Departamento de Ecología e Hidrología
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Ecological Basis for Assessing Environmental Flow Regimes in the Segura Basin

Bases Ecológicas para el Establecimiento de Regímenes de Caudales Ambientales en la Cuenca del Segura

Memoria presentada para la obtención del grado de doctor

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D. José Miguel Martínez Paz, Profesor Titular de Universidad del Área de Economía Aplicada A, Departamento de Economía Aplicada, y **Presidente Comisión Académica programa doctorado** * Tecnología Administración y Gestión del Agua (TAyGA), INFORMA:

Que una vez evaluado, de conformidad con el procedimiento establecido en el artículo 21 del Reglamento de doctorado de la Universidad de Murcia, el expediente completo de la tesis doctoral titulada "Bases Ecológicas para el Establecimiento de Regímenes de Caudales Ambientales en la Cuenca del Segura", realizada por D. Óscar Belmar Díaz, bajo la inmediata dirección y supervisión de Dª. Josefa Velasco García y D. Francisco Martínez-Capel, esta Comisión Académica, en sesión celebrada en fecha 11/12/12, ha dado su autorización para su presentación ante la Comisión General de Doctorado.

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A mi familia y amigos,
por el tiempo robado

There is no lack of water in the Mojave Desert unless you try to establish a city where no city should be

Edward Abbey

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Introducción general

Durante milenios, el ser humano ha alterado los caudales de los ríos por una miríada de razones, incluyendo la captación de agua para abastecimiento, irrigación y usos recreativos así como la laminación de avenidas y el uso hidroeléctrico (Gleick, 2003). En áreas Mediterráneas, la creciente manipulación del ciclo hidrológico y exacerbación del cambio climático por parte del ser humano han resultado en presiones sobre los recursos que afectan a la estructura y funcionamiento de los ecosistemas, causando considerable daño ecológico y la pérdida de servicios ecosistémicos valorados por la sociedad. Puesto que la mayoría de los ríos están cada vez más regulados para satisfacer las demandas de agua, la alteración de los regímenes de caudales continúa aumentando en todo el mundo. Las demandas y actividades humanas han dado lugar a extendidas alteraciones de la variabilidad, predictibilidad y recurrencia de los caudales, y como resultado, han degradado los ecosistemas fluviales, creando de ese modo un conflicto entre conservación y explotación.

En este contexto, la Directiva Marco del Agua (DMA, 2000/60/CE) ha establecido un marco europeo para la protección de las aguas continentales superficiales, subterráneas, de transición y costeras para prevenir o reducir su polución, promover su uso sostenible, proteger el medio ambiente, mejorar el estado de los ecosistemas acuáticos y mitigar los efectos de las avenidas y las sequías. La DMA introduce un enfoque ecológico y ambiental en el planeamiento y la gestión de los recursos hídricos. Sin embargo, aplicar medidas para mejorar la calidad de los ríos y sus áreas adyacentes carece de fundamento si sus caudales no mantienen al menos las características esenciales de sus regímenes hidrológicos naturales.

Por lo tanto, el estudio de la interacción de los procesos hidrológicos y ecológicos es fundamental para la gestión de los ecosistemas acuáticos, y ha derivado en una materia interdisciplinar que ha cobrado una importancia considerable desde finales de la década de los 90. La "Ecohidrología" ha sido definida como la "cuantificación y modelado de la regulación dual de la biota por la hidrología y viceversa en una cuenca y la comprensión de su modificación e integración sinérgica para amortiguar los impactos del hombre con el fin último de preservar, mejorar o restaurar la capacidad de los ecosistemas acuáticos de la cuenca para su uso sostenible" (Zalewski *et al.*, 1997).

El régimen natural de un río define su patrón de variabilidad hidrológica inherente, que refleja la interacción entre el régimen climático (definido principalmente por la precipitación y la temperatura) y las características que regulan la escorrentía (principalmente geología, litología y cubierta vegetal). Los cinco componentes que caracterizan el régimen hidrológico de un río (Poff & Ward, 1989; Richter *et al.*, 1996; Walker *et al.*, 1995) son la magnitud, frecuencia, duración y predictibilidad de los distintos eventos de caudal, así como su tasa de cambio. Los caudales varían a diferentes escalas temporales (diaria, estacional y anual) y espaciales (Poff *et al.*, 2006), con regímenes similares en ríos de cuencas cercanas.

El régimen hidrológico constituye el principal determinante de los ecosistemas acuáticos (Hart & Finelli, 1999; Poff *et al.*, 1997; Richter *et al.*, 1996) puesto que define su estructura y función a escalas que van de locales a regionales y de días (efectos ecológico) a milenios (efectos evolutivos) (Lytle & Poff, 2004). En general, ello surge de la combinación de dos elementos: (1) los cambios experimentados por el hábitat físico, debido al efecto de factores ambientales derivados como velocidad del agua, estrés sobre las orillas, turbulencia, granulometría, temperatura, contenido de oxígeno y actividad fotosintética en la columna de agua (Richter *et al.*, 1998; Sedimentation Committee, 1992), y (2) la capacidad de las comunidades para desarrollar estrategias de vida en respuesta directa a estos cambios (Bunn & Arthington, 2002).

Puesto que los regímenes de caudal influyen en la integridad de los ecosistemas directa e indirectamente a través de su efecto en otros reguladores primarios (Poff *et al.*, 1997), su modificación tiene un efecto en cascada en la integridad ecológica de los ríos (Karr, 1991). La extensiva alteración antrópica de los caudales de los ríos ha dado lugar a cambios geomorfológicos y ecológicos ampliamente extendidos en estos ecosistemas (Poff *et al.*, 1997).

En general, los cambios sufridos por los regímenes hidrológicos pueden clasificarse como directos e indirectos. Los cambios directos son consecuencia de infraestructuras diseñadas para modificar los caudales; generalmente presas hidroeléctricas, de abastecimiento, de laminación o agrícolas. A comienzos del siglo XXI, había alrededor de 45 000 grandes presas (World Commission on Dams, 2000) en 140 países y 800 000 pequeñas presas en todo el mundo (McCully, 1996). Por el contrario, los cambios indirectos son aquellos producidos por actividades que no persiguen modificar el régimen hidrológico en sí pero ocurren como un efecto colateral. Tienden a estar asociados con actividades que implican cambios en los usos del suelo, especialmente deforestación, urbanización y agricultura (Poff *et al.*, 1997).

Los efectos de las infraestructuras hídricas en el régimen hidrológico son más pronunciados en ríos Mediterráneos. Puesto que la mayoría de las áreas de clima Mediterráneo están densamente pobladas, sus escasos recursos y altas demandas hídricas determinan las necesidades de almacenamiento y capacidades de embalse (Batalla *et al.*, 2004; López-Moreno *et al.*, 2009; Lorenzo-Lacruz *et al.*, 2010). En consecuencia, estas áreas son más vulnerables a la alteración hidrológica, especialmente si se considera que las proyecciones climáticas pronostican un descenso generalizado de la precipitación, escorrentía y recarga subterránea y un aumento de la evapotranspiración (CEDEX, 2011; IPCC, 2007).

El reconocimiento del aumento global de la alteración de los ríos y de la degradación ambiental resultante ha conducido al desarrollo de metodologías diseñadas para la definición de regímenes hidrológicos asociados con objetivos de gestión específicos: una estrategia proactiva antes de la alteración, que mantenga los regímenes hidrológicos tan cercanos como sea posible a la condición de referencia, o una estrategia reactiva para restaurar ciertas características del caudal y del ecosistema en regímenes ya alterados.

Dichas estrategias incluyen la definición de “Regímenes Ambientales de Caudales” (RACs). “Caudal Ambiental” es un término ampliamente aceptado que cubre la “cantidad, recurrencia, duración, frecuencia y calidad de caudales requerida para mantener los ecosistemas de agua dulce y estuarios y el sustento y bienestar humanos que dependen de estos ecosistemas” (Brisbane Declaration, 2007). Por tanto, implementar regímenes de caudales ambientales constituye una medida clave para proteger y restaurar los ecosistemas fluviales (Arthington *et al.*, 1991; Arthington *et al.*, 2006; Arthington *et al.*, 2010; Poff *et al.*, 1997; Richter *et al.*, 1996; Richter *et al.*, 1997; Sparks, 1992).

En Europa, la Directiva Marco del Agua no utiliza explícitamente el término “Caudal Ambiental”, aunque requiere la consecución de un “buen estado ecológico” en los cuerpos de agua antes de 2015. Sin embargo, la legislación de aguas española establece específicamente la necesidad de definir caudales ambientales en los planes de gestión (*ORDEN ARM/2656/2008, Ministerio de Medio Ambiente y Medio Rural y Marino*).

Más de 200 metodologías han sido creadas para definir caudales ambientales desde los años setenta (Tharme, 2003). En resumen, tres grupos principales han aparecido secuencialmente, puesto que constituyen aproximaciones gradualmente más complejas: métodos hidrológicos, de simulación de hábitat y holísticos. La “Instrucción de Planificación Hidrológica” española (IPH, *ORDEN ARM/2656/2008*) establece el uso de los métodos hidrológicos y de simulación de hábitat para la definición de regímenes ambientales de caudales.

Los métodos hidrológicos, basados en el estudio de largas series temporales de aforo, han sido la aproximación más frecuentemente utilizada en España (e.j. Palau, 1994). Usan estadísticos para caracterizar en mayor o menor medida los regímenes de caudal y definir objetivos de gestión (por ejemplo, un rango de variación) para las métricas hidrológicas seleccionadas. Se han desarrollado sistemas de métricas para caracterizar los cinco componentes del régimen hidrológico, tales como las contenidas en los “Indicadores de Alteración Hidrológica” (Richter *et al.*, 1996; Richter *et al.*, 1997) o los “Indicadores de Alteración Hidrológica en Ríos” (Martínez & Fernández, 2006).

Los métodos de simulación de hábitat se basan en la premisa de que la disponibilidad de hábitat para los organismos fluviales es un factor limitante cuando se producen cambios en el caudal. Estos métodos integran modelos hidráulicos y de simulación de hábitat que evalúan cambios en los indicadores de hábitat (e.g. área ponderada útil, APU) y estiman la idoneidad de tales condiciones para las especies “objetivo” seleccionadas. Por lo tanto, las salidas de los modelos permiten la evaluación de diferentes escenarios de gestión (Waddle, 1998). El método IFIM y su modelo asociado PHABSIM (Bovee, 1982; Milhous, 1998; Milhous *et al.*, 1989; Nestler *et al.*, 1989; Stalnaker *et al.*, 1995) constituyen un punto de referencia en los métodos de simulación de hábitat. Para más detalles, ver Stalnaker *et al.* (1995), Bovee *et al.* (1998) y Díez-Hernández (2006).

Los métodos holísticos proporcionan un enfoque más completo de la definición de “Caudal Ambiental” que abarca el ecosistema entero en lugar de únicamente aspectos específicos (*sensu* Arthington *et al.*, 2004; Tharme, 2003). Esencialmente, cuatro pasos definen estas metodologías: (1) clasificación de ríos de referencia en grupos basados en combinaciones de componentes hidrológicos ecológicamente relevantes, (2) desarrollo de las frecuencias de distribución de los componentes para representar el rango de variabilidad natural de cada clase, (3) comparación con los regímenes alterados y (4) desarrollo de relaciones “Régimen de caudal-respuesta ecológica” utilizando indicadores ecológicos para cada componente y clase.

Los “Límites Ecológicos de la Alteración Hidrológica” (ELOHA; Arthington *et al.*, 2006; Poff *et al.*, 2010) han cobrado gran importancia en este grupo dado su amplio uso en todo el mundo (ConserveOnline, 2012). El proceso consiste en cuatro pasos principales construidos sobre la aproximación holística (Arthington *et al.*, 2006). Las relaciones entre la alteración del caudal y las características ecológicas para distintos tipos de río, desarrollados sobre la base del análisis y la clasificación hidrológicos, proporciona un input científico para un proceso que sopesa esta información con valores y metas sociales.

Objetivos

El objetivo general de esta tesis fue establecer las bases ecohidrológicas para la definición de caudales ambientales mediante una aproximación holística (ELOHA) en una cuenca semiárida Mediterránea, altamente regulada, con un amplio espectro de regímenes naturales: la Cuenca del Río Segura (SE español).

Para ello, los objetivos específicos fueron:

1. Definir una clasificación hidrológica para los ríos y arroyos de la cuenca basada en la similaridad de sus regímenes naturales de caudal, caracterizados utilizando índices hidrológicos.
2. Evaluar la capacidad de dos clasificaciones ambientales (*a priori*) para discriminar la variación hidrológica natural de la cuenca, así como su concordancia con la clasificación hidrológica (*a posteriori*).
3. Determinar el efecto de los diferentes regímenes naturales de caudales sobre la composición y riqueza de la comunidad de macroinvertebrados a diferentes resoluciones taxonómicas (familia, género y especie).
4. Caracterizar y cuantificar las principales alteraciones hidrológicas en la cuenca por tipo hidrológico.
5. Determinar los efectos de la alteración hidrológica en los hábitats fluviales y en las condiciones riparias para cada tipo.

Área de estudio

La elección de la Cuenca del Río Segura se basa en que representa uno de los extremos más áridos del Mediterráneo occidental, hacia el que otras cuencas de áreas templadas tenderán debido al cambio climático y donde la implementación de caudales ambientales es una tarea urgente.

A pesar de su tamaño relativamente pequeño, la cuenca presenta fuertes gradientes de NO a SE: (1) un gradiente climático y altitudinal desde las frías y húmedas montañas hasta las semiáridas y calurosas llanuras, sujetas a fuertes tormentas otoñales, y (2) un gradiente de densidad poblacional entre las escasamente pobladas cabeceras y las densamente pobladas llanuras (Mellado, 2005).

Como otras regiones Mediterráneas, se caracteriza por unos recursos hídricos escasos e irregularmente distribuidos y una alta variabilidad hidrológica. Las grandes demandas de agua, principalmente para irrigación (90%), exceden los recursos disponibles (Gil-Olcina, 2000), produciendo así un déficit estructural que se ha sido acentuado en las últimas décadas por una tendencia decreciente en la precipitación (CHS, 2005). Debido a estas intensas presiones, las aguas superficiales están sobreexplotadas y las subterráneas sufren una extracción de aproximadamente el 80% de la recarga natural, convirtiendo la cuenca en una de las más reguladas de España y Europa.

Río Segura
Embalse de Almadenes

Capítulo 1. Clasificación hidrológica de regímenes naturales de caudal para apoyar la estimación de caudales ambientales en ríos Mediterráneos intensivamente regulados, cuenca del Río Segura (España)

Belmar, O., Velasco, J. & Martínez-Capel, F. (2011) Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River basin (Spain). *Environmental Management* **47**, 992-1004

La clasificación hidrológica constituye el primer paso de un reciente marco holístico para el desarrollo de caudales ambientales a escala regional: los “Límites Ecológicos de la Alteración Hidrológica” (ELOHA). El objetivo de este estudio fue desarrollar una clasificación para 390 secciones de río de la cuenca del Río Segura basada en 73 índices hidrológicos que caracterizan su régimen natural de caudales. Los índices hidrológicos fueron calculados con 25 años de caudales mensuales naturales (1980/81-2005/06) derivados de un modelo precipitación-aportación desarrollado por el Ministerio español de Medio Ambiente y Obras Públicas. Estos índices incluyeron, a una escala mensual o anual, medidas de duración de sequía y de tendencia central y dispersión de la magnitud del caudal (en condiciones de medio, bajo y alto caudal). El Análisis de Componentes Principales (PCA) mostró una alta redundancia entre la mayoría de los índices hidrológicos, así como dos gradientes: magnitud del caudal para los ríos principales y variabilidad temporal para los afluentes. Una clasificación con 8 tipos de régimen hidrológico fue elegida como la más fácilmente interpretable en la Cuenca del Segura, lo que fue apoyado por el análisis ANOSIM. Estas clases pueden simplificarse en 4 grupos más amplios, con diferente patrón estacional de descarga: grandes ríos, arroyos perennes estables, arroyos perennes estacionales y arroyos intermitentes y efímeros. Las clases mostraron un amplio grado de cohesión espacial, siguiendo un gradiente asociado con la aridez climática de Noroeste a Sureste, y estuvieron bien definidas en términos de las variables fundamentales en arroyos Mediterráneos: la magnitud y la variabilidad temporal del caudal. Por lo tanto, esta clasificación es una herramienta esencial para apoyar la gestión y planificación del agua en la cuenca del Río Segura y establecer la base para diseñar caudales ambientales científicamente creíbles siguiendo el marco ELOHA.

Capítulo 2. ¿Son válidas las clasificaciones ambientales "a priori" de ríos para la estima de caudales ambientales en cuencas Mediterráneas?

Belmar, O., Velasco, J., Martínez-Capel, F., Peredo-Parada, M. & Snelder, T. (2012) Do Environmental Stream Classifications Support Flow Assessments in Mediterranean Basins? *Water Resources Management* **26**, 3803-3817

Los regímenes naturales de caudal son de interés primario para el diseño de caudales ambientales y por tanto esenciales para la gestión y la planificación del agua. Este capítulo discrimina la variación hidrológica natural utilizando dos clasificaciones ambientales (*a priori*) diferentes (REC-Segura y ecotipos-DMA) y testa su acuerdo con una clasificación hidrológica (*a posteriori*) en una cuenca Mediterránea española (Río Segura, Sureste español). La REC-Segura fue desarrollada como una clasificación jerárquica de dos niveles basada en variables ambientales que determinan la hidrología (clima y origen de caudal). Los ecotipos-DMA fueron desarrollados por el Ministerio español de Medio Ambiente para implementar la Directiva Marco del Agua (DMA) utilizando variables hidrológicas, morfológicas y físico-químicas jerárquicamente. El nivel climático de la REC-Segura reflejó en líneas generales el patrón hidrológico observado a lo largo del gradiente de aridez Noroeste-Sureste de la cuenca. Sin embargo, el origen del caudal (definido por la geología cárstica) sólo fue capaz de discriminar variaciones entre regímenes hidrológicos dentro de una de las categorías climáticas. Los ecotipos-DMA, a pesar de incorporar variables hidrológicas, no discriminaron totalmente la variabilidad hidrológica de la cuenca. Ecotipos en afluentes localizados en climas secos o semiáridos abarcan diferentes regímenes de caudal (tanto perennes como intermitentes). La congruencia entre las clasificaciones ambientales y la hidrológica fue baja. Por lo tanto, desaconsejamos el uso de clasificaciones ambientales para la definición de regímenes ambientales de caudales sin testar primero su capacidad para discriminar los patrones hidrológicos.

Capítulo 3. La influencia de los regímenes naturales de caudal en las comunidades de macroinvertebrados en una cuenca Mediterránea semiárida

Belmar, O., Velasco, J., Gutiérrez-Cánovas, C., Mellado-Díaz, A., Millán, A. & Wood, P. J. (2012) The influence of natural flow regimes on macroinvertebrate assemblages in a semiarid Mediterranean basin. *Ecohydrology*. DOI: 10.1002/eco.1274

La investigación de las relaciones hidrología-ecología constituye la base para el desarrollo de criterios de definición de caudales ambientales. La necesidad de comprender estas conexiones en sistemas naturales ha aumentado debido a las perspectivas de cambio climático y a la gestión de los caudales, especialmente en áreas de recursos hídricos escasos como las cuencas Mediterráneas. Este capítulo analiza la respuesta de la comunidad de macroinvertebrados a nivel de familia, género y especie a la dinámica de regímenes naturales en los ríos de agua dulce de una cuenca semiárida Mediterránea (Río Segura, SE español) e identifica los componentes del caudal que influyen en la composición y riqueza de las comunidades biológicas. La estabilidad del caudal y los caudales mínimos fueron los principales determinantes hidrológicos de las comunidades de macroinvertebrados, mientras que la magnitud de los caudales medios y máximos tuvo un efecto limitado. Los arroyos perennes estables estuvieron caracterizados por taxones lóticos (EPT; Ephemeroptera, Plecoptera y Trichoptera) y los arroyos intermitentes por taxones predominantemente lénticos (OCHD; Odonata, Coleoptera, Heteroptera y Diptera). Sin embargo, a lo largo de este gradiente de estabilidad de caudal, las diferencias en la composición de las comunidades entre clases hidrológicas intermedias fueron menores. La variación estacional y los caudales mínimos son por tanto componentes hidrológicos clave que necesitan ser considerados para la gestión de los ríos y los caudales ambientales de la Cuenca del Segura, así como de otras cuencas Mediterráneas. La modificación antropogénica de estos parámetros, debida tanto a actividades humanas como al cambio climático, conduciría probablemente a cambios significativos en la estructura y la composición de las comunidades en arroyos perennes estables. Ello se caracterizaría por una reducción de los taxones EPT más sensibles y un aumento de los taxones OCHD más resilientes.

Capítulo 4. Efectos de la alteración del régimen de caudales en los hábitats fluviales y la calidad riparia en una cuenca Mediterránea semiárida

Belmar, O., Bruno, D., Martínez-Capel, F., Barquín, J. & Velasco, J. (In Review) Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. *Ecological Indicators*

La cuenca del Río Segura, una de las áreas más áridas y reguladas de la zona Mediterránea y de Europa, incluye cuatro tipos hidrológicos de río, según sus regímenes naturales de caudal: ríos principales, arroyos perennes estables (cabeceras), arroyos perennes estacionales y arroyos temporales (intermitentes o efímeros). La relación entre los regímenes de caudal y los hábitats fluviales y riparios (características y calidad) fue estudiada en sitios de referencia e hidrológicamente alterados en los cuatro tipos. La alteración de los regímenes de caudal fue valorada utilizando dos procedimientos: 1) un índice indirecto, derivado de variables asociadas a las principales presiones hidrológicas en la cuenca, y 2) el análisis de series naturales y alteradas de caudales utilizando los "Indicadores de Alteración Hidrológica" (IHA) y los "Indicadores de Alteración Hidrológica en Ríos" (IAHRIS). Los hábitats fueron caracterizados utilizando el "River Habitat Survey" (RHS) y su índice derivado, el "Habitat Quality Assessment" (HQA), mientras que la condición riparia fue evaluada usando el "Índice de Calidad Riparia" (RQI) y un inventario de especies de plantas nativas/exóticas. La estabilidad y magnitud del caudal fueron identificadas como los principales determinantes hidrológicos de los hábitats fluviales en la cuenca del Segura. La alteración hidrológica fue similar a la descrita en otras áreas Mediterráneas áridas y semiáridas, donde las presas han reducido la magnitud y la variabilidad del caudal y producido la inversión de los patrones estacionales. Además, la cuenca del Segura presentó dos tendencias generales de alteración: un aumento de torrencialidad en los ríos principales y un aumento de temporalidad es los arroyos estacionales y temporales. Con el índice indirecto de alteración, los ríos principales presentaron el mayor grado de alteración hidrológica, que derivó en cauces de mayores dimensiones y en menos macrófitos y mesohábitats. Sin embargo, según los análisis hidrológicos, los arroyos estacionales presentaron la mayor alteración, lo que fue respaldado por el gran número de cambios en las características de los hábitats. Dichos cambios estuvieron asociados con una mayor proporción de vegetación uniforme en las orillas así como con una reducción de la riqueza de plantas riparias nativas y de la densidad de mesohábitats. Ambos tipos presentaron consecuentes reducciones en las calidades de hábitat y riparia conforme aumentó el grado de alteración. Sin embargo, los arroyos estables, los menos alterados de la cuenca, y los arroyos temporales, que sufren un fuerte estrés hidrológico en condiciones naturales, mostraron menos cambios en el hábitat físico a causa de la alteración hidrológica. Este capítulo establece la relación entre el régimen hidrológico y el hábitat físico en cuencas Mediterráneas. Los indicadores hidrológicos y de hábitat que responden a las presiones humanas y los umbrales que implican cambios relevantes en las calidades de hábitat y riparia que aquí se presentan desempeñarán un papel fundamental en el uso de marcos holísticos para el desarrollo de caudales ambientales a escala regional.

Río Zumeta

Conclusiones

1. Las principales métricas que definieron los tipos de régimen hidrológico en la Cuenca del Río Segura fueron el caudal medio anual, el coeficiente interanual de variación y la duración de las sequías.
2. Una clasificación de 8 tipos fue considerada la solución óptima para abarcar la variación hidrológica a lo largo del gradiente de aridez NO-SE en el área de estudio. Para fines de gestión, 4 tipos más amplios con significado biológico deben utilizarse: *ríos principales, afluentes estables, afluentes estacionales y afluentes temporales*.
3. El uso de clasificaciones ambientales (*a priori*) jerárquicas como sustitutivas de las basadas en datos hidrológicos es desaconsejable cuando dicha información está disponible, dada su baja precisión discriminando la variación hidrológica. La REC-Segura sólo reflejó el patrón hidrológico NW-SE groseramente, mientras que los ecotipos de afluentes localizados en climas secos o semiáridos abarcaron diferentes regímenes de caudales (tanto perennes como intermitentes).
4. La estabilidad del caudal y los caudales mínimos fueron los principales determinantes hidrológicos de los macroinvertebrados de la Cuenca del Río Segura, mientras que la magnitud de los caudales medios y máximos tuvo efectos limitados. Estos efectos fueron más evidentes en la composición que en la riqueza, y conforme la resolución taxonómica aumentó.
5. Se encontró una relación relevante entre la magnitud-estabilidad del caudal y el ratio de taxones EPT/EPTOCHD. Los afluentes estables se caracterizaron por taxones sensibles al caudal (EPT; Ephemeroptera, Plecoptera, Tricoptera) y los afluentes intermitentes por taxones predominantemente lénticos (OCHD; Odonata, Coleoptera, Heteroptera y Diptera).
6. La estabilidad y magnitud del caudal fueron los principales determinantes hidrológicos de los hábitats fluviales de la Cuenca del Río Segura, lo que explica su efecto en los macroinvertebrados.
7. En general, las presas redujeron la magnitud y variabilidad del caudal e invirtieron los patrones estacionales, aunque también se observaron otras dos tendencias en tipos de río específicos: un aumento de la torrencialidad del caudal en los ríos principales y un aumento de la temporalidad en los afluentes

estacionales y temporales. Las reglas de operación de las presas, no sólo sus capacidades, determinaron el grado de alteración hidrológica.

8. La alteración hidrológica produjo cambios importantes en los hábitats y características riparias del área de estudio. En los ríos principales, la liberación de grandes volúmenes desde las presas implicó un aumento en las dimensiones del cauce, la homogeneización de los hábitats acuáticos y la ausencia de restos vegetales, con una reducción de la densidad de mesohábitats y de la presencia de vegetación sumergida. Sin embargo, en los afluentes estacionales fue evidente una "terrestrialización" asociada a reducciones en la riqueza de mesohábitats y de vegetación riparia y a ocasionales invasiones del cauce por parte de especies riparias o climatófilas leñosas. A pesar de la reducción de la riqueza de especies nativas riparias, no hubo aumento de la riqueza de exóticas.
9. Tanto los ríos principales como los afluentes estacionales presentaron consecuentes reducciones en las calidades de hábitat y riparia conforme el grado de alteración aumentó. El "Índice de Calidad Riparia" (RQI) fue más sensible que el "Habitat Quality Assessment" (HQA).
10. Los resultados obtenidos son esenciales para la gestión del agua así como para la conservación y restauración de los ecosistemas fluviales, y señalan los componentes del régimen hidrológico necesarios para preservar los hábitats y la biota nativa de la Cuenca del Río Segura. Por lo tanto, la variación estacional y los caudales mínimos son componentes hidrológicos clave que necesitan ser considerados para la definición de caudales ambientales en cuencas Mediterráneas y templadas, puesto que el cambio climático acentuará presumiblemente la aridez de estas áreas.

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General Introduction

Madera River near Peña Rubia

Overview

Over the millennia, humans have altered stream flows in riverine systems for a myriad of reasons that include harnessing water for drinking, irrigation and recreation as well as providing flood control and hydropower (Gleick, 2003). In Mediterranean areas, the increasing anthropogenic manipulation of the hydrological cycle and exacerbation of climate change has resulted in resource pressures that affect ecosystem structure and functioning, causing considerable ecological damage and the loss of ecosystem services that are valued by society. As most rivers are being increasingly regulated to satisfy water demands, flow regime alteration continues to grow globally. Human freshwater demands and activities have resulted in widespread alterations of the variability, predictability and timing of stream flows, and as a result, have degraded river ecosystems, thereby creating a conflict between conservation and exploitation.

In this context, the Water Framework Directive (WFD, 2000/60/CE) has established a European framework for the protection of continental surface, groundwater, transitional and coastal waters to prevent or reduce their pollution, promote their sustainable use, protect the environment, improve the status of aquatic ecosystems and attenuate the effects of floods and droughts. The WFD introduces an ecological and environmental approach in water resource planning and management. However, implementing measures to improve the quality of rivers and their adjacent areas is pointless if their flows do not maintain at least the essential characteristics of their natural hydrologic regimes.

Therefore, studying the interaction of hydrological and ecological processes is fundamental for water ecosystems management, and has developed into an emerging interdisciplinary subject area that has gathered considerable importance since the late 1990s. “Ecohydrology” has been defined as the “quantification and modelling of the dual regulation of biota by hydrology and vice versa within a basin, understanding their modification and synergistic integration in order to buffer man-made impacts with the ultimate goal of preserving, enhancing or restoring the capacity of the basin’s aquatic ecosystems for sustainable use” (Zalewski *et al.*, 1997).

The ecological importance of natural hydrologic regimes

The natural flow regime of a river defines its inherent hydrologic variability pattern, which reflects the interaction between the climatic regime (defined mainly by precipitation and temperature) and the characteristics that regulate runoff (mainly geology, lithology and vegetal cover). This variability occurs at different temporal (daily, seasonal and annual) and spatial scales (Poff *et al.*, 2006), with similar flow regimes in rivers located in nearby basins.

Five components characterise the hydrologic regime of a river (Poff & Ward, 1989; Richter *et al.*, 1996; Walker *et al.*, 1995):

- Magnitude: Volume of water that circulates through a point per unit of time.
- Frequency: Number of times that a flow condition recurs during a time interval.
- Duration: Period of time associated with the flow condition.
- Timing or predictability: Measure of the regularity of the flow condition.
- Rate of change: Indicates the velocity of change between distinct flow conditions.

Flow regime constitutes the main determinant of aquatic ecosystems (Hart & Finelli, 1999; Poff *et al.*, 1997; Richter *et al.*, 1996) as they shape their structure and function from local to regional scales and from days (ecological effects) to millennia (evolutionary effects) (Lytle & Poff, 2004). In general, this is a result of the combination of two elements: (1) the changes experienced by the physical habitat, due to the effect of derived environmental factors such as water velocity, shear stress, turbulence, granulometry, temperature, oxygen content and photosynthetic activity in the water column (Richter *et al.*, 1998; Sedimentation Committee, 1992), and (2) the ability of communities to evolve life story strategies in direct response to such changes (Bunn & Arthington, 2002).

The primary effect produced by flows is the geomorphologic development of the stream channel. Rivers undergo a continuous series of channel adjustments over time, although many of them can occur quite rapidly (Rosgen, 1996). Subsequently, specific regime characteristics such as magnitude and frequency of extreme flows, timing of high and low flows, flow duration, water table depth, inter- and intrannual variability, groundwater depth and sediment flux (Merritt *et al.*, 2010) determine different vegetal formations. From an ecological perspective, the development of macrophytes results in a biodiversity peak due to the diverse habitat conditions generated along lateral and vertical gradients (García *et al.*, 2012). It is a key factor in the selection of habitats by organisms such as fish (Chick & Mcivor, 1994; Chick & Mcivor, 1997a; Chick & Mcivor, 1997b; Grenouillet *et al.*, 2000) or macroinvertebrates (Humphries *et al.*, 1996; Lodge, 1985), because each habitat is colonised by species with similar ecological requirements and tolerances (including hydraulic conditions and food resources; Brunke *et al.*, 2002). Additionally, other aspects that are indirectly influenced by flow regime may be determinant for biotic communities. The appearance of leafy and woody debris, which has been associated with the occurrence of extreme floods (Hering *et al.*, 2004), provides habitat and food resources (Anderson, 1982; Pereira *et al.*, 1982; Schulte *et al.*, 2003) that increase invertebrate abundance and diversity (Schneider & Winemiller, 2008).

Alterations in Mediterranean flow regimes

As flow regimes influence ecosystem integrity both directly and indirectly through effects on other primary regulators (Poff *et al.*, 1997), their modification has cascading effects on the ecological integrity of rivers (Karr, 1991). The extensive human alteration of river flows has resulted in widespread geomorphic and ecological changes in these ecosystems (Poff *et al.*, 1997).

In general, flow regime changes can be classified as direct or indirect. Direct changes are a consequence of infrastructures aimed at modifying flows; generally dams for hydroelectric power, human supply, lamination or agriculture. At the beginning of the 21st century, there were around 45 000 large dams (World Commission on Dams, 2000) in 140 countries and 800 000 small dams worldwide (McCully, 1996). On the contrary, indirect changes are those produced by activities that do not intend to modify the flow regime itself but occur as a collateral effect. They tend to be associated with activities that imply a change in land use, emphasising deforestation, urbanisation and agriculture (Poff *et al.*, 1997).

Dams reduce flow magnitude and variability and, in some cases, invert seasonal patterns (Graf, 2006; Walker *et al.*, 1995). Such alterations impact freshwater diversity

(McAllister *et al.*, 2001) that are mediated by changes in habitats, channels and banks (Hill *et al.*, 1991; Simons, 1979), as well as modifications in physicochemical variables such as water temperature (Camargo & García de Jalón, 1990; Webb & Walling, 1993), solid flow (Pratt *et al.*, 1988), organic (Brinson *et al.*, 1983) and inorganic (Elser & Kimmel, 1984) matter, dissolved oxygen (Camargo & García de Jalón, 1990) or even the concentration of contaminants (Peters, 1982) and pH (García de Jalón *et al.*, 1987). The impact on vegetation is highly variable, because aquatic, littoral, riparian and floodplain plants differ in flood tolerance and dependence (Blanch *et al.*, 1999). Sharp declines in riparian biodiversity downstream from dams (Johnson *et al.*, 1976; Ligon *et al.*, 1995; Petts, 1980) have been described, as well as the fragmentation of riparian forests and substitution of native plant species by exotic ones associated with the reduction of floods (e.g. Cooper *et al.*, 2003) and flow variability (Mortenson & Weisberg, 2010; Poff *et al.*, 1997). Other studies have analysed the effects of flow alteration on animals such as macroinvertebrates (Kennen *et al.*, 2010; Konrad *et al.*, 2008; Monk *et al.*, 2006), fishes (Kennard *et al.*, 2007; Pegg & Pierce, 2002; Poff & Allan, 1995; Snelder *et al.*, 2009) or multiple taxonomic groups (Clausen & Biggs, 1997; Jowett & Duncan, 1990), concluding that macroinvertebrates undergo changes in abundance and diversity that mirror the changes in flow magnitude, whereas fish tend to decline with any change to this variable.

However, the effects of water infrastructures on flow regime are more pronounced in Mediterranean rivers. These rivers are characterised by dry summers and intense autumn-winter floods associated with great interannual rainfall variability, which sometimes results in dry winters and, consequently, long supraseasonal droughts. Depending on the duration of the dry periods, as well as on basin and reach characteristics, drought intensity ranges from declines in discharge to below average baseflow levels to intermittency and even to the total drying of the river channel. As most areas with a Mediterranean climate are densely populated, scarce water resources and high demand drive storage needs and reservoir capacities (Batalla *et al.*, 2004; López-Moreno *et al.*, 2009; Lorenzo-Lacruz *et al.*, 2010). As a consequence, these areas are more vulnerable to hydrologic alteration, especially considering that climate projections forecast a generalised decrease in precipitation, runoff and groundwater recharge and increased evapotranspiration (CEDEX, 2011; IPCC, 2007).

Environmental Flow Regimes (EFRs)

Recognition of the global increase in river alteration and resulting environmental degradation has led to the development of methodologies aimed at defining hydrologic regimes associated with specific management objectives:

- A proactive strategy that maintains the hydrologic regimes as closely as possible to reference conditions, ensuring the protection of ecosystems before their modification.
- A reactive strategy to restore certain flow and ecosystem characteristics for previously-modified hydrologic regimes.

Such strategies include the definition of Environmental Flow Regimes (EFRs). "Environmental Flow" is a widely-accepted term that covers the "quantity, timing, duration, frequency and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). Therefore, implementing environmental flow regimes constitutes a key measure for protecting and restoring river ecosystems in Mediterranean areas, given their high human pressures, as well as globally (Arthington *et al.*, 1991; Arthington *et al.*, 2006; Arthington *et al.*, 2010; Poff *et al.*, 1997; Richter *et al.*, 1996; Richter *et al.*, 1997; Sparks, 1992).

In Europe, the Water Framework Directive does not explicitly use the term "Environmental Flow", although it requires the achievement of a "good ecological status" in water bodies before 2015. However, the Spanish water legislation (*ORDEN ARM/2656/2008, Ministerio de Medio Ambiente y Medio Rural y Marino*) specifically establishes the need to define environmental flows in water management plans.

Methodologies used to define EFRs

More than 200 methodologies have been created to define environmental flows since the 1970s (Tharme, 2003). In summary, three main groups have appeared sequentially, as they constitute gradually more complex approaches: hydrologic, habitat simulation and holistic methods. The Spanish “Hydrologic Planning Instruction” (IPH, *ORDEN ARM/2656/2008*) establishes the use of the hydrologic and habitat simulation methods for defining environmental flow regimes.

Hydrologic methods

Based on long flow time series studies, they have been the most frequently used approach in Spain (e.g. Palau, 1994) and use statistics to characterise flow regimes to a greater or lesser extent and define management objectives (for example, a range of variation) for selected hydrologic metrics. The more elementary methods tend to select simple metrics such as percentages of the mean annual flow (Tennant, 1976) or percentiles selected from the corresponding flow duration curves. More complex variants appeared gradually, such as the Spanish “Basic Flow” method, based on mobile averages (Palau & Alcázar, 1996). Finally, sets of hydrologic metrics were developed to characterise the five main flow components, such as those contained in the “Indicators of Hydrologic Alteration” (Richter *et al.*, 1996; Richter *et al.*, 1997) and the “Indicators of Hydrologic Alteration in Rivers” (Martínez & Fernández, 2006). However, it has been highlighted that hydrologic objectives should be completed for every river with field research, as hydrological records must not be the only source of information when defining environmental flows (Richter *et al.*, 1996).

Habitat simulation methods

Work under the premise that habitat availability for stream-dwelling organisms is a limiting factor when changes in flow occur. These methods integrate hydraulic and habitat simulation models that evaluate changes in habitat indicators (e.g. weighed usable area, WUA) and estimate the suitability of such conditions for selected “target” species. Generally, fish have been the most widely used group (e.g. Bovee, 1982), although macroinvertebrates (e.g. King & Tharme, 1994) and even non-biotic ecosystem components such as sediment dragging (Milhous, 1998) have also been used.

Therefore, the outputs of the model allow different scenarios of water management to be evaluated (Waddle, 1998).

The Instream Flow Incremental Methodology (IFIM) and its associated Physical Habitat Simulation System (PHABSIM) (Bovee, 1982; Milhous, 1998; Milhous *et al.*, 1989; Nestler *et al.*, 1989; Stalnaker *et al.*, 1995) constitute a landmark in habitat simulation methods. Developed in the 1970s by the "Co-operative Instream Flow Service Group of the US Fish and Wildlife Service" (USFWS), some authors considered them to be the most scientifically and legally defensible approach for assessing environmental flow regimes for decades (Dunbar *et al.*, 1998; Gore & Nestler, 1988), although some others warned against uncertainty associated with their use (Castelberry *et al.*, 1996; Shirvell, 1986; Williams *et al.*, 1997). The reason for these two different positions was that, although they contained only a few variables [namely depth, velocity and channel index (usually a combination of substrate material and cover)], these variables were consistently found to be important determinants of species' distributions and abundance in nearly all of the studies conducted on habitat partitioning among stream-dwelling animals (Stalnaker *et al.*, 1995).

The IFIM comprises five steps: identifying and diagnosing the problem, planning the study, developing the PHABSIM model, analysing alternatives and solving the problem. Further details can be found in Stalnaker *et al.* (1995), Bovee *et al.* (1998) and Díez-Hernández (2006).

Holistic methodologies

Provide a more complete definition of Environmental Flow Regimes that encompass the whole ecosystem instead of only specific aspects based on "target" species (*sensu* Arthington *et al.*, 2004; Tharme, 2003). Essentially, four stages define these methodologies (Fig. 1):

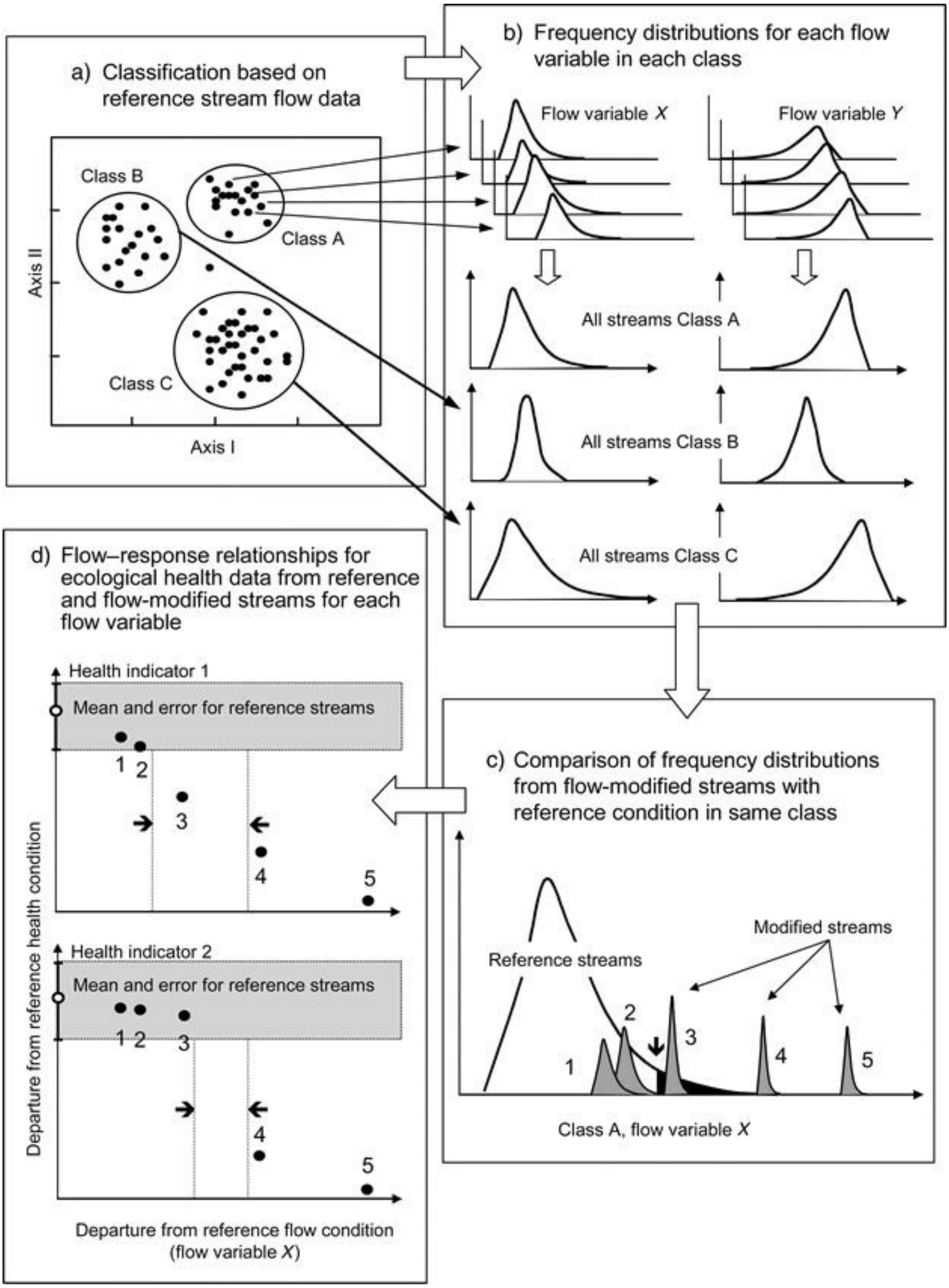

Figure 1. Main phases used to define environmental flow regimes using holistic methodologies. Two critical “risk levels” or “benchmarks” (dotted vertical lines and arrows) to guide the setting of environmental flow standards are established as an example. Source: Arthington *et al.* (2006)

a) Reference rivers are classified in hydrologic groups according to combinations of ecologically relevant flow components. Reference hydrologic classifications have been developed worldwide; for example, in the United States (Henriksen *et al.*, 2006; Poff, 1996; Poff & Ward, 1989) and Australia (Hughes & James, 1989).
b) Distribution frequencies for the flow components are developed and combined to represent the natural range of variability within each class.
c) The frequencies are compared with those presented by altered flow regimes.
d) "Flow regime-ecological response" relationships are developed for each flow component using a set of ecological indicators through a gradient that goes from the reference state to the most altered regimes for each flow component and class.

Using suitable stream classifications constitutes a key component when assessing environmental flow regimes, as each river type will have differing natural or "reference" conditions. However, given the high number of systems available, choosing the classification method constitutes a challenge for water managers, as it involves considering limitations such as the availability of data, human and economic resources and computational capacity.

The "Ecological Limits of Hydrologic Alteration" (ELOHA) (Arthington *et al.*, 2006; Poff *et al.*, 2010) have become very important within this group given their worldwide use (ConserveOnline, 2012). The scientific process consists of four major steps, each with a number of technical components. This process is built upon the approach recommended in Arthington *et al.* (2006). The relationships between flow alteration and ecological characteristics for different river types, developed on the basis of hydrologic analysis and classification, provide scientific input into a social process that balances this information with societal values and goals to set environmental flow standards (Fig. 2).

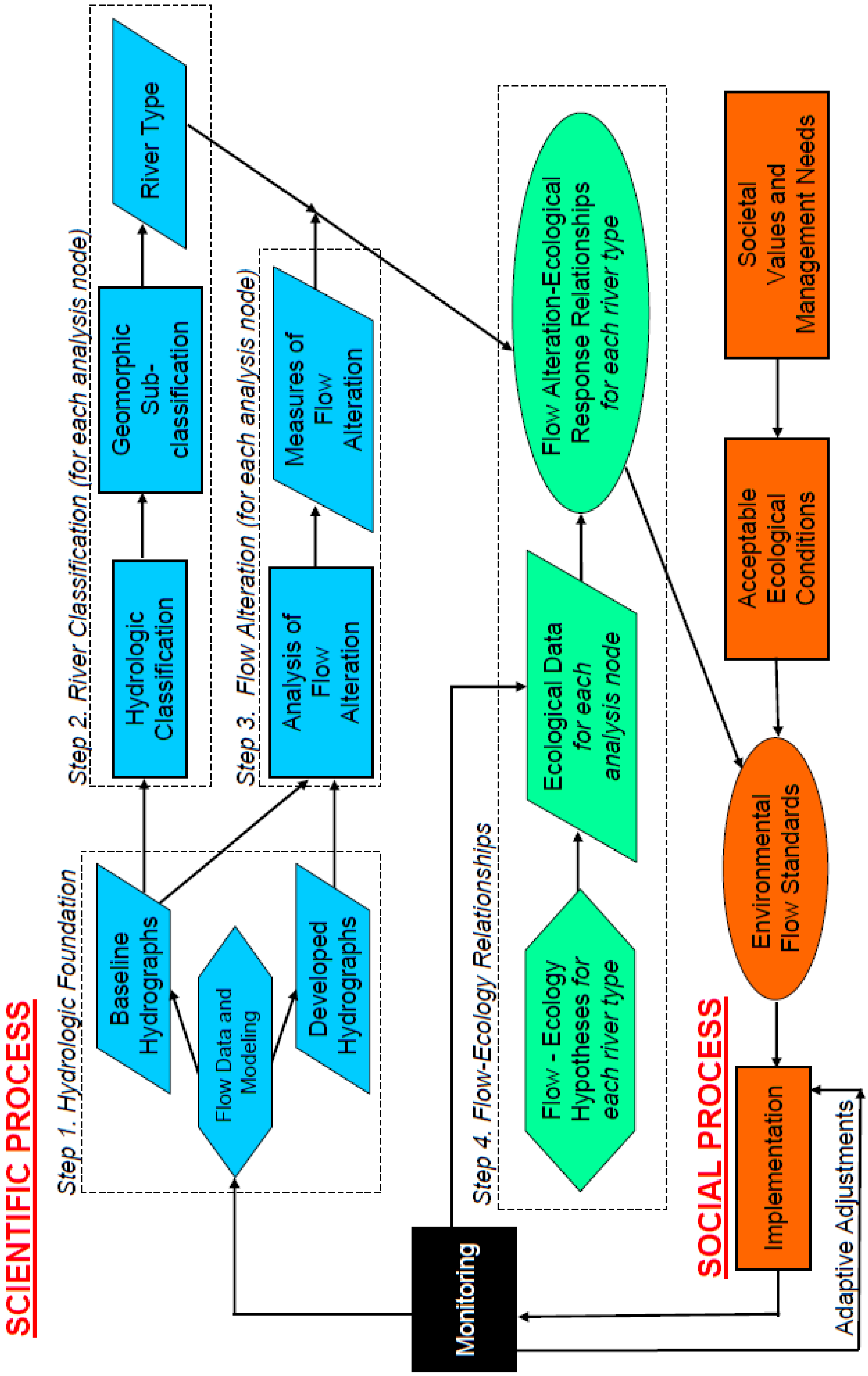

Figure 2. The ELOHA framework. Source: Poff *et al.* (2010)

Objectives

This thesis aimed to set an ecohydrological basis for the definition of environmental flows using a holistic approach (ELOHA) in a highly regulated, semiarid Mediterranean basin with a broad spectrum of natural regimes: the Segura River Basin (SE Spain). Specific objectives were to:

1. Define a hydrologic classification for the rivers and streams in the basin based on the similarity of their natural flow regimes, characterised using hydrologic indices.
2. Evaluate the capacity of two environmental (*a priori*) classifications to discriminate the natural hydrologic variation in the basin, as well as their concordance with the hydrologic (*a posteriori*) classification.
3. Determine the effect of the different natural flow regimes on macroinvertebrate community composition and richness at different taxonomic resolutions (family, genus and species).
4. Characterise and quantify the main hydrologic alterations in the basin by hydrologic type.
5. Determine the effects of hydrologic alteration on fluvial habitats and riparian conditions for each type.

To achieve these goals, the thesis was structured into four chapters:

- Chapter 1. *Hydrological Classification of Natural Flow Regimes to Support Environmental Flow Assessments in Intensively Regulated Mediterranean Rivers, Segura River Basin (Spain).* A hydrological classification based on similarity in natural flow regime was developed for the streams and rivers of the Segura Basin. This work allowed those hydrologic variables that best discriminated the different flow regimes to be determined and the spatial distribution of the resulting river classes to be identified. The results were published in *Environmental Management* (Belmar *et al.*, 2011).
- Chapter 2. *Do Environmental Stream Classifications Support Flow Assessments?* In this chapter, the ability to discriminate the natural hydrologic variation of the rivers and streams in the basin by two environmental (*a priori*) classifications, as well as their agreement with the hydrologic (*a posteriori*)

classification obtained in the previous chapter, were tested. The environmental classifications consisted of an approach based on the River Environment Classification (REC; Snelder and Biggs 2002; Snelder et al 2005) and the ecotypes developed by the Spanish government to fulfil the Water Framework Directive (WFD). This chapter assessed not only the suitability of environmental methodologies as surrogates of the hydrologic classifications, but also the suitability of the ecotypes as management units for Spanish rivers and streams. This chapter was published in *Water Resources Management* (Belmar *et al.*, 2012b).

- Chapter 3. *The influence of natural flow regimes on macroinvertebrate assemblages in a semiarid Mediterranean basin*. The effect of the different natural flow regimes on communities in the Segura Basin was tested at different resolutions using macroinvertebrate records at family, genus and species levels. Given the recognised role of macroinvertebrates aquatic biodiversity indicators (Bilton et al. 2006; Sánchez-Fernández et al. 2006), this section encompassed the biotic response of ecosystems to flow regime in reference Mediterranean streams, allowing the determination of the taxonomic level that performed best. Published in *Ecohydrology* (Belmar *et al.*, 2012a).
- Chapter 4. *Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin*. First, the main hydrologic alterations in the basin were characterised and quantified by hydrologic type. Second, the effects of these alterations on fluvial habitats and riparian condition were assessed for each type. This section completed the assessment of Mediterranean ecosystems response to flow alteration, covering the changes in physical habitat and riparian quality that mediate the response of biotic communities. Currently under review by *Ecological Indicators* (Belmar *et al.*, In Review).

The study area: the Segura River Basin

The Segura River Basin was selected because it represents one of the most arid extremes in the western Mediterranean, towards which other basins in temperate areas will tend due to climate change and where implementing environmental flows constitutes an urgent task.

Despite its relatively small size, the basin presents strong gradients from NW to SE: (1) a climatic and altitudinal gradient from wet (>1000 mm mean annual precipitation) and cold mountains (>1000 masl) to semiarid (<350 mm mean annual precipitation) and warm lowlands, subject to strong autumnal storms (CHS, 2007), and (2) a population density gradient between the lowly populated headwaters and the highly populated lowland cities, with intermediate densities in the agricultural midlands (Mellado, 2005).

As other Mediterranean regions, it is characterised by scarce, unevenly distributed resources and high hydrologic variability (low rainfall irregularly distributed in time and space). Large storm events often produce flooding during spring and autumn (CHS, 2007). Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). High temperatures and low rainfall during the summer season lead to natural water scarcity, generating drought events and in some cases the complete cessation of flow in rivers.

The lithology of the plains is characterised by limestone (karst) and Miocene and Triassic marls, with some minor influences of volcanic strata. In contrast, calcites and dolomites dominate the mountain headwaters. The landscape ranges from Mediterranean conifer forest in the mountains to arid and semiarid shrublands in the lowlands. Agricultural (52.1%), forest and seminatural (45.2%) and artificial (2.1%) land uses predominate in the basin (estimated from Corine Land Cover 2000).

Most surface water is provided by tributaries in the upper sector of the basin, mainly the Mundo River. High water demands, mainly for irrigation (90%), exceed all available resources (Gil-Olcina, 2000), thereby producing a structural deficit that has been accentuated in recent decades by a decreasing trend in precipitation (CHS, 2005). Due to such intense pressure, surface waters are overexploited and groundwaters suffer an extraction of approximately 478 hm^3/year (over 80% of the natural recharge), turning the basin into one of the most regulated in Spain and Europe. A great regulatory capacity (770 hm^3, over 90% of the natural input) is provided by 24 dams that are more than 10 m in height (Grindlay *et al.*, 2009; Grindlay *et al.*, 2011), 121 higher than 2 m (CHS, 2007) and two big infrastructures: the Tagus-Segura Transfer and the Taibilla Channel.

The Tagus-Segura Transfer leads water from the Tagus River to the Talave Reservoir (in the Mundo River). The transferred volumes (a mean of 325 hm^3 yr^{-1}) are used for irrigation (62%) and human supply through the *Mancomunidad de Canales del Taibilla* (24%), the entity that manages more than 90% of water for human supply (CHS, 2007). The Taibilla Channel is used to conduct the transferred volumes for human supply and additional resources extracted from the Taibilla stream.

Therefore, the Segura Basin (Fig. 3) constitutes an excellent area to research hydrology-ecology relationships in Mediterranean areas. Not only due to the fact that its high variability in natural conditions represents the entire spectrum of hydrologic regimes that can occur in other Mediterranean basins (which allows their effect on communities to be analysed), but also because its high regulation permits the human pressures associated with each flow regime and their consequences on river ecosystems to be determined.

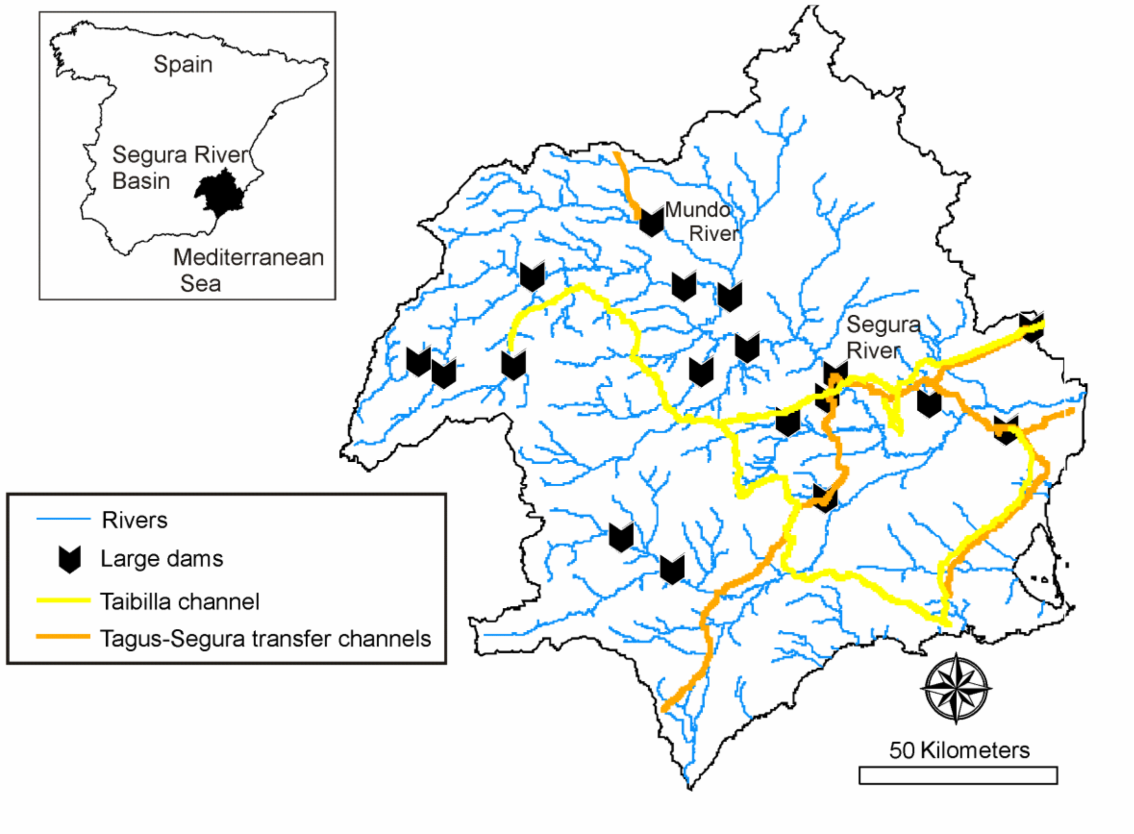

Figure 3. Location and main water infrastructures in the Segura River Basin

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Chapter 1. Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River Basin (Spain)

Madera River close to its mouth

Belmar, O., Velasco, J. & Martínez-Capel, F. (2011) Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River basin (Spain). *Environmental Management* **47**, 992-1004

Abstract and keywords

Hydrological classification constitutes the first step of a new holistic framework for developing regional environmental flow criteria: the “Ecological Limits of Hydrologic Alteration (ELOHA)”. The aim of this study was to develop a classification for 390 stream sections of the Segura River Basin based on 73 hydrological indices that characterize their natural flow regimes. The hydrological indices were calculated with 25 years of natural monthly flows (1980/81 - 2005/06) derived from a rainfall-runoff model developed by the Spanish Ministry for the Environment and Public Works. These indices included, at a monthly or annual basis, measures of duration of droughts and central tendency and dispersion of flow magnitude (average, low and high flow conditions). Principal Component Analysis (PCA) indicated high redundancy among most hydrological indices, as well as two gradients: flow magnitude for mainstream rivers and temporal variability for tributary streams. A classification with eight flow-regime classes was chosen as the most easily interpretable in the Segura River Basin, which was supported by ANOSIM analyses. These classes can be simplified in 4 broader groups, with different seasonal discharge pattern: *large rivers*, *perennial stable streams*, *perennial seasonal streams* and *intermittent and ephemeral streams.* They showed a high degree of spatial cohesion, following a gradient associated with climatic aridity from NW to SE, and were well defined in terms of the fundamental variables in Mediterranean streams: magnitude and temporal variability of flows. Therefore, this classification is a fundamental tool to support water management and planning in the Segura River Basin. Future research will allow us to study the flow alteration-ecological response relationship for each river type, and set the basis to design scientifically credible environmental flows following the ELOHA framework.

Ecological Limits of Hydrologic Alteration (ELOHA) · Environmental flows · Regulated Mediterranean rivers · Modelled monthly flows · Temporal variability · Intermittent streams · Drought

Introduction

Flow regime has become a fundamental part of running water ecosystems ecological studies and management (Arthington & Pusey, 2003; Bunn & Arthington, 2002; Richter *et al.*, 2006). Since the publication of the "natural flow regime paradigm" (Poff *et al.*, 1997), ecologists have recognized intra- and interannual flow variability as a primary driver of the structure and function of riverine ecosystems and many of the adaptations of its biota (Arthington *et al.*, 2006; Lytle & Poff, 2004; Naiman *et al.*, 2008). Many authors have emphasized the need to characterise the similarity among flow regimes to provide typologies that can support *a priori* predictions (e.g. ecological and evolutionary convergence under geographically disjoint regimes) and the development of general principles for flow regime management, such as the assessment of environmental flows (Arthington *et al.*, 2006; Poff *et al.*, 2006).

"Environmental flows" is now a widely accepted term that covers the "quantity, timing, duration, frequency and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems" (Brisbane Declaration, 2007). Implementing environmental flows will be a key measure for protecting and restoring river ecosystems (Arthington *et al.*, 1991; Arthington *et al.*, 2010; Poff *et al.*, 1997; Richter *et al.*, 1996; Richter *et al.*, 1997; Sparks, 1992; Stanford *et al.*, 1996). More than 200 methodologies have been described to define environmental flows since the decade of 1970 (Tharme, 2003). Hydrological methods are based on the study of long hydrological series. The simplest ones only define rules to set a minimum flow for the river (Tennant, 1976). However, there are more complex approaches such as the RVA (Range of Variability Approach) method (Richter *et al.*, 1997). This method characterizes flow records using 32 different hydrological parameters, the "Indicators of Hydrologic Alteration", and establishes a range of variation (for example, the mean ± the standard deviation) as the objective for each one. The authors point out that these objectives must be completed for every river with field research, suggesting that hydrological records cannot be the only source of information in the definition of environmental flows. Habitat simulation methods determine the flow requirements of some "target species", usually fishes (Bovee, 1982), but they have been applied to macroinvertebrates (King & Tharme, 1994) or even to achieve objectives related to the morphology of the river (Milhous, 1998). Finally, holistic methodologies broaden the definition of “environmental flow” considering the fluvial ecosystem as a whole instead of focusing only in the requirements of a few species (Arthington & Pusey, 1993; King & Tharme, 1994; Poff *et al.*, 1997; Richter *et al.*, 1996; Sparks, 1992; Sparks, 1995). The relationship between flow alteration and ecological characteristics for different river types constitute the key element of a new holistic framework for developing scientifically-credible regional environmental flows criteria: the “Ecological Limits of Hydrologic Alteration” (ELOHA) (Arthington *et al.*, 2006; Poff *et al.*, 2010). A principle for setting environmental flows is that this should be carried out at a regional level, because they are related to river types that will have differing natural or “reference” conditions (Poff *et al.*, 2010). Therefore, there is a need to develop river classifications to identify the natural flow regime for each stream, to develop the flow-ecology relationship and to assist the assessment of environmental flows.

Several hydrological classifications have been made for large river basins (Hannah *et al.*, 2000; Harris *et al.*, 2000), states (Apse *et al.*, 2008; Cade, 2008; Kennen *et al.*, 2007; Kennen *et al.*, 2009) or even entire countries, such as USA (Mcnamay *et al.*, 2011; Olden & Poff, 2003; Poff, 1996), New Zealand (Snelder & Biggs, 2002; Snelder & Hughey, 2005), Germany (Pottgiesser & Sommerhäuser, 2004), France (Snelder *et al.*, 2009), Australia (Kennard *et al.*, 2010) and Chile (Peredo-Parada *et al.*, 2011) using different methods. Two basic approaches have been used to achieve this goal: (1) *a priori* classifications using climatic and other environmental variables that influence hydrology and (2) *a posteriori* classifications based on hydrological statistics.

In Spain, according to the water legislation, environmental flows should be included in Basin Management Plans to fulfil the EU Water Framework Directive (WFD). However, no national hydrological classification has been published. Ecoregions and ecotypes classifications based on non-altered geographical, morphological, climatic and geological variables have previously been attempted following the WFD system B (Annex II) at national (CEDEX, 2004) and Mediterranean scale (Bonada *et al.*, 2002; Moreno *et al.*, 2006; Munné & Prat, 2004; Sánchez-Montoya *et al.*, 2007), respectively. But these classifications did not include hydrological variables or described only one or two flow-regime components (e.g. mean annual discharge). Nevertheless, hydrological classifications based on hydrological indices have been developed for the Tajo and Ebro basins (Alcázar & Palau, 2010; Baeza & García de Jalón, 2005; Bejarano *et al.*, 2010).

The present study addresses a hydrological classification for stream and river segments in the Segura River Basin, an intensively regulated Mediterranean basin in the Southeastern Spain, based on the similarity in their natural flow regimes, characterised using hydrological indices. Specific objectives were to determine the hydrological variables that best discriminate and characterize the different flow types and to identify the spatial distribution of the resulting river classes.

Methods

Study area

The Segura River Basin, as management unit (including coastal watercourses), represents one of the most arid zones of the Mediterranean area, presenting great heterogeneity in its flow regimes. It is located in the SE of Spain (Fig. 1). Despite its small size (18 870 km^2), there is a strong climatic and altitudinal gradient from NW to SE. The climate ranges from wet (>1000 mm mean annual precipitation) and cold in the mountains (>1000 m.a.s.l.) of the NW to semiarid (< 350 mm mean annual precipitation) in the SE lowlands (200 mm precipitation near the coast). Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). The lithology of the plains is characterised by the dominance of limestone as well as Miocene and Triasic marls, with some volcanic areas, whereas calcites and dolomites dominate the mountain headwaters. The landscape ranges from Mediterranean conifer forests in the mountains to arid and semiarid shrublands in the south-east lowlands. This longitudinal gradient in altitude and climate is coupled with a human density gradient. The river network has low populated forested headwaters, populated agricultural midlands with intense flow regulation and densely populated cities in the lowlands (Mellado, 2005). Agricultural (52.1%), forest and seminatural (45.2%) and artificial (2.1%) land uses predominate in the Segura Basin (estimated from Corine Land Cover 2000).

As for other Mediterranean regions, the basin is characterised by scarce and unevenly distributed water resources and high hydrologic variability (low rainfall irregularly distributed in time and space). Large storm events often produce flooding during spring and autumn (CHS, 2007). High temperatures and low rainfall during the summer season lead to a natural water scarcity, generating drought events and in some cases the complete cessation of flow. The largest volume of surface water is provided by the tributaries in the upper sector of the basin. The Mundo River, the major tributary, provides most of water resources. The regulation capacity by dams (24 dams higher than 10 m.) in the Segura Basin is approximately 770 hm^3, equivalent to over 90% of its natural input (CHS, 2007). There is also significant regulatory volume (approximately 325 hm^3) of interbasin transfers from the Tagus River. Mean groundwater abstraction is 478 hm^3/year, over 80% of the natural recharge. Water for irrigation represents the main water withdrawal (90% of resources). These human activities in the rivers and their catchments profoundly alter the natural flow regimes, producing a significant reduction in the magnitude of flows and a reversal in their seasonal pattern. River reaches below dams present maximums in summer and minimums in winter, with droughts becoming more frequent and long-lasting (Belmar *et al.*, 2010; Vidal-Abarca *et al.*, 2002).

Drainage network

A drainage network was derived from a 25 m. digital elevation model (DEM), developed by the National Geographic Institute of Spain (IGN), and fragments extracted from layers available in the website of the Ministry for the Environment, in order to achieve higher precision. The ArcGIS software v 9.2 with the ArcHydro extension v 1.2 (ESRI, Redlands, California, USA) were the tools used. The network comprises sections that link each network junction (node). Each node, at the end of each section, is associated with its corresponding watershed (derived from the DEM). The minimum watershed area to define a section was 10 km^2. The hydrological network comprises 390 nodes and sections (Fig. 1).

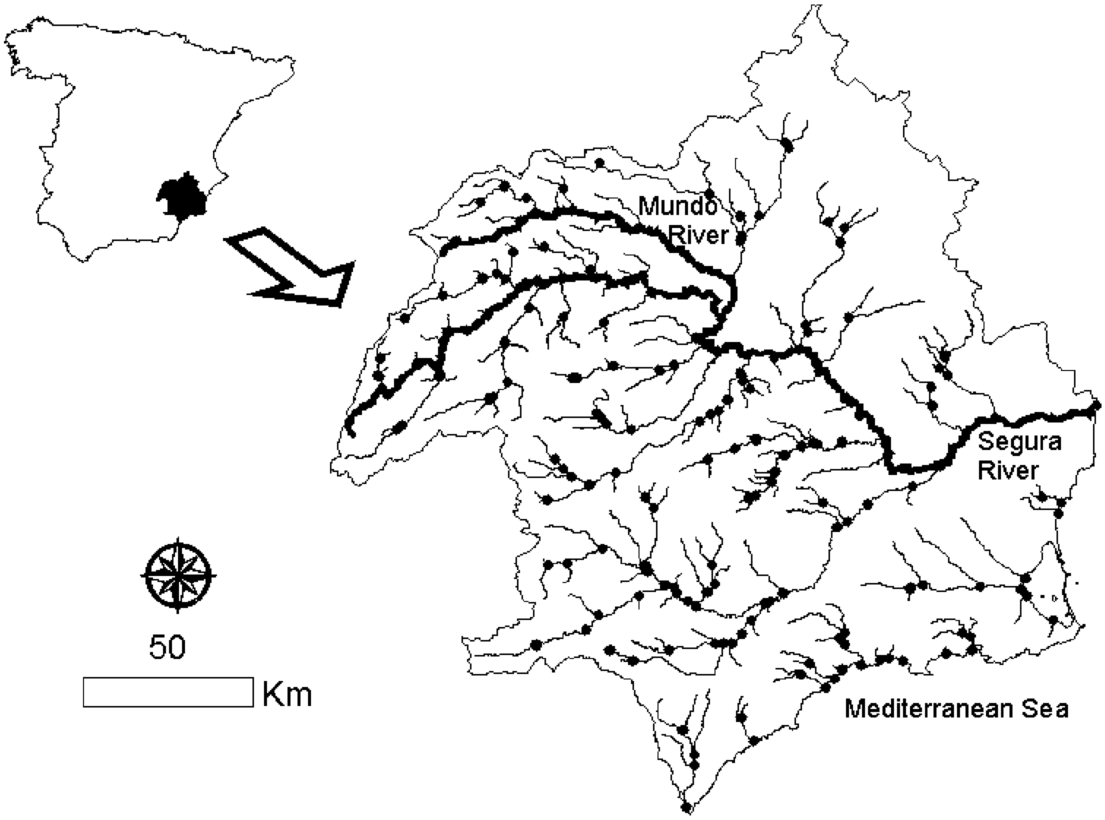

Figure 1. Location of the Segura River Basin in Spain, showing the drainage network and nodes (black points) obtained from a digital elevation model

Baseline or reference flow conditions

Within the Segura Basin, there is limited hydrological information from gauging stations representing unaltered regimes. Gauged sites are scarce and located principally in the mainstream; impacted by dam and reservoir operations, water withdrawals and diversions.

To build a database of flow time-series that represents the baseline or reference conditions we used the SIMPA model (the Spanish acronym meaning "Integrated System for Rainfall-Runoff Modelling"), developed by the Centre for Hydrographic Studies (CEDEX, Ministry for the Environment and Public Works, Spain). This model is an implementation of a classic soil moisture balance model (Témez, 1977) where soil and aquifer storages are considered, as well as a collation of transfer laws (Estrela & Quintas, 1996a; Estrela & Quintas, 1996b; Ruiz, 1998). Some publications illustrate SIMPA's progress (Álvarez *et al.*, 2005; Barranco & Álvarez-Rodríguez, 2009; Potenciano & Villaverde, 2009). It takes monthly precipitation from 1 km. grid maps created by the Spanish Ministry for the Environment by means of an interpolation procedure (the inverse to the square distance) with data from the more than 5000 weather stations of the Spanish network. For this interpolation, double regression and "white noise" procedures were used to complete incomplete series without altering the natural variance of data, as well as specific procedures for the highest elevation areas (Estrela *et al.,* 1999). Calibrated by regionalization of different variables (maximum moisture capacity, as a function of land use; maximum infiltration, as a function of lithology; etc.), the model has been validated by means of comparison with reference and restored records in more than 100 control points (Estrela *et al.*, 1999). Besides, it has been used in Spain for water resources assessment, in the White Paper Book of Waters (Ministry for the Evironment, 2004) and the National Water Master Plan (Ministry for the Evironment, 2000), and for a hydrological classification of the streams and rivers in the Ebro Basin (Bejarano *et al.*, 2010).

We generated monthly data that represented natural flow conditions for the period 1980/81-2005/06 in each node of the hydrological network to calculate a set of hydrological indices.

Classification of river flow regimes

73 hydrological indices describing either monthly or annual characteristics (see Appendix 1) were calculated. These indices, based on the "Indicators of Hydrologic Alteration" (Mathews & Richter, 2007), represent a wide range of ecologically-relevant flow statistics (Mathews & Richter, 2007; Monk *et al.*, 2006; Monk *et al.*, 2007; Olden & Poff, 2003; Richter *et al.*, 1996) and include measures of the duration of droughts as well as the central tendency and dispersion of flow magnitude (average, low and high flow conditions), two of the major components of the flow regime in Mediterranean rivers. However, other significant components related to the frequency, duration and rate of change of high flood events were not estimated because of the lack of daily flow data.

Hydrological indices have considerable multicollinearity (Olden & Poff, 2003). We reduced our set to a smaller set of non-redundant indices using the procedure outlined in Olden & Poff (2003). A Principal Components Analysis (PCA) was used to examine dominant patterns of intercorrelation among the hydrological indices and to identify subsets of indices that describe the major sources of variation while minimize redundancy (i.e. multicollinearity). This PCA was conducted, using PC-ORD v 4.41 (McCune & Grace, 2002), with the correlation matrix rather than the covariance matrix to ensure that all indices contributed equally to the PCA and that these contributions were scale-independent (Legendre & Legendre, 1998). We selected the simplest and most easily interpretable indices to characterize flow regimes, based on criteria of high correlation with the three first PCA axes.

Scores for the first three axes were weighted by the proportion of the variance explained by each PCA axis and used as new synthetic hydrological variables for a cluster analysis. A flexible-β clustering technique (Legendre & Legendre, 1998; McCune & Grace, 2002) was used to group streams according to their similarity in flow regime, measured using Euclidean distances. This technique allows the user to select the number of clusters desired and choose the most interpretable classification. Besides, as an internal validation, Analyses of Similarities (ANOSIM) (Clarke, 1993) were run on the Euclidean distances to test the effect of the number of classes on the degree of separation among them. Each test in ANOSIM produces an R-statistic, which contrasts the similarities of nodes within a class with the similarities of nodes among classes (when the R value is close to one, similarities between nodes within a class are higher than those between nodes from different classes, and values close to zero indicate no differences among classes). These analyses were conducted in PRIMER v 6 (Clarke & Gorley, 2006).

In order to visually appreciate the differences between hydrological classes we represented annual hydrographs showing the standardized monthly flows of the streams and rivers included in each class, as well as whisker box plots showing environmental variables: average precipitation in the drainage area, drainage area, Strahler order (Strahler, 1957), average altitude as well as slope of the drainage area and percentage of karstic surface. The latter was derived from the Spain’s Map of Karst (1:1.000.000) developed by the Mining Geologic Institute of Spain (IGME).

Results

Redundancy among hydrological indices

Most of variation (73.35%) in the hydrological variables was explained by the first two axis of the PCA. Figure 2 presents the two-dimensional ordination illustrating the major patterns of intercorrelation among the 73 hydrological indices for the combined set of 390 stream and river sections; the symbols by stream classes correspond to the clusters, shown in Figure 3. The majority of indices were highly correlated (either positively or negatively). The percentage of months with zero flow (D_L) was the only one with a high significant correlation with all the other indices.

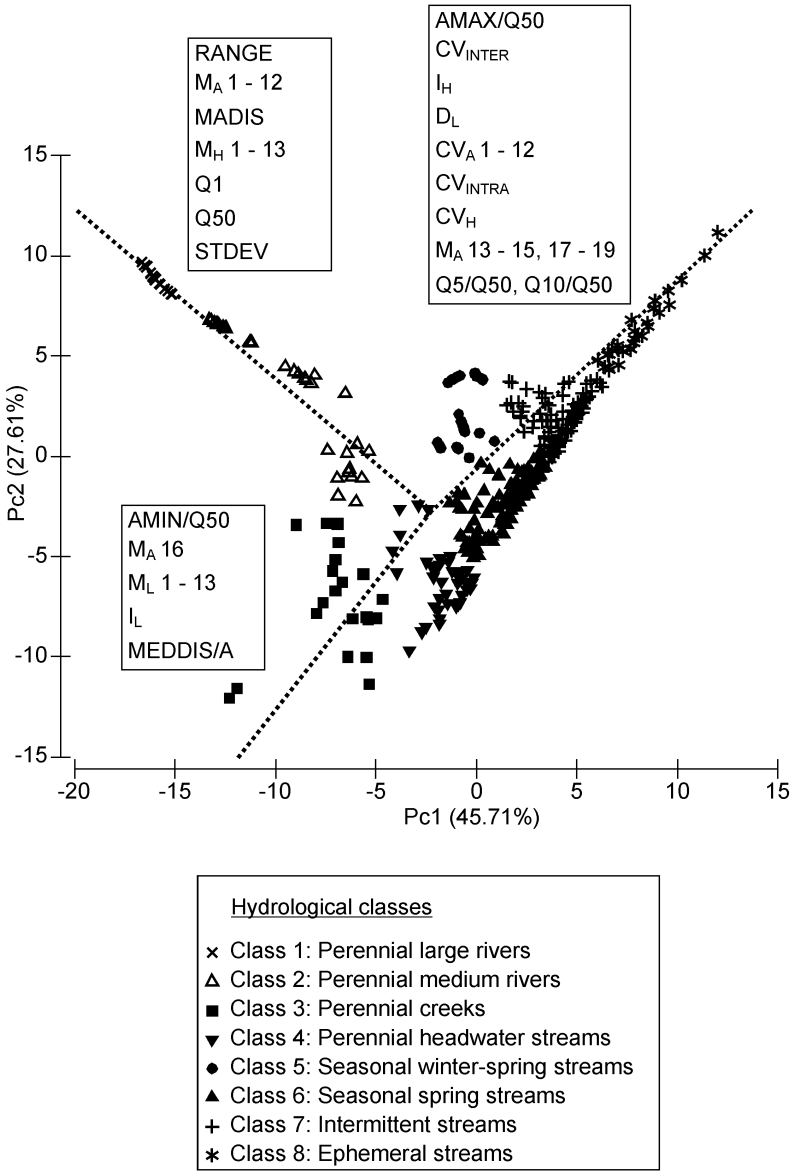

Figure 2. Two-dimensional PCA ordination of the 390 stream and river sections showing the correlated hydrological metrics (see Appendix 1 for definition), the gradients detected (magnitude and temporal variability) and the hydrological class for each stream according to the clustering in Figure 3

Three groups of hydrological indices were differentiated. A first group, in the first quadrant of Figure 2, included indices related to the intensity of droughts (D_L) and floods, such as indices of annual maximums (AMAX/Q50, I_H). This group also included indices of dispersion describing the variability of the flow regime, such as the coefficient of variation in mean annual flows (CV_{INTER}), the coefficient of variation in mean monthly flows (CV_{INTRA}), the coefficients of variation in monthly flows (CV_A 1-12), the coefficient of variation in maximum monthly flows (CV_H) and other variability indices based on percentiles (Q5/Q50, Q10/Q50).

In the third quadrant there was a second group of indices. This group contains indices that characterize the magnitude of low flows, such as the mean minimum monthly flows (M_L 1-12), the average of minimum monthly flows (M_L13), the annual minimum discharge divided by the median (AMIN/Q50); and the magnitude of average flows, such as the mean and median annual runoff (M_A16 and MEDDIS/A).

A third group of correlated variables (second quadrant) included measures of central tendency in flow magnitude and high flows, such as the mean and median annual discharge (MADIS, Q50), mean monthly flows (M_A 1-12), mean maximum monthly flows (M_H 1-12), the average of maximum monthly flows (M_H13) and some measures of variability (STDEV, Q1, RANGE).

From the non-correlated indices in the two first quadrants, the mean annual discharge (MADIS), the percentage of months with zero flow (D_L) and the coefficient of variation in mean annual flows (CV_{INTER}) represent the major gradients of variation in the Mediterranean flow regimes. The two first indices were highly correlated (negatively and positively, respectively) with the first axis, while CV_{INTER} was correlated with both PCA axes. Thus, stream and river sections were interpreted in the two-dimensional space (Fig. 2) following two gradients: (1) a flow magnitude gradient, crossing the second quadrant, that ordered the mainstream sections of the rivers Segura and Mundo from larger (upper left corner) to smaller discharge; and (2) a temporal variability gradient, crossing the first and third quadrant, that ordered the tributaries from ephemeral and intermittent streams (upper right corner in Fig. 2) to permanent and more regular ones.

Hydrological classes

With the β-flexible clustering based on weighted PCA scores, a classification with eight hydrological classes (Fig. 3) was chosen as the most easily interpretable solution for the Segura River Basin.

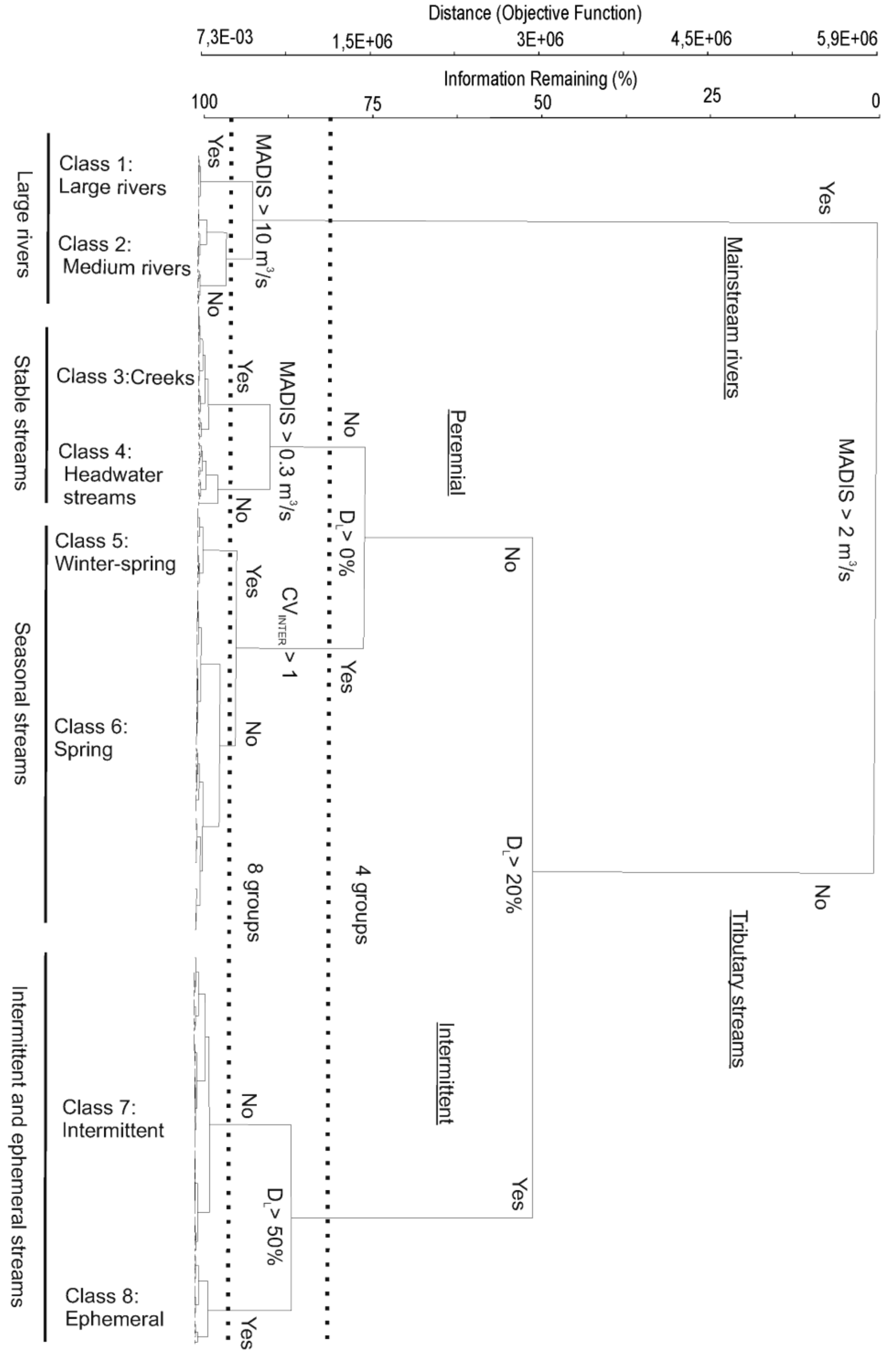

Figure 3. Dendrogram obtained of the flexible-β clustering procedure carried out with Euclidean distances. Two levels of classification, eight and four hydrological classes (see dotted lines), and the critical values of hydrological metrics that best discriminate them are showed

Besides, the ANOSIM analyses defined the 8 classes solution as the most convenient. It produced the greatest increase in the R-value and, despite that the 9 classes solution produced the biggest R-value, the increase is negligible (Fig. 4). The magnitude of annual flows (MADIS), the duration of droughts (D_L) and the interannual variation of flows (CV_{INTER}) were discriminators of these 8 flow-regime classes (Fig. 5). The first division of the cluster distinguished between perennial mainstream rivers (Classes 1–2), with an average annual flow larger than 2 m^3/s, and tributaries (Classes 3-8), with smaller mean discharges. Tributaries include sites ranging from perennial streams, which never (Classes 3-4) or eventually (Classes 5-6) cease flowing, to intermittent and ephemeral streams (Classes 7 and 8), which stop flowing a 20% and a 50% of time respectively.

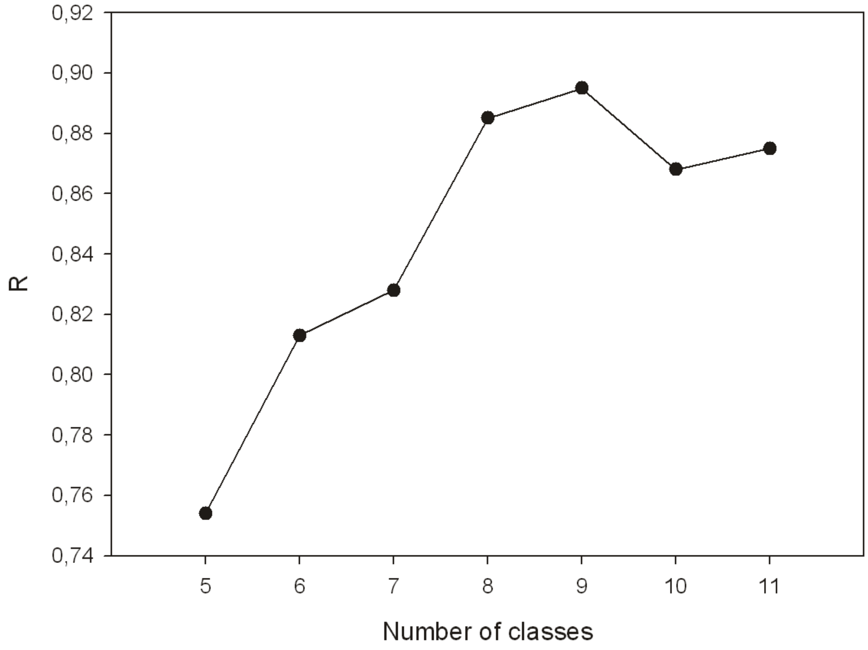

Figure 4. Evolution of the ANOSIM R-Value as the number of classes resulting from the flexible-β clustering increases

Therefore, the eight classes (Fig. 3, bottom dotted line) can be grouped into four broader groups (Fig.3, upper dotted line): *large rivers* (Classes 1 and 2), *perennial stable streams* (Classes 3 and 4), *perennial seasonal streams* (Classes 5 and 6) and *intermittent and ephemeral streams* (Classes 7 and 8). Distinctions within each couple were evident in terms of differences in annual hydrographs (Fig. 6) and environmental characteristics of the watersheds (Fig. 7).

Classes 1 and 2, *perennial large rivers* and *perennial medium rivers*, respectively, present similar hydrographs with high base flow and moderate peak flows in February or April and minimum flows in July or August. Differences on flow magnitude between these classes are due to their environmental characteristics (Fig. 7), defined by their location in the Segura Basin (Fig. 8). Class 1 (MADIS > 10 m^3/s) includes medium and low sections of the Segura River (Strahler order 5) with large drainage areas (more than 5000 km^2), medium altitude (around 800 m.a.s.l.) and slope (around 20%) and an annual mean precipitation of 450 mm. However, Class 2 (MADIS = 2-10 m^3/s) corresponds to upper sections (Strahler order 3) of the Segura River as well as medium and low sections of the Mundo River, in wetter (700 mm of average precipitation) and highly karstified (75% mean karstic surface) watersheds. These watersheds are higher than 1100 m.a.s.l., smaller than 2000 km^2 and have a 30% of slope.

The rest of hydrological classes, tributaries, follow environmental gradients (Fig. 7). Classes 3 (*perennial creeks*) and 4 (*perennial headwater streams*) correspond to headwater streams dominantly of orders 2 and 1, respectively, located in the upper sectors of the Segura Basin with an average karstic surface in their watersheds greater than 70%. These classes are characterized by soft (groundwater-driven) hydrographs with flows varying among streams for most months but higher in winter than in summer (Fig. 6). However, classes 5 (*seasonal winter-spring streams*) and 6 (*seasonal spring streams*) comprise streams with similar flows during summer-autumn but different in winter-spring. They present maximum flows in December and March (Class 5) or only in March (Class 6) due to seasonal precipitation peaks. For these classes, watersheds were low (less than 40%) and medium (around 50%) karstified respectively. Class 5 includes medium size streams (orders 3-4) that rarely dry up, located principally in the medium (800 m.a.s.l.) elevations of the Segura Basin. Class 6 is composed of springs located in the headwaters of small watersheds with similar altitude and slightly higher slope (Fig. 7), in any sector of the basin, that can cease flowing during less than one month per year. However, streams in class 5 presented higher variability in annual flows than streams in class 6 (Fig. 5).

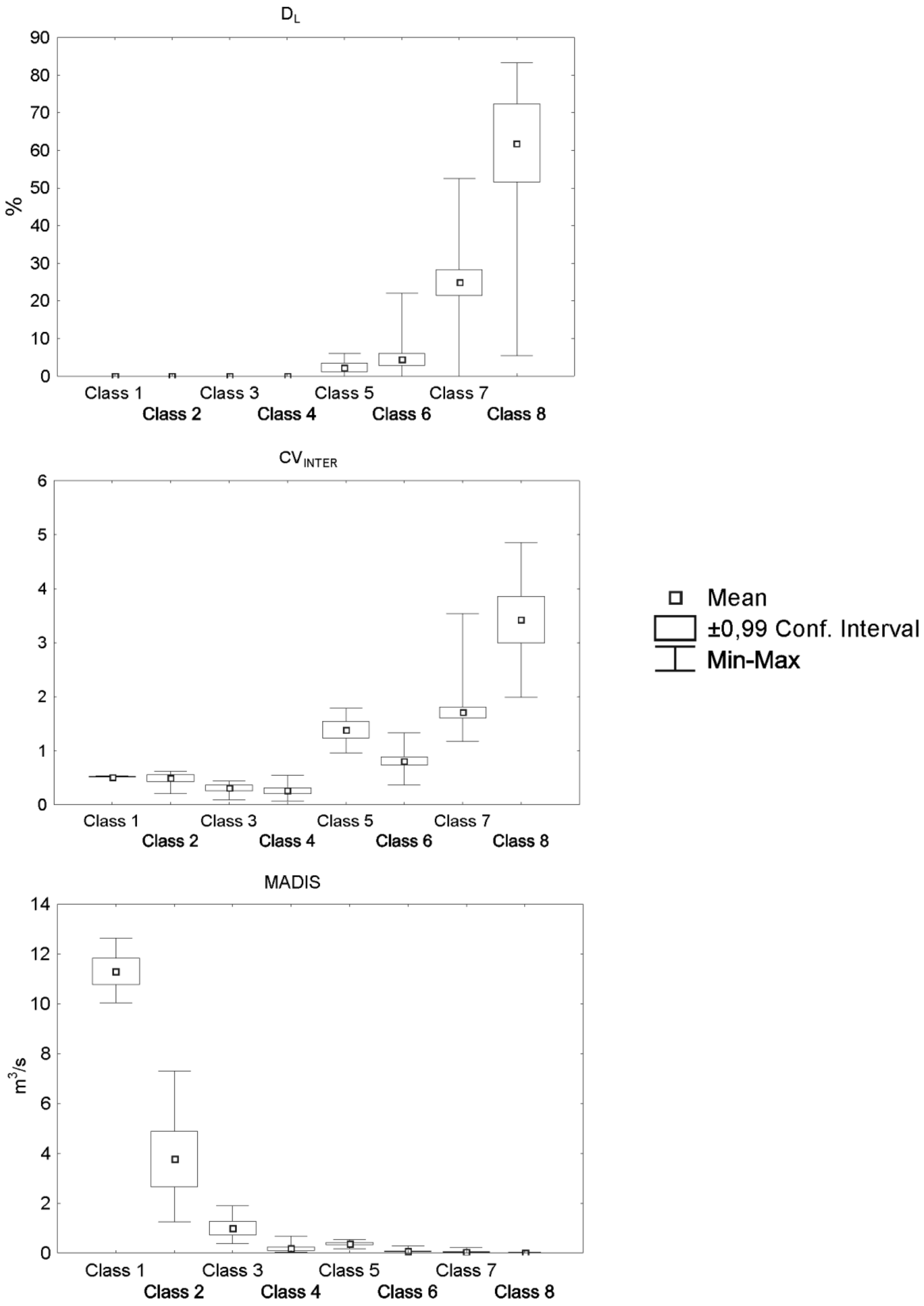

Figure 5. Box-plots for the comparison of the duration of droughts (D_L), the coefficient of interannual variation (CV_{INTER}) and the magnitude of annual flows (MADIS) for the eight hydrological classes defined in the Segura River Basin. Names of classes detailed in Figure 3

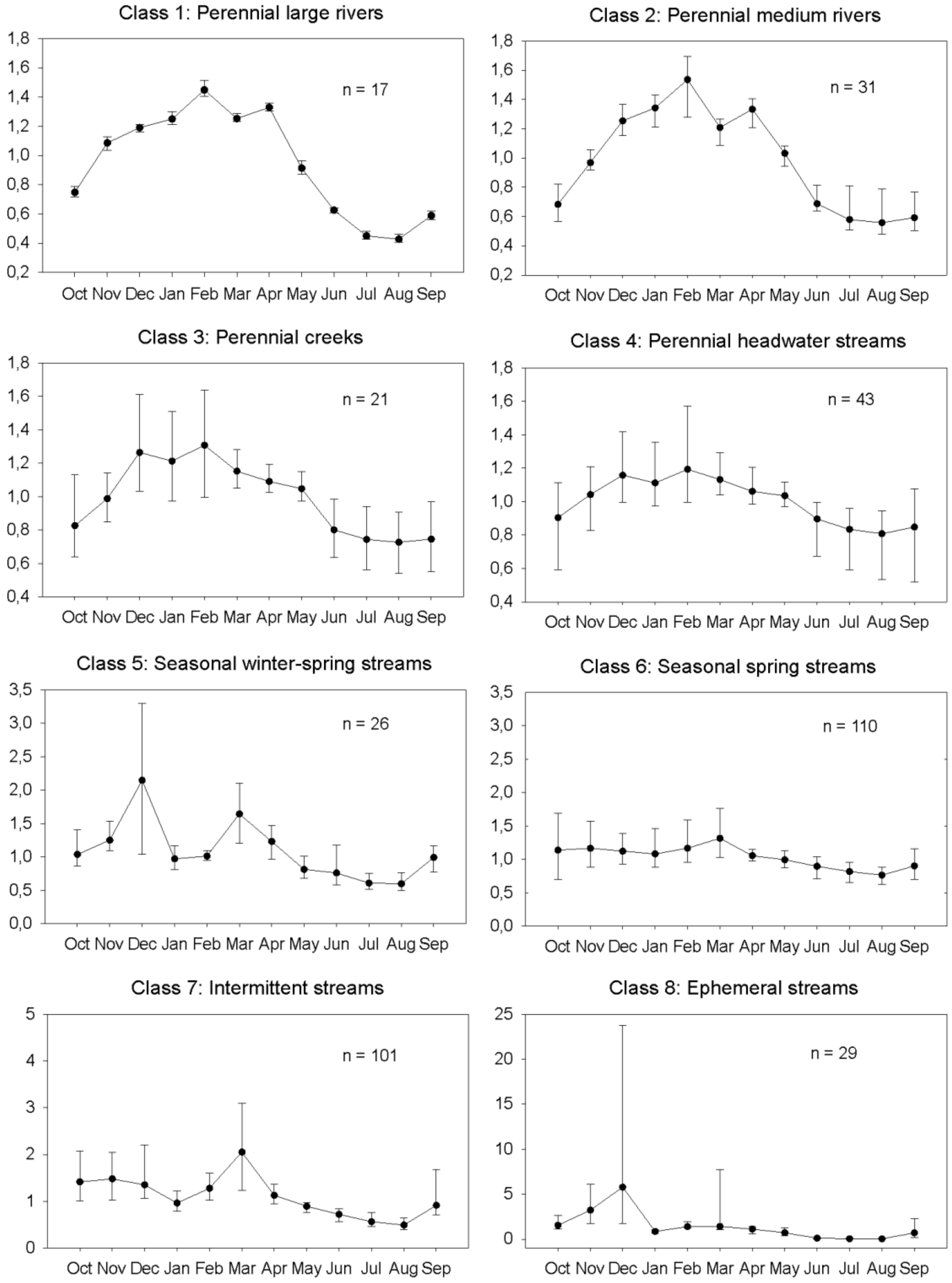

Figure 6. 90th and 10th percentiles (in bars) and means (solid circles) of standardized monthly flows (monthly flows divided by its median) of all river and stream sections included in each hydrological class. Ordinates are showed at different scales to improve the visualization

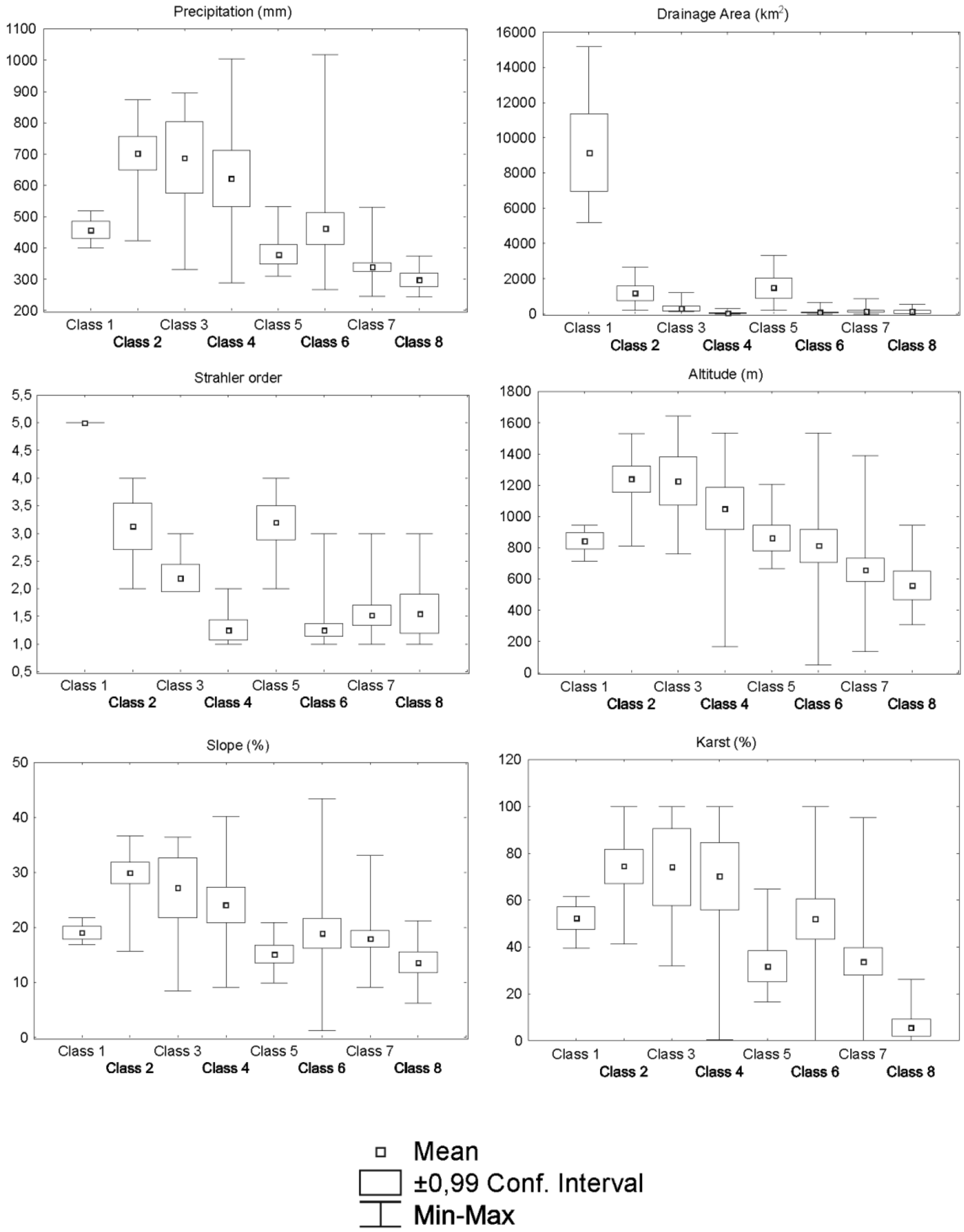

Figure 7. Box-plots for the comparison of the environmental variables (average precipitation in the drainage area, drainage area, Strahler order, average altitude as well as slope of the drainage area and percentage of karstic surface) among the eight hydrological classes defined in the Segura River Basin. Names of classes detailed in Figure 3

Classes 7 and 8 (*intermittent streams* and *ephemeral streams*, respectively) have the smallest mean annual flows, but the largest coefficients of variation for both annual (Fig. 5) and monthly flows. They are characterized by intense and frequent droughts and flash floods. Intermittent streams presented more predictable flows (Fig. 5) and softer peaks (Fig. 6) than ephemeral streams. Associated to strong rain events, these peaks are punctual in spring (March) and sustained in autumn (October-November). However, ephemeral streams presented a higher coefficient of variation (Fig. 5) and only a peak of flow (Fig. 6) in winter (December), greater than the ones for intermittent rivers. This peak is associated to torrential precipitation episodes that compose most annual water resources in this class. Both intermittent and ephemeral streams present low orders (1-2) and small drainage areas (less than 150 km^2), restricted to the southern half of the Segura Basin, in areas of low altitude (around 600 m.a.s.l.), small slope (around 15%), reduced karstic surface (close to 30% and 5%, respectively) and low average precipitations (Fig. 7).

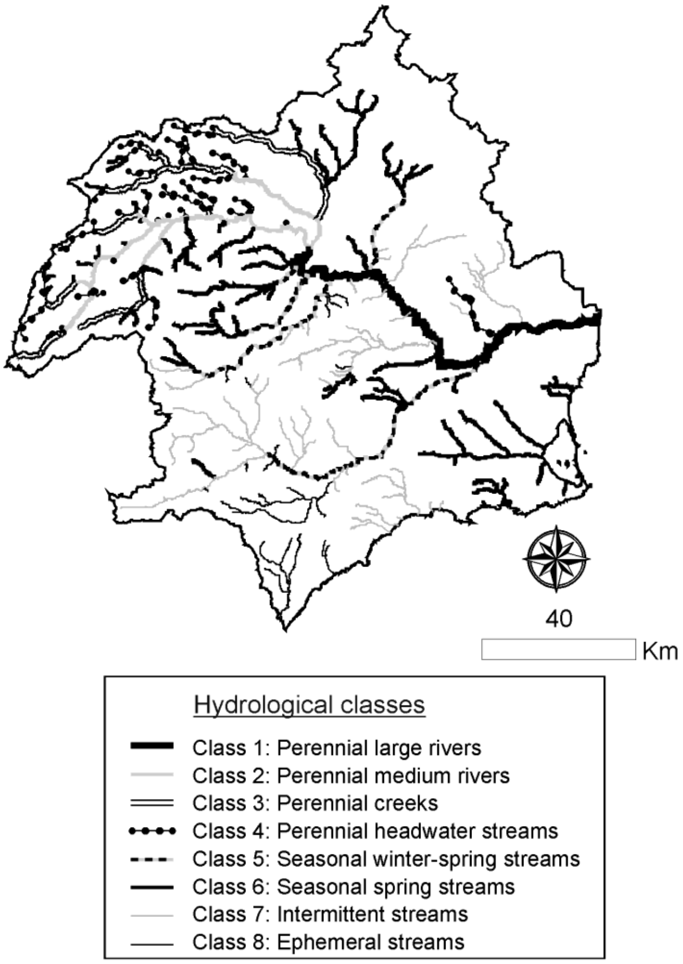

Figure 8. Map of the Segura River Basin showing the river segments and the 8 hydrological classes defined by Euclidean distances flexible-β clustering

Discussion

From the 73 hydrological indices studied, three metrics describe the patterns of hydrological variability in the Segura River Basin: mean annual flow (MADIS), interannual coefficient of variation (CV_{INTER}) and duration of droughts (D_L); since they represent the dominant gradients detected on flows: (1) magnitude and (2) temporal variability. They reflect the specific hydroclimatic characteristics of the study region: scarce and irregular precipitation as well as discharge associated with hydrological extremes (drought and floods), typical for Mediterranean areas (Gasith & Resh, 1999).

The ability to reduce the population of indices to a small, manageable subset has a number of benefits, including the reduction of analytical time and resources (Olden & Poff, 2003). Other classification studies in Mediterranean rivers have used similar hydrological variables related to flow magnitude, variability and drought intensity as the main discriminators of flow regime classes (Baeza *et al.*, 2006), sometimes in combination with morphological, geological and climatic variables following the system B of the EU WDF (Munné & Prat, 2004; Sánchez-Montoya *et al.*, 2007).

The distribution of flow regime classes showed a high degree of spatial cohesion, with most classes following the aridity gradient from NW to SE in the Segura River Basin. The most permanent and regular flows were found in the NW and the most intermittent and irregular flows in the SE. This regular-irregular flow gradient found in the Segura River Basin is similar to the observed by Baeza *et al.* (2006) in the Tagus River Basin in central Spain, Poff & Allan (1995) in the rivers of Wisconsin and Minessota and Mcnamay *et al.* (2011) in the southeastern US. However, the flow regime Class 6, described as *seasonal spring streams*, is broadly distributed across all sectors of the Segura Basin in small and scarce karstic watersheds.

Differences on geology along the NW-SE gradient, coupled with climatic differences, explain the differences of base flow among hydrological classes. The upper sector (high elevations) of the Segura Basin is more karstic than the medium and low sectors, which determines a more stable and regular hydrograph in the classes 3 and 4 (*perennial creeks* and *perennial headwater streams*, respectively), located in the Northwest. However, in the opposite extreme, the dominance of impermeable sediments (clay and marls) produces quick runoff and flashy hydrographs, characteristic of classes 7 and 8 (*intermittent* and *ephemeral streams*, respectively).

With more than a third of all the nodes and a drainage area greater than 60%, intermittent and ephemeral streams are the predominant classes in the Segura Basin, as in other arid and semiarid areas of Australia (Boulton & Suter, 1986) and South Africa (Davies *et al.*, 1993; Uys & O'Keeffe, 1997). In these streams high flow variability indicates periods without flows, whereas in perennial streams it denotes fluctuations (Uys & O'Keeffe, 1997), making difficult to establish discrete classes along the temporal variability continuum. However, the duration and periodicity of no-flow phases, the season when flow peaks occur and the variability in flow regimes within and among years are key components to define and characterize these streams.

In other Mediterranean basins, like the Ebro Basin, the duration and timing of low flows are the most important hydrological variables to discriminate flow regime classes (Bejarano *et al.*, 2010). We considered the drought duration as the most important parameter because it was correlated with all the studied metrics and represents the gradient of temporal variability in the Segura Basin. The drought duration metric has ecological significance emphasizing the biological consequences of the intensity of droughts (Martínez & Fernández, 2006). It is probably the most important environmental parameter affecting the aquatic biota in temporary rivers (Boulton, 1989). Drought events can result in the stream channel drying, partially or completely, and both aquatic space and quality declining, which undoubtedly affect organisms. Droughts play a key role in the distribution of species, community structure and life-history strategies of resident species (Gasith & Resh, 1999), although some responses are stream and community-specific (Argerich *et al.*, 2004; Dewson *et al.*, 2007). Although droughts in Mediterranean climatic regions are predictable and periodic (Gasith & Resh, 1999), their intensity can vary because of interannual variations in weather (Boix *et al.*, 2010). In Mediterranean climates, native biota have life history traits that provide them with greater resistance to droughts and an improved ability to get over a disturbance (Bonada *et al.*, 2007; Ferreira *et al.*, 2007), but may make them particularly vulnerable to the alteration of flow regimes (Lytle & Poff, 2004).

Human activities both in streams (e.g. flow regulation) and catchments (e.g. agriculture and urbanization) can exacerbate droughts and floods (Lake, 2007), especially in Mediterranean areas densely populated with intense water abstraction and regulation. In the Segura River, and some tributaries, reservoirs profoundly alter the natural flow regime, causing a significant reduction in the magnitude of flows and a relevant modification of the seasonal pattern, with droughts during winter (instead of summer) months becoming more frequent and durable (Belmar *et al.*, 2010; Vidal-Abarca *et al.*, 2002). The effects of these alterations on ecosystem structure and functioning are poorly known in the basin. In other Mediterranean rivers, Boix *et al.* (2010) found that reservoirs intensified the effect of droughts on the composition and structure of diatoms and fish assemblages downstream of dams. Besides, the decrease of flood frequency and the occurrence of extended droughts facilitate the invasion of exotic species, as occurs in other regulated rivers (Lake, 2003).

The hydrological classification scheme obtained provides a first level mean of arranging, conceptualizing and describing the natural or “reference” flow regimes in the study area at two levels of resolution. Despite the absence of components related to the frequency, duration and rate of change of high flow events, due to the use of monthly data, a functional classification was obtained. Like in other hydrological classifications that used monthly flow records (Bejarano *et al.*, 2010; Harris *et al.*, 2000), important spatial and temporal variations in hydrologic characteristics were detected. Therefore, monthly data may be adequate to analyze peak flows in Mediterranean streams, given the high seasonality that makes them relatively insensitive to temporal scales (Poff, 1996), and this classification is potentially relevant to develop environmental flows in the study area considering the magnitudes of the high flows necessary for an environmental regime. Similarly, monthly flows may be useful to determine the magnitude and duration of low flow events, which generally present larger duration than high flow events. However, monthly flows present some limitations to the design of environmental flows, such as the determination of the rise and fall rates during extreme events, which require daily or hourly flow series (Bejarano *et al.*, 2010).

The resulting classification will provide a strong basis for the study of the flow alteration-ecological response relationship in each hydrological type, a critical step to assess environmental flows within the ELOHA framework (Poff *et al.*, 2010). The comparison between the obtained reference flows and the actual ones, determined from gauging data, will allow us to characterise the hydrological alteration in each river type. Then, the flow alteration-ecological response relationship will be established by biological monitoring in sites selected along the gradient of hydrologic alteration. The development of this relationship for different river types will provide flow standards for water managers to guide the development of environmental flows both for rivers and for river segments in the Segura Basin.

In summary, the resulting classification is an example of a reference hydrologic classification in a Mediterranean basin where there are very limited unaltered flow data and only modelled monthly flows are available. A useful tool to support ecologically sustainable water resources planning and management in the Segura River Basin within the ELOHA framework.

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Appendices

1. Hydrological indices used for hydrological classification. (N: number of indices; T: time basis, being “M” monthly and “A” annual)

Identification code	N	T	Hydrologic index	Description	Units
Magnitude of flow events					
Average flow conditions					
M_A 1 - 12	12	M	Mean monthly flows	Mean monthly flow for all months	$m^3 \cdot s^{-1}$
CV_A 1 - 12	12	M	Variability in monthly flows	Coefficient of variation in monthly flows for all months	-
M_A 13 - 14	2	M	Variability across monthly flows 1	Variability in monthly flows divided by median monthly flows, where variability is calculated as range and interquartile	-
CV_{INTRA}	1	M	Variability across monthly flows 2	Coefficient of variation in mean monthly flows	
M_A 15	1	M	Skewness in monthly flows	(Mean monthly flow—median monthly flow)/median monthly flow	-
M_A 16	1	A	Mean annual runoff	Mean annual flow divided by catchment area	-
M_A 17 - 18	2	A	Variability across annual flows	Variability in annual flows divided by median annual flows, where variability is calculated as range and interquartile	$m^3 \cdot s^{-1} \cdot km^{-2}$ -
M_A 19	1	A	Skewness in annual flows	(Mean annual flow—median annual flow)/median annual flow	-
Q1	1	A	Variability across annual flows 1	Percentile flow with the annual discharge exceeded 1% of the time	$m^3 \cdot s^{-1}$
Q5/Q50, Q10/Q50	2	A	Variability across annual flows 2	Percentile flows with the annual discharge exceeded 5% and 10% divided by median annual discharge	-
Q50	1	A	Median annual discharge	Median annual flow for all years	$m^3 \cdot s^{-1}$
MEDDIS/A	1	A	Median annual runoff	Median annual discharge divided by catchment area	$m^3 \cdot s^{-1} \cdot km^{-2}$
RANGE	1	A	Range of flows	Maximum annual discharge minus minimum annual discharge	$m^3 \cdot s^{-1}$
STDEV	1	A	Variability across annual flows 3	Standard deviation of annual discharge	$m^3 \cdot s^{-1}$
CV_{INTER}	1	A	Variability in annual flows	Coefficient of variation in annual flows for all years	-
MADIS	1	A	Mean annual discharge	Mean annual flow for all years	$m^3 \cdot s^{-1}$
Low flow conditions					
M_L 1 - 12	12	M	Mean minimum monthly flows	Mean minimum monthly flow for all months	$m^3 \cdot s^{-1}$
M_L 13	1	A	Average minimum monthly flow	Mean of the mean minimum flows for all months	$m^3 \cdot s^{-1}$
AMIN/Q50	1	A	Annual minimum	Minimum annual discharge divided by Q50	-
I_L	1	A	Drought intensity	Monthly flow equalled or exceeded 95% of the time divided by mean annual flow	-
High flow conditions					
M_H1 - 12	12	M	Mean maximum monthly flows	Mean of the maximum monthly flows for all months	$m^3 \cdot s^{-1}$
CV_H	1	M	Variability across maximum monthly flows	Coefficient of variation in mean maximum monthly flows	-
M_H 13	1	M	Average maximum monthly flow	Mean of the mean maximum flows for all months	$m^3 \cdot s^{-1}$
AMAX/Q50	1	A	Annual maximum	Maximum annual discharge divided by Q50	-
I_H	1	M	Flood intensity	Monthly flow equalled or exceeded 5% of the time divided by mean monthly flow	-
Duration of low flow conditions					
D_L	1	M	Percent of zero-flow months	Percentage of all months with zero flow	%

2. Examples of rivers and streams belonging to each hydrologic class in summer

1. Perennial large rivers

Segura River after the confluence with the Mundo River, Cañaverosa

2. Perennial medium rivers

Zumeta River, Tobos

3. Examples of rivers and streams belonging to each hydrologic class in summer (continued)

3. Perennial creeks

Mundo River, La Alfera-Los Alejos

4. Perennial headwater streams

Tus River, Los Vados

3. Examples of rivers and streams belonging to each hydrologic class in summer (continued)

5. Seasonal winter-spring streams

Quípar River, Gilico

6. Seasonal spring streams

Argos River, Las Oicas

3. Examples of rivers and streams belonging to each hydrologic class in summer (continued)

7. Intermittent streams

Turrilla stream

8. Ephemeral streams

Malvariche wadi

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Chapter 2. Do environmental stream classifications support flow assessments in Mediterranean basins?

Segura River before its confluence with the Zumeta River

Belmar, O., Velasco, J., Martínez-Capel, F., Peredo-Parada, M. & Snelder, T. (2012) Do Environmental Stream Classifications Support Flow Assessments in Mediterranean Basins? *Water Resources Management* **26**, 3803-3817

Abstract and keywords

Natural flow regimes are of primary interest in designing environmental flows and therefore essential for water management and planning. The present study discriminated natural hydrologic variation using two different environmental classifications (REC-Segura and WFD-ecotypes) and tested their agreement with an *a posteriori* (hydrologic) classification in a Spanish Mediterranean basin (the Segura River, SE Spain). The REC-Segura was developed as a two-level hierarchical classification based on environmental variables that influence hydrology (climate and source-of-flow). The WFD-ecotypes were developed by the Spanish Ministry for the Environment to implement the Water Framework Directive (WFD) using hierarchical hydrologic, morphologic and physicochemical variables. The climate level in the REC-Segura broadly described the hydrologic pattern observed along the NW-SE aridity gradient of the basin. However, source-of-flow (defined by karstic geology) was only able to discriminate variation in flow regimes within one climatic category. The WFD-ecotypes, despite incorporating hydrologic variables, did not fully discriminate hydrologic variation in the basin. Ecotypes in tributary streams located in dry or semiarid climates embrace different flow regimes (both perennial and intermittent). There was little agreement between environmental and hydrologic classifications. Therefore, the authors advise against the use of environmental classifications for the assessment of environmental flows without first testing their ability to discriminate hydrologic patterns.

Mediterranean rivers · Stream classification · Environmental flows · Water Framework Directive · Ecotypes

Introduction

Characterising stream flows is of prime interest for water resource planning and management as well as for ecohydrologic studies. Many authors have emphasised the need to classify flow regimes at the regional scale to provide typologies that can support the assessment of environmental flows (Arthington *et al.*, 2006; Poff *et al.*, 2006). Hydrologic classification constitutes the first step of a new holistic framework intended to develop regional environmental flow criteria called the "Ecological Limits of Hydrologic Alteration (ELOHA)" (Poff *et al.*, 2006), where the unaltered hydrology of rivers and streams constitutes the basis for assessing the effects of flow alteration and estimating environmental flows. However, the utility of different river classification systems is still being evaluated (Leathwick *et al.*, 2011; Olden *et al.*, 2011).

There are two basic approaches used to classify rivers according to their natural regimes (Olden *et al.*, 2011): (1) inductive, or *a posteriori,* and (2) deductive, or *a priori*. The *a posteriori* (hydrologic) approach involves analysing at least 15 (Kennard *et al.*, 2010) or 20 (Richter *et al.*, 1997) years of hydrologic records. Flow series may be obtained from gauging stations or inferred from precipitation-runoff models (Olden *et al.*, 2011; Poff *et al.*, 2010) in order to calculate hydrologic metrics, such as the "Indicators of Hydrologic Alteration" (Mathews & Richter, 2007; Richter *et al.*, 1996), that allow clustering rivers and streams according to their similarity in flow regime. This procedure has been applied at different resolutions, from catchments in Mediterranean areas (Alcázar & Palau, 2010; Baeza & García de Jalón, 2005; Bejarano *et al.*, 2010; Belmar *et al.*, 2011) to countries such as the USA (Mcnamay *et al.*, 2011; Poff, 1996), France (Snelder *et al.*, 2009) and Australia (Kennard *et al.*, 2010).

The *a priori* approach describes and quantifies spatial variation in flow regime attributes across broad spatial scales where the availability of measured (gauged) or modelled hydrologic data is scarce or absent. It embraces three different methodologies (Olden *et al.*, 2011): environmental regionalisation, hydrologic regionalisation and environmental classification. For environmental regionalisation, specific regions are considered homogeneous with respect to certain environmental and hydrologic characteristics at a particular scale (Bryce & Clarke, 1996; Loveland & Merchant, 2004). However, hydrologic regionalisation delineates geographic areas with similar streamflow patterns, uses regression to relate environmental catchment characteristics to hydrologic metrics and assesses model reliability (for an example of methodological proposal, see Tsakiris *et al.*, 2011). Finally, environmental classification defines classes on the basis of physical and climatic attributes that are assumed to broadly produce similar hydrologic responses in stream systems, often geographically independent and depicted by a spatial mosaic of hydrologic types across the landscape (Detenbeck *et al.*, 2000).

The River Environment Classification (REC) (Snelder & Biggs, 2002) has been a landmark for stream environmental classifications. Originally applied in New Zealand, it has also been applied in Chile (Peredo-Parada *et al.*, 2011). Moreover, its ability to detect variations in hydrologic characteristics (Snelder *et al.*, 2005), invertebrate assemblages (Snelder *et al.*, 2004b) and nutrient concentrations (Snelder *et al.*, 2004a) has been demonstrated. The REC is based on a hierarchical scheme of controlling factors (or classification levels) that are assumed to be the dominant causes of variation in the physical and biological characteristics of rivers at a variety of spatial scales. Therefore, different classification solutions are possible using the same schema of controlling factors, with the choice of level depending upon the objective. In particular, the first and second levels, “climate” and “source-of-flow” respectively, were those used to discriminate rivers according to their differences in flow regime (Snelder *et al.*, 2005).

The Water Framework Directive (WFD) proposed two river classification systems (A and B, Annex II) to provide a basis for managing aquatic ecosystems. In Spain, water legislation (ORDER *ARM/2656/2008*, Ministry for the Environment) includes an environmental classification (WFD-ecotypes) based on the system B, which was developed for river segments considered as management units (i.e those where the definition of environmental flow regimes is mandatory). This hierarchical classification uses seven environmental variables: two hydrologic (annual specific runoff and discharge), three morphologic (mean slope and altitude of the watershed, and stream order) and two physicochemical (mean annual temperature and estimated water conductivity); however, it has not been hydrologically evaluated for use in assessing environmental flows.

In this study, the ability to discriminate the natural hydrologic variation of the rivers and streams in a Spanish Mediterranean basin (the Segura River) by two environmental classifications (REC-Segura, based on the REC, and WFD-ecotypes) and their agreement with an *a posteriori* (hydrologic) classification were tested. This study will provide researchers and water managers with useful information regarding if (1) environmental classifications can be used as surrogates of hydrologic methodologies to discriminate distinct natural flow regimes and (2) WFD-ecotypes are management units suitable for defining environmental flows.

Methods

Study area

Located in south eastern Spain, the management area of the Segura River basin (which includes coastal watercourses draining to the Mediterranean Sea) presents a great heterogeneity of flow regimes (Belmar *et al.*, 2011). Despite its small size (18 870 km^2), there is a strong climatic and altitudinal gradient from NW to SE. The climate ranges from wet (>1000 mm mean annual precipitation) and cold in the mountains (>1000 m.a.s.l.) of the NW to semiarid (<350 mm mean annual precipitation) in the SE lowlands (200 mm precipitation near the coast). Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). The lithology of the plains is characterised by limestone and marls with some volcanic areas, whereas calcites and dolomites dominate the mountain headwaters.

Seven out of the thirty-two WFD-ecotypes defined in Spain are present in the Segura Basin (Fig. 1): mineralised Mediterranean lowland streams (ecotype 7), mineralised Mediterranean low mountain streams (ecotype 9), Mediterranean limestone mountain streams (ecotype 12), highly mineralised Mediterranean streams (ecotype 13), low altitude Mediterranean mainstems (ecotype 14), mineralised Mediterranean-continental mainstems (ecotype 16) and large Mediterranean mainstems (ecotype 17).

An *a posteriori* classification based on hydrologic metrics (Belmar *et al.*, 2011) defined distinct natural flow regime classes in the Segura Basin along the stated aridity gradient. The southeast was characterised by intermittent or ephemeral flow regimes with zero-flows for more than 20% and 50% of the year, respectively, and high peaks in autumn associated with typical torrential rains. At the opposite extreme, in the northwest, larger and more stable flows with a soft decrease in summer were found. Rivers in intermediate areas presented bimodal hydrographs, due to seasonal spring and autumn rains, and medium intra- and interannual flow variability.

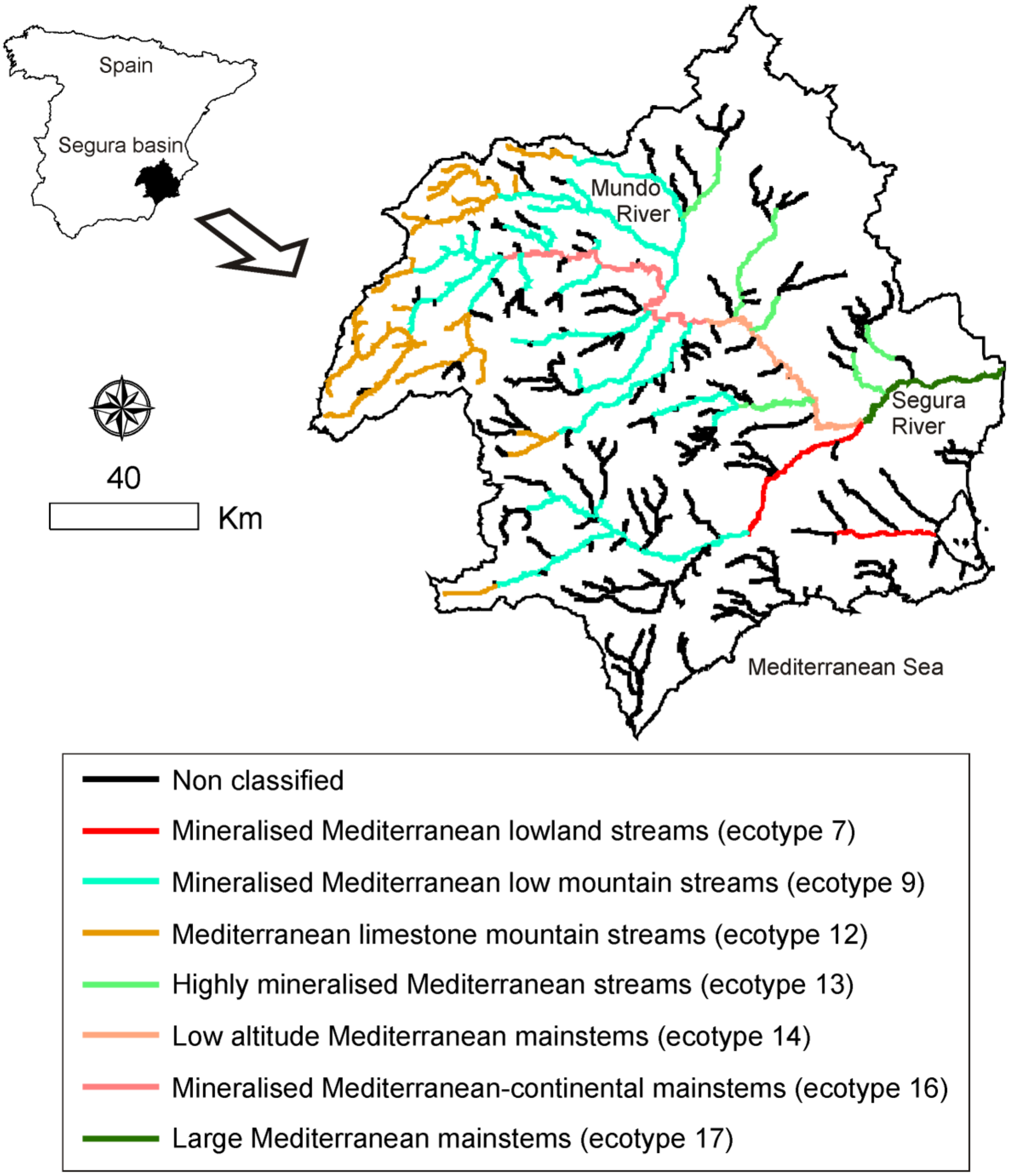

Figure 1. Location of the Segura Basin and Mediterranean ecotypes present

Hydrologic basis

The hydrologic network defined in Belmar *et al.* (2011) (in which all streams have a minimum drainage area of 10 km^2) and its associated hydrologic information were used as a baseline to characterise the hydrologic properties of the rivers and streams in the Segura Basin. A summary of the methodology used by the authors is presented below (for further details, see Belmar *et al.*, 2011).

First, due to the lack of suitable gauged flow data, natural monthly flows were generated for the period 1980/81-2005/06 using the ‘‘Integrated System for Rainfall–Runoff Modelling” (SIMPA), developed by the Centre for Hydrographical Studies (CEDEX, Ministry for the Environment, Spain). Second, 73 monthly and annual hydrologic indices were calculated. These metrics, based on the “Indicators of Hydrologic Alteration” (Mathews & Richter, 2007; Richter *et al.*, 1996) among others (Monk *et al.*, 2006; Monk *et al.*, 2007; Olden & Poff, 2003), included measures of flow magnitude (central tendency and dispersion) and drought duration. Third, a Principal Component Analysis (PCA) performed using the PC-ORD software v 4.41 (McCune & Mefford, 1999) summarised this hydrologic information. The PCA scores of the first three axes, which explained 85% of variance, were weighed by the proportion of variance explained by each and selected as a set of new synthetic, non-intercorrelated hydrologic variables. Finally, a flexible-β clustering technique (Legendre & Legendre, 1998; McCune & Grace, 2002) grouped streams according to their similarity of natural flow regime using Euclidean distances.

In the present study, this hydrologic classification (Belmar *et al.*, 2011) was pruned to obtain versions with the same number of classes as each environmental classification, which allowed their agreement to be tested.

REC-Segura Classification

The present study’s environmental classification (REC-Segura) was built using an approach similar to that applied in New Zealand for the River Environment Classification (Snelder *et al.*, 2005; Snelder & Biggs, 2002): two hierarchical levels to discriminate rivers according to their differences in flow regime. Categories were assessed for each stream by spatial integration of variables across its watershed using a Geographic Information System (GIS).

The first level (climate) comprised categories based on the magnitude and seasonality of precipitation, which has already showed behaviour analogous to that of streamflows in close Mediterranean basins (Nalbantis & Tsakiris, 2009). Temperature was discarded due to its strong correlation (Spearman Rank Correlation: -0.86, p = 0.000) with precipitation. Mean monthly watershed precipitation was estimated for all nodes from a 1 km grid map created by the Spanish Ministry for the Environment by means of an interpolation using data from the Spanish weather station network. Precipitation categories were based on those in Rivas-Martinez (1983): semiarid, dry and subwet (Table 1). Seasonality was estimated using the Precipitation Concentration Index (PCI) (Oliver, 1980) calculated for October, as recommended by Pascual *et al.* (2001), assuming that most precipitation occurs during this month in streams belonging to torrential basins. Three categories were defined: moderately seasonal, seasonal and strongly seasonal (Table 1), based on critical values used by Michiels & Gabriels (1996). Within each climate class, flow regimes were expected to have a pattern similar to the precipitation regime, with maximum mean monthly flows in rainy seasons (autumn, winter or spring) and minimum mean monthly flows in summer.

The second level (source-of-flow) was based on karstic geology due to its effect on groundwater storage capacity and transmissivity, and therefore, its major influence on base flow (Snelder & Biggs, 2002). Gárfias-Soliz *et al.* (2010) pointed out the necessity of taking into account the degree of karstification in *a priori* classifications. In this context, karstic areas were expected to discriminate subtle differences related to the magnitude of flows and their seasonal variation. Using Spain’s Map of Karst 1:1.000.000 developed by the Mining Geologic Institute of Spain (IGME), two subclasses based on the dominancy of karstic geology in the watershed, ≥50% surface and <50% respectively, were defined for each climate class (Table 1).

Hydrologic discrimination by environmental classifications

The discrimination of hydrologic variation by the REC-Segura, both at climate and source-of-flow levels, as well as by the WFD-ecotypes was tested by means of a Permutational Multivariate Analysis of Variance (PERMANOVA), using the three new synthetic, non-intercorrelated hydrologic variables from the PCA (Belmar *et al.*, 2011). PERMANOVA analyses were performed using PRIMER v 6.1.12 (Clarke & Gorley, 2006).

Table 1. Levels, classes and criteria used to construct the REC-Segura

Classification level	Classes	Mapping characteristics	Category Assignment Criteria
1. Climate	1. Moderately Seasonal Subwet	Mean annual precipitation and Precipitation Concentration Index (PCI) for October	Subwet: Mean annual precipitation ≥ 600 mm
	2. Moderately Seasonal Dry		Dry: Mean annual precipitation = 350 - 600 mm
	3. Seasonal Dry		Semiarid: Mean annual precipitation = 200 - 350 mm
	4. Moderately Seasonal Semiarid		Strongly Seasonal: Precipitation Concentration Index for October ≥ 20
	5. Seasonal Semiarid		Seasonal: Precipitation Concentration Index for October = 15 -19
	6. Strongly Seasonal Semiarid		Moderately Seasonal: Precipitation Concentration Index for October = 10 -14
2. Source-of-flow	1. Non karstic	Percentage of karstic surface in the basin	Non karstic: Percentage of karstic surface ≤ 50 %
(geology)	2. Karstic		Karstic: Percentage of karstic surface > 50 %

Agreement between environmental and hydrologic classifications

The environmental classifications were compared with hydrologic classifications with the same number of classes through the Adjusted Rand Index (ARI) (Hubert & Arabie, 1985). This index, a measure of cluster agreement (Steinley, 2004), is based on the relationship of each pair of objects and whether they differ between two cluster solutions. It ranges between 0 (indicating that agreement between two clustering solutions is no better than chance) and 1 (indicating perfect agreement). ARI was calculated with the mclust v 3.4.8 package for R (Fraley & Raftery, 2010).

Results

REC-Segura classification

At the first level (climate), the REC-Segura split up the streams and rivers in the Segura Basin into all of the defined classes (Table 1). As expected, there was a match between the geographical distribution of these classes (Fig. 2a) and the increasing aridity gradient from NW to SE reflected by the modelled flows. Moderately seasonal subwet streams (class 1) were composed of upper river segments of the Segura and Mundo rivers which never cease flowing (Fig. 3). Moderately seasonal dry streams (class 2) presented the highest average mean annual flow and also the widest range of values, as they include both the bottom half of the Segura River and some of its tributaries, located mainly on the right bank. Seasonal dry (class 3), moderately seasonal semiarid (class 4), seasonal semiarid (class 5), and strongly seasonal semiarid (class 6) streams represent a gradient of increasing temporality as zero-flow duration increases. These classes were composed of tributaries with inter- and intrannual coefficients of variation greater than those of classes 1 and 2 and bimodal hydrographs with strong flow peaks in winter and spring. Only class 6 showed a different hydrograph, with flows mainly associated to storm events.

The second classification level (source-of-flow) defined 11 subclasses (Fig. 2b) out of the 12 possible, because there were no karstic geologic materials in seasonal dry areas.

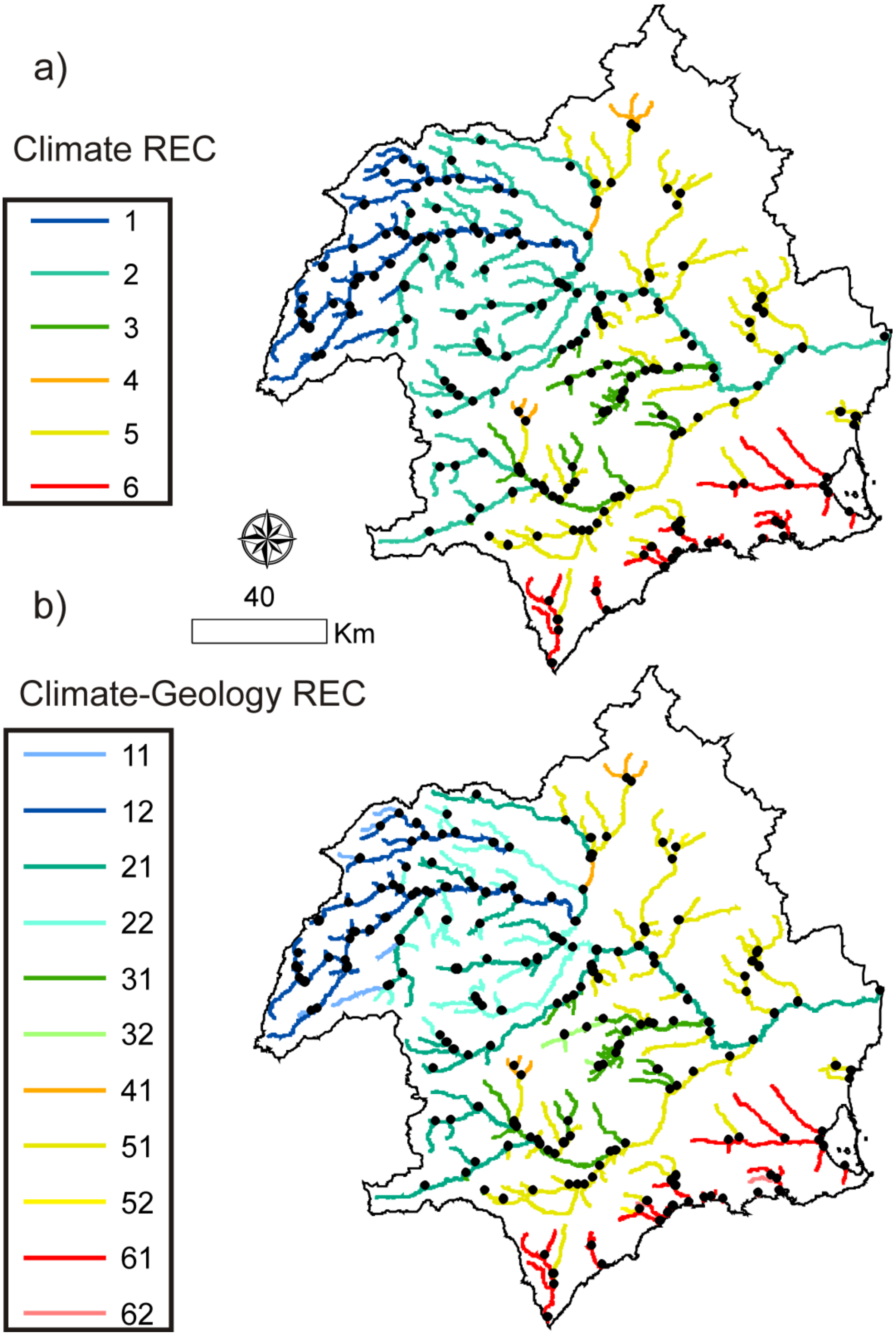

Figure 2. REC-Segura classification at the first (a) and second (b) hierarchical level. Classes are numbered as shown in Table 1. Note that, for the second level, two digits show the class both for the first (climate) and second (source of flow) levels, respectively

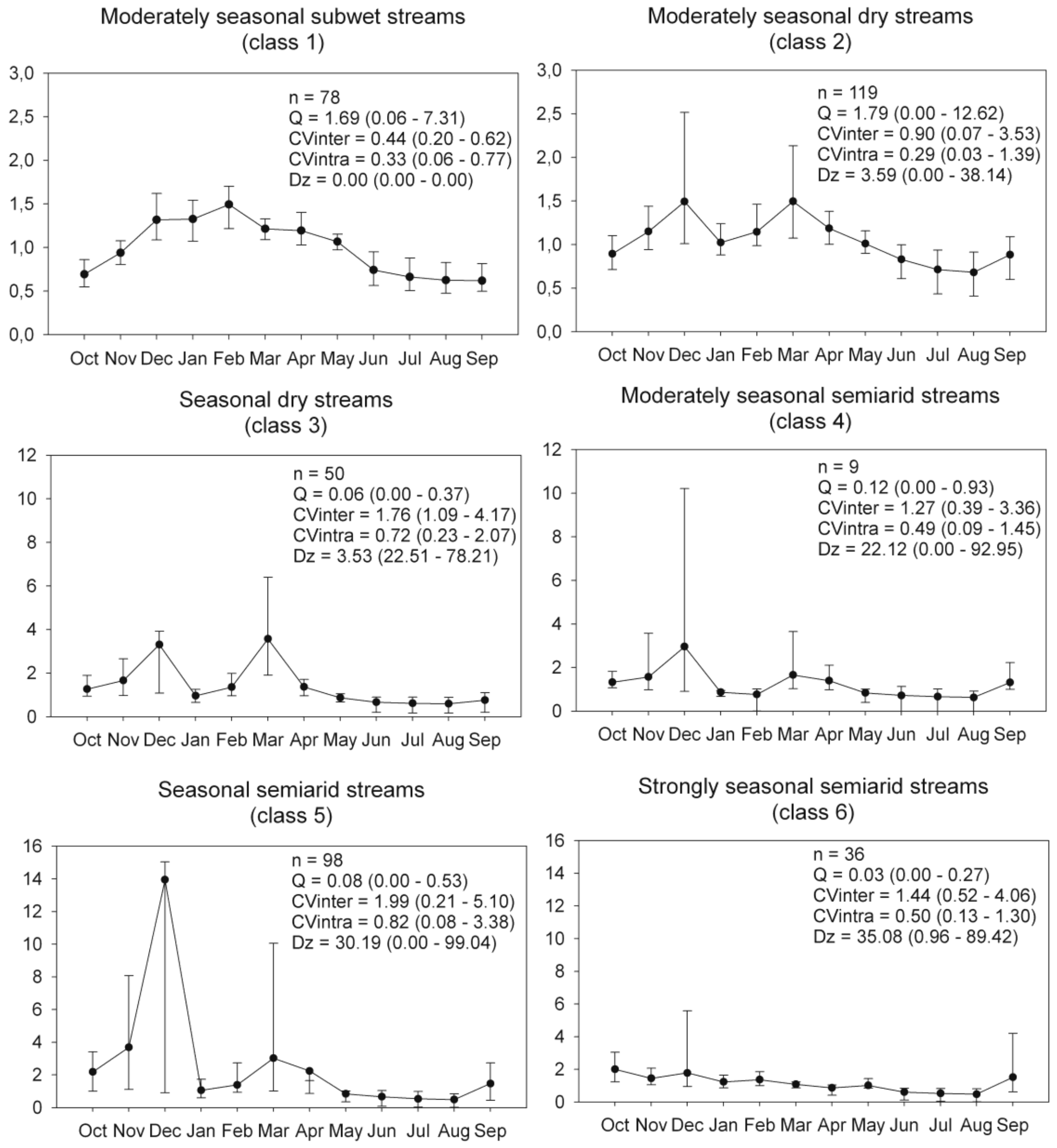

Figure 3. Mean monthly flows divided by the median annual flows for the REC-Segura classes at the first hierarchical level (climate). The numeric values correspond to the average (out of the parentheses), minimum and maximum of the following variables: mean annual flow in $m^3 \cdot s^{-1}$ (Q), interannual coefficient of variation (CVinter), intrannual coefficient of variation (CVintra) and duration of zero-flows in % (Dz)

Discrimination of flow regimes by the REC-Segura

PERMANOVA pair-wise comparisons showed significant hydrologic differences ($p<0.05$) among most REC-Segura climate classes (Table 2a). However, moderately seasonal semiarid streams (class 4) were not different from moderately seasonal subwet (class 1), moderately seasonal dry (class 2) and strongly seasonal semiarid (class 6) streams. In addition, seasonal dry (class 3) and seasonal semiarid (class 5) streams were not different from each other.

Table 2. PERMANOVA results (bold text when $p < 0.05$) showing hydrologic differences among pairs of REC-Segura classes at the first (a) and second (b) hierarchical level of classification. Classes are numbered as shown in Table 1. Note that, for the second level, two digits show the class both for the first (climate) and the second (source-of-flow) levels, respectively.

a)

Classes	t	P
1, 3	**5.962**	**0.001**
1, 5	**6.717**	**0.001**
1, 6	**4.378**	**0.001**
2, 1	**3.238**	**0.001**
2, 3	**4.562**	**0.001**
2, 5	**5.263**	**0.001**
2, 6	**2.792**	**0.001**
3, 6	**3.198**	**0.002**
4, 1	1.596	0.076
4, 2	1.098	0.293
4, 3	**2.582**	**0.007**
4, 5	**1.915**	**0.037**
4, 6	1.355	0.152
5, 3	0.599	0.640
5, 6	**2.755**	**0.005**

b)

Classes	t	P
11, 12	1.391	0.141
21, 22	**2.505**	**0.003**
31, 32	1.119	0.227
51, 52	0.967	0.357
61, 62	0.721	0.530

Only the moderately seasonal dry streams (class 2) presented hydrologic differences in karstic areas (Table 2b), showing a softer seasonality (Fig. 4).

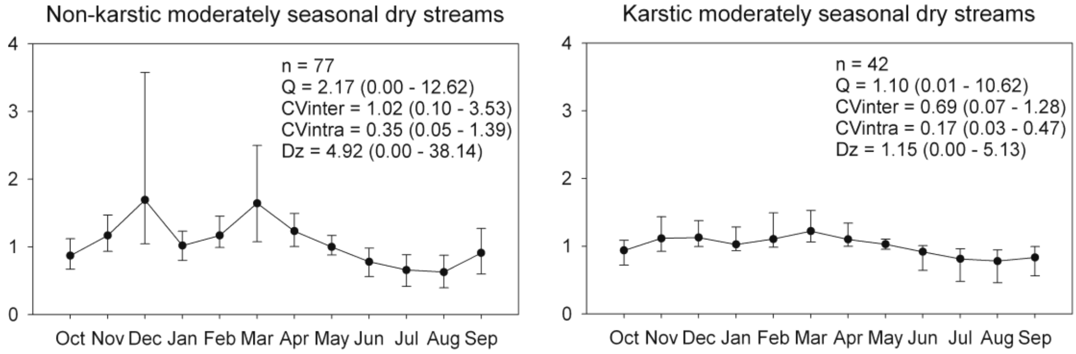

Figure 4. Mean monthly flows divided by the median annual flows for non-karstic and karstic moderately seasonal dry streams. The numeric values correspond to the average (out of the parentheses), minimum and maximum of the following variables: mean annual flow in m3·s-1 (Q), interannual coefficient of variation (CVinter), intrannual coefficient of variation (CVintra) and duration of zero-flows in % (Dz)

Discrimination of flow regimes by the WFD-ecotypes

PERMANOVA pair-wise comparisons indicated significant hydrologic differences ($p \leq 0.006$) among Mediterranean limestone mountain streams (ecotype 12), low altitude Mediterranean mainstems (ecotype 14), mineralised Mediterranean-continental mainstems (ecotype 16) and large Mediterranean mainstems (ecotype 17) (Table 3). However, there were not significant differences among mineralised Mediterranean lowland streams (ecotype 7), mineralised Mediterranean low mountain streams (ecotype 9) and highly mineralised Mediterranean streams (ecotype 13).

Table 3. PERMANOVA results showing hydrologic differences among pairs of ecotypes (bold text when $p<0.05$). Ecotypes have been labelled following the numeration established by the Ministry for the Environment: 7, mineralised Mediterranean lowland streams; 9, mineralised Mediterranean low mountain streams; 12, Mediterranean limestone mountain streams; 13, highly mineralised Mediterranean streams; 14, low altitude Mediterranean mainstems; 16, mineralised Mediterranean-continental mainstems; 17, large Mediterranean mainstems

Ecotypes	t	P
9, 7	1.007	0.297
9, 13	0.973	0.388
9, 14	**5.340**	**0.001**
9, 16	**5.132**	**0.001**
9, 17	**3.220**	**0.006**
12, 7	**2.866**	**0.001**
12, 9	**2.834**	**0.001**
12, 13	**3.015**	**0.003**
12, 14	**7.972**	**0.001**
12, 16	**7.871**	**0.001**
12, 17	**4.779**	**0.001**
13, 7	1.435	0.123
13, 14	**12.432**	**0.001**
13, 16	**11.785**	**0.001**
13, 17	**7.376**	**0.001**
14, 7	**11.792**	**0.001**
14, 17	**5.020**	**0.003**
16, 7	**10.527**	**0.001**
16, 14	**5.944**	**0.001**
16, 17	**4.416**	**0.001**
17, 7	**6.875**	**0.006**

Mediterranean limestone mountain streams (ecotype 12) include highly karstic headwaters located in the upper sector of the Segura Basin characterised by low average mean annual flow and moderate peak flows in winter (Fig. 5). Low altitude Mediterranean mainstems (ecotype 14), mineralised Mediterranean-continental mainstems (ecotype 16) and large Mediterranean mainstems (ecotype 17) comprise perennial sections of the Segura River that differ in flow magnitude, and increases downstream. These ecotypes are characterised by large flows in the winter-spring period and moderate intra- and interannual coefficients of variation (Fig. 5).

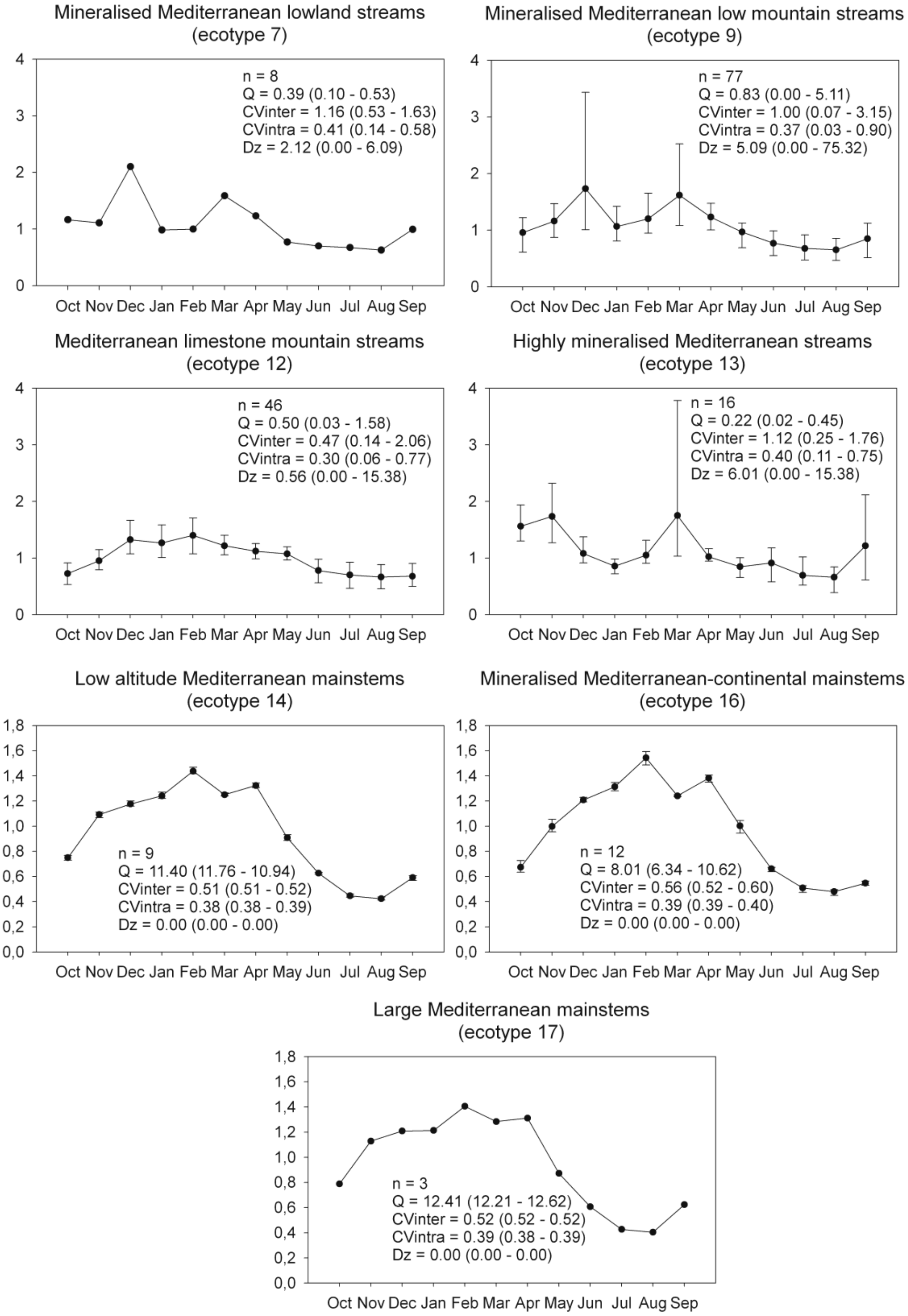

Figure 5. Mean monthly flows divided by the median annual flows for the WFD-ecotypes. The numeric values correspond to the average (out of the parentheses), minimum and maximum of the following variables: mean annual flow in $m^3 \cdot s^{-1}$ (Q), interannual coefficient of variation (CVinter), intrannual coefficient of variation (CVintra) and duration of zero-flows in % (Dz)

However, mineralised Mediterranean lowland streams (ecotype 7), mineralised Mediterranean low mountain streams (ecotype 9) and highly mineralised Mediterranean streams (ecotype 13), all located in the medium and low (dry and semiarid) sectors of the Segura Basin, presented greater zero-flow duration and interannual variation as well as bimodal hydrographs with peak flows in autumn and spring.

Agreement among classifications

Little agreement was found between environmental and hydrologic classifications. The Adjusted Rand Index (ARI) was 0.09 and 0.1, respectively, for the first (climate) and second (source-of-flow) levels of the REC-Segura, whereas the WFD-ecotypes presented a value of 0.1.

Discussion

The ability to infer hydrologic variation for river sections where unimpaired flow data are not available is an important issue for water management and planning in Mediterranean rivers, in general, and for developing environmental flow rules, in particular. If environmental classifications were able to discriminate the key attributes of the natural flow regime, they could define regional management units (*sensu* Arthington *et al.*, 2006). These classifications would then be useful for extrapolating hydrologic information from streams in the same class (i.e. from gauged to ungauged streams) and designing environmental flows (Snelder *et al.*, 2005). However, their hydrologic performance in our study area, as well as that of another *a priori* approach such as the environmental regionalisation in other temperate areas (Deckers *et al.*, 2010), was not enough.

The agreement between the REC-Segura and the hydrologic classification was very low. Although the first level (climate) broadly matched the NW-SE pattern of hydrologic variation in the Segura Basin, seasonal dry (class 3), moderately seasonal semiarid (class 4) and seasonal semiarid (class 5) streams did not discriminate hydrologic variation, because dry and semiarid areas presented both perennial and intermittent flow regimes. The second level (source-of-flow) only increased performance slightly. The poor discrimination of karstic geology could be due to the homogeneity of the materials (calcites and dolomites in the subwet sector and marls in the semiarid sector) or the resolution of the information available. Therefore, further improvements in our ability to explain and predict hydrologic variation may also be achieved by undertaking these analyses at finer spatial scales (Sanborn & Bledsoe, 2006; Stein *et al.*, 2008), as well as considering other factors. Winter (2001) stated that flow regime varies geographically in response to climate (precipitation and temperature), topography, geology, land cover and stream order. All of these factors are present in the REC (Snelder & Biggs, 2002), but those factors not considered in this study (land cover and stream order) occupy low hierarchical levels (the fourth and fifth, respectively) and were not described as "hydrology drivers" by the author (Snelder *et al.*, 2005; Snelder & Biggs, 2002). However, Peredo-Parada *et al.* (2011) found that the use of stream order in the REC for Chilean rivers improved results. These different outcomes prove that environmental variables do not necessarily reflect only hydrologic variation, which is in accordance with our results, because they usually encompass more general principles concerning the causes of physical variation in streams and rivers (Carlisle *et al.*, 2010; Snelder *et al.*, 2005), instead of direct hydrologic measures, and exclude significant local (e. g. reach-scale) factors. In any case, the use of land cover, in recognition of the importance of vegetation controlling evapotranspiration and infiltration (Peel *et al.*, 2001), was not possible in the study area due to the impossibility of accessing this information under natural conditions.

Even considering two hydrologic variables (the annual runoff coefficient and mean annual discharge), the WFD-ecotypes did not fully discriminate the variability of flow regimes in the basin. Hydrologic differences were found in four out of the seven analysed ecotypes. Therefore, attributing the same hydrologic reference to ecotypes in dry or semiarid areas (mineralised Mediterranean lowland streams, mineralised Mediterranean low mountain streams and highly mineralised Mediterranean streams; ecotypes 7, 9 and 13, respectively), where perennial and temporary regimes coexist, could lead to the definition of erroneous environmental flow regimes. The low performance of the WFD-ecotypes was not surprising, as this classification does not take into account the variability of flows or the extent of droughts, giving more importance to the altitude and degree of mineralisation.

In conclusion, although the REC-Segura classes and the WFD-ecotypes were able to detect statistically significant differences in hydrologic regimes, they showed limited discrimination of hydrologic variability and little agreement with the hydrologic classification. Therefore, caution is recommended in the use of environmental classifications for assessing environmental flows in the Segura Basin, as well as in other Mediterranean basins with similar hydrologic characteristics. More systematic methods are needed to validate and improve these classifications (Loveland & Merchant, 2004), as they still present uncertainty in the choice of hydrologic drivers. In this context, the use of new emergent techniques, such as generalised dissimilarity modelling (GDM), may optimise the ability to discriminate patterns using parallel sets of data (for a biological example, see Leathwick *et al.*, 2011).

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Chapter 3. The influence of natural flow regimes on macroinvertebrate assemblages in a semiarid Mediterranean basin

Tus River before the baths

Belmar, O., Velasco, J., Gutiérrez-Cánovas, C., Mellado-Díaz, A., Millán, A. & Wood, P. J. (2012) The influence of natural flow regimes on macroinvertebrate assemblages in a semiarid Mediterranean basin. *Ecohydrology.*
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Abstract and keywords

The investigation of hydrology-ecology relationships constitutes the basis for the development of environmental flow criteria. The need to understand these linkages in natural systems has increased due to the prospect of climate change and flow regime management, especially in water-scarce areas such as Mediterranean basins. Our research quantified the macroinvertebrate community response at family, genus and species level to natural flow regime dynamics in freshwater streams of a Mediterranean semiarid basin (Segura River, SE Spain), and identified the flow components that influence the composition and richness of biotic assemblages. Flow stability and minimum flows were the principal hydrological drivers of macroinvertebrate assemblages, whereas the magnitude of average and maximum flows had a limited effect. Perennial stable streams were characterised by flow sensitive lotic taxa (EPT: Ephemeroptera, Plecoptera, Tricoptera) and intermittent streams by predominately lentic taxa (OCHD: Odonata, Coleoptera, Heteroptera and Diptera). Relatively minor biological changes were recorded for intermediate flow regime classes along a gradient of flow stability. Seasonal variation and minimum flows are key hydrological components that need to be considered for river management and environmental flows in the Segura River Basin and other Mediterranean basins. The anthropogenic modification of these parameters, due to both human activities and climate change, would probably lead to significant changes in the structure and composition of communities in perennial stable streams. This would be characterised by a reduction of flow sensitive EPT taxa and an increase in more resilient OCHD taxa.

Natural flow regime · Flow stability · Minimum flows · Macroinvertebrate composition · Richness · Segura River Basin · Semiarid Mediterranean streams

Introduction

The search for links between instream ecology and hydrology has become one of the fundamental issues in contemporary river science (Vaughan *et al.*, 2009). Empirical investigation of regional flow-ecology relationships constitutes the basis for the development of environmental flow (e-flow) criteria (Arthington *et al.*, 2006; Poff *et al.*, 2010). In addition, the need to understand ecology-hydrology linkages in natural systems has been highlighted by the need to define reference conditions against which modified dynamics can be compared (Tockner *et al.*, 2003). These needs are particularly pressing in the light of predicted climate change (European Environment Agency, 2008) and anthropogenic modification of natural flow regimes, especially in water-scarce areas such as Mediterranean basins.

Instream hydrological variability, encapsulating elements of the entire flow regime such as the daily, seasonal and annual patterns of discharge, the frequency, timing, predictability and duration of extreme flows (high and low), rates of change in discharge, and the magnitude of flows, is widely recognised as key ecological organizer in fluvial ecosystems (Bunn & Arthington, 2002; Hart & Finelli, 1999; Poff *et al.*, 1997; Richter *et al.*, 1996). Spatial variation of these characteristics is determined by variations in climate and mediated by basin geology, topography and vegetation (Winter, 2001). These hydrological and environmental factors influence the physical habitat for aquatic and riparian biota determining the conditions for reproduction and recruitment and affecting the availability of trophic resources, refuges during adverse situations and opportunities for dispersal (Naiman *et al.*, 2008). Consequently, flow variability has strong ecological implications which shape the structure and function of riverine ecosystems from the local to regional scales, and from days (ecological effects) to millennia (evolutionary effects) (Lytle & Poff, 2004). It has been hypothesised that sites with similar hydrological characteristics should share similar faunal community composition, traits and ecosystem functioning (Poff & Ward, 1989). Therefore, as Arthington *et al*. (2006) and Poff *et al*. (2010) suggested, ecological responses of flow regimes to a given anthropogenic change should be broadly similar in rivers with similar natural flow regimes.

This hypothesis provides a powerful foundation to predict ecological responses to future flow regime changes, constituting the key element of a new holistic framework for developing scientifically-credible regional environmental flows: the ‘‘Ecological Limits of Hydrologic Alteration’’ (ELOHA) (Arthington *et al.*, 2006; Kennard *et al.*, 2010; Poff *et al.*, 2010). Therefore, identifying and quantifying specific relationships between flow regimes and biological communities in undisturbed river ecosystems are essential steps to ensure sustainable river management (Arthington *et al.*, 2006; Jowett & Biggs, 2009). Such relationships have been studied in general at the regional scale, using macroinvertebrates (e.g. Armanini *et al.*, 2012; Kennen *et al.*, 2010; Konrad *et al.*, 2008; Monk *et al.*, 2006), fisheries (e.g. Kennard *et al.*, 2007; Pegg & Pierce, 2002; Poff & Allan, 1995; Snelder *et al.*, 2009) or multiple taxonomic groups (e. g. Clausen & Biggs, 1997; Jowett & Duncan, 1990). However, the strength and nature of relationships between the flow regime and the biological assemblage vary depending on the geographical region, the floral or faunal group considered and the taxonomic resolution analysed.

In some areas, such as Mediterranean-climate regions, organisms have to withstand high intra- and interannual hydrological variability, together with frequent natural flow extremes (floods and droughts) (Gasith & Resh, 1999). Species may respond over evolutionary time scales by developing morphological, physiological and/or life-history traits to bear such stresses (Bonada *et al.*, 2007a; Bonada *et al.*, 2007b; Poff *et al.*, 1997). Previous studies of Mediterranean streams (e. g. Argyroudi *et al.*, 2009; Bonada *et al.*, 2002; Bonada *et al.*, 2004; Jáimez-Cuéllar *et al.*, 2002; Mellado, 2005; Sánchez-Montoya *et al.*, 2007; Vivas *et al.*, 2002) as well as other semiarid areas (e. g. Boulton & Lake, 2008) have highlighted the importance of flow permanence on the composition and structure of macroinvertebrate communities. A progressive replacement of Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa by Odonata, Coleoptera and Heteroptera (OCH) taxa has been reported as flow permanence decreases (Argyroudi *et al.*, 2009; Sánchez-Montoya *et al.*, 2007) or hydrological connectivity is reduced (Bonada *et al.*, 2006); although Diptera have also been associated with river sections with low or no flows and dominate lentic habitats in Southeast Spain (Vivas *et al.*, 2002). Consequently, flow stability and hydrological extremes (especially low flows) are expected to be the most important components of Mediterranean flow regimes shaping instream assemblages, although its relative importance is still unclear.

The aim of this study was to quantify the effect of different flow regimes on macroinvertebrate communities. We utilised a dataset containing stream macroinvertebrate records at family, genus and species level across a semiarid Mediterranean region that encompasses a wide gradient of hydrological regimes (Belmar et al 2011) to test these predictions: (1) Flow stability and minimum flows should be the principal hydrological drivers of macroinvertebrate assemblage composition and richness; (2) an increase in the explanatory power of hydrology should occur as taxonomic resolution increases; and (3) a replacement of taxa should take place along a hydrological gradient from permanent streams with stable discharges to streams with high flow intermittence and flow variability. In general, a decrease in the percentage of flow sensitive Ephemeroptera, Plecoptera and Trichoptera families should occur as an increase in the percentage of more resilient Odonata, Coleoptera, Heteroptera and Diptera families takes place.

Methods

Study area

Located in the Southeast of Spain, the Segura River Basin drainage network, including coastal watercourses draining to the Mediterranean Sea, was selected as the study area. The management area of the Segura River Basin, one of the most arid zones of the Mediterranean region, includes watercourses with highly heterogeneous flow regimes. These water bodies range from perennial rivers, with low seasonal and interannual flow variability, to highly seasonal ephemeral streams (Belmar *et al.*, 2011). This variability is due to a strong climatic and altitudinal gradient from NW to SE, despite its relatively small size (18 870 km^2). Climate ranges from wet (>1000 mm mean annual precipitation) and cold in the high elevation mountains of the NW (>1000 m.a.s.l.) to semiarid and hot in the SE lowlands (<350 mm mean annual precipitation). Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). The lithology of the plains is characterised by limestone (karst) and Miocene and Triassic marls, with some small influences of volcanic strata. In contrast, calcites and dolomites dominate the mountainous headwaters. The vegetation is varied and ranges from Mediterranean conifer forests in the NW mountains to arid and semiarid shrublands in the SE lowlands. This gradient in altitude and climate is coupled with an anthropogenic population density gradient. The river network has low population densities in the forested headwaters, intermediate densities in the agricultural midlands (with major flow regulation) and highly populated cities in the lowlands (Mellado, 2005). Agricultural (52.1%), forest and seminatural (45.2%), and artificial (2.1%) are the dominant landuses in the Segura Basin (estimated from Corine Land Cover 2000), making it one of the most regulated in Europe (Ministry for the Evironment, 2004). Water resource demands exceed 224% of that available and only 4% of runoff reaches the mouth of the river (Zimmer, 2010). This has resulted in over exploitation of the surface waters, an interbasin transfer from the Tagus River (a mean of 325 hm^3 yr^{-1}), a mean groundwater extraction of around 478 hm^3/year (over 80% of natural recharge) and a high regulatory capacity of 770 hm^3 (over 90% of the natural input) due to 24 dams over 10 m in height (Grindlay *et al.*, 2009; Grindlay *et al.*, 2011).

Hydrological data

A drainage network was derived from a 25 m digital elevation model (DEM) developed by the National Geographic Institute of Spain (IGN) and layers available from the website of the Spanish Ministry for the Environment, using the ArcGIS software v 9.2 and the ArcHydro extension v 1.2 (ESRI, Redlands, California, USA). The network comprises sections that link each network junction or node, and each node was associated with its corresponding watershed (derived from the DEM). The minimum watershed area to define a river section was 10 km^2, resulting a hydrological network with 390 river sections.

The hydrological classification developed for the Segura River Basin in Belmar *et al.* (2011) was used to define distinct natural hydrological regimes. This classification was developed using 73 indices based on the “Indicators of Hydrologic Alteration” (IHA) (Mathews & Richter, 2007). These flow indices represent a wide range of ecologically relevant flow statistics (Mathews & Richter, 2007; Monk *et al.*, 2006; Monk *et al.*, 2007; Olden & Poff, 2003; Richter *et al.*, 1996) and comprise monthly and annual flow statistics including measures of duration of droughts as well as the central tendency and dispersion of flow magnitude (average, low and high flow conditions). Indices related to the frequency, duration and rate of change of high flow events were not used by Belmar *et al.* (2011) due to the absence of daily flow data. Natural flows were derived from a monthly rainfall-runoff model developed by the Centre for Hydrographic Studies (CEDEX, Ministry for the Environment and Public Works, Spain), for the period

1980/81-2005/06. The classification of the flow regimes recorded comprised eight flow-regime classes (names are provided throughout to aid interpretation) principally characterised by the magnitude of mean annual flow, the duration of droughts and the interannual variation of flow (Table 1).

Table 1. Mean and standard deviation of the mean annual flow (MADIS), time with zero flow (D_L) and coefficient of variation in annual flows (CV_{INTER}) for the natural flow regime classes defined in the Segura River Basin (Belmar *et al*. 2011)

Hydrological class	Number of stream sections	MADIS (m^3/s)	D_L (%)	CV_{INTER}
1. Perennial large size rivers	17	11.30 (± 0.74)	0.00 (± 0.00)	0.52 (± 0.01)
2. Perennial medium size rivers	31	3.76 (± 2.26)	0.00 (± 0.00)	0.50 (± 0.13)
3. Perennial stable creeks	21	1.00 (± 0.45)	0.00 (± 0.00)	0.32 (± 0.09)
4. Perennial stable headwater streams	43	0.18 (± 0.17)	0.00 (± 0.00)	0.26 (± 0.13)
5. Perennial winter peak flow seasonal streams	26	0.37 (± 0.09)	2.31 (± 2.06)	1.39 (± 0.29)
6. Perennial spring peak flow seasonal streams	110	0.06 (± 0.06)	4.46 (± 6.32)	0.81 (± 0.30)
7. Temporary intermittent streams	101	0.04 (± 0.04)	24.88 (± 13.15)	1.71 (± 0.38)
8. Temporary ephemeral streams	41	0.01 (± 0.01)	61.90 (± 20.21)	3.43 (± 0.84)

The resulting flow regimes can be placed into four broad hydrological groups: (1) mainstem rivers, with perennial flow thorough the year, low interannual variation and an average annual discharge greater than 10 m^3/s (class 1, *large rivers*) or between 2 and 10 m^3/s (class 2, *medium rivers*); (2) perennial stable streams, which only difference respect to mainstem rivers is their reduced average discharge, between 0.3 and 2 m^3/s (class 3, *creeks*) or lower than 0.3 m^3/s (class 4, *headwater streams*); (3) perennial seasonal streams, which eventually cease flowing (although perennial surface water persists) and with peak discharges in winter (class 5, *winter peak flow seasonal streams*) or spring (class 6, *spring peak flow seasonal streams*); and (4) temporary streams, including *intermittent streams* (class 7), which do not flow for between 20% and 50% of the time, and *ephemeral streams*, that do not experience flow for more than 50% of the time (class 8). Indices and classes were assigned to their corresponding river section.

Macroinvertebrate data

Macroinvertebrate abundance data at family, genus and species level were compiled from the *Biodiversidad* database (*Ecología Acuática* research group, Department of Ecology and Hydrology, University of Murcia, Spain). Species data were available for beetles (Coleoptera), which have been recorded in all kinds of water bodies in the region and have been shown to be good indicators of aquatic biodiversity (Bilton *et al.*, 2006; Sánchez-Fernández *et al.*, 2006). Samples had been taken along 100 m stream transects using a kick-net (500-1000 µm) and following the multi-habitat protocol (Jáimez-Cuéllar *et al.*, 2002). Baseline macroinvertebrate samples were collected between 1980 and 2006.

A minimum of 5 samples per hydrological class were selected, ensuring that they had been collected in freshwater streams (conductivity <5000 $\mu S\ cm^{-1}$), above water regulation infrastructures (e.g. dams or weirs) and abstraction areas and in absence of significant evidences of anthropogenic alteration. However, using the criteria above two classes did not have any biological data: *large rivers* (class 1), due to the absence of reference conditions, and *ephemeral streams* (class 8), where no sampling had been undertaken due to their frequent dry status.

Every sample was collected during the spring or early summer from a different sampling site (Fig. 1). This time-period is considered the most representative of the annual macroinvertebrate community composition in Mediterranean streams (Bonada *et al.*, 2009). Each site was paired with the closest downstream node in the drainage network. In order to avoid pseudoreplication, when there was more than one site (and sample) available for the same node, only the closest to the hydrological node was selected. The final dataset consisted of 35 samples associated with 84 macroinvertebrate families, and 133 genera, and 43 samples associated with 110 Coleoptera species (see Appendix).

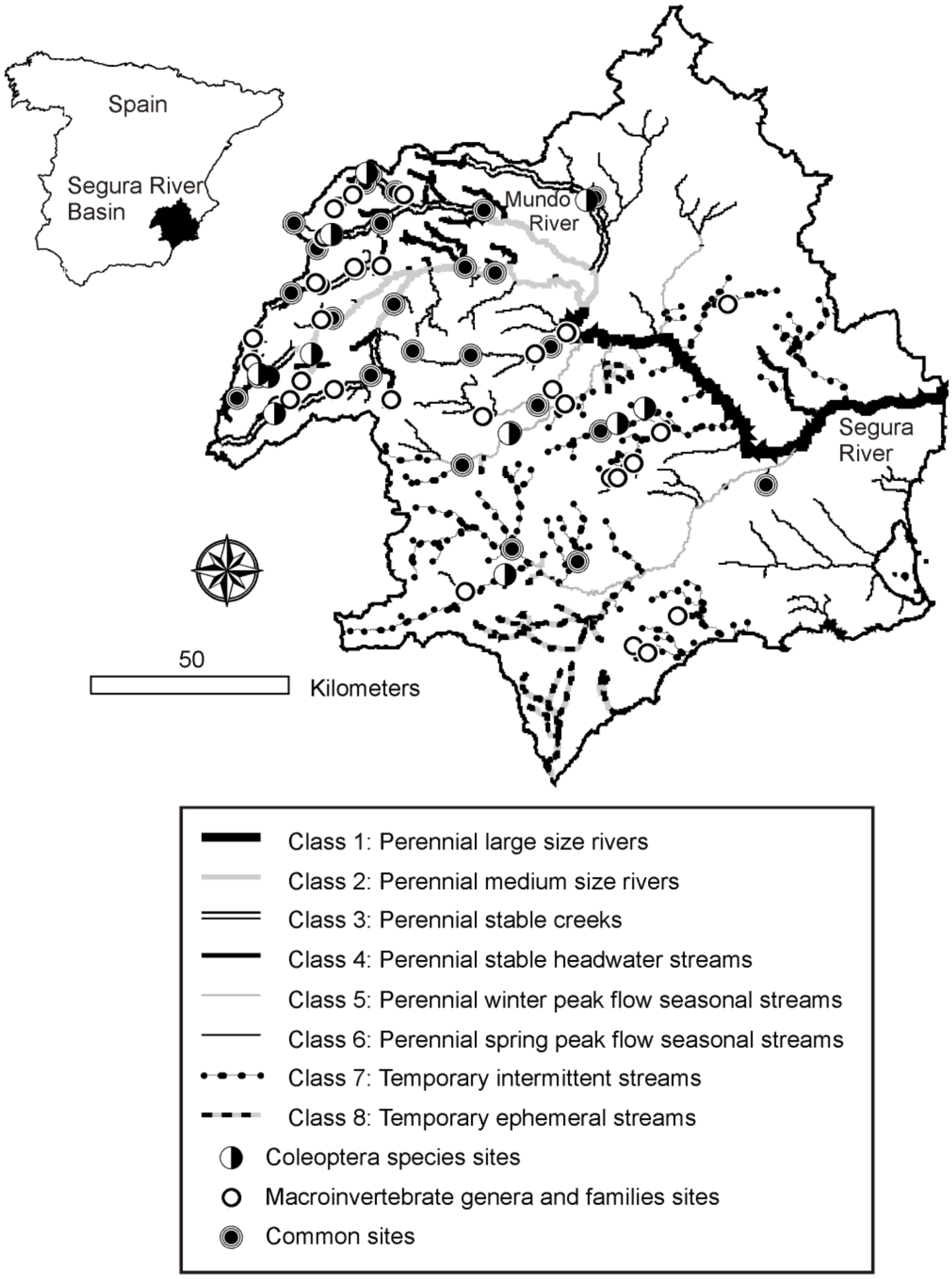

Figure 1. Location of the study area, hydrological classes in the river network and sampling sites

Environmental data

Climatic, topographic and geologic variables that were assumed to control hydrological processes (Snelder *et al.*, 2005) were derived from different Geographic Information System (GIS) layers available for the watershed. Average annual precipitation and air temperature were derived from 1 km grid maps created by the Spanish Ministry for the Environment by means of interpolation using data from the Spanish weather stations network (Estrela *et al.*, 1999). Drainage area, mean altitude and slope were calculated using the National Geographic Institute of Spain's digital elevation model (DEM). Geology was characterised by the percentage of karst area in each watershed and derived from the "Spain's Map of Karst" 1:1 000 000 developed by the Mining Geologic Institute of Spain (IGME) and, indirectly, through water conductivity (recorded for every biological sample). We hypothesised that the karstic surface would control groundwater storage and baseflow (Snelder & Biggs, 2002) and that higher conductivities would reflect the predominance of sedimentary marls that result in flashy hydrographs that reflect precipitation patterns (Bracken *et al.*, 2008).

Data analysis

A Principal Component Factor Analysis (PCFA) (i.e. a Principal Components Analysis (PCA) combined with a Varimax rotation) was used to examine dominant patterns of intercorrelation among the hydrological indices (Belmar *et al.*, 2011) and to identify subsets of indices that describe the major sources of variation while minimizing redundancy (i.e. multicollinearity). The Varimax rotation allows obtaining a clearer pattern of loadings (indices clearly marked by high loadings for some axes and low loadings for others) and, therefore, a better interpretation of the meaning of each axis. The hydrological characteristics of each stream in the network were defined through the corresponding PCFA scores (hydrological components) and hydrological class.

Rare taxa (those collected at fewer than 5% of sampling sites) were removed for multivariate analyses. Abundance data were transformed by means of the Beals smoothing function (Beals, 1984; McCune, 1994) to reduce noise by enhancing the pattern of joint occurrences. This function is appropriate in the current investigation because the data consist of a large number of small sample units (Peck *et al.*, 1995) and fulfil the requirements established by De Cáceres & Legendre (2008).

For each taxonomic level analysed, we performed a non-metric multidimensional scaling (NMDS) ordination based on Bray-Curtis distances among the sampling sites. The strength of the correlation between the NMDS axes and the environmental variables, as well as the hydrological components, was plotted as vectors. In addition, the individual variables and components were analyzed using Pearson coefficients. Covarying (redundant) environmental variables were removed for subsequent model development since the primary objective of the research was to determine the most important flow components influencing macroinvertebrate assemblages and not to distinguish the independent effect of hydrological and environmental drivers.

Distance based Linear Models (DistLM) were developed to assess the importance of hydrological components driving taxonomical differences among sites. DistLM calculates a multivariate multiple regression analysis between any symmetric distance matrices, including a permutation test, as described by McArdle & Anderson (2001). The final models were selected following a forward-stepwise procedure. For each taxonomic level, marginal tests determined the variance explained by each flow component and the sequential procedure discarded the variance shared by more than one thereby avoiding the overestimation of their effect on the community.

Similarly, Generalised Linear Models (GLM) were employed to determine how hydrological components (independent variables) affected faunal richness patterns. Models were constructed using log-transformed data following a forward-stepwise procedure, assuming a Gaussian error distribution for the dependent variables. These variables were the richness of Coleoptera species, number of macroinvertebrate genera, number of macroinvertebrate families and the ratio EPT/EPTOCHD (defined by the richness of Ephemeroptera, Plecoptera, Trichoptera, Odonata, Coleoptera, Heteroptera and Diptera families). The latter is based on the EPT/EPTOCH ratio, which is used to characterise temporary and lotic-lentic conditions in Mediterranean-climate regions (Bonada *et al.*, 2006).

A non-metric single-factor Analysis of Similarity (ANOSIM) was used to test whether assemblage composition differed among hydrological classes and, therefore, if natural regimes can be used to differentiate distinct groups of invertebrate communities. Global R indicates if assemblages are randomly grouped (i.e. $R=0$) or not (usually $0<R\leq1$,

although negative values are possible *sensu* Clarke, 1993). R pairwise values were also obtained for each pair of classes, indicating whether intraclass similarities were greater than interclass similarities (R value close to 1).

Indicator taxa were defined for each hydrological class using the Indicator Species analysis (IndVal) of Dufrêne & Legendre (1997). This analysis generates an indicator value index (IV) for each taxon and class, calculated on the basis of the specifity (maximum when a taxon only occurs in one class) and fidelity (maximum when all sites in a class have the taxon) of each taxon to each class.

All permutation tests (DistLM, ANOSIM and IndVal) were undertaken using 999 permutations. PCFA was undertaken in STATISTICA v 6 (Statsoft, 2001). NMDS and IndVal were conducted using PC-ORD software v 4.42 (McCune & Grace, 2002). ANOSIM and DistLM were undertaken in PRIMER v6 (Clarke & Gorley, 2006). GLM were performed using the R statistical software v 2.12.2 (R Development Core Team, 2011).

Results

Hydrological components

The three first PCFA axes were selected to represent the set of hydrological indices since all of them explained greater than 10% of the variance (46, 28 and 12%, respectively) and the forth axis only explained an additional 4%. The first axis was positively correlated with mean and maximum monthly flows (Table 2a), representing the flow magnitude component of the IHA. The second axis was negatively correlated with the interannual coefficients of variation in monthly flows, the intrannual coefficient of variation in maximum monthly flows and the percentage of time without flows. These variables characterise the inter- and intrannual variability of the flow regime and, as a result, this axis was defined as the flow stability component (Table 2b). The third axis, magnitude of minimum flows, was correlated with all the minimum monthly flows and their average value (Table 2c).

These three hydrological components (PCFA axes) displayed significant positive correlations with mean altitude and precipitation in the watershed, and negative correlations with mean temperature (Table 3). In addition, karst surface and slope were positively correlated with flow stability and minimum flows, while drainage area was associated with the magnitude of flow. As anticipated, conductivity displayed a negative association with flow magnitude and stability.

Table 2. Pearson correlation coefficients between the three first axes from the Principal Component Factor Analysis (PCFA) and the 73 hydrological indices. Horizontal lines separate indices associated to the three flow components represented by the axes: (a) magnitude (average and maximum flows), first axis (46% of variance); (b) flow stability, second axis (28% of variance); and (c) minimum flows, third axis (12% of variance)

			PCFA axis		
	Variable	Description	1st	2nd	3rd
(a)	M_A 1	Mean monthly flow (October)	**0.98**	0.13	0.02
	M_A 2	Mean monthly flow (November)	**0.98**	0.13	0.02
	M_A 3	Mean monthly flow (December)	**0.99**	0.12	0.05
	M_A 4	Mean monthly flow (January)	**0.98**	0.14	0.04
	M_A 5	Mean monthly flow (February)	**0.98**	0.14	0.04
	M_A 6	Mean monthly flow (March)	**0.99**	0.12	0.03
	M_A 7	Mean monthly flow (April)	**0.98**	0.14	0.02
	M_A 8	Mean monthly flow (May)	**0.98**	0.15	0.04
	M_A 9	Mean monthly flow (June)	**0.98**	0.15	0.03
	M_A 10	Mean monthly flow (July)	**0.97**	0.16	0.04
	M_A 11	Mean monthly flow (August)	**0.97**	0.16	0.05
	M_A 12	Mean monthly flow (September)	**0.98**	0.13	0.02
	M_A 16	Mean annual flow divided by catchment area	0.18	0.50	0.35
	MEDDIS/A	Median annual discharge divided by catchment area	0.22	0.52	0.35
	M_H1	Mean of the maximum monthly flows (October)	**0.96**	0.08	0.01
	M_H2	Mean of the maximum monthly flows (November)	**0.96**	0.06	0.07
	M_H3	Mean of the maximum monthly flows (December)	**0.91**	0.00	0.05
	M_H4	Mean of the maximum monthly flows (January)	**0.97**	0.14	0.08
	M_H5	Mean of the maximum monthly flows (February)	**0.97**	0.15	0.11
	M_H6	Mean of the maximum monthly flows (March)	**0.94**	0.03	0.02
	M_H7	Mean of the maximum monthly flows (April)	**0.98**	0.10	0.04
	M_H8	Mean of the maximum monthly flows (May)	**0.98**	0.15	0.08
	M_H9	Mean of the maximum monthly flows (June)	**0.98**	0.13	0.00
	M_H10	Mean of the maximum monthly flows (July)	**0.98**	0.13	-0.03
	M_H11	Mean of the maximum monthly flows (August)	**0.98**	0.13	-0.03
	M_H12	Mean of the maximum monthly flows (September)	**0.95**	0.05	-0.04
	M_H13	Mean of the mean maximum flows for all months	**0.98**	0.08	0.04
	MADIS	Mean annual flow for all years	**0.98**	0.14	0.03
	RANGE	Maximum annual discharge minus minimum annual discharge	**0.98**	0.06	-0.05
	Q1	Percentile flow with the annual discharge exceeded 1% of time	**0.99**	0.09	0.01
	Q50	Median annual flow for all years	**0.97**	0.14	0.03

Coefficients higher than |0.70| are in bold

Table 2 (continued). Pearson correlation coefficients between the three first axes from the Principal Component Factor Analysis (PCFA) and the 73 hydrological indices. Horizontal lines separate indices associated to the three flow components represented by the axes: (a) magnitude (average and maximum flows), first axis (46% of variance); (b) flow stability, second axis (28% of variance); and (c) minimum flows, third axis (12% of variance)

			PCFA axis		
	Variable	Description	1st	2nd	3rd
(b)	CV_A 1	Coefficient of variation (October)	-0.08	**-0.83**	-0.30
	CV_A 2	Coefficient of variation (November)	-0.12	**-0.86**	-0.15
	CV_A 3	Coefficient of variation (December)	-0.09	**-0.84**	-0.19
	CV_A 4	Coefficient of variation (January)	-0.19	**-0.88**	-0.21
	CV_A 5	Coefficient of variation (February)	-0.21	**-0.89**	-0.17
	CV_A 6	Coefficient of variation (March)	-0.19	**-0.81**	-0.25
	CV_A 7	Coefficient of variation (April)	-0.26	**-0.90**	-0.20
	CV_A 8	Coefficient of variation (May)	-0.02	**-0.91**	-0.19
	CV_A 9	Coefficient of variation (June)	0.02	**-0.83**	-0.35
	CV_A 10	Coefficient of variation (July)	0.09	**-0.82**	-0.37
	CV_A 11	Coefficient of variation (August)	0.09	**-0.84**	-0.36
	CV_A 12	Coefficient of variation (September)	-0.03	**-0.81**	-0.34
	M_A 13	Range divided by median monthly flow	-0.06	**-0.90**	-0.03
	M_A 14	Interquartile divided by median monthly flow	0.09	**-0.80**	0.05
	CV_{INTRA}	Coefficient of variation in mean monthly flows	0.02	**-0.90**	-0.03
	M_A 15	Mean minus median monthly flow divided by median monthly flow	-0.15	**-0.73**	0.06
	M_A 17	Range divided by median annual flow	-0.22	**-0.93**	-0.10
	M_A 18	Interquartile divided by median annual flow	-0.17	**-0.83**	-0.05
	M_A 19	Mean minus median annual flow divided by median annual flow	-0.17	**-0.84**	0.03
	CV_H	Coefficient of variation in mean maximum monthly flows	-0.27	**-0.79**	-0.08
	D_L	Percentage of months with zero flow	-0.38	**-0.75**	-0.24
	CV_{INTER}	Coefficient of variation in annual flows for all years	-0.21	**-0.92**	-0.25
	Q5/Q50	Q5 divided median monthly flow	-0.23	**-0.88**	-0.08
	Q10/Q50	Q10 divided median monthly flow	-0.21	**-0.87**	-0.06
	STDEV	Standard deviation of annual discharge	**0.99**	0.07	-0.09
	AMAX/Q50	Maximum annual discharge divided by Q50	-0.23	**-0.92**	-0.08
	AMIN/Q50	Minimum annual discharge divided by Q50	-0.25	0.63	0.42
	I_H	Q5 divided mean monthly flow	0.08	-0.04	-0.27
	I_L	Q95 divided mean monthly flow	-0.26	0.60	0.48
(c)	M_L 1	Mean minimum monthly flow (October)	0.02	0.19	**0.92**
	M_L 2	Mean minimum monthly flow (November)	0.04	0.19	**0.92**
	M_L 3	Mean minimum monthly flow (December)	0.03	0.19	**0.92**
	M_L 4	Mean minimum monthly flow (January)	0.11	0.20	**0.77**
	M_L 5	Mean minimum monthly flow (February)	0.08	0.18	**0.88**
	M_L 6	Mean minimum monthly flow (March)	0.04	0.18	**0.93**
	M_L 7	Mean minimum monthly flow (April)	0.10	0.23	**0.78**
	M_L 8	Mean minimum monthly flow (May)	0.03	0.17	**0.93**
	M_L 9	Mean minimum monthly flow (June)	0.00	0.17	**0.90**
	M_L 10	Mean minimum monthly flow (July)	0.01	0.17	**0.90**
	M_L 11	Mean minimum monthly flow (August)	0.04	0.16	**0.89**
	M_L 12	Mean minimum monthly flow (September)	0.05	0.16	**0.88**
	M_L 13	Mean of the mean minimum flows for all months	0.06	0.20	**0.96**

Coefficients higher than |0.70| are in bold

Table 3. Pearson correlation coefficients between environmental variables and hydrological components (the three first axes from the Principal Component Factor Analysis, respectively)

Environmental variable	Flow magnitude	Flow stability	Minimum flows
Mean precipitation (mm)	**0.26**	**0.64**	**0.39**
Conductivity (µS cm^{-1})	**-0.28**	**-0.54**	-0.21
Mean altitude (m)	**0.34**	**0.64**	**0.34**
Mean slope (º)	0.24	**0.37**	**0.27**
Karst surface (%)	0.21	**0.36**	**0.37**
Mean temperature (º C)	**-0.37**	**-0.57**	**-0.27**
Drainage area (km^2)	**0.83**	-0.16	-0.14

Significant correlations ($p < 0.05$) are in bold

Hydrological components determining assemblage composition

The macroinvertebrate NMDS ordinations for different taxonomic resolutions identified similar patterns (Fig. 2). Sites were structured along a flow stability gradient from perennial headwater streams (left side, class 4) to intermittent streams (right side, class 7), although some classes were widely dispersed (particularly class 6, spring peak flow seasonal streams). This gradient was associated with several environmental variables and hydrological components (PCFA axes). Perennial stable streams (classes 3 and 4) were predominately located on karstic rocks and sites in higher altitude areas with steeper slopes, higher flow stability and relatively high minimum flows. In contrast, intermittent streams were associated to low slopes, reduced flow stability and low minimum flows, but higher conductivity and air temperature.

The DistLMs indicated that hydrological components accounted for a significant proportion of the variance in the macroinvertebrate community that increased with taxonomic resolution (Table 4): 28% for families, 30% for genus and 38% for Coleoptera species. In all cases, flow stability and minimum flows were the dominant hydrological drivers of taxonomical differences among sites.

Table 4. Results of the Distance-based Linear Models for each taxonomic level

	Macroinvertebrate families		Macroinvertebrate genera		Coleoptera species	
Hydrological component	Marginal (%)	Sequential (%)	Marginal (%)	Sequential (%)	Marginal (%)	Sequential (%)
Flow magnitude	7	6*	6	5	4	3*
Flow stability	12***	9**	24***	24***	27***	27***
Minimum flows	13**	13***	11**	6*	16***	8***
Total (%)		**28**		**30**		**38**

Significance levels are indicated with asterisks (*: $p \le 0.05$; **: $p \le 0.01$; ***: $p \le 0.001$)

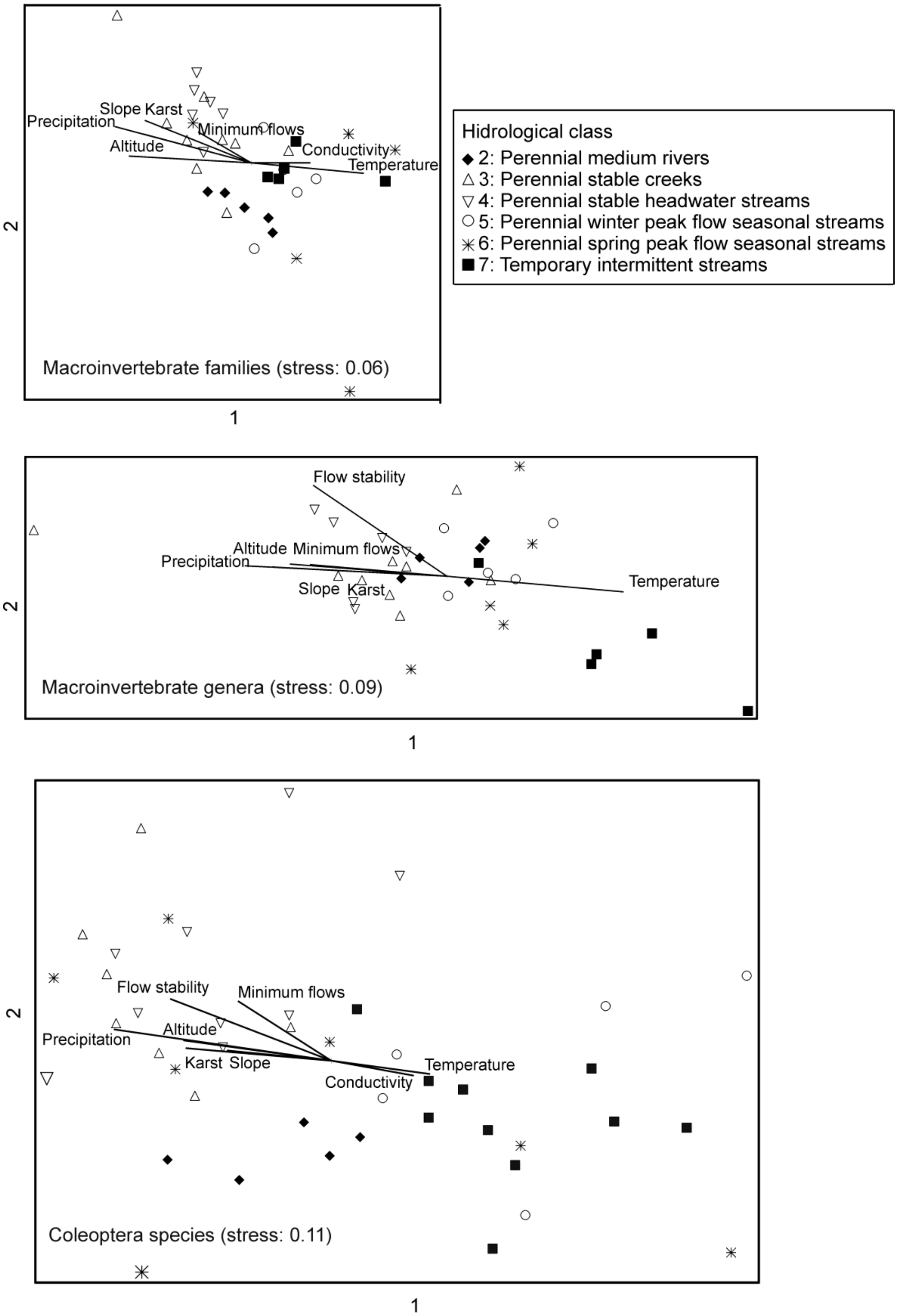

Figure 2. NMDS plots of sites for each taxonomic level. The magnitudes of the correlations between the NDMS axes and the hydrological components as well as the environmental variables are shown as vectors

Response of taxonomic richness to hydrological components

The GLMs showed a moderate effect of hydrological variables on the richness of macroinvertebrate families, genera and species (Table 5). However, the model obtained for the EPT/EPTOCHD ratio explained 36% of the variance using flow magnitude and flow stability as independent variables. Gradual changes to the relative richness of EPT families were observed from perennial to intermittent hydrological classes, decreasing along the flow magnitude gradient, whilst the OCHD families displayed the opposite pattern (Fig. 3).

Table 5. Generalised Linear Models for the different dependent variables, on the basis of richness

Dependent variable	Variance explained (%)	Explanatory hydrological components
EPT/EPTOCHD	36	Flow magnitude**, flow stability*
Macroinvertebrate families	21	Minimum flows**
Macroinvertebrate genera	24	Minimum flows**
Coleoptera species	17	Minimum flows**

Significance levels are indicated with asterisks (*: p≤0.05; **: p≤0.01; ***: p≤0.001)

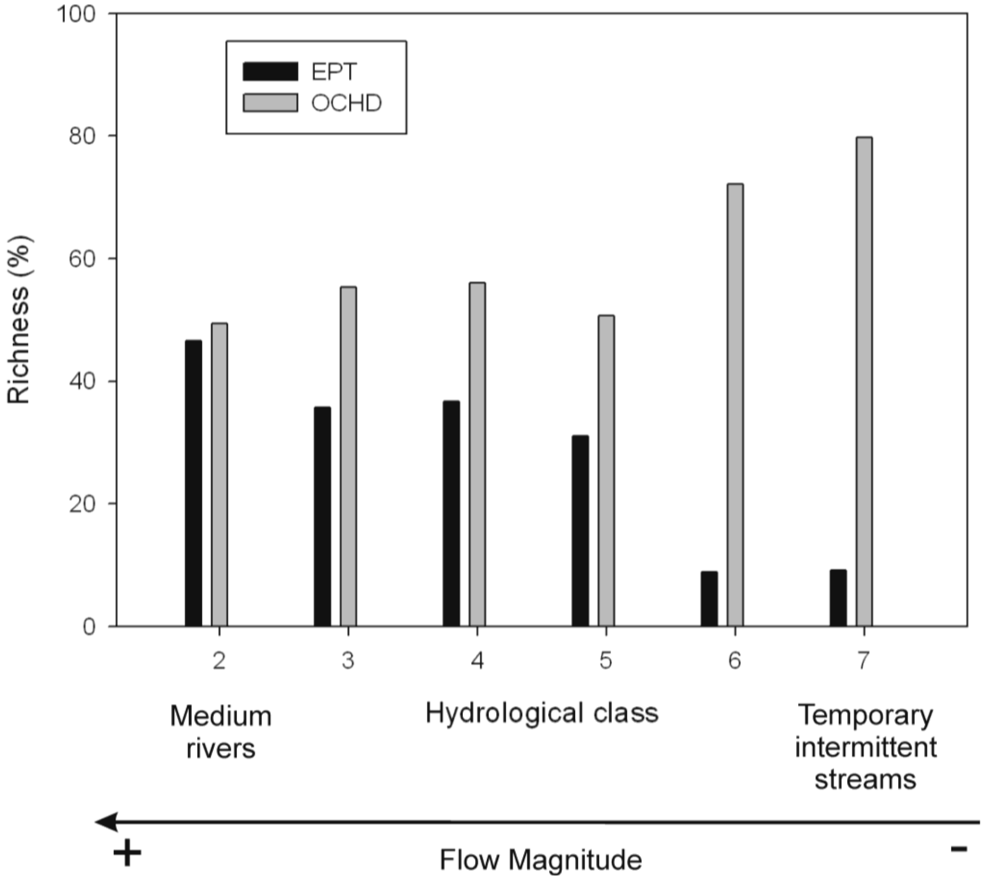

Figure 3. Variation of the percentage of families of the EPT (Ephemeroptera, Plecoptera and Trichoptera) and OCDH (Odonata, Coleoptera, Heteroptera and Diptera) groups in the different hydrological classes along the flow magnitude gradient

Differences in assemblage composition among hydrological classes

The hydrological classes identified supported significantly different invertebrate assemblages at the family (ANOSIM, R=0.39; *P*-value <0.05), genus (ANOSIM, R=0.34; *P*-value <0.05) and species taxonomic level (ANOSIM, R=0.40; *P*-value <0.05) (Table 6). Pair-wise comparisons revealed significant assemblage differences at all taxonomic resolutions between the extremes of the hydrological gradient, perennial stable streams (creeks and headwaters, classes 3 and 4 respectively) and intermittent streams (class 7). Differences between creek and medium river communities (class 2) as well as between creeks and perennial seasonal streams with peak flows during the winter (class 5) increased with the taxonomic resolution, except for the genus level. However, intermittent streams and perennial seasonal streams, both with winter (class 5) and spring peak flows (class 6), differed at the genus or at the genus and species levels, respectively. No significant differences were found both between creeks and headwater streams or within seasonal streams (winter and spring peak flows) (Table 6).

Table 6. Result of the analysis of similarity. Class 2, perennial medium rivers; class 3, perennial stable creeks; class 4, perennial stable headwater streams; class 5, perennial winter peak flow seasonal streams; class 6, perennial spring peak flow seasonal streams; and class 7, temporary intermittent streams

Classes	Macroinv. families	Macroinv. genera	Coleop. species
2, 5	0.22	0.15	0.50**
2, 7	0.59*	0.62*	0.49**
3, 2	0.26*	0.06	0.56**
3, 5	0.25*	0.20	0.76***
3, 6	0.49**	0.30*	0.05
3, 7	0.50**	0.53**	0.86***
4, 2	0.85**	0.67**	0.37**
4, 3	0.00	-0.02	-0.09
4, 5	0.81**	0.80**	0.66***
4, 6	0.53**	0.77**	0.09
4, 7	0.88**	0.86**	0.77***
5, 7	0.29	0.42*	0.17
6, 2	0.27**	0.33**	-0.01
6, 5	0.12	0.02	0.16
6, 7	0.09	0.44*	0.38**
Global R	0.39***	0.34***	0.40***

Significance levels are indicated with asterisks (*: $p \leq 0.05$; **: $p \leq 0.01$; ***: $p \leq 0.001$)

The IndVal analyses determined indicator families for medium rivers (class 2), headwater streams (class 4), spring peak flow seasonal streams (class 6) and intermittent streams (class 7) (Table 7). Medium rivers were characterised by Polycentropodidae (Trichoptera) and Potamanthidae (Ephemeroptera). Headwater streams were defined by six families of Trichoptera (particularly Philopotamidae, with the highest IV) and one Crustacea (Astacidae). Spring peak flow seasonal streams were characterised by Syrphidae (Diptera), which presented the highest Indicator Value in the Segura Basin. Intermittent streams were defined by the presence of Coenagrionidae and Libellulidae (Odonata), Pleidae (Heteroptera) and Noteridae and Hydrophilidae (Coleoptera).

Indicator genera were found for all classes except creeks (class 3) and winter peak flow seasonal streams (class 5). Medium rivers (class 2) and headwater streams (class 4) were characterised by Ephemeroptera: *Habrophlebia* and *Potamanthus* for the former and *Epeorus* and *Rhithrogena* for the latter. Headwaters were also characterised by seven Coleoptera genera (*Oreodytes*, *Graptodytes*, *Esolus*, *Limnebius*, *Normandia*, *Hydrocyphon* and *Oulimnius*), two Trichoptera (*Rhyacophila* and *Sericostoma*), one Crustacea (*Austropotamobius*) and two Plecoptera (*Perla* and *Isoperla*). Spring peak flow seasonal streams (Class 6) were characterised by one genus of Coleoptera (*Dytiscus*), Hirudinea (*Helobdella*), Molusca (*Pseudamnicola*) and Odonata (*Platycnemis*), with identical indicator values. Intermittent streams (class 7) highlighted the highest number of indicator genera, with the highest Indicator Values for two Diptera (*Dasyhelea* and *Anopheles*), two Heteroptera (*Heliocorisa* and *Anisops*), two Odonata (*Anax* and *Sympetrum*) and two Coleoptera (*Enochrus* and *Berosus*).

Coleoptera indicator species were detected for all classes except spring peak flow seasonal streams (class 6) (Table 7). Medium rivers (class 2) were primarily characterised by *Hydraena manfredjaechi* and *Normandia nitens*; creeks (class 3) by *Hydraena exasperata*; headwater streams (class 4) by *Helophorus alternans*; winter peak flow seasonal streams (class 5) by *Eretes griseus* and *Ranthus suturalis;* and intermittent streams (class 7) by *Ochthebius delgadoi*.

Table 7. Indicator taxa (IV≥25 & p ≤ 0.05) for each hydrological class and taxonomic level

Hydrological class	Macroinvertebrate families	IV (%)	Macroinvertebrate genera	IV (%)	Coleoptera species	IV (%)
2. Perennial medium rivers	Polycentropodidae	31	*Habrophlebia*	28	*Hydraena manfredjaechi*	47
	Potamanthidae	27	*Potamanthus*	27	*Normandia nitens*	47
					Limnius intermedius	44
					Ochthebius difficilis	34
					Limnius opacus	28
					Pomatinus substriatus	25
3. Perennial stable creeks					*Hydraena exasperata*	55
					Ilybius meridionalis	50
					Ochthebius bellieri	46
					Limnius volckmari	34
					Agabus brunneus	32
					Hydroporus marginatus	30
					Ochthebius bonnairei	30
					Anacaena bipustulata	29
					Deronectes moestus	29
					Hydraena carbonaria	29
					Hydraena capta	27
					Hydraena rufipennis	26
					Stictonectes epipleuricus	26
					Agabus didymus	25
4. Perennial stable headwater streams	Philopotamidae	41	*Oreodytes*	45	*Helophorus alternans*	29
	Limnephilinae	29	*Epeorus*	35	*Helophorus brevipalpis*	28
	Beraeidae	29	*Rhyacophila*	31	*Laccobius obscuratus*	28
	Brachycentridae	28	*Graptodytes*	30	*Hydroporus tessellatus*	26
	Rhyacophilidae	27	*Austropotamobius*	30	*Limnebius cordobanus*	26
	Sericostomatidae	26	*Esolus*	29		
	Astacidae	26	*Sericostoma*	29		
			Limnebius	28		
			Normandia	27		
			Hydrocyphon	27		
			Rhithrogena	27		
			Oulimnius	25		
			Perla	25		
			Isoperla	25		

Table 7 (continued). Indicator taxa (IV≥25 & p ≤ 0.05) for each hydrological class and taxonomic level

Hydrological class	Macroinvertebrate families	IV (%)	Macroinvertebrate genera	IV (%)	Coleoptera species	IV (%)
5. Perennial winter peak flow seasonal streams					*Eretes griseus*	76
					Rhantus suturalis	76
					Hydrochus nooreinus	52
					Stictotarsus duodecimpustulatus	52
					Berosus hispanicus	34
					Hydrophilus pistaceus	32
					Laccobius moraguesi	31
					Agabus ramblae	29
6. Perennial spring peak flow seasonal streams	Syrphidae	85	*Dytiscus*	35		
			Helobdella	35		
			Pseudamnicola	35		
			Platycnemis	35		
7. Temporary intermittent streams	Noteridae	35	*Dasyhelea*	63	*Ochthebius delgadoi*	42
	Pleidae	35	*Anopheles*	63	*Enochrus politus*	38
	Coenagrionidae	30	*Heliocorisa*	63	*Helophorus fulgidicollis*	38
	Libellulidae	28	*Anisops*	63	*Laccophilus minutus*	38
	Hydrophilidae	26	*Anax*	52	*Ochthebius auropallens*	38
			Enochrus	48	*Ochthebius grandipennis*	38
			Sympetrum	48	*Ochthebius viridis fallaciosus*	38
			Berosus	45	*Ochthebius jaimei*	35
			Sigara	45	*Helochares lividus*	27
			Plea	45		
			Ischnura	45		
			Noterus	42		
			Potamopyrgus	42		
			Cercion	42		
			Libellula	42		
			Helochares	41		
			Bidessus	40		
			Procambarus	40		
			Limnophora	40		
			Tipula	40		
			Microvelia	40		
			Agabus	36		
			Dryops	32		
			Laccobius	32		
			Orthetrum	32		
			Gerris	30		
			Nebrioporus	27		
			Cloeon	27		
			Micronecta	25		

Discussion

The importance of hydrological components on macroinvertebrate assemblages

The research presented herein supports the general hypothesis that streams with similar flow regimes express greater than random similarity in macroinvertebrate assemblages composition (Poff, 1996; Resh *et al.*, 1988). Our results demonstrate relatively strong relationships between community composition and the flow regimes at different taxonomic levels. The strength of these relationships increased with taxonomic resolution suggesting that the species level data yields the strongest relationships and that, where it is available, it should be used in ecohydrological investigations (Monk *et al.*, 2012). Flow stability and minimum flows were shown to be the principal hydrological drivers/descriptors of the macroinvertebrate community assemblages in the Segura River Basin. Similar results were reported by Chinnayakanahalli *et al*. (2011) in western USA, where baseflows and seasonality were the main predictors of invertebrate composition. However, these results contrast with studies performed in temperate-maritime regions where the magnitudes of mean flows or high flows were reported to be the best predictors of macroinvertebrate assemblages (Clausen & Biggs, 1997; Monk *et al.*, 2006; Monk *et al.*, 2008).

Flow stability and minimum flows are major determinants of habitat availability and connectivity that affect aquatic macroinvertebrate assemblages. Flow stability reflects seasonal and interannual patterns of variation, associated with the predictability of flows (Poff, 1996) and the stability of habitat conditions in terms of depth, flow velocity and hydraulic forces (Suen & Herricks, 2009). The variation of stream flow velocity configures stream morphology, water temperature, bed stability and consequently the availability of aquatic habitats for instream organisms (Jowett & Duncan, 1990). Minimum flows represent an extreme of the flow, particularly in the dry season, and reflect the magnitude of seasonal droughts (Smakhtin, 2001). Habitat heterogeneity is reduced under low flow conditions because wetted width, water depth and flow velocity also diminishes (Walters & Post, 2011). In addition, extreme low flows can reduce longitudinal connectivity and increase physical stresses transforming streams into series of isolated pools with higher water temperature and elevated conductivity (Stanley *et al.*, 1997). Consequently, droughts have been recognised as an important part of the natural flow regime in intermittent streams (Boulton, 2003; Chase, 2007; Lake, 2003;

Sheldon & Thoms, 2006). Species inhabiting intermittent streams must have physiological, behavioural or life-history adaptations to cope with higher conductivities, predation pressures and habitat isolation, such as short life-histories, generalist feeding, aerial respiration or active aerial dispersal (e.g. Bonada *et al.*, 2007b). Under these conditions, dispersal abilities and distances between or along water bodies have been found to be primary determinants of community composition (McAbendroth *et al.*, 2005), because active movement when the riverbed is dry is limited to a small number of taxa such as dytiscid and hydrophilid beetles (Boulton *et al.*, 2006; Larned *et al.*, 2010).

Our results indicate a moderately strong relationship between flow regime and faunal richness at the different taxonomic resolutions, weaker than that between flow regime and community composition (especially at species level). Other studies have also reported a moderate effect of minimum flows (Walters & Post, 2011), flow seasonality or the number of days with zero flow (Chinnayakanahalli *et al.*, 2011).

In Mediterranean regions, ephemeral and intermittent streams are recognised to be significantly less diverse than perennial streams (Bonada *et al.*, 2007b) and to differ in community composition (e.g. Argyroudi *et al.*, 2009; Bonada *et al.*, 2006). Our results found a strong relationship between flow magnitude, and stability, and the ratio of EPT/EPTOCHD. This supports the findings of Bonada *et al.* (2006) and Sánchez-Montoya *et al.* (2007), who reported a decrease in EPT richness as hydrological isolation and the length of the dry period (temporality) increased. EPT taxa in particular tend to occur in riffles, whereas pools support the majority of OCHD taxa (Oscoz *et al.*, 2011; Vivas *et al.*, 2002). Therefore, riffle permanence has a strong effect on the structure of benthic assemblages in streams (Feminella, 1996).

Biological significance of hydrological classes

The six hydrological classes examined in this study indicate distinct macroinvertebrate assemblages at all of the taxonomic resolutions considered. Taxonomic differences were greatest between the classes at both extremes of the flow stability gradient, and are similar to results reported by other studies in the Iberian Peninsula (Sánchez-Montoya *et al.*, 2007) and in the Segura Basin (Carbonell *et al.*, 2011; Díaz *et al.*, 2008; Millán *et al.*, 2006). However, when the other classes were considered, only minor and gradual biological changes along the gradient were detected. Consequently, a simpler classification with four broad hydrological types (Belmar *et al.*, 2011) is more appropriate for management purposes in the Segura River Basin and other semiarid Mediterranean basins: (1) main stem rivers (classes 1 and 2), (2) perennial stable streams (classes 3 and 4), (3) perennial seasonal streams (classes 5 and 6) and (4) temporary streams (classes 7 and 8).

We found a clear agreement between the selection of indicator taxa in this study and those from other studies in the Mediterranean region in Spain (e.g. Bonada *et al.*, 2004; Mellado, 2005; Sánchez-Montoya *et al.*, 2007). Headwater streams were characterised by taxa that inhabit the upper reaches of rivers with colder and oxygen-rich waters, in areas of cobbles and small boulders. These sites supported the greatest presence of Trichoptera families, such as Philopotamidae, and were also characterised by the presence of typically reophilic Ephemeroptera (*Epeorus* and *Rhitrogena*) and Plecoptera (*Perla* and *Isoperla*) genera. In general, these taxa are considered to have high oxygen requirements and their presence is associated with good water quality (Jacobsen *et al.*, 2003). Medium rivers were characterised by Ephemeroptera genera, such as *Potamanthus* and *Habrophlebia,* typical of reaches of large rivers where low to moderate flow velocities, associated with gravel and sand substrates, predominate (Puig *et al.*, 1984). Intermittent streams were associated with taxa from shallow standing waters or those with reduced velocities, such as numerous Coleoptera (e.g. *Enochrus*, *Berosus* and *Noterus*), Odonata (e.g. *Anax, Sympetrum* and *Isnchnura*) and Heteroptera (e.g. *Heliocorisa*, *Anisops* and *Sigara*), with highly mobile adults (Bilton *et al.*, 2001) and short life-history development times (Barahona *et al.*, 2005; Velasco *et al.*, 1990). The importance of Coleoptera in temporary streams highlighted in this study has also been demonstrated in previous studies (Picazo *et al.*, 2012).

Implications to river restoration and conservation

Based on the results presented, the magnitude of monthly minimum flows and the inter- and intrannual natural variation of flows are two key flow components for the definition of environmental flows in Mediterranean basins. Currently, many historically perennial streams have already become intermittent due to excessive abstraction and impoundment, while others exhibit an inverse seasonal pattern due to water release from reservoirs during the summer months (Belmar *et al.*, 2010). Such hydrological modifications could become more intense in the future as a result of climate change (European Environment Agency, 2008), which is expected to intensify supra-seasonal droughts and lead to more anthropogenic water withdrawals. This may lead to the depletion of groundwater in local aquifers and, therefore, flow intermittency in previously perennial streams. Such intermittency could result in significant changes to the faunal community, increasing the risk of local extinctions of drought-sensitive taxa. This effect has already been documented in desert streams (Bogan & Lytle, 2011), where simplified pools composed of the most tolerant and resilient species have been described (*sensu* Côte & Darling, 2010). Therefore, the conservation and, where appropriate, restoration of natural hydrological variability is crucial for the maintenance of riverine ecosystem integrity (i.e. ecosystem structure and function) (Thoms, 2006; Vaughan *et al.*, 2009).

Future research should focus on how the degree of hydrological alteration affects aquatic communities and ecosystem functioning. Aquatic macroinvertebrates are ideal candidates for the development of hydroecological models to quantify the effects of flow reduction (Castella *et al.*, 1995; Niu & Dudgeon, 2011a; Niu & Dudgeon, 2011b). Using the four broad hydrological types stated we will be able to provide a reference framework in the near future to achieve a more sustainable management of ecohydrological resources in the Segura River Basin and other Mediterranean basins, fulfilling the objectives of the “Ecological Limits of Hydrologic Alteration” and the European Union Water Framework Directive (WFD).

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Appendix. Taxa collected in the Segura Basin grouped by taxonomic level

Hirudinea
Erpobdellidae
Dina
Glossiphoniidae
Helobdella
Mollusca
Ancylidae
Ancylus
Ferrissia
Hydrobiidae
Mercuria
Potamopyrgus
Pseudamnicola
Lymnaeidae
Lymnaea
Melanopsidae
Melanopsis
Physidae
Physella
Planorbidae
Gyraulus
Planorbarius
Sphaeriidae
Pisidium
Crustacea
Astacidae
Austropotamobius
Atyiidae
Atyaephyra
Cambaridae
Procambarus
Gammaridae
Echinogammarus
Insecta
Coleoptera
Dryopidae
Dryops
Dryops gracilis (Karsch, 1881)
Dryops sulcipennis (Costa, 1883)
Pomatinus
Pomatinus substriatus (Müller, 1806)
Dytiscidae
Eretes griseus Motschulsky 1849
Hygrotus confluens (Fabricius, 1787)
Hyphydrus aubei Ganglbauer, 1892
Ilybius meridionalis Aubé, 1836
Meladema coriacea Castelnau, 1834
Rhantus suturalis (McLeay, 1825)
Stictotarsus duodecimpustulatus (Fabricius, 1792)
Agabus
Agabus biguttatus (Olivier, 1795)
Agabus bipustulatus (Linnaeus, 1767)
Agabus brunneus (Fabricius, 1798)
Agabus didymus (Olivier, 1795)
Agabus nebulosus (Forster, 1771)
Agabus nitidus (Fabricius, 1801
Agabus paludosus (Fabricius, 1801)
Agabus ramblae Millán & Ribera, 2001
Bidessus
Bidessus minutissimus (Germar, 1824)
Deronectes
Deronectes depressicollis (Rosenhauer, 1856)
Deronectes fairmairei (Leprieur, 1876)
Deronectes hispanicus (Rosenhauer, 1856)
Deronectes moestus Leprieur, 1876
Dytiscus
Graptodytes
Graptodytes fractus (Sharp, 1880-82)
Graptodytes ignotus (Mulsant, 1861)
Graptodytes varius (Aubé, 1836)
Hydroglyphus
Hydroglyphus geminus (Fabricius, 1792)
Hydroglyphus signatellus (Klug, 1834)
Hydroporus
Hydroporus discretus Fairmaire, 1859
Hydroporus lucasi Reiche, 1866
Hydroporus marginatus (Duftschmid, 1805)
Hydroporus nigrita (Fabricius, 1792)
Hydroporus pubescens (Gyllenhal, 1808)
Hydroporus tessellatus Drapiez, 1819
Laccophilus
Laccophilus hyalinus (De Geer, 1774)
Laccophilus minutus (Linnaeus, 1758)
Nebrioporus
Nebrioporus bucheti cazorlensis (Lagar, Fresneda & Hernando, 1987)
Nebrioporus clarki (Wollaston, 1862)
Oreodytes
Stictonectes
Stictonectes epipleuricus (Seidlitz, 1887)
Stictonectes optatus (Seidlitz, 1887)
Yola
Yola bicarinata (Latreille, 1804)
Elmidae
Elmis
Elmis aenea (Müller, 1806)
Elmis maugetii maugetii Latreille, 1798
Elmis rioloides (Kuwert, 1890)
Esolus
Esolus parallelepipedus (Müller, 1806)
Limnius
Limnius intermedius Fairmaire, 1881
Limnius opacus Müller, 1806
Limnius volckmari (Panzer, 1793)
Normandia
Normandia nitens (Müller, 1817)
Normandia sodalis (Erichson, 1847)
Oulimnius
Oulimnius troglodytes (Gyllenhal, 1827)
Oulimnius tuberculatus perezi Sharp, 1872
Potamophilus
Riolus
Riolus cupreus (Müller, 1806)
Riolus illiesi Steffan, 1958

Appendix (continued). Taxa collected in the Segura Basin grouped by taxonomic level

Gyrinidae
Aulonogyrus
Aulonogyrus striatus (Fabricius, 1792)
Gyrinus
Gyrinus dejeani Brullé, 1832
Orectochilus
Orectochilus villosus (Müller, 1776)
Haliplidae
Peltodytes rotundatus (Aubé, 1836)
Haliplus
Haliplus lineatocollis (Marsham, 1802)
Haliplus mucronatus Stephens, 1832
Helophoridae
Helophorus
Helophorus alternans Gené, 1836
Helophorus brevipalpis Bedel, 1881
Helophorus fulgidicollis Motschuslky, 1860
Helophorus occidentalis Angus, 1983
Helophorus nubilus Fabricius, 1776
Helophorus seidlitzii Kuwert, 1885
Hydraenidae
Hydraena
Hydraena capta Orchymont, 1936
Hydraena carbonaria Kiesenwetter, 1849
Hydraena exasperata Orchymont, 1935
Hydraena hernandoi Fresneda & Lagar, 1990
Hydraena manfredjaechi Delgado & Soler, 1991
Hydraena pygmaea Waterhouse, 1833
Hydraena quilisi Lagar, Fresneda & Hernando, 1987
Hydraena rufipennis Boscá Berga, 1932
Hydraena servilia Orchymont, 1936
Limnebius
Limnebius cordobanus Orchymont, 1938
Limnebius maurus Balfour-Browne, 1978
Limnebius oblongus Rey, 1883
Ochthebius
Ochthebius auropallens Fairmaire, 1879
Ochthebius bellieri Kuwert, 1887
Ochthebius bonnairei Guillebau, 1896
Ochthebius delgadoi Jäch, 1994
Ochthebius difficilis Mulsant, 1844
Ochthebius dilatatus Stephens, 1829
Ochthebius (Enicocerus) exsculptus Germar, 1824
Ochthebius grandipennis Fairmaire, 1879
Ochthebius jaimei Delgado & Jäch, 2007
Ochthebius quadrifoveolatus Wollaston, 1854
Ochthebius tudmirensis Jäch, 1997
Ochthebius viridis fallaciosus Ganglbauer, 1901
Hydrochidae
Hydrochus
Hydrochus grandicollis Kiesenwetter, 1870
Hydrochus nooreinus Henegouven & Sáinz-Cantero, 1992
Hydrophilidae
Anacaena bipustulata (Marsham, 1802)
Anacaena globulus (Paykull, 1798)
Anacaena lutescens (Stephens, 1829)
Coelostoma hispanicum (Küster, 1848)
Hydrophilus pistaceus (Castelnau, 1840)
Berosus
Berosus hispanicus Küster, 1847
Enochrus
Enochrus ater (Kuwert, 1888)
Enochrus politus Küster, 1849
Helochares
Helochares lividus (Forster, 1771)
Laccobius
Laccobius bipunctatus (Fabricius, 1775)
Laccobius hispanicus Gentili, 1974
Laccobius gracillis gracillis Motschulsky, 1849
Laccobius moraguesi Régimbart, 1898
Laccobius neapolitanus Rottenberg, 1874
Laccobius obscuratus Rottenberg, 1874
Laccobius sinuatus Motschulsky, 1849
Laccobius ytenensis Sharp, 1910
Noteridae
Noterus
Noterus laevis Sturm, 1834
Scirtidae
Cyphon
Elodes
Hydrocyphon
Diptera
Anthomyiidae
Limnophora
Athericidae
Atrichops
Ibisia
Ceratopogonidae
Dasyhelea
Chironomidae
Chironomini
Corynoneura
Tanytarsini
Culicidae
Anopheles
Diamesinae
Dixidae
Empididae
Ephydridae
Hemerodromiinae
Limoniidae
Eloeophyla
Pseudolimnophila
Orthocladiinae
Simuliidae
Stratiomyidae
Oxycera
Syrphidae
Tabanidae
Tabanus
Tanypodinae
Tipulidae
Tipula

Appendix (continued). Taxa collected in the Segura Basin grouped by taxonomic level

Ephemeroptera
Baetidae
Baetis
Centroptilum
Cloeon
Procloeon
Caenidae
Caenis
Ephemerellidae
Ephemerella
Serratella
Torleya
Ephemeridae
Ephemera
Heptageniidae
Ecdyonurus
Epeorus
Rhithrogena
Leptophlebiidae
Habroleptoides
Habrophlebia
Paraleptophlebia
Polymirtacidae
Ephoron
Potamantidae
Potamanthus
Heteroptera
Aphelocheiridae
Aphelocheirus
Corixidae
Heliocorisa
Micronecta
Sigara
Gerridae
Aquarius
Gerris
Hydrometridae
Hydrometra
Naucoridae
Naucoris
Nepidae
Nepa
Notonectidae
Anisops
Notonecta
Pleidae
Plea
Veliidae
Microvelia
Velia
Odonata
Aeshnidae
Anax
Boyeria
Calopterigydae
Calopteryx
Coenagrionidae
Cercion
Ischnura
Pyrrhosoma
Cordulegastridae
Cordulegaster
Gomphidae
Gomphus
Onychogomphus
Libellulidae
Libellula
Orthetrum
Sympetrum
Platycnemididae
Platycnemis
Plecoptera
Leuctridae
Leuctra
Nemouridae
Nemoura
Protonemura
Perlidae
Dinocras
Eoperla
Perla
Perlodidae
Isoperla
Trichoptera
Beraeidae
Brachycentridae
Micrasema
Drusinae
Hydropsychidae
Cheumatopsyche
Hydropsyche
Hydroptilidae
Agraylea
Hydroptila
Lepidostomatidae
Lasiocephala
Leptoceridae
Athripsodes
Limnephilidae
Allogamus
Halesus
Stenophylax
Limnephilinae
Philopotamidae
Polycentropodidae
Psychomyiidae
Metalype
Tinodes
Rhyacophilidae
Rhyacophila
Sericostomatidae
Sericostoma

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Chapter 4. Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin

Mundo River, Liétor

Belmar, O., Bruno, D., Martínez-Capel, F., Barquín, J. & Velasco, J. (In Review) Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. *Ecological Indicators*

Abstract and keywords

The Segura River Basin is one of the most arid and regulated zones in the Mediterranean as well as Europe that includes four hydrologic river types, according to their natural flow regime: mainstream rivers, perennial stable streams (headwaters), perennial seasonal streams and temporary streams (intermittent or ephemeral). The relationships between flow regime and fluvial and riparian habitats (characteristics and quality) were studied at reference and hydrologically-altered sites for each of the four types. Flow regime alteration was assessed using two procedures: (1) an indirect index, derived from variables associated with the main hydrologic pressures in the basin, and (2) reference and altered flow series analyses using the “Indicators of Hydrologic Alteration” (IHA) and the “Indicators of Hydrologic Alteration in Rivers” (IAHRIS). Habitats were characterized using the River Habitat Survey (RHS) and its derived Habitat Quality Assessment (HQA) score, whereas riparian condition was assessed using the Riparian Quality Index (RQI) and an inventory of riparian native/exotic species. Flow stability and magnitude were identified as the main hydrologic drivers of the stream habitats in the Segura Basin. Hydrologic alterations were similar to those described in other Mediterranean arid and semiarid areas where dams have reduced flow magnitude and variability and produced the inversion of seasonal patterns. Additionally, the Segura Basin presented two general trends: an increase in flow torrentiality in main stems and an increase in temporality in seasonal and temporary streams. With the indirect alteration index, main stems presented the highest degree of hydrologic alteration, which resulted in larger channel dimensions and less macrophytes and mesohabitats. However, according to the hydrologic analyses, the seasonal streams presented the greatest alteration, which was supported by the numerous changes in habitat features. These changes were associated with a larger proportion of uniform banktop vegetation as well as reduced riparian native plant richness and mesohabitat density. Both stream types presented consequent reductions in habitat and riparian quality as the degree of alteration increased. However, stable streams, those least impacted in the basin, and temporary streams, which are subject to great hydrologic stress in reference conditions, showed fewer changes in physical habitat due to hydrologic alteration. This study clarifies the relationships between hydrologic regime and physical habitat in Mediterranean basins. The hydrologic and habitat indicators that respond to human pressures and the thresholds that imply relevant changes in habitat and riparian quality presented here will play a fundamental role in the use of holistic frameworks when developing environmental flows on a regional scale.

Hydrologic alteration indicators · Habitat modification · Riparian zone · Ecological indicators

Introduction

Flow regime is a major determinant of physical habitat in streams and rivers (Bunn & Arthington, 2002), and its alteration by human activities has caused serious degradation in aquatic and riparian ecosystems (Nilsson & Berggren, 2000). Hydrologic alteration influences habitat components such as wetted area (Froend & Van Der Moezel, 1994; Humphries *et al.*, 1996; Roy & Messier, 1989); bars, benches and islands (Ligon *et al.*, 1995); pools (Erskine *et al.*, 1999); organic matter (Gawne *et al.*, 2000); woody debris (Humphries *et al.*, 1996); substrate composition (Sherrard & Erskine, 1991); and sediment transport, a co-determinant of physical habitat in river systems (Lloyd *et al.*, 2003). The effects of hydrologic alteration on communities are driven by these changes (among others), given the fundamental role that physical habitat characteristics play in their structure and composition (e.g. Moore & Hovel, 2010).

Most existing global literature focuses on the effects found downstream from dams, as they can explain up to 91% of total changes in flow and bed mobility parameters (Burke *et al.*, 2009). However, the wide variety of effects does not allow a general quantitative relationship between flow alteration and ecological response to be developed (Poff & Zimmerman, 2010). In general, dams and their associated reservoirs impact freshwater diversity (McAllister *et al.*, 2001) as a result of sharp decreases in riparian biodiversity downstream (Johnson *et al.*, 1976; Ligon *et al.*, 1995; Petts, 1980). The impact of flow modification on vegetation varies depending upon the taxonomic group considered (Bunn & Arthington, 2002), because aquatic, littoral, riparian and floodplain plants differ in flood tolerance and dependence (Blanch *et al.*, 1999). Various studies have examined the relationship between riparian vegetation and flows (e.g. Bejarano *et al.*, 2010; Bejarano *et al.*, 2012; Garófano-Gómez *et al.*, 2012; Greet *et al.*, 2011a; Greet *et al.*, 2011b; Merritt & Poff, 2010). Altered flow regimes in general (Bunn & Arthington, 2002) and reduced floods (e.g. Cooper *et al.*, 2003) and flow variability (Mortenson & Weisberg, 2010; Poff *et al.*, 1997) in particular have been associated with the fragmentation of riparian forests and substitution of native plant species by exotic ones. Other studies have focused on animals, such as macroinvertebrates (e.g. Kennen *et al.*, 2010; Konrad *et al.*, 2008; Monk *et al.*, 2006), fisheries (e.g. Kennard *et al.*, 2007; Pegg & Pierce, 2002; Poff & Allan, 1995; Snelder *et al.*, 2009) or multiple taxonomic groups (e.g. Clausen & Biggs, 1997; Jowett & Duncan, 1990). Macroinvertebrates have shown changes in abundance and diversity that mirrored those of flow magnitude, whereas fish tend to decline with any change to this variable.

However, despite their importance for communities (Power *et al.*, 1988) and the fact that physical habitats in fluvial ecosystems can change more easily and quickly than in other ecosystems, studies on ecologically significant habitat features associated with river morphology and flow regime are scarce. Such studies are essential, as these changes are key to understanding the long-term ecological consequences of dams and other disturbances (Ligon *et al.*, 1995).

In this context, developing flow alteration-ecological response relationships that reflect the direct and indirect influences of hydrologic alteration on both ecological processes and ecosystems by river type constitutes the basis of a holistic methodology for the assessment of environmental flows at regional scales, the "Ecological Limits of Hydrological Alteration" (ELOHA) (Arthington *et al.*, 2006; Poff *et al.*, 2010). Due to the combination of increasingly high demands for water (e.g. Lorenzo-Lacruz *et al.*, 2010) and its scarcity in Mediterranean areas, studying these relationships is essential for ecologically-based water management. Human pressures in these areas have resulted in flow regulation through dams and reservoirs, water abstraction, diversion channels and inter-basin water transfers (e.g. the Tagus-Segura Transfer in SE Spain). Such infrastructures, especially those associated with agricultural demands, lead to significant modifications in flow regimes (see Belmar *et al.*, 2010). In most rivers of the southern Iberian Peninsula, dam management to meet summer water demands has produced important changes in flow magnitude, variability and seasonality throughout the 1945-2005 period (Lorenzo-Lacruz *et al.*, 2012). Such changes could increase globally in the coming decades, as future climate projections forecast a generalized decrease in precipitation and increased evapotranspiration in the Iberian Peninsula (Rodriguez-Puebla & Nieto, 2010) and Mediterranean areas (IPCC, 2007). Given their fundamental role in Mediterranean streams (Gasith & Resh, 1999), changes in the natural frequency and magnitude of floods and droughts dramatically threaten the maintenance of their structure, function and dynamics. Floods are essential for maintaining river morphology, geometry, substrate grain size (Brizga *et al.*, 2001; Poff *et al.*, 1997), riffles and pools (Bunn & Arthington, 2002), natural branches (Poff *et al.*, 1997), bars (Brizga *et al.*, 2001) and the transport and input of large-sized plant remains to the river, thereby providing hydraulic diversity and shaping ecologically valuable microhabitats (Poff *et al.*, 1997). Drought dynamics determine the maintenance of the water surface during dry months, the moisture content on banks (which determines the survival of the riparian belt during dry months) (Richter *et al.*, 1998), the desiccation of the river and its associated habitat fragmentation (Strange *et al.*, 1999), the connection to the water table (Richter *et al.*, 1998) and connectivity between riffles and pools (Thoms & Sheldon, 2002).

Therefore, it is essential to improve existing knowledge regarding the relationship between hydrologic alteration and ecological response, both for organisms and the physical habitat in which they live, in Mediterranean areas in general and in the most arid ones in particular. Some foundations have already been laid in Iberian Mediterranean basins. Batalla *et al.* (2004) defined and quantified hydrologic alteration in the Ebro River (NE Spain), where dams reduced variability in mean daily flows and caused an inversion in the monthly seasonal patterns (with reduced fall and winter peaks and summer releases for irrigation that increase baseflows). An index (IR, reservoir capacity/annual runoff) was developed to quantify the degree of impoundment. Magdaleno & Fernández (2011) studied the effect of high and low flow alterations on riparian forests and channel morphology by dams in a segment of the Ebro River. Boix *et al.* (2010) determined the effects of water abstraction on stream communities in some Catalonian rivers (NE Spain). Navarro-Llácer *et al.* (2010) revealed degradation in the ecological condition of reaches downstream from reservoirs in the Segura and Mundo rivers (SE Spain) using macroinvertebrate, fish and riparian quality indices. Garófano-Gómez *et al.* (2012) documented the stages of hydrologic alteration in the Júcar Basin (SE Spain) and analyzed changes in the riparian habitats. However, no author has delved into the diversity of hydrologic types present, which can be subject to different management strategies and, therefore, flow regime alterations. In this sense, no study undertaken in any Mediterranean area has characterized hydrologic alteration or defined relationships between flow alteration and physical habitat for different hydrologic types at basin scale.

The aims of this study were to: (1) characterize and quantify the main hydrologic alterations in the different river types of a semiarid Mediterranean basin (Segura River), using an indirect index and two sets of hydrologic indicators, and (2) determine the effects of flow regime alteration on fluvial habitats and riparian conditions for each type. The Segura River Basin is highly suitable for this purpose, as it presents a wide range of natural flow regimes (Belmar *et al.*, 2011) and is also one of the most regulated basins in Europe (Ministry for the Evironment, 2004), with water demands exceeding 224% of that available and only 4% of runoff reaching the river mouth (Zimmer, 2010).

Hydrologic alteration was expected to present different patterns and effects for each river type. It was hypothesized that main stems would present the greatest hydrologic alteration due to increasing water demands and dams along their longitudinal axis, and in particular, an inversion in their seasonal pattern and a reduction in their inter- and intrannual flow variability, as has been observed in other Mediterranean basins. However, tributaries were expected to present specific alterations associated with their individual management, dependent on natural flow regimes and land use configurations. Only punctual flow reductions with unaltered seasonal patterns were predicted in the stable and permanent flows of headwater watersheds in forested areas due to the presence of small water abstractions. Streams with seasonal flow variations or even temporary regimes located in mid- and lowlands with large crop areas and flood control dams were expected to show a significant reduction both in flow magnitude and variability, as well as the greatest alteration in floods and droughts.

Such hydrologic alterations were anticipated to cause an overall reduction in fluvial habitat and riparian quality, although distinct effects were also expected in each river type. It was hypothesized that discharging large volumes of water from dams into main stems to address irrigation demands could produce increased channel dimensions, the homogenization of aquatic habitats, predominant turbulent flows and coarse substrates, lessen the diversity of aquatic and native riparian vegetation and increase alien species. At the opposite extreme, flow regulation by dams in more seasonal or even temporary streams should exacerbate droughts and cause a reduction of aquatic habitats and the invasion of riparian vegetation in channels.

Methods

Study area

The management area of the Segura River Basin, one of the most arid zones in the Iberian Mediterranean Region, presents four broad flow regime types (Belmar *et al.*, 2011): main stem rivers, with an average annual discharge greater than 2 m^3/s; perennial stable streams, which never cease flowing and have low seasonal flow variation; seasonal streams, which have a marked seasonal variation and eventually cease flowing (although perennial surface water persists); and temporary streams, without any flow more than 20% of the time. These river types were defined through a hydrologic classification developed using modelled natural flows and 73 indices that comprise monthly and annual measurements of flow magnitude central tendency and dispersion, as well as measurements of drought and flood duration. Moreover, they have biological significance, as they present distinct macroinvertebrate communities (Belmar *et al.*, 2012).

Despite the relatively small size of the basin (18 870 km^2), the coexistence of these four flow regimes is explained by a strong climatic and altitudinal gradient from NW to SE. Climate ranges from wet (>1000 mm mean annual precipitation) and cold in the NW mountains (>1000 m.a.s.l.) to semiarid and hot in the SE lowlands (<350 mm mean annual precipitation), where autumnal storms can discharge up to 300 mm in hours. Mean annual temperatures range between 10 and 18 ºC (CHS, 2007). This altitudinal and climatic gradient is coupled with a corresponding population density gradient. The river network has low population densities in the forested headwaters, intermediate densities in the agricultural midlands and highly populated cities in the lowlands (Mellado, 2005).

The Segura River Basin is one of the most regulated hydrologic networks in Spain and Europe. Irrigation (responsible for 90% of water demands) constitutes the main anthropogenic pressure on stream flows. The high regulatory capacity in the basin (770 hm^3, over 90% of the natural input) is provided by 24 dams that are more than 10 m in height (Grindlay *et al.*, 2009; Grindlay *et al.*, 2011) and 121 weirs higher than 2 m (CHS, 2007). Many small dams have been constructed in seasonal and temporary streams for flood control, but they constitute agricultural reservoirs that distribute water to irrigation channels. Additionally, two large water management infrastructures can be found in the basin. First, the Tagus-Segura interbasin water transfer, which leads water from the Tagus River to the Talave reservoir (in the Mundo River, the main tributary of the Segura River). The transferred volumes (a mean of 325 hm^3 yr^{-1}) are used for irrigation (62%) and human supply through the “Mancomunidad de Canales del Taibilla” (24%), the entity that manages more than 90% of water for human supply in the basin (CHS, 2007). Second, the Taibilla channel, which is used to conduct the transferred volumes for human supply and additional resources extracted from the Taibilla stream.

These intense pressures on water resources have resulted in the overexploitation of surface waters and a mean groundwater extraction of approximately 478 hm^3/year (over 80% of the natural recharge), and as a consequence, water demands have created structural hydrologic deficits that cannot be mitigated even with the Tagus-Segura transfer (Gil-Olcina, 2000).

Hydrological alteration

Hydrologic alteration was assessed using two approaches. First, an indirect index computed from variables associated with alterations in the basin provided a global measurement for each habitat sampling site. Second, two sets of hydrologic alteration indicators were calculated from gauged records to characterize and quantify the alteration in those streams and rivers with appropriate data series.

The indirect index, based on Falcone *et al.* (Falcone *et al.*, 2010a; Falcone *et al.*, 2010b), was derived using the surface of irrigated land (%), number of dams (count) and their regulatory capacity (hm^3), as they are associated with the main hydrologic alterations in the basin (Belmar *et al.*, 2010). Sampling sites were assigned between 0 to 8 points for each variable based on their percentile value within the data range. Then, those points were added for all three variables, providing an index which ranges potentially from 0 (minimum flow alteration) to 24 (maximum flow alteration).

Gauged data were obtained from the Spanish Hydrographic Studies Center (CEH) database (CEH, 2010) and consisted of flow series recorded before and after the main alterations (dam construction, mainly) in rivers representative of each hydrologic type.

A minimum of 15 years (Martínez & Fernández, 2006) and an optimum of 20 years (Richter *et al.*, 1997) of records were considered for analyses to ensure the inclusion of wet, average and dry periods. Given the limited hydrologic information representing unaltered regimes in the basin, only seven gauging stations were selected, four in main stems (Mundo and Segura Rivers, type 1) and one in each tributary type (Taibilla stream, type 2; Argos stream, type 3; and Mula stream, type 4) (Table 1). In general, series conducted before the dams' construction were used as "pre-impact" data, whereas the "post-impact" data consisted of the most recent gauged series. However, given their long history of hydrological alteration, the "pre-impact" data for main stems consisted of series preceding the greatest (i.e. most recent) flow regime alteration.

The two sets of hydrologic indicators were implemented using specialized software: the "Indicators of Hydrologic Alteration" (IHA), developed by The Nature Conservancy (based on Richter *et al.*, 1996), and the "Indicators of Hydrologic Alteration in Rivers" (IAHRIS), developed specifically for Mediterranean rivers by the Polytechnic University of Madrid (based on Martínez & Fernández, 2006). The latter has been used by the Spanish Ministry to evaluate the degree of flow regime alteration and the impact of dams in various Spanish basins and to aid the definition of environmental flows (Magdaleno *et al.*, 2009; Magdaleno, 2009).

The IHA software computes 33 hydrologic indices. As Mortenson & Weisberg (Mortenson & Weisberg, 2010) proposed, and given the high redundancy of hydrologic metrics (Olden & Poff, 2003), a subset of the indices that change consistently with dam construction (Graf, 2006; Magilligan & Nislow, 2005) was selected to represent the flow regime changes for each hydrologic type (Table 2a). The IHA software enables users to implement the Range of Variability Approach (RVA) described in Richter *et al.* (1997). The full range of "pre-impact" data for each index is divided into three different percentile categories: low (≤33rd), middle (34th to 67th) and high (>67th). The program then computes the frequency with which the "post-impact" values of the IHA indices fall within each classification. Finally, a Hydrologic Alteration factor is calculated for each grouping as: "(observed frequency - expected frequency) / expected frequency". A positive value means that the frequency has increased from the "pre-impact" to the "post-impact" period (maximum: infinity), while a negative value means the opposite (minimum: -1).

Table 1. Selected dams in the Segura Basin by hydrologic type, year of construction, main uses associated (EP: Electric power, FC: Flood control, HS: Human supply, I: Irrigation, WT: Water transfer) and flow series analysed

Dam	River	Hydrologic type	Year	Capacity (Hm^3)	Natural series	Altered series	Main uses	Other significant impacts
Fuensanta	Segura	Main stem rivers (type 1)	1933	210	1913 - 1928	1987 - 2007	I/FC/EP	
Cenajo	Segura	Main stem rivers (type 1)	1960	437	1929 - 1960	1986 - 2006	I/FC/EP	Fuensanta dam
Talave	Mundo	Main stem rivers (type 1)	1918	35	1943 - 1978	1979 - 2006	WT/I/FC/EP	Tajo-Segura transfer (1978 - ...)
Camarillas	Mundo	Main stem rivers (type 1)	1960	36	1961 - 1978	1979 - 2006	I/FC/EP	Talave dam, Tajo-Segura transfer
Taibilla	Taibilla	Stable streams (type 2)	1955,1979*	9.1	1916 - 1949	1979 - 1995	HS	
Argos	Argos	Seasonal streams (type 3)	1974	10	1914 - 1929	1988 - 2008	I/FC	
La Cierva	Mula	Temporary streams (type 4)	1929	7	1913 - 1927	1986 - 2006	I/FC	

* Years for the dam and water pumping station, respectively

Table 2. Selected (a) “Indicators of Hydrologic Alteration” (IHA) and (b) “Indicators of Hydrologic Alteration in Rivers” (IAHRIS) with ecological significance for habitats and riparian plants (Martínez & Fernández, 2006; The Nature Conservancy, 2007)

a)

IHA Group	Main effects	Hydrologic parameters
Magnitude of monthly water conditions	Habitat availability for aquatic plants and water resources for riparian bands	December median flow August median flow
Magnitude and duration of annual extreme water conditions	Lateral movement of channel and creation of physical habitat, which involves plant colonization and the distribution of these plants in lakes, ponds and floodplains	7-day maximum flow 7-day minimum flow Base flow Zero-flow duration
Frequency and duration of high and low pulses	Influence on bedload transport, channel sediment textures and substrate grain size	High pulse count Low pulse count High pulse duration Low pulse duration
Rate and frequency of water condition changes	Stress on plants and influence on mechanical stress (e.g. incission on tributaries)	Rise rate Fall rate Number of reversals

b)

IAHRIS Aspect	Main effects	Hydrologic parameters
Habitual values (variability)	Stress on plants and influence on mechanical stress (e.g. incission on tributaries)	Coefficient of variation of annual volumes Coefficient of variation of monthly **Global Conservation Index**
Droughts (magnitude - variability)	Maintenance of water table levels or saturated sediments and encroachment of riparian vegetation into channel	Average minimum daily flows along the year (Qs) Coefficient of variation of Qs **Global Conservation Index for droughts**
Floods (magnitude - variability)	Flush of woody debris, purge of invasive species, shape of channel and river-floodplain connection	Average maximum daily flows along the year (Qc) Magnitude of effective discharge (Q_{GL}) Magnitude of connectivity discharge (Q_{CON}) Coefficient of variation of Qc **Global Conservation Index for floods**

The IAHRIS software classifies years as wet, average or dry according to the location of their annual volumes in the first (dry), second (average) or third (wet) quartile. Seven indicators based on magnitude, variability and seasonality are computed to characterize habitual values, whereas eight indicators characterize the flood events and seven the drought events. Alteration is assessed by dividing the altered value by the value corresponding to the natural or reference state. The variation interval is restricted between 0 (the most degraded situation or maximum alteration) and 1 (optimum situation or minimum alteration). Only indicators that complemented the IHA indices were selected (Table 2b); in particular, those associated with the intra- and interannual flow variability and extremes (floods and droughts) as well as the global indicators for habitual, flood and drought values (which define the hydrologic conservation state).

Habitat and riparian surveys

Sites in freshwater streams (conductivity <5000 µS cm^{-1}) were selected both in reference and impaired conditions for each hydrologic type. Impaired sites were located in streams regulated by dams, but in the absence of other impacts. Habitat and riparian surveys were undertaken in dry-weather months (Environment Agency, 2003), when natural droughts and flow regulation are at their highest in the study area. A total of 65 sampling sites (Fig. 1) were visited between 2010 and 2011.

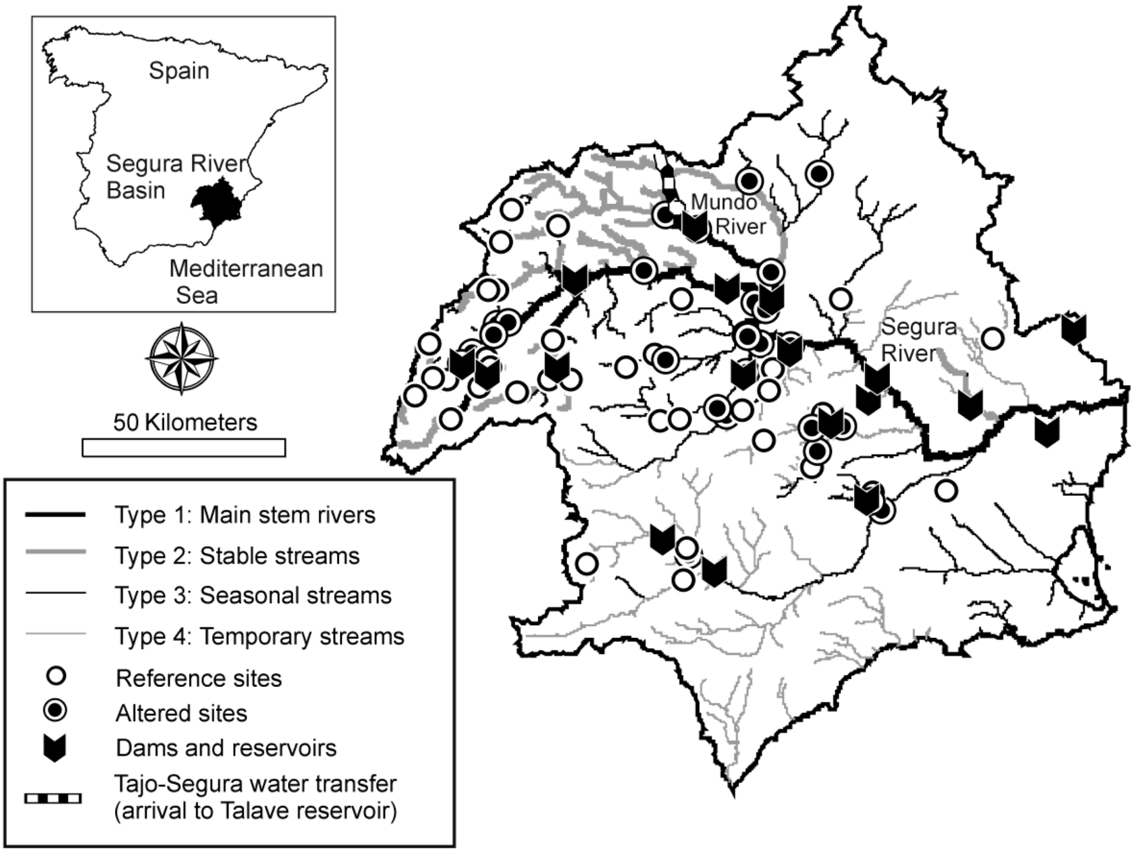


Figure 1. Study area and sampling sites (reference and altered), indicating the hydrologic types and the location of the main water infrastructures (dams and arrival of the Tagus-Segura water transfer)

Physical habitat was characterized at each site using the River Habitat Survey (RHS) (Environment Agency, 2003; Raven *et al.*, 1997), adapted for the MARCE project (IH Cantabria, 2012). The RHS is the standard riverine hydromorphology survey in the UK that has also been used extensively in numerous countries across Europe and beyond for site quality appraisal, habitat feature inventories (Manel *et al.*, 2000; Raven *et al.*, 2010; Szoszkiewicz *et al.*, 2006a), management planning (Raven *et al.*, 2000; Walker *et al.*, 2002) and in a range of ecological research applications (e.g. species' habitat suitability;

Hastie *et al.*, 2003; Vaughan *et al.*, 2007). Designed to characterize and assess the physical structure of freshwater streams and rivers, the survey is carried out along a standard 500 m length of river channel. Flow types, substrates, channel and bank features and vegetation as well as special features such as very large boulders are considered. Observations are made at ten equally spaced spot-checks along the channel, while information on valley form and land use in the river corridor provide additional context. General information is recorded using a sweep-up checklist that assesses the extent of features over the entire 500 m river reach. The version for the MARCE project recorded the channel dimensions at each spot-check, the presence of woody and leafy debris and additional mesohabitat types (areas exhibiting similar hydraulic characteristics, in terms of water depth and velocity, visually discernible). The Habitat Quality Assessment (HQA) (Raven *et al.*, 1998), a heterogeneity measure derived from RHS data to express the diversity of features considered to engender habitat "quality", was also applied. This metric allows the integration of widely used habitat characteristics to diagnose potential impacts on biota (Balestrini *et al.*, 2004; Erba *et al.*, 2006; Szoszkiewicz *et al.*, 2006b) in one score and nine sub-scores (flow type, channel substrate, channel features, bank features, bank vegetation structure, in-stream channel vegetation, land use within a 50 m buffer, trees and associated features, and special features).

Within each 500 m reach, riparian condition was assessed using the Riparian Quality Index (RQI) (González del Tánago *et al.*, 2006; González del Tánago & García de Jalón, 2011) and by making an inventory of riparian woody plants and distinguishing between native and exotic species. Moreover, the RQI sub-indices provided additional information concerning longitudinal continuity, width, composition, structure and natural regeneration as well as bank condition, transversal connectivity between the riparian corridor and the river channel, and riparian soil (permeability and condition).

Habitat and riparian data analyses

A total of 64 variables were obtained from the 14 RHS attributes associated with the hypotheses (see Results, Table 5). When possible, categorical variables were quantified by splitting their categories into new variables and using their proportional extension along the 500 m reach. Then, using all derived variables, a distance matrix was compiled among sites for subsequent analyses employing the Gower Dissimilarity

Index (Gower, 1971), which can handle the coexistence of quantitative, semiquantitative and missing values (Gower, 1971; Legendre & Legendre, 1998; Podani, 1999).

A Principal Coordinate Analysis (PCoA) was employed to examine dominant intercorrelation patterns among the RHS variables and define ordination axes that described the major sources of variation while also minimizing redundancy (i.e. multicollinearity). A hydrologic interpretation was assigned to each selected axis according to its correlation (Spearman) with the habitat variables and location of the sampling sites in the plot, considering their hydrologic type and condition (reference or altered). Additionally, Permutational Multivariate Analyses of Variance (PERMANOVA) were used to test the overall discrimination of habitat features by hydrologic type in reference and altered conditions. Mann-Whitney U tests were performed to explore differences between reference and altered sites in individual RHS variables, HQA and RQI scores and sub-scores, as well as the number of native and exotic riparian plants, which allowed sets of indicators that change with hydrologic alteration to be obtained. An adjusted p-value was computed to avoid family-wise errors (Siegel, 1956; Siegel & Castellan, 1988) and correct the effect of the number of samples (Tukey, Unpublished Work).

Gower dissimilarities were performed with the FD v 1.0.11 (Laliberté & Shipley, 2011) package for R (R Development Core Team, 2011). PCoA, DistLm and PERMANOVA were carried out using PRIMER v 6.1.12 (Clarke & Gorley, 2006) software. Mann-Whitney U tests were developed in STATISTICA v 6.0 (Statsoft, 2001).

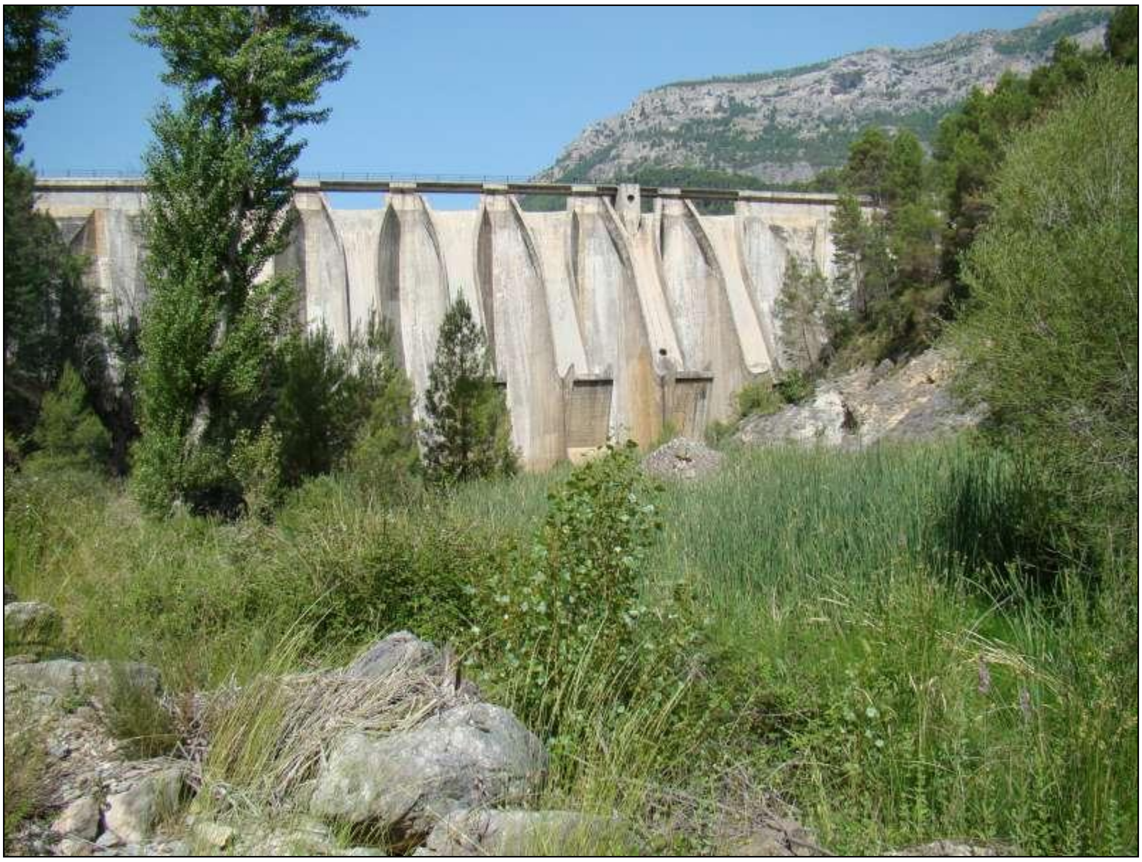
Results

Hydrologic alteration

The indirect alteration index provided values that ranged between 0 and 5 at reference stations and between 6 and 12 for hydrologically altered stations. The greatest values were obtained in main stem rivers (type 1) and the lowest in stable streams (type 2), whereas seasonal (type 3) and temporary (type 4) streams presented intermediate values (Table 3). However, the hydrologic alteration analysis from representative gauged series presented a different alteration gradient, with the seasonal streams as the most altered (Table 4).

Table 3. Average and extreme values for the indirect alteration index by hydrologic type

		Alteration index		
Hydrologic type	n	Minimum	Maximum	Average
Main stem rivers (type 1)	14	1	10	7.07
Stable streams (type 2)	15	1	7	2.53
Seasonal streams (type 3)	24	0	12	4.83
Temporary streams (type 4)	11	0	10	3.73



Anchuricas Dam

Table 4. Results for the (a) Indicators of Hydrologic Alteration (IHA) and (b) Indicators of Hydrologic Alteration in Rivers (IAHRIS) for the flow series associated with each dam. Note that the IHA include the results for the three percentile categories: low (≤33rd), middle (34th to 67th) and high (>67th). Blank cells indicate indetermination

a) Indicators of Hydrologic Alteration (IHA)	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High
December median flow	1.59	-0.62	-0.85	1.74	-0.74	-1.00	-0.14	-0.04	0.18	0.38	-0.91	0.73	-1.00	2.00	-1.00	1.86	-0.86	-1.00	2.10	-0.88	-1.00
August median flow	-0.54	0.52	-0.09	0.11	-0.09	-0.02	-0.79	-1.00	1.79	-0.88	-1.00	2.11	-1.00	-0.65	1.65	1.29	-0.29	-1.00	-1.00	-1.00	2.25
7-day maximum flow	2.20	-1.00	-1.00	-0.15	1.15	-1.00	-1.00	-0.79	1.79	-1.00	-1.00	2.22	2.00	-1.00	-1.00	1.86	-0.86	-1.00	1.48	-0.50	-0.85
7-day minimum flow	2.43	-0.67	-1.00	2.00	-1.00	-1.00	1.14	-0.46	-0.68	1.65	-0.72	-0.77	-1.00	-1.00	2.00	2.00	-1.00	-1.00	1.63	-0.75	-0.69
Base flow	0.83	-0.62	-0.09	2.00	-1.00	-1.00	2.00	-1.00	-1.00	2.22	-1.00	-1.00	-1.00	-1.00	2.00	2.00	-1.00	-1.00	1.63	-0.50	-1.00
Zero-flow duration		-0.07	0.52		-0.04			-0.04			-0.25			0.00			-0.76	3.05			5.50
High pulse count	3.00	-1.00	-1.00	0.30	0.47	-0.80	-0.77	0.19	0.50	0.29	-0.25	0.48	2.00	-1.00	-1.00	5.43	-0.82	-0.86	-1.00	-0.90	2.10
Low pulse count	-0.39	0.74	-0.81		-0.44	1.20	-0.74	-0.26	0.71	-0.74	-0.14	0.84		0.50	-1.00		-0.29	0.79	-1.00	-1.00	3.33
High pulse duration		-1.00	0.52	-0.43	-0.61	1.45	-0.86	0.29	1.29	-1.00	-1.00	2.50	-1.00	-1.00	-1.00	-0.46	-1.00	-1.00	1.68	-0.07	-0.59
Low pulse duration	0.02	-0.39	1.29	-0.67	-0.10	2.59	-0.23	1.22	-0.74	-0.11	0.68	0.21	-0.53	-1.00	-1.00	-0.05	0.43	1.14	3.33	-1.00	-1.00
Rise rate	1.59	-0.49	-1.00	-1.00	-0.15	1.15	-1.00	-0.36	1.36	-1.00	-1.00	2.22	2.00	-1.00	-1.00	1.71	-0.86	-0.86	-1.00	-1.00	2.25
Fall rate	0.52	-0.62	0.22	0.57	0.43	-1.00	0.39	0.38	-0.88	2.22	-1.00	-1.00	-1.00	-1.00	2.00	-0.86	0.29	0.57	2.25	-1.00	-1.00
Number of reversals	2.24	-1.00	-0.39	1.61	-0.61	-1.00	-0.89	1.89	-1.00	1.88	-0.72	-1.00	-1.00	-1.00	2.43	-1.00	-0.86	1.86	-1.00	-0.88	2.10

b) Indicators of Hydrologic Alteration in Rivers (IAHRIS)	Fuensanta	Cenajo	Talave	Camarillas	Taibilla	Argos	Mula
Coefficient of variation of annual volumes	0.23	0.26	0,43*	0.34*	0.14	0.11	0.61
Coefficient of variation of monthly volumes	0.75	0.82	0,79*	0.66	0.85	0.71	0.81
Global Conservation Index for Habitual Values	0.19	0.33	0.28	0.30	0.26	0.05	0.46
Hydrologic status for Habitual Values	Moderate	Moderate	Moderate	Moderate	Moderate	Bad	Good
Average minimum daily flows along the year (Qs)	0.24	0.05	0.51	0.79	0.50*	0.02	0.00
Coefficient of variation of Qs	0,87*	0.56	0,83*	0,33*	0.30	0,39*	0.00
Global Conservation Index for Droughts	0.20	0.12	0.57	0.43	0.10	0.07	0.02
Hydrologic status for Droughts	Moderate	Poor	Good	Good	Poor	Poor	Bad
Average maximum daily flows along the year (Qc)	0.08	0.28	0,76*	0.59*	0.07	0.27	0.60
Magnitude of effective discharge (Q_{GL})	0.27	0.39	0.91	0,96	0.20	0.56	0.86
Magnitude of connectivity discharge (Q_{CON})	0.00*	0.00*	0,18*	0.40*	0.00*	0,01*	0,51*
Coefficient of variation of Qc	0.67	0.15	0.20	0.18	0.13	0,75*	0,65*
Global Conservation Index for Floods	0.06	0.09	0.14	0.18	0.02	0.13	0.47
Hydrologic status for Floods	Poor	Poor	Poor	Moderate	Bad	Poor	Good

* Inverse values (the altered indicator is higher than the reference)

Main stem rivers (type 1)

In the Segura River, the Fuensanta dam caused a reduction of flows throughout the year except in August, when a slight inversion in the natural pattern occurred (Fig. 2a). There was a decrease in minimum, maximum and base flows, as well as an increase in the zero-flow duration (Table 4). A great reduction in the number of high pulses was also registered, as well as an increase in the duration of low pulses. Both the rise rate and the number of reversals decreased. Moreover, there was a relevant reduction in the coefficients of variation of habitual flows, especially in the monthly volumes. Floods presented the greatest global alteration, which was evident considering the reduction in the magnitude of maximum daily flows and the effective discharge. However, the connectivity discharge showed a huge increase, and the global conservation status was moderate for habitual values and droughts and poor for floods as a result. Downstream, the construction of the Cenajo dam exacerbated the inversion of the natural flow regime produced by the Fuensanta reservoir, reducing the magnitude of flows from autumn to spring and the opposite in summer (Fig. 2b). There was also a reduction in the magnitude of minimum and base flows and an increase in the number and duration of low pulses, as well as in the rise rate and duration of the high pulses (Table 4). Floods and droughts presented a poor status, emphasizing the reduction of the minimum daily flows over the year and the coefficient of variation of the maximum ones. Whereas maximum daily flows decreased, the connectivity discharge rose.

The Tagus-Segura Transfer (1978-…) in the Mundo River produced a huge increase in flow magnitude and a great modification in the regime downstream from the Talave reservoir (Fig. 2c). Maximum flows and December and August median flows increased, whereas minimum and base flows decreased (Table 4). Altered flows presented a higher number of low and high pulses (the latter more long-lasting) and a greater rise rate. Contrary to what was observed in previous cases, the coefficients of variation for habitual flows rose. Floods suffered the highest alteration again, with an important reduction in their coefficient of variation. However, droughts presented a good conservation status, despite the reduction experienced by the minimum daily flows and the increase in their coefficient of variation. Downstream, the Camarillas dam created a similar alteration pattern (Fig. 2d), with an increase in the August median flow and a reduction in minimum and base flows (Table 4). High pulses became more durable, yet less frequent. Moreover, whereas the rise rate decreased, the fall rate increased. The lowest global alteration was that for droughts, which presented a good conservation status despite the reduction in minimum daily flows and increased coefficient of variation (Table 4). Habitual values and floods presented a moderate conservation status.

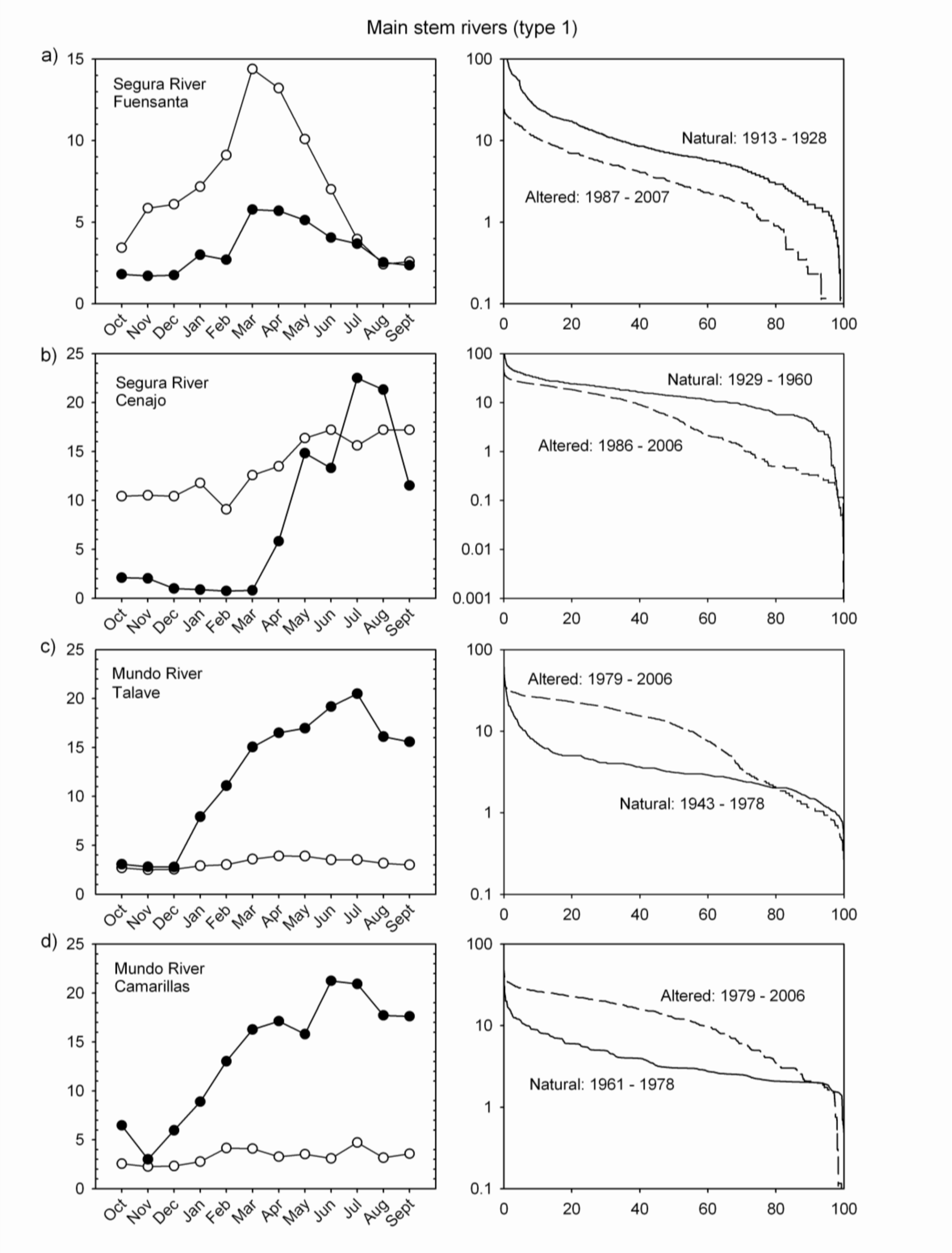


Figure 2. Hydrographs and flow duration curves for reference (white dots) and altered (black dots) flow series. Note that median flows ("y" axis) are in m^3/s and time ("x" axis) is shown monthly or by percentage, respectively

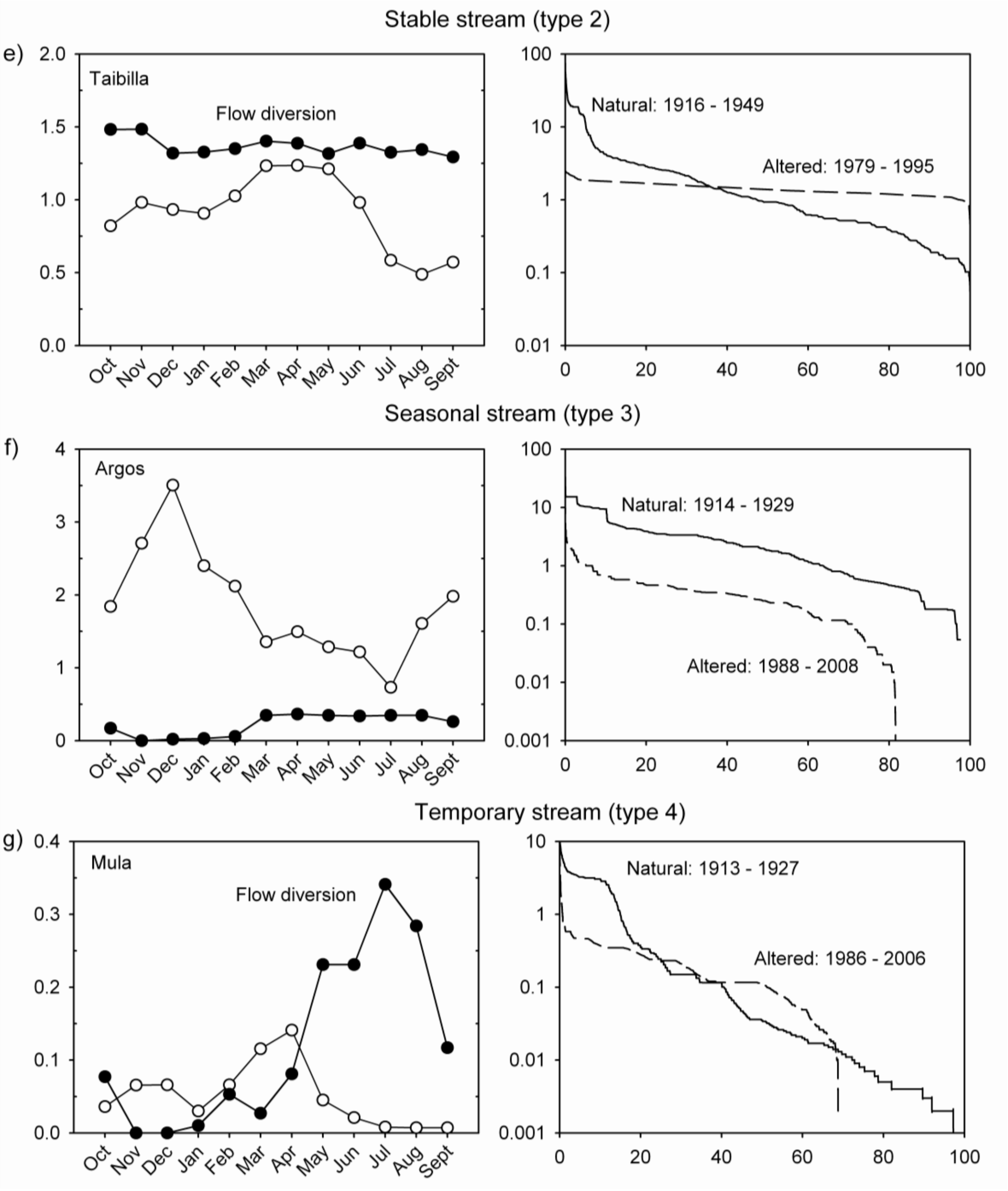


Figure 2 (continued). Hydrographs and flow duration curves for reference (white dots) and altered (black dots) flow series. Note that median flows ("y" axis) are in m^3/s and time ("x" axis) is shown monthly or by percentage, respectively

Stable streams (type 2)

Due to its importance for the human water supply, the Taibilla stream represents the main example of flow regime alteration in stable streams, which are usually unregulated or present only small abstractions. The Taibilla reservoir was constructed in 1979 to derive water for urban use from a pumping station 4 km downstream, which desiccated the river bed and drastically changed the flow regime along the section separating the infrastructures. Water diversion was almost constant throughout the year and produced an increase in median monthly flows and a flattened flow duration curve associated with reduced flow variability (Fig. 2e). Maximum flows, the number of high pulses and the rise rate decreased, whereas minimum flows, base flows and the fall rate rose. Consequently, floods had the greatest global alteration (“bad” status), followed by droughts (“poor” status) and habitual values (“moderate” status) (Table 4).

Seasonal streams (type 3)

The Argos reservoir created both a significant reduction in monthly flows and an inversion of the natural flow regime downstream from the dam (Fig. 2f). There was a reduction in minimum, maximum and base flows, as well as a large increase in the zero-flow duration. A sharp decrease in the high pulse count and a slight increase in the low pulse count (more durable) were also recorded, as well as a decreased rise rate and an increase in the number of reversals (Table 4). Habitual values, droughts and floods reflected a “poor” or “bad” conservation status. Within habitual values, a greater alteration in the inter- than in the intrannual variation was evident. For droughts and floods, magnitude was the most altered aspect, emphasizing the huge increase in the connectivity discharge.

Temporary streams (type 4)

In the Mula stream, diversion channels link La Cierva reservoir with its associated agricultural areas. Irrigation demands require large water volumes in spring and summer (Fig. 2g), significantly reduce maximum, minimum and base flows and dramatically increase the zero-flow duration (Table 4). As a result, the droughts presented a “bad” conservation status. The channel remains dry during most of the year downstream.

The effect of hydrologic alteration on fluvial habitats and riparian condition

With 42.31% of variation explained, only the first two axes of the PCoA were selected, because the addition of a third axis only provided an additional 8.25% and did not facilitate the interpretation of results.

The first axis (30% variance) was positively correlated with broken standing waves, cobbles, vegetated rocks, complex banktop vegetation, liverworts, mesohabitat density, very large boulders and debris. However, clay substrates as well as those river beds that were dry and choked with vegetation (extensive emergent reeds) were negatively correlated (Table 5). These habitat characteristics were associated, respectively, with stable flows (headwaters and low order river sections) and variable flows (tributaries in low and arid sectors of the basin). Reference sites were distributed along a gradient from stable streams (type 2) and main stem rivers (type 1), located on the positive extreme, to seasonal (type 3) and temporary (type 4) streams, on the negative extreme (Fig. 3).

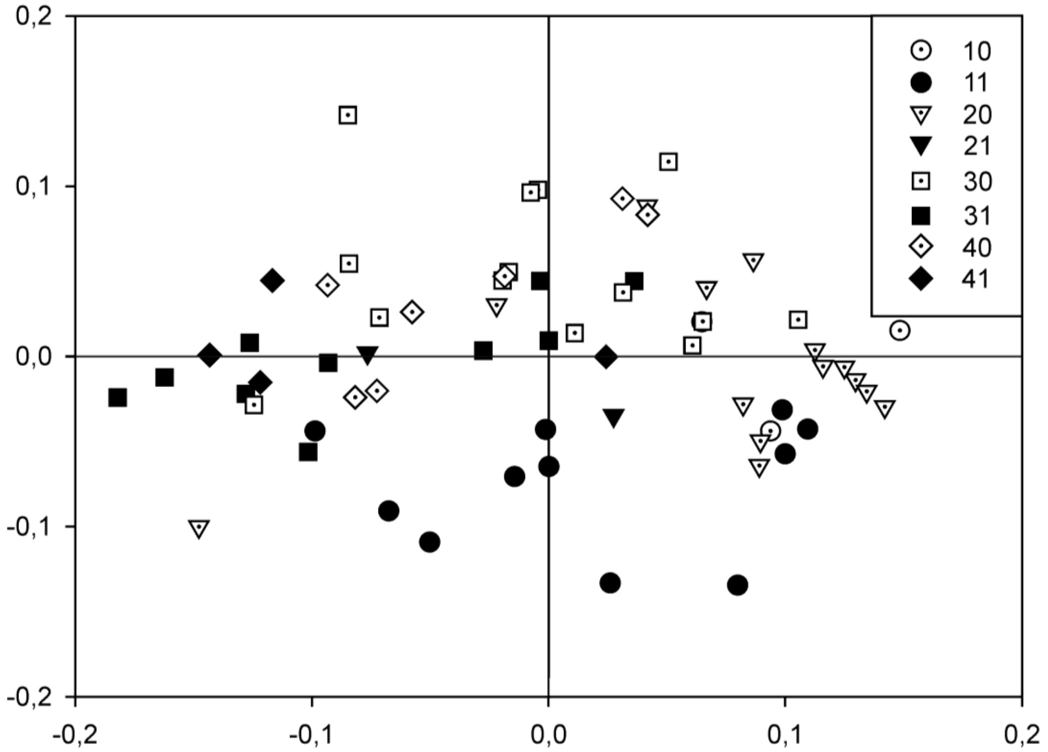


Figure 3. Biplot of the Principal Coordinate Analysis for the RHS samples by category. Note that the first digit indicates the hydrologic type and the second digit the reference condition (0: reference, 1: altered)

The second axis (12.4% variance) was positively correlated with smooth flow types, uniform or bare banktop vegetation and mesohabitat density, particularly the number of glides and steps, whereas it was negatively related to channel dimensions (water and channel width as well as depth), complex banktop vegetation, broken standing waves, the number of rapids and absence of in-channel debris (Table 5). Impaired sites belonging to main stem rivers (type 1) that presented turbulent flow regimes as a result of large flow releases from the biggest dams were located on the negative extreme (Fig. 3). Therefore, this axis reflected habitat characteristics associated with a gradient in flow magnitude and turbulence, from relatively low and laminar flows (positive extreme) to high and turbulent flows (negative extreme).

Table 5. Correlation between the RHS variables derived (“New variable”) and the two first Principal Coordinates (“PCo1” and “PCo2”). Units: “/1”, parts per unit; “m”, meters; “Count”, number of features; “SQ”, semiquantitative variable; “P/A”, binary (presence/absence) variable

Original variable	New variable	Units	PCo1	PCo2
Channel substrate	Bedrock	/1	-0.07	0.50
	Boulder (≥256 mm diameter)	/1	0.45	-0.10
	Cobble (64-256 mm diameter)	/1	0.71	-0.13
	Gravel/Pebble (2-64 mm diameter)	/1	0.32	0.18
	Sand (0.06-2 mm diameter)	/1	0.18	0.05
	Silt (≤0.06 mm diameter)	/1	-0.30	-0.03
	Clay (≤0.06 mm diameter)	/1	-0.58	0.46
	Earth	/1	-0.33	-0.21
Flow type	Broken standing waves	/1	0.62	-0.32
	Smooth	/1	-0.05	0.55
	No perceptible	/1	-0.48	0.22
	Dry (no water)	/1	-0.48	-0.10
	Rippled	/1	0.31	-0.24
	Unbroken standing waves	/1	0.37	0.01
Marginal & Bank Features	None	/1	-0.46	0.14
	Cliffs	/1	0.37	-0.06
	Bars	/1	0.37	0.10
Channel features	None - Channel	/1	-0.57	-0.11
	Exposed bedrock	/1	-0.06	0.36
	Exposed rock	/1	0.63	0.18
	Mature island	/1	0.32	-0.28
	Vegetated rock	/1	0.69	-0.10
Channel width		m	-0.05	-0.38
Water width		m	0.42	-0.45
Water depth		m	0.54	-0.40
Vegetation structure (banktop)	Complex	/1	0.70	-0.42
	Simple	/1	-0.03	-0.17
	Uniform	/1	-0.47	0.41
	Bare	/1	-0.07	0.42
Vegetation (channel)	None - Channel vegetation	/1	-0.07	0.02
	Liverworts/mosses/lichens - present	/1	0.74	0.15
	Liverworts/mosses/lichens - extensive	/1	0.47	0.03
	Emergent broad-leaved herbs - present	/1	0.20	0.30
	Emergent broad-leaved herbs - extensive	/1	-0.21	0.09
	Emergent reeds/sedges/rushes/grass/... - present	/1	0.40	-0.07
	Emergent reeds/sedges/rushes/grass/… - extensive	/1	-0.51	0.32
	Submerged broad-leaved - present	/1	0.13	0.25
	Submerged broad-leaved - extensive	/1	-0.03	0.24
	Submerged linear-leaved - present	/1	0.11	0.06
	Submerged linear-leaved - extensive	/1	-0.09	0.19
	Submerged fine-leaved - present	/1	0.05	0.21
	Submerged fine-leaved - extensive	/1	-0.13	0.17
	Filamentous algae - present	/1	0.23	0.17
	Filamentous algae - extensive	/1	0.00	0.09
Debris (channel)	None - Debris	/1	-0.41	-0.29
	Large woody debris - present	/1	0.12	-0.02
	Small woody debris - present	/1	0.53	0.25
	Leafy debris - present	/1	0.50	0.33
	Leafy debris - extensive	/1	0.02	0.22
Mesohabitats	Total number of mesohabitats	Count	0.67	0.51
	Number of waterfalls	Count	0.23	0.23
	Number of cascades	Count	0.36	0.18
	Number of trench flows	Count	-0.01	0.43
	Number of rapids	Count	0.74	-0.30
	Number of riffles	Count	0.57	-0.05
	Number of runs	Count	0.56	0.13
	Number of steps	Count	0.57	0.55
	Number of pools	Count	0.43	0.41
	Number of dammed pools	Count	0.29	0.30
	Number of glides	Count	-0.12	0.73
Physical features (channel)	Sedimentary deposits	SQ	0.32	0.22
Features of special interest	Very large boulders	SQ	0.60	-0.04
	Floodplain boulder deposits - present	SQ	0.27	0.07
Choked channel	Choked channel - present	P/A	-0.56	0.28

In general, impaired sites were located on the ordination plot to the left and bottom of their respective reference sites. Consequently, the observable effects of hydrologic alteration on habitats were those associated with an increase in flow seasonality or temporality (displacement to the negative part of the first axis) and an increase in magnitude and turbulence associated with large releases from dams (displacement to the negative part of the second axis), which was especially evident for main stem rivers (type 1).

PERMANOVA analyses (Table 6a) determined that under reference conditions there were no significant habitat differences between the main stems and stable streams (types 1 and 2), on one hand, or between the seasonal and temporary streams (types 3 and 4), on the other. However, when comparing reference and altered sites within each type, only main stem rivers (type 1) and seasonal streams (type 3) presented significant habitat differences (Table 6b). According to the Mann-Whitney U test (Table 7, Fig. 4), altered main stem rivers (type 1) presented wider channels as well as a lesser proportion of step mesohabitats and submerged macrophytes than their reference reaches. These changes were supported by a reduction in the HQA sub-score for channel vegetation as well as in the RQI sub-index for bank conditions. Seasonal streams (type 3) presented the greatest number of habitat features with significant changes under altered conditions, emphasizing a significant reduction in the number of mesohabitats (particularly runs, steps, pools and glides) and riparian native plant richness as well as a major proportion of uniform banktop vegetation. The HQA global score (as well as its flow type sub-score) and the RQI global value (as well as all its sub-indices) also presented a reduction in altered sites (Table 7, Fig. 4). Both main stems and seasonal streams displayed a decreasing linear relationship between the overall degree of hydrologic alteration (indirect index) and the quality scores (RQI and HQA) (Fig. 5). A hydrologic alteration equal to six (the minimum value detected in altered sites) constituted the threshold between “very good” and “good” riparian quality (RQI) for main stems and between “good” and “moderate” for seasonal streams (Fig. 5). However, in-stream habitat quality (HQA) was “moderate” at this degree of alteration in main stems and changed from “moderate” to “poor” in seasonal streams (Fig. 5).

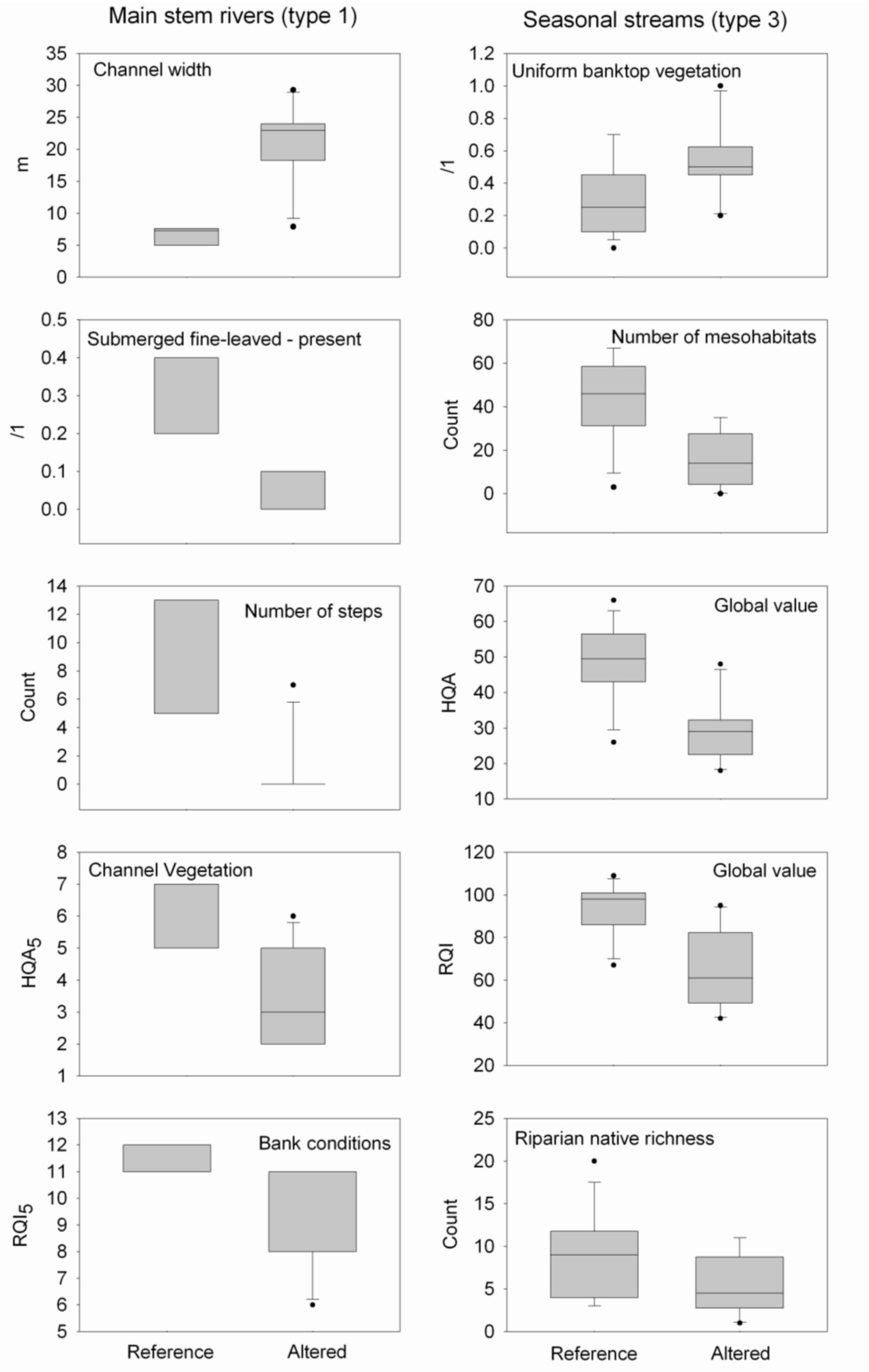


Figure 4. Box-plots summarizing the RHS variables and quality scores that significantly differ in reference and altered conditions in main stem rivers and seasonal streams. Note that the central line corresponds to the median, the box borders to the 25th and 75th percentiles, the whiskers to the minimum and maximum and the dots to outliers

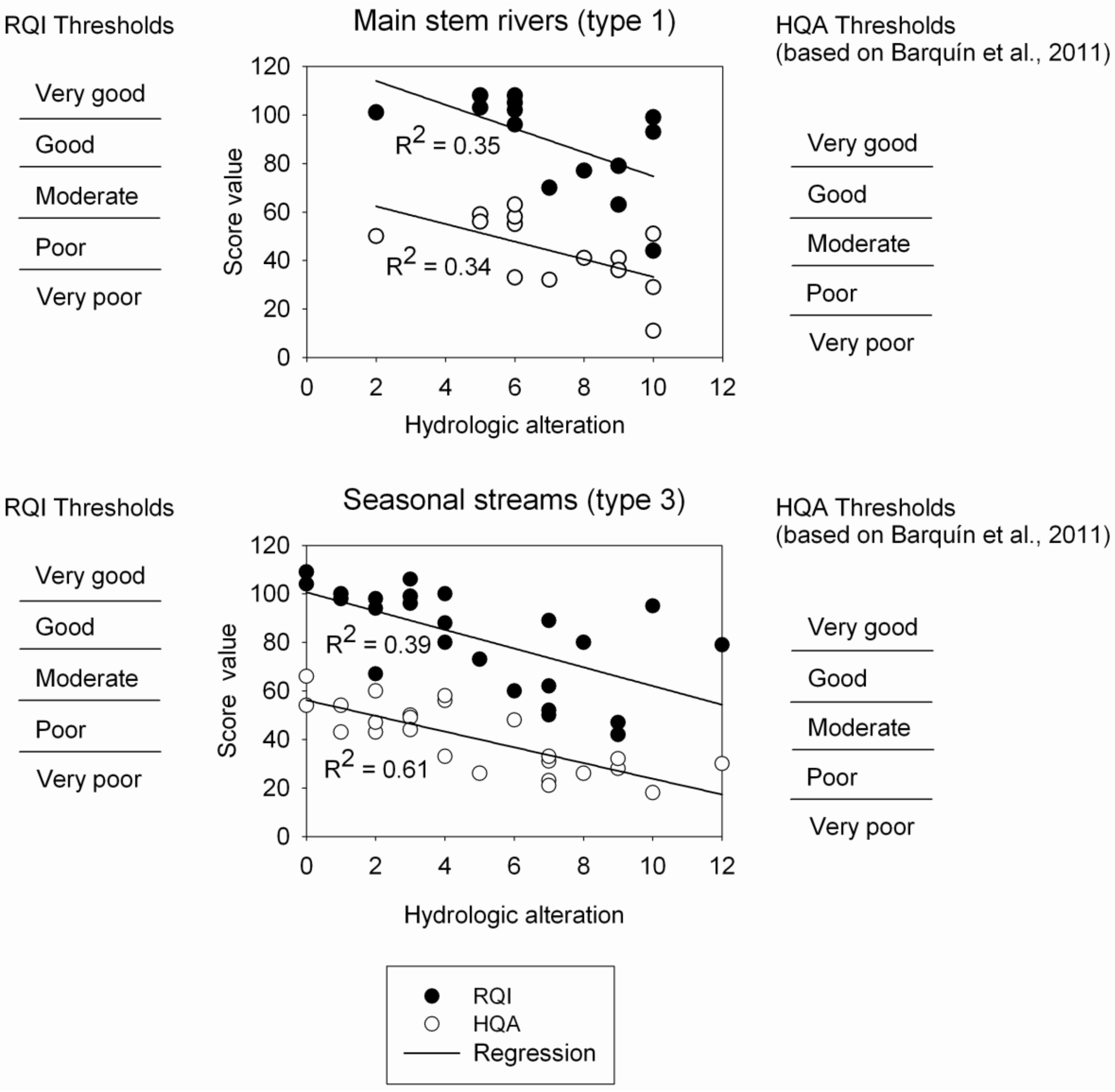


Figure 5. Regression ($p < 0.05$) of the Riparian Quality Index (RQI) and Habitat Quality Assessment score (HQA) on the indirect index of hydrologic alteration for main stem rivers and seasonal streams

Despite the overall lack of differences between the habitats in reference and altered sites within stable (type 2) and temporary streams (type 4), significant reductions in specific features such as riparian quality (bank conditions and transversal connectivity), for the former, and the presence of submerged fine-leaved macrophytes, for the latter, were also detected (Table 7).

Table 6. PERMANOVA pair-wise comparisons of habitat characteristics (a) among hydrologic types in reference conditions and (b) between reference and altered conditions within each hydrologic type. Note that every group is composed of two digits: hydrologic type and condition (0: reference, 1: altered) respectively

a)

Groups	t	p
10, 40	**1.72**	**0.01**
20, 10	0.95	0.49
20, 30	**1.87**	**0.00**
20, 40	**1.87**	**0.00**
30, 10	**1.54**	**0.01**
30, 40	0.83	0.81

b)

Groups	t	p
10, 11	**1.77**	**0.03**
20, 21	1.25	0.13
30, 31	**1.72**	**0.01**
40, 41	0.84	0.72

Significant pairs ($p<0.05$) are indicated in bold

Table 7. Significant Mann-Whitney U tests for the derived RHS variables, riparian plants richness and HQA and RQI scores and sub-scores

Hydrological type	RHS original variable/Score	RHS derived variable/Richness/Score meaning	Change	Adjusted p
Main stem rivers (type 1)	Channel width	-	+	0.01
	Water width	-	+	0.01
	Vegetation (channel)	Submerged fine-leaved - present	-	0.01
	Mesohabitats	Number of steps	-	0.02
	HQA_5	Channel vegetation	-	0.02
	RQI_5	Bank conditions	-	0.02
Stable streams (type 2)	RQI_5	Bank conditions	-	0.03
	RQI_6	Transversal connetivity	-	0.03
Seasonal streams (type 3)	Flow type	Smooth	-	0.02
	Vegetation structure (banktop)	Uniform	+	0.03
	Vegetation (channel)	Emergent reeds/sedges/rushes/grass/... - present	-	0.01
	Mesohabitats	Total number of mesohabitats	-	0.00
	Mesohabitats	Number of runs	-	0.04
	Mesohabitats	Number of steps	-	0.01
	Mesohabitats	Number of pools	-	0.01
	Mesohabitats	Number of glides	-	0.03
	HQA	Global value	-	0.00
	HQA_1	Flow type	-	0.00
	RQI	Global value	-	0.00
	RQI_1	Longitudinal continuity	-	0.00
	RQI_2	Width	-	0.01
	RQI_3	Composition and structure	-	0.02
	RQI_4	Natural regeneration	-	0.00
	RQI_5	Bank conditions	-	0.00
	RQI_6	Transversal connetivity	-	0.02
	RQI_7	Pemeability and condition of riparian soil	-	0.00
	-	Native riparian species richness	-	0.05
Temporary streams (type 4)	Vegetation (channel)	Submerged fine-leaved - present	+	0.04

Discussion

Hydrologic alteration

Rivers and streams in the Segura Basin experienced changes in flow regimes similar to those described in other Mediterranean arid and semiarid areas. In general, dams reduce flow magnitude and variability and invert seasonal patterns (Graf, 2006; Walker *et al.*, 1995). However, it is acknowledged that the effects of such water infrastructures on flow regime are more pronounced in Mediterranean areas than in other temperate zones due to storage needs and great reservoir capacities that respond to naturally scarce water resources (Batalla *et al.*, 2004; López-Moreno *et al.*, 2009; Lorenzo-Lacruz *et al.*, 2010). In fact, in the Ebro Basin (NE Spain), floods have been described to be more affected by reservoirs in its southern Mediterranean tributaries than those in the Atlantic zone, even with similar impoundment levels (Batalla *et al.*, 2004). In the Segura Basin, the significant alteration observed in flow regimes is mainly due to water demands that exceed the available resources (Gil-Olcina, 2000), creating a structural deficit that has been further accentuated in recent decades by decreasing precipitation trends (CHS, 2005).

Differences arose depending on the tool used to define hydrologic alteration. With the proposed indirect index, main stem rivers presented the greatest hydrologic alteration, due to the higher regulatory capacity of their reservoirs, whereas stable streams showed the lowest (except the Taibilla stream), as most of them did not include dams or any other notable human pressures in their watersheds. Seasonal and temporary streams displayed an intermediate degree of alteration, with lower storage capacities in their reservoirs but large agricultural areas in their basins. However, the indicators of hydrologic alteration (IHA and IAHRIS), which take into consideration all aspects of flow regime (habitual, drought and flood values), concluded that seasonal streams experienced the greatest hydrologic alteration. As a consequence, the management regulations in dams (not only their capacity) also play a fundamental role when quantifying hydrologic alteration in streams and rivers.

As expected, the applied indicators revealed different patterns of hydrologic alteration (by stream types). Alterations mainly included changes in flow magnitude (maximum, minimum and base flows), in the inter- and intrannual variability as well as in drought and flood regimes. Main stem rivers demonstrated a progressive inversion in their flow regimes as new reservoirs appeared along the channel, producing a longitudinally increasing gradient of hydrologic alteration. Like other Mediterranean rivers (Batalla *et al.*, 2004; Boix *et al.*, 2010; Lorenzo-Lacruz *et al.*, 2012), the Segura River displayed this inversion in its seasonal pattern due to the retention of fall and winter peaks as well as to summer flow releases by dams for irrigation. It also presented reduced flow magnitude and variability, as reported by previous studies (Gil-Olcina, 2000; López-Bermúdez, 2004; Vidal-Abarca, 1990). However, the Mundo River had a more pronounced inversion and, in particular, a large increase in flow magnitude and variability due to the Tagus-Segura transfer (intended to meet agricultural demands). The outstanding importance of this water transfer in the hydrologic alteration suffered by the Tagus, Mundo and Segura rivers has been stated (Lorenzo-Lacruz *et al.*, 2010; Lorenzo-Lacruz *et al.*, 2012). Additionally, in the near future, an increase in the hydrologic alteration of the Segura River is also expected due to the recent construction of a tunnel from the Talave to the Cenajo reservoir, which will transfer water from the Mundo to the Segura River 20 km upstream from their natural confluence.

The tributaries presented specific alterations according to their water management. Stable streams with perennial and stable flows throughout the year underwent the least alteration because of the low agricultural demands in their forested watersheds. However, the Taibilla stream experienced a great alteration in droughts and floods, given the sustained derivation of flows to guarantee an almost constant discharge for urban demands.

Seasonal streams (e.g. the Argos stream) located in agricultural midlands with flood control and irrigation reservoirs presented a notable reduction in monthly flows and an inversion of flow seasonality downstream from the dam with a considerable increase in the duration of droughts and a decrease in the frequency and magnitude of floods. Finally, in temporary streams (e.g. Mula stream), droughts were intensified by the excessive water abstraction directly from the reservoir for irrigation purposes, which greatly reduced the water available downstream (see Belmar *et al.*, 2010).

In summary, two hydrologic alteration trends were observed: increased flow torrentiality in main stem rivers and increased flow temporality in seasonal and temporary streams.

Hydrologic alteration-habitat relationships

Flow stability/variability and flow magnitude have proven to be the major determinants of fluvial habitats and riparian condition in the Segura Basin. Flow variability is related to morphological, hydraulic and biological characteristics (Jowett & Duncan, 1990). In the present study, flow stability was associated with channel morphology and vegetation, favouring coarse substrates, aquatic macrophytes (particularly liverworts and vegetated rocks), mesohabitat diversity and the complexity of banktop vegetation. Moreover, it prevented the channel from being choked with emergent vegetation and promoted the appearance of leafy and small woody debris. Its important role in determining the composition and richness of macroinvertebrates in the study area has already been shown (Belmar *et al.*, 2012). However, low flows were associated with habitat characteristics such as smooth flow types, fine sediments, poorly developed banktop vegetation and reduced mesohabitat density.

Altering these determinants produced changes in the overall physical habitat in main stem rivers and seasonal streams, with decreasing habitat and riparian quality as the degree of alteration increased. In main stems, the releases from big dams to address irrigation demands involved increased channel dimensions, the homogenization of aquatic habitats and absence of in-channel debris. This homogenization reduced mesohabitat density and the presence of submerged vegetation, which contributed to a decrease in the quality of channel vegetation and banks. These habitat changes explain the negative effects described by Navarro-Llácer *et al.* (2010) on macrophyte, macroinvertebrate and fish communities downstream from the Talave dam in the Mundo River. In hydrologically altered seasonal streams, the most prominent effect was a decrease in the richness of mesohabitats and riparian native species, with a reduction in the complexity of banktop vegetation and the occasional invasion of riparian or upland woody species into the channel. A reduction in the frequency and/or intensity of flood scouring leads to a terrestrialization of fluvial ecosystems. Drought intensifications and decreasing groundwater accelerate the loss of phreatophyte species, which have the lowest tolerance to dry conditions (e.g. *Salix alba* in Mediterranean rivers, González *et al.*, 2012), and lead to the establishment of riparian vegetation that is more tolerant of long dry periods, such as *Tamarix* species (Nippert *et al.*, 2010) and the reed *Phragmites australis* (Brock *et al.*, 2006). Channel encroachment by riparian or upland woody vegetation has also been observed globally in semiarid and arid systems, presenting serious implications for hydrology and ecology (Huxman *et al.*, 2005). Such vegetation patches block flows and divert them around and above their canopy. As a result, velocities decrease substantially within the vegetation patch, promoting the accumulation of fine sediments with a high nutrient content (Cotton *et al.*, 2006; Sand-Jensen & Mebus, 1996), although they increase in surrounding open areas, tending to erode and become modified into chute channels (Schnauder & Sukhodolov, 2012; Wolfert *et al.*, 2001).

River corridors regulated by dams represent major conduits for the invasion of alien species, favouring the spread of cosmopolitan, non-indigenous species at the expense of locally adapted native biota (Poff *et al.*, 2007). An example in the western United States is the expansion of *Tamarix* and the contraction of *Populus* native species (Birken & Cooper, 2006; Merritt & Poff, 2010), associated with periods of extensive river damming (Braatne *et al.*, 2008; Dixon & Johnson, 1999; Friedman *et al.*, 1998; Johnson *et al.*, 1995). However, contrary to expectations, there was no relationship in the Segura Basin between the richness of riparian exotic species and the hydrologic alteration by the dams, which could be due to the relatively low richness of exotic species in Mediterranean basins (e.g. Salinas & Casas, 2007; Tabacchi *et al.*, 1996).

Despite the fact that temporary streams experience pressures similar to those suffered by seasonal streams, the effects of flow regulation by dams on habitats and riparian condition were less clear. The higher natural inter- and intrannual flow variability that characterises this type and communities that persist through natural disturbances of floods and droughts as well as their temporal and spatial variability (Brock *et al.*, 2006) can mask the effects of flow regulation. Finally, in stable streams that are subject to low flow alteration (characterised by a habitual lack of dams), reduced flow magnitude only negatively affected riparian quality (bank condition and transversal connectivity).

This study determined the habitat indicators and quality scores sensitive to short- and long term flow regime alterations in the different river types present in the Segura

Basin. The quantification of flow alteration-habitat relationships for main stem rivers and seasonal streams allowed the identification of those thresholds in which the degree of hydrologic alteration produced significant changes in habitat and riparian quality. The RQI was more sensitive to flow alteration than the HQA. This fact was not surprising considering that even small changes in water levels may induce observable changes in vegetation composition and structure (Nilsson & Svedmark, 2002). Additionally, the use of habitat heterogeneity as a surrogate of habitat quality in the HQA score has been questioned in other temperate basins (Barquín *et al.*, 2011).

The information presented here is essential for water management as well as fluvial ecosystem conservation and restoration, and highlights the flow regime components needed to preserve habitat features and native biota. These findings have implications for water planning, as they may be useful for dam management and the development of environmental flow regimes in this basin or in other similar Mediterranean areas. Further research must focus not only upon determining the effects of flow and habitat alteration on aquatic communities and their implications on regional and global biodiversity, but also on the effects of expected climate change on unimpaired and impaired rivers.

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Appendix

Examples of the two main hydrologic alteration trends observed in the Segura River Basin

1. Increased torrentiality produced by large dams in main stem rivers

Segura River, Paules. Release of flows from *La Fuensanta* dam

Segura River, Gallego. The great oscillations in the water table are evident

Examples of the two main hydrologic alteration trends observed in the Segura River Basin (continued)

2. Increased temporality in seasonal and temporary streams, with encroachment by vegetation

Pliego River, downstream from the dam

Quípar River, Rivazo

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Conclusions

Segura River, source-Poyotello

1. The main metrics that defined flow regime types in the Segura River Basin were the mean annual flow, the interannual coefficient of variation and the duration of droughts.

2. A classification of 8 types was considered to be the optimum solution to encompass the hydrologic variation along the NW-SE aridity gradient in the study area. For management purposes, 4 broader types with biological significance must be used: *main stem rivers*, *perennial stable streams*, *perennial seasonal streams* and *temporary streams*.

3. Given their low performance discriminating hydrologic variation, the use of environmental (*a priori*) hierarchical classifications as surrogates of those based on hydrologic data is inadvisable when such information is available. The REC-Segura only matched the NW-SE hydrologic pattern broadly, whereas the ecotypes in streams located in dry or semiarid climates embraced different flow regimes (both perennial and intermittent).

4. Flow stability and minimum flows were the principal hydrological drivers of macroinvertebrate assemblages in the Segura River Basin, whereas the magnitude of average and maximum flows had limited effects. These effects were more evident on composition than on richness, and as taxonomic resolution increased.

5. A relevant relationship between flow magnitude-stability and the ratio of EPT/EPTOCHD taxa was found. Perennial stable streams were characterised by flow-sensitive lotic taxa (EPT; Ephemeroptera, Plecoptera, Tricoptera) and intermittent streams by predominately lentic taxa (OCHD; Odonata, Coleoptera, Heteroptera and Diptera).

6. Flow stability and magnitude were the main hydrologic drivers of the fluvial habitats in the Segura River Basin, which explains their effect on macroinvertebrate assemblages.

7. In general, dams reduced flow magnitude and variability and inverted seasonal patterns, although two other trends were also observed in specific stream types: increased flow torrentiality in main stem rivers and increased temporality in seasonal and temporary streams. Dam operation rules, not only their capacities, determined the degree of hydrologic alteration.

8. Hydrologic alteration produced clear changes in habitats and riparian characteristics in the study area. In main stems, releases from big dams involved an increase in channel dimensions, the homogenisation of aquatic habitats and absence of vegetal debris with a reduction in the density of mesohabitats and presence of submerged vegetation. However, a “terrestrialisation” associated with reductions in mesohabitat and riparian vegetation richness and occasional channel encroachments by riparian or upland woody species were evident in seasonal streams. Despite the reduced richness of riparian native species, no increase in the richness of exotics was observed.

9. Both main stems and seasonal streams presented consequent reductions in habitat and riparian qualities as the degree of alteration increased. The Riparian Quality Index (RQI) was more sensitive to flow alteration than the Habitat Quality Assessment (HQA).

10. The results obtained are essential for water management as well as fluvial ecosystem conservation and restoration, and highlight the hydrologic regime components needed to preserve habitats and native biota in the Segura River Basin. Therefore, seasonal variation and minimum flows are key hydrological components that need to be considered when defining environmental flows in Mediterranean and temperate basins, as climate change will presumably accentuate aridity in these areas.