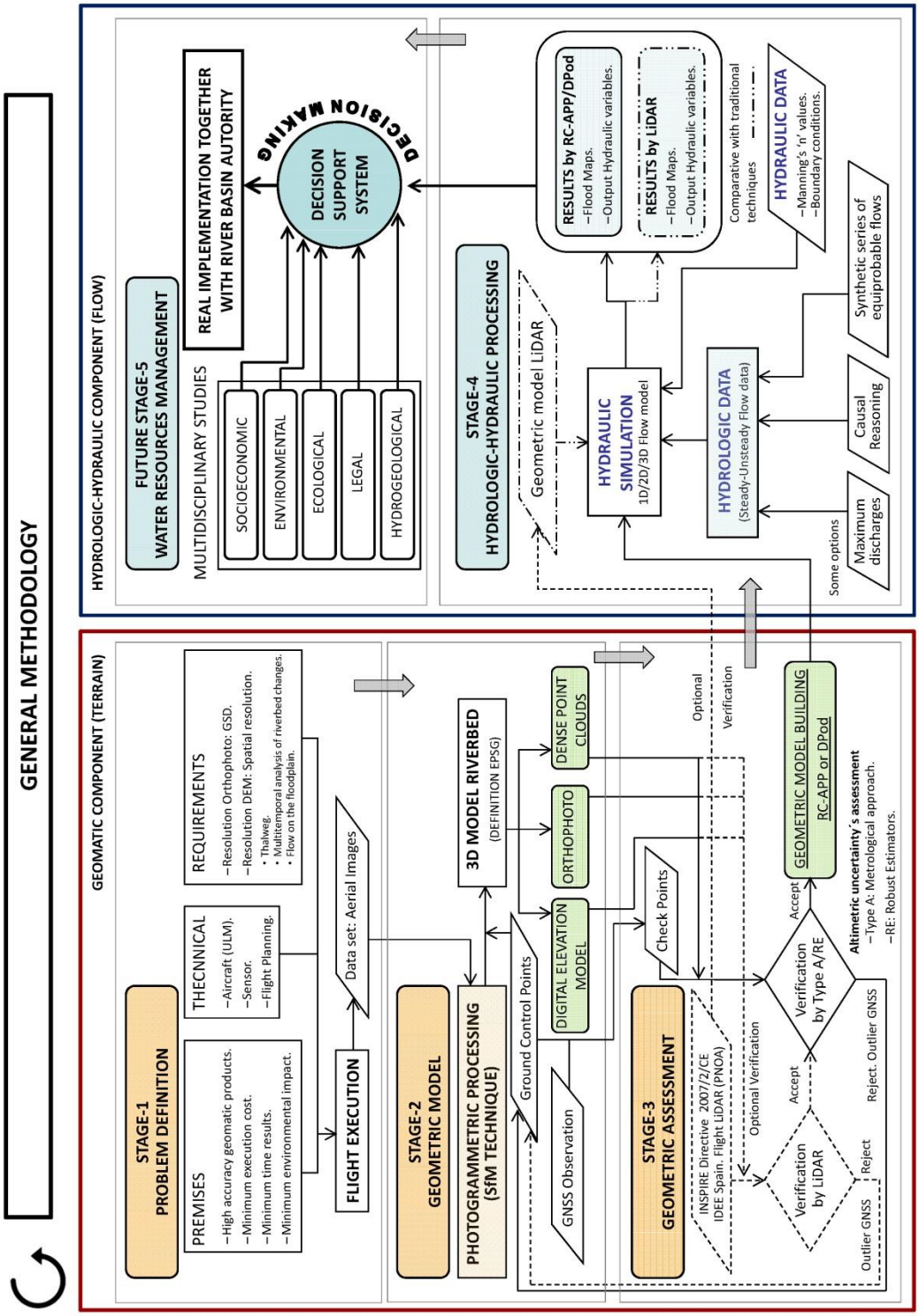

Figura 1. Metodología General

I.7 HIDROLOGÍA ESTOCÁSTICA. DESDE LOS ENFOQUES TRADICIONALES AL RAZONAMIENTO CAUSAL

La complejidad propia de los sistema hídricos además de un conocimiento incompleto sobre las relaciones que en ellos subyacen (Giupponi y Sgobbi, 2013; Liu *et al*., 2015; Sivapalan *et al*., 2012), hace necesario aplicar un enfoque holístico (Lerma *et al*., 2014) sí se aspira a una gestión sostenible y segura de este tipo de sistemas naturales. Para conseguir este fin, resulta indispensable un tratamiento eficiente y adecuado de las series temporales (Akintug y Rasmussen, 2005; Fortin *et al*., 2004). Esto supone analizar la evolución y dependencias de variables puramente aleatorias (Croitoru y Minea, 2015; Romano *et al*., 2013) como las hidrológicas.

Probablemente en la hidrología estocástica, los estudios con un mayor impacto hayan sido el Coeficiente de Hurst, entendido como medida de la persistencia o interdependencia temporal a largo plazo, (Hurst, 1951), la metodología de modelado de series propuesta en Box y Jenkins (1976), y el modelado de series temporales específicamente hidrológicas de Salas *et al*., (1980), trabajos vigentes hoy en día y referentes en esta disciplina.

Las propias características intrínsecas y diferenciadoras de cada zona de estudio, cuenca hidrográfica y/o de los registros históricos de las variables hidrometeorológicas, suponen la imposibilidad de abordar el problema de la modelización desde una única perspectiva (Ilich y Despotovic, 2008; Srivastav *et al*., 2011). Esta doble estocasticidad, del flujo y del terreno, ha dado píe a múltiples puntos de vista para abordar esta problemática entre la comunidad científica, siendo la división admitida tradicionalmente la de modelos estocástico paramétricos y no-paramétricos.

De entre los modelos paramétricos, han tenido una gran aceptación, por su simplicidad y versatilidad (Salas, 1993), los modelos Autorregresivos (AR; Bogner *et al*., 2016; Kendall y Dracup, 1991; Zhao y Chen, 2015), y los modelos Autorregresivos de Medias Móviles (ARMA; Burlando *et al*., 1993; Karthikeyan y Kumar, 2013; Salas *et al*., 1982), generalmente aplicados a series temporales estacionarias (Nourani *et al*., 2011; Salas *et al*., 1980), donde es habitual ordenes temporales bajos para el modelado de series hidrológicas anuales (Salas, 1993).

Como generalización de este tipo de modelos, surgen los modelos Autorregresivos Integrados de Medias Móviles (ARIMA; Valipour *et al*., 2013), que ofrecen, por su flexibilidad, representar varios tipos diferentes de series temporales, como procesos puros autorregresivos (AR), de medias móviles (MA) puras o la combinación de ambos en modelos ARMA (Zhang, 2003).

En general, los modelos ARIMA se basan en la metodología clásica enunciada en Box y Jenkins (1976), donde la selección del orden del modelo es una etapa relevante, en especial en los modelos ARMA (Lee y Ouarda, 2011). Por esta razón, y al amparo de la Teoría de la Información, han surgido enfoques para la selección del orden del modelo, basados en los Criterios de Información (Wang *et al*., 2015). En este sentido, los criterios más ampliamente aplicados, según muestra (Díaz Caballero, 2011), son el Criterio de Información de Akaike (AIC; Akaike, 1974), y el Criterio de Información de Schwarz (Schwarz, 1978). Este último con un enfoque Bayesiano, razón por la que también se le denomina Criterio de Información Bayesiano (BIC).

Es preciso tener en cuenta que el orden del modelo es un parámetro que incide directamente en la complejidad de éste y por tanto en el carácter parsimonioso que pueda tener. En este contexto resulta interesante la aplicación del criterio BIC frente al AIC, pues este último tiende a seleccionar ordenes de tiempo mayores y por tanto modelos menos parsimoniosos (Peña, 2005).

Los modelos no-paramétricos, surgidos y desarrollados en las últimas décadas (Kim y Valdes, 2005; Vogel y Shallcross, 1996), se caracterizan por no asumir *a priori* una distribución de probabilidad concreta (Srinivas y Srinivasan, 2005; Srivastav *et al*., 2011), y por superar los problemas de transformación de datos hidrológicos no normales a una distribución gaussiana (Lee y Ouarda, 2011).

Ejemplo de este tipo de modelos son: Método del Índice Secuencial (*Index Sequential Method*; Ouarda *et al*., 1997), Muestreo del K-Vecino más Cercano (*K-Nearest Neighbor Resampling*; KNNR; Lall y Sharma, 1996). KNNR ha tenido una amplia repercusión entre la comunidad hidrológica internacional (Caraway *et al*., 2014, Lee y Ouarda, 2010; Mehrotra y Sharma, 2006; Rajagopalan y Lall, 1999), debido a su simplicidad, flexibilidad de aplicación, buena reproducción de las propiedades estadísticas observadas así como facilidad de modificación (Lee y Ouarda, 2011).

Por otro lado, la creciente demanda global de recursos hídricos (Koutroumanidis *et al*., 2009; Molina *et al*., 2010), asociada a la necesidad de una mayor precisión en sus predicciones (Jain y Kumar, 2007; Nourani *et al*., 2011), junto con los avances en el procesado masivo de datos experimentados en la Informática en los últimos años (Jayakrishnan *et al*., 2005), están permitiendo la aparición de métodos innovadores en el modelado hidrológico, fundamentados en la Inteligencia Artificial (Nourani *et al*., 2011).

Estas técnicas resultan especialmente útiles en el análisis de datos-información procedente de sistemas complejos no-lineales, como los naturales, en los que no se tiene un conocimiento certero de las relaciones físicas que en ellos se dan (Aqil *et al*., 2007).

Las ventajas del enfoque mediante Inteligencia Artificial se pueden resumir en:

- Utilizar directamente la información en bruto (*raw-data*) sin simplificaciones, ni procedente de simulaciones (Zounemat-Kermani y Teshnehlab, 2008).
- No requerir un conocimiento "*a priori*" del proceso (Nourani *et al*., 2011).
- Posibilidad de manejar una gran cantidad de información procedente de sistemas dinámicos y no-lineales (Aqil *et al*., 2007).
- Definición, relativamente sencilla, de las complejas relaciones propias de los sistemas naturales (Molina *et al*., 2013).

Algunos ejemplos significativos de estos enfoques aplicados a los recursos hídricos son: las Redes Neuronales Artificiales (*Artificial Neural Networks*; ANNs), las Redes Bayesianas (*Bayesian Networks*) y las Redes Bayesianas Dinámicas (*Dynamic Bayesian Networks*) entendidas como una generalización de las BNs en las que el desarrollo del sistema se modela con el tiempo y no que la estructura del modelo y sus parámetros cambian con el tiempo (Dean y Kanazawa, 1989; Molina *et al*., 2013).

Las BNs merecen especial atención en el contexto y temática de esta Tesis, donde han sido la herramienta empleada para el análisis del comportamiento temporal.

Formalmente en (Charniak, 1991) las BNs se definen como "*Una técnica de modelado que reproduce las características esenciales del razonamiento plausible (razonamiento en condiciones de incertidumbre) de una manera consistente, eficiente y matemáticamente correcta*". Desde un punto de vista conceptual y eminentemente práctico, se pueden considerar como relaciones de causa-efecto, en las que modela y representa explícitamente, de forma sencilla, la incertidumbre (Cain, 2001), y donde las variables aleatorias son representadas como "nodos" interconectados en una estructura acíclica, es decir sin bucles cerrados, que interactúan unos con otros (Molina, 2009).

Asimismo las BNs son un modelo probabilístico gráfico (Pearl, 1998), que permite una representación compacta de la distribución de la probabilidad conjunta sobre un conjunto de variables aleatorias (Molina *et al*., 2013), permitiendo la propagación de la probabilidad condicionada, mediante la implementación del Teorema de Bayes, de un modo "omnidireccional". De esta forma, ante una observación dada sobre cualquiera de los nodos (variable aleatoria) de una red (o subconjunto de nodos), se pueden obtener las probabilidades *a posteriori* de todos los demás, independientemente de su situación en la red, mediante la inferencia observacional (Cain, 2001), es decir, la información pasada proporcionará un conocimiento previo sobre el futuro (Molina *et al*., 2010). Así es posible cuantificar la fuerza de la relación entre variables aleatorias (Castelletti y Soncini-Sessa, 2007), lo que ha permitido su aplicación como Sistemas de Apoyo a la Decisión (*Decision Support System*; DSS; Molina *et al*., 2013; Pearl, 1988). Esta capacidad para analizar el comportamiento temporal de las series paso a paso (*time step by time step*), permite disponer de una herramienta dinámica de simulación idónea para el Razonamiento Causal.

Llegados a este punto, puede tenerse la sensación que los enfoques tradicionales quedan totalmente relegados y superados por los métodos basados en la Inteligencia Artificial. Sin embargo, la realidad es otra. Según ponen de manifiesto recientes investigaciones, la hibridación entre modelos ARMA y ARIMA con modelos basados en Inteligencia Artificial puede llevar a obtener resultados más precisos en el análisis y modelado de procesos naturales complejos, como el comportamiento hidrológico de una cuenca (Nourani *et al*., 2011; Sang YanFang *et al*., 2013; Valipour *et al*., 2012). Siendo esta la idea que ha inspirado el enfoque que en esta Tesis se aplica al análisis del comportamiento temporal de las series hidrológicas de aportaciones.

I.8 LA GEOMÁTICA AL SERVICIO DE LA MODELIZACIÓN HIDRÁULICA

La gestión sostenible y segura de los recursos hídricos de una cuenca no sólo se apoya en un conocimiento en profundidad del recurso en sí mismo, en cuanto a su disponibilidad, frecuencia, régimen de caudales, variabilidad, etc, también es necesario evaluar la interacción de éste con el medio natural en el que se desarrolla el ciclo hidrológico (Andreu, 1993; Mateo-Lázaro, 2011), y por tanto profundizar en el conocimiento de la Hidrodinámica e Hidráulica Fluvial; quedando patente el enfoque holístico expuesto en el punto anterior.

Variables hidráulicas como la velocidad y el calado, muy dependientes de la geometría del cauce (USACE, 2010), permiten una mejor determinación del comportamiento del flujo y de la peligrosidad de las inundación hacia personas y bienes (Martín Vide, 2009). La morfodinámica fluvial, el transporte y caracterización de los sedimentos (Sena Fael *et al*., 2006), junto con la geometría de las estructuras sobre los cauces fluviales (Fael *et al*., 2016), los elementos de protección en márgenes (Cardoso y Fael, 2009), entre otros, también son aspectos significativos a considerar, desde una perspectiva de seguridad.

En este contexto, la adecuada evaluación y gestión de los riesgos naturales fluviales impone un exhaustivo conocimiento del terreno, donde juega un papel primordial la precisión y el detalle en la representación del terreno (Bales y Wagner, 2009; Jung y Merwade, 2012). Esto está llevando, a nivel mundial, a una creciente necesidad de datos geoespaciales de calidad, en forma de DEM para la creación de modelos hidráulicos e hidrodinámicos, que con frecuencia constituye en sí mismo un problema técnico y económico (Saksena y Merwade, 2015). Asimismo, la dependencia del terreno en los resultados de las simulaciones hidráulicas es analizada en varios trabajos (Cook y Merwade, 2009; Merwade *et al*., 2008; USACE, 2010; Zazo *et al*., 2015a), así como la influencia que la densidad de puntos del DEM tiene en ellos (Zazo *et al*., 2015b, 2016).

Ante esta situación, la ciencia geomática resulta extremadamente útil como un *medio* al servicio de la hidrodinámica y la hidráulica fluvial, gracias a las características que las nuevas tecnologías y metodologías desarrolladas son capaces de aportar a los productos geomáticos que de ellas se derivan. Así es posible mejores y más realista

modelizaciones del comportamiento del flujo en ríos, definiendo con mayor objetividad la susceptibilidad a las inundaciones y la determinación de la vulnerabilidad a los riesgos naturales fluviales.

Técnicas para la adquisición de información geoespacial basadas en la observación mediante satélites, LiDAR, en sus variantes aérea/terrestre (*Airbone*/*Terrestrial Laser Scaner*; ALS/TLS) y la observación, ahora clásica, mediante GNSS, están completamente asentadas entre la comunidad científica (Brasington *et al*., 2000; Chaubey *et al*., 2005; French, 2003; Legleiter y Overstreet, 2012; Rosser *et al*., 2005). Además, los avances en los sensores digitales, algoritmos de procesado de imágenes, la visión artificial y en las plataformas alternativas aéreas, están permitiendo la aparición de nuevos enfoques que han revolucionado sustancialmente el modelado 3D del terreno y abriendo nuevas líneas de investigación a la comunidad científica (Lejot *et al*., 2007; Ortega-Terol *et al*., 2014; Westoby *et al*., 2012, 2015). En el trabajo Molina *et al*., (2014) se lleva a cabo una exhaustiva revisión de las actuales técnicas geomáticas aplicadas al modelado de recursos hídricos, con indicación de sus resoluciones espaciales, precisiones y limitaciones.

En la constante revolución tecnológica a la que asistimos en las últimas décadas, la Fotogrametría Digital, como disciplina geomática, no ha sido ajena. Las nuevas plataformas aéreas y la posibilidad de adquirir información completa sobre un objeto/modelo tridimensional, a través exclusivamente de imágenes digitales, e incluso desde una única imagen (Gonzalez-Aguilera y Gomez-Lahoz, 2008), ha revolucionado, sin lugar a dudas, la Fotogrametría Digital hacia una Fotogrametría Digital adaptada a las necesidad del usuario final, que se puede denominar bajo demanda.

Esto ha sido posible, en gran medida, gracias a los avances en la Visión Artificial, que han permitido la reconstrucción digital de objetos/modelos a partir de algoritmos SfM (Snavely, 2008). Éstos, mediante el paralaje [6] determinan la orientación externa (posición del punto de vista y orientación en el espacio) de las imágenes (Lu *et al*., 2004). De esta forma es posible obtener, por procesado de imágenes, nubes de puntos 3D densas (coordenadas XYZ y valores RGB aplicables a la reconstrucción de texturas).

6. Paralaje. Movimiento aparente de un objeto respecto al fondo cuando cambia el punto de vista del observador.

El potencial de los algoritmos SfM reside en la capacidad de reconstrucción de una geometría 3D a partir de imágenes 2D adquiridas desde diferentes puntos de vista e incluso con diferentes cámaras no-calibradas. Esto es posible, matemáticamente, gracias a la Geometría Epipolar (Hartley y Zisserman, 2004), que se fundamenta en el principio de los planos nucleares, que posteriormente daría lugar al Teorema de Terrero-Hauck [7], totalmente vigente a día de hoy.

Este nuevo enfoque fotogramétrico, conceptualmente distinto a la Fotogrametría Digital clásica (Fonstad *et al*., 2013), permite, además de inmediatez y una adecuada relación tiempo-coste (Tonkin *et al*., 2014), el desarrollo de las soluciones de coste reducido e incluso bajo coste, así como productos geomáticos con unas resoluciones espaciales y precisiones, especialmente interesantes para su aplicación en la hidrodinámica e hidráulica fluvial (ver Capítulo III, punto III.1 y III.2).

I.9 ESTRUCTURA DEL DOCUMENTO

La organización se articula en cuatro capítulos básicos que siguen el orden lógico de la investigación, de acuerdo a los objetivos generales y específicos fijados para la Tesis Doctoral, y dos apéndices que se han considerado necesario incluir como medida externa y objetiva de la calidad de las revistas científicas donde han sido publicadas las investigaciones y de la repercusión de estas últimas entre la comunidad científica.

El Capítulo I "Introducción", proporciona una visión general de la Tesis. En él se justifica y motiva el interés que ésta tiene para la comunidad científica e ingenieril en particular, como para la sociedad en general. Se exponen las hipótesis consideradas, se concretan los objetivos generales y específicos de las investigaciones a desarrollar, así como se definen las zonas de estudio consideradas, a nivel hidrológico e hidráulico-geomático. Además, se detallan las metodologías aplicadas y se realizan dos visiones generales de los distintos enfoques realizados hasta la fecha.

7. Principio de los Planos nucleares: Todo haz de rayos nucleares generados por puntos del terreno pasarán por el punto nuclear y se cortarán dos a dos en la recta nuclear.
La recta epipolar es un concepto central en Fotogrametría Digital pues establece el lugar geométrico de los puntos homólogos, es decir, establece el espacio de búsqueda (Gomez-Lahoz, 2008).

En la primera de ellas, de la componente hidrológica, desde los enfoques clásicos estocásticos hasta las más recientes y novedosas líneas de investigación enmarcadas en las Redes Neuronales y el Razonamiento Causal. La segunda, de la componente geomática, lleva a cabo una síntesis de las distintas técnicas y metodologías aplicadas a la adquisición de información geoespacial en el ámbito de la gestión de los recursos hídricos, la hidrodinámica y la hidráulica fluvial, hasta los nuevos enfoques que ha permitido la Visión Artificial. Por último se indica la estructura general del documento.

Los Capítulos II y III constituyen el núcleo central de la investigación. En ellos se presentan los resultados obtenidos en las investigaciones realizadas, a través de las tres publicaciones científicas indexadas generadas.

El Capítulo II, “Comportamiento hidrológico de ríos mediante Razonamiento Causal”, está dedicado a la aplicación del Razonamiento Causal como *medio* para profundizar en el conocimiento interno y el entendimiento de la dependencia-independencia temporal de las series hidrológicas de aportaciones-caudales. Se basa en la aplicación de técnicas propias de la Inteligencia Artificial, atendiendo a las propiedades que tienen las Redes Bayesianas en este sentido. En él se presentan los resultados de la investigación en forma de artículo científico:

> II.1: Artículo científico I:“*Innovative Analysis of Runoff Temporal Behavior through Bayesian Networks*”. Supone un nuevo enfoque dinámico del análisis de la dependencia-independencia temporal de las series de aportaciones-caudales. Por otro lado, propone una metodología para evaluar la dependencia a medio plazo como novedad frente a los enfoques tradiciones con indicadores a corto y largo plazo exclusivamente.

El Capítulo III, "La Visión Artificial al servicio de la modelización hidráulica y la hidrodinámica", constituye la parte geomática de la investigación. Muestra un enfoque de la ciencia geomática, como *medio*, al servicio de la hidrodinámica y la hidráulica fluvial, con el que se pueden conseguir mejores y más realista modelizaciones del comportamiento y la caracterización del flujo en ríos, así como de la susceptibilidad y vulnerabilidad a los riesgos naturales fluviales. Esto aporta un punto de vista nuevo sobre el enfoque clásico que se ha tenido de esta ciencia, tradicionalmente considerada generadora de productos finalistas. A continuación se presentan los dos artículos de investigación restantes de esta Tesis:

III.1: Artículo científico II: "*Analysis of flood modeling through innovative geomatic methods*". Propone una metodología eficiente en tiempo y coste, satisfactoriamente aplicada, para la adquisición de información geoespacial en el ámbito fluvial basado en técnicas SfM, mediante sensores estabilizados en vuelo, de coste reducido embarcados en plataformas aéreas alternativas, frente a las técnicas habituales con sensores activos como el LiDAR. Por otro lado, aborda la problemática de la evaluación de la incertidumbre de los modelos geométricos fluviales ofreciendo un nuevo enfoque desde un punto de vista estrictamente metrológico.

III.2: Artículo científico III: "*Flood analysis supported by low-cost geometric modelling*". Investiga la aplicación de sensores pasivos de muy bajo coste en la generación de modelos geométricos aplicables a la modelización fluvial. Profundiza en la evaluación de la incertidumbre geométrica cuando la función de densidad de los errores en los modelos 3D no siguen distribuciones normales, proponiendo la aplicación de estimadores robustos de la centralidad y la dispersión, para superar estos inconvenientes y evaluar la parte métrica de la incertidumbre del proceso.

En el Capítulo IV "Conclusiones y Futuras líneas de investigación", se exponen las conclusiones finales y las aportaciones de esta Tesis de acuerdo a las conclusiones y discusiones realizadas en los distintos artículos científicos. Este capítulo final se organiza de acuerdo a los objetivos particulares y generales previamente definidos. Asimismo se proponen futuras líneas de investigación que permitan continuar con las investigaciones iniciadas.

El Capítulo V (Chapter V) "Conclusions and Future research lines", es la redacción en lengua inglesa del Capítulo IV. Dicho contenido se incluye para cumplir con los requisitos que la Universidad de Salamanca establece para optar a la Mención Internacional de la Tesis.

Los Apéndices I y II, representan una medida externa y objetiva de la calidad de los artículos publicados. Resumen los principales índices de calidad de las revistas científicas donde han sido publicados los artículos de investigación, e indican el número de citas recibidas por los artículos desde su publicación hasta la fecha de redacción de esta Tesis.

A.I: Apéndice I. “Índices de calidad de las revistas científicas”. Detalla las revistas científicas internacionales de prestigio, indexadas en las bases de datos Journal Citation Report (JCR) y SCImago Journal Rank (SJR), donde han sido publicados los artículos que constituyen la Tesis. Se indica la clasificación por cuartiles de éstas, en el área de conocimiento de las investigaciones desarrolladas, y se detallan sus factores de impacto e índices en las principales bases de datos bibliográficas.

A.II. Apéndice II. “Repercusión de las investigaciones”. En él se recogen las citas recibidas de los artículos que componen la Tesis, a nivel internacional, por parte de investigadores.

CAPÍTULO II

Comportamiento hidrológico de ríos mediante Razonamiento Causal

II.1 PUBLICACIÓN CIENTÍFICA I

Este apartado contiene el artículo científico titulado *"Innovative Analysis of Runoff Temporal Behavior through Bayesian Networks"*, publicado en la revista científica de alto factor de impacto *Water* (ISSN: 2073-4441) en Octubre de 2016.

Resumen

El comportamiento de los procesos y series hidrológicas se caracterizan, en gran medida, por su inherente y fuerte aleatoriedad. Recientemente se están observando cambios-alteraciones significativos en los patrones típicos del comportamiento de las series temporales, tanto a nivel de las precipitaciones como por supuesto en las aportaciones y en el régimen de caudales. Naturalmente estas modificaciones, aparte de no resultar obvias en muchos casos, no son una cuestión trivial. Especialmente significativas son las influencias difusas y los órdenes de dependencia temporal, tan relevantes a la hora de una gestión integrada, sostenible, eficiente y segura de los recursos hídricos de una cuenca; demandando un conocimiento más detallado y una mayor capacidad de análisis de las series temporales.

Ante la alteración tangible de los patrones típicos hidrológicos, tradicionalmente considerados como "cíclicos", esta investigación tiene por objetivo principal analizar, como punto de partida en el caso de las series anuales de aportaciones, el comportamiento de las dependencias temporales desde un punto de vista dinámico, considerando su evolución temporal año a año. El enfoque aplicado comprende una combinación entre las técnicas clásicas, mediante un modelo Autorregresivo de Medias Móviles (conocido por sus siglas en inglés como ARMA), y otras novedosas basadas en la Inteligencia Artificial, a través de un modelo gráfico probabilístico mediante Redes Bayesianas (BNs, siglas en inglés), con el que se realiza la inferencia. Para este fin, en primer lugar se llevó a cabo la generación y construcción de un modelo ARMA (1,1) parsimonioso y no condicionado, con el que obtener series sintéticas temporales equiprobables y de la misma longitud que los registros históricos, con la suficiente fiabilidad como para posteriormente, proporcionar "datos de entrada" al Razonamiento Causal mediante BNs, y al análisis de sensibilidad de los resultados vía métodos de Teoría de la Información.

La aplicación del Teorema de Bayes, implementado gracias a las BNs, permite definir e identificar, de forma eficiente, las complejas relaciones y estructuras lógicas que las dependencias temporales pueden establecer dentro de las series hidrológicas. En este sentido, la probabilidad condicional resultante del teorema permite cuantificar el porcentaje relativo de cambio anual en la aportación, además de proporcionar el orden correcto de tiempo de la dependencia temporal de la serie, de una manera dinámica.

Esta investigación introduce una metodología original, potente y gráfica capaz de construir una estructura lógica para un análisis estocástico innovador del comportamiento temporal. Además demuestra como mediante el Razonamiento Causal, la Probabilidad Condicionada y la Teoría de la Información es posible mejorar y profundizar en la comprensión y el análisis del comportamiento dinámico de las series temporales. Esto supone una importante ventaja frente a los enfoques tradicionales basados en los correlogramas con los que se obtiene una idea del comportamiento medio y estático temporal de la dependencia a través de la intensidad del coeficiente de correlación.

Por otro lado, la aplicación de la inferencia bayesiana ha detectado relaciones de dependencia no triviales (desfases temporales anuales mayores de 1). Además, su potencial analítico ha permitido evaluar la persistencia de la dependencia y/o la propagación de la dependencia temporal de las series, mediante el análisis de la intensidad de la propagación de la probabilidad. En este sentido se ha conseguido definir funciones polinómicas de propagación de la dependencia continuas a corto y medio plazo. Sin duda, disponer de un indicador sobre la dependencia temporal a medio plazo supone una innovación sobre las técnicas tradicionales, ya que éstas únicamente proporcionaban, de forma independiente, una evaluación a corto plazo, mediante correlogramas y/o modelos AR (Autorregresivos), ARMA por ejemplo, y a largo plazo, a través del coeficiente de Hurst.

La investigación se ha aplicado con éxito en dos sub-cuencas no reguladas del río Duero, la mayor cuenca fluvial en términos de superficie en la Península Ibérica, en los ríos Porma al norte y Adaja en el sur, con comportamientos hidrológicos temporales diferenciados.

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Innovative Analysis of Runoff Temporal Behavior through Bayesian Networks

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Abstract: Hydrological series are largely characterized by a strong random component in their behavior. More noticeable changes in the behavior patterns of rainfall/runoff temporal series are recently being observed. These modifications are not a trivial issue, especially in regards to peculiarities, non-linearities, diffused influences or higher time orders of dependence. This study mainly aimed to analyze the temporal dependence of an annual runoff series dynamically. This approach comprises a coupling between classic techniques (Autoregressive Moving Average Model, ARMA) and novel ones, based on Artificial Intelligent for hydrological research (Bayesian Networks, BNs). An ARMA model was built to provide reliable data to populate BNs. Then, causal reasoning, through Bayes's theorem, allows the identification of the logic structure of temporal dependences within time series. Furthermore, the resultant conditional probability permits the quantification of the relative percentage of annual runoff change, and provides the right time order of dependence. This research introduces an original methodology able to build a logic structure for a stochastic analysis of temporal behavior. This approach also aimed to provide a powerful and graphic modeling method for improving the understanding of the dynamic runoff series temporal behavior. This was successfully demonstrated in two unregulated river basin stretches, belonging to the Duero river basin which is the largest basin in Spain.

Keywords: stochastic modelling; temporal analysis; Bayesian networks; hydrological time series; water resources management

1. Introduction

Meteorological events, mainly precipitation patterns and temperature records, and their subsequent hydrological effects are increasingly variable in a particular territory. Traditional temporal and spatial behavior patterns are being ever more modified over the world. In this sense, extreme events such as floods or droughts, among others, are more frequent in recent times [1–4]. There is a consequent strong necessity for powerful and reliable tools to build accurate models that reproduce the past and present hydrological behavior and forecast the future hydrological behavior of a river system. However, in order to build tools for dynamically analyzing the present behavior, as well as predicting the future, the historical behavior should be more deeply understood. In this sense, it has been recently shown that stationarity in hydrological time series is not as strict as in historical records. This fact, due to the increase of extreme events occurrence, means that the tools needed for prediction need to be much more flexible and powerful. For instance, a possible implication may be the need of designing tools able to deal with non-normal probability distributions.

Temporal behavior of hydrological analysis has been studied for some considerable time. Nowadays, many of those concepts and methodologies are valid benchmarks in stochastic

hydrology [5,6]. Those concepts involve temporal–spatial correlation, statistical properties, including droughts and storage statistics, as well as trends, shifts and seasonality testing. Furthermore, time series analysis has been used for several applications such as filling in missing data, extending records, building mathematical models to generate synthetic hydrologic records, and detecting trends and shifts in hydrologic records, among others [7–9].

Nevertheless, a more complete and accurate time series analysis is needed, mainly because of the need to enhance the stochastic analysis. In this sense, traditional techniques describe the average temporal behavior of the time series largely deterministically or with some slight stochastic component. Additionally, it is necessary to have tools and/or methods that are able to analyze the influence of time steps on following ones within the time series, in a dynamic way. Furthermore, it is important to more accurately quantify the temporal dependency of time series to characterize water management scenarios and behavior patterns more realistically. This will allow a better assessment of water availability, and therefore, an optimum dimensioning of hydraulic infrastructures such as reservoirs.

This study aimed to dynamically analyze the temporal dependence of a runoff data series within a hydrological time series and to provide an estimation of the right time order (model order) of a hydrological time series. This is done through a hybrid method that comprises a combination of traditional techniques, (ARMA models), and new approaches based on Artificial Intelligent (Bayesian Networks).

Since this study comprises two river basins under different conditions (meteorological, morphodynamics, hydrological, hydraulic, etc.) this analysis will be useful for extrapolating to other similar basins. This research demonstrates that the proposed methodology can be an appropriate complement to traditional approaches.

Hydrological series are largely characterized by a strong random component in their intrinsic behavior [10]. A more sustainable and efficient management of basin water resources necessarily involves a deeper knowledge of time series' behavior [7,9]. This comprises, among other factors, an analysis of the temporal evolution as well as the temporal dependence of hydrological variables such as precipitation, stream flows or total runoff [11,12].

It is well known that every model is an abstraction of the reality [13]. In this context, different approaches for hydrological modelling have been proposed since the middle of last century [14]. Therefore, in order to define an appropriate hydrological stochastic model, the main problem will be obtaining representative patterns of basin behavior. This definition should be largely based on features such as a goodness of fit, building lower complexity model (parsimonious model) and the maintenance of the statistical properties observed in the time series, among others [13,15]. Results from this model can be expressed in terms of probability for the involved stochastic processes.

Traditionally, stochastic hydrology models have been classified in two large groups: Parametric (PM) and nonparametric (NP). Among parametric models, the Autoregressive models (AR) [4,16–18], and Autoregressive Moving Average models (ARMA) have had great acceptance, as seen in [19–23]. Generally, these models have been applied to stationary time series [24,25], usually used for modeling low-order annual hydrologic time series, and they are characterized by their simplicity and versatility [22]. Furthermore, the hybridization with NP ensures that non-stationary and higher order series can be also modelled.

Nonparametric models have been mainly developed in the last decades [8,26,27]. These models not make a priori assumptions about probability distributions [28,29]. Relevant examples are the index sequential method [30], moving block bootstrap [27], kernel based methods [31] and k-nearest neighbor resampling (KNNR, [32]). Theoretical background on parametric and nonparametric models can be consulted in-depth on [25,33].

Currently, the high capacity of data processing, thanks to advances in computer technology, has allowed the emergence of innovative alternatives based on Artificial Intelligence (AI). These approaches are interesting because of the following reasons: first, the a priori information of the process is not needed [24,34,35]; then, they allow the use of field raw-data [35]; they are able to process a great

amount of data from dynamic and nonlinear systems, so they are useful for identifying physical relationships which are not completely understood [36]; and finally, it is relatively simple to define the relationship in sophisticated systems [37].

In the field of water resources and management, Bayes's theorem, implemented through Bayesian Networks (BN) and derivative techniques such as Dynamic Bayesian Networks (DBNs) have been widely used in the last decade. BNs have been frequently and successfully applied to environmental studies [37–39], and to deal with problems within the water resources management field [40–44].

Innovative applications of Bayes's theorem to hydrological forecasting have recently successfully emerged [45–48]. These applications quantify the uncertainty in post-process deterministic streamflow forecasts [49]. In this sense, an interesting point of view is suggested in Wang et al. [48], where BNs are applied to reduce uncertainties in flood prediction by real-time correction. Nevertheless, the application of Bayes's theorem purely in the context of temporal dependence–independence over runoff time series is still quite an unexplored field.

In this sense, BNs belong to probabilistic graphic models [50,51]. They deserve particular attention because they are extremely useful to define logical relationships among variables into complex models by means of causal reasoning, as it happens in water resources management. They also incorporate an advantage over other techniques, particularly interesting for this kind of study, because they allow the quantification of the variables' relationship strength through Bayes's theorem expressed as conditional probability [41].

From a theoretical point of view, a BN consists of three main elements: (1) a set of variables that represent the factors relevant to a particular system; (2) the relationships between these variables that quantify the links between variables; and (3) the set of conditional probability tables (CPTs) that quantify the links between variables and are used to calculate the node states [50]. The first two elements form a Bayesian Diagram and the addition of the third forms a full network. BNs permit the computation of probability distributions over subsets of their variables' conditional. Mathematical fundamentals and formal aspects in Bayes's theorem are discussed in detail in [37,51].

Furthermore, BNs allow an analysis of the temporal behavior of a series, time step by time step. This last property has important consequences because it allows a dynamic tool of the simulated process. Finally, the theoretical background of all approaches is extensively covered in the abovementioned references.

On the other hand, recent researches suggest that the hybridization between classic models, such as ARMA, with novel AI models, provide more accurate results in the modeling of complex natural processes such as hydrological behavior [24,52–54]. This last issue has inspired this research.

This manuscript is organized as follows. First, Section 1 comprises the Introduction and the state of the art where the main techniques, approaches and new tendencies on stochastic Hydrology are described. Section 2 shows a description of case studies, data and the applied methodology. Section 3 is dedicated to showing the main results drawn from the research. Finally, Section 4 addresses the conclusions and discussion generated from the study.

2. Materials and Methods

2.1. Study Areas

Water resources in Spain are characterized by an extreme variability, between the wet north, and the dry south. This has produced large irregularities among periods of droughts and rainfalls, as well as an increasing occurrence of extreme events (flooding and droughts), with an overall impact on the society [55].

In Spain, the rainfall distribution offers an irregular behavior, with a positive gradient with respect to latitude and southern asymmetry (Figure 1a). Furthermore, it increases with altitude and it is also closely linked to its strong orography.

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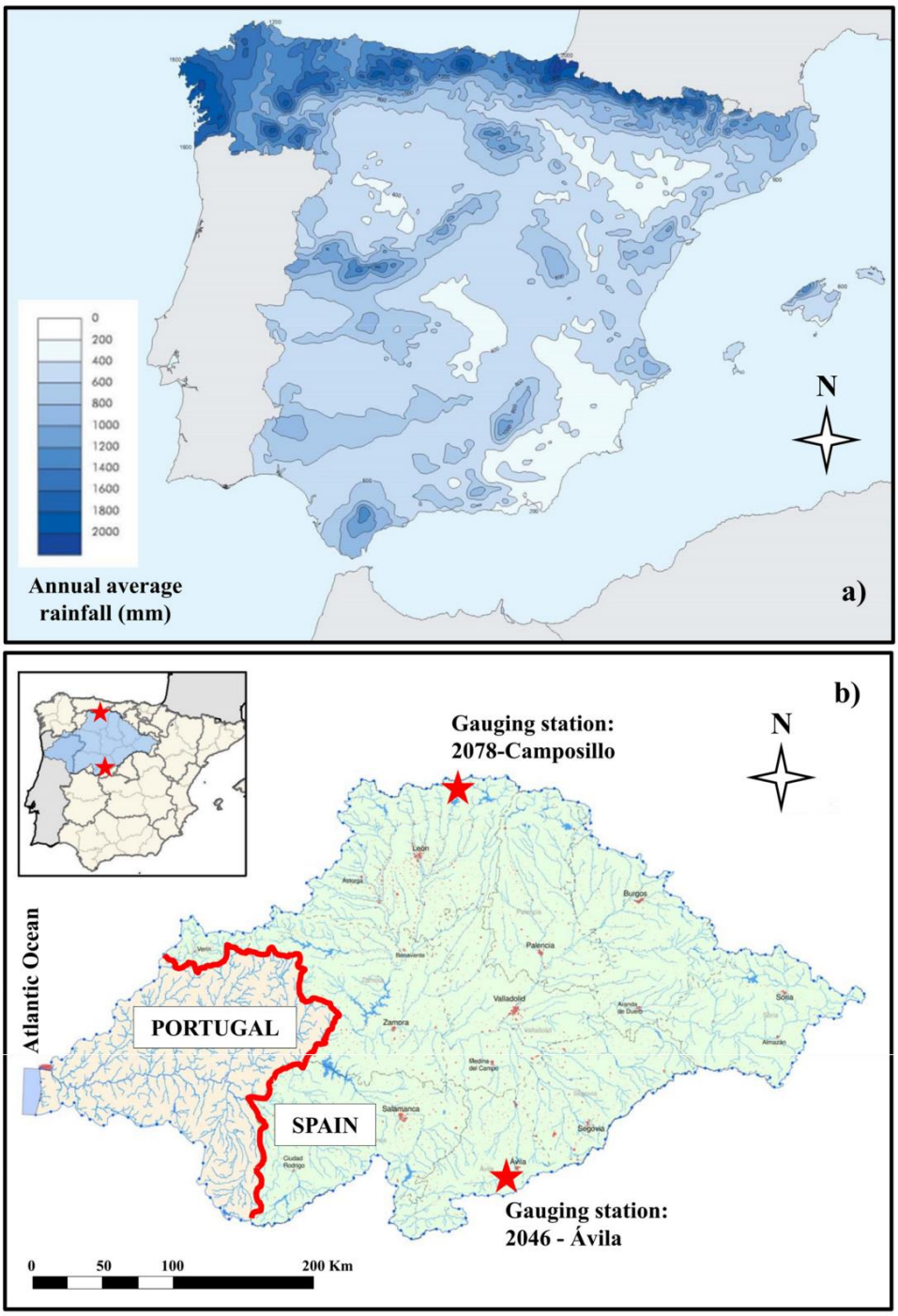

Figure 1. (**a**) Annual average rainfall distribution in Spain; (**b**) Duero river basin and location of case studies. Note: The gauging stations 2046 and 2078 are used to define both unregulated sub-basins.

Case studies are defined by gauging stations which are located upstream of the first regulating reservoirs. Consequently, these case studies comprise unregulated rivers stretches. The selection process was based on the annual average rainfall and rainfall variability north–south. Therefore, taking into account that annual average rainfall in Spain is 666 mm [56], two sub-basins were chosen

(Figure 1b). First, in the Adaja sub-basin in the south, annual rainfall is lower than the average. Second, gauging station Ávila (code number 2046), the Porma sub-basin in the north, has an annual rainfall higher than the average. Gauging station Camposillo (code number 2078).

2.1.1. Adaja River

This case covers the whole upper basin of the Adaja river, also known as Ambles valley, where this river comprises the main riverbed. The study area occupies a central position within Iberian Peninsula with an area of 770.51 km^2, according to gauging station 2046-Avila.

Regarding climatic features, the zone is defined as cold Mediterranean, high continental, with moderately warm summers and severe winters. Mean annual temperature is 11 °C and the average annual rainfall is about 400 mm. Rainfall is presented as scarce and irregular. The key morphometric parametric are a main channel length of 47.09 km and a time of concentration of 13.58 h. Notice that the considered time of concentration is the legal requirement in Spain, which has the following formulation:

$$T_c = 0.3 \cdot L_c \cdot J_c^{-0.19} \quad (1)$$

where T_c is the time of concentration expressed in hours, L_c is the length of the main channel in kilometers, and J_c is the average slope of the main channel in meter/meter (dimensionless value).

2.1.2. Porma River

This basin is located in the northern and wet part of Spain. The analyzed area is placed in the southern slope of the Cantabrian range, in the north of the León province. The area of study, taking into account the gauging station 2078-Camposillo, has an extension of 140.16 km^2. From the hydrological point of view, Porma river is characterized by a pluvio-nival hydrological regime, with an annual average rainfall of around 1430 mm, and an average yearly temperature of 8.8 degrees Celsius (°C). From a morphometric point of view, the sub-basin is characterized by a main channel length of 17.99 km and a low time of concentration of about 5.24 h.

2.2. Data Description

Annual runoff time series were obtained through the network of gauging stations belonging to Duero river basin Authority, the largest river basin in Iberian Peninsula. As the case studies are unrelated to each other, there are two different time periods of analysis for each sub-basin. In both cases, there are not missing data in the time series.

2.3. Methodology

The proposed methodology (Figure 2) starts with an analysis of basic statistics of the time series that also comprises the generation of correlograms. Then, an ARMA model was built to generate reliable equiprobable synthetic runoff series that populate the causal reasoning process. This was done through Bayes's theorem that allowed the identification of the logic structure of a Bayesian Network (BN) that represents the complex relationships of time series temporal dependences. Synthetic series from the previous ARMA model populated the BNs. Finally, the right time order (model order) estimation for runoff series, obtained by BNs, was checked by a suitability identification of the time order by means of Risk Simulator software [57]. This analysis was developed considering the main criteria for appropriate model selection, such as Schwarz Criteria or Akaike Information Criterion, both based on Information Theory. However, the selection was made considering exclusively the Schwarz Criteria, because Akaike information Criteria tends to select higher time orders and less parsimonious models [58].

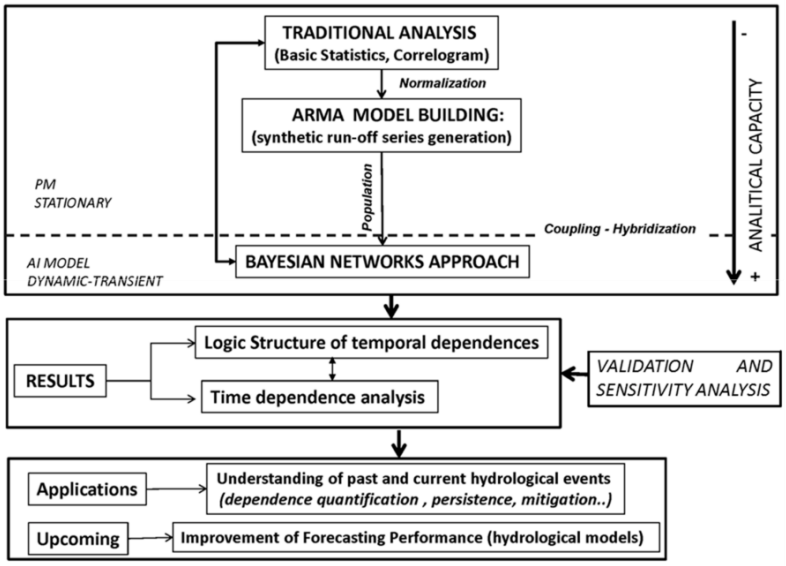

Figure 2. General methodology.

From a numeric point of view, Bayes's theorem allows the calculation of the conditional probability. Consequently, prior (first time step) and posterior probability distributions of runoff for each time step (year) are generated at the population stage. A conditional probability statement is of the following type: if the variable B is in state b_1, then from either evidence or experience, we know that, as a result, the probability of the variable A in state a1, is x. The notation for this statement is:

$$P\left(a_1|b_1\right) = x \tag{2}$$

The expression $P(A \mid B)$ denotes a Conditional Probability Table (CPT) containing numbers $P(a_i \mid b_j)$. This probability distribution of B, written as $P(B)$, together with the values given in the CPT can be used to calculate the resulting (a posteriori) probability distribution for $P(A)$. To obtain this distribution BNs use the fundamental Bayes's theorem.

$$P\left(B|A\right) = P\left(A|B\right) P\left(B\right) / P\left(A\right) \tag{3}$$

Here, the term $P(A \mid B)$ is an expression of the joint probability for the variables A and B. Bayes's theorem can be used to obtain the table $P(B \mid A)$, which is the CPT showing the likely state of the variable B given the variable A, which is the reverse of the previous situation, also called back propagation of probability.

Furthermore, the resultant conditional probability permits the quantification of the relative percentage of annual runoff change, as well as providing the right time order of dependence. This approach is done time step by time step (dynamically), in contrast to other traditional approaches.

2.3.1. Stage 1. Traditional Time Analysis

First, a traditional time analysis, which mainly comprised basic statistics parameters, such as mean, standard deviation and variation and skewness coefficients, and a temporal correlation analysis through correlograms, was performed.

2.3.2. Stage 2. ARMA Model Building

It is well known that an Autoregressive Moving Average (ARMA) (p,q) is the extension of the AR model that uses two components to model the temporal correlation in time series.

An ARMA model comprises two components. The first component (p) is the autoregressive (AR) that uses a number of series delays. Consequently, p is the first term of an ARMA equation and represents the temporal dependence delay within a series. For instance, an annual series with $p = 2$ means that there are 2 years of temporal dependence. In other words, data depend on what happened up to 2 years earlier. The second component is the term (q) moving average (MA) that uses delays of the forecast errors to improve this process. Finally, an ARMA model is expressed as follows:

$$y_t = \mu + \sum_{j=1}^{p} \theta_j \left(y_{t-j} - \mu\right) + \varepsilon_t - \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} \tag{4}$$

where μ is the mean of the time series, θ represents the correlation coefficient, y_t is the value of the temporal series at a certain time step j, q is the number of time steps and ε_t represents the historical residuals.

Generally, hydrological data are characterized by biased probability distributions that need to be normalized [26], because ARMA models assume Gaussian distributions for their variables [8,25]. This is made by normalizing functions but this is not enough to guarantee the normality. For this reason, and according to [25] (p. 93), the skewness test for normality was developed. The Skewness Coefficient test was applied to the historical series and both series (Adaja and Porma) show positive a skewness coefficient, outside the Snedecor and Cochran limits, for a confidence level of 95%, (the Adaja sub-basin: $1.23 \notin [-0.56, 0.56]$, the Porma sub-basin $0.98 \notin [-0.75, 0.75]$). Consequently, this test is negative which means that both series are not normal and they should be normalized for generating the ARMA models.

In order to take advantage of the BNs' analytical potential, the generation of synthetic series were developed through a parsimonious ARMA (1,1) model. Given that BNs building requires that variables are connected consecutively, the analysis with the ARMA (1,1) model is appropriate because it is developed with the highest freedom degree. Thus, relationships among variables are not previously conditioned ("p" part of the ARMA model). Synthetic series were generated according to the general framework of [25]. All synthetic series have the same length as the historical records for each sub-basin. In order to avoid the boundary effect within ARMA modelling technical jargon, this generation process is called "non-conditioned", in which a warm-up period of 20 years was established for both sub-basins.

The quality of the synthetic data generated by the ARMA models was assessed. This was done through the Kolmogorov–Smirnov–Lilliefors correction test, where goodness of fit between historical data and synthetic data was checked [59,60].

2.3.3. Stage 3. Bayesian Networks Building

The Bayesian approach is populated and trained from 200 synthetic annual runoff series that were previously generated through an ARMA model. The BN model automatically generates probabilistic distributions of runoff data for each year, as well as a logic structure, according to its internal dependences relationships (dependences and independences) in the data. This was done through Learning Wizard of HUGIN Expert (V 7.3).

This stage was started by building the logic structure that represents the complex temporal dependences between time steps (years) which are the decision variables within the BN. The dependence between consecutive years (Time Steps) seems obvious but the identification and assessment of time order dependences larger than one (non-consecutive years) is less trivial (Figure 3).

The logic structure is largely driven by the fact that each decision variable is assigned to each year of the respective data series. In this sense, BNs models comprise a set of variables, covering the whole period of the temporal series that interact year by year. The partition for every single variable was based on five intervals with the same range. Thus, Bayes's theorem is propagated over time, using the conditional probability and calculating probability distributions for each year.

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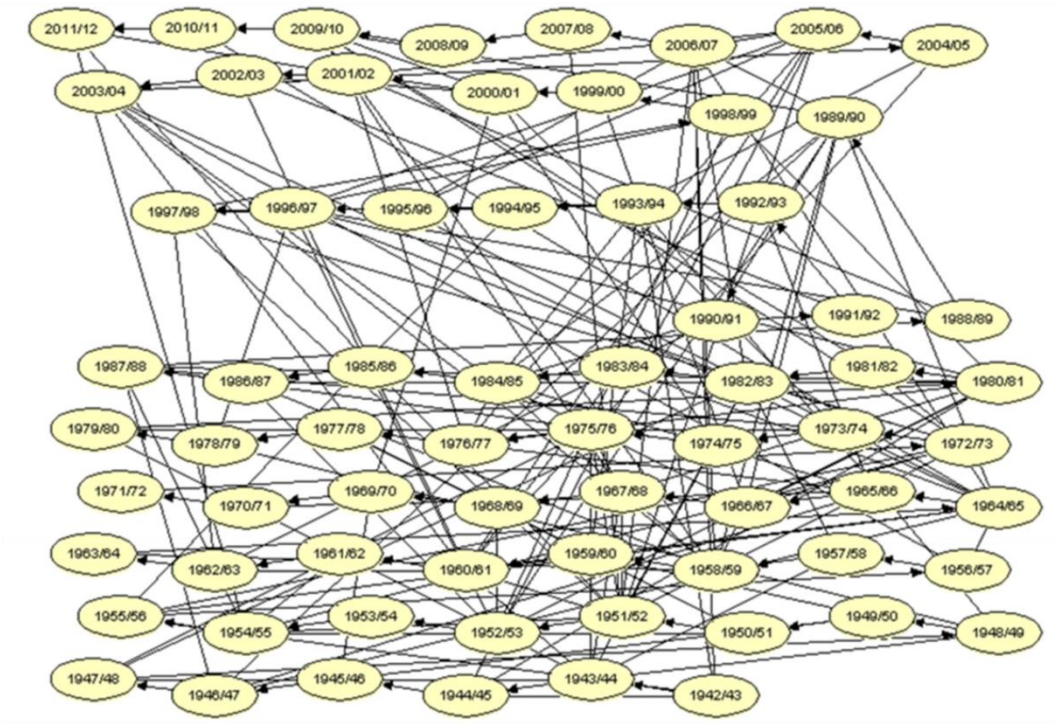
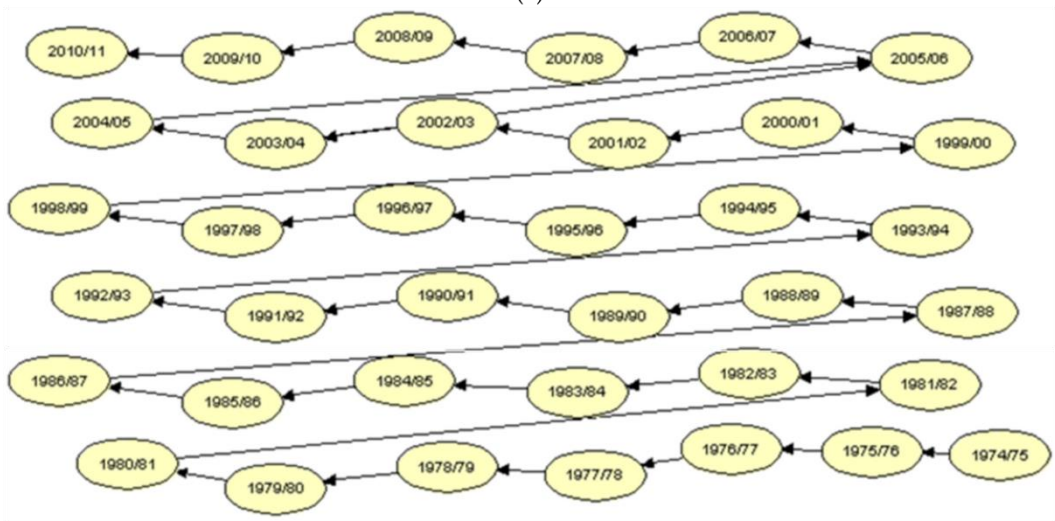


(**a**)



(**b**)

Figure 3. Bayesian Network Logic structure. (**a**) Adaja sub-basin; (**b**) Porma sub-basin. Note: Threshold level of independence (*p*-value) 0.10 (up to 10% of relationships of independence between decision variables are shown).

Figure 3 shows the logic structure for both basins where the noticeable independent nature of Adaja river basin's temporal behavior is represented through the relationships among variables. Each arrow connecting non-consecutive years represents an independent relationship measured by a *p*-value. The *p*-value threshold is set at 0.1 which means that up to 10% of relationships of independence between decision variables are shown. It can also be seen that the complexity of independence connections is much higher for the Adaja sub-basin (a) than for the Porma sub-basin (b) for the same *p*-value threshold.

3. Results

3.1. Traditional Time Analysis and Synthetic Series Prior Analyses

Figure 4a,b shows the main results drawn from the descriptive statistical analysis (Stage 1). This comprises a basic and prior stage for the subsequent BN development and analysis.

In the case of the Adaja sub-basin, all analyzed correlation coefficients (r_k = 1 to 13) are within Anderson limits which means that the series has a pure independent and continuous temporal behavior. In contrast, the Porma sub-basin correlation coefficients for certain time orders (lags) are outside Anderson limits which comprise variable or discontinuous dependence/independence behavior. The first lag interval reaches time lag 2, and it comprises a dependent behavior in the short term. Following lags (interval 5 to 9 and 13), shows a dependent and discontinuous behavior in the medium term. Both temporal behaviors should not be taken absolutely because the dependence/independence analysis through correlograms provides an average behavior and static analysis.

It is remarkable that the ARMA model preserved the main features of the historical series, such as mean and standard deviation (see Table 1 and Figure 5). In order to analyze the goodness of fit of historical series and each synthetic series, a Kolmogorov–Smirnov–Lilliefors was developed. This test shows a very high goodness of fit. Furthermore, correlation coefficients of synthetic series preserve the same nature, regarding the temporal behavior, as the ones for historical series.

Table 1. Porma Sub-basin. (**a**) Goodness of fit results of synthetic series vs historical series made by Lilliefors corrected Kolmogorov–Smirnov test. Note: Test significance level (α) 5% (p-value). (*) Lilliefors significance correction. ** Lower bound of the true significance; (**b**) Autoregressive Moving Average Model (ARMA) models.

(a)	**Porma Sub-Basins. Synthetic Series**							
Synthetic annual runoff series	**01**	**02**	**07**	**18**	**27**	**62**	**94**	**104**
Test Statistic	0.102	0.099	0.098	0.098	0.094	0.085	0.139	0.144
Asymp. Sig (2-tailed), *p*-value (*)	0.200 **	0.200 **	0.200 **	0.200 **	0.200 **	0.200 **	0.069	0.052
Synthetic annual runoff series	**145**	**152**	**161**	**181**	**192**	**196**	**197**	**200**
Test Statistic	0.101	0.139	0.101	0.126	0.139	0.072	0.103	0.115
Asymp. Sig (2-tailed), *p*-value (*)	0.200 **	0.069	0.200 **	0.147	0.069	0.200 **	0.200 **	0.200 **
(b)	**Porma Sub-Basins. ARMA Models**							
Annual runoff series	**01**	**02**	**07**	**18**	**27**	**62**	**94**	**104**
Mean	173.85	186.84	205.07	182.69	169.84	243.98	203.08	223.99
Standard deviation	44.05	60.03	62.94	59.75	71.36	82.29	71.65	110.60
Skewness Coefficient	1.09	0.77	0.83	1.00	1.09	0.99	0.79	1.65
Annual runoff series	**145**	**152**	**161**	**181**	**192**	**196**	**197**	**200**
Mean	193.57	224.43	151.63	163.53	248.38	176.28	154.97	186.27
Standard deviation	49.51	101.10	50.49	63.23	105.83	83.20	53.64	75.93
Skewness Coefficient	0.86	0.96	0.99	0.91	1.30	0.80	0.89	1.21
	Average of All Annual Runoff Series					**Historical Records**		
Mean	192.59					191.29		
Standard deviation	74.66					80.92		
Skewness Coefficient	0.88					0.98		

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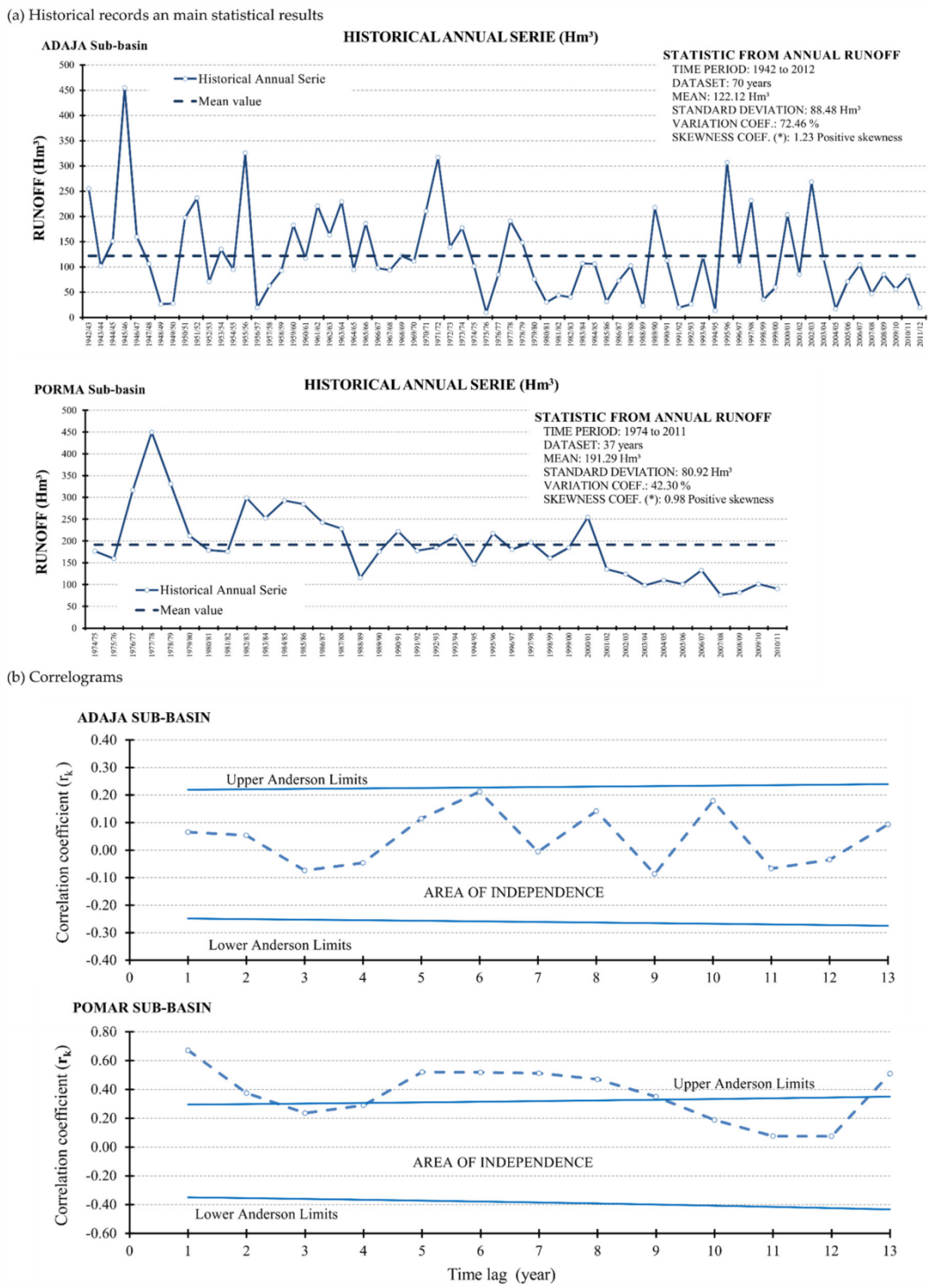

Figure 4. (**a**) Historical records and main statistical result (*) Classic Skewness Coefficient; (**b**) Correlograms that are generated from historical series. Probability limits at the 95% confidence level for an independent variable, according to Anderson limits methodology.

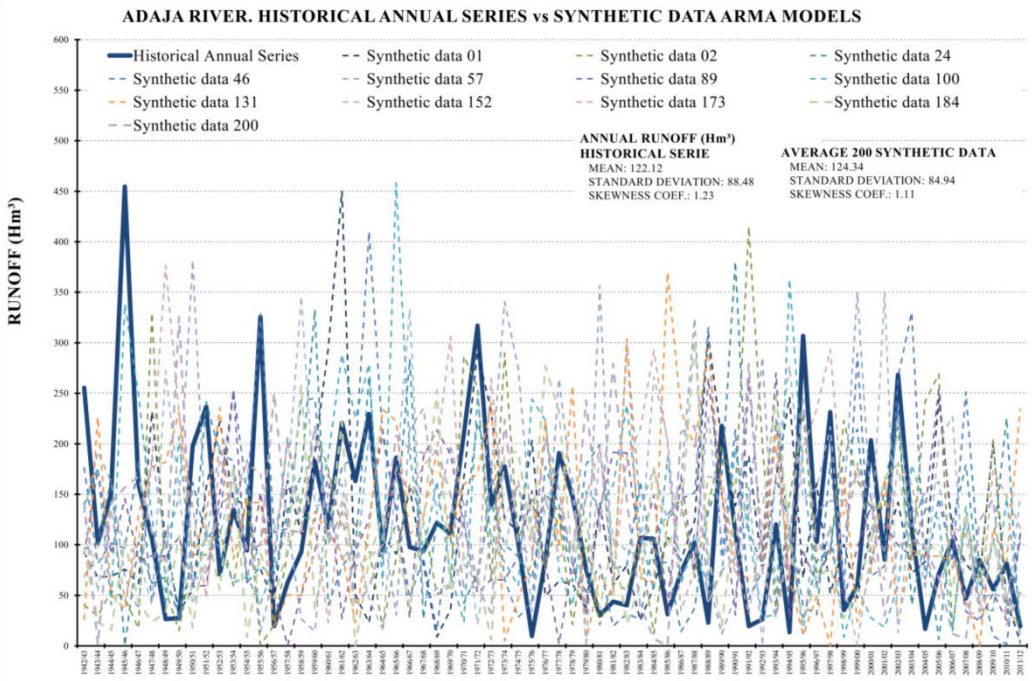

Figure 5. Adaja case study. Comparison of annual runoff synthetic series vs. historical record.

3.2. Hydrological Interpretation. Time Dependence Analysis

The temporal dependence analysis was developed through the relative percentage of runoff change estimation that a time step dynamically produces on the following ones. This was made in two ways. First, it was developed through the maximization of the highest interval of the probability distribution belonging to a year (Time Step) (Figure 6; maximization of the whole probability distribution); Second, it was developed by means of the analysis of the dependence propagation function (Figure 7; wrap-around MAX and MIN). In order to achieve a good understanding of this research methodology, results shown in Figure 7 should be seen as a whole, through the analysis of wrap-around MAX and MIN functions (wrap-around shapes).

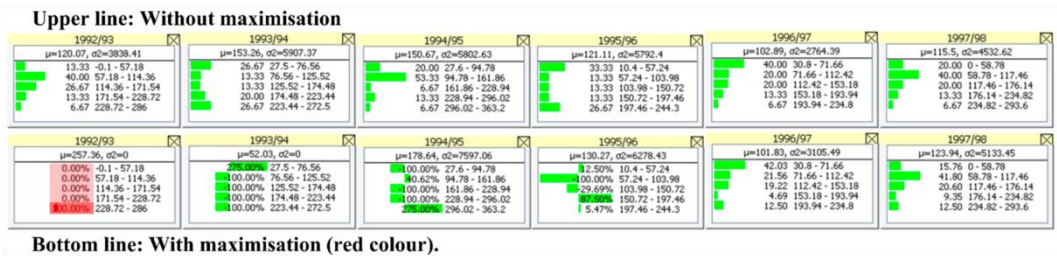

Figure 6. Output of BNs Simulation for the Adaja sub-basin (Max 1992/1993 year). Results expressed as relative percentage of change (dynamic and causal dependence) in intervals. Software: HUGIN Expert (V 7.3) [61].

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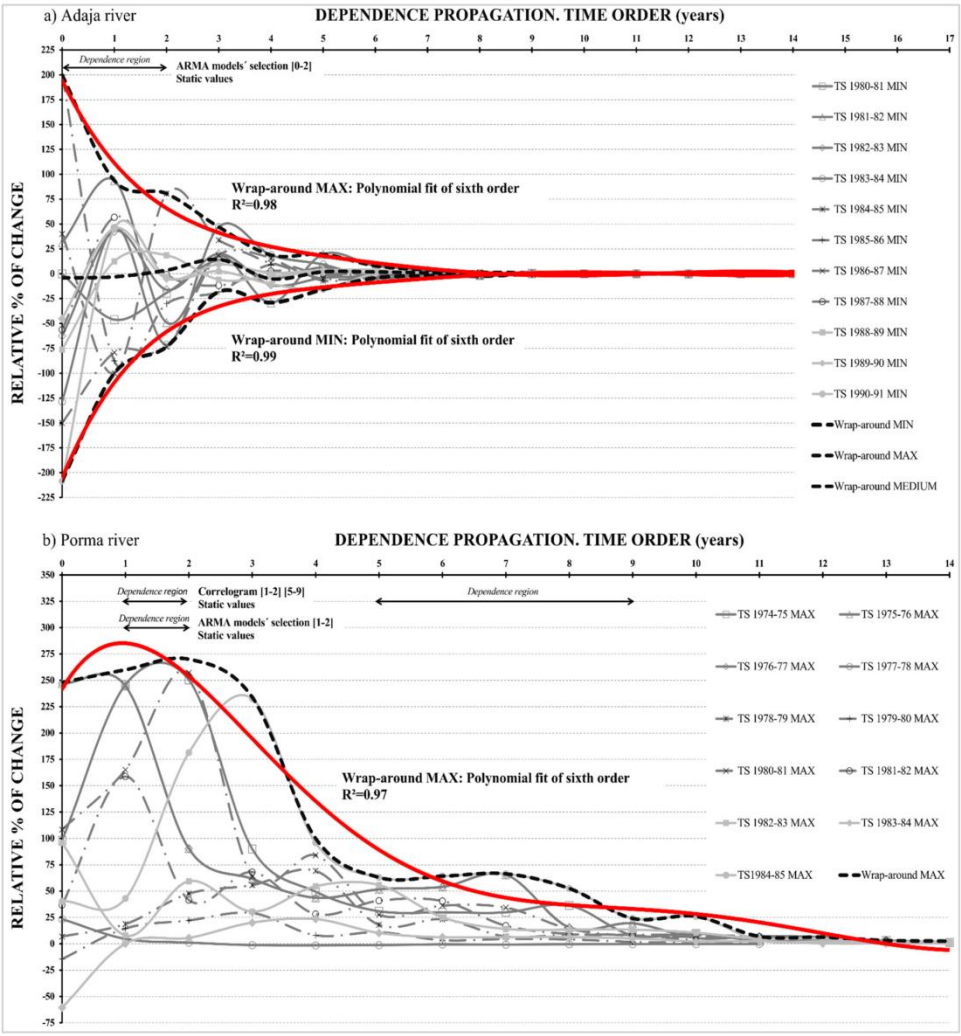

Figure 7. Temporal behavior results from the BN approach. (**a**) Adaja river; (**b**) Porma river. Note: Temporal dependence expressed as relative percentage of change.

3.2.1. Adaja River

In this case, the maximization of the highest intervals of probability distribution does not generate a logical or related impact on following years along the whole time period. This is demonstrated by the absence of a general common behavior or recognizable pattern on the influence that different time steps apply on the following ones (Figure 6). Therefore, time dependence analysis shows a pure independent temporal behavior.

On the other hand, as can be appreciated in Figure 7a, an analysis of the propagation function of dependence shows two wrap-around results. Here, the area under the wrap-around MAX (positive area) and the area above the wrap-around MIN (negative area) is essentially compensated (symmetric graph), which gives a total result of null temporal dependence. Furthermore, it is worth emphasizing that:

- Resulting symmetry on the shapes of wrap-around MAX and MIN practically coincides with the x-axis.
- Both wrap-around MAX and MIN tend (or decay) to zero rapidly (Figure 7a).

- There exists a very high goodness of fit of the shapes' MAX and MIN of 0.98 and 0.99 respectively, measured by coefficient of determination R^2.
- This fit corresponds to a sixth order function for all time steps.

In this sense, the dynamic analysis of the dependence propagation (Figures 6 and 7a) leads to an interpretation of the independent temporal behavior of time series which is from the beginning and is continuous. In contrast, the analysis carried out by the correlograms (Figure 4b) shows some cases (time lags 6 and 10) where the *rk* is very close to the limit and it can provide some doubts on the independent nature of the river basin. This different performance is due to the average result that the correlograms provide, in contrast to the dynamic and specific analysis that the BN provides.

3.2.2. Porma River

In this case, there is a non-insignificant variability on the change (dependence) that a particular time step applies on the following ones. According to the BN approach, dependence Time Order is placed in the range or region from 1 to 5 in the short-term (Figure 7b). The asymptotic behavior of the dependence over time is also remarkable. Here, the attenuation and convergence of all series in 0 takes place in a much longer time period than the previous case (Adaja river). This behavior of the time series could indicate an influence in the medium term.

Figure 7b shows that the wrap-around MAX (positive area) is clearly dominant, in contrast to the negative area which is practically null. Consequently, the distribution between positive and negative areas is not balanced (asymmetric graph). Furthermore, the shape and the high goodness of fit (R^2 = 0.97) of the wrap-around MAX (sixth order) for all time steps (Figure 7b) is significant. This shape is very representative of the general behavior of the analysis and it is the mathematical way to quantify and define the dependence. The fact that the dependence decay (mitigation) is not continuous (Figure 7b) is also remarkable. The dependence persistence and decay (mitigation) can be also observed in Figure 7b by analyzing the dependence behavior over time. In this sense, all series converge in 0 (*y*-axis), providing a very detailed way for the analysis of the dependence persistence-mitigation in the medium-term (13 years). A double dependence behavior can be clearly seen. Firstly, a continuous and rapid decay of dependence (or dependence mitigation from time order [1,2] up to time order 5. Secondly, a slight increase begins from time order 5 that smoothly concludes in time order 13. This continuous and differentiated behavior (from 1 up to 13) may indicate a temporal dependence, persistent in the short and medium term, which is not detected by a correlogram (see Figure 4b, independent behavior in the intervals [3,4] and [10–12]). However, in a correlogam, there is also a lag (Time order) range where dependence raises between lags 5 and 9, as shown in Figure 4b, that noticeably coincides with a slight raise in dependence analysis though the BN approach (Figure 7b).

On the other hand, in this case study, there are also two points of indeterminacy in the correlograms analysis. The first one is for time lag 4 and the second one for time lag 9. In both of them, the indeterminacy may be caused by the same aforementioned reasons as in the Adaja case study. The analysis of dependence propagation removes these indeterminacy points, improving and deepening the knowledge of temporal behavior of a hydrological series.

3.3. Time Order (Model Orden) Suitability Analysis

A suitability analysis of different time orders' ARMA models was done by means of Risk Simulator software [57]. This should be taken as another way of validating the calculated results via BN models. Table 2 shows the main results for each case study. Furthermore, Table 3 summarizes the time order suitability analysis from the different techniques. The ARMA models' selection through Risk Simulator software agrees with the BNs' approach results. In this sense, for the Adaja sub-basin, the ARMA model that best fits the indicates that the temporal basin behavior is independent. In fact, the ARMA model that fits better is ARMA (0,1). On the other hand, for the Porma river basin, this analysis provides a selection of models where the right time order is around 2, which coincides with the

analysis from the BN in the short term. Due to the aforementioned technical reasons and to the fact of letting the temporal analysis have the maximum freedom, decision variables should be connected consecutively in BN building. Consequently, the ARMA models built for Adaja and Porma rivers were ARMA (1,1). Temporal behavior of the runoff series in the medium term cannot be validated through ARMA models' selection. Consequently, in order to analyze the internal coherence of temporal behavior in the medium term, an analysis of all series for each river basin was developed. As more equiprobable data series are available, this analysis becomes a more useful way to check the internal coherence of a temporal behavior data series.

Table 2 shows a summary of the results (temporal dependence behavior) obtained from all applied techniques.

Table 2. Suitability identification of time order through ARMA modelling. Note: Results ordered according to Schwarz Criteria.

Sub-Basins	ARMA Model	Schwarz Criteria	Akaike Information Criteria
Adaja	$p = 0, q = 1$	11.792	11.669
	$p = 1, q = 1$	11.981	11.795
	$p = 2, q = 0$	12.083	11.895
	$p = 1, q = 0$	12.245	12.121
	$p = 0, q = 2$	12.580	12.394
	$p = 2, q = 0$	12.764	12.573
Porma	$p = 2, q = 0$	11.025	10.720
	$p = 0, q = 2$	11.026	10.733
	$p = 2, q = 2$	11.206	10.698
	$p = 1, q = 0$	11.224	11.025
	$p = 1, q = 1$	11.308	11.010

Table 3. Comparison of time order suitability analysis from applied techniques. (*) Static (**) Dynamic.

Sub-Basins	Technique		
	Correlogram (*)	BNs (**)	Suitability Analysis. "p" Part of ARMA Models (*)
Adaja	Full independent	0 (Independent)	[0–2] (*)
Porma	[1–2] and [5–9] Discontinuous dependent behavior	[0–13] Continuous dependent behavior	[1–2] (*) Particular dependent behavior

3.4. Consistency and Quality Assessment of the BNs Model and Its Analysis

After developing the model's structure, estimating the conditional probabilities and getting the results, the BN and its analysis needs to be evaluated. Given that this is a pure quantitative BN model, its evaluation should include assessments of predictive accuracy and sensitivity analysis. Predictive accuracy refers to a quantitative evaluation of the model, by comparing model predictions with observed data [62].

Capturing and reproducing the real behavior patterns of temporal hydrological series is a crucial issue for prediction. This was developed by means of the comparison of the results drawn from BNs versus raw runoff observed data, directly drawn from gauging stations. Thus, the internal consistency and quality of this causal analysis is tested in the short and medium term. Figure 8 shows the results for Porma river. In order to obtain comparable information between both ways, probabilistic distributions were converted into deterministic data by means of multiplying the dependence among variables $(1 - p_{value})$ by the corresponding historical value (datum from gauge station).

This is expressed in general terms as:

$$[Deterministic_{value}]_{t\ lag\ y}^{t\ lag_{y-n}} = [(1 - p_{value})]_{t\ lag_i}^{t\ lag_{i-n}} \cdot HS \quad (5)$$

where $(1 - p_{value})$ is the dependence rate, HS is the historical value, y represents the considered year, and n is the number of years from the year used to calculate the series' beginning.

The fact that this method is able to reproduce so accurately a single time series, after raw gauge stations data had passed through several stages (basic statistic study, generation of synthetic series through ARMA model and generation of BN model), makes the whole approach much more robust and reliable as well as validating the whole process.

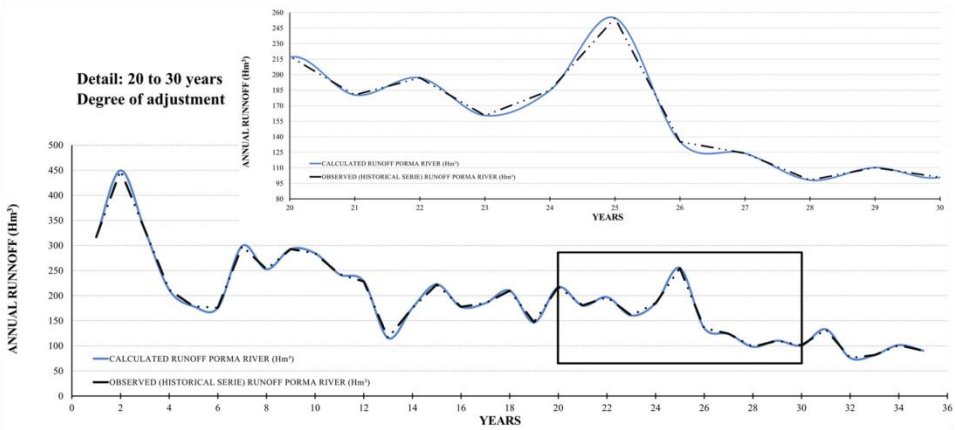

Figure 8. Predictive accuracy test of the temporal behavior by BNs. BN (calculated) vs. Historical runoff series (Observed).

Sensitivity analysis can be performed using two types of measures: entropy and Shannon's measure of mutual information [50]. The entropy measure is based on the assumption that the uncertainty or randomness of a variable X, characterized by probability distribution $P(x)$, can be represented by the entropy function $H(X)$:

$$H(X) = -\sum_{x \notin X} P(x) \, logP(x) \tag{6}$$

Entropy of a probability distribution can be defined as a measure of the associated uncertainty to that random process that this distribution describes. Consequently, a score of the uncertainty/certainty level of events can be made attending to this entropy, $H(X)$.

Reducing $H(X)$ by collecting information, in addition to the current knowledge about the variable X, is interpreted as reducing the uncertainty about the true state of X [63]. The entropy measure therefore enables an assessment of the additional information required to specify a particular alternative. Shannon's measure of mutual information is used to assess the effect of collecting information about one variable (Y) on reducing the total uncertainty about variable X, using:

$$I(Y.X) = H(Y) - H(Y \mid X) \tag{7}$$

where $I(Y.X)$ is the mutual information between variables. This measure reports the expected degree to which the joint probability of X and Y diverges from what it would be if X were independent of Y. If $I(Y.X) = 0$, X and Y are mutually independent [50].

$H(Y \mid X)$ is conditional entropy which means the uncertainty that remains about Y, when X is known to be x.

This has been very useful in this research because the temporal dependence analysis, shown in Figure 7 (Section 3.2), has been satisfactorily compared with this analysis. The fact that two variables, that represent the annual runoff of two years, have a mutual information $\neq 0$ shows that they are dependent [50]. On the contrary, in that case that the mutual information is 0, they are independent. This analysis represents another way for characterizing and quantifying the temporal dependence and behavior of a hydrological series.

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An assessment of the entropy associated to each variable, the conditional entropy and mutual information for each variable and connection were developed for Adaja and Porma rivers using HUGIN expert software (Figure 9). This analysis reasonably agrees with the analysis and results interpretation developed in Section 3.2. Thus, Porma river presents around 13–14 years (time lag) where mutual information is not cero and consequently, variables are, to some extent, dependent. The fact that this time lag coincides with the dependence temporal analysis shown in Figure 7 is remarkable. For the Adaja river basin, this analysis also coincides with the previous analysis and the time lag of non-null mutual information is around 9 years. It is important to make clear that, given the extremely low values of the mutual information for the Adaja river basin, this result does not invalidate the conclusion about its independent nature.

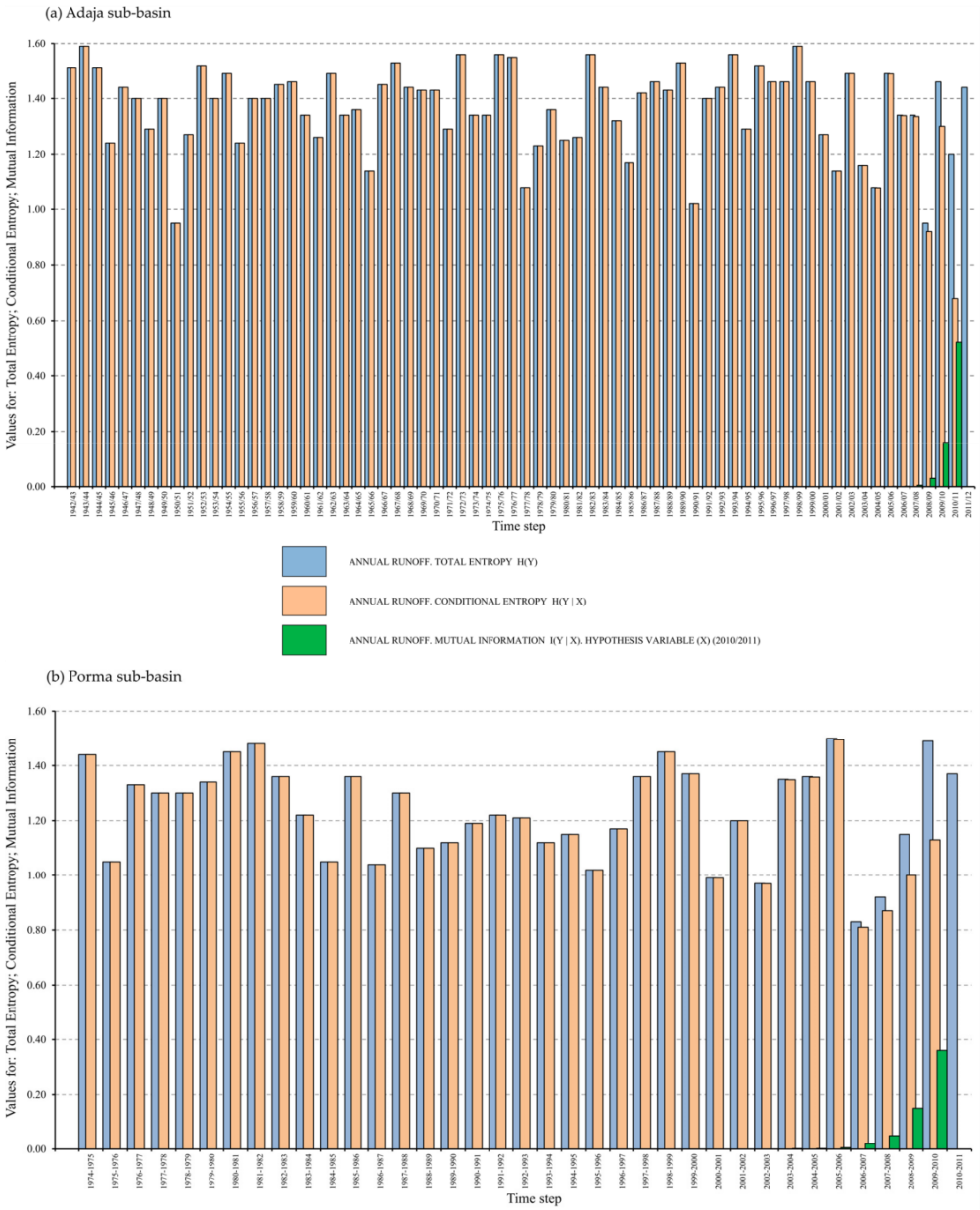

Figure 9. Sensitivity analysis of the BN model and analysis: Entropy, Conditional Entropy and Mutual Information. (**a**) Adaja sub-basin; (**b**) Porma sub-basin.

A sensitivity analysis of this BN is made by means of the assessment of Total Entropy, which, in turn, is the summation of Mutual Information and Conditional Entropy (Figure 9). If two variables that represent the annual runoff of two years have a mutual information = 0, they are independent. In other words, they are not temporally connected. On the contrary, if the mutual information is $\neq 0$, this means that they are dependent. In Figure 9, blue bars represent the value for Total Entropy, orange bars represent the value for Conditional Entropy and green bars represent the value for Mutual Information. Notice that those time steps that are independent have the same value for Total Entropy and Conditional Entropy, and the value for Mutual information is cero. On the other hand, when there is some dependence between time steps, there is a non-null value for mutual information.

4. Discussion and Conclusions

Causality and conditional probability has been demonstrated in this research to be very useful in the analysis of the temporal behavior of runoff series. According to the new tendencies on hydrological research, BNs can be hybridized or coupled with traditional techniques, providing the engineer and scientist with robust and powerful tools. Due to the aforementioned BNs' properties, this technique can be categorized within the Artificial Intelligent discipline.

Traditional techniques such as a correlogram, PM and NP models have been extensively used over the last decades. The application of BNs for hydrological temporal analysis has been demonstrated to be suitable due to the following reasons. First, the inherent uncertainty/randomness of hydrological processes is well captured and assessed by this technique, because apart from the definition of probability distributions with their basic statistics, several tests (Entropy, Mutual Information, Conditional Entropy, p-value, $1 - p_{value}$), belonging to Information Theory, can be applied; second, the dynamic nature of temporal analysis is properly incorporated because of the flexibility and modularity of BNs; and finally, recent observed increasing variability in hydrological patterns could be much more properly analyzed and incorporated through BNs because the real knowledge increases.

Furthermore, another advantage is the fact that BNs' application does not require that the relationships between model variables are defined mathematically before establishing the analysis. BNs, through Bayesian observational inference via the Bayesian theorem, calculate prior and posterior probability functions. This advantage ensures that the performance working with non-stationary hydrological time series is much more accurate.

On the other hand, it is known that a correlogram comprises a static picture and average result of the temporal behavior of a hydrological series. This fact provokes the existence of indeterminacy points when it comes to defining the temporal dependence/independence of time series (see Section 3.1 and Figure 4b). In this sense, BNs have allowed, by means of the dynamic and specific analysis of the temporal dependences, time step by time step, the removal of this indeterminacy (Figure 4b). This is possible because the attention can be focused on a particular time step and this provides a more accurate analysis. Furthermore, the dynamic analysis that causal reasoning delivers allows quantifying and establishing thresholds of dependence relationships (Figure 3).

Furthermore, the BNs' application has allowed the detection of non-trivial dependence relationships (time lag >1). Also, the analytical potential of BNs has been demonstrated when the functions for propagation of the dependence were defined (Figure 7). Consequently, from parsimonious and non-conditioned ARMA (1,1) models that populated and trained the BNs, dependence of relationships was detected in the short and medium term.

Causality and conditional probability through BNs is aimed here to assess the influence of time (time step) on the rest of the time series (rest of time steps). Therefore, every year (time step) becomes a decision variable into the BNs system. It is remarkable that, within the BN, a little change in the probabilities of runoff can condition or affect a great runoff volume, corresponding to following years. This is very useful and novel because it allows the assessment of the dependence persistence and/or the dependence propagation (mitigation or attenuation) of a series, by means of analyzing the intensity of probability propagation. Likewise, it is possible to assess the dependence of one time step on the

previous ones through the back-probability propagation, in other words, past information will provide prior knowledge of the future.

Consequently, this pure quantitative BN model becomes a predictive model for forecasting purposes. Its evaluation includes assessments of predictive accuracy and sensitivity analysis. Predictive accuracy refers to a quantitative evaluation of the model, by comparing model predictions with observed data. On the other hand, sensitivity analysis was carried out through the assessment of the Entropy and Mutual information of each decision variable. Thus, the internal consistency and quality of this causal analysis is tested.

It is also necessary to remark the reasonable coherence in the short-term between time orders obtained from a correlogram, suitability analysis via ARMA models and the one obtained through BNs. Additionally, the main contribution of this approach is that it allows the assessment of the temporal dependence in the medium term. This is an innovation over traditional techniques where the short term can be assessed by means of a correlogram and ARMA models, and the long term can be evaluated through Hurst coefficient.

Dependence quantification is a concept that has not been sufficiently studied. It is well known that a correlogram provides an idea of temporal dependence intensity through the correlation coefficient. However, it seems necessary to have tools that allow the quantification of that dependence more accurately. Causal reasoning through BNs allows the quantification of that dependence for every single time step of a hydrological series. In this sense, upcoming research studies will aim to provide a sort of indicator of the rate of dependence for different river basins. Of course, this rate will be dynamic as it will change as the series develops over time. This dependence rate might be expressed in Hm^3 units for annual runoff series. Consequently, this could provide a useful technique, primarily for water management, because it would improve the knowledge on the water resources' availability in a river basin. Furthermore, it would generate more accurate information in order to achieve a better planning and dimensioning of water infrastructures, especially in unregulated rivers, for instance, in the optimization of reservoir operation rules. All of this would lead to defining more realistic water management scenarios. Future research lines will also aim to generate stochastic forecast or predictive models through identifying and quantifying patterns of change, as well as identifying and solving the functions that drive the dependence of a certain series, considering the uncertainty.

Integrated and sustainable water management demands approaches such as causal reasoning-BNs that improve existing knowledge and enhance the analytic capacity.

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CAPÍTULO III

La Visión Artificial al servicio de la modelización hidráulica y la hidrodinámica

III.1 PUBLICACIÓN CIENTÍFICA II

Este apartado contiene el artículo científico titulado *"Analysis of flood modeling through innovative geomatic methods"*, publicado en la revista científica de alto factor de impacto *Journal of Hydrology* (ISSN: 0022-1694) en Marzo de 2015.

Resumen

Una correcta evaluación y gestión del nivel de exposición ante los riesgos naturales frente a inundaciones implica, necesariamente, un exhaustivo conocimiento del terreno susceptible de ser afectado. Resulta crucial disponer de una correcta representación de esa realidad inundable, a través de continuos, detallados y precisos Modelos Digitales de Elevación (DEM), dado su influencia para una correcta modelización fluvial.

El objetivo principal de esta investigación ha sido evaluar la idoneidad de una innovadora técnica, denominada Fotogrametría Aérea de Precisión de Coste Reducido (RC-APP, por sus siglas en inglés, *Reduced Cost Aerial Precision Photogrammetry*), basada en la utilización de plataformas aéreas ligeras-alternativas del tipo ULM (siglas en inglés de *Ultra Light Motor*, o ultraligero motorizado de poco peso, baja velocidad y apto para el vuelo tripulado) para la adquisición de información geoespacial mediante la hibridación de sensores de coste reducido. La aplicación de esta técnica ha permitido generar productos geomáticos detalladas y precisos, en tiempo y coste, de aplicación en la Ingeniería Fluvial para el modelado geométrico y en la evaluación del riesgo de inundaciones. En concreto, se han obtenido ortoimágenes de alta resolución espacial (2,5 cm), DEM con un tamaño de malla de 0,10 m de resolución y una alta densidad de puntos (del orden de 100 puntos/m², especialmente interesante para su aplicación en softwares de simulación hidráulica 2D), que han servido como base para una posterior simulación hidráulicas que ha permitido mejorar la definición de la zona inundable, con las importantes implicaciones que esto tiene a nivel de la evaluación y gestión del riesgo natural frente a inundaciones.

Por otro lado, a la hora de evaluar la incertidumbre del modelo geométrico resultante, se ha aplicado un nuevo enfoque, desde un punto de vista metrológico, mediante una evaluación Tipo A de la incertidumbre altimétrica, con el fin de valorar la componente estrictamente métrica de la incertidumbre asociada a la modelización de la inundación. En este sentido se ha obtenido una precisión altimétrica de (-0,02 ± 0,03) m.

De acuerdo con los resultados de la investigación, la metodología desarrollada y la tecnología aplicada han permitido una mayor precisión en la representación del cauce, frente a técnicas comúnmente aplicadas en el ámbito fluvial como el LiDAR (*Light Detection and Ranging*). En este sentido, la comparación de resultados llevada a cabo entre la modelización de las inundaciones mediante ambas técnicas ha revelado que la técnica RC-APP ofrece una representación más detallada que la obtenida mediante metodología LiDAR.

Por tanto la técnica RC-APP se muestra como una eficiente y apropiada herramienta de especial aplicación en áreas con un alto riesgo de inundaciones naturales. A nivel hidráulico, el grado de detalle alcanzado en el modelo 3D, ha permitido alcanzar un incremento significativo en el conocimiento de las variables hidráulicas en cauces naturales.

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Analysis of flood modeling through innovative geomatic methods

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SUMMARY

A suitable assessment and management of the exposure level to natural flood risks necessarily requires an exhaustive knowledge of the terrain. This study, primarily aimed to evaluate flood risk, firstly assesses the suitability of an innovative technique, called Reduced Cost Aerial Precision Photogrammetry (RC-APP), based on a motorized technology ultra-light aircraft ULM (Ultra-Light Motor), together with the hybridization of reduced costs sensors, for the acquisition of geospatial information. Consequently, this research generates the RC-APP technique which is found to be a more accurate–precise, economical and less time consuming geomatic product. This technique is applied in river engineering for the geometric modeling and risk assessment to floods. Through the application of RC-APP, a high spatial resolution image (orthophoto of 2.5 cm), and a Digital Elevation Model (DEM) of 0.10 m mesh size and high density points (about 100 points/m^2), with altimetric accuracy of −0.02 ± 0.03 m have been obtained. These products have provided a detailed knowledge of the terrain, afterward used for the hydraulic simulation which has allowed a better definition of the inundated area, with important implications for flood risk assessment and management. In this sense, it should be noted that the achieved spatial resolution of DEM is 0.10 m which is especially interesting and useful in hydraulic simulations through 2D software. According to the results, the developed methodology and technology allows for a more accurate riverbed representation, compared with other traditional techniques such as Light Detection and Ranging (LiDAR), with a Root-Mean-Square Error (RMSE ± 0.50 m). This comparison has revealed that RC-APP has one lower magnitude order of error than the LiDAR method. Consequently, this technique arises as an efficient and appropriate tool, especially in areas with high exposure to risk of flooding. In hydraulic terms, the degree of detail achieved in the 3D model, has allowed reaching a significant increase in the knowledge of hydraulic variables in natural waterways.

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1. Introduction

The availability of surface water in terms of quality, reliability and safety to people, properties and dependent productive activities, is crucial to any society. There is some consensus in the scientific community that achieving this is only possible through a sustainable resource use within an integrated exploitation framework. This is the international paradigm of performance and analysis of water studies, known as "Integrated Water Resources Management" (IWRM) (Molina et al., 2013).

The reality of climate change, expressed in terms of occurrence of extreme hydrological events, produces a stronger pressure on water resources systems (Chávez Jiménez, 2012; Molina et al., 2013) and the physical environment (Ashley et al., 2005). Consequences on the terrain are slowly conducting the society to take effective protective and adaptive interventions (EU Directive, 2007; Zechner et al., 2011). Most of these interactions are being currently studied in research through non-structural actions (Escuder-Bueno et al., 2012). For that, the decision making on water resources management should include economic considerations, involving the search for a maximum efficiency in the analysis and design of solutions (Sayers et al., 2002). Given this situation, it becomes necessary to have a set of efficient and flexible tools, techniques and methodologies, to facilitate the process of decision making and solutions design.

For a correct assessment of exposure level to natural flood risks is crucial obtaining a detailed-accurate reconstruction of the terrain susceptible to be affected, which provides a proper inundation modeling. In Spain, floods are a natural disaster causing considerable damage, estimated to total about 800 million Euros per year (0.08% of GDP). According to the Consortium of secured property, in the period 1971–2012, 42.9% of the cases processed were due to flood damage, which have accounted for 60.3% of total compensation (MAGRAMA, 2014).

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Nowadays, data acquisition and generation of accurate and reliable geomatic products, in the field of fluvial hydraulics and hydrodynamics, was carried out with costly instrumentation, equipment and platforms (Bates et al., 2003; Garcia-Pintado et al., 2013; Horritt and Bates, 2001; Tsubaki and Fujita, 2010; Turner et al., 2013), requiring highly specialized work teams, with very rigid technical constraints that prolong the process of decision making.

Having data in a quick and accurate way is usually associated with a higher cost. On the contrary, lower cost is usually accompanied by low accuracy and less reliable representation of the terrain, which is directly transmitted to the analysis/risk assessment (Merwade et al., 2008b), and design solutions, with their subsequent economic implications.

However, the new paradigms of geomatic science, result of the progress achieved in the last three decades, provide the scientific and engineering community of a set of reduced cost and even low cost techniques and methodologies. This, directly impacts on more efficient use of economic resources affecting at public administrations and private corporations.

Some of the computer advances in geomatic materialize in aerial imagery processing software, characterized by friendly, sequential, and to some extent automated workflows. This enables non-geomatic expert's users, process their own dataset, configured as an efficient alternative, to the highly specialized professional photogrammetric software packages.

This case study is aimed to assess the suitability of hybrid low-cost sensors, embarked in alternative aerial platforms (lightweight, low speed and suitable for manned flight) of ULM type (Ultra-Light Motor). This, together with the innovative image processing software, gives some alternatives ways in the sphere of river engineering, applied to the modeling and analysis of flow and flood risk assessment. This innovative technique is called Reduced Cost Aerial Precision Photogrammetry (RC-APP).

2. State of the art

The modeling of flooding is characterized by the relationship between flow and physical environment. The surface flow is a physical phenomenon that presents a great randomness in frequency and magnitude, which makes it deterministically unpredictable. For a better assessment and prediction, stochastic models in form of probability (probabilistic distributions or functions) are used in rainfall-runoff modeling (Martínez and Salas, 2004; Ng and Panu, 2010) and, they are indirectly also subjects of this research. Since precipitation is practically pure random process, and physical environment also is random itself, this stochasticity is twofold. Furthermore, land uses and modifications of the terrain and vegetation cover are associated to seasonality. On the other hand, the terrain is the physical support or container of hydrological–hydraulic processes, where the hydrological cycle is related to the environment and humans (Andreu, 1993). The manifestation of the basin behavior related to the hydrological cycle is produced as runoff surface, or as flooding, when the carrying capacity of rivers or channels is exceeded, when hydrological extreme events occur or when infrastructure is not correctly designed.

Nowadays, there is a relative consensus among researchers and engineers on the knowledge of the physical and hydraulic surface hydrology principles, which has enabled water resources planning and management (Balairón Pérez, 2002; Biswas and Tortajada, 2003). However, it should not be overlooked that extreme events are becoming more recurrent over time and consequently, they are less anomalous events over the time. This brings serious consequences on water resources systems functioning (Bates et al., 2008; Estrela et al., 2012), surface hydrology (Dawson et al., 2005) and groundwater (Molina et al., 2013), which makes the climatic variables even more unpredictable, generating more uncertainty.

The accuracy in the definition of flooding is an essential factor, in cartographic and globally terms (Merwade et al., 2008b; Wechsler, 2007; Bales and Wagner, 2009; Jung and Merwade, 2012). The influence of the riverbed terrain and how it has been obtained should not be overlooked in the results of hydraulic simulations (Cook and Merwade, 2009). For this reason, the research is focused on the flooding from the perspective of the physical environment.

The variety of geomatic techniques for data acquisition in modeling flow sensors are exposed and detailed intensively in the study (Molina et al., 2014), where also the precision of each is indicated. In this sense, in the last 30 years, there has been a constant revolution consequence of hybridization between techniques and sensors, as an example the developments in LiDAR (Light Detection and Ranging) exposed in (Irish and White, 1998).

This degree of development has originated, in the last decades of the twentieth century, the appearance of Digital Photogrammetry (DP), as a discipline of geomatic science. DP is fully integrated into many scientists and technicians, such as civil engineering, building, energy, risk assessment, robotics, an even medicine. The main reason is that the photographic image can provide complete information about the object being studied, including metric level and having an image (Gonzalez-Aguilera and Gomez-Lahoz, 2008).

Technological advances in remote sensing and geomatic techniques, in the field of hydraulics and river engineering, are focused on the use of different type of images, mentioned as follows. High spatial resolution, Very High Resolution images (VHR imagery) of 5–10 cm spatial resolution (Lejot et al., 2007), LiDAR Digital Elevation Models (DEM), with nominal accuracies from ±0.15 m to ±0.25 m (Lane et al., 2003), classic surveying with accuracy of ±0.05 m (Prinos, 2008), the use of observations Synthetic Aperture Radar (SAR) as a source of calibration flood modeling (Horritt and Bates, 2001), and the use of innovative aerial platforms low flying height, Unmanned Aerial Vehicles (UAV) (Vallet et al., 2011), which allow high spatial resolutions, but have a set of limitations, technical and administrative described in (Hardin and Jensen, 2011; Watts et al., 2010). The temporary flight restriction penalizes its applicability in river studies as it is shown in (Ortega-Terol et al., 2014), with a study case length of 132 km.

In order to generate flood risk maps, the construction of continuous Digital Terrain Model (DTM) is essential. In this case, it is common the integration of geometric data from different sources (Prinos, 2008), such as Topographic and Bathymetric LiDAR, classic surveying, with different accuracies (Molina et al., 2014), and the combination of these, through grids (Raster/GRID) and Triangular Irregular Network (TIN) (Merwade et al., 2008b).

On the other hand, Geographic Information Systems (GIS) as a procedural and integrated tool, applied as a physical terrain support for modeling flows are fully seated in the scientific and engineering community, as seen in (Chen et al., 2009; Liu et al., 2014; Merwade et al., 2008a; Wiles and Levine, 2002). Likewise the combination of geomatic techniques and GIS, in the geometric study of riverbeds can be viewed in works such as (Bates and De Roo, 2000; Marcus and Fonstad, 2008). However, the majority of the work and studies have in common that the acquisition of geometric information is from aerial platforms and/or satellite with onboard sensors, in both cases, high cost (Bates and De Roo, 2000; Legleiter and Overstreet, 2012; Marcus and Fonstad, 2010). For example, an individual high spatial resolution satellite image, up to 0.25 m, could cost around € 7000 (Airbus Defense & Space and Infoterra SGSA, 2015), with a minimum area of 14.8 km^2 (4 × 3.7 km). This minimum area can be much higher than the one needed for the study case, and it may be possible to require more than one image, due to the specific characteristics of the sensor data acquisition protocol.

Furthermore, regarding technical resources, precisions, errors and limitations, this study is framed within a context of economic efficiency. The first goal is generating specific geomatic products of high accuracy (−0.02 ± 0.03) m, with a lower magnitude order or error than the usual methods. Consequently, this speeds up the process of data acquisition and decision making in the field of fluvial hydraulics with the minimum environmental impact and to be applied on large riverbeds surfaces and lengths, up to 130 km (Ortega-Terol et al., 2014).

At this point, it has been investigated the applicability of innovative MUSAS® (Multispectral Sensors Airborne System), operated in a platform of light flying, ULM type (tandem trike) and processed with photogrammetric software (an innovative application of this software in natural resources management field), aerial imagery, for the generation of orthophotos and 3D models of riverbeds. The MUSAS® platform can ship multiple sensors, acquiring data within different spectral regions (visible, infrared, thermal, ...), although in this study only the visible spectrum was used.

3. Case study

The study is aimed to apply simulations of stream flow and flood modeling for the analysis, assessment and defense against flooding (Tsakiris, 2014). For that, certain hydrological–geometrical specifications have been considered regarding flows through the central channel cross section.

The case study comprises a surface of 0.50 km^2, and a riverbed stretch length of 3.9 km. The area is nominated as "special interest" in the municipality of El Fresno (Fig. 1), located about 6.5 km upstream the city of Ávila in the province of Avila (Spain).

The study area is located in the Amblés Valley, Upper Basin of the Adaja River, SW of the city of Ávila, north of the Central System, in the northern Spanish plateau, where this stream comprises the main riverbed. This subsystem is integrated within the Duero River Basin (the largest basin in the Iberian Peninsula, in terms of surface).

The point of assessment for hydraulic flow simulations (X = 351829 m, Y = 4497706 m EPSG 25830) determines a watershed of 530 km^2 versus 740 km^2 of the total surface of the Upper Basin of the Adaja river.

In the analyzed stretch, on the right bank, the village center as well as basic municipal utilities (water, sanitation, electricity and telecommunications), sports facilities and recreational areas are located. Likewise, on the left bank, there are several farms and livestock, scattered buildings, and a bridge over the riverbed.

There is a range of altitudes, between 1500 m a.s.l and 1070 m a.s.l. As regards climate of the basin, this is characterized by a cold Mediterranean climate, high continental, with moderately warm summers and severe winters, where the altitude conditions the temperature, with a mean annual of 11 °C. Rainfall patterns are scarce and irregular, consequence of the Foehn effect, with an average annual value of about 400 mm.

4. Methodology

This research has a double fluvial hydraulic and geomatic component articulated in 4 stages, problem definition,

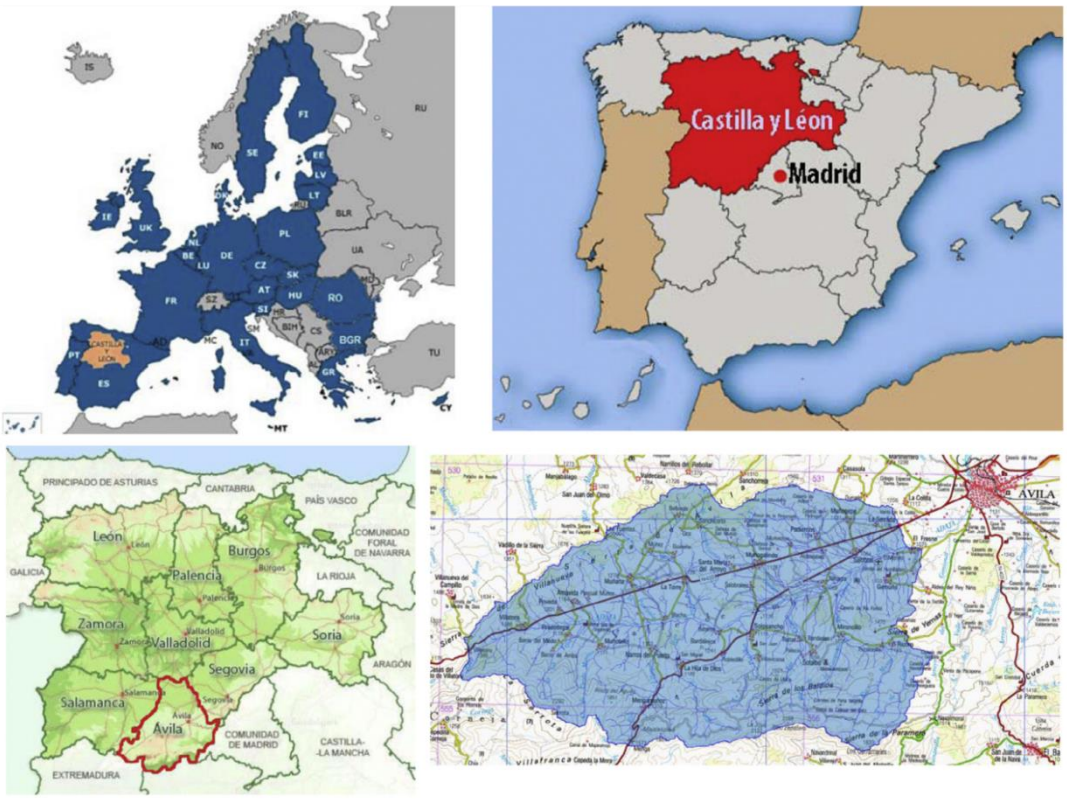

Fig. 1. Situation and basin.

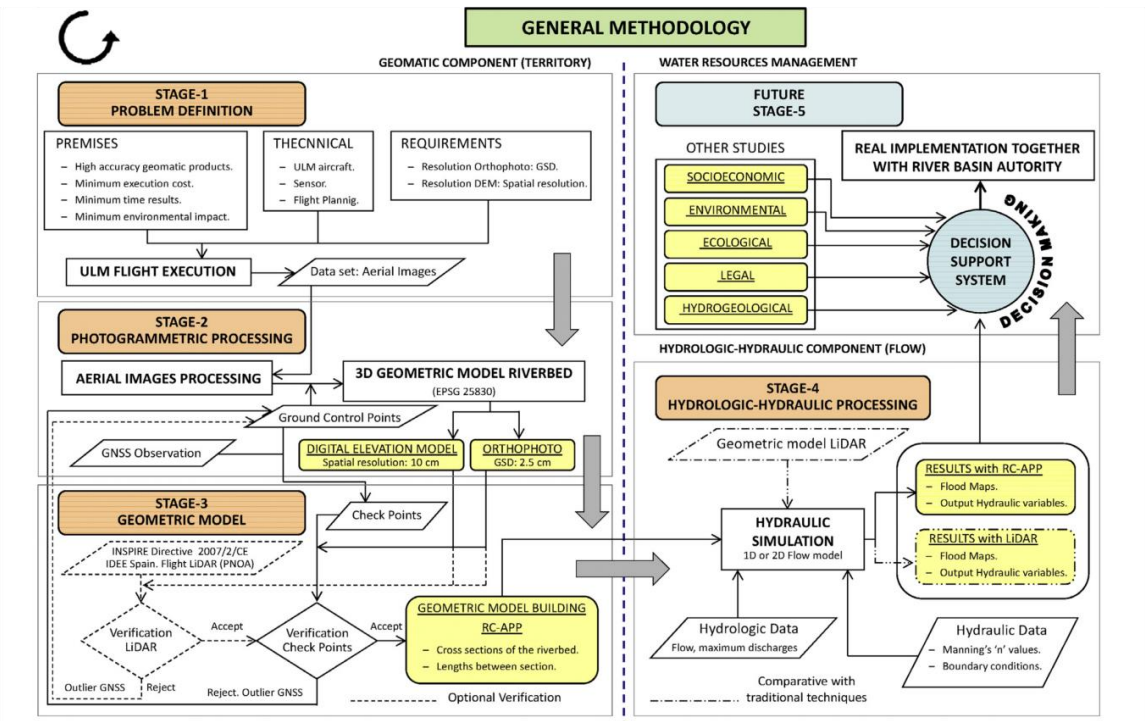

Fig. 2. General methodology.

photogrammetric processing, geometric model and hydrological–hydraulic process, and finally a fifth stage about future research (Fig. 2).

4.1. Stage-1. Problem definition

In this initial stage, the objectives, constraints and technology to apply are formulated and defined. For accurate modeling of floods is essential to have a detailed continuous geometric model the riverbed (Merwade et al., 2008a), given the significant importance of the terrain on the result of fluvial modeling (Merwade et al., 2008b; Wechsler, 2007). This task is reached by the making of an orthophoto and a Digital Elevation Model (DEM). For that it is necessary to define, *a priori*, their resolution, establishing resolutions of 2.5 cm for the orthophoto, and 0.10 m for the DEM. According to previous empirical studies (Zazo and Rodríguez-Gonzálvez, 2014), this is the way to suitably represents the riverbed 3D model and possible structures and existing buildings, and it decisively drive the flow analysis.

The workflow presented in this section is optimized according to: (a) the requirements of accuracy, (b) the processing time to improve the process of decision making and (c) the environmental impact.

The optimal technique for acquiring the geometry of the riverbed is affected by the environmental conditions of the case study. The low and seasonal rainfall, leading to a severe and long (several months a year) dry period with no surface flow in the riverbed, enabling total inspection of the riverbed. This inspection is made with a single technique, and without using bathymetric techniques to represent the riverbed, which certainly allows for better modeling of flooding, as set out in Cook and Merwade (2009) and Merwade et al. (2008b).

For choosing the most suitable technique, it was considered that LiDAR elevation errors may be biased presenting systematic errors (Aguilar and Mills, 2008; Cooper et al., 2013). In studies, such as (Kraus and Pfeifer, 1998; Schmidt et al., 2011), these errors show a negative bias, in contrast to the studies where the bias is positive (Adams and Chandler, 2002; Hodgson et al., 2005). Consequently, since it may produce lack of definition on the inundated area, this bias has important consequences for the floods modeling.

Within the context of maximum efficiency (time-cost) and considering the following: (a) suitability assessment of geomatic methods based on photogrammetric techniques (Molina et al., 2014), (b) assessing accuracy values and spatial resolution, according to previous empirical studies (Zazo and Rodríguez-Gonzálvez, 2014), (c) the singular seasonality of the study area, and (d) the problem regarding bias of LiDAR data (Cooper et al., 2013), RC-APP technique can be considered as one of the most suitable geomatic technique. In order to support the previous statement, technical characteristics of geomatic products, their temporal availability and suitability assessment are outlined in Table 1.

Cost factor is an important decision variable on the technique choice. Acquired data from satellite platforms require large minimum areas (Airbus Defense & Space and Infoterra SGSA, 2015), and also, the acquisition constraint about the minimum area extension, are important disadvantages. Because of this, the associated cost to this data source is extremely high, and it is not appropriate for small study areas. Regarding LiDAR platforms, boarded on aircraft or helicopter, their costs are also important, because of, in both cases, the high mobilization costs. According to (Haugerud et al., 2009), the relationship between the final cost and the surveyed area follows a negative exponential curve. For areas between 130 and 260 km^2 the final cost per hectare is the

Table 1
Main characteristic of techniques for flood modeling.

Technique	Geomatic products		Temporal availability	Suitability
	Orthophoto GSD[f]	DEM Altimetric resolution		
Satellite[a]	Max. 0.25 m	2–0.5 m	About 30 days	Low
LiDAR[b]	Max. 0.25 m	0.5 points/m^2	7–15 days	Medium
Topographic LiDAR[c]	0.15–0.25 m	25 points/m^2	7–15 days	Medium
RC-APP[d]	Up to 0.025 m	100 points/m^2	<3 days	High
Classic surveying[e]	Impossible	Limited by operator	10–15 days	Medium–low

[a] Satellite data by Synthetic Aperture Radar (SAR). Since the cost of Interferometric Synthetic Aperture Radar (InSAR) data is higher than SAR data, InSAR technique is not considerated.
[b] LiDAR data aboard aircraft.
[c] Topographic LiDAR aboard helicopter.
[d] Proposed technique.
[e] GNSS – kinematic.
[f] GSD: ground sample distance (pixel size on the ground).

double than for areas greater than 648 km^2, being an inefficient technique for reduced study areas of few km^2. As regards classic surveying, allows a good vertical uncertainty (Molina et al., 2014), however the altimetric spatial resolution is affected by operator expertise. This is an important disadvantage because an insufficient number of measured points and/or badly distributed will affect the inundation area definition, as well as the generation of a robust and continuous geometric model of the river. Furthermore it does not allow obtaining an orthophotos either. Classic surveying would be a suitable technique for small extension study cases studies. Finally, the proposed technique can achieve better spatial resolution and higher density of points than other techniques. Moreover, a significant reduction in costs is achieved, because the mobilization costs are approximately ten times less than techniques such as LiDAR as well as the others cost elements (flight operator, tandem trike renting, flight insurance, planning and flight).

RC-APP comprises a manned aerial platform (tandem trike, ULM type) equipped with a navigation system and gyro-stabilized cameras platform MUSAS®. The MUSAS® system guarantees the orientation of the camera according to flight planning. Both platforms, air and gyro-stabilized, constitute an innovative alternative to airplanes and satellites in the acquisition of geospatial information, in the range proximal remote sensing, to integrate into a single aerial platform, remote sensing and photogrammetry, with the advantages of obtaining a high spatial resolution and accuracy.

As regards the UAV, the proposed procedure avoids the limitations of autonomy of these systems (Hardin and Jensen, 2011). The technical specifications of the aerial platform and system gyro-stabilized are detailed in Ortega-Terol et al. (2014).

To get the defined restrictions of spatial resolution is necessary rigorous flight planning, which will determine the choice of camera lens and flight parameters. The planning and execution of flight was carried out with MFlip software (Hernandez-Lopez et al., 2013) taking into account the overlap between images and GSD variation due to terrain, as well as estimated errors of aircraft positioning.

The camera selection was made according to the specifications of the sensor, due to their better dynamic range and higher pixel size. In addition to these factors, the performance of the lens used must be considered. As regards the focal length was chosen for the final compromise between spatial resolution and covered area, taking into account the Spanish legal provisions on the maximum height of flight for the type of aircraft (Table 2).

On the other hand, it should not be overlooked that the photogrammetric model should be geo-referenced to the legal system coordinates of the area, UTM 30N ETRS89 (EPSG 25830) by Ground Control Points (GCP), and it should be identifiable on the ground

Table 2
Camera, technical specifications and flight height.

Camera. Technical specifications			
Sensor type			CMOS
Sensor size			36 × 24 mm
Resolution (effective pixels)			21.1 Mp
Image size			5616 × 3744 pixels
Pixel density			1.5 Mp/cm^2
Pixel size			6.41 × 10^{-3} mm
Radiometric resolution			14 bits
Focal length			50 mm
Flight height			
	150 m	200 m	300 m
GSD (m)	0.019	0.026	0.038
Cover area (m)	107 × 71	146 × 97	213 × 142

and on the images. For that, it has been used a Global Navigation Satellite System (GNSS) observation, with a bi-frequency receiver Leica GPS1200 as rover and reference station AVIL, of the regional GNSS network (ITACyL, 2014). A total of 24 points, 10 GCP and 14 check points were observed, these latter for geometric control and accuracy assessment of the 3D model (Fig. 2).

4.2. Stage-2. Photogrammetric processing

At this stage, 3D geometric riverbed model reconstruction takes place through photogrammetry. It is an important phase of the study, because the errors generated in the 3D model is fully transmitted to the hydraulic simulation, which should address in a rigorous way to reduce the error of the geometric model, and improving the following hydraulic analysis (stage 4) (see Fig. 3).

At present, the photogrammetric processing has experienced significant progress thanks to the SfM techniques, Structure from Motion (Agarwal et al., 2009; Snavely et al., 2010). These are based on the principle of epipolar geometry (Hartley and Zisserman, 2004) to recover the 3D geometry of a scene or object captured from uncalibrated cameras, through the calculation of the fundamental matrix (Luong, 1992; Luong and Faugeras, 1996), which is based on the essential matrix (Longuet-Higgins, 1981).

Under this new approach of processing and in order to automate and facilitate the workflow, several software (commercial and open source) have been developed This is an advantage since allowing researchers and engineers process their own dataset and consequently, it is possible to speed up the decision making process by reducing the number of people involved. However, this ease of use has the disadvantage of the lack of details on the generation of processing and the internal model (Cramer et al., 2013). Therefore, the planning evaluation and accuracy in data

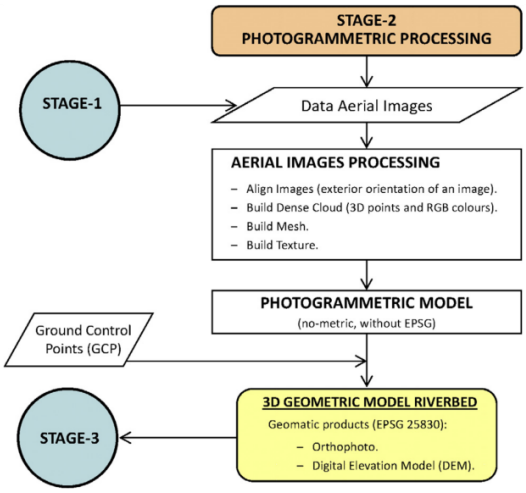

Fig. 3. Processing scheme.

acquisition is a critical issue to ensure the quality of the final 3D model.

In today's digital context, it cannot be ignored that the processing time increases exponentially with the number of images (Rieke-Zapp and Nearing, 2005). Therefore it is necessary to optimize the processing time through approximate knowledge of the external orientation of the flight cameras. This took place by the mono-frequency GNSS equipment on board the airborne platform because the positioning error is not significant compared to the flight baseline, or distance between fotocenters.

The 3D model generation took place through software PIX4D Mapper®. The operation of matching between images is solved by the descriptor DAISY, very efficient for computing dense models (Tola et al., 2010) because it uses a circular grid due to its better location than the rectangular one (Mikolajczyk and Schmid, 2005).

In the process, the phase of geo-referenced 3D model legal system coordinates of the area is crucial, UTM 30N ETRS89 (EPSG 25830), using GCP of the GNSS observation. These were chosen considering their spatial distribution, and applying to them the criterion 3 sigma for acceptance of points (Nkurunziza and Vermeire, 2014). Table 3 shows the errors obtained for the riverbed 3D model.

4.3. Stage-3. Geometric model

A correct modeling of floods over a terrain must be based, first, on the construction of a continuous, accurate and robust geometric model, which correctly synthesizes the riverbed. Furthermore, the bed channel has been more carefully studied according to the inundated area for the 10 years Return Period (RP) (high probability scenarios), according to the National System of Flood Zone Mapping (SNCZI) (MAGRAMA, 2011).

Since it determines the validity of fluvial 3D geometric model obtained in processing, this Stage-3 is crucial in the proposed methodology. The decision of using the 3D model for the construction of geometric model of the hydraulic simulations is made through the verification and determination of the 3D model accuracy.

The National Plan for Territory Observation (PNOT) (IGN, 2014), and the application of directive INSPIRE, Infrastructure for Spatial Information in the European Community (MFOM, 2014), allows getting digital aerial orthophotos with resolution of 25 or 50 cm and LiDAR DEM, at ground level (RMSE ± 0.50 m), with initial density 0.5 points/m^2 and update period of 2–3 years (IGN, 2014), through the National Plan of Aerial Orthophotography (PNOA).

This level of cartographic development allows a double verification by (1) LiDAR flight of the study area, and (2) check points. It should be noted that in Spain LiDAR flight PNOA is the fundamental geometric basis of SNCZI (MAGRAMA, 2011) to obtain from the National Center for Geographic Information (CNIG, 2014).

4.3.1. LiDAR Verification

Fig. 4 shows the checking of the detail technique applied in the representation of the topography of the riverbed against which can be obtained with LiDAR technology.

4.3.2. Check points verification

By means of check points, or ground truth, obtained in the GNSS observation, altimetry 3D model accuracy is evaluated. The geometric accuracy data is relevant to support the decision making because it influences directly the reliability of the results of the hydraulic simulations and modeling of floods.

The determination of the accuracy of the 3D model takes place from a metrological point of view, through an evaluation of the type A uncertainty altimetry, obtained from a probability density function derived from an observed frequency distribution, according with point 4.2 of (CEM, 2008).

The accuracy of the 3D model is determined by the differences between the surface of the RC-APP and the surface of verification by check points. Theoretically, instrumental errors, typical of survey observations as GNSS observation, follow normal distributions as it is shown in (Montgomery and Runger, 2006). In order to check this hypothesis, different normality tests such, as the nonparametric Shapiro–Wilk test, for its robustness, and Q–Q Plot graphical test (Table 4, Fig. 5) have been applied.

Regarding the evaluation type A, and according to the following assumptions (a) they have been made n independent observations of an input variable, (b) under the same conditions of measurement, and (c) the measurement process has enough resolution, it is possible to observe a dispersion of the obtained values, which is used as a measure of uncertainty.

Table 3
Results processed with PIX4D Mapper®.

Processing PIX4D Mapper®				
Summary	Camera name	Canon EOS 5D Mark II		
	Average ground sampling distance (GSD)	2.29 cm		
	Images	Median of 78292 points per image		
	Matching quality	Median of 43997.2 matches per calibrated image		
Bundle block adjustment	Number of 2D/3D keypoint: observations	7529622/2502589		
	Mean reprojection error	0.33 [pixels]		
Ground Control Points (GCP)		Error X[m]	Error Y[m]	Error Z[m]
	Mean	−0.0051	0.0064	0.0185
	RMS error	0.0858	0.1043	0.0667

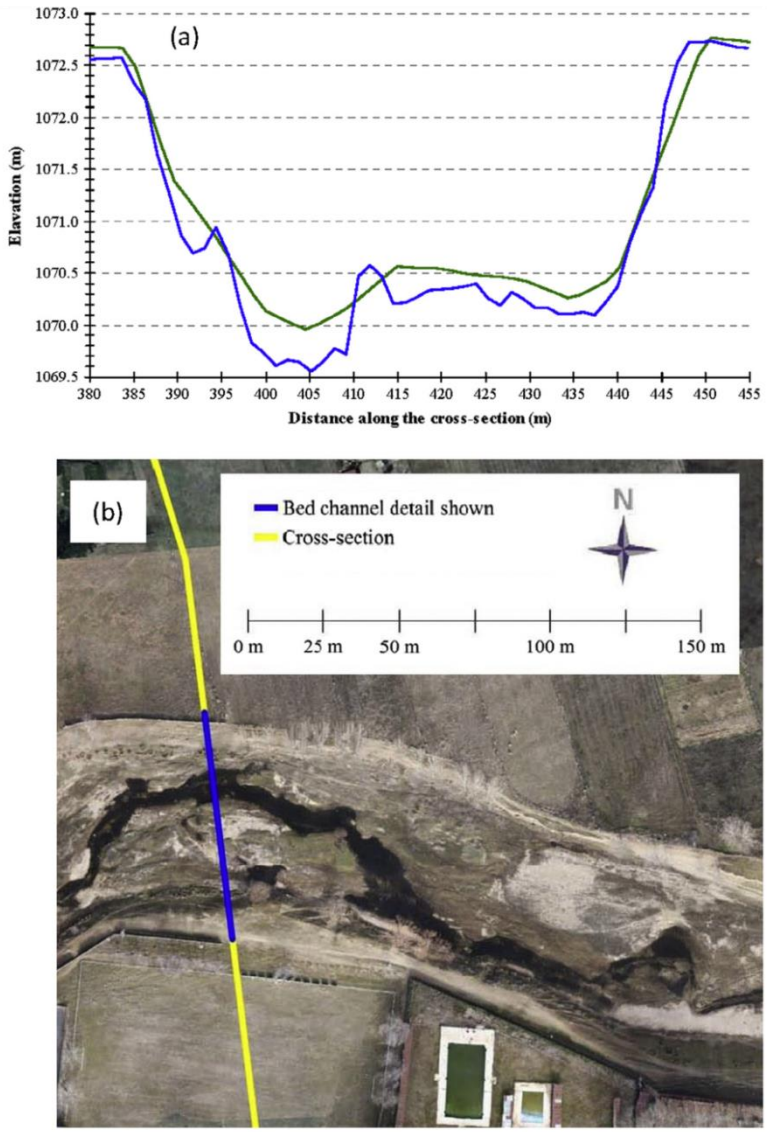

Fig. 4. LiDAR Verification river channel. S-1 cross-section of the study. (a) S-1 cross-section of the study. Blue cross-section: ground RC-APP DEM. Green cross-section: ground LiDAR DEM. (b) Aerial view of detail of the cross-section (2.5 cm orthophoto). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Statistics and normality test.

Statistics. Differences RC-APP DEM variable			
Differences RC-APP DEM	*N* valid/missing	Mean	Std. deviation
	14/0	−0.0234	0.1008
Test of normality: Shapiro–Wilk			
Differences RC-APP DEM	Statistic	*n*	*p*-value
	0.981	14	0.981

In this sense, the best estimate of the expectation mathematical of a random variable is the arithmetic mean $\bar{q}$ of the n values observed $q_j (j = 1, 2, \ldots, n)$ Eq. (1). Moreover, the values of individual observations q_j differ due to random effects; therefore the variance $\sigma^2(q)$ of the probability distribution of input variable is estimated through the experimental variance $s^2(q)$ of the q_j observations Eq. (2). The variability of the observed values q_j, named the experimental standard deviation, is obtained by positive square root of the experimental variance $s^2(q)$.

Since the variance of the arithmetic mean is suitably estimated by experimental variance of the arithmetic mean $s^2(\bar{q})$ Eq. (3), according to (CEM, 2008), the experimental variance of the arithmetic mean $s^2(\bar{q})$ and the experimental standard deviation of the arithmetic mean $s(\bar{q})$ (positive square root of $s^2(\bar{q})$), quantify how well the arithmetic mean $\bar{q}$ estimates the expectation mathematical

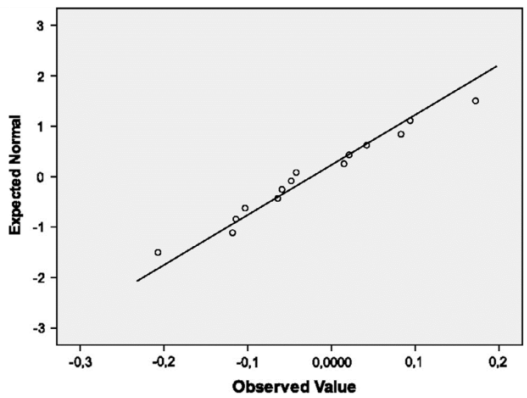

Fig. 5. Q–Q plot for normality assessment.

of an input variable. Therefore, it is possible measure of the uncertainty of $\bar{q}$ by the standard uncertainty u Eq. (4).

On the other hand, since geometric data from two different sources, GNSS observation and RC-APP model have been used, the experimental standard deviation of the arithmetic mean and the uncertainty must be reformulated according to Eqs. (5) and (6) respectively. In Eq. (5), $\sigma_{z_{GNSS}}$ is the altimetric precision of the check points utilized (average of their altimetry precision), and $\sigma_{z_{RC\text{-}APP}}$ is the altimetric precision, of RC-APP model (standard deviation of the differences between the surface of the RC-APP and the surface of verification by check points). Lastly, the model accuracy RC-APP is obtained by Eq. (6).

$$\bar{q} = \frac{1}{n}\sum_{j=1}^{n} q_j \tag{1}$$

$$\sigma^2(q) = s^2(q) = \frac{1}{n-1}\sum_{j=1}^{n}(q_j - \bar{q})^2 \tag{2}$$

$$s^2(\bar{q}) = \frac{s^2(q)}{n} \tag{3}$$

$$u = \frac{s(\bar{q})}{\sqrt{n}} \tag{4}$$

$$s(\bar{q}) = \sigma_{\varepsilon_i} = \sqrt{(\sigma_{z_{GNSS}})^2 + (\sigma_{z_{RC\text{-}APP}})^2} \tag{5}$$

$$u_A = \frac{\sigma\varepsilon_i}{\sqrt{n}} \tag{6}$$

Table 5 shows the result of model accuracy RC-APP.

Therefore, the accuracy of RC-APP model, by evaluation type A, is (-0.02 ± 0.03) m.

4.3.3. Geometric model

Nowadays, GIS tools are indispensable for geospatial information analysis, such as DEMs or digital aerial orthophotos. Firstly, it has been built riverbed geometric models through GIS software, LiDAR and RC-APP, performing strategically, and in the same places, the channel cross sections in both models, and determining the relative distances between sections. Secondly, the cross sections of the model LiDAR have been used in the LiDAR Verification (Figs. 2 and 4).

On the other hand, it should not be overlooked that a high density of points (about 100 points/m^2) has important effects in the construction of geometric model, such as (a) more detail of the cross section, which improves the knowledge of the hydraulic variables in natural waterways, (b) it is not necessary to use GIS simulation models for cross section definition that would imply a digitization, which bring uncertainty in its definition, and (c) it is not required processing point cloud (in the case of a low points density), which is other source of uncertainty, all these make more efficient the methodology used.

Table 5
Model accuracy RC-APP DEM.

Check points (ground truth)		RC-APP DEM	
N	14	*N*	14
Error of mean (m)	0.012	Error of mean (m)	−0.02
A priori error, precision (m)	0.012	*A priori error*, precision (m)	0.10
A posteriori, accuracy (m)		*A posteriori*, accuracy (m)	0.10
		u_A (m)	0.03

4.4. Stage-4. Hydraulic processing

This represents the last stage of the research. It comprises the hydraulic simulations, according to the scenarios of occurrence probability under European legislation (EU Directive, 2007) and Spanish (Ministerio de la Presidencia, 2010): (a) low or extreme events (RP 500 years), delimitation of the flood zone, (b) average (RP ⩾ 100 years) materializing the Preferential Flow Area, and (c) high (Return Period 10 years), and using the 3D riverbed geometric models, LiDAR and RC-APP (Table 6).

The hydraulic simulations cannot be separated from its spatial component. In this respect, the watershed, as territorial unity, is the set of water realities through the natural drainage network, which converge at a point where natural flows are evaluated in the analyzed stretch (X = 351828 m, Y = 4497706 m, EPSG25830), determining a watershed of 530 km^2 and defining a concentration time of 11.7 h, depending on the main channel length (39.9 km) and range of altitudes (between 1500 m a.s.l and 1070 m a.s.l).

On the other hand, the watershed behavior is evidenced through the water flow. Hydrological conditions, basic hydraulic parameters, along with the reduction of transport capacity of the watercourse and modification of the natural conditions of basin runoff (anthropogenic factors) are, among others, the causes that make the existence of flooding.

However, this study is approached from a geomatic point of view, where the water flow, understood as the product of section (depending on the depth) by the speed (depending on the hydraulic radius depending on the section), is eminently a geometrical product. Consequently, within this geomatic context it was not considered a specific rainfall–runoff model. This would have involved taking into account the random component of rain and/or the study of equiprobable series, for the definition of rainfall patterns, and getting the water flows to the hydraulic simulations with a certain degree of uncertainty. This is to be made for forthcoming investigations.

In this sense, the hydrological study is addressed through maximum discharges series, relating the magnitude of peak flood flow with its annual probability of occurrence or RP (quantile), which is essentially a statistical problem.

Table 6
Geomatic products used in hydraulic simulations.

Geomatics products		LiDAR (PNOA)	RC-APP
Orthophoto	Resolution (GSD)	0.25 m	0.025 m
	Time reference	2010–2011	2013/12/13
Digital Elevation Model (DEM)	Initial density	0.5 points/m^2	Approx 100 points/m^2
	Output planimetric	GRID 5 × 5 m	GRID 0.10 × 0.10 m
	Output altimetric	RMSE: ±0.50 m	Accuracy: ±0.10 m

Data gauging of peak flows are adjusted to a distribution function, once a validation of quality and data consistency is carried out. Three different Return Periods (RPs) of 10, 100 and 500 years have been selected, corresponding to the stage of high, medium and low probability of the applicable legislation. Consequently, the selected quantiles are obtained at the gauged points. The adjustment of frequency is carried out through Generalized function Extreme Values (GEV), adjusted by the method of L-moments. These methods have been used in different hydrological studies such as Norbiato et al. (2007) and Yang et al. (2010).

Considering that the point of flow assessment is not a gauging station, results extrapolation is made for the quantile at that point. This extrapolation is carried out according to statistical multiple regression models that relate the quantiles of gauging stations or specific statistics with physiographic and climatic characteristics of the basin. Consequently, by knowing physiographic and climatic characteristics of the regression, quantiles can be estimated.

Water flows are provided, by the Duero river basin authority and comprise a map of instant peak flows in natural regime (CEDEX, 2013). This flows are $Q_{10} = 112\ m^3\ s^{-1}$, $Q_{100} = 229\ m^3\ s^{-1}$ y $Q_{500} = 330\ m^3\ s^{-1}$.

Regarding the construction of the hydraulic model, the existing structure (bridge) on the analyzed stretch is not modeled hydraulically. The study is focused on the study of the influence of the two considered geometric sources (innovative RC-APP vs. traditional LiDAR) in the floods modeling results. Furthermore, the study is also aimed to estimate the hydraulic parameters associated with it, and consequently, assessing the technical and methodological suitability for application to Hydraulic Studies, river engineering and risk assessment flood.

HEC-RAS® software, has been used because simplification in the calculation of flood wave propagation in 1D flow, is suitable for the geomatic field of study. The simulations are performed under a mathematical model with fixed river bed channel, non-erodible without accretion, based on establishing the continuity equation and energy between two sections of the riverbed, considering the constant flow as steady state (Martínez Marín, 2001). In forthcoming studies further elements will be incorporated and 2D flow conventional softwares, such as MIKE21

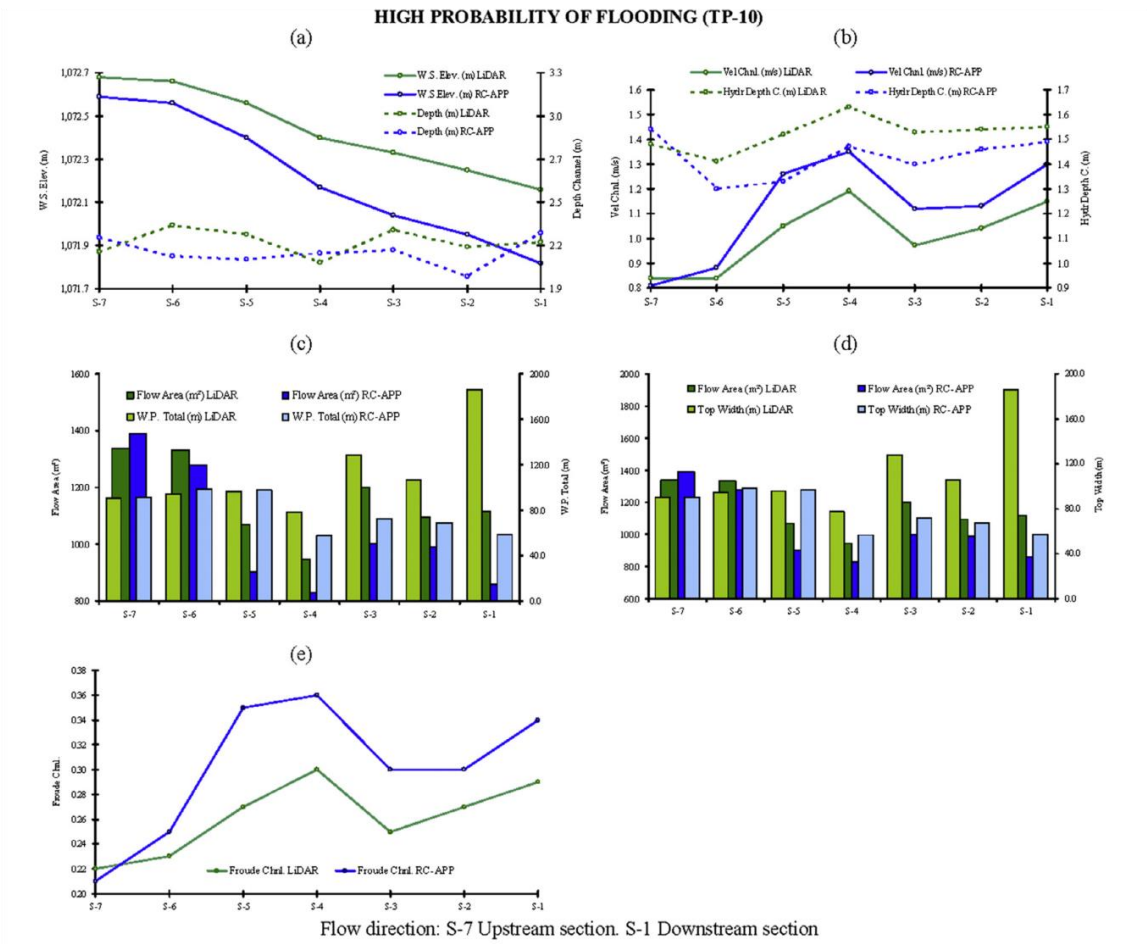

Fig. 6. High probability of flooding. Hydraulic parameters. (a) Water surface and depth in the central channel, (b) speed and hydraulic radius in the center channel, (c) area and perimeter wet, (d) wet area and free surface of the fluid and (e) Froude number.

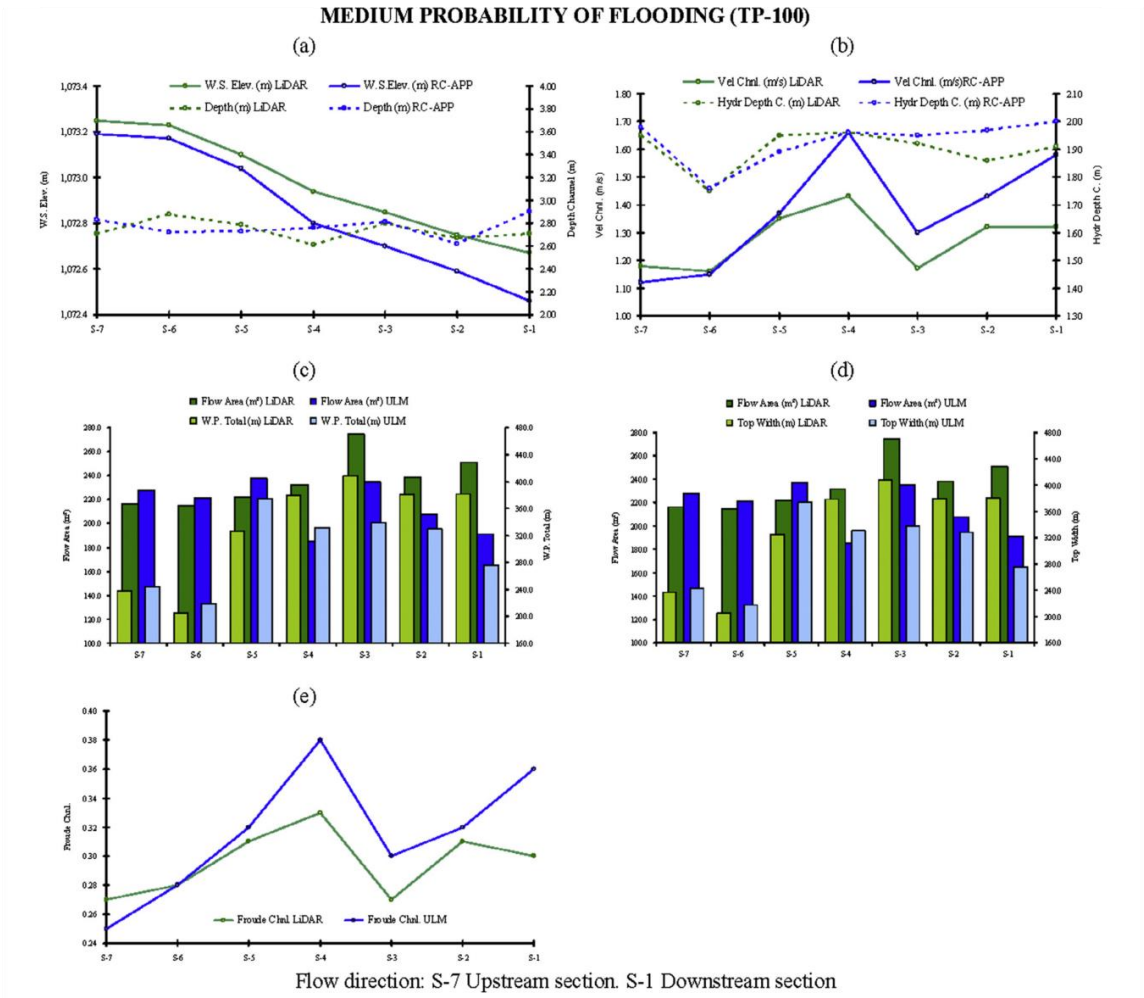

Fig. 7. Medium probability of flooding. Hydraulic parameters. (a) Water surface and depth in the central channel, (b) speed and hydraulic radius in the center channel, (c) area and perimeter wet, (d) wet area and free surface of the fluid and (e) Froude number.

(Warren and Bach, 1992) or latest, such as IBER (Blade et al., 2014), will be used according to the results in studies such as Horritt and Bates (2002) and Tsakiris (2014). Furthermore, a specific hydrological study to define the flows in the study area will be performed as well.

Given this situation, two hydraulic simulations were carried out, in which the hydraulic parameters are unique, varying only the DEM (cross section) and the boundary conditions associated with it (normal hydraulic depth). Given the geometrical context, average values for roughness coefficient (n) were adopted according to US Army Corps of Engineers (2010), so that the simulations reflect reality in the area ($n = 0.006$ for tree-covered, $n = 0.045$ main channel). Finally, once executed simulations, Flood Maps and desired hydraulic parameters are generated through the GIS tool, for the process of decision making in the river field. The hydraulic model was calibrated with the hydraulic depth values and water flows taken at the Gauge Station Ávila (code number 2046) located 5.5 km downstream the studied river stretch.

Under this approach, the differences in flood conditions and hydraulic outcomes must be produced, exclusively, due to the influence of the 3D model river geometry.

5. Results

5.1. Influence of geometry on hydraulic parameters

Typical hydraulic free regime parameters in open channels and rivers, such as the Froude number (F) or influence of weight, speed, wetted perimeter-section, hydraulic radius or average value of shear stress per section, among others, have in common that they are determined by geometric parameters, so an accurate and detailed geometry of the channel will result in a better understanding of them and hydraulic systems.

The influence of geometry is limited to the cases of high and medium probability, because for a low probability (RP-500), the

water flow is obtained by a rating curve, where information is often not available upstream and may not produce a valid water flow value. For the case of RP-500 years, the effect of a wide and homogeneous flood plain in the attenuation of the flood wave it has been highlighted. In this sense, it has been observed, that only increase the purely geometric hydraulic parameters due to the increased elevation of the water surface. Consequently, the variation of the rest of the parameters is not significant, compared to those obtained from the simulation of RP-100 flow.

In Figs. 6 and 7, a comparative analysis of the main hydraulic variables obtained through the two DEMs, RC-APP and LiDAR, is carried out for scenarios of high and medium probability.

In Graphic a, of Figs. 6 and 7, it is seen that the larger detail from RC-APP section and the difference between both models implies a higher water surface elevation for LiDAR model than for RC-APP model. The most pronounced discrepancy is in the case of RP-10, due to the effect of larger detail in the RC-APP model. The influence between both terrains, due to the accuracy of 3D models as well as to a greater topographical detail, is evident in the hydraulic depth; which is significantly lower in the RC-APP model, leading to a lower water surface elevation. Furthermore, the best definition of the wet section provides a better knowledge of the velocity at the center channel, Graphics b and c, Figs. 6 and 7.

The positive effects of a better riverbed geometric definition are more evident in the case of water flow RP-10, c and d Graphic Fig. 6. As consequence of that, both the section and the wetted perimeter are significantly lower in the RC-APP model than in the LiDAR model. This provides a substantial difference in the inundated area of the free water surface, and therefore, the flooding modeling (Sections S-3, S-2, especially S-1). This is especially interesting when defining and limiting the susceptible areas to flooding. In this sense, in Fig. 8, it is shown that the more detailed and the less uncertainty model RC-APP provides the lower inundated area modeling of floods. This has important implications for the assessment of exposure to the risk to flooding.

The effects of a more detailed RC-APP model against the LiDAR model are clearly evidenced itself, if they are globally analyzed for the entire stretch (390 m). Those effects can be evidenced on the, strictly hydraulic geometrical parameters and those, derived from them:

- Flow area: An increase of 10% is produced in the LiDAR section for water flow RP-10 (116 and 104 m^2). The same trend is maintained in the case of flow RP-100, where the increase is about 9% (236 and 215 m^2).
- Wetted perimeter: The difference reaches 30% (112 and 78 m), LiDAR section higher than RC-APP section, in the flow RP-10, and in the case of RP-100 is 9% (331 and 302 m).
- Top width wetted cross section: The difference in inundated area water flow for the RP-10 is 31% (111 and 77 m) higher in LiDAR section, in water flow RP-100 the discrepancy is 9% (331 and 301 m).
- Average velocity of flow in main channel: The lower section of the RC-APP model increases speed by 11% for RP-10, and 8% with RP-100.
- Hydraulic depth in channel: The geometric influence is reduced to only 2% for the flow T-100, and 6% for water flow T-10. Both with higher value in the LiDAR section than in the RC-APP section.
- Froude number for the main channel: The difference reaches 15%, the water flow RP-10, and 7% in the case of RP-100. With both water flows, this parameter is lower in the LiDAR section, which provides uncertainty when it comes to assessing the stream regime.

5.2. Influence of geometry on the simulation modeling

As it has been already proven, the geometric accuracy affects directly on the hydraulic variables and, consequently on the modeling and identification of susceptible areas to flooding (Figs. 8 and 9). Therefore, an accurate representation of relief and minimal uncertainty of 3D reference model are determining factors.

In Table 7, inundated area surfaces associated with the established water flows probability scenarios are indicated, according to the DEM used in each hydraulic simulation.

For high probability, the average difference is relevant (0.22 m) for the water surface elevation. This is because of the more detailed model and less elevation of the RC-APP model. This demonstrates the positive influence of the detail degree on the representation of riverbed central channel, through the applied technique-methodology.

On the other hand, the central channel geometry has sufficient transport capacity for the considered water flow, implying that there is no practically an impact on the modeling of floods. In this case, the RC-APP model shows a lower inundated area. Due to the section transport capacity, the influence of geometric accuracy has no significant effect on the modeling of floods. However, the model accuracy LiDAR causes that the inundated area is 4.4% higher than it would have been with the RC-APP model.

In the case of medium probability, on a stretch of just 390 m, the inundated area by LiDAR model is higher than inundated area by RC-APP model about 29,250 m^2. This involves 21.5% more inundated area for an average difference in the surface water elevation of only 0.12 m between both 3D models.

Regarding the low occurrence probability, the higher inundated area from LiDAR model is maintained. This inundated area through LiDAR implies an absolute difference of 5600 m^2 (3.7%), for an average difference between surface water of only 0.10 m. In this sense, the existence of a difference of 5600 m^2 in the inundated area is still relevant, because it is common, for this type of flooding, that a small different in inundated area cause serious damage.

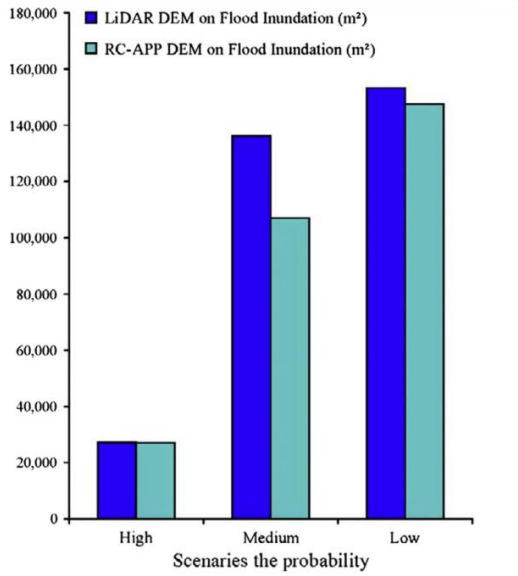

Fig. 8. Effect of RC-APP and LiDAR DEM on flood inundation under European legislation (EU Directive, 2007) and Spanish (Ministerio de la Presidencia, 2010).

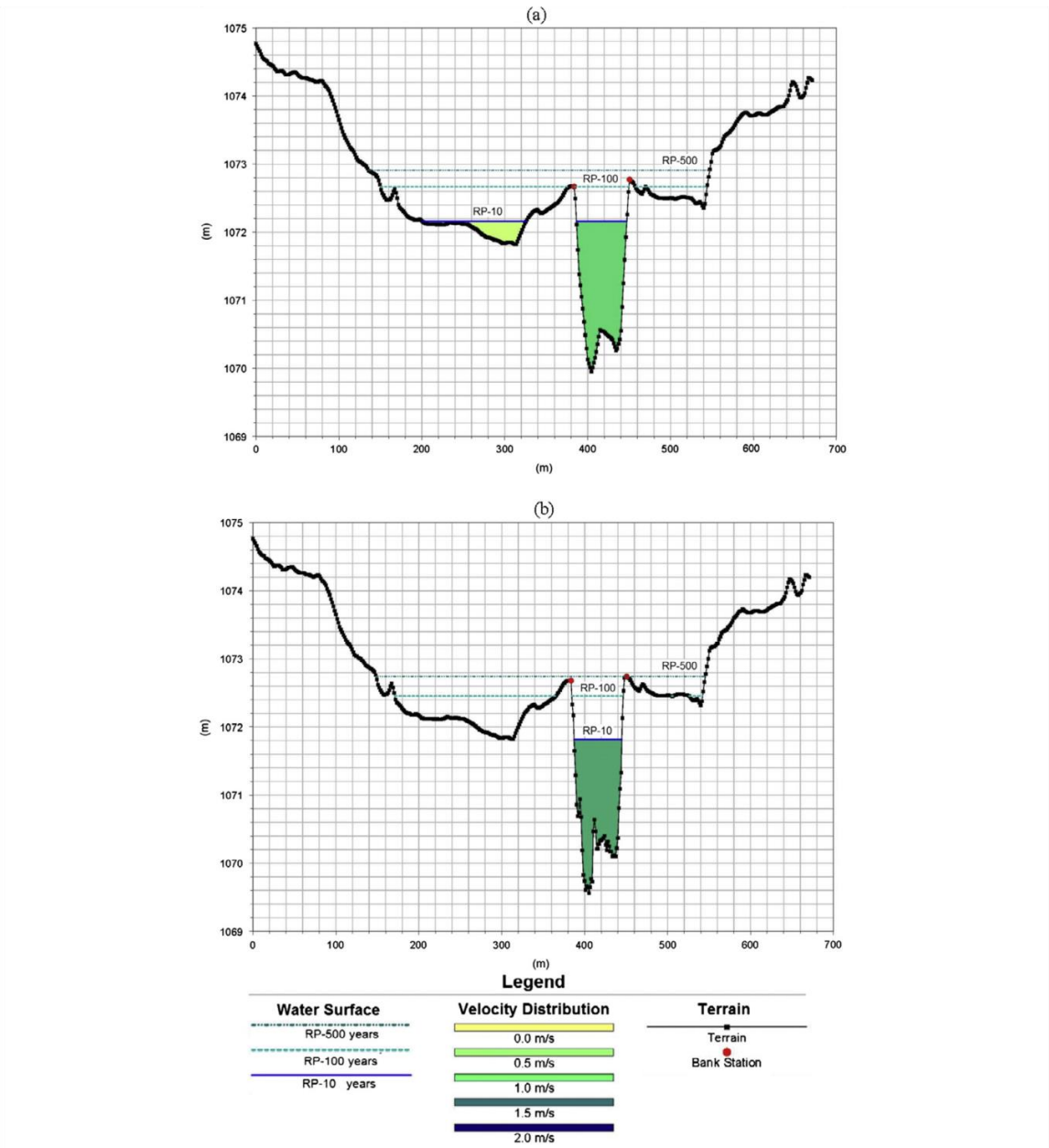

Fig. 9. Simulation results. S-1 cross-section. Vertical axis represents water surface elevation (m), and horizontal axis represents distance along the cross-section (m). Manning $n = 0.045$ in all cross-section. (a) LiDAR DEM. (b) RC-APP DEM.

Table 7
Effects of geomatic products on inundation map.

Geomatics products – flood modeling (m^2)		
Probability scenarios	Traditional (LiDAR DEM)	Innovative (RC-APP DEM)
High (RP-10)	27,200	27,050
Medium (RP-100)	136,250	107,000
Low (RP-500)	153,200	147,600

Moreover, this higher surface area can lead to an unnecessary increase of the risk level.

In order to summarize, for this case study, results on inundated area from LiDAR model area are larger than those obtained through RC-APP model. Thus, LiDAR model might produce an overestimation of the water surface (see Casas et al., 2006).

Fig. 10 shows the influence of the different models (RC-APP and LiDAR) on the flood inundation.

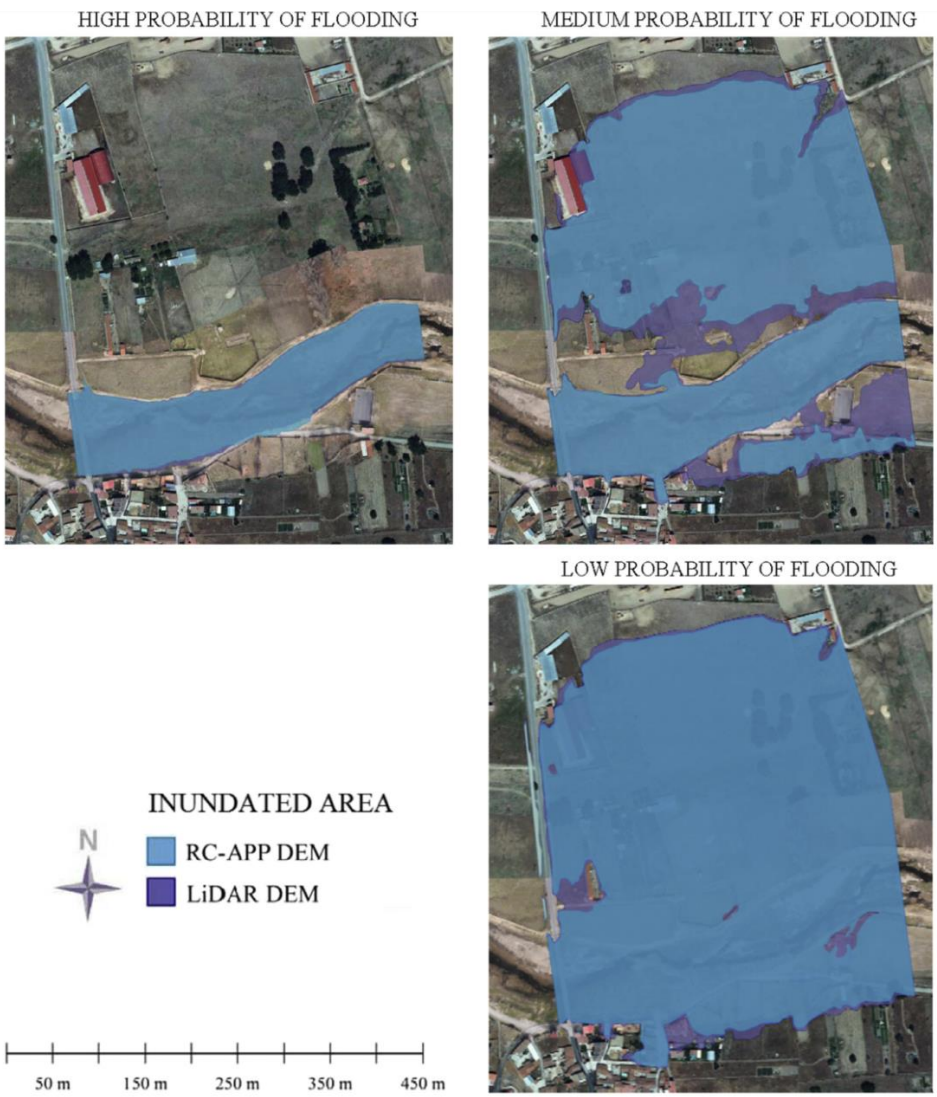

Fig. 10. Map flood modeling, with RC-APP and LiDAR DEMs, under European legislation (EU Directive, 2007) and Spanish (Ministerio de la Presidencia, 2010).

6. Discussion and conclusions

In the modeling and analysis of flooding, the relationship between flow and terrain is inseparable. On the other hand, the hydrological behavior of a basin is characterized by randomness, in magnitude and occurrence of events. Extreme events are increasing in frequency and magnitude, partly due to the phenomenon of climate change. It is therefore, necessary for the society to adapt to these new hydrological realities in the most efficient way (time-cost).

This adaptation must be articulated on a decision making process of and based on optimal design of technical solutions. Here, the geometric component is essential, not only as a cartographic support, but also as a component that reduce uncertainty in the process. In this sense, it is necessary to work with efficient and accurate methodologies for representing 3D fluvial geometric model.

All that technical methodology, applied in this study, offers important advantages in geomatic component, modeling and analyzing risk flood. First, it is possible to have a continuous geometric 3D riverbed model, with an accuracy of (−0.02 ± 0.03) m. This involves one magnitude order higher than the traditional and conventional techniques such as LiDAR (RMSE ± 0.50 m). Furthermore, good results of LiDAR technology (Cook and Merwade, 2009), have been improved significantly through RC-APP.

For a medium probability of flooding, the difference between 3D models in the definition of the average water surface elevation is about 0.12 m that represents a difference of 29,250 m^2. This involves a 21.5% increase in inundated area in the case of model LiDAR. This difference is significant in assessing the risk of floods.

It has been checked, in the three considered probability scenarios, that the inundated areas obtained by the RC-APP model are lower than those obtained when using the LiDAR model. These results are due to the high density of points in addition to the accuracy the RC-APP data compared to LiDAR data. The decreasing trend in inundated area when are employed more accurate geometric models, is described in (Casas et al., 2006), is maintained with RC-APP.

As it was seen through the manuscript, the RC-APP technique has favorable effects when it is applied to areas of high exposure to floods, it is allows the risk level as a consequence of a more faithful representation.

Regarding the hydraulic variables, RC-APP technical-methodology has allowed a better understanding of them. For RP-10 (high probability) there is a decrease of 30% in the variables wetter perimeter, top width wetted cross section. For RP-100 (medium probability), the decrease is about 10% in the same variables. With high water flows, the influence of a wide and regular floodplain has produced only significant changes in the purely geometric hydraulic parameters. On the contrary, the hydraulic parameters derived from these they do not have relevant modifications. However, when dealing with low water flow, greater detail in the representation of the riverbed has a positive effect, which produces significant changes in the geometric hydraulic parameters strictly and those derived from them.

3D geometric model reconstructed presents the important feature of data homogeneity, being obtained from a single geometric source. On the other hand, problems of interpolation, integrability and combination of data, indicated in Merwade et al. (2008b), are eliminated due to the density of points in the model, which influence the precision of the results.

The resolution and high accuracy of the geomatic products obtained in Stage-2, allow better risk assessment and knowledge flow. This has a significant economic advantage in decision-making and the definition of technical solutions in the field of river engineering. In the case of the technical characteristics of generated geomatic products (Stage-2), the orthophoto generated is between 6 and 10 times more resolution than those obtained by traditional techniques (2.5 cm and 15–25 cm). Furthermore, DEM (approx 100 points/m^2), has a density of points hard to get by the same techniques (0.5–2 points/m^2 for LiDAR embarked on aircraft and 25–40 points/m^2 in the case of topographic LiDAR using helicopters).

The ULM aerial platform used for this study offers significant advantages because it does not require airfields to operate, has a capacity of up to 110 kg, the possibility of boarding the MUSAS® platform, and a flight autonomy of up to 3.5 h. Furthermore the means employed (aircraft, camera, software) for its simplicity, may be regarded as innovative and alternative compared to traditional and commonly used.

The interest of this study, compared with traditional studies lies also at an economic level. In this sense, ULM flight platform, sensors, software and flight infrastructure provide a significant reduction in cost, especially in mobilization costs (ten times less than techniques such as LiDAR). These aspects strengthen the idea of effectiveness established as a basic premise of this study. In economics terms, will enable more efficient use of economic resources, by public administrations and private corporations. This economic-social efficiency can be realized in more adjusted designs to the reality.

Regarding the acquisition of geometric information, and as a consequence of its photogrammetric character, it should be pointed, that this technique is sensitive to the concealments, especially in areas of dense vegetation, as well as to the specific limitations of passive sensors (photographic camera) that capture energy but do not emit any radiation to take a measurement. These apparent disadvantages can be minimized, and even not be relevant, as in this study, if it is possible to coordinate the execution of ULM flight with the phenology of vegetable species existing in the analysis area (riverside vegetation and channel). Also, the fact of using an aerial platform, makes it is more exposed to the weather than traditional aircraft.

It is intended to continue the application of this technique in future research. For instance, on the evaluation of sediment transport and its influence on reducing available water storage in reservoirs and its implications for the optimal design of scour outlet of the dam, making a multitemporal analysis of riverbed change. Furthermore, elements will be incorporated to improve the hydraulic system knowledge, as the generation of a specific model of rainfall-runoff and using softwares 2D flow like MIKE21 or IBER, among others.

Furthermore, within the field of river engineering and hydraulics, and based on technical and reduced cost geomatic sensors, it will be analyzed their application to the study of the local and general erosion phenomenon, as well as the analysis, preventive control and maintenance of riverbeds existing structures may affected by erosion, scour or any other affection.

It is important to emphasize the accuracy of the RC-APP (-0.03 ± 0.02) m, which is similar to classic surveying technique, that can encourage the use of this technique in surveying large areas. This is because of the possibility of producing continuous models, with high point density and homogeneous precision, which results in the final suitably metric precision of the generated products, because of the integration of both techniques.

This technique-methodology may have another important niche application, not just in the river area as a low cost and high resolution tool, but also, for the management, control and surveillance of public water and wastewater discharges. Furthermore, is also possible to identify the particularity of the temperature by embarking a thermographic sensor.

Finally in other civil engineering fields such as the Land Transport Infrastructure, it is immediate the implementation as a tool for mapping, control and monitor the implementation of this type of linear projects.

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III.2 PUBLICACIÓN CIENTÍFICA III

Este apartado contiene el artículo científico titulado *"Flood analysis supported by low-cost geometric modelling"*, publicado en la revista científica de alto factor de impacto *Journal of Hydrology* (ISSN: 1535-1467) en Octubre de 2016.

Resumen

Hoy en día, es cada vez más evidente la no-estacionalidad de los procesos hidrológicos e hidráulicos, en gran medida atribuible al fenómeno del Calentamiento Global. En consecuencia, los fenómenos hidrológicos extremos son cada vez más frecuentes, menos anómalos, más recurrentes en el tiempo, y sus efectos están provocando mayores impactos negativos en el medio ambiente y en la sociedad, derivados de los daños por inundaciones.

Ante esta situación, la implementación de medidas de mitigación y de adaptación resultan vitales, así como un mayor conocimiento de la interacción entre el agua (flujo) y el medio físico (terreno). Para una comprensión de la interacción entre los términos del binomio "flujo-terreno", disponer de un correcto Modelo Digital de Elevación (DEM) resulta esencial, debido a la importancia de éste para un correcto modelado fluvial. Sin embargo, con frecuencia, suele ser un problema técnico y económico.

El objetivo de esta investigación ha sido, en primer lugar evaluar la idoneidad de un nuevo DEM con tamaño de malla de 0,15 m, densidad de puntos del orden de 40 puntos/m², y precisión altimétrica de (0,102±0,081) m, para aplicaciones fluviales. Éste fue obtenido mediante el procesado, a través de técnicas SfM (*Structure from Motion*), de las imágenes aéreas digitales adquiridas con una cámara no-convencional para la reconstrucción 3D, embarcada en una plataforma aérea alternativa del tipo ULM (siglas en inglés de *Ultra Light Motor*). A continuación, se determinó la calidad del modelo 3D resultante mediante Estimadores Robustos de la centralidad y la dispersión de los errores del mismo. Este enfoque, para la evaluación de la incertidumbre altimétrica, tiene la ventaja de no precisar un conocimiento previo de la función de distribución de los errores, y por tanto aplicable sobre cualquier muestra geométrica de errores, frente a los planteamientos clásicos fundamentados en distribuciones gaussianas.

A continuación se generó un modelo hidráulico específico, para un caudal de periodo de retorno 100 años (valor típico en la evaluación de riesgos naturales) gracias a los valores de caudales instantáneos máximos en régimen natural facilitados por la Confederación Hidrográfica del Duero, y con el soporte del modelo 3D fotogramétrico previamente generado. De esta forma se determinaron los parámetros hidráulicos básicos del flujo y la modelización de la inundación resultante.

Por último, y para comprobar la idoneidad de la técnica, metodología y sensor empleado, denominada DPod (siglas en inglés de *Digital Photogrammetry on demand*), se ha realizado un análisis comparativo, hidráulico-geomático, frente a la técnica LiDAR (*Light Detection and Ranging*), tecnología asentada en la comunidad científica. Esta comparación puso de manifiesto que el modelado de la inundación mediante el DEM fotogramétrico fue considerablemente más detallado que el proporcionado a través del modelo 3D LiDAR. Esto es debido, principalmente, a la mayor densidad de puntos y precisión vertical del modelo geométrico investigado.

En consecuencia, la DPod puede considerarse como un planteamiento competitivo, fiable y preciso para el análisis del comportamiento de los sistemas fluviales, siendo de aplicación en zonas donde no se dispone de datos LiDAR o donde los datos topográficos no tienen la suficiente calidad como para obtener modelizaciones hidráulicas fiables. Además resulta eficaz como complemento a técnicas como el LiDAR o la Topografía clásica, habitualmente aplicadas en la modelización 3D fluvial.

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FLOOD ANALYSIS SUPPORTED BY LOW-COST GEOMETRIC MODELLING

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ABSTRACT

Today, it is increasingly clear that non-stationarity hydrological and hydraulic variables and processes are occurring largely because of global warming. Accordingly, extreme hydrological events are becoming more common over time, and their effects are creating greater negative impacts on the environment (fluvial geomorphology and floodplains) and society (flood damage). Given this situation, the implementation of adaptation-mitigation measures is vital, as well as an increased knowledge of the interaction between water and physical environments. In the binominal water-terrain, having a reliable digital elevation model (DEM) is essential because of its important influence on fluvial modelling. However, this is frequently a technical-economic problem. The aim of this paper is first to evaluate the compatibility between hydraulics and geometrics for fluvial applications and second to determine the quality of a novel DEM by robust estimators. This was obtained through the photogrammetric processing of digital aerial images acquired from a low-cost camera mounted on an alternative aerial platform. Flood modelling and hydraulic parameters were obtained with the assistance of photogrammetric DEM (mesh size: 0.15 m, vertical accuracy: 0.102 ± 0.081 m, point density: ≈40 point/m^2). Finally, our other goal is to develop a comparative analysis between light detection and ranging and digital photogrammetry on-demand. This comparison revealed that flood modelling by photogrammetric DEM was considerably more detailed than that by light detection and ranging-DEM, mainly because of higher point density and vertical accuracy. Consequently, flood analysis assisted by this novel geometric modelling approach qualifies as a reliable and competitive approach. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: flood analysis; river geomorphology; fluvial hydraulic; DEM accuracy; structure from motion (SfM); digital photogrammetry on-demand (DPod)

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INTRODUCTION

The non-stationarity of hydrological variables due primarily to global warming, together with other factors, is a tangible reality, recognizable even by non-experts. Consequently, hydrological-hydraulic extreme events such as floods, droughts and other events have become more frequent in the water cycle over the last several decades (Huntington, 2006; Labat *et al.*, 2004; Lepori *et al.*, 2015; Praskievicz, 2016; Reihan *et al.*, 2012, Yang *et al.*, 2012).

In this sense, global warming causes considerable negative impacts for society, as well as involves considerable environmental, social and economic costs. Furthermore, measures to subvert climate change are having limited effects in the short-medium term, largely attributable to the persistence of anthropogenic effects (IPCC, 2014).

Given this growing global challenge, the implementation of adaptation and/or mitigation measures seems crucial (Poussin *et al.*, 2012; Williams *et al.*, 2013). Such measures should be addressed not only on the basis of different hydrological scenarios but also via a detailed representation of the physical environment, an essential element for the proper evaluation and management of natural flood risks.

Thus, having reliable and accurate topographic data in a continuous digital elevation model (DEM) form is crucial (Saksena and Merwade, 2015; Wechsler, 2007). Furthermore, it is well known that the accuracy of terrain 3D models is highly dependent on fluvial modelling and hydraulic parameters (Merwade *et al.*, 2008, USACE, 2010; Zazo *et al.*, 2015). Nevertheless, acquiring DEM data may present a technical-economic problem.

The aim of this paper is to assess the joint behaviour and performance of hydraulics and geometrics, by means of a novel DEM for river applications. This was obtained through the photogrammetric processing of digital aerial images by the structure from motion (SfM) technique. Finally, a comparative analysis of light detection and ranging (LiDAR) technique was performed. A 'pilot test' was carried out via a low-cost passive sensor (digital camera) mounted on a fixed-wing alternative aerial platform. This ultralight motor represented an intermediate solution between aircrafts and unmanned aerial vehicles (Ortega-Terol *et al.*, 2014).

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Additionally, this paper proposes a method for evaluating the DEM's vertical precision through robust estimators (RE); this method does not require a priori knowledge of errors distribution function (EDF).

Finally, this work demonstrates that digital photogrammetry (DP) can deliver accurate DEMs to analyse the behaviour of fluvial systems on a reliable and competitive basis.

Over the last several decades, geomatic advances have facilitated the development of new instruments and techniques to acquire high-resolution, accurate topographic data. This is mainly due to digital sensors, artificial vision and image processing algorithms. Within the field of river hydraulic and fluvial geomorphology, these advances have substantially transformed 3D ground modelling (Westoby *et al.*, 2012). Instruments such as Global Navigation Satellite System (GNSS) and other techniques such as airborne/terrestrial laser scanning are firmly established among researchers (Brasington *et al.*, 2000; French, 2003; Hodge *et al.*, 2009; Rosser *et al.*, 2005). However, they present some limitations. For example, GNSS data have a spatial resolution limited by the operator (Molina *et al.*, 2014). Alternatively, airborne laser scanning data entail high operating and logistical costs (Hugenholtz *et al.*, 2013; Westoby *et al.*, 2012), whereas the terrestrial laser scanning technique is suitable for specific zones but requires a significant investment (Westoby *et al.*, 2012), and the data processing is time consuming (Molina *et al.*, 2014). A review of current geomatic techniques applied to water resources modelling (with their uncertainties, limitations and spatial resolutions) is available in Molina *et al.* (2014).

On the other hand, artificial/computer vision and novel imagery processing algorithms have revolutionized DP because of the SfM technique (Fonstad *et al.*, 2013; Snavely, 2008). Specifically, an object's 3D geometry is reconstructed by 2D images acquired from multiple viewpoints and from various non-calibrated cameras supported by the principle of epipolar geometry (Hartley and Zisserman, 2004). These techniques are extremely useful (Molina *et al.*, 2014) and offer maximum time-cost efficiency (Tonkin *et al.*, 2014; Zazo *et al.*, 2015). However, their highest potential remains in the geomatic products that can be derived, such as dense point clouds, DEMs and orthoimages (Fonstad *et al.*, 2013; Tamminga *et al.*, 2015).

Additionally, DP creates geomatic products from a unique instrument, a camera (passive sensor). In contrast, the LiDAR technique requires an active sensor to obtain a DEM and a photogrammetric camera that provides an orthoimage.

Currently, alternative aerial platforms [ultra-light motor (ULM), unmanned aerial vehicles (UAV)] based on fixed-wing or multirotor platforms are opening new research doors for the geoscience community (Lejot *et al.*, 2007; Westoby *et al.*, 2015). Solutions based on fixed-wing platforms are appropriate for flood modelling and fluvial analysis, given their suitability to flight over wide or narrow areas (Ortega-Terol *et al.*, 2014; Zazo *et al.*, 2015). In contrast, multirotor solutions exhibit an important limitation in autonomy (Hardin and Jensen, 2011) that may negatively impact their applicability to river studies (Ortega-Terol *et al.*, 2014).

The growing necessity of producing adequate DEMs for flood modelling (Saksena and Merwade, 2015) is driving the emergence of innovative solutions (time-cost) on the basis of DP on-demand (DPod).

This new research direction towards hybridization between hydraulic and geomatic sciences is characterized by simplicity, quickness and efficiency in the acquisition of topographic data (Molina *et al.*, 2014). It also provides efficient and low-cost solutions (Ortega-Terol *et al.*, 2014; Tamminga *et al.*, 2015; Zazo *et al.*, 2015), as well as accurate and detailed topographic products (Tamminga *et al.*, 2015; Zazo *et al.*, 2015).

MATERIALS

Photogrammetric data

To take full advantage of the potential of new photogrammetry algorithms for the DEM generation, a low-cost digital camera was employed (GoPro Hero 2 model, GoPro, Inc., San Mateo, California, USA). Its main technical characteristics included low weight (167 g) and small dimensions (42 × 60 × 30 mm) suitable for the new generation of fixed-wing UAVs (Toth and Jóźków, 2016). Moreover, the fisheye lens yields a wide field of view of up to 170°, whereas its moderate resolution of 11 megapixels (3840 × 2880) leads to an optimal trade-off for this case study.

According to previous studies in the area (Zazo and Rodríguez-Gonzálvez, 2014; Zazo *et al.*, 2015), the planned flight height was established at 200 m above ground level. Flight planning and execution was determined by MFLIP software (Hernandez-Lopez *et al.*, 2013).

Light detection and ranging data

Light detection and ranging data are usually applied to flood modelling. In Spain, LiDAR is the geometric base for flood zone mapping (MAGRAMA, 2011). Recently, these data have been provided by the National Plan of Aerial Orthophotography (PNOA, 2016). Here, LiDAR-DEM will be used as ground truthing to evaluate the suitability of DPod-DEM for hydraulic purposes. Table I summarizes the technical characteristics of LiDAR data.

Hydrological data

Water flow data were supplied by the Duero River Basin Authority through a map of instant peak flows under the natural regime (CEDEX, 2013).

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Table I. Technical specifications of LiDAR data

Geomatics products		LiDAR data
Point clouds	Spatial resolution. Point density:	0.5 points/m^2
	Average distance between points:	1.41 m
	Vertical precision, RMSE(Z):	±0.20 m
	Maximum error (in 95% of points):	±0.40 m
	Maximum allowable error (Z):	±0.60 m
	Update period (temporal reference)	6 years
Digital elevation model	Mesh size:	1.50 × 1.50 m
Orthoimage	Image resolution:	0.25 m
	Update period (temporal reference):	2 to 3 years

Root mean square rrror, RMSE; LiDAR; light detection and ranging.

Map values were obtained through maximum discharges series, relating the peak flood flow with its annual probability of occurrence (quantile). Through a process of quality and data consistency validation, the gauging of peak flows was adjusted to a distribution function. Frequency adjustment was accomplished through a generalized extreme values function and adjusted by the L-moments method (CEDEX, 2013). Because the point of flow assessment was not a gauging station, a results extrapolation was made for the quantile at that point. This extrapolation was performed according to statistical multiple regression models that relate the quantiles of gauging stations or specific statistics with physiographic and climatic characteristics of the basin. Thus, a quantile can be estimated by these characteristics of the regression.

Methodology

Case Study. The location of the case study was the upper basin of the Adaja River. This subsystem is integrated within the Duero River basin, the largest basin in the Iberian Peninsula (Figure 1a). The area under study (0.50 km^2) is characterized by a meandering fluvial channel with a wide and regular floodplain and a well-defined gravel-bed main channel. It has a length of 1300 m (straight line 1140 m) and according to Martín Vide (2009), a low sinuosity ($s = 1.14$; $1 < s < 1.3$; Figure 1b).

At the morphometric level, the sub-basin of 530 km^2 has a main stream 39.9 km in length, an average height difference of 430 m and a time of concentration of 11.7 h.

Methodology. Our methodology comprises four stages. First, a continuous DEM was built through an image data set acquired from a low-cost digital camera. Then, a complete geometric assessment of this DEM was carried out by means of RE methodology. Subsequently, hydraulic modelling was performed, first via a hydrological model and second via a 1D hydraulic simulation. Finally, as a means of verification, the results (flood modelling and basic hydraulic parameters) were compared with those obtained through more commonly employed DEMs, such as the LiDAR technique (Figure 2).

Stage-1. digital elevation model generation. In this initial stage, DEM was generated by the photogrammetric processing of image data run through Agisoft Photoscan® software. This commercial software is based on the principle of SfM. The objective of this article is not the process itself; however, in depth background on theoretical photogrammetric can be consulted in Snavely (2008), Fonstad *et al.* (2013), Javernick *et al.* (2014), Tonkin *et al.* (2014) and Westoby *et al.* (2012). However, it should be noted that the matching of homologous points among images was performed by the Scale Invariant Feature Transform detector and descriptor (Lowe, 2004).

This processing presents a twofold challenge: 1 the inherent lack of technical details common in black-box solutions for 3D image processing (Cramer *et al.*, 2013; Javernick *et al.*, 2014) and 2 the singular behaviour that a fisheye lens exhibits in a photogrammetric workflow. More specifically, these types of lens have limitations in terms of lens quality and camera shutter. Regarding the former, lens quality is related to variation of interior camera parameters over time. This is solved by the self-calibration protocol of the SfM technique. The latter (camera shutter) determines how light is recorded. Non-professional cameras do not record all light from a scene at the same time, which could cause undesirable effects. To avoid this, flight planning was designed taking into account the platform speed (approximately $11\,\mathrm{m \cdot s^{-1}}$) and a safety ground sample distances (GSD) threshold (5 cm) to compute the minimum necessary exposure time. The images were acquired with a minimum exposure time of 1/800, far from the safety threshold of 1/220 ($0.05\,\mathrm{m}/11\,\mathrm{m \cdot s^{-1}}$).

Empirical experiments lead to the assumption that the employed low-cost camera lens follows a stereographic model. This lens model presents different behaviours than the normal lens, especially between the central point and extremes, because of the great perspective distortion of the lens. Consequently, for a flight height of 200 m, there will be different GSD, ranging from 128 mm at the central point to 300 mm in the extremes. Consequently, to reduce the influence of distortion, it is necessary to consider a specific mathematical distortion model and use masks in the digital images, excluding those excessive GSD points.

The resulting DEM must be geo-referenced: 1 planimetrically with the legal system coordinates of the area, based on

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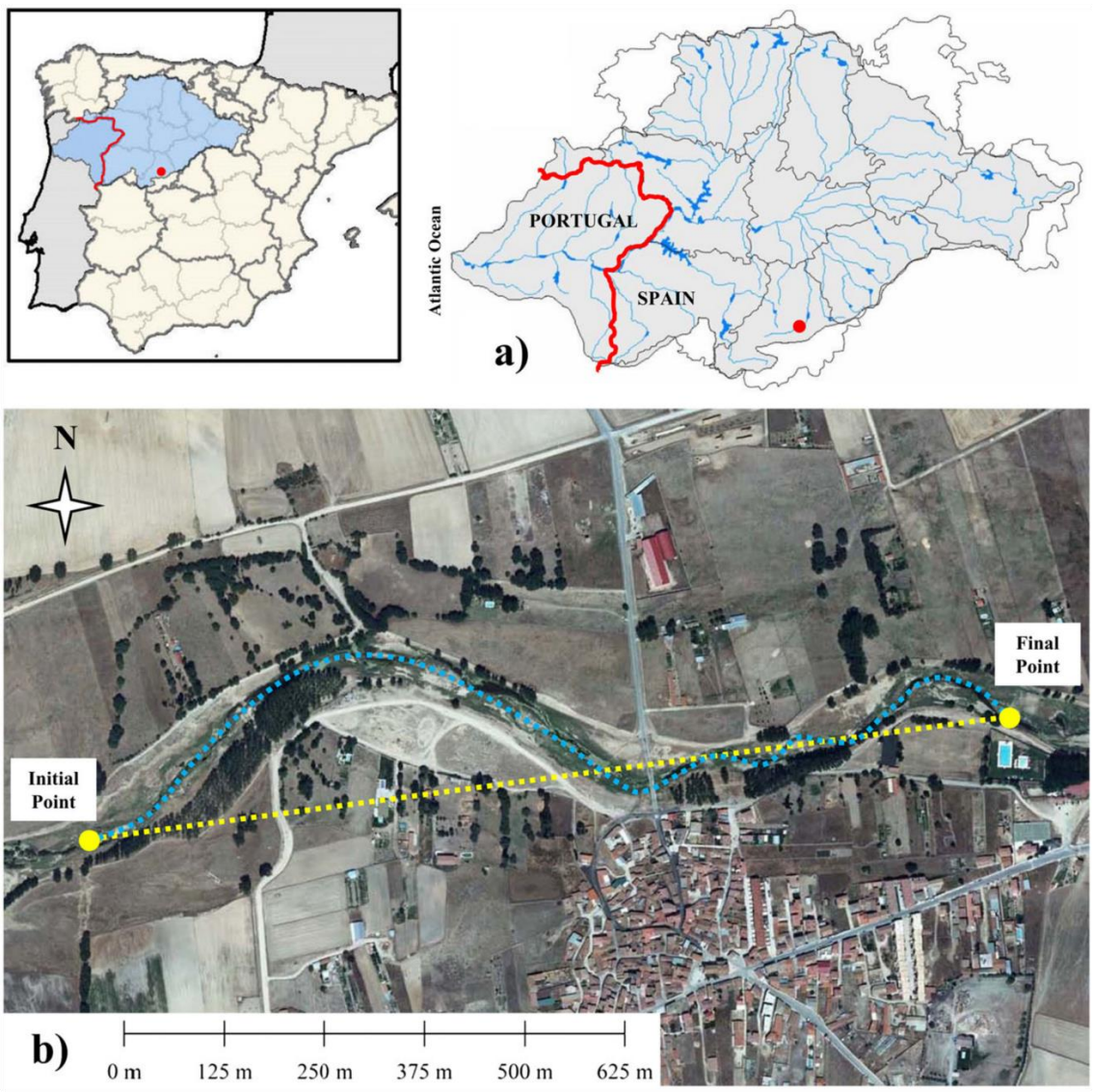

Figure 1. (a) Duero River basin and case study. (b) Studied stretch (Coordinate Reference System: EPSG:25830). [Colour figure can be viewed at wileyonlinelibrary.com]

the following cartographic projection and reference system UTM30N, ETRS89, EPSG:25830 and 2 vertically with the Spanish vertical reference system EPSG:5782. For that, a differential GNSS survey was completed via bi-frequency receiver TRIMBLE R6 as a rover and reference station AVIL (regional GNSS network). The observation method was real–time kinematic. A total of 70 points were observed; 12 ground control points corresponding to artificial targets were used for precise photogrammetric geo-referencing, while the remaining 58 points were used as check points (natural features) for the geometric assessment (Figure 3). Table II shows a summary of the photogrammetric processing, and Table III shows the geomatic products.

Regarding potential problems arising from vegetation, as shown in Hugenholtz *et al.* (2013), Javernick *et al.* (2014) and Lane (2000), they were not relevant to our experiment

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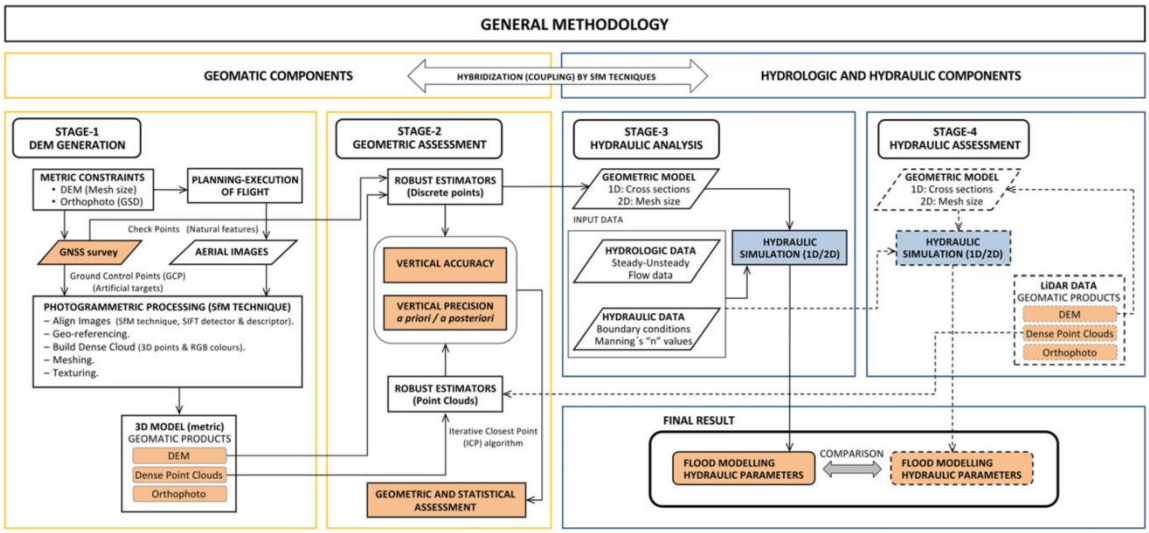

Figure 2. General methodology. [Colour figure can be viewed at wileyonlinelibrary.com]

because the flight execution was carried out according to the phenology of vegetable species in the area. In this way, the influence of vegetation was minimized, allowing the study area to be considered 'vegetation-free'.

In spite of the different substeps involved in photogrammetric DEM generation (images acquisition, GNSS observations, etc.), the final temporal efficiency is optimal for flood analysis tasks. In the first place, image acquisition was carried out at speeds of $11\,\mathrm{m}\cdot\mathrm{s}^{-1}$, requiring only the displacement of the aerial platform near to the study zone. Secondly, the time required for GNSS observations is directly proportional to the study area extension, which was 2 h in the presented study case. Finally, the processing substep, which can be parallelized and/or subdivided into clusters, was the costliest, requiring 60 h for the case study.

Stage-2. Geometric assessment. The geometric quality of DEM is a fundamental factor for flood modelling because its errors are transmitted entirely to the hydraulic simulation (Bales and Wagner, 2009; Merwade *et al.*, 2008; Wechsler, 2007).

Traditionally, DEM accuracy has been evaluated by mean error, standard deviation, mean absolute error and root mean square error (RMSE) (Hugenholtz *et al.*, 2013; Schwendel *et al.*, 2012, Tamminga *et al.*, 2015). Alternatively, Zazo *et al.* (2015) suggests a metrological approach via an evaluation of the type A uncertainty. However, all of these approaches are characterized by the assumption of a normal distribution of DEM errors.

If EDF does not follow a normal distribution, Gaussian approaches cannot be applied and must be addressed by RE. In this case, the normality assumption was checked by

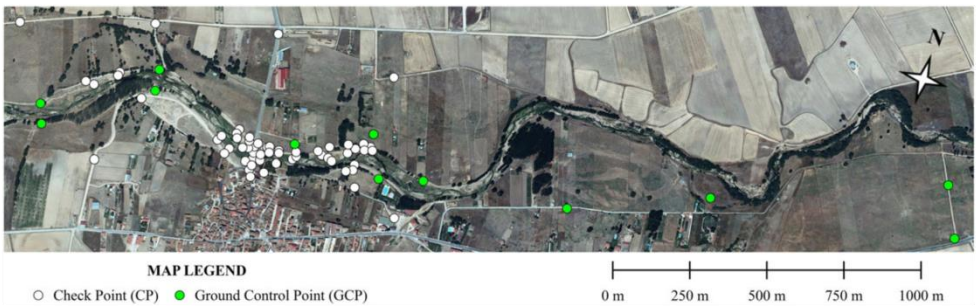

Figure 3. Situation of ground control points (GCP) and check points (CP). [Colour figure can be viewed at wileyonlinelibrary.com]

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Table II. Results of photogrammetric processing

Dataset	Images	1786 (total). Median footprint: 1,340 m^2/image (aprox.)
	Mean executed flight height	187 m
	Average GSD	12.02 cm (orthoimage)
Bundle block adjustment	Matching points	2 394 536 points. Median of 1341 points/image
	Mean reprojection error	0.746 pixels

GSD, ground sample distances.

numerical tests, such as Shapiro–Wilk (Shapiro and Wilk, 1965).

A priori knowledge of EDF is not necessary for RE, an important advantage. Through DEM errors, via a GNSS observation, and in accordance with (Rodriguez-Gonzalvez et *al.*, 2014), it is possible to determine the central tendency and the dispersion of errors through the median (m) and the square root of the BiWeight MidVariance (*BWMV*), respectively. According to Wilcox (1993), *BWMV* is a robust estimator of the statistical dispersion, expressed as

$$BWMV = \frac{j\sum_{i=1}^{j} a_i (x_i - m)^2 \left(1 - U_i^2\right)^4}{\left(\sum_{i=1}^{j} a_i \left(1 - U_i^2\right)\left(1 - 5U_i^2\right)\right)^2} \quad (1)$$

$$U_i = \frac{x_i - m}{9MAD} \quad (2)$$

$$MAD = m(|x_i - m_x|) \quad (3)$$

where j is the number of check points, U is obtained by Equation 2, *MAD* is median absolute deviation (Equation 3), and m_x is the median of the sample data. Lastly, the a parameter could be 0 or 1 depending on the U value. If $-1 \leq U \leq 1$, then a is 1; in any case, a is *0*.

Table III. Characteristics of geomatic products obtained by DPod

Geomatics products		DPod data
Point clouds	Spatial resolution. Point density:	≈40 points/m^2
	Average distance between points:	≈0.15 m
	Vertical precision, by RE(Z):	0.102 ± 0.081 m
	Temporal reference:	Specific (ad hoc)
Digital elevation model	Mesh size:	0.15 × 0.15 m
Orthoimage	Image resolution:	0.12 m
	Temporal reference:	Specific (ad hoc)

DPod, digital photogrammetry on-demand; RE, robust estimators.

It is important to note that this approach by RE over check points (discrete points) could also be applied between point clouds. In this case, one of them would be considered as a reference (LiDAR-DEM) for a direct comparison, as long as they both share the same coordinate system. Alternatively, one could compare points by aligning with the iterative closest point algorithm (Besl and McKay, 1992) to address geo-referencing errors and analyse only the intrinsic geometric cloud errors. The comparison between both point clouds was performed with CloudCompare open source software. Then, the median and *BWMV* were calculated by a custom script.

To contextualize the RE analysis, given that geometric data are provided from two different sources (LiDAR and DPod), the a priori error of the comparison will be expected as

$$e = \pm\sqrt{\left(\sigma_{Z_{LiDAR}}\right)^2 + \left(e_{DPod} \cdot GSD\right)^2} \quad (4)$$

where $\sigma_{Z\ LiDAR}$ is the vertical precision of LiDAR data in metres (PNOA, 2016), e_{DPod} is the reprojection error of bundle block adjustment expressed in pixels and *GSD* is expressed in m/pixel. It is thus possible to obtain a comprehensive comparison, at both the geometric and statistical levels (Figure 2).

Stage-3. Hydraulic analysis. This stage requires the generation of a specific hydraulic model. Based on previous work in this area (Zazo and Rodríguez-Gonzálvez, 2014; Zazo *et al.*, 2015), a water flow corresponding to the 100-year return period (100-YRP) was simulated. For this flow, the floodplain is significantly affected because the carrying capacity of the main channel is significantly exceeded. Additionally, higher return periods do not produce relevant effects on flood modelling because the flood wave undergoes a process of attenuation as a result of the wide and regular floodplain. On the other hand, 100-YRP is a common design flow to describe natural flood risks (Cook and Merwade, 2009).

Steady flow conditions were assumed (Saksena and Merwade, 2015). According to the point of assessment for hydraulic flow (X = 351736 m, Y = 4497736 m, EPSG: 25830; see Figure . 1b, Final Point) and the map of instant peak flows under the natural regime (CEDEX, 2013), the 100-YRP flow was 229 $m^3 s^{-1}$.

Because during high flow periods, the main channel and floodplain act as a unique channel with no floodplain storage areas and both are totally inundated (Saksena and Merwade, 2015), a 1D flow simulation was carried out with HEC-RAS® software.

Given the strong geomatic component of this research, the following hypotheses were assumed: 1 fixed riverbed

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channel, 2 constant flow and 3 the validity of continuity equations and energy between two sections.

Normal hydraulic depth and roughness coefficients (n) were defined as boundary conditions (USACE, 2010). To reflect reality in the study area, the following roughness coefficients were applied: 1 main channel: n from 0.035 to 0.075, 2 floodplain area: n from 0.035 to 0.075 and 0.015 for road. This hydraulic model was calibrated with the Gauge Station Ávila (code number 2046) located downstream of the studied stretch of river.

Stage-4. Hydraulic assessment. Once the previously defined hydraulic simulation was executed, hydrologic and hydraulic parameters were kept fixed. Later, a new hydraulic model was defined, in which DPod-DEM was replaced by LiDAR-DEM (PNOA, 2016). Guided by this approach, the differences in flood analysis and hydraulic outcomes will be exclusively produced by DEMs. Once both hydraulic simulations were completed, the results of basic hydraulic parameters were employed to create flood inundation maps made with a Geographical Information System.

This methodology proves the hydraulic suitability of DPod-DEM. However, it should be noted that this final stage might be optional, depending on LiDAR data availability in the study area. If LiDAR data are not available, DPod-DEM would be carried out exclusively from a geometrical point of view (Stage-2).

Results

Geometric assessment. Firstly, the precision (RMSE(Z)) of GNSS check points was 0.012 ± 0.001 m. Secondly, by these check points, the EDF of DPod-DEM was obtained. Next, the Shapiro–Wilk test was applied to determine whether this EDF followed a Gaussian distribution. The resulting p-value of the hypothesis testing was ≈ 0.005. Because the value achieved was smaller than the signification level ($\alpha = 0.05$), the sample was non-normal. Thus, traditional approaches cannot be applied, and the assessment should be addressed by RE.

From a purely geometric point of view, the REs of the vertical accuracy of DPod-DEM, via 58 discrete points, resulted in a median of 0.102 m and ± 0.081 m as the square root of the *BWMV*. Therefore, the vertical accuracy was (0.102 ± 0.081) m, representing approximately half of the LiDAR-DEM accuracy (± 0.20 m; Table I). In Table III, the main characteristics of geomatic products obtained by the DPod technique are summarized. On the other hand, a complete statistical comparison was performed by point clouds (LiDAR vs DPod). The following ratios should be noted: 0.746 pixel for e_{DPod}, a GSD of 0.12 m/pixel for photogrammetric data and a $\mathrm{RMSE}_{(Z)}$ of ± 0.20 m for LiDAR data. Hence according to Equation 4, the a priori error of the comparison, e, was ± 0.219 m.

Applying Equations 1–3 (Stage 2) over 192 097 points, the square root of the *BWMV* was ± 0.169 m. Please note that the comparison was performed at the ground level exclusively, with the goal of detecting differences in the main channel of the river and the floodplain. For that analysis, buildings and vegetation-covered areas were excluded from LiDAR data. Thus, the comparable number of LiDAR points was only 192 097. Figure 4a shows the non-normality of this sample by QQ-plot (as a result of the large amount of points), along with their RE parameters.

Regarding comparisons between point clouds, it is noteworthy that dispersion measures, both a priori (± 0.219 m) and a posteriori (± 0.169 m), show homogeneous values. According to EDF quantiles (Figure 4a), approximately 80% of the errors are within the expected range, with an a priori error interval of [−0.219, +0.219]. Likewise, 95% of the errors belong to the interval [−0.374, +0.343], a range similar to the LiDAR maximum error (± 0.40 m; Table I).

Figure 4b shows the differences between both point clouds, which fell within the expected a priori error interval. Point density and high mesh size resolution of DPod-DEM play a decisive role [Tables I and III; 40 points/m^2 (DPod-DEM) vs 0.5 points/m^2 (LiDAR-DEM), at 0.15×0.15 m (DPod-DEM) vs 1.50×1.50 m (LiDAR-DEM)]. DPod-DEM allows for the in-depth representation of the gravel-bed main channel, as well as the existing masonry walls in the floodplain area (Figure 4b). In fact, the greatest detected discrepancies are associated with these places, as well as in the zone where the bridge is located, because these features were not modelled. In this sense, LiDAR-DEM's resolution does not facilitate the detailed representation of specific zones, such as the thalweg (fluvial geomorphology) and the narrow walls through which the channel flows.

Hydraulic assessment. As previously noted, the last stage of the methodology involves a hydraulic assessment. This was developed through main hydraulic variables obtained from two hydraulic simulations, corresponding to both 3D models considered, LiDAR-DEM and DPod-DEM.

The general flow behaviour is analogous in both cases. Froude number, for the entire cross sections, has similar values ranges [(0.16, 0.65), (0.21, 0.62) to DPod-DEM and LiDAR-DEM, respectively]. The same occurs for average velocity [(0.51 m·s^{-1}, 1.20 m·s^{-1}), (0.61 m·s^{-1}, 1.11 m·s^{-1})] along all the cross sections (XS1–XS13). Nevertheless, there is a minimal variation in these parameters along the same sections under the two hydraulic simulations (Figure 5a and b).

On the other hand, the variation discovered for the water surface parameter is within the expected geometric interval [−0.374 m, +0.343 m] (see previous section). The mean difference for water surface between both hydraulic simulations was 0.25 m (Figure 5c).

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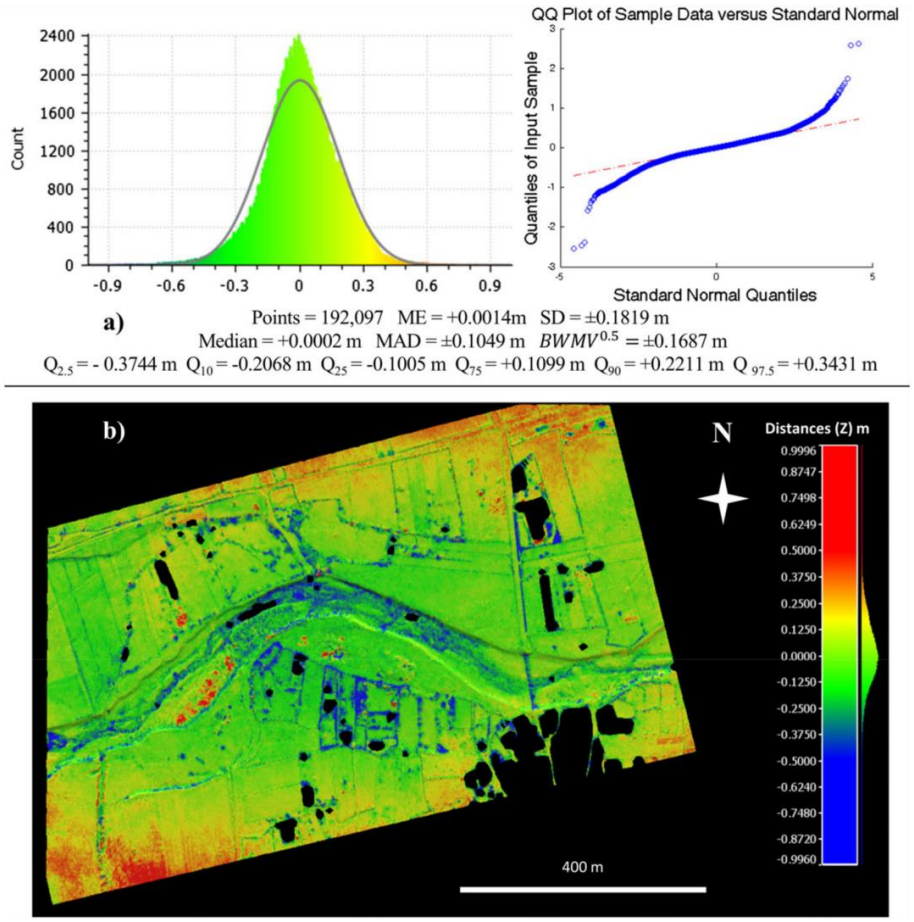

Figure 4. (a) Errors distribution function between point clouds, QQ-plot and quantiles of errors distribution function. (b) Vertical differences between light detection and ranging and digital photogrammetry on-demand data (units: metres) [Colour figure can be viewed at wileyonlinelibrary.com]

In contrast, if LiDAR-DEM results are compared with those obtained by DPod-DEM, there are several noteworthy differences. The average variation is 6.3% for the flow area, 1.8% for the wetted perimeter and 2% for the top width. Furthermore, these differences increase considerably in the case of maximum and minimum values. For flow area (XS12 and XS2), maximum and minimum values were 20% and 8%, respectively. For the wetted perimeter (XS6 and XS5), the maximum and minimum values were 17% and 10%, respectively, and for the top width (XS6 and XS5), the maximum and minimum values were 17% and 10%, respectively, as shown in Figure 5c, d and e. Additionally, these differences could become important in zones without a wide and homogenous floodplain (e.g. urban and peri-urban areas under high anthropogenic pressure due to the existence various elements capable of interacting with flow) and/or in very susceptible floods areas. This might lead to an increased risk and/or uncertainty of flooding. Please note the distinction between risk, defined as the probability that a negative event may happen in the future (always related to events that produce negative or harmful consequences or impacts), and uncertainty, defined as the quantified absence of certainty and typical of hydrological events such as rainfall, runoff or water flow, which are characterized by their highly stochastic nature.

Regarding flooding results, the global differences are not very significant. In fact, the affected and inundated areas vary by only 0.4% (Figure 6a). This is because of the similar floodplain that both DEMs present (Figure 4b) and the resultant attenuation effect. However, the results highlight the positive effect of a higher point density of DPod-DEM over LiDAR-DEM (80 times more), which produces a better

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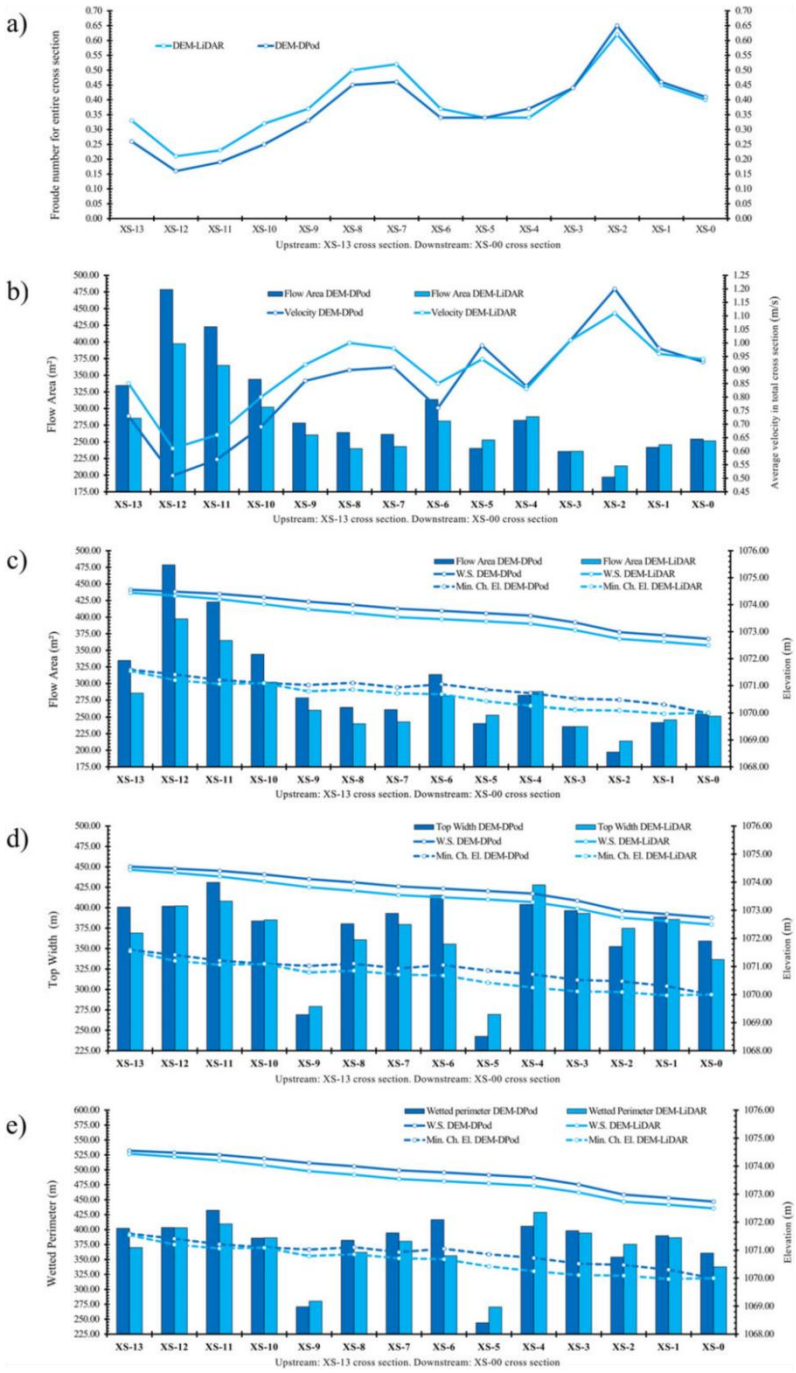

Figure 5. Comparison of 3D models' influence on analysed hydraulic parameters. (a) Froude number. (b) Flow area and average velocity. (c) Flow area and water surface (WS) and minimum channel elevation (Min. Ch. El.). (d) Top width. (e) Top width and WS and Min. Ch. El. (e) Wetted perimeter and WS and Min. Ch. El. Cross section (XS). [Colour figure can be viewed at wileyonlinelibrary.com]

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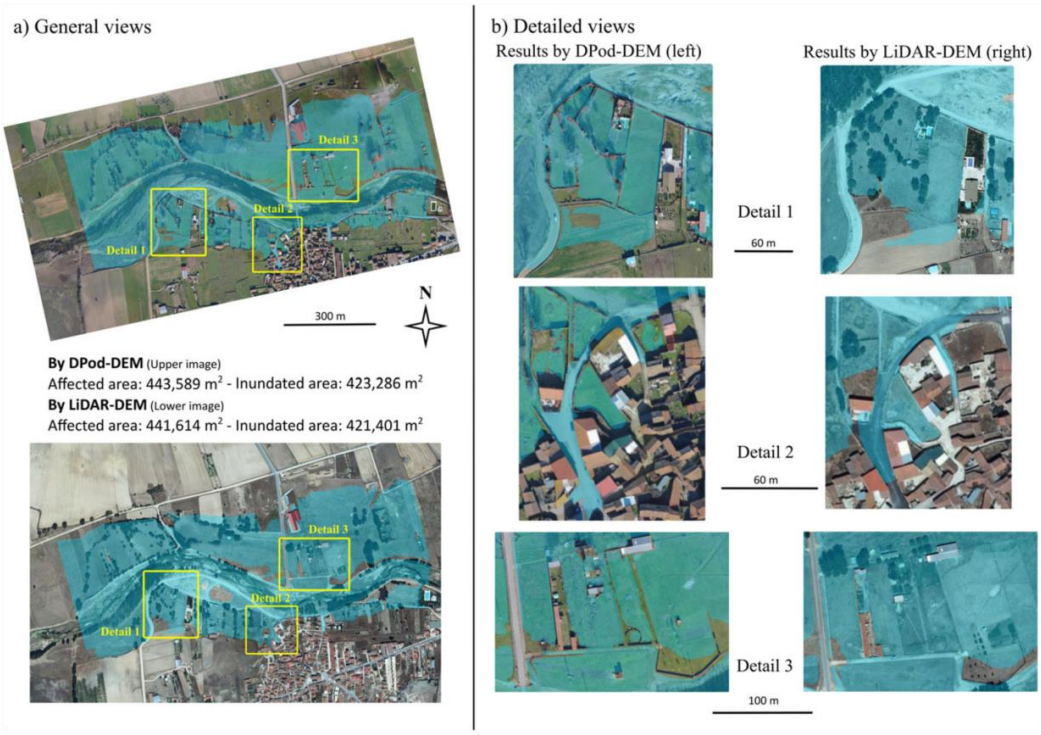

Figure 6. (a) General and (b) detailed view of the flood analysis and influence of point density [Colour figure can be viewed at wileyonlinelibrary.com]

definition of affected and inundated areas. Please note the detailed representation of narrow walls, gates and elements that facilitate the channelling of the flow, especially on the floodplain provided by DPod-DEM (Figure 6b, left images).

DISCUSSION AND CONCLUSIONS

For effective flood analysis, given the inseparable nature of the binominal water-terrain, a reliable DEM is crucial. The proposed photogrammetric 3D model exhibits a vertical accuracy that is double that of LiDAR data (±0.081 vs ±0.20 m) using discrete points. Likewise, in the case of the comparison between point clouds, 95% of errors occur within the interval [−0.374 m, +0.343 m], which is similar to ME (*Z*) LiDAR data (±0.40 m). Furthermore, the geometric assessment (through discrete points and point clouds) showed a similar range of values in relation to their a-priori error estimation.

Regarding hydraulic simulations, at the global level, there were slight variations in basic hydraulic parameters. This is due to the better mesh size achieved by DPod-DEM over LiDAR-DEM as a result of the higher point density and superior vertical accuracy. Consequently, DPod-DEMs applied to other fluvial systems could facilitate the performance of more accurate natural flood risk assessment and knowledge of flow than LiDAR-DEMs.

On the other hand, the higher point density obtained by DPod (40 points/m^2) versus LiDAR (0.50 points/m^2) has provided a more detailed representation of the terrain. If it is expressed as mesh size, 0.15 × 0.15 m vs 1.50 × 1.50 m, this means that DPod-DEM has 10 times more spatial resolution than LiDAR-DEM. At the fluvial geomorphology level, this spatial resolution could detect changes within specific areas, such as the thalweg, as well as increase the knowledge of flow on the floodplain. Mesh size achieved and findings obtained could be useful for the multitemporal analysis of riverbed changes and developing 2D/3D hydraulic models.

Digital photogrammetry on-demand has provided updated data, ad hoc, without a time lag. Because of the intrinsic versatility of flights, narrow and linear areas could be recorded and analysed, representing a suitable solution for river applications. Future research should focus on the application of this technique to determine the optimal relationship between the point density of DEMs and vertical accuracy in terms of hydrological data precision. This will result in knowing the

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final precision of the hydraulic simulation, taking into account the accuracy that the hydraulic model can offer.

There was a reasonable geometric and statistical compatibility among both DEMs (photogrammetric versus LiDAR). However, because spatial resolutions (0.15 m vs 1.41 m) and vertical accuracies (0.081 m vs 0.20 m) are different, they should be taken into account if one wants to integrate both products (LiDAR and photogrammetric) in a continuous DEM. Regarding the photogrammetric technique, it should be noted that via a GSD control, it is possible to scale the geomatic products, by different flight heights or platforms (ULM and UAV based on fixed-wing or multirotor). Accordingly, a lower flight height could possibly obtain superior spatial resolution and thus higher point density and vertical accuracy, as well as a higher processing time, because of the increased number of images. Moreover, the low weight of tested sensor makes it compatible to use on board fixed-wing or multirotor UAV types.

A methodology is also proposed for evaluating the DEM vertical accuracy by RE, which can be applied without a priori knowledge of EDF over any geometric error sample.

This paper has demonstrated that DPod can be considered: 1 an accurate, reliable and cost effective tool to analyse the behaviour of fluvial systems, 2 a suitable technique in places where LiDAR data are not available or where high quality topographic data are unavailable and 3 an effective complement to common flood analysis techniques, such as LiDAR or classic topography.

Regarding future research, the authors plan to investigate the variability of river bed channel monitoring based on river bed channel geometry as well as add the new understanding of riverbed geometry to simulated hydraulic models. Consequently, geometric dynamics could be discerned and incorporated via this methodology, resulting in a recalculation of the hydraulic behaviour of the system.

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CAPÍTULO IV

Conclusiones y Futuras líneas de investigación

IV.1 CONCLUSIONES GENERALES

Esta Tesis Doctoral, aspira a ofrecer un marco metodológico conjunto de actuación ante el reto que supone la creciente no-estacionalidad de los procesos hidrológicos e hidráulicos, consecuencia del fenómeno del Calentamiento Global; y debido a la interdependencia de los términos del binomio “flujo-terreno” para una evaluación más objetiva de los riesgos naturales fluviales.

En este sentido, se pretende conseguir una gestión eficiente, sostenible y segura de los recursos hídricos de una cuenca, hacia personas, bienes y actividades productivas. Todo ello mediante un incremento del conocimiento, tanto del comportamiento del flujo mediante series temporales de aportaciones, como del medio donde se evidencia el ciclo hidrológico, a través de una representación detallada del terreno.

En el contexto de medidas efectivas contra el Cambio Climático, y sobre la base de métodos de análisis y técnicas de observación eficientes en tiempo y coste, se ha propuesto una metodología general que permite agilizar el proceso de toma de decisiones en el ámbito fluvial, con el objetivo principal de predecir y prevenir.

De acuerdo a los objetivos generales inicialmente formulados, en primer lugar se puede concluir que el Razonamiento Causal se ha demostrado muy adecuado y potente para el análisis del comportamiento temporal de las series de aportaciones en cuencas no reguladas. Aquí, la inferencia bayesiana (causalidad-probabilidad condicionada) se ha mostrado como una herramienta eficiente y útil para este fin, dado que:

- El análisis dinámico que ofrece el Razonamiento Causal permite cuantificar y establecer umbrales para las relaciones de dependencia, con los que es posible cuantificar la fuerza de independencia-dependencia temporal.
- El potencial analítico de la inferencia bayesiana ha permitido definir funciones continuas de la propagación de la dependencia temporal, y detectar relaciones de dependencia no triviales, es decir, con desfase temporales mayores de 1 año, a partir de un modelo ARMA (1,1) parsimonioso y no condicionado. Esto resulta extremadamente útil para la mejora del conocimiento hidrológico y por consiguiente, de la gestión de los recursos hídricos.

- La inherente aleatoriedad/incertidumbre de los procesos hidrológicos ha sido adecuadamente capturada y representada.

En segundo lugar, respecto a la aplicación de la Visión Artificial al modelo 3D del terreno, se ha probado que:

- Los nuevos enfoques metodológicos y técnicas basadas en la hibridación de sensores, plataformas aéreas alternativas, cámaras y la aplicación de los algoritmos SfM, son capaces de proporcionar soluciones de muy bajo coste o de coste reducido, frente a las técnicas habituales.
- Los productos geomáticos que se pueden obtener, al servicio de la Hidrodinámica-Hidráulica Fluvial tienen características técnicas (resoluciones espaciales y precisiones) muy interesantes para su aplicación en este ámbito; siendo una alternativa viable, factible y adecuada para disponer de datos topográficos de calidad.
- Las condiciones ambientales (bajas precipitaciones y largos periodos de estiaje sin flujo superficial), favorecen la inspección y observación del cauce fluvial mediante la aplicación de la técnica expuesta, siendo ésta óptima en el caso de cauces fluviales de arenas y gravas.

IV.2 COMPORTAMIENTO HIDROLÓGICO

En cuanto a los objetivos específicamente hidrológicos expuestos:

- Ha sido posible definir un marco metodológico para el análisis de la dependencia temporal dinámica de series hidrológicas de aportaciones en cuencas no reguladas a partir del porcentaje relativo de cambio, entendido como el cambio influido o debido a la probabilidad condicionada.
- Se ha comprobado que el Razonamiento Causal, a través de la inferencia bayesiana, permite la evaluación dinámica de las dependencias temporales y su cuantificación.

- El análisis gráfico de la propagación y/o mitigación de la dependencia, permite una visualización rápida conjunta y eficiente de la dependencia a corto y medio plazo. Disponer de un indicador dinámico a medio plazo es sin duda una novedad derivada de la aplicación del enfoque metodológico de esta Tesis.
- Se ha conseguido representar el comportamiento hidrológico mediante una matriz de dependencias dinámicas temporales. Esto supone una importante ventaja a la hora de definir escenarios más realistas de gestión.
- Las indeterminaciones, que el comportamiento medio y estático de un correlograma suponen, son solventadas gracias al enfoque dinámico que ofrece la inferencia observacional bayesiana. El análisis dinámico temporal etapa a etapa (*step by step*) elimina esas indeterminaciones al poner el foco de atención sobre una determina etapa, siendo así el análisis mucho más detallado.
- A la vista de los resultados obtenidos, es posible que la creciente variabilidad observada en los patrones hidrológicos pueda analizarse de un modo más adecuado a través de la inferencia bayesiana, mediante las Redes Bayesianas.

IV.3 GEOMÁTICA APLICADA A LA MODELIZACIÓN HIDRÁULICA

Respecto a los objetivos específicamente hidráulicos-geomáticos indicados:

- Ha quedado patente el potencial de utilización de las metodologías y técnicas aplicadas en la adquisición de información geoespacial de calidad frente a los enfoques tradicionales.
- Son metodologías de observación eficientes en tiempo-coste, que agilizan el proceso de toma de decisiones en el ámbito fluvial con el objetivo de disponer de recursos hídricos en condiciones de fiabilidad y seguridad. Esto es debido a la inmediatez en la toma de datos "*ad hoc*" al caso de estudio, así como a la posibilidad de autoprocesado de los set de datos. Los trabajos complementarios necesarios son mínimos (una observación GNSS).

- La inmediatez, precisión y óptima relación tiempo-coste en la obtención de los productos geomáticos de esta investigación les hace altamente competitivos para los propósitos de estudios fluviales además de significativamente más económicos. Los modelos 3D obtenidos presentan unas resoluciones espaciales muy útiles para su aplicación en modelos hidráulicos 2D/3D.
- La comparación entre los productos geomáticos obtenidos mediante las técnicas de muy bajo coste y de coste reducido propuestas en esta investigación y aplicadas a los casos de estudio, han mostrado unas resoluciones espaciales y precisiones altimétricas sustancialmente superiores a sus homólogos obtenidos por técnicas más comúnmente aplicadas en la modelización hidráulica como el LiDAR.
- Los productos geomáticos que han servido de base a las simulaciones hidráulicas, han proporcionado un mejor conocimiento del comportamiento del flujo; no sólo han sido mejores los resultados de las variables hidráulicas analizadas, sino también la modelización de las inundaciones estimadas, consecuencia de la precisión y densidad de puntos alcanzada. Esto tiene importantes implicaciones a la hora de definir la susceptibilidad y determinar la vulnerabilidad ante los riesgos naturales de origen fluvial.

Por otro lado los enfoques sugeridos para la evaluación de la incertidumbre altimétrica de los modelos 3D, son novedosos, y aplicables a cualquier tipo de modelo digital de elevaciones, no sólo en el ámbito fluvial. De esta forma es posible evaluar la componente, estrictamente métrica de incertidumbre de una modelización hidráulica, y que es atribuible al modelo 3D que sirve de base a la simulación hidráulica. En este sentido, se sugiere una metodología desde un punto de vista metrológico que asume una distribución normal de errores en el modelo. Por el contrario, en el caso de que esas mismas distribuciones de probabilidad no sean normales, se ha propuesto un marco de actuación mediante estimadores robustos de la centralidad y de la dispersión que elimina además la necesidad de realizar las pruebas de normalidad.

En este punto, merece la pena indicar que los productos métricos obtenidos no deben verse como excluyentes frente a otras técnicas, es decir, pueden constituir un adecuado complemento, a técnicas comúnmente aplicadas en este ámbito como el LiDAR (ALS/TLS) o la Topografía clásica (estación total, observaciones GNSS).

Sin embargo, en cuanto a las técnicas de adquisición de información propuestas, también hay que indicar que presentan algunos inconvenientes que son precisos indicar:

- Tienen las limitaciones propias de las técnicas de observación mediante sensores pasivos (captación de energía exclusivamente), en cuanto a la ocultación de detalles. En el caso de la vegetación, esto puede eliminarse coordinando la adquisición de la información con la fenología de las especies vegetales existentes en la zona de actuación.
- La inherente falta de detalles técnicos comunes en los software "*black box*" para el procesamiento 3D de imágenes mediante algoritmos SfM, en relación con el propio proceso.

IV.4 LÍNEAS FUTURAS DE INVESTIGACIÓN

Como consecuencia de esta Tesis se proponen las siguientes líneas de investigación para profundizar y avanzar en el conocimiento de la interacción agua-terreno, en el ámbito fluvial.

En el ámbito de la hidrología estocástica

- Generar modelos predictivos, en cuencas no reguladas, a partir de las dependencias temporales del comportamiento, profundizando en la determinación de la fracción dependiente de la aportación condicionada.
- Plantear un enfoque de periodo de retorno conforme a las estructuras internas de dependencias de las series temporales, de un modo dinámico y estocástico, como respuesta a la no-estacionalidad de los procesos hidrológicos actuales.
- Analizar la posibilidad de obtener matrices de dependencia dinámica como resultado del comportamiento hidrológico de una cuenca, que permitan la aplicación de los enfoques basados en el tratamiento digital de imágenes para la obtención de patrones de comportamiento.

En el ámbito de la hidrodinámica-hidráulica

- Análisis multitemporal de la evolución de la morfología fluvial con modelos 3D de alta resolución espacial.
- Aplicación de los principios de la modelización 3D del terreno mediante técnicas SfM a la experimentación hidráulica fluvial en laboratorio sobre modelo reducido, con el objetivo de desarrollar nuevas formulaciones y aplicaciones informáticas.

  En este campo de aplicación, las técnicas SfM se pueden configurar como una alternativa extremadamente ágil y eficiente, en comparación con los enfoques mediante LiDAR en su variante de TLS, para el estudio y análisis de procesos y fenómenos fluviales. En este sentido podría aplicarse al transporte de sedimentos, la erosión general y local asociada a pilas y estribos en cauces fluviales, el diseño y geometría de los elementos de protección en márgenes y los cambios inducidos en el thalweg, así como la evolución de las morfologías fluviales.

CHAPTER V

Conclusions and Future research lines

V.1 GENERAL CONCLUSIONS

This Doctoral Thesis is aimed to offer a joint methodological framework from a double perspective: first, facing the challenge of growing non-stationarity of hydrological and hydraulic processes, as a consequence of Global Warming phenomenon; and second, because of the interdependence of the terms of the "flow-terrain" binomial for a more objective assessment of natural fluvial risks.

In this sense, the aim is to achieve an efficient, sustainable and safe management of the water resources of a basin directed towards people, properties and productive activities. All of this is made by means of a knowledge increase on the river flow behavior through runoff time series, as well as through a detailed representation of the terrain.

In the context of effective measures against Climate Change and on the basis of efficient (time-cost) methods of analysis and observation techniques, a general methodology has been proposed that allows speeding up the decision-making process in the fluvial field, with the main objective of predicting and preventing.

In accordance with the general objectives initially formulated, in the first place it can be concluded that the Causal Reasoning has been proved very adequate and powerful for the analysis of the temporal behavior of the runoff series in unregulated basins. Here, Bayesian inference (causality-conditional probability) has been shown as an efficient and useful tool for this purpose, because of the following reasons:

- The dynamic analysis by Causal Reasoning allows quantifying and establishing thresholds for dependency relationships. This makes possible to quantify the force of independence-temporal dependence.
- The analytical potential of Bayesian inference has allowed us to define continuous functions of the propagation of temporal dependence, and to detect non-trivial relationships of dependence, that is to say, with time lag of more than 1 year, from an ARMA model (1,1) parsimonious and non-conditioned. This is extremely useful for the improvement of hydrological knowledge, and consequently, for the management of water resources.
- The inherent randomness/uncertainty of hydrological processes has been adequately captured and represented.

Secondly, in relation to the Artificial Vision to the 3D model of the terrain, it has been proved that:

- New methodological and technical approaches based on hybridization of sensors, alternative aerial platforms, cameras and the application of the SfM algorithms, are able to provide solutions of very low-cost or reduced-cost over usual techniques.
- The geomatic products that can be obtained, at the service of Hydrodynamics-Fluvial Hydraulics, have very interesting technical characteristics (spatial resolutions and accuracies) for their application in this field; being a viable, feasible and adequate alternative in order to have quality topographic data.
- Environmental conditions (low rainfall and long periods of dryness without surface flow) make easier the inspection and observation of the river bed by applying the exposed technique, which is optimal in the case of gravel-bed and sandy and gravelly river channels.

V.2 HYDROLOGICAL BEHAVIOR

In regards to the specifically hydrological objectives:

- It has been possible to define a methodological framework for the analysis of the dynamic temporal dependence of hydrological runoff series in unregulated basins. This is done through the relative percentage of change, which is understood as the change due to the conditioned probability.
- It has been proved that Causal Reasoning, through Bayesian inference, allows the dynamic evaluation of temporal dependencies and their quantification.
- The graphical analysis of the propagation and / or mitigation of dependency allow a quick and efficient visualization of the dependency in the short and medium term. Having a dynamic indicator in the medium term is undoubtedly a novelty due to the application of the methodological approach of this Thesis.

- It has been achieved to represent the hydrological behavior through an array of temporal dynamic dependencies. This is an important advantage when it comes to define more realistic scenarios of management.
- The indeterminations, that the average and static behavior of a correlogram assumes, are solved due to the dynamic approach by observational Bayesian inference. The step by step temporal dynamic analysis eliminates those indeterminations since focuses the attention on a given stage. In this way, the analysis is much more detailed.
- In view of the obtained results, it is possible that the growing variability observed in the hydrological patterns can be analyzed more appropriately through Bayesian inference and Causal Reasoning, implemented by Bayesian Networks.

V.3 GEOMATIC APPLIED TO HYDRAULIC MODELING

Regarding the specifically hydraulic-geomatic objectives indicated:

- It has clearly emerged the potential of using the methodologies and techniques applied in the acquisition of quality geospatial information over traditional approaches.
- They are efficient methodologies of observation regarding time-cost that allow speeding up the process of decision making in the fluvial field with the objective of having water resources in conditions of reliability and security. This is due to the immediacy in the data acquisition "ad hoc" to the case study, as well as the possibility of self-processing of data sets. The required additional works are minimal (a GNSS observation).
- The immediacy, accuracy and optimal time-cost relation in obtaining the geomatics products of this research make them highly competitive for the purposes of fluvial studies; furthermore, they are significantly more economical. The generated 3D models have very useful spatial resolutions for the application in 2D / 3D hydraulic models.

- The comparison between the generated geomatic products, by the very low-cost and reduced-cost proposed techniques have shown spatial resolutions and altimetric accuracies substantially higher than their homologues obtained by techniques most commonly applied in hydraulic modeling, such as LiDAR.
- Geomatic products that have acted as a support for the hydraulic simulations have provided a better knowledge of the flow behavior, not only the results of the analyzed hydraulic variables but also the modeling of the inundated areas, as a consequence of the accuracy and density of points. This has important implications for defining susceptibility and determining vulnerability to natural hazards of fluvial origin.

On the other hand, the suggested approaches for the evaluation of the 3D models altimetric uncertainty , are novel, and applicable to any sort of digital model of elevations, not only in the fluvial field. In this way, it is possible to evaluate the strictly metric component of uncertainty of a hydraulic modeling, which is attributable to the 3D model that supports the hydraulic simulation. In this sense, a methodology is suggested from a metrological point of view that assumes a normal distribution of errors in the model. On the contrary, in the case that the analyzed probability distribution is not normal, a methodological framework by robust estimators of centrality and dispersion, which also eliminates the need to perform normality tests, has been proposed.

At this point, it is worthy to remark that the obtained metric products should not be seen as exclusive to other techniques, in other words, they may constitute an adequate complement, to techniques commonly applied in this field such as LiDAR (ALS / TLS) or classical Topography (total stations, GNSS observations).

However, regarding the proposed information acquisition techniques, it should also be noted that there are some handicaps to be noted:

- They present the limitations of the techniques of observation through passive sensors (energy capture only), as far as hiding details. In the case of vegetation, this can be eliminated by coordinating the information acquisition with the phenology of the plant species existing in the area of action.
- The inherent lack of technical details, common in black box softwares for 3D image processing using SfM algorithms, related to the process itself.

V.4 FUTURE RESEARCH LINES

As a consequence of this Thesis, the following lines of research are proposed to deepen and advance the knowledge of the water-terrain interaction in the fluvial area.

In the field of stochastic hydrology

- To generate predictive models, in unregulated basins, from the temporal dependencies of the behavior, deepening in the determination of the fraction dependent on the conditioned runoff.
- To propose a return period assessment approach, according to the internal structures of dependencies of the time series, in a dynamic and stochastic way, in response to the non-stationarity of the current hydrological processes.
- To analyze the possibility of obtaining dynamic dependency arrays as a result of the hydrological behavior of a basin, allowing the application of those approaches based on the treatment of digital images to obtain behavior patterns.

In the field of hydrodynamic-hydraulic

- Multitemporal analysis of the fluvial morphology evolution with 3D models of high spatial resolution.
- Application of the principles of 3D modeling of the terrain using SfM techniques to fluvial hydraulic experimentation in the laboratory, using "clear-water" on a reduced model, with the aim of developing new formulations and computer applications.

  In this field of application, SfM techniques can be configured as an extremely agile and efficient alternative, over the approaches using LiDAR in its TLS variant, for the study and analysis of processes and fluvial phenomena. In this sense, it could be applied to sediment transport, to general and local erosion (scour) associated with piers and stirrups on riverbeds, to the design of protective elements geometry in margins and the induced changes in thalweg, as well as to the evolution of fluvial morphologies.

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APÉNDICE I.
Índices de calidad de las revistas científicas

ÍNDICES DE CALIDAD DE LAS REVISTAS CIENTÍFICAS
SCIENTIFIC JOURNAL QUALITY INDEXES

SJR (SCImago Journal Rank) indicator

It expresses the average number of weighted citations received in the selected year by the documents published in the selected journal in the three previous years.

H Index

The H index expresses the journal's number of articles (*h*) that have received at least *h* citations. It quantifies both journal scientific productivity and scientific impact and it is also applicable to scientists, countries, etc.

Total Documents

Output of the selected period. All types of documents are considered, including citable and non-citable documents.

Total Documents (3years)

Published documents in the three previous years (selected year documents are excluded). All types of documents are considered, including citable and non-citable documents.

Citable Documents (3 years)

Number of citable documents published by a journal in the three previous years (selected year documents are excluded). Exclusively articles, reviews and conference papers are considered.

Non-citable Docs. (Available in the graphics)

Non-citable documents ratio in the period being considered.

Total Cites (3 years)

Number of citations received in the seleted year by a journal to the documents published in the three previous years. All types of documents are considered.

Self Cites

Number of journal's self-citations in the seleted year to its own documents published in the three previous years. All types of documents are considered.

Cites per Document (2 years)

Average citations per document in a 2 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the two previous years.

Cites per Document (3 years)

Average citations per document in a 3 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the three previous years.

Cites per Document (4 years)

Average citations per document in a 4 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the four previous years.

Cited Documents

Number of documents cited at least once in the three previous years, --i.e. years X-1, X-2 and X-3

Uncited Documents

Number of uncited documents in the three previous years.

References per Document

Average number of references per document in the selected year.

% International Collaboration

Document ratio whose affiliation includes more than one country address.

Journal of Hydrology (Netherlands)

- Editorial: Elsevier
- ISSN: 0022-1694
- URL: https://www.journals.elsevier.com/journal-of-hydrology/
- Impact Factor (2015): 3.043
- 5-year Impact Factor: 3.882
- Source Normalized Impact per Paper (SNIP-2015): 1.667
- SCImago Journal Rank (SJR-2015): 1.743
- H Index: 148
- CiteScore (SCOPUS-2015): 3.54
- CiteScore (SCOPUS-2016): 3.82
- Quartile (Journal Citation Reports-2015):

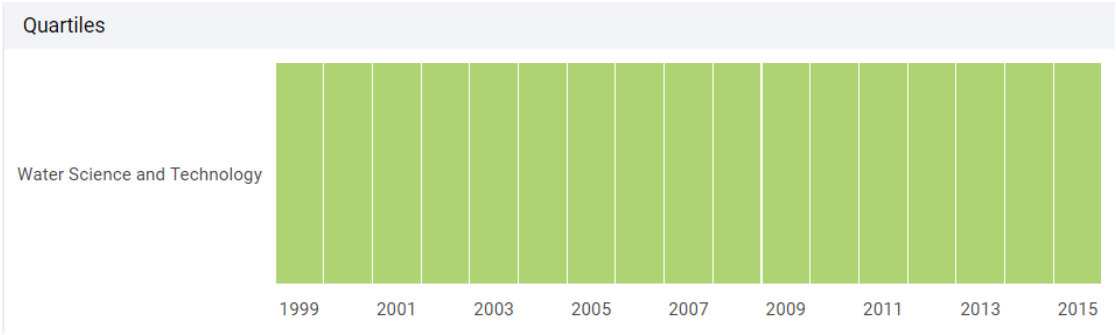
  Rank: 6/85 (Q1, First decile) Water Resources

  5/126 (Q1, First decile) Engineering, Civil

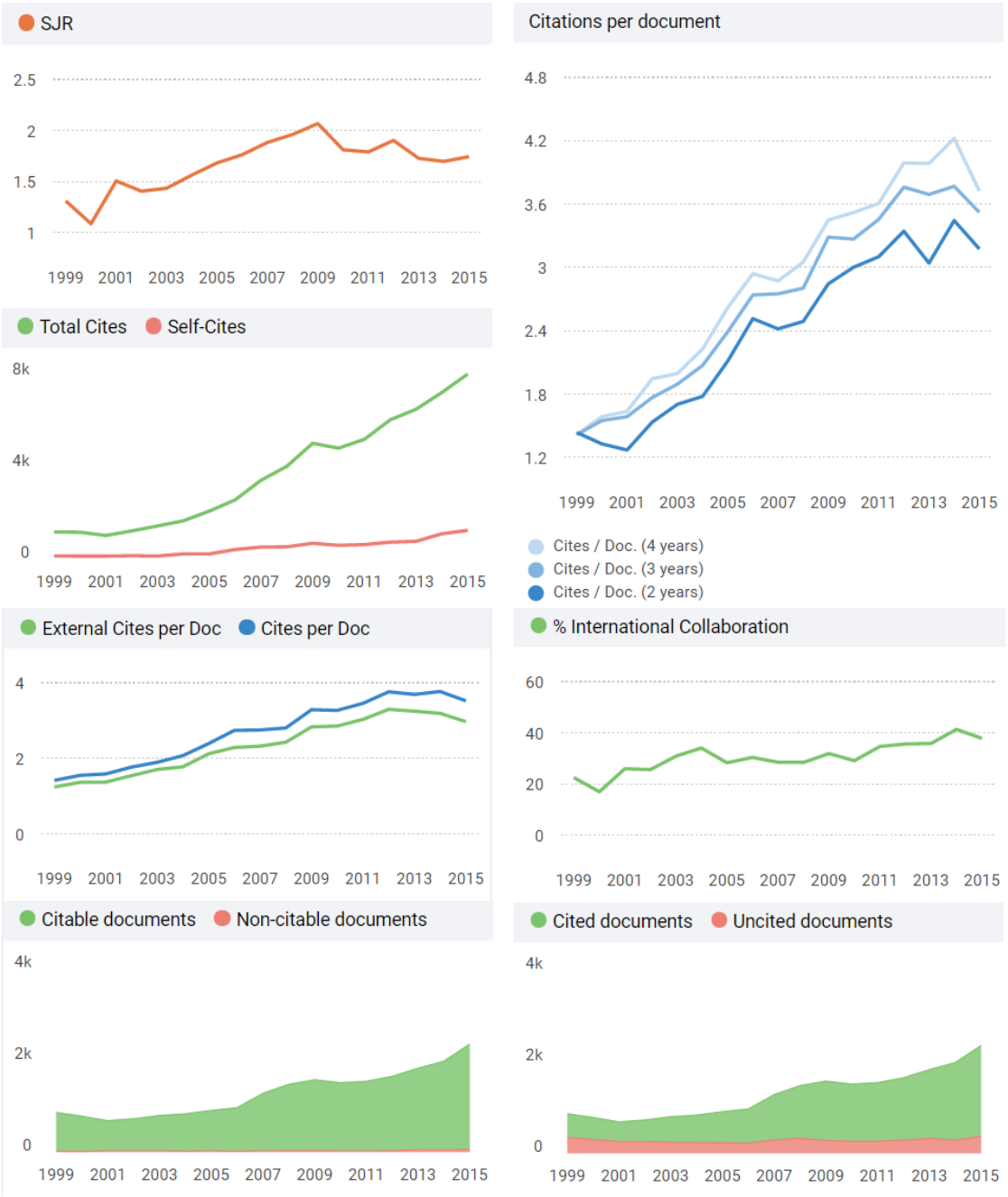
  33/184 (Q1) Geosciences, Multidisciplinary
- Quartile (SCImago Journal Rank-2015):

  Rank: (Q1, First decile) Water Science and Technology
- Quartile (SCOPUS-2015):

  Rank: 10/185 (Q1, First decile) Water Science and Technology



Q1 (green). Q2 (yellow). Q3 (orange). Q4 (red).



Scimago Journal & Country Rank (http://www.scimagojr.com)
Note: “k” is expressed in thousands of documents or citations

River Research and Applications (United Kingdom)

- Editorial: John Wiley & Sons Ltd
- ISSN / e-ISSN: 1535-1459 / 1535-1467
- URL: http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1535-1467
- Impact Factor (2015): 1.980
- 5-year Impact Factor: 2.341
- Source Normalized Impact per Paper (SNIP-2015): 1.069
- SCImago Journal Rank (SJR-2015): 0.984
- H Index: 67
- CiteScore (SCOPUS-2015): 1.99
- CiteScore (SCOPUS-2016): 1.99
- Quartile (Journal Citation Reports-2015):

  Rank: 22/85 (Q2) Water Resources

  102/225 (Q2) Environmental Sciences
- Quartile (SCImago Journal Rank-2015):

  Rank: (Q1) Water Science and Technology

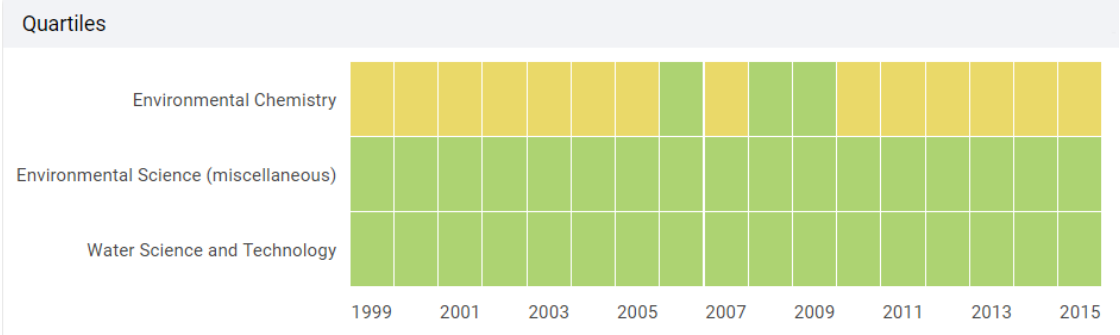
  (Q1) Environmental Sciene

  (Q2) Environmental Chemistry
- Quartile (SCOPUS-2015):

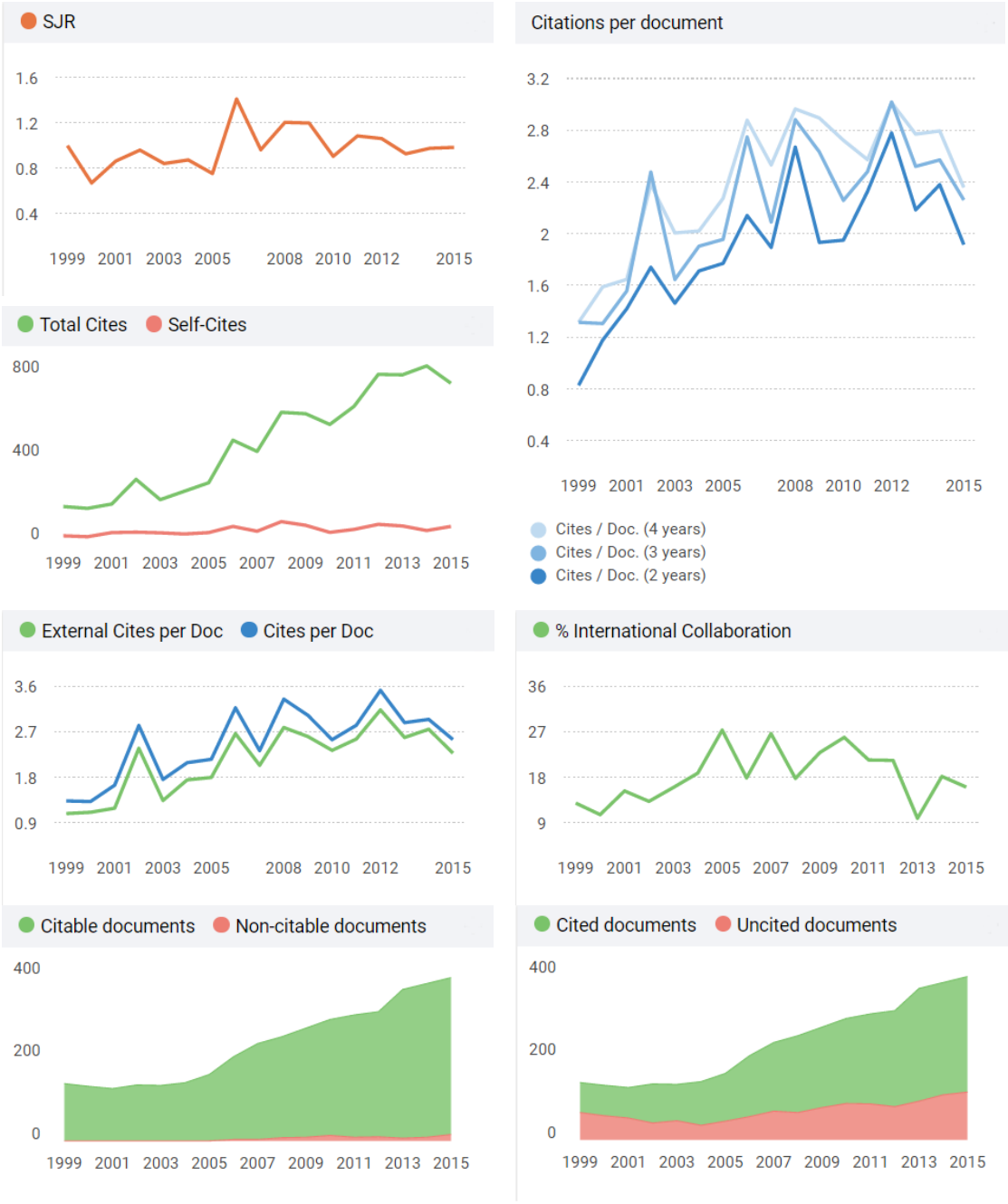
  Rank: 29/185 (Q1) Water Science and Technology

  33/186 (Q1) Environmental Sciene

  45/92 (Q2) Environmental Chemistry



Q1 (green). Q2 (yellow). Q3 (orange). Q4 (red).



Scimago Journal & Country Rank (http://www.scimagojr.com)
Note: “k” is expressed in thousands of documents or citations

Water (Switzerland)

- Editorial: Multidisciplinary Digital Publishing Institute (MDPI)
- ISSN: 2073-4441
- URL: http://www.mdpi.com/journal/water
- Impact Factor: 1.687
- 5-year Impact Factor: 1.912
- Source Normalized Impact per Paper (SNIP-2015): 1.022
- SCImago Journal Rank (SJR): 0.536
- H Index: 11
- CiteScore (SCOPUS-2015): 1.96
- CiteScore (SCOPUS-2016): 1.98
- Quartile (Journal Citation Reports-2015):

  Rank: 33 /85 (Q2) Water Resources
- Quartile (SCImago Journal Rank-2015):

  Rank: (Q2) Water Science and Technology

  (Q2) Geography, Planning and Development

  (Q2) Aquatic Science

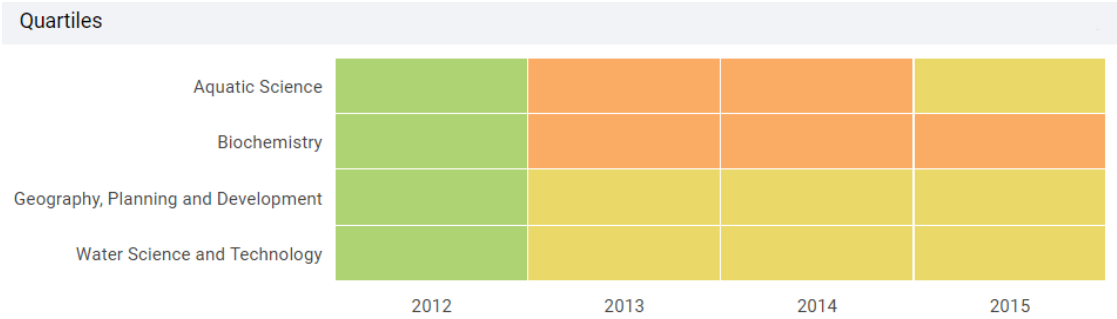
  (Q3) Biochemistry
- Quartile (SCOPUS-2015):

  Rank: 30/185 (Q1) Water Science and Technology

  64/569 (Q1) Geography, Planning and Development

  45/192 (Q1) Aquatic Science

  209/382 (Q3) Biochemistry



Q1 (green). Q2 (yellow). Q3 (orange). Q4 (red).

Scimago Journal & Country Rank (http://www.scimagojr.com)
Note: “k” is expressed in thousands of documents or citations

APÉNDICE II.

Repercusión de las investigaciones

A continuación se detalla el historial de los artículos que conforman las investigaciones de esta Tesis Doctoral y la repercusión de éstos entre la comunidad científica internacional, hasta 31 de marzo de 2017, fecha de redacción de la Tesis.

Publicación científica I.

Innovative Analysis of Runoff Temporal Behavior through Bayesian Networks

HISTORIAL DEL ARTÍCULO

- Revista: Water.
- Enviado: 8 de septiembre de 2016.
- Aceptación para publicación: 20 de octubre de 2016.
- Publicación online: 27 de octubre de 2016.
- Indexación Web of Science (WOS): Noviembre 2016.
- Total de citas recibidas: 1.
- Total de autocitas: 0.

INVESTIGACIONES DONDE SE HA CITADO LA PUBLICACIÓN

Multivariate Analysis of Joint Probability of Different Rainfall Frequencies Based on Copulas

Yang Wang, Chuanzhe Li, Jia Liu, Fuliang Yu, Qingtai Qiu, Jiyang Tian, Mengjie Zhang

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China.

Water. Marzo de 2017.

Publicación científica II.

Analysis of flood modeling through innovative geomatic methods

HISTORIAL DEL ARTÍCULO

- Revista: Journal of Hydrology.
- Enviado: 26 de diciembre de 2014.
- Revisión: 21 de febrero de 2015.
- Aceptación para publicación: 5 de marzo de 2015.
- Publicación online: 14 de marzo de 2015.
- Publicación en revista: Mayo 2015, Volumen 524.
- Indexación Web of Science (WOS): Mayo 2015.
- Total de citas recibidas: 5.
- Total de autocitas: 1 (River Research and Applications).

INVESTIGACIONES DONDE SE HA CITADO LA PUBLICACIÓN

Evaluation of the U.S. Geological Survey standard elevation products in a two-dimensional hydraulic modeling application for a low relief coastal floodplain

Emitt C. Witt III

U.S. Geological Survey, Center of Excellence for Geospatial Information Science, Rolla, MO 65401, United States.

Missouri University of Science & Technology, Department of Geologic Sciences and Engineering, Rolla, MO 65409, United States.

Journal of Hydrology. Diciembre de 2015.

Flood risk assessment and mapping in Abidjan district using multi-criteria analysis (AHP) model and geoinformation techniques, (cote d'ivoire)

Jean Homian Danumah[1], Samuel Nii Odai[1], Bachir Mahaman Saley[2], Joerg Szarzynski[3], Michael Thiel[1], Adjei Kwaku[1], Fernand Koffi Kouame[2] and Lucette You Akpa[2]

1 Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, WASCAL PhD Program in Climate Change and Land Use, Kumasi, Ghana.

2 Centre Universitaire de Recherche et d'Application en Télédétection (CURAT), Laboratoire Associé Francophone (LAF n° 401), UFR des Sciences de la Terre et des Ressources Minières, Université Felix Houphouët Boigny.

Journal of Geoenvironmental Disasters. Mayo 2016.

1-D Mathematical Modelling of Flood Wave Propagation

Olga Ivanova, Mikhail Ivanov

Bauman Moscow State Technical University.

CISAP7: 7th International Conference on Safety & Environment in Process Industry. Ischia (Italia). 25-28 de Septiembre de 2016.

Chemical Engineering Transactions. Septiembre 2016.

Towards periodic and time-referenced flood risk assessment using airborne remote sensing

Claire Brenner, Claude Meisch, Benjamin Apperl, Karsten Schulz

University of Natural Resources and Life Sciences, Vienna, Institute of Water Management, Hydrology and Hydraulic Engineering (IWHW), Muthgasse 18, 1190 Vienna, Austria.

Journal of Hydrology and Hydromechanics. Octubre de 2016.

Flood analysis supported by low-cost geometric modelling (Autocitación)

S. Zazo[a], P. Rodríguez-Gonzálvez[a], J.-L. Molina[a], D. Hernández-López[b], D. González-Aguilera[a]

a High Polytechnic School of Engineering, University of Salamanca, Hornos Caleros, 50, 05003, Ávila, Spain.

b Institute for Regional Development (IDR), University of Castilla-La Mancha. Campus Universitario s/n, 02071, Albacete, Spain.

River Research and Applications. Octubre 2016.

Publicación científica III.

Flood analysis supported by low-cost geometric modelling

HISTORIAL DEL ARTÍCULO

- Revista: River Research and Applications.
- Enviado: 16 de julio de 2016.
- Revisión: 11 de octubre de 2016.
- Aceptación para publicación: 27 de octubre de 2016.
- Publicación online: 23 de diciembre de 2016.
- Publicación en revista: No disponible todavía.
- Indexación Web of Science (WOS): No disponible todavía.